NUMERICAL SOLUTIONS OF COMPLETE AND REDUCED NAVIER-STOKES EQUATIONS FOR SUPERSONIC CHEMICAL LASER FLOW MODELING

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INTRODUCTION

The use of nonequilibrium, high-speed, convective flows for producing a continuous laser action has recently led to the creation of various CW diffusion-type laser systems. What is required is a widely applicable computer model for analyzing the ducted flow configurations in the mixing zone of two chemically reacting coaxial streams with strong lateral pressure gradients. Computational efficiency is also a matter of paramount importance.

The analysis is limited to the numerical modeling of mixing and chemical reactions between gas components of the chemical diffusion-type HCl-laser in the base region produced by nozzle trailing edges of planar or axisymmetric geometry. One nozzle (A) injects vibrationally excited hydrogen, while the other (B) contains products of diluted molecular chlorine thermal dissociation. It is possible in principle to realize vibrational energy transfer from excited H₂(v) molecules to HCl(v) molecules produced in chemical reactions. We also examine the influence of additional fuel feeding by injecting a cold sonic jet of hydrogen through the nozzle (C).

In the general case the jet static pressures are not matched and the pressure gradients induced by compression and expansion waves as well as by chemical heat release greatly influence the energy conversion process. The latter phenomenon is a matter of importance for HCl chemical laser operation since vibrationally excited HCl(v) molecules can be produced only in the "hot" branch of a chemical mechanism and the degree of Cl₂ dissociation cannot be arbitrarily increased. A "hot" branch is characterized by
essential heat release that leads at a low concentration of diluent to "thermal blockage" of the flow. The use of a nozzle bank with a base relief region has proved\textsuperscript{1} to be an effective means for preventing this phenomenon. The presence of the base relief region favors reducing of the pressure level due to the expansion fan interaction with a reacting flow immediately downstream of the base. Such a coupling of hydrodynamics and chemical kinetics has been examined using both time-dependent and steady-state numerical models.

COMPUTER MODEL

A system of complete Navier-Stokes equations supplemented with the mass and energy conservation laws in the form of the relevant partial differential equations was used to model the flow of a multicomponent mixture with finite-rate physical and chemical processes. These equations are well known and are presented here for reference:

\begin{align*}
\frac{\partial \rho}{\partial t} &= -\nabla \rho \mathbf{v} \quad (1) \\
\frac{\partial (\rho \mathbf{v})}{\partial t} &= -\nabla \rho \mathbf{v} \cdot \mathbf{v} - \nabla p + \nabla \eta \nabla \mathbf{v} \quad (2) \\
\frac{\partial \rho_i}{\partial t} &= -\nabla \rho_i \mathbf{v} + \nabla D_i \rho_i \mathbf{v} + \{\frac{\partial \rho_i}{\partial t}\}_{\text{chem}} \quad (3) \\
\frac{\partial E}{\partial t} &= -\nabla \mathbf{v} \cdot \mathbf{v} - \nabla p \mathbf{v} + \nabla \eta \nabla T + \{\frac{\partial E}{\partial t}\}_{\text{chem}} \quad (4)
\end{align*}

where $\rho$, $\rho \mathbf{v}$, $E$, and $p$ are the total mass, momentum, and energy densities, and pressure, respectively. The $\rho_i$ and $D_i$ are the mass density and the "effective" diffusion coefficient of the individual species. The quantities $\eta$ and $\lambda$ represent viscosity and thermal conductivity of the gas mixture. The effective diffusion coefficients $D_i$ for individual species, depending in a complicated manner on the mixture composition and the binary diffusion coefficients for all the pairs of species, were approximated by simplified relations presented in Ref. 2. A stricter formulation using Stephan-Maxwell relations seems to be impractically complex, though it gives us a possibility of overcoming the difficulties associated with a correct description of species diffusion with highly different diffusion coefficients $D_i$. A mathematical statement of the problem suggests the specification of kinetic equations in the form of a phenomenological mass action law in accordance with a mechanism of kinetic processes or chemical reactions, reaction rate coefficients, and thermal properties of mixture components. Details of the physical model are presented in Ref. 3.

The finite-difference analogues of the general conservation laws in terms of the complete Navier-Stokes equations are solved by using the partially implicit (RICE) method\textsuperscript{4} that employs a