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Numerical study on similarity of plume infrared radiation between reduced-scale solid rocket motors

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Abstract This study seeks to determine the similarities in plume radiation between reduced and full-scale solid rocket models in ground test conditions through investigation of flow and radiation for a series of scale ratios ranging from 0.1 to 1. The radiative transfer equation (RTE) considering gas and particle radiation in a non-uniform plume has been adopted and solved by the finite volume method (FVM) to compute the three dimensional, spectral and directional radiation of a plume in the infrared waveband 2–6 μm. Conditions at wavelengths 2.7 μm and 4.3 μm are discussed in detail, and ratios of plume radiation for reduced-scale through full-scale models are examined. This work shows that, with increasing scale ratio of a computed rocket motor, area of the high-temperature core increases as a 2 power function of the scale ratio, and the radiation intensity of the plume increases with 2–2.5 power of the scale ratio. The infrared radiation of plume gases shows a strong spectral dependency, while that of Al_2O_3 particles shows spectral continuity of gray media. Spectral radiation intensity of a computed solid rocket plume's high temperature core increases significantly in peak radiation spectra of plume gases CO and CO_2. Al_2O_3 particles are the major radiation component in a rocket plume. There is good similarity between contours of plume spectral radiance from different scale models of computed rockets, and there are two peak spectra of radiation intensity at wavebands 2.7–3.0 μm and 4.2–4.6 μm. Directed radiation intensity of the entire plume volume will rise with increasing elevation angle.

1. Introduction

The plume radiation of solid rockets is an important tracking target in strategic attack and is an essential problem in thermal protection design of rocket motors. Most published experimental research of rocket plume radiation is conducted with reduced-scale models. The similarity in test results between reduced-scale and full-sized model is a key consideration for applying them to thermal analysis of actual rocket motors.

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Given the complexity of the plumes from solid rocket motors, plume radiation varies significantly in spectrum and direction, thus causing difficulty in fully investigating characteristics of the similarity problem through experimental study. Ground testing usually needs to be performed in a huge enclosed area to avoid environment influences.[1] Also, to establish similarity rules between the plume radiation of a reduced-scale rocket model and a full-sized rocket motor, experiments with multiple motor sizes of similar geometry must be conducted. From the perspectives of technique and economy, experimental methods are very difficult to perform, so related research in this area has not yet been reported.

Several works on the theoretical aspects of this study have focused on the similarity problem of gas and particle radiation. Forward peak-light scattering and the integral similarity method (aka the Delta-M method), which analyzes the truncation error in the Legendre progression of high-polarity scattering phase functions and forward-scattering peak cones, have been studied.[2] Change in the self-similarity of transmittance depth and radiation energy in a cool medium, with time, boundary temperature, and medium density have been investigated.[3] Duracz and Mccormick focused on two similarity parameters: the ratio of radiation intensity and irradiance, and their relation to single-scattering albedo, and dissymmetry coefficient in optically thick media.[4] Similarity of the forward scattering portion and number of incident energy scattering directions in the radiation transmission equation of anisotropic scattering media have been studied by Mitrescu and Stephens.[5] Considering temperature and radiation of jet nozzles, Bril et al. studied similarities of the near-nozzle temperature and concentration fields, as well as the non-dimensional radiant intensity determined by the outlet parameters, radiation wavelength, and the temperature gradient of absorptivity.[6]

The plume radiation of a solid rocket motor is a multidimensional problem of high-order calculus that involves the radiation of a strong spectral sensitive gas and scattering of multiple groups of Al_2O_3 particles. The radiative gases in the plume consist of H_2O, CO_2, CO, HCl and OH, with each gas having thousands of spectral lines in the infrared waveband.[7] The spectral properties of gases are always solved with the waveband model[8,9] or the weighted-sum-of-gray-gases model.[10] Considering radiation of Al_2O_3 particles, particle concentration and size have important effects on spectral properties of particles[11], which are commonly solved with the Mie theory.[12,13] In calculating the 3D spectral radiance of an abs orptive/emissive/scattering medium, the Monte Carlo methods,[14] streaming model,[15] discrete-ordinate method,[16] and finite volume methods (FVM)[17] have been widely adopted. As a better compromise of computational accuracy and execution time, the FVM is often suggested to solve the 3D spectral radiance of an inhomogeneous absorption–emission–scattering medium with a divergent form.

As similarity of plume infrared radiation between reduced-scale and full-sized rocket motors is still not fully studied, this work aims to contribute to the numerical research on similarity of plume radiation with a group of scaled rocket motors of similar geometry and flow data. This study adopts the geometric and operational parameters of Trident D5 rocket motor ground testing. A CFD code is used to compute the axis-symmetric flow parameter inside the nozzle and the plume in a series of scaled model rockets with the same total temperature and pressure at the rocket nozzle inlet. The weighted-sum-of-gray-gases model is adopted to compute the spectral absorptivity of gas molecules H_2O, CO_2, CO, HCl and OH, and the Mie scattering theory is used to compute the spectral absorption/scattering coefficient and phase function of Al_2O_3 particles of eight diameters. Finally, the FVM is used to solve the RTE equation, and corresponding code is developed to compute the 3D spectral radiance of a plume in infrared waveband 2–6 μm. Also, the directed radiation intensity from the plume's hot core with gas temperature exceeding 500 K is calculated by integrating radiance on plume peripheral surface in one direction, and the ratio of radiation intensity for the reduced-scale plume to that of full-sized rocket motors is to be derived.

2. Calculation of plume flow field

To obtain flow parameters of the rocket motor plume and that of reduced-scale models, the Chemical Equilibrium and Application (CEA) program is adopted to compute the compound chemical equilibrium components of propellants and the inlet flow parameters. A CFD code is then used to perform simulation of flow parameters in the nozzle and of the plume. The time-marching method and advection upstream splitting method (AUSM) spatial discretization schemes are chosen for a numerical solution. Blending of the plume and atmosphere, and the resulting secondary combustion of H_2, CO and HCl will be computed with a finite rate chemistry model of 12 components and 17 reactions,[18] where the k–ε turbulence model is adopted. To simulate temperature and size distribution of Al_2O_3 particles, the Lagrangian trajectory model of particles is used to compute the exchange of energy and momentum between particles and gases, while the self combustion, evaporation, collision and polymerization of particles is neglected. Distribution of particle diameters is determined based on the Braithwaite size distribution function.[19]

The Trident D5 solid rocket uses a composite propellant that contains Al as 10% of its weight. In calculating plume flow data of the full-scale motor and reduced-scale models, the same input data are used: pressure is 9 MPa, and temperature is 3750 K. The full-scale rocket motor has a nozzle of 1.55 m length, 0.35 m throat diameter and 9.7 ratio of area expansion in ground testing. The reduced-scale model has the same geometry, but with a reduced diameter and length.

Flow field of plumes for the full-sized Trident D5rocket motor and models with scale ratios between 0.1 and 0.9 have been computed. Fig. 1 shows contours of flow data for the full sized motor, including gas temperature (t_g), pressure (p_g) and volume fractions of H_2O, CO_2 and CO. Concentration (Am_p) and temperature (t_p) of one group of Al_2O_3 particles with diameters (d_p) of 8 μm are also represented. Contours of flow data for the 9 reduced-scale models are highly similar with that of the full-sized motor in Fig. 1, only varying in plume size. The ratio between the length or radius of each plume's hot core at different scales is almost equal to the ratio of geometric size. The high temperature area is separately distributed in the plume, and a secondary high temperature area can be easily found downstream of the first at the nozzle outlet, where volume fractions of H_2O and CO_2 are very high because of secondary combustion. The volume fraction of CO is consistently high in central areas of the plume. According to