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High Efficient Numerical Simulation of Infrared Radiation from a Hot Exhaust Nozzle

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Abstract. A coupled model, capable of simulating transonic flow, solid heat conduction, species transport, and gas radiation, is developed that provides better computational treatment of infrared radiation from hot exhaust nozzles. The modeling of gas radiation is based on a statistical narrow-band correlated-k analysis, whose parameters are deduced from the HITEMP line-by-line database. To improve computational efficiency, several methods are employed. A mixed analytical-numerical algorithm is described for the stiffness of the two-equation turbulence model and an alternating direction implicit pretreatment for the ill-conditioned matrix appearing in the coupled problem of flow and solid heat conduction. Moreover, an improved multigrid method and a symmetry plane treatment of the radiation transfer-energy equations are also introduced. Four numerical simulations are given to confirm the efficiency and accuracy of the numerical method. Finally, an account of the aerothermodynamics and infrared characteristics for two types of nozzles are presented. The infrared radiation intensity of the Chevron ejecting nozzle is clearly smaller than that of the common axisymmetric ejecting nozzle. All computations can be performed on a personal computer.

AMS subject classifications: 65L20, 74A15, 76F60, 76H05, 78A40

Key words: Numerical simulation, infrared radiation, exhaust nozzle, stiffness of two-equation turbulence model.

1 Introduction

In recent years, infrared detection/stealth technology has developed rapidly. Some key techniques, such as the suppression of infrared radiation from exhaust systems crucial to stealth aircraft have attracted wide attention and keen investigation. The infrared

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signature band of 3 to 5 μm from an aircraft's exhaust system corresponds to the infrared transmission window of air. As a consequence an aircraft's exhaust system becomes a primary target of heat-seeking missiles with infrared detectors.

There are several models to describe gas radiation characteristics. Among these, the line-by-line model [1] is accurate, but can only be used to validate other models. It is nearly impossible to use it to predict radiation from practical devices, because of its huge calculation overheads. The wide-band model [2] is often adopted to simulate gas radiation and heat transfer. The SNB (Statistical Narrow-Band) model [1], which generally involves 200-2 000 spectral bands, is often used to calculate gas infrared radiation intensity. The parameters of the SNB model are deduced from the HITEMP line-by-line database [3]. HITEMP is a database developed by Air Force Geophysics Laboratory [1] for high resolution atmosphere absorption lines.

However, a direct implementation of this model to radiation transfer in multi-dimensional geometries will encounter severe computational difficulties because it formulates the gas radiation behavior in terms of transmissivity (τ) rather than the more fundamental absorption coefficient (k). At present, this problem can be solved by the correlated-k model [4, 5]. Because the calculation still entails huge computational overheads with wide/narrow-band models, most researchers of these models calculate radiation intensities/heat transfers assuming that no correlation exists between radiation and other physical quantities [6].

In this paper, a coupled model is developed that can be used to calculate flow and solid heat conduction, gas radiation transfer and heat exchange, and species transport. To improve computational efficiency, several methods are employed, including a mixed analytical-numerical algorithm, an improved multigrid strategy, the Brian alternating direction implicit (BADI) pretreatment, and a symmetry-plane treatment of radiation. To confirm the efficiency and accuracy of our methods, four numeric calculations are presented, namely the pressure distribution around an axisymmetric nozzle, the temperature distribution of a rocket engine water-cooling nozzle, the radiation heat exchange within a cylindrical furnace, and the carbon dioxide radiation absorptivity at a wavelength of 4.3 μm. Finally, aero-thermodynamics and infrared characteristics of an axisymmetric ejecting nozzle (AEN) and a Chevron ejecting nozzle (CEN) are generated, which show that the algorithm has highly-improved computational efficiency.

2 Mathematical models

2.1 Coupled model between flow and solid heat conduction

The second-order Roe scheme [7] is employed to discretize the governing equations, which are the three-dimensional generalized Navier-Stokes equations [8]:

$$\frac{\partial}{\partial t}\iiint_V \mathbf{Q}dV+\oiint_S(\mathbf{F}-\mathbf{F}_V-\mathbf{F}_W)dS=\iiint_V \mathbf{G}dV, \tag{2.1}$$