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A Compressible Conserved Discrete Unified Gas-Kinetic Scheme with Unstructured Discrete Velocity Space for Multi-Scale Jet Flow Expanding into Vacuum Environment

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Abstract. The mechanism of jet flow expanding into vacuum environment (or extremely low density environment) is important for the propulsion unit of micro-electro-mechanical systems (MEMS), the thruster of spacecraft, the attitude control system of satellite, etc.. Since its flow field is often composed of local continuum region and local rarefied region, the jet flow into vacuum has noteworthy multi-scale transportation behaviors. Therefore, the numerical study of such flows needs the multi-scale schemes which are valid for both continuum and rarefied flows. In the past few years, a series of unified methods for whole flow regime (from continuum regime to rarefied regime) have been developed from the perspective of the direct modeling, and have been verified by sufficient test cases. In this paper, the compressible conserved discrete unified gas-kinetic scheme is further developed and is utilized for predicting the jet flows into vacuum environment. In order to cover the working conditions of both aerospace and MEMS applications, the jet flows with a wide range of inlet Knudsen (Kn) numbers (from 1E-4 to 100) are considered. The evolution of flow field during the entire startup and shutdown process with Kn number 100 is predicted by the present method, and it matches well with the result of analytical collisionless Boltzmann equation. For Kn numbers from 1E-4 to 10, the flow field properties such as density, momentum, and pressure are investigated, and the results are provided in details, since the published results are not sufficient at the present stage. The extent and intensity of the jet flow influence are especially investigated, because they are strongly related to the plume contamination and momentum impact on objects facing the jet, such as the solar paddles which face the attitude control thruster during the docking process.

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1 Introduction

The flow from high pressure nozzle expanding to vacuum or low density environment is a common problem in many fields [1–4]. Its typical applications can be found in attitude control thruster of spacecraft [4], the propulsion of micro-electro-mechanical systems (MEMS) [5], spray in vacuum chamber [6], etc.. The quantitative investigation of the jet flow field and its influence is very important. For example, when jet flow expands freely into outer space and becomes plume, it would cause contamination and impact on devices such as solar paddles, and may lead to severe damage.

According to the Knudsen (Kn) number, which is the ratio of molecular mean free path (m.f.p.) to characteristic length, the flow can be qualitatively categorized into continuum flow ($\mathrm{Kn} < 0.001$), slip flow ($0.001 < \mathrm{Kn} < 0.1$), transitional flow ($0.1 < \mathrm{Kn} < 10$) and free molecular flow ($\mathrm{Kn} > 10$). Since the flow is often continuum at the inlet of the jet, when expanding into the vacuum environment, it will experience these regimes consequently and finally become free molecular flow. Therefore, these regimes will exist in the same flow field simultaneously, making the physical problem a challenging multi-scale and multi-regime one.

At the present stage, several works have conducted to address the problem of jet flow into vacuum. With the aid of scientific instruments such as supersonic nozzle and low density wind tunnel, the jet flows into vacuum and plumes are investigated in experiments [2, 7, 8]. In the numerical investigations, the plume effect is analyzed using a semi-empirical hybrid continuum/rarefied method [9], and the jet flow into vacuum with large inlet Kn number is calculated with the gas-kinetic unified algorithm (GKUA) [10]. In the free molecular flow limit, the problem of jet flow into vacuum has an analytical solution, and it is found in the theoretical works in Refs. [11–13]. Not all the setting of jet flow can be achieved in the experiment due to the limitation of current experimental conditions [14], and prevailed numerical methods such as Navier-Stokes (N-S) method for continuum flow and the DSMC method for rarefied flow are single-scale methods [15,16]. Therefore, for investigating the multi-scale problem of jet flow into vacuum, multi-scale and multi-regime numerical methods are in strong demand, which can calculate the evolution of flow field from continuum regime to rarefied regime simultaneously without domain decomposition.

Given the model Boltzmann equation in the gas-kinetic theory, which can describe the multi-scale physics [17], the unified gas-kinetic scheme (UGKS) [18–21], the discrete unified gas-kinetic scheme (DUGKS) [22–25], the GKUA [26–28] and the improved discrete velocity method (improved DVM) [29, 30] have been developed for accurate simulation