Commun. Comput. Phys. Vol. **37**, No. 1, pp. 250-288
doi: 10.4208/cicp.OA-2024-0145 January 2025

Application of Gas-Kinetic Unified Algorithm for Solving Boltzmann Model Equation with Vibrational Energy Excitation

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Received 29 June 2024; Accepted (in revised version) 23 August 2024

Abstract. In recent decades, the gas-kinetic unified algorithm (GKUA) is proposed to simulate the gas flow in the whole flow regimes. In previous studies, GKUA was extended to problems of flows around the aircraft and internal flows considering the influence of rotational energy, as well as the flows around the aircraft considering the influence of vibrational energy. In this paper, we try to apply the model considering the effect of vibrational energy to the engine internal and external mixed flow problem, and build a numerical simulation framework of engine internal and external mixed flow considering the effect of vibrational energy. The reliability of the algorithm is verified by using one-dimensional shock tube problem and two-dimensional nozzle internal flow problem. The results show that the model can describe the flow problem of high temperature nozzle internal flow. Then the two-dimensional nozzle internal and external mixed flow problem of 25N attitude control engine is studied, the unsteady evolution and non-equilibrium effect of the mixed flow field are analyzed, and the flow parameter distribution of the mixed flow field without internal energy excitation, considering rotational energy excitation and considering vibrational energy excitation are compared.

AMS subject classifications: 35Q20, 76P05, 82C40

Key words: Thermodynamic non-equilibrium, Boltzmann model equation, gas-kinetic unified algorithm, aerodynamics covering various flow regimes, nozzle flow.

1 Introduction

With the gradual maturity of the mass production of recoverable vehicles and satellites, the pace of human space development has gradually accelerated, and the number of various types of spacecraft in orbit has shown an explosive growth trend. Attitude and orbit

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engine reaction control system (RCS) is often used for maneuver and attitude control of space in-orbit flight and reentry vehicles [1–3]. The flow in the high-pressure air chamber at the nozzle entrance and the flow near the nozzle exit area of the attitude orbit control engine belong to continuum flow, with near-continuum flow near the nozzle exit and highly rarefied flow near the vacuum far away from the nozzle exit. The coexistence of multi-flow regimes in the same flow field due to the different degrees of rarefaction of gas poses a great challenge to the numerical simulation method.

For multi-regime flow problems, wind tunnel experiment has limitations because it cannot reproduce similar parameters such as Reynolds number, Mach number, Knudsen number, and wall temperature ratio at the same time [4]. In practice, people usually use the hybrid method [3, 5–8] and the unified method [9–13] to deal with such problems. The commonly used hybrid method is to couple the NS method with the DSMC method and realize the combination of the two methods in the transitional flow region. Since it is a coupling method in nature, both the accuracy and stability need to be considered when designing coupling ideas, and the problem of statistical fluctuation caused by DSMC method always exists. Based on the kinetic theory of gases, the unified method aims to use one method to simulate multi-scale flow problems in the whole regimes. The unified methods include unified gas-kinetic scheme (UGKS) [14–16], discrete unified gas-kinetic scheme (DUGKS) [17,18], gas-kinetic unified algorithm (GKUA) [19,20], unified stochastic particle BGK, (USP-BGK) [21] and unified gas kinetic wave-particle (UGKWP) [22,23]. In this paper, gas-kinetic unified algorithm solving multi-regime flow around problem and parallel computing application research platform for aerodynamic/thermal problems of spacecraft reentry multi-regime multi-scale flow around which are established by Li [19,20] are used to study the in-orbit spacecraft engine internal and external mixed flow problem.

Since the gas ejected from the engine is a high-temperature polyatomic mixture gas, the combustion chamber temperature is higher, and the high-temperature environment makes the internal energy of the gas medium in an excited state, which affects the gas transport coefficient and the parameter distribution of the internal and external mixed flow field of the engine. Wang et al. [24] proposed a semi-classical method for treating polyatomic gases with internal energy effects and obtained the WCU equation. Based on this, Morse [25] constructed a model equation considering the interrupted energy levels of the intramolecular energy. However, the above studies did not distinguish rotational and vibrational energy, and the internal energy was a single mode. In the case of ignoring the quantum effect in high temperature gas flow, the internal energy state of gas molecules is considered as continuous, and the classical thermodynamic method was adopted to obtain the Rykov model [26] of diatomic gas considering the influence of rotational energy. On the basis of Morse's research, Holway [27] used classical thermodynamic methods to deal with rotational energy and discontinuous energy level methods to deal with vibrational energy, and established an ES-BGK model suitable for polyatomic gases. In previous works, Peng et al. [28] used continuous energy levels to deal with rotational energy and vibrational energy, and decomposed the collision