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Unified Gas Kinetic Scheme and Direct Simulation Monte Carlo Computations of High-Speed Lid-Driven Microcavity Flows

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Abstract. Accurate simulations of high-speed rarefied flows present many physical and computational challenges. Toward this end, the present work extends the Unified Gas Kinetic Scheme (UGKS) to a wider range of Mach and Knudsen numbers by implementing WENO (Weighted Essentially Non-Oscillatory) interpolation. Then the UGKS is employed to simulate the canonical problem of lid-driven cavity flow at high speeds. Direct Simulation Monte Carlo (DSMC) computations are also performed when appropriate for comparison. The effect of aspect ratio, Knudsen number and Mach number on cavity flow physics is examined leading to important insight.

AMS subject classifications: 82C40, 76P04, 65C05

Key words: UGKS, DSMC, lid driven cavity, kinetic theory, Knudsen number.

1 Introduction

High-speed rarefied microcavity flows are of importance in the study of hypersonic flight and atmospheric re-entry flows. Scratches, impact damage or manufacturing defects in the thermal protection system of the flight vehicles can be conveniently modeled as microcavities. The presence of a microcavity on the thermal protection system surface may potentially be hazardous. According to Bertin and Cummings [1], one of the main contributing factors to the Columbia space shuttle accident was hot gas breaching through a cavity in the thermal protection system of the vehicle during its re-entry, causing catastrophic damage. Many of these flows of interest exhibit a wide range a Knudsen numbers within the flow domain of interest. For example, in high-altitude hypersonic and re-entry

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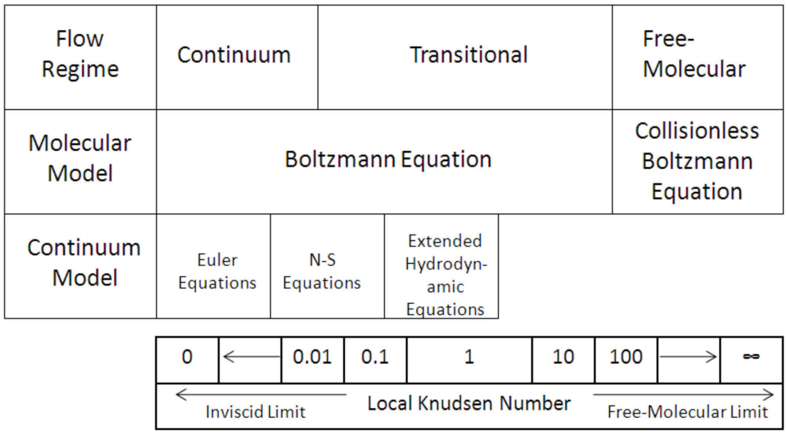

Figure 1: Knudsen number limits on the mathematical models.

flows, the freestream may be rarefied but the flow in the cavity could be close to continuum due to the entrapment of many molecules. It is important to characterize mixing and heat exchange efficiency of a cavity of given shape and size as functions of Reynolds, Mach and Knudsen numbers. Therefore, it is critical that the simulation tool be capable of capturing a range of Mach number and Knudsen number physics within a single flow domain.

Different Knudsen number regimes and corresponding physical features and governing equations are shown in Fig. 1. Efforts have been made in literature to couple continuum and discrete solvers to derive a hybrid scheme or even to extend the Boltzmann equation based solvers to continuum regime. However, the restrictions on time-step (of the order of mean collision time) and grid size (of the order of mean-free path) cannot be avoided because of the operator-splitting methods used for separating the collision and transport phenomena. The UGKS of Xu [2], is potentially efficient in both rarefied and continuum regimes due to the novel approach of coupling between particle transport and collision. The finite-volume UGKS evaluates the flux across each numerical cell according to the BGK-Shakhov [3,4] model with a discretized velocity space [5]. The advantage of UGKS is due to the fact that the time-step and the cell size are restricted by the Courant-Friedrichs-Lewy (CFL) condition rather than the corresponding mean collision time or mean-free path.

The main objectives of the paper are to: (i) extend the applicability of UGKS by implementing, testing and verifying a WENO (weighted essentially non-oscillatory) interpolation scheme; and (ii) examine the effect of Mach number, Knudsen number and aspect ratio on the flow characteristics in a lid-driven microcavity flow. In the first part, various WENO [6, 7] variants are compared against the original Van Leer [8] scheme to establish the applicability of the different interpolation schemes. Then the UGKS is compared against the well-established DSMC solver OpenFOAM (dsmcFOAM) at high Knudsen numbers. Once the verification is complete, the UGKS solver is used to investi-