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Extension of CE/SE method to non-equilibrium dissociating flows

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ABSTRACT

In this study, the hypersonic non-equilibrium flows over rounded nose geometries are numerically investigated by a robust conservation element and solution element (CE/SE) code, which is based on hybrid meshes consisting of triangular and quadrilateral elements. The dissociating and recombination chemical reactions as well as the vibrational energy relaxation are taken into account. The stiff source terms are solved by an implicit trapezoidal method of integration. Comparison with laboratory and numerical cases are provided to demonstrate the accuracy and reliability of the present CE/SE code in simulating hypersonic non-equilibrium flows.

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Introduction

When a space vehicle enters the atmosphere at an orbital speed, a detached bow shock forms in front of its blunt nose and the temperature behind the shock, especially in the stagnation region, can reach high levels, due to the conversion of kinetic flow energy into thermal energy by strong shock compression. The important gas molecule dissociation and other real gas effects of hypersonic flows will occur. Consequently, the air can no longer be treated as a perfect gas and the dissociative non-equilibrium phenomenon complicates the flow physics [1].

Due to the extreme flow conditions, experimental approaches to study the hypervelocity flows are difficult in general, not to mention the expensive cost. Sometimes, inevitable large errors must be compromised. Theoretical methods are also limited in exploring the global dissociative non-equilibrium flow physics. Only some simple analytical solutions can be obtained, such as the dimensionless shock-off distance as a function of dimensionless dissociation rate [2–4]. Therefore, to thoroughly understand the hypersonic dissociative non-equilibrium flows, numerical studies are essential.

Because in the field of computational fluid dynamics (CFD) a conflict between stability and numerical accuracy is one that affects most of the established methods, Chang and To [5] developed the space–time conservation element and solution element (CE/SE), using the unique approach of enforcing flux conservation in both space and time with extensive physics considerations. Since its inception in 1991, it has been used to obtain highly accurate numerical solutions for 1D, 2D, and 3D flow problems involving shocks, contact discontinuities, vortices, etc. [5–8].

Chang [9,10] and Chang and Choudhari [11] had successfully applied the CE/SE method to study viscous hypersonic flows without considering the non-equilibrium effects. The present work aims to extend the inviscid CE/SE code based on hybrid

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meshes consisting of triangular and quadrilateral elements [12,13] to solve hypersonic chemical reacting non-equilibrium flows. Both chemical dissociation and vibrational energy relaxation are considered. The code is capable to use the CV–CV [14] model developed by Knab and the two-temperature chemical kinetic model developed by Park [15–17].

Cases of nitrogen, air and carbon dioxide are provided to demonstrate the accuracy and reliability of the method regarding non-equilibrium flows where the flow features of hypersonic flows are analyzed in detail and compared with the theoretical results. Furthermore, an Air flow case from Knab [14] experiments was used to test the code capabilities regarding the coupled CV–CV model multiple vibrational temperature effects.

Governing equations and physical model

Usually, high-speed flows are described by classic Navier–Stokes equations or inviscid Euler equations with a perfect gas equation of state. However, due to the high temperature effect, the important gas molecule dissociation, ionization and other real gas effects of hypersonic flows may occur. In addition, the high molecular energy mode, e.g. vibrational energy, will also be excited. Therefore, more terms must be added into the classic Navier–Stokes equations or Euler equations to take these phenomena into account and hence, the general form of the equations governing 2D reactive non-equilibrium flows with n_s species can be written as

$$\frac{\partial \boldsymbol{U}}{\partial t}+\frac{\partial \boldsymbol{F}(U)}{\partial x}+\frac{\partial \boldsymbol{G}(U)}{\partial y}-\Psi_v\left(\frac{\partial \boldsymbol{F_v}(U)}{\partial x}+\frac{\partial \boldsymbol{G}_v(U)}{\partial y}\right)=\Psi_s \boldsymbol{S}(U)+\Psi_r \boldsymbol{R}(U) \tag{1}$$

where $\boldsymbol{U}=[\rho_1,\ldots,\rho_{n_s},\rho u,\rho v,E,E_{v_{m_1}},\ldots,E_{v_{m_s}}]^T$ is the conservative quantity vector. $\boldsymbol{F}$ and $\boldsymbol{G}$ are the convection fluxes, which are given by

$$\boldsymbol{F}=\left[\rho_1 u,\ldots,\rho_{n_s}u,\rho u^2+p,\rho uv,(E+p)u,E_{v_{m_1}}u,\ldots,E_{v_{m_s}}u\right]^T \tag{2}$$

and

$$\boldsymbol{G}=\left[\rho_1 v,\ldots,\rho_{n_s}v,\rho uv,\rho v^2+p,(E+p)v,E_{v_{m_1}}v,\ldots,E_{v_{m_s}}v\right]^T \tag{3}$$

The viscid fluxes $\boldsymbol{F_v}$ and $\boldsymbol{G_v}$ can be expressed in the following form

$$\boldsymbol{F_v}=\begin{bmatrix} -\rho u_1^d \\ \vdots \\ -\rho u_{n_s}^d \\ \tau_{xx} \\ \tau_{xy} \\ \tau_{xx}u+\tau_{xy}v-q_x-q_x^v-\sum_{s=1}^{n_s}\rho_s u_s^d h_s \\ -q_x^v-\rho_{m_1}u_{m_1}^d e_{m_1}^v \\ \vdots \\ -q_x^v-\rho_{m_s}u_{m_s}^d e_{m_s}^v \end{bmatrix} \tag{4}$$

$$\boldsymbol{G_v}=\begin{bmatrix} -\rho v_1^d \\ \vdots \\ -\rho v_{n_s}^d \\ \tau_{xy} \\ \tau_{yy} \\ \tau_{yy}v+\tau_{xy}u-q_y-q_y^v-\sum_{s=1}^{n_s}\rho_s u_s^d h_s \\ -q_y^v-\rho_{m_1}v_{m_1}^d e_{m_1}^v \\ \vdots \\ -q_y^v-\rho_{m_s}v_{m_s}^d e_{m_s}^v \end{bmatrix} \tag{5}$$

$\boldsymbol{S}$ is the source term caused by symmetry (y being the axis of symmetry) and $\boldsymbol{R}$ is that caused by chemical reactions and energy relaxation. They can be expressed in the following form

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