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Radical recombination in a hydrocarbon-fueled scramjet nozzle

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Abstract To reveal the radical recombination process in the scramjet nozzle flow and study the effects of various factors of the recombination, weighted essentially non-oscillatory (WENO) schemes are applied to solve the decoupled two-dimensional Euler equations with chemical reactions to simulate the hydrocarbon-fueled scramjet nozzle flow. The accuracy of the numerical method is verified with the measurements obtained by a shock tunnel experiment. The overall model length is nearly 0.5 m, with inlet static temperatures ranging from 2000 K to 3000 K, inlet static pressures ranging from 75 kPa to 175 kPa, and inlet Mach numbers of 2.0 ± 0.4 are involved. The fraction Damkohler number is defined as functions of static temperature and pressure to analyze the radical recombination progresses. Preliminary results indicate that the energy releasing process depends on different chemical reaction processes and species group contributions. In hydrocarbon-fueled scramjet nozzle flow, reactions with H have the greatest contribution during the chemical equilibrium shift. The contrast and analysis of the simulation results show that the radical recombination processes influenced by inflow conditions and nozzle scales are consistent with Damkohler numbers and potential dissociation energy release. The increase of inlet static temperature improves both of them, thus making the chemical non-equilibrium effects on the nozzle performance more significant. While the increase of inlet static pressure improves the former one and reduces the latter, it exerts little influence on the chemical non-equilibrium effects.

1. Introduction

The supersonic combustion ramjet (scramjet) engine is the key to air-breathing hypersonic flight. Internationally, the scramjet engine has been widely investigated, and there is continuing interest in its performance.[1] As a main component of the scramjet, the nozzle makes high enthalpy flow fully expand from the combustion chamber and produces most of thrust,

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whose magnitude and direction have decisive effects on the scramjet performance.[2] Thus related research is necessary.

Due to high speed, a thermal and chemical non-equilibrium phenomenon is visible in the external and internal flow fields of a hypersonic vehicle, and different regions require different levels of chemical and thermal modeling.[3] One of the characteristics of the scramjet nozzle flow is the chemical non-equilibrium flow. The scramjet operating temperature is extremely high and a fuel-sufficient combustion is difficult because of the exceedingly high speed. Radical recombination and kinetic afterburning exist in the nozzle flow,[4,5] which causes some chemical energy released during the nozzle flow. Because of this effect, the distributions of the wall pressure get a change and the nozzle performance is improved.

Previous studies on the chemical non-equilibrium nozzle flow mostly focused on calculation methods and effects on nozzle performance, mainly based on a hydrogen-fueled scramjet nozzle. The chemical non-equilibrium process in the nozzle was rarely discussed, especially the radical recombination as its effects on nozzle performance appeared only in high-temperature conditions. A computer model for describing quasi-one-dimensional flow was used by Sangiovanni et al.[6] to study the role of hydrogen/air chemistry in nozzle performance for a hypersonic propulsion system. The study showed that the finite-rate chemistry should not be neglected in nozzle performance simulations, because the beneficial chemical process persisted throughout the entire nozzle length. Thomas and Wolfgang[7] used a finite element code to model the chemical reactions considering the finite-rate chemistry and the vibrational relaxations. Different test cases were computed, and the results were compared with the measured data. Stallker et al.[4] thought that kinetic afterburning could be taken as occurring when the combustion reaction was interrupted by the nozzle expansion. The reactions were not completely quenched and proceeded to produce substantial heat release in the nozzle. Wang's study[8] indicated that the nozzle could supplement the combustion in a supersonic combustor so that the performance of the nozzle could be increased.

The high temperature makes the gas dissociate partially in the scramjet combustion, and the radical components recombine in the nozzle due to the decrease of temperature with some energy released to increase the nozzle performance. This paper aims at analyzing the phenomenon of radical recombination in the nozzle flow and studying the effect on the scramjet nozzle performance, based on a perfect combustion at the exit of a kerosene-fueled scramjet combustor.

2. Numerical simulation and verification

2.1. Physical model

As shown in Fig. 1, the vehicle studied is a fully integrated scramjet[9] which employs the entire windward surface of the forebody in the inlet compression process and the entire windward surface of the afterbody in the exhaust expansion process. A representative entire-cowl two-dimensional nozzle is designed by the cubic spline curve method. The geometric parameters of the nozzle used in experiments and numerical simulations are: nozzle total length $L = 0.497$ m, nozzle entrance height $H_{\text{in}} = 0.047$ m, nozzle exit height $H_{\text{out}} = 0.241$ m, and nozzle width $W = 0.06$ m.

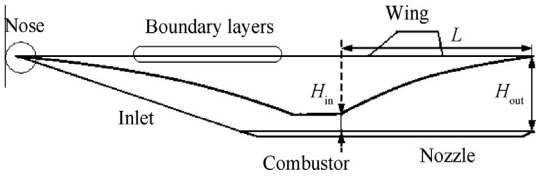

Fig. 1 General configuration of a hypersonic vehicle.

2.2. Numerical method

The scramjet nozzle expansion process is modeled in sufficient details to adequately simulate the pressure/temperature history in the nozzle, and thereby is able to isolate the role of chemical reaction mechanisms. Since the emphasis of this study is on nozzle chemistry, the effects due to viscosity and mixing are neglected in this model. On the basis of the assumptions, the governing equations are made from the two-dimensional Euler equations with the conservation of mass in Cartesian coordinates, applying 17 species and 26 elementary reaction models:

$$\frac{\partial \boldsymbol{U}}{\partial t}+\frac{\partial \boldsymbol{E}}{\partial x}+\frac{\partial \boldsymbol{F}}{\partial y}=\boldsymbol{S} \tag{1}$$

where the conservative vector $\boldsymbol{U}=[\rho,\rho u,\rho v,\rho e,\rho_1,\rho_2,\cdots,\rho_{n-1}]^{\mathrm{T}}$, $\boldsymbol{E}$ and $\boldsymbol{F}$ are convective terms, and $\boldsymbol{S}=[0,0,0,0,\sigma_1,\sigma_2,\cdots,\sigma_{n-1}]^{\mathrm{T}}$ is a source term; ρ is the density; u and v are the velocity components in x-direction and y-direction; e is the specific internal energy; ρ_i and σ_i are the density and mass production rate of each species, and $\sum_{i=1}^{n}\sigma_i=0$, $\sum_{i=1}^{n}\rho_i=\rho$.

The governing equations are decoupled by the method proposed in Refs.[10,11]. Firstly, the equations are mathematically transformed by

$$\rho e^{*}=\rho e-\sum_{i=1}^{n}\rho_i h_i^0(T)=0.5\rho(u^2+v^2)+\frac{p}{\gamma-1} \tag{2}$$

where e^{*} and γ have no precise physical meanings, but they are equivalent to the internal energy and specific heat ratio of perfect gas in mathematical forms; p is the pressure and h_i^0 is the standard state specific enthalpy of species i. The variable e in the conservative vector $\boldsymbol{U}$ is replaced with e^{*}, and the source term gets a new transformation of

$$\boldsymbol{S}^{*}=\left[0,0,0,-\sum_{i=1}^{n}\sigma_i h_i^0(T),\sigma_1,\sigma_2,\cdots,\sigma_{n-1}\right]^{\mathrm{T}} \tag{3}$$

Then, the equations are divided into two parts, flow equations and chemical equations, according to the operator splitting method as follows:

$$\frac{\partial \boldsymbol{U}}{\partial t}+\frac{\partial \boldsymbol{E}}{\partial x}+\frac{\partial \boldsymbol{F}}{\partial y}=\boldsymbol{0} \tag{4}$$

$$\frac{\partial \boldsymbol{U}}{\partial t}=\boldsymbol{S}^{*} \tag{5}$$

To ensure the second-order accuracy of the solution, Strang splitting is used to decouple the equations. While the equivalent of specific heat ratio is introduced, the flow equations are similar to the Euler equations of perfect gas, and upwind WENO schemes[12,13] are applied.