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Air Chemical Non-Equilibrium Effects on the Hypersonic Combustion Flow of RCS with Gaseous Ethylene Fuel

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Abstract. In this paper, air chemical non-equilibrium effects on the shock-induced combustion flow are numerically investigated for a reaction control system (RCS) with gaseous ethylene fuel by solving multi-component Navier-Stokes (N-S) equations. An integrated numerical method is developed that considers two different chemical reaction mechanisms: the high temperature air chemical non-equilibrium reactions and ethylene-oxygen combustion reactions. The method is independently validated by two types of reacting flow: the hypersonic air chemical non-equilibrium flow over a sphere and supersonic ethylene-oxygen combustion flow for a dual combustion chamber. Furthermore, the mixed reacting flow over a blunt cone with a transverse multi-component gaseous jet is analyzed in detail. Numerical results indicate that air chemical non-equilibrium effects could lead to a reduction of the shock detachment distance, a decrease of the temperature behind the shock wave and a reduction of the combustion products.

AMS subject classifications: 76D05, 76K05, 80A30

Key words: RCS, ethylene-oxygen combustion, air chemical non-equilibrium effects, hypersonic.

1 Introduction

Most reentry vehicles are equipped with a reaction control system for attitude and maneuver control in order to counteract the aerodynamic inadequacy at high space. The RCS generally uses hydrogen or hydrocarbon fuel [1]. The combustion flow field is fairly complex. Meanwhile, the high-temperature air surrounding the vehicles often undergoes chemical non-equilibrium processes, such as dissociation, vibrational excitation and ionization, during the reentry period [2]. In this case, the combustion flow will be affected

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by air chemical non-equilibrium reactions. To precisely predict the mixed reacting flow field of hypersonic vehicles with RCS and capture the flow field properties, it is necessary to consider air chemical non-equilibrium effects on the combustion flow.

There are several differences between combustion and air chemical non-equilibrium reactions, such as the components, thermodynamic data, reaction equations and reaction temperature. Taking ethylene-oxygen combustion as an example, tens of reaction equations are used in the chemical kinetics model. Many researchers have conducted extensive studies on the simplification of chemical reaction models. As a result, some commonly simplified models have been developed, including the 10-component model with 10 reaction equations [3], 10-component model with 8 reaction equations [4] and 7-component model with 3 reaction equations [5]. Additionally, the temperatures for which thermodynamic data are available range from 300 to 5000K [6], and the reaction temperature is less than 5000K. Nevertheless, most in-air chemical non-equilibrium reactions involve 11 components (O_2, N_2, O, N, NO, NO^+, N^+, O^+, N_2^+, O_2^+ and e^-). The popular air chemical non-equilibrium reaction models are the 5-component model [7], 7-component model [8] and 11-component model [9,10]. An appropriate reaction model should be adopted according to the flight altitude and velocity [11] for better analysis of aerodynamics and aerothermodynamics. The temperature range of the thermodynamic data is 300-30000K, and the reaction temperature could reach as high as 15000K.

Solving the regime of mixed reacting flow that contains combustion reactions and air chemical non-equilibrium reactions is quite difficult. Hence, currently, independent numerical investigations are conducted. In numerical studies of combustion flow, Choi et al. [12] carried out a comprehensive numerical analysis in a scramjet engine combustor with and without a cavity, considering transverse injection of hydrogen over a broad range of injection pressures, and the oscillatory flow characteristics were captured to identify the physical mechanisms. Wang and Wu [13] developed a parallelized program to simulate the reacting flow on hybrid meshes, and the premixed/combustion flow with a normal injection of hydrogen was analyzed to reveal the combustion effect on the flow field structures. Gao and Lee [14] conducted a numerical analysis of a scramjet engine, considering the variation of dimensionless parameters in the flow field, and discussed the characteristics of the turbulent combustion flow field. On the other hand, Park [15] discussed the assumptions, approximations and limitations of a two-temperature chemical-kinetic model for air by comparing the theoretical results with the experimental data obtained in shock tubes, ballistic ranges and flight experiments. Ouyang and Xie [16] performed numerical simulations for the entire flow field over a blunt sphere cone, using the overall Teflon-air chemical reaction model. Dong et al. [17] simulated the thermo-chemical non-equilibrium flow field by using the numerical code "AEROPH Flows" and analyzed the influence of the chemical reaction model, thermodynamic non-equilibrium model, surface temperature and surface material catalytic action on the distribution of the heat transfer rate.

In this paper, an integrated numerical method is developed based on hybrid grid techniques for simulating the mixed reacting flow, considering both air chemical non-