Table 2 Average ignition delay in case of insoluble catalysts

Catalyst	I.D., sec
None	1.8
Cupric oxide	1.1
Cuprous oxide	1.0
Ammonium metavanadate	0.9
Sodium metavanadate	0.5
Potassium dichromate	0.4
Potassium permanganate	0.3
Potassium ferrocyanide	0.25

can be facilitated if the mechanism of the reaction between the fuel and the oxidizer leading to ignition is known. If the intermediate stage which takes longer time can be indentified, then one may think of a suitable catalyst for accelerating it. With this aim, a detailed study of the mechanism of the reaction between furfuryl alcohol and RFNA is, therefore, in progress.

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Effects of Polarization on Radiant Heat Interchange between Simply Arranged Surfaces

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Nomenclature

A = area
B_{i-j} = absorption factor
B_{e-j} = absorption factor for external incoherent radiation
E = emitted energy flux
I_b = intensity of blackbody radiation given by Planck's law
N = number of reflections in the enclosure
T = temperature
ϵ = emissivity
θ = angle between surface normal and ray
κ = $\epsilon_p(\theta)/\epsilon(\theta)$
ρ = reflectivity
σ = Stefan-Boltzmann constant
Ω = solid angle

Subscripts and superscripts

p,s = parallel and perpendicular planes of polarization, respectively
$*$ = polarized
1,2,3 = surfaces 1, 2, and 3

Introduction

THE effect of polarization is usually ignored in engineering calculations of radiant heat transfer. Edwards and Bevans[1] have, however, shown that the absorption of solar energy can be seriously in error if polarization is neglected, and Edwards and Tobin[2] have found that the transmittance of incoherent radiation through long passages is quite sensitive to polarization of radiation.

The purpose of this Note is to investigate the effect of polarization on the radiant heat transfer for some simple configurations of engineering interest. Three different geometrical configurations are considered, but for the sake of brevity, the problem is formulated only for configuration 1 (see Fig. 1). The plates are taken to be made of smooth isotropic materials of sufficient optical depth as to be opaque to nearly all the thermal radiation emitted by these bodies.

Analysis

Consider radiant heat exchange between two isothermal bodies 1 and 2 (see Fig. 1, configuration 1), one at temperature T_1 and another at temperature T_2, due to their own emission as well as an external incident radiation. Since the general problem is linear it can be separated into two subproblems and the general solution obtained by superposition of the two subproblems.[3] It is assumed in the analysis that the geometric optics theory is valid for radiant heat exchange and that the surfaces are separated by a nonabsorbing, nonscattering medium having a constant index of refraction. To reduce the number of parameters the radiation characteristics of the surfaces are assumed to be identical.

The energy emitted from the elementary area per unit area and time into the solid angle $d\Omega$ around the direction θ is

$$dE = dE_p + dE_s = \tfrac{1}{2}[\epsilon_p(\theta) + \epsilon_s(\theta)]I_b \cos\theta d\Omega \qquad (1)$$

Since the plane of emission and incidence for this energy is the same and the two surfaces are identical, the fraction of this energy absorbed[4] at surface 1, denoted by dB_{d1-1}, can be written as

$$dB_{d1-1} = \rho(\theta)[1 - \rho^{2N_1}(\theta)]/[1 + \rho(\theta)] \qquad (2)$$

Note that for a given geometry the number of interreflections N_1 at surface 1 depends not only on the polar angle θ but

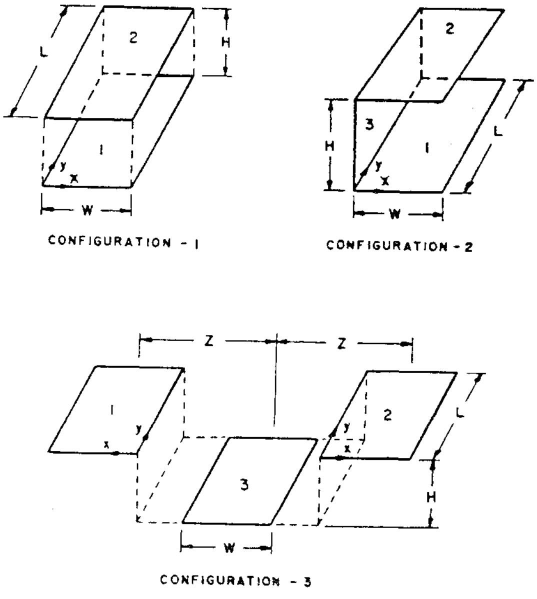

Fig. 1 Configurations analyzed; all surfaces specular.

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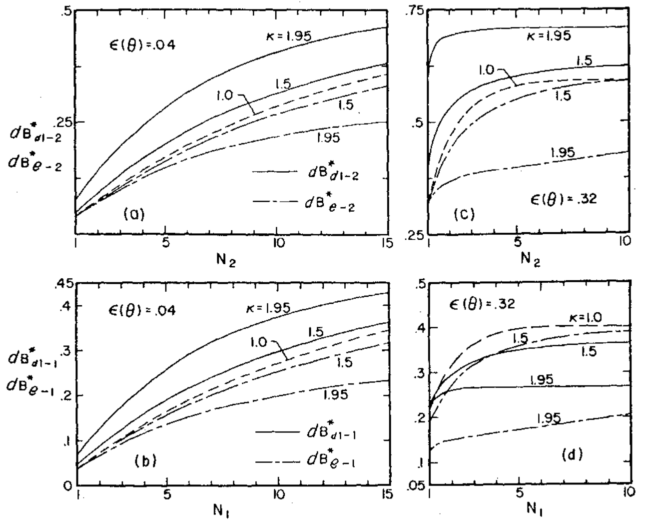

Fig. 2 Absorption factors for configuration 1.

also on the azimuthal angle ϕ. For the sake of simplicity in notation this dependence will not be specifically denoted in either N or dB_{d1-1} but will be implied. Similar expressions can be written for the components of radiation polarized parallel and perpendicular to the plane of incidence. For example, the fraction of the parallel component of radiation emitted by the elementary area dA_1 in the elementary solid angle $d\Omega$ and absorbed by surface 2 is

$$dB^p_{d1-2} = [1 - \rho_p^{N_2}(\theta)]/[1 + \rho_p(\theta)] \tag{3}$$

For polarized radiation the corresponding relation to Eq. (2) is

$$dB^*_{d1-1} = [\epsilon_p(\theta)dB^p_{d1-1} + \epsilon_s(\theta)dB^s_{d1-1}]/2\epsilon(\theta) \tag{4}$$

A similar expression can be written for dB_{d1-2}.

If there is incoherent external radiation incident on surface 2 from a particular direction, the fraction of energy absorbed at surface 1 follows from Eq. (4) by letting $\epsilon_s(\theta) = \epsilon_p(\theta) = \epsilon(\theta)$ and becomes

$$dB^*_{e-1} = (dB^p_{e-1} + dB^s_{e-1})/2 \tag{5}$$

if polarization effects are accounted for. The fraction of incoherent external radiation incident on surface 2 and eventually absorbed at surface 2 is given by a similar equation.

For the parallel plate system the local heat flux in the absence of external radiation nondimensionalized with respect to the emissive power of surface 1 is

$$q_1/\epsilon\sigma T_1^4 = 1 - \{\textstyle\int_\triangle \epsilon(\theta)[dB_{d1-1} + (T_2/T_1)^4 dB_{d1-2}] \times \cos\theta d\Omega\}/\pi\epsilon \tag{6}$$

If the polarization effects are accounted for, the local heat flux can be expressed as

$$q_1^*/\epsilon\sigma T_1^4 = 1 - \{\textstyle\int_\triangle \epsilon(\theta)[dB^*_{d1-1} + (T_2/T_1)^4 dB^*_{d1-2}] \times \cos\theta d\Omega\}/\pi\epsilon \tag{7}$$

It is seen from Eq. (7) that the only parameters affected by polarization are dB^*_{d1-1} and dB^*_{d1-2}.

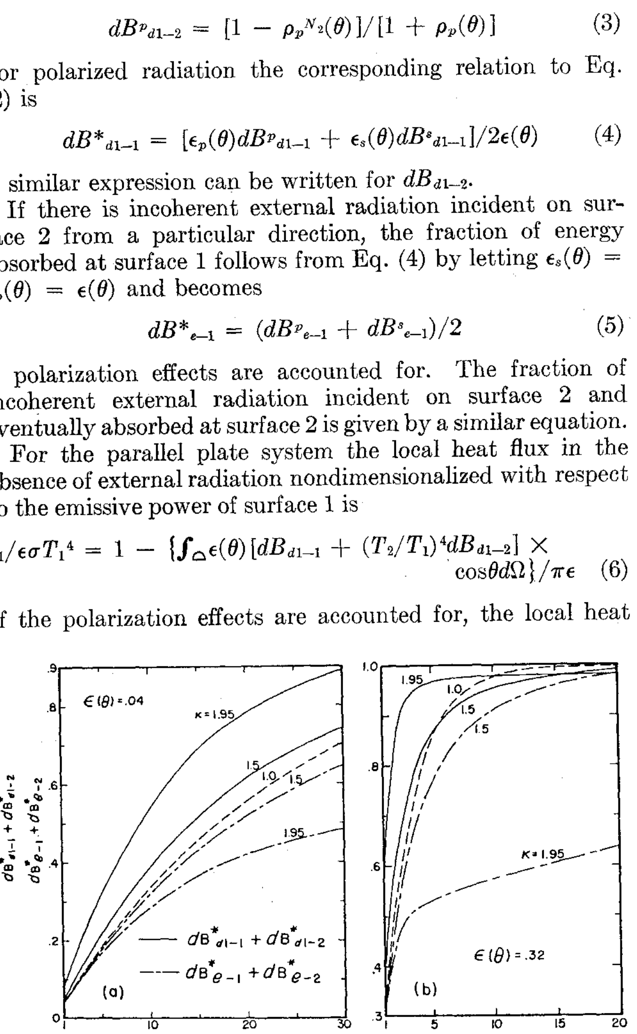

Fig. 3 Sum of absorption factors for configuration 1.

To gain some insight into the effect of polarization on radiant heat transfer it is only necessary to compare dB^*_{d1-1} and dB^*_{d1-2} with the corresponding quantities without polarization. For any angle of emission θ, $\epsilon_p(\theta)$ and $\epsilon_s(\theta)$ can be written in terms of the factor $\kappa(\theta)$ defined as

$$\kappa(\theta) = \epsilon_p(\theta)/\epsilon(\theta) \tag{8}$$

In view of this definition, $\epsilon_s(\theta) = [2 - \kappa(\theta)]\epsilon(\theta)$. For $\theta = 0$ or $\pi/2$, $\kappa(\theta) = 1$ and $\kappa(\theta) = 2$ for $\epsilon_s(\theta) = 0$. Hence, with the factor $\kappa(\theta)$ in the range $1 \le \kappa(\theta) \le 2$ all possible values (materials and directions) of $\epsilon_p(\theta)$ and $\epsilon_s(\theta)$ can be represented in terms of $\epsilon(\theta)$. $\kappa(\theta) = 1$ for all θ corresponds to the case of unpolarized radiation, $\epsilon_p(\theta) = \epsilon_s(\theta) = \epsilon(\theta)$.

Results and Discussion

In Figs. 2 and 3 $\epsilon(\theta)$ and $\kappa(\theta)$ are the characteristic independent parameters. It must be recognized that for specified $\epsilon(\theta)$ and $\kappa(\theta)$ the values of $\epsilon_p(\theta)$ and $\epsilon_s(\theta)$ are uniquely defined, but for a particular material both $\epsilon(\theta)$ and $\kappa(\theta)$ change as θ varies from 0 to $\pi/2$; however, the conclusions drawn apply for all values of $\epsilon(\theta)$.

It can be seen from Figs. 2a and 2c that for any number of reflections $dB^*_{d1-2} > dB_{d1-2}$, and the percentage difference between the two is largest for a single reflection. The results show that up to a very large number of reflections $dB^*_{d1-1} > dB_{d1-1}$; however, for a larger $\epsilon(\theta)$, Fig. 2d, dB^*_{d1-1} becomes smaller than dB_{d1-1} after a smaller number of reflections. It should be noted here that for large $\epsilon(\theta)$ almost the entire energy is absorbed after the first few reflections and the values of dB_{d1-1} and $dB_{d1-1}{}^*$ are also smaller. Also most of the energy, for which polarization is important, is emitted and is incident at very oblique angles so that it leaves the enclosure after only a few reflections. Examination of Eq. (6) shows that for large $(T_2/T_1)^4$ the main contribution to q is from dB_{d1-2}, and dB_{d1-1} may be completely ignored. A similar conclusion can be drawn for q^*. It is clear from the above discussion that for large $(T_2/T_1)^4$, the local heat flux is always smaller with polarization effects included.

It can be easily shown that the above conclusions apply also to configuration 2, when surface 3 is perfectly reflecting. For configuration 3, with surface 3 perfectly reflecting, the local heat flux is always smaller for all temperatures and $Z/W > 1$ if polarization effects are included. This is due to the fact that dB_{d1-1} is always zero because of the nature of the system.

The individual absorption factors dB^*_{e-1} and dB^*_{e-2} are shown in Fig. 2 and their sum (fraction of incident energy absorbed by the system) is illustrated in Fig. 3. It can be seen from the figure that this sum is always smaller for the polarized case, $\kappa(\theta) > 1$. This finding is in some disagreement with the predictions of Edwards and Tobin[2] (Fig. 7) who have shown that for an infinitely wide slot the transmittance with polarization effects neglected may be greater. Although not presented in this Note, it can be easily shown that this sum is smaller for the polarized than for the unpolarized case even for unequal emissivities of the two surfaces. It should also be noted that there is no difference in the energy absorbed for the two cases when the external radiation leaves the system after only one reflection. The above conclusions apply also to configurations 2 and 3 when surface 3 is perfectly reflecting.

Conclusions

The above analysis and results lead to the following qualitative conclusions:

1) Errors from the neglect of polarization may be appreciable when the angles of emission or incidence are such that there is a large difference between the emissivities in the p and s directions.

2) The percent difference between the energy absorbed with and without polarization effects is maximum when there is only one reflection in the system.

3) When external incoherent radiation is incident on the system the fraction of energy absorbed by the system is smaller when polarization effects are considered and the maximum difference occurs after some finite number of reflections.

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Fragmentation of Liquid Metallic Particles in Two-Phase Nozzle Flow into a Vacuum

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Introduction

FOR the generation of Ba ion clouds in space experiments,[1] partial combustion of Ba with CuO in a reaction vessel and subsequent expansion of the liquid reaction products through a nozzle into vacuum is one of the most economical processes. Thermodynamics predicts[2] for an initial temperature of approximately 2500°K, a good yield of Ba vapour, which can be photoionized by the sun's radiation.

When effusing through the nozzle the liquid breaks up into little droplets. The vaporization efficiency from this two-phase jet is then mainly governed by transport phenomena. The droplet size distribution determines: 1) the rate of vaporization, which, in the case of multicomponent droplets (Ba, BaO, Cu), is not so much controlled by the equilibrium vapour pressure, and, e.g., the Hertz-Knudsen equation, as rather by the diffusion of liquid Ba to the droplet's surface[3]; 2) drag, source drag[4,5] and thermal conduction between the polydisperse liquid and the vapour phase, and hence the degree of dynamic and thermal disequilibrium in that part of the jet, where vaporization takes place; 3) recondensation of vapour in the outer parts of the expanding two-phase jet, because the larger the particle size, the sooner recondensation is thermodynamically possible[4] and will take place in jets from larger release payloads; 4) the nonsteady expansion of the vapour from the two-phase jet into the free molecular flow regime; the terminal expansion velocity of the vapour is determined essentially by friction and heat transfer from the particulate phase.[6] Thus, the desire for knowledge and control of the particle size distribution has prompted this laboratory study on the particulate phase of a Ba-vapour jet in a vacuum chamber.

Experimental Description

1. *Source*

A liquid mixture of Ba, BaO, and Cu at a temperature of 2500°K was obtained by burning Ba and CuO in a molar ratio 2.5:1 in a 50 cm^3 reaction vessel. The pressurizing gas, the effect of which on particle atomization was to be investigated, was N$_2$, which was split off during the reaction from NaN$_3$ administered to the original reaction mixture in amounts of about 0.4% by weight. Chemical conversion was complete within less than 10 msec[7] and the liquid reaction products were expelled through a convergent tungsten nozzle (diam: 5 mm) into a 20 m^3 vacuum chamber, initially at 10^{-5} torr. The mass-flow rate through the nozzle decayed steadily to zero within about 300 msec after ignition.[7] Except for the first precursor,[8] the residence time of the reaction products inside the vessel at a pressure between 20 and 100 atm was long enough to initially establish thermal equilibrium.

2. *Jet boundaries*

The flow lines of particles become source-like early in the expansion with an angular density profile of $\cos^2$-shape,[7] the maximum flow angle, determined with a high-speed camera,[8] being close to $\theta_m = 60°$ and nearly constant throughout the effusion.[7,8] Even though the initial pressure in the chamber was low enough to permit free expansion of the vaporizing two-phase jet, any analysis might have been affected by N$_2$ reflected from the chamber walls, and by H$_2$ released from not thoroughly dried surfaces by impinging metal atoms. Prediction of the location of the Mach disk in two-phase jets under these conditions is laden with uncertainties.[9] To exclude such perturbations on the centerline of the jet, where the particle analysis was to be made, the variation of the number density of liquid particles with time was monitored by means of laser-light scattering at a distance of 330 cm from the nozzle.

Because the scattered radiation had to be much more intense than both reflected light from the nozzle ($\sim$2500°K) and the brightness of the particles themselves ($\sim$1350°K),[8] both the incident light beam from a 80 mw cw He-Ne-laser and the light scattered at an angle of 40° (Fig. 1) were protected by light tubes. To suppress any reflections 7 stops had to be inserted into the tube surrounding the scattered light beam. The recording photomultiplier was equipped with a narrow band interference filter (half-width 20 Å at 6328 Å). At the junction of the tubes a 14 cm^2 aperture transmitted part of the two-phase jet.

Oscilloscope traces show that it takes about 20 msec from the commencement of the effusion until the first particles pass the laser beam, indicating a front velocity of the jet of about 160 m/sec. A strong increase in particle number density was observed about 250 msec after the effusion had ceased. This is associated with the Mach disk, which degenerates into a pressure wave as the effusion stops and carries fine dust toward the nozzle. Hence, measurements anywhere on the centerline were expected to reflect the free jet properties.

3. *Particle collector*

Particles were collected on a glass plate in the free jet for analysis by micrography and electron micrography. Because solid barium droplets react vigorously with air, it

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