Radiant Heat Transfer between Nongray Directional Surfaces

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Real surface property effects on local and over-all heat transfer are studied for a simple system of interacting opaque surfaces. Wavelength, temperature and directional dependence of surface properties is included in the analysis for equal and unequal temperature specularly reflecting surfaces. Tungsten is employed as a representative metal and Roberts' model is used to describe the wavelength and temperature dependence of its optical parameters. The relationships of electromagnetic theory are employed to describe the directional dependence of spectral properties. Numerical results establish that gray direction independent property analysis adequately predicts the general trends of real surface analysis. The results also establish that spectral and temperature dependence of surface properties influences radiant heat transfer to a greater degree than does directional dependence of properties. Property models which adequately account for the nongray character of engineering surfaces while neglecting directional dependence of properties can provide heat transfer results of acceptable engineering accuracy.

Nomenclature

c	= speed of light in vacuum
dA	= surface area element
e_b	= emissive power of a black body
f_n	= function defined in Eq. (4)
G	= dimensionless absorbed irradiation defined in Eq. (3)
H	= absorbed irradiation or irradiation
k	= absorption index
n	= refractive index
q	= local heat-transfer rate per unit area
Q	= over-all heat-transfer rate per unit width
r_n	= length of ray between elements defined in Eq. (5)
R_λ	= monochromatic emissive power ratio, $[e_{b,\lambda}(T_2)/e_{b,\lambda}(T_1)]$
x, y	= dimensionless coordinates
$\beta_{om}, \delta_m, \lambda_{sm}, \lambda_{\tau n}, \sigma_n$	= parameters in Eq. (12)
γ	= opening angle
ε	= emittance
ε_0	= permittivity of free space
λ	= wavelength
θ	= polar angle
σ	= Stefan-Boltzmann constant

Subscripts

$'$	= primed quantities refer to surface 2
a	= absorbing element
e	= emitting element
r	= reflecting element
H	= hemispherical
λ	= monochromatic
γ	= open angle

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Introduction

RADIATION properties of engineering materials generally depend on wavelength, temperature, and direction of emitted and incident radiation. Such real surface characteristics may be broadly classified as nongray (wavelength and temperature) and directional dependencies. The influence of directional dependence of surface properties on radiant heat transfer between surfaces in the absence of nongray affects has received some attention.[1–4] Likewise, the influence of nongray characteristics of surface properties on radiant heat transfer with directional aspects neglected has been the subject of other studies.[5–9] It has been established[2,9] that when either nongray or directional property effects are accounted for, local heat flux may differ from that evaluated with property models which ignore such affects by a factor as large as two. With the exception of a study by Holt and Grosh[10] which gave results only for over-all radiant heat exchange, quantitative results are noticeably lacking for the combined influence of wavelength, temperature, and directional aspects of real surface properties on radiant heat transfer. It is the purpose of this study to provide such results as well as to investigate the relative importance of nongray and directional dependencies and to evaluate the magnitude of heat flux error incurred when simple direction independent gray property models are employed in analysis.

The system of interacting opaque surfaces selected for study consists of unit length plates of infinite width sharing a common edge and including angle γ (see Fig. 1). This system was chosen for a number of reasons. First, extensive results are available for radiant heat transfer using a gray spectral model for both direction dependent[2] and direction independent[11,12] surface properties. Second, this system has also been studied[9] ignoring directional property dependence while accounting for detailed wavelength and temperature dependence of material properties. Finally, unlike many geometries previously studied, the system can readily accommodate an external radiant flux, and, hence, analysis may be extended to include an important feature of the space environment; namely, a collimated solar flux. For the purposes of this study, each surface has a uniform temperature and uniform properties, external sources of radiant energy are absent, and the intervening medium is radiatively nonparticipating. The surfaces are taken as specular reflectors of radiant energy with directional properties described by

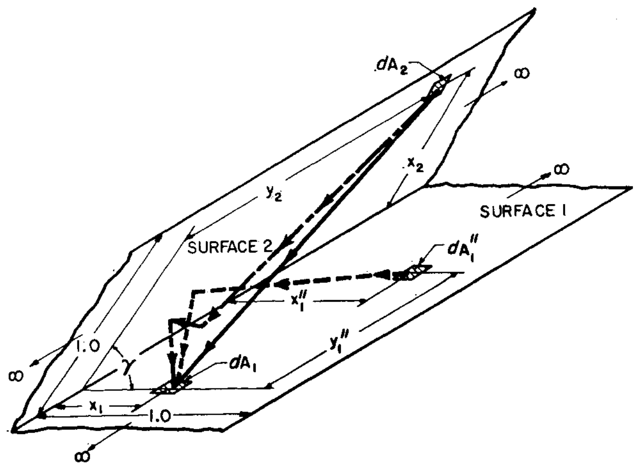

Fig. 1 Adjoint plate system.

electromagnetic theory. Wavelength and temperature dependence of properties are accounted for by Roberts' model for the optical parameters which are needed to evaluate the relations of electromagnetic theory. Energy transfer mechanisms other than radiative transport are ignored.

Analysis

Since each surface is isothermal and has uniform properties, local radiant heat flux on either plate depends only on the distance measured normal to the common edge. For purposes of discussion, the surfaces are hereafter denoted as 1 and 2 according to Fig. 1. Furthermore, primed property values will refer to surface 2 and unprimed to surface 1. Local monochromatic heat flux for a typical surface area element dA_1 $(= dx_1dy_1)$ of surface 1, $q_{1,\lambda}(x_1)$ is the difference between emission rate and rate of absorption of incident energy with wavelengths between λ and $\lambda + d\lambda$. Thus, on a per unit wavelength interval basis

$$q_{1,\lambda}(x_1) = \varepsilon_{H,\lambda}e_{b\lambda}(T_1) - H_{1,\lambda}(x_1) \tag{1}$$

where $H_{1,\lambda}$ denotes the local rate of absorption of incident radiation at wavelength λ. In Eq. (1), $\varepsilon_{H,\lambda}$ and $e_{b,\lambda}(T_1)$ represent monochromatic hemispherical emittance and monochromatic emissive power of a black surface at temperature T_1, respectively. For included angles in the interval $45° \leq \gamma < 60°$, the function $H_{1,\lambda}$ is given by the following relationship[2]

$$H_{1,\lambda}(x_1) = 2e_{b,\lambda}(T_1)R_\lambda \int_0^1 \int_0^\infty G_{1,\lambda}(x_1,x_2,y_2)dy_2dx_2 \tag{2}$$

where

$$R_\lambda = [e_{b,\lambda}(T_2)/e_{b,\lambda}(T_1)]$$

and

$$G_{1,\lambda}(x_1,x_2,y_2) = \varepsilon_{a,\gamma}\varepsilon_{e,\gamma}'f_\gamma + \frac{1}{R_\lambda}\varepsilon_{a,2\gamma}\varepsilon_{e,2\lambda}[1 - \varepsilon_{r,\gamma,11}']f_{2\gamma} + \varepsilon_{a,3\gamma}\varepsilon_{e,3\gamma}'[1 - \varepsilon_{r,\gamma,12}]\cdot[1 - \varepsilon_{r,\gamma,22}']f_{3\gamma} \tag{3}$$

with

$$f_\eta(x_1,x_2,y_2) = (x_1x_2\sin^2\eta/\pi)/r_\eta^4(x_1,x_2,y_2) \tag{4}$$

and

$$r_\eta(x_1,x_2,y_2) = (x_1^2 + x_2^2 + y_2^2 - 2x_1x_2\cos\eta)^{1/2} \tag{5}$$

A brief notation has been introduced for the monochromatic emittance in which $\varepsilon_{a,\gamma}$ and $\varepsilon_{e,\gamma}'$ denote $\varepsilon_\lambda(\theta_{a,\gamma})$ and $\varepsilon_\lambda'(\theta_{e,\gamma})$, respectively. The argument of the monochromatic emittance is the polar angle at which the emittances must be evaluated. The cosines of the various angles $\theta_{a,\eta}$ and $\theta_{e,\eta}$ may be evaluated in terms of the coordinates as

$$\begin{aligned}\cos\theta_{a,\eta} &= x_2\sin\eta/r_\eta(x_1,x_2,y_2)\\ \cos\theta_{e,\eta} &= x_1\sin\eta/r_\eta(x_1,x_2,y_2)\end{aligned} \tag{6}$$

The remaining factors of the form

$$\varepsilon_{r,\gamma,ij}(\varepsilon_{r,\gamma,ij}')$$

are the monochromatic emittance of surface 1[2] evaluated at $\theta_{r,\gamma,ij}$ where the subscripts i and j denote the ith reflection in a j-reflection sequence. The cosines of the angles $\theta_{r,\gamma,ij}$ at which monochromatic emittances must be evaluated as follows

$$\begin{aligned}\cos\theta_{r,\gamma,11} &= (x_1 + x_2)\sin\gamma/r_{2\eta}(x_1,x_2,y_2)\\ \cos\theta_{r,\gamma,12} &= (x_1\sin2\gamma + x_2\sin\gamma)/r_{3\eta}(x_1,x_2,y_2)\\ \cos\theta_{r,\gamma,22} &= (x_1\sin\gamma + x_2\sin2\gamma)/r_{3\eta}(x_1,x_2,y_2)\end{aligned} \tag{7}$$

The monochromatic radiative flux may then be written as

$$q_{1,\lambda}(x_1) = e_{b,\lambda}(T_1)\left[\varepsilon_{H,\lambda} - 2R_\lambda(T_1,T_2)\cdot \int_0^1\int_0^\infty G_{1,\lambda}(x_1,x_2,y_2;T_1,T_2)dy_2dx_2\right] \tag{8}$$

Equation (8) may be integrated over wavelength to give local radiant flux. Thus

$$q_1(x_1) = \int_0^\infty q_{1,\lambda}(x_1)d\lambda \tag{9}$$

or

$$q_1(x_1) = \varepsilon_H(T_1)e_b(T_1) - 2\int_0^\infty\int_0^1\int_0^\infty e_{b,\lambda}(T_1)R_\lambda(T_1,T_2)\cdot G_{1,\lambda}(x_1,x_2,y_2;T_1,T_2)dy_2dx_2d\lambda \tag{10}$$

In Eq. (10) $\varepsilon_H(T_1)$ and $e_b(T_1)$ denote the total hemispherical emittance and total block body emissive power $(= \sigma T_1^4)$ of surface 1 at temperature T_1. Finally, over-all radiative heat transfer is determined by integration of local flux over plate length

$$Q_1 = \int_0^1 q_1(x_1)dx_1 \tag{11}$$

Similar expressions for monochromatic radiative flux, total radiant flux, and over-all radiative heat transfer may be obtained for surface 2 from Eqs. (8, 10, and 11) by interchanging primed property values with unprimed and R_λ with $1/R_\lambda$.

Gray Analysis

Gray analysis ignores spectral and temperature dependence of radiation properties and yields expressions identical to those of Eqs. (1–11) except for the replacement of all spectral quantities with corresponding total (integrated over wavelength) values. For the purpose of distinguishing gray results presented later, the expression for total heat flux is written

$$q_i(x_i) = \varepsilon_{Hi}e_{bi} - \alpha_iH_i(x_i) \qquad (i = 1,2) \tag{12}$$

where ε_{Hi}, e_{bi}, and $H_i(x_i)$ are total hemispherical emittance at temperature T_i, total emissive power of a black surface at T_i $(= \sigma T_i^4)$, and total irradiation function for surface i, respectively. Symbol α_i denotes total absorptance of surface i. Values for α_i and the corresponding total reflectance ρ_i

($= 1 - \alpha_i$) in the equations of gray analysis distinguish the gray theory results presented later. Surface absorptances were approximated by evaluating the expression

$$\alpha_i = \frac{1}{\tilde{H}_i}\int_0^\infty \varepsilon_{Hi,\lambda}\tilde{H}_{i,\lambda}d\lambda \tag{13}$$

with $\tilde{H}_{i,\lambda}$ a representative spatially uniform irradiation function and $\tilde{H}_i$ the corresponding wavelength integrated value. It is also convenient at this point to let surface 1 be the higher temperature surface when plate temperatures are unequal.

In an earlier study,[9] four different gray calculations corresponding to different choices for the values of plate absorptance were investigated. Here we limit consideration to the two gray models designated as models A and D in the cited study. Gray model A employed total absorptance equal to total emittance for both surfaces ($\alpha_i = \varepsilon_{Hi}$). This model completely ignores the difference between emittance and absorptance and is valid for spatially uniform irradiation when the monochromatic emittances are wavelength independent. Model D, which was the most successful of the gray models in approximating the nongray results in the earlier investigation,[9] is motivated by observing that for highly reflecting metal surfaces, the spectral variation of irradiation absorbed by the surfaces is probably most closely represented by the spectral emissive power of the higher temperature surface. These absorptances correspond to the use of $\tilde{H}_{1,\lambda} = \tilde{H}_{2,\lambda} = \varepsilon_{H1,\lambda}e_{b1,\lambda}$ and $\tilde{H}_1 = \tilde{H}_2 = \varepsilon_{H1}e_{b1}$ in Eq. (13).

Surface Properties

One of the most uncertain aspects of heat-transfer calculations for engineering materials is an accurate representation for radiative properties. The most satisfactory technique is probably the use of property data of representative materials. Unfortunately, property measurements of sufficient scope in wavelength, temperature, and directional characteristics are not available for any material. It is useful, therefore, to employ theoretical models which have the general characteristics observed for classes of engineering materials.

Electromagnetic theory[13] provides expressions for the specular reflectance of optically smooth surfaces which are physically and chemically uncontaminated in terms of the optical indices of the material, polarization of the incident radiation, and the angle of incidence. In the present study, polarization of emitted and incident radiation is ignored and the expressions for directional emittance and reflectance for unpolarized radiation are employed.

In order to utilize the relationships of electromagnetic theory to evaluate spectral directional radiation properties, the wavelength and temperature dependence of the optical indices n_λ and k_λ are required. Roberts[14] extended Drude theory and incorporated some of the phenomena predicted by quantum theory in developing a relationship for the optical indices of a metal. By fitting data and using some physically motivated constraints, Roberts proposed the following expression for n_λ and k_λ of a metal

$$n_\lambda^2(1 - ik_\lambda) = 1 + \sum_m \frac{\beta_{om}\lambda^2}{\lambda^2 - \lambda_{sm}^2 + i\delta_m\lambda_{sm}\lambda} - \sum_n \frac{\lambda^2}{2\pi\varepsilon_0 c}\frac{\sigma_n}{\lambda_{\tau n} - i\lambda} \tag{14}$$

where $i = (-1)^{1/2}$ and ε_0 and c are permittivity of free space and speed of light in vacuum, respectively. The symbols β_{om}, λ_{sm}, δ_m, σ_n and $\lambda_{\tau n}$ denote empirical parameters which are generally temperature dependent and are determined from experimental data for application to a particular metal. Once the optical parameters n_λ and k_λ are evaluated, spectral directional and hemispherical properties for the optically smooth uncontamined surface may be determined by employing the relationships of electromagnetic theory.[13]

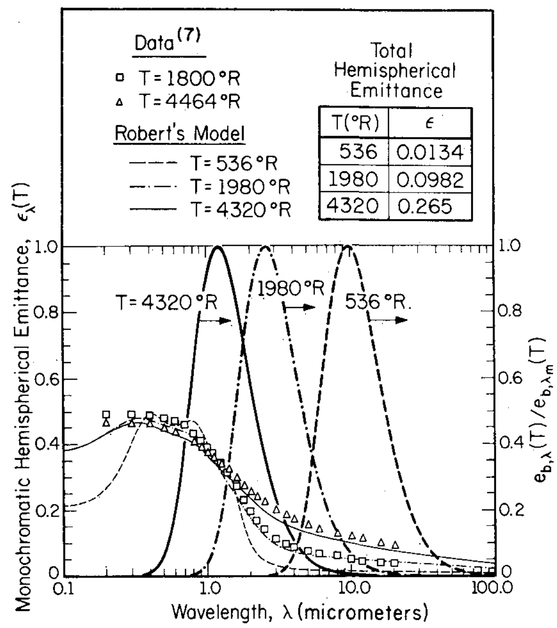

Fig. 2 Comparison of Roberts' property model to data for tungsten.

Tungsten is a convenient material to employ for investigating real surface property effects on radiative heat transfer because its spectral properties are well documented over a wide range of temperature and wavelength. Furthermore, Roberts has reported values for the empirical parameters of Eq. (12) for tungsten. These values were used in the relations of electromagnetic theory to evaluate spectral hemispherical emittance for tungsten. In Fig. 2, spectral hemispherical emittance calculated by this procedure is illustrated with data for tungsten. Although the temperature for the calculated emittance values and the data are not identical the results evaluated with the model generally exhibit the trends observed in the data.

Results

Nongray and directional effects on local and total radiant heat transfer were investigated for equal and unequal temperature tungsten plates for an included angle (γ) of 45°. The general character of local flux distribution and the over-all influence of emittance value as well as reflectance model on this distribution has been discussed elsewhere[11] and is not repeated here. Since the individual effects of spectral dependence[9] and directional property dependence[2] are not expected to significantly alter the general character of trends predicted using gray direction independent property models, emphasis is placed on the differences between the results which fully account for the spectral, temperature, and directional characteristics of the surface properties and those obtained with simpler property models. To differentiate various results the notation CP is used for direction independent property models (constant properties) and DP for direction dependent property models (directional properties).

Equal Temperature Surfaces

Dimensionless radiant flux distributions, $q(x)/\varepsilon_H\sigma T^4$, are illustrated in Fig. 3 for equal temperature tungsten plates at temperatures of 536°R, 1980°R, and 4320°R. Over this temperature range total hemispherical emittance increases twenty-fold from a value of 0.013 at 536°R to a value of 0.26 at 4320°R (see insert on Fig. 2). Distributions are presented for nongray and gray property models with directional and direction independent properties.

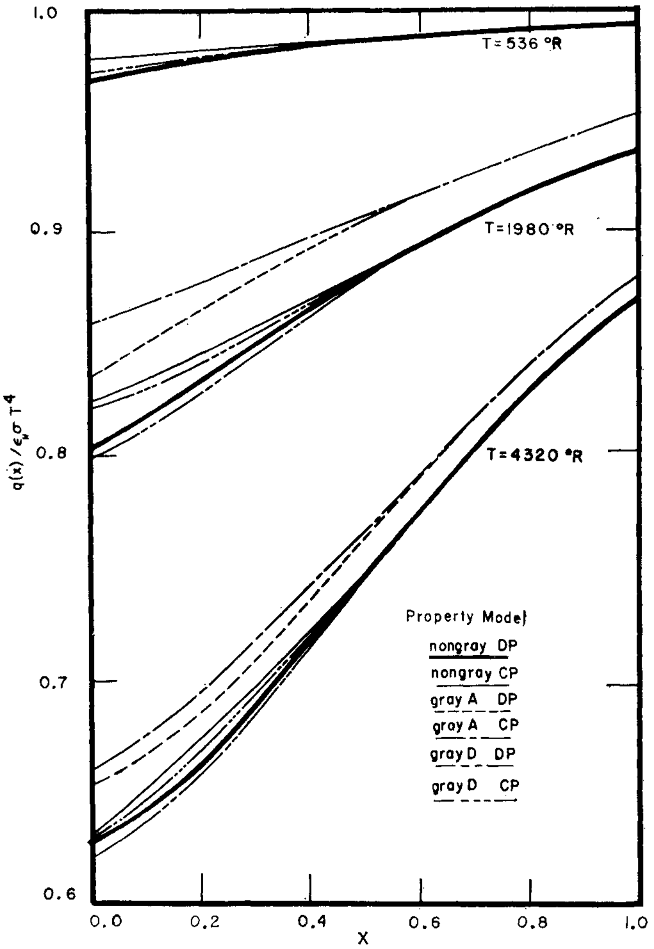

Fig. 3 Gray and nongray dimensionless radiant flux distribution for equal temperature tungsten plates ($\gamma = 45°$).

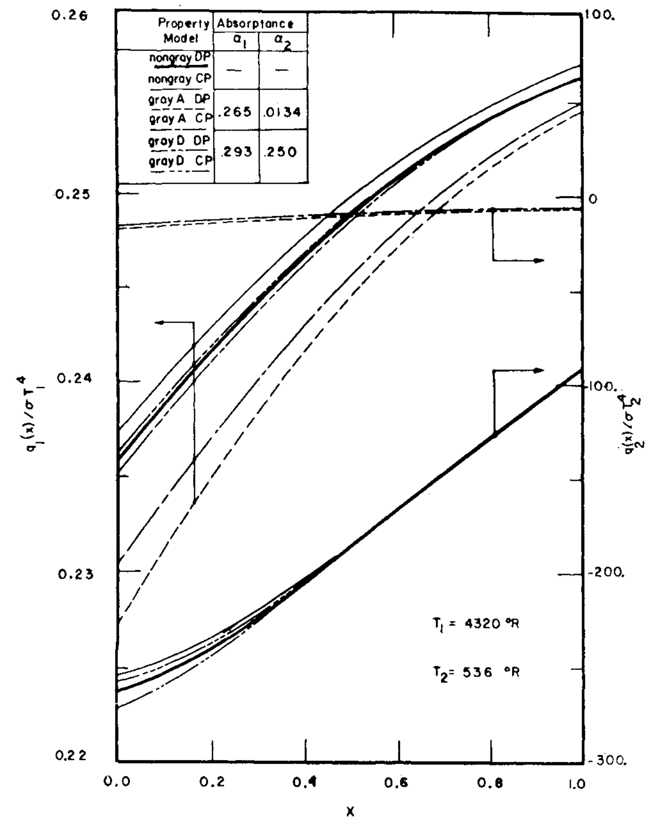

Fig. 4 Gray and nongray dimensionless radiant flux distributions for unequal temperature tungsten plates ($\gamma = 45°$, $T_1 = 4320°R$, $T_2 = 536°R$).

As expected, the general character of the flux distributions is not significantly influenced by the spectral, temperature, and directional dependence of surface properties. In accord with gray constant property analysis, local flux per unit emissive power decreases with increasing emittance. Furthermore, in agreement with the conclusions of an earlier study,[2] analysis which neglects directional property dependence for low emittance surfaces yields local flux values near the apex which are high. Thus, gray constant property analysis adequately predicts the general characteristics of the real surface results.

The results of Fig. 3 clearly indicates that for low emittance surfaces, the major error introduced by neglecting real surface characteristics is associated with the spectral and temperature dependence of surface properties. The directional dependence of surface properties is of secondary importance and for the conditions studied introduces a maximum error in local flux of approximately 3%. Gray model D with directional properties yields results which are in excellent agreement with the nongray directional properties result but even when this spectral model neglects directional property dependence, results of acceptable engineering accuracy are obtained.

A comparison of dimensionless over-all heat transfer, $Q/\sigma T^4$, based on gray and nongray analysis with both direction independent and direction dependent property models is presented in Table 1. Neglecting directional dependence of surface properties in nongray analysis introduces a small error of less than 1% in over-all heat transfer. Gray model D results are substantially in agreement with the real surface results and even Model A yields results of acceptable engineering accuracy. The results of Table 1 demonstrate that directional property effects have a negligible influence on total heat transfer.

Unequal Temperature Surfaces

Representative results for dimensionless radiant flux distributions are presented in Figs. 4 and 5 for unequal temperature plates with the high temperature surface at 4320°R. Results of Figs. 4 and 5 pertain to low temperature surfaces of 536°R and 1980°R, respectively.

It is evident from both Figs. 4 and 5 that the general character of the flux distribution calculated from gray constant property analysis continues to yield the trends observed

Table 1 Comparison of over-all dimensionless radiant heat transfer $Q/\sigma T^4$ for equal temperature tungsten plates ($\gamma = 45°$)

Temperature (°R)	Nongray		Gray DP		Gray CP	
	D	A	D	A	D	A
536	0.0132	0.0133 (−0.76)[a]	0.0132 (0.0)	0.0132 (0.0)	0.0132 (0.0)	0.0132 (0.0)
1980	0.0860	0.0866 (−0.70)	0.0859 (0.12)	0.0884 (−2.8)	0.0864 (−0.46)	0.0891 (−3.6)
4320	0.198	0.199 (−0.50)	0.198 (0.0)	0.203 (−2.5)	0.198 (0.0)	0.204 (−3.0)

[a] Percent error based on nongray directional results.

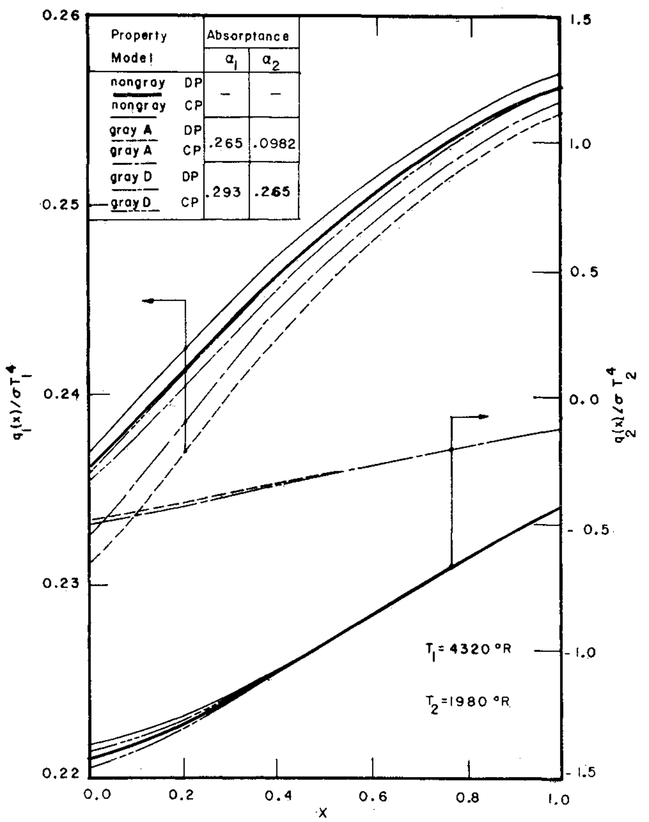

Fig. 5 Gray and nongray dimensionless radiant flux distributions for unequal temperature tungsten plates ($\gamma = 45°$, $T_1 = 4320°$R, $T_2 = 1980°$R).

in the nongray directional property results. Gray model A for direction dependent and constant properties underestimates local heat flux for the high-temperature surface and overestimates flux for the low-temperature surface. Although gray model A results yield acceptable accuracy for the high-temperature surface (maximum error less than 4%), large discrepancies between nongray and gray results are clearly evident for the low-temperature surface. Gray model D yields exceptionally accurate results which differ only slightly from those determined using nongray analysis. This should be expected since local heat flux of the low-temperature surface is dominated by the absorption of energy emitted by the high-temperature surface. Clearly, the absorptance evaluated with the high-temperature surface spectral emissive power corresponds to the physical situation very closely.

According to both Figs. 4 and 5, directional dependence of properties continues to be of secondary importance in comparison to the spectral and temperature dependence of surface properties insofar as local radiant heat flux is concerned. In fact, gray model D with a direction independent property model yields flux distributions in exceptional agreement with those for the real surface.

Table 2 presents dimensionless over-all radiant heat transfer values for unequal temperature specularly reflecting plates based on nongray and gray analysis both with and without direction dependent property models for a hot surface temperature of 4320°R. Neglecting the directional dependence of surface properties in nongray analysis introduces errors which do not exceed 1%. Gray model D with a constant property model yields total heat transfer in exceptional agreement with the real surface results. Gray model A results for the low-temperature surface are significantly in error with differences from the real surface results sometimes as large as a factor of two.

Conclusions

Analysis and results have been presented for local and over-all radiant heat transfer between interacting opaque tungsten surfaces which include the detailed spectral, temperature, and directional dependence of radiation surface properties. Roberts' model was used to account for the spectral and temperature dependence of surface properties. The results of electromagnetic theory for directional dependence of surface properties for specularly reflecting surfaces were utilized in the analysis. It has been demonstrated that gray analysis with a direction independent property model adequately predicts the general trends observed in real surface results. For the system studied, the results clearly indicated that the nongray character of real surface properties, namely the spectral and temperature dependence of surface properties, influences radiant heat transfer to a much greater degree than does directional property dependencies. Property models which adequately account for nongray characteristics of specularly reflecting surfaces while neglecting the directional dependence of surface properties in evaluating heat transfer can give results of acceptable engineering accuracy.

Table 2 Comparison of over-all dimensionless radiant heat transfer $Q_1/\sigma T_1^4$, and $Q_2/\sigma T_2^4$ for unequal temperature tungsten plates ($\gamma = 45°$, $T_1 = 4320°$)

T_2/T_1	Nongray		Gray DP		Gray CP	
	D	A	D	A	D	A
			High-temperature plate, $Q_1/\sigma T_1^4$			
0.124	0.248	0.249 (−0.4)[a]	0.248 (0.0)	0.244 (1.6)	0.248 (0.0)	0.245 (1.2)
0.458	0.248	0.249 (−0.4)	0.248 (0.0)	0.245 (1.2)	0.248 (0.0)	0.246 (0.81)
1.000	0.198	0.199 (−0.5)	0.198 (0.0)	0.203 (−2.5)	0.198 (0.0)	0.204 (−3.0)
			Low-temperature plate, $Q_2/\sigma T_2^4$			
0.124	−183.0	−182.0 (0.55)	−184.0 (−0.55)	−10.6 (94.0)	−183.0 (0.0)	−10.0 (94.0)
0.458	−0.953	−0.944 (0.94)	−0.957 (−0.42)	−0.308 (68.0)	−0.952 (0.10)	−0.298 (69.0)
1.000	0.198	0.199 (−0.5)	0.198 (0.0)	0.203 (−2.5)	0.198 (0.0)	0.204 (−3.0)

[a] Percent error based on nongray directional results.

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