Technical Comments

Comment on "Thermal Radiation from the Exhaust Plume of an Aluminized Composite Propellant Rocket"

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IN a recent paper Morizumi and Carpenter[1] presented a technique for calculating the thermal radiation from the exhaust plume of an aluminized solid-propellant rocket. In their analysis, gas-phase radiation was assumed negligible, and radiation from the particle cloud was treated as that from an equivalent radiating surface. This approach reduced the problem to determination of the apparent surface emissivity of the plume and its effective temperature $\bar{T}$, where the former depends on the optical thickness of the plume and, more significantly, on the spectral emissivity of the individual particles comprising the plume. It is the purpose of this Comment to show that the description of particle optical properties used by Morizumi and Carpenter is not appropriate for evaluation of plume radiation and, furthermore, that their definition of effective temperature is not valid for optically thick clouds.

The particle emissivity can be determined from the complex index of refraction, $m = n_1 - n_2 i$, of aluminum oxide (sapphire) and, in particular, from imaginary part n_2. Figure 1 shows the spectrally dependent n_2 over the infrared (IR) wavelengths of interest.[2–5] With this information, Mie

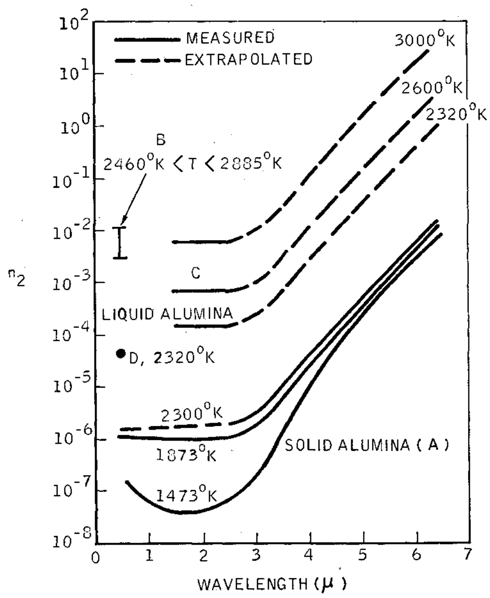

Fig. 1 Imaginary part of refractive index of aluminum oxide. A) Gryvnak and Burch,[2] B) Carlson,[3] C) Adams and Colucci,[4] and D) Diamond and Dragoo.[5]

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theory[6] can be used to determine the scattering and absorption efficiency factors $Q_\lambda^{(s)}$ and $Q_\lambda^{(a)}$, respectively, where the latter is identical to the spectral emissivity ϵ_p (Ref. 6, p. 452). As an example, the spectral emissivity of alumina at its melting point is shown in Fig. 2 for several particle sizes typical of rocket exhausts.

This procedure, of course, was recognized by Morizumi and Carpenter who pointed out, however, that *with the existing data* the total particle emissivity ϵ_p resulting from Mie theory was less than 0.1, in contrast to the larger values of ϵ_p determined from gross measurements of rocket exhausts. (Morizumi and Carpenter incorrectly identified the particle emissivity with the quantity $Q_\lambda^{(a)}/Q_\lambda^{(t)}$, where $Q_\lambda^{(t)} = Q_\lambda^{(a)} + Q_\lambda^{(s)}$, although this did not affect the subsequent results of their work.) Consequently, from extrapolation of bulk alumina data they assumed that $\epsilon_p = \epsilon_{p\lambda} = 0.25$, independent of temperature, wavelength, particle size, or physical state. This assumption was based in part on an experimental measurement of plume radiation with a total radiometer (although evaluation of the gas-phase radiation from the plume was neglected) and on poorly documented spectral observations. They further attempted to justify their assumption by suggesting that the optical properties of sapphire are not representative of those for aluminum oxide particles in rocket exhausts. In support of their argument they contended that the absorptive properties of the particles are higher than those of sapphire, because of a polycrystalline-porous structure of the former.

This position, however, is in contrast to the generally accepted view of the effect of surface roughness and bulk structure on the radiative properties of metal oxides. According to Cox[7] the effects of these characteristics on emittance are closely related to the ratio of the size of the irregularities to the thickness of the material required for opacity and decrease as opacity decreases. Cox demonstrated in a qualitative manner that when the irregularity is small compared to the photon mean-free path, it has no effect on the emittance, and he cited experimental evidence obtained with polycrystalline alumina to substantiate this. A similar position has been maintained by Gaumer,[8] who stated further that the substructure of a bulk metal oxide is a more dominant factor than surface irregularity in determining the effective

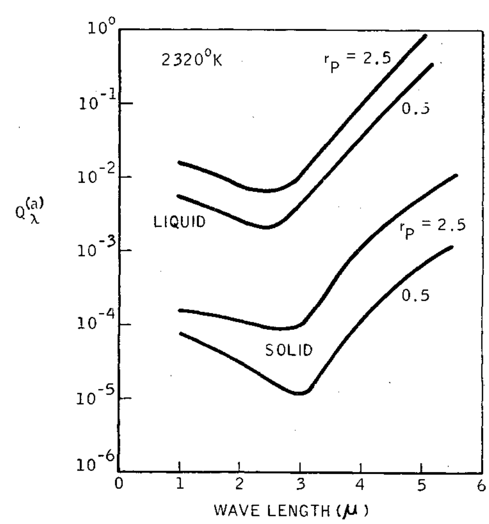

Fig. 2 Spectral emissivity of aluminum oxide at its melting point for several particle sizes typical of rocket exhausts. The particle radius r_p is in microns.

radiation parameters. Since the metal oxide particles that appear in exhaust plume are transparent over a significant portion of the IR spectrum and are of a size comparable to the wavelength, then the surface roughness and crystalline substructure of the particles are of a scale considerably smaller than the wavelength and should have negligible effect on the radiative properties of the material. Consequently, the emissivity of bulk material, which is orders of magnitude larger in size with correspondingly larger surface irregularities, voids, and crystalline substructure, is inappropriate for characterizing the emittance of micron-size particles.

The most serious consequences of the assumption for particle emissivity made by Morizumi and Carpenter are that 1) it obscures the exact physical mechanism of plume radiation (which can be enhanced, for example, by supercooling or "searchlight" emission‡), and 2) it fails to predict the correct spectral radiancy of the plume. The latter is particularly important since it may be possible to minimize base heating using materials with appropriate spectral reflectivity when the spectral radiancy is known.

Morizumi and Carpenter place an unnecessary restriction on their method by calculating the radiant heat transfer on the basis of the quantity $\sigma\bar{T}^4$ [Eq. (23) of Morizumi and Carpenter]. The quantity $\bar{T}$ is based upon a number of sources (particles) which exist at various temperatures. Generally, there will not be a Planckian distribution of radiancy from such a multitemperature source. Since a total radiant flux expressed by $\sigma\bar{T}^4$ results from integrating a Planckian radiancy distribution over wavelength then, before the radiant heat transfer can be expressed in this manner, it must be shown that integration of the prevalent non-Planckian spectral distribution will indeed correspond to that quantity. More properly, one should avoid defining an effective temperature, dealing rather in terms of spectral radiancy or spectral-radiant flux, and finally compute heat transfer by integrating the (non-Planckian) computed spectral-radiant flux over wavelength.

Another serious error arises in their Eq. (24) which defines $\bar{T}$. That expression, because of the limits of integration, is valid only for the optically thin case. When the plume becomes thick to absorption, radiation from particles in the interior of the plume is absorbed by the surrounding particles, and only radiation from particles near the plume boundary is received by the surface element. Only the temperatures of particles that can be "seen" should be used to determine an "effective temperature" of the plume.

Techniques for calculating plume radiation were reviewed recently by Laderman and Carlson,[9] who compared the method of Morizumi and Carpenter with experimental measurements[10,11] obtained for the Saturn S-II ullage motor. Details of this comparison are discussed in Ref. 9, and only salient conclusions are presented here. First, it was demonstrated the gas-phase radiation cannot be ignored a priori. For the S-II ullage motor, gas-band emission amounted to 23% of the measured radiation. Second, since the S-II ullage plume was optically thin, it was possible to calculate the spectral radiancy directly by summation of contributions from all particles viewed by the detector. This calculation, reflecting the variation in emissivity shown in Fig. 2, indicated that the particle continuum is bimodal, substantiating the experimental observations, with strong peaks in both the near and far IR, around 1 and 5 μ, respectively. However, because of the graybody assumption for particle emissivity, the method of Morizumi and Carpenter predicted the radiation to be centered in the near IR, corresponding to the peak of the blackbody curve associated with their effective temperature, with negligible radiation beyond 5 μ. Although both calculations provided a reasonable estimate of the integrated radiation, the latter led to an inaccurate specification of the spectral radiancy of the plume. A new method for calculating radiation from an optically thick plume, which takes into account the appropriate spectral optical properties of the particles, will be published shortly.[12]

‡ "Searchlight" is the term frequently used to denote radiation emitted by a blackbody combustion chamber, transmitted through the nozzle throat, and subsequently scattered in the direction of the detector by particles in the plume.

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