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On the Emissivity of Alumina/Aluminum Composite Particles

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Introduction

THERE is substantial uncertainty concerning the infrared emissivity of alumina particles in the exhausts of aluminized solid-propellant rocket engines. The basic problem is that pure macroscopic samples of alumina have a very small imaginary index of refraction and hence a very small absorbtivity/emissivity. On the other hand, aluminized solid-propellant rocket plumes are observed to radiate quite strongly in the infrared, and much of this radiation comes from the exhaust alumina. In some radiative regimes the particulate radiation dominates the entire plume signature.

In the past, plume radiation modelers have resorted to using phenomenologically determined and relatively large values of particulate emissivity in order to bring predictions into agrement with data.[1,2] While there has been discussion of the physical mechanisms responsible for producing these relatively large values, there is no concensus as to the dominant mechanism.

The purpose of this Note is to examine one possible source of enhanced exhaust alumina emissivity, namely, that the alumina particles contain a small fraction of unburned metallic aluminum. Solid propellants burn fuel rich (e.g., most of the carbon in the propellant comes out as CO rather than CO_2), and it is possible that some aluminum may emerge from the combustion chamber unburned. Furthermore, much of the aluminum combustion is observed to take place in large droplets of aluminum/alumina migrating around on the propellant surface,[3] which may prevent all the aluminum in the droplet from burning before leaving the chamber.

Alumina/Aluminum Composite Particles

The structure of such an alumina/aluminum composite particle is very difficult to predict. It will be a very sensitive function of the time history of the droplet and of the droplet's behavior as it experiences the shear forces during acceleration in the expanding nozzle flow. It will also depend on the details of the liquid droplet's solidification process, which is complicated by the large difference in solidification temperatures between alumina and aluminum. The final particles are likely to be complicated, inhomogeneous composites.

The particulate emissivity is generally calculated using the well-known Mie theory.[4] Once the particle structure is specified, the Mie theory must be cast in the appropriate form. For an inhomogeneous complex composite particle this is a difficult task and, in general, no such theory is available.

For the symmetric case of a composite particle composed of a spherical core surrounded by a spherical mantle, the extension of Mie theory has been considered by Güttler.[5] The complete theory for such particles is complex, but much of the behavior of such composite particles can usefully be studied in the Rayleigh limit:

$$2\pi a/\lambda \ll 1 \tag{1}$$

where a is the particle radius and λ is the wavelength. For this limit the absorption cross section σ_{abs} for a sphere of radius a, made up of two different materials, is given in Refs. 5 and 6. If the complex index of refraction is m_1 out to radius a_1 and m_2 out to radius a (i.e., between a_1 and a), then

$$\sigma_{abs} = -4\pi\kappa Im\beta \tag{2}$$

where $\kappa = 2\pi/\lambda$, and

$$\beta = a^3 \frac{a^3(m_2^2-1)(m_1^2+2m_2^2)+a_1^3(2m_2^2+1)(m_1^2-m^2{}_2)}{a^3(m_2^2+2)(m_1^2+2m_2^2)+a_1^3(2m_2^2-2)(m_1^2-m_2^2)} \tag{3}$$

Note that if $m_1 = m_2$, this reduces to the Rayleigh limit for a single material sphere:

$$\sigma_{abs} = (\pi a^2)\left[-4\frac{2\pi a}{\lambda} Im\left(\frac{m^2-1}{m^2+2}\right)\right] \tag{4}$$

This limit is also obtained if $a_1 = a$ or if $a_1 = 0$, of course.

In the Rayleigh limit the absorption coefficient $(= \sigma_{abs}/\sigma_{geo})$, and hence the emissivity, depends on the particle radius in a simple fashion, as can be seen in Eqs. (2-4). Consequently, a size-independent quantity can be introduced:

$$Y_{Ray} = \sigma_{abs}/(\pi a^2)/(2\pi a/\lambda) \tag{5}$$

Y_{Ray} is, therefore, the emissivity ϵ normalized to the Mie size parameter $q = 2\pi a/\lambda$, or

$$\epsilon = qY_{Ray} \tag{6}$$

The subscript Ray is used to emphasize that what follows is in the Rayleigh limit.

Emissivity Results

In order to evaluate the expressions for the emissivity, the indices of refraction for the subvolumes of the particle are needed; e.g., the indices of refraction of alumina and aluminum. These quantities are quite uncertain, however, so ranges of representative values were chosen for alumina that cover the spread of values that might be considered typical. The spectral region of interest is often the infrared (especially the region from 2-5 μm), so the real and imaginary parts of the index of refraction were chosen to be representative of such wavelengths. The index of refraction of aluminum was chosen to be typical of a conducting material, i.e., with a large imaginary part. Different values of the aluminum index lead to results qualitatively the same as those presented below. These values were chosen to cover an interesting region and are not meant to be definitive values for rocket exhaust alumina and aluminum.

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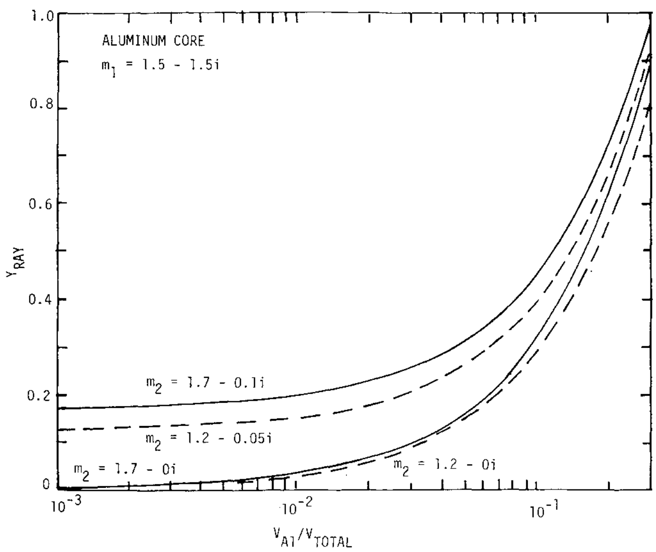

Fig. 1 Normalized alumina particle emissivity Y_{Ray} as a function of volume fraction of aluminum for a spherical particle with a spherical aluminum core and for several values of alumina complex index of refraction.

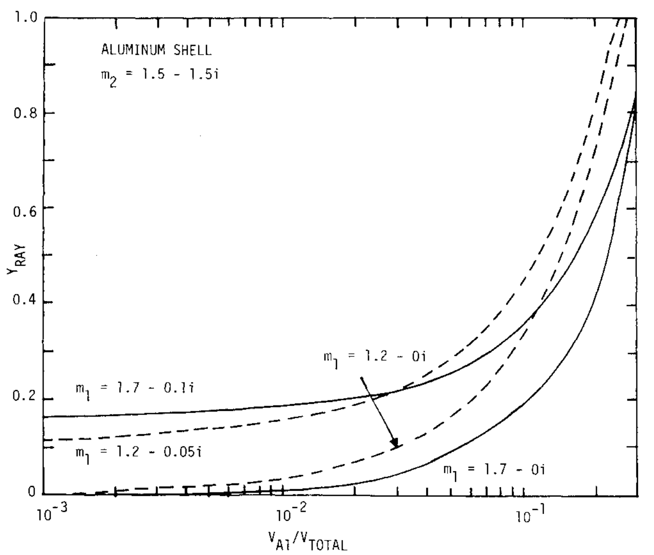

Fig. 2 Normalized alumina particle emissivity Y_{Ray}, as a function of volume fraction of aluminum for a spherical particle with a spherical shell of aluminum and for several values of alumina complex index of refraction.

Figure 1 shows the Rayleigh limit normalized emissivity Y_{Ray} for alumina particles with an unburned aluminum core. The emissivity is plotted against the ratio of volume of aluminum to total particle volume. The range of values of this ratio of primary interest here is up to 10^{-1} or so. The basic trend in the figure is that the emissivity increases as the amount of aluminum is increased. For particles containing a few percent metallic aluminum the enhancement of the emissivity is substantial, even for alumina which is by itself strongly absorbing (e.g., $m_{Al_2O_3} = 1.7 - 0.1i$). For an otherwise nonabsorbing particle (i.e., $k = 0$), a small aluminum core provides an emissivity large enough to provide a strongly radiating particle.

Figure 2 shows the emissivity for the opposite case of a thin metallic coating on the outside of an alumina sphere. The same trend is seen in this figure, viz., the emissivity increases as the amount of aluminum increases.

Conclusions

It is seen from the results presented here that small amounts of aluminum (on the order of a few percent by volume) lead to relatively large values for composite particle emissivities, even for cases in which the matrix material (i.e., alumina) is poorly absorbing by itself. These calculations were performed for the symmetric cases of a spherical core and a spherical shell and for the small-particle Rayleigh limit. Different values of alumina or aluminum complex index of refraction from those used in Figs. 1 and 2 lead to quite similar results.

Qualitatively, it would be expected that this behavior of emissivity enhancement would also exist in the Mie regime (particle radius ~ wavelength) and the bulk behavior regime (particle radius ≫ wavelength). In addition, it would be expected that the qualitative features of enhancement would also exist for composite particles of complex and nonsymmetric structure. In order to treat such particles quantitatively, a suitable nonsymmetric model would have to be constructed.

Clearly, small amounts of unburned aluminum contained in or on rocket exhaust alumina would go a long way toward explaining the discrepancies between measured pure alumina emissivity and the large amount of infrared particulate emission typically seen from aluminized solid-propellant rocket plumes.

Acknowledgments

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Launch Window for a Shuttle-Based Geosynchronous Orbit Mission

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Introduction

IN launching geosynchronous orbit payloads there is a well-established sequence of events that proceeds from a low circular parking orbit to an elliptic transfer orbit with apogee near geosynchronous altitude and an inclination near 27 deg, and finally to the geosynchronous orbit with nearly zero inclination and eccentricity. During the transfer orbit phase the satellites are almost always spin-stabilized. Many

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