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Multiscale Simulation of Rarefied Gas Flows in Simplified Divertor Tokamak Test Facility Particle Exhaust

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Abstract. Simulating gas flow within the divertor, which is a crucial component in nuclear fusion reactors, is essential for assessing and enhancing its design and performance. Traditional methods, such as the direct simulation Monte Carlo and the discrete velocity method, often fall short in efficiency for these simulations. In this study, we utilize the general synthetic iterative scheme to simulate a simplified Tokamak divertor model, demonstrating its fast convergence and asymptotic-preserving properties in complex three-dimensional scenarios. A conservative estimate of speedup by three orders of magnitude is achieved by the general synthetic iterative scheme when compared to the direct simulation Monte Carlo method. We further investigate the relationship between pumping efficiency and factors like temperature, absorptivity, and the Knudsen number, providing valuable insights to guide the design and optimization of divertor structures.

AMS subject classifications: 65-XX, 76-XX

Key words: Vacuum pump, rarefied gas flow, general synthetic iterative scheme.

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1 Introduction

Nuclear fusion, a reaction process with immense energy potential, is considered a promising source of future clean energy. Divertors are essential components in fusion reactors, which enhance the efficiency and sustainability of fusion reactions by reducing energy loss and impurity accumulation. For example, the Divertor Tokamak Test (DTT) facility in Europe aims to conduct scaled experiments to develop divertor solutions compatible with the anticipated physical conditions and technological environment of the

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DEMO reactor. The pumping rate is one of the critical factors in the design of divertor [1–3], and numerical methods are used to determine optimal pumping port configurations [4, 5]. However, the complex structure of divertor results in a wide range of Knudsen numbers (Kn, the ratio of mean molecular free path λ to the characteristic flow length L), and poses significant challenges in the numerical simulations, as the gas flow should be described by the Boltzmann equation rather than the traditional Navier-Stokes equations.

The Boltzmann equation can be solved by the stochastic direct simulation Monte Carlo (DSMC) method [6] and deterministic discrete velocity method (DVM) [7]. The DSMC uses simulation particles to mimic the streaming and collision of real gas molecules, and there are only a few simulation particles in each spatial cell. Therefore, it has become the prevailing method to simulate the rarefied gas dynamics as the usage of computer memory is acceptable. However, because the streaming and collision are splitted, the cell size and time step must be smaller than the mean free path and mean collision time of gas molecules, respectively, rendering the DSMC extremely time-consuming in simulating near-continuum flows. In order to improve the computational efficiency in the near continuous flow region, the NS-DSMC coupling method [8, 9] has been proposed, that is, the NS equation and DSMC method are used in the near continuous and rarefied flow regimes, respectively. However, in many engineering applications, it is difficult to distinguish the boundary between them. In order to avoid such problems, scholars have proposed a series of new methods such as the time relaxation Monte Carlo method [10, 11], the exponential Runge-Kutta method [12] and the asymptotic-preserving Monte Carlo method [13]. In addition, scholars have also conducted in-depth studies on stochastic methods. Fei *et al.* used the Chapman-Enskog expansion to eliminate first-order numerical flux errors and proposed a unified random particle Bhatnagar–Gross–Krook (BGK) method [14]; Pfeiffer *et al.* introduced the exponential differencing BGK method, which applies implicit integration to the BGK equation [15]. Kim *et al.* proposed a random particle Fokker-Planck method, which combined with stochastic interpolation technology and achieve second-order accuracy under fixed CFL conditions [16]. However, since the statistical averaging is needed, the DSMC is slow in resolving small and/or transit flow fields. As a consequence, in the simulation of DTT particle exhaust [1], 40 million spatial cells and 0.688 million CPU core hours are required to find the steady state, making the optimization of divertor difficult.

In DVM, in addition to the spatial discretization, the molecular velocity space is also discretized [17,18]. Since each physical cell contains thousands of discrete velocity points, the computer memory requirement can be hundreds times greater than that of the DSMC. However, due to its deterministic nature, the statistic averaging process is eliminated, making it faster than the DSMC in simulating low-speed and/or transit flows.

Early versions of DVM also separate the streaming and collision processes, leading to large numerical dissipation similar to the DSMC. In the past decades, significant progresses are made by Chinese scholars to eliminate these deficiencies and boost the simulation efficiency by several orders of magnitude. For example, the implicit unified gas-