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HYBRID CONTINUUM-PARTICLE COMPUTATION OF HYPERSONIC FLOWS

AFOSR GRANT FA9550-05-1-0115

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Abstract

Development is described of a Modular Particle-Continuum (MPC) hybrid CFD/DSMC code for physically accurate and numerically efficient computation of hypersonic configurations involving mixed regions of continuum and rarefied flow. Recent studies focus on the application and assessment of the hybrid code to complex hypersonic configurations including a cylinder-flare and a blunt capsule. The hybrid method can provide as much as a factor of 12 speedup in comparison to a full DSMC computation while providing almost identical results.

Introduction

The interaction between the bow shock of a hypersonic vehicle and the shock waves from a wing or control surface are of great interest in vehicle design because of the potentially high, localized temperature and the associated extremely high heating rates in the interaction region. Due to the tremendous technical difficulties and costs in obtaining laboratory and flight measurements under realistic conditions, numerical methods play an important role in the design of new hypersonic vehicles. Computational Fluid Dynamics (CFD) is the most suitable computational approach for the lower altitude portions of a hypersonic vehicle trajectory and for those parts of the vehicle with large physical length scales. The direct simulation Monte Carlo method (DSMC) [1] is a more appropriate technique for rarefied conditions that may be encountered at high altitude or on parts of the vehicle with small length scales, such as a sharp leading edge or an engine inlet cowl lip. Each of these techniques has their strengths and weaknesses in terms of physical accuracy and numerical efficiency.

Objective

The primary objective of this work is to develop and apply a hybrid CFD/DSMC code for physically accurate and numerically efficient computation of hypersonic configurations involving mixtures of continuum and rarefied flows.

Approach

We have taken the obvious approach of trying to fuse together existing CFD and DSMC codes into a hybrid Modular Particle-Continuum (MPC) algorithm. There are three critical steps in the development of such a hybrid CFD-DSMC code: (1) identifying when to switch between the methods; (2) communication of information between two very different simulation methods; and (3) integration of these methods into a single, numerically efficient computer code.

Progress

In the first two years of the grant, a baseline hybrid method was developed that employs a general, unstructured implicit method for solving the Navier-Stokes equations on the continuum side [2], and a general implementation of the DSMC technique on the particle side [3]. To communicate information between the DSMC and CFD codes, we use fluxes of the conserved variables (mass, momentum, energy) across cell faces. The natural statistical fluctuations that occur in the DSMC fluxes are controlled using a new sub-relaxation sampling scheme that we developed recently [4]. Buffer cells are used within the CFD region to accurately sample DSMC particles from the Chapman-Enskog distribution function. The hybrid simulation is first initialized by a CFD solution. The initial continuum and particle regions in the hybrid simulation are then identified using a continuum breakdown parameter based on Knudsen numbers evaluated using local mean free path and flow field gradient length scales [5]. The interfaces are re-evaluated periodically throughout a hybrid simulation until there is no further change in their location. The hybrid code has been previously demonstrated to accurately simulate planar shock waves and hypersonic flow around a cylinder [6,7]. The hybrid code re-produced expensive, full DSMC results at the level of the velocity distribution function while providing the solution up to three times faster.

In this last year, the focus has been on modularizing the hybrid code and applying it to flows for which more significant cost benefit is anticipated. The hybrid code is expected to offer greatest speedup for flows in which the fraction of area (or volume) requiring local DSMC analysis is small. For example, in a 2D flow, if half of the flow domain area requires DSMC analysis, then the greatest speedup that the hybrid code can provide is a factor of about two.

Among the hypersonic flow configurations considered this year are a cylinder-flare and a blunt planetary probe. Each configuration has been tested experimentally in previous studies [8,9]. The freestream flow conditions are provided in Table 1.

Case	U_{∞} (m/s)	T_{∞} (K)	ρ_{∞} (kg/m ³)	Kn_{global}
Hollow Cylinder Flare - CUBRC Run 11 -	2484.1	95.6 K	5.566e-4	0.0008
Planetary Probe - SR3 Case 3 -	1633.0	15.0 K	4.660e-4	0.001

In each case, the Navier-Stokes code LeMANS [2] was first used to obtain a continuum solution and the DSMC code MONACO [3] was obtained to obtain a particle solution. The continuum solution was then used to initialize the hybrid code.

Figure 1 shows geometric details of the cylinder-flare configuration along with contours of the mean free path that is found to vary by over a factor of 30. The variation in mean free path combined with the global Knudsen number indicates that there will be complex regions of localized rarefied flow that should be simulated using DSMC.

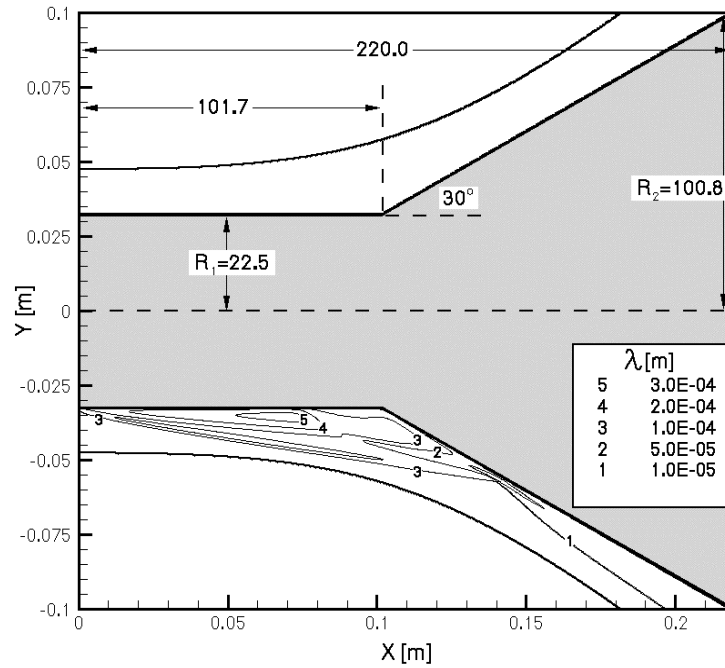


Figure 1. Dimensions of the cylinder-flare (in mm) and contours of mean free path.

Figure 2 shows geometric details of the planetary probe configuration along with contours of the mean free path that is found to vary by over a factor of 100 between the forebody and the wake. In this case, most of the forebody flow is continuum and the rarefied region begins at the shoulder of the vehicle and extends into the wake.

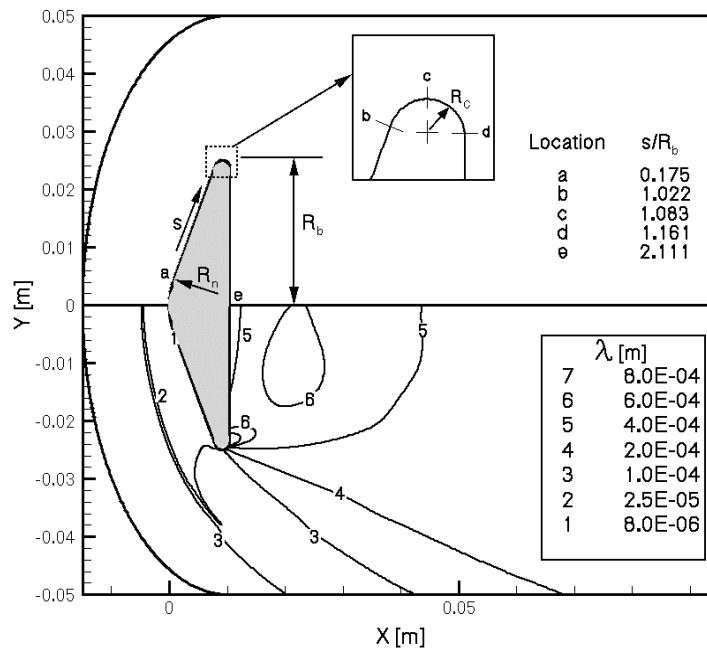


Figure 2. Planetary probe dimensions (in mm) and variation of mean free path.

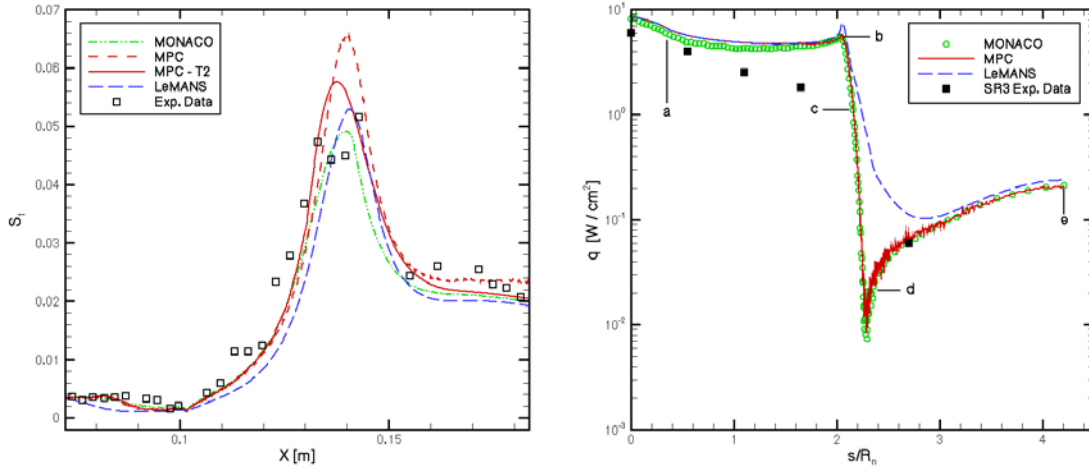


Figure 3. Heating rates along the surface: (a) cylinder flare; (b) planetary probe.

Figure 3(a) compares full-DSMC, full-NS, and hybrid (MPC) results for the heat flux on the surface of the cylinder-flare. The size of the separation region has been successfully reduced by the MPC method and agrees well with that predicted by full DSMC. Although not shown, the MPC simulation reproduces exactly the results for heat transfer predicted by full DSMC near the leading edge. This is expected, since the MPC method is found to accurately capture velocity slip, temperature jump, and thermal non-equilibrium near the leading edge. The MPC method is seen to improve the prediction of heat transfer in the separation region over the initial NS prediction. However, downstream of the flare junction the MPC results for heat transfer begin to differ from full DSMC results and over-predict the heat transfer by 20-30% for $X > 0.135$ m. The DSMC region created by the MPC method next to the flare surface is very thin. A better approach comes from realizing that aside from the strong shock wave, the re-attached flow near the flare surface is well within the continuum regime and DSMC may not be necessary at all. Comparing the initial NS solution to the full DSMC solution reveals no significant difference between DSMC and NS solutions (except inside the shock wave). Additionally, the NS simulation is found to accurately predict the experimental data downstream of the flare junction. Attempting to use DSMC in a thin, continuum region, involving steep flow gradients next to the surface is very difficult and unnecessary. In order to address this, a second MPC simulation (MPC - T2) is run where DSMC regions are only allowed to develop prior to $X = 0.13$ m and the NS equations are solved for the remainder of the flare. As seen in Fig. 3(a), this improves the heat transfer result over that predicted by the original MPC simulation.

The heat transfer results for full DSMC, NS, and MPC simulations are displayed in Fig. 3(b) and compared with experimental measurements. Comparing full DSMC and NS results, it can be seen that both predict the same peak heating rate at the stagnation point. Along most of the fore-body (locations a-b), DSMC predicts a slightly lower heating rate than the NS equations, however both simulations predict heating rates ranging from 2-3 times larger than measured experimentally. While the reason for this remains unclear, both DSMC and NS results agree very well with simulations performed by other researchers. Around the capsule shoulder and along the capsule base (locations b-e), DSMC is seen to predict a much lower heating rate than the NS equations, and DSMC is in better agreement with experimental results. In Fig. 3(b), the MPC

simulation is shown to reproduce DSMC results very accurately. In the highly compressed fore-body region where DSMC and NS simulations produce similar results, the MPC method successfully uses the NS equations and therefore reproduces full NS results. Just prior to the shoulder, where the MPC method switches to DSMC, we see the heating rate transition from the NS result to the DSMC result. For the entire shoulder and base region, the MPC method is seen to reproduce full DSMC results with a high degree of accuracy.

In terms of code performance, the planetary probe configuration is found to be much more suited to the use of the hybrid code for which a factor of 12.5 reduction in CPU time and factor of 5 reduction in memory over full DSMC is obtained. By comparison, the cylinder-flare configuration was computed using MPC with a factor of only 1.4 savings in CPU time over full DSMC.

Future Work

Several aspects of the existing hybrid MPC code require further development. The code must be extended to run on parallel computers. Each of the CFD and DSMC codes is parallelized so the main issue involves effective domain decomposition. Also, the present code is essentially for a perfect gas and so additional thermochemical modeling capabilities must be added. Once again, such models already exist in the CFD and DSMC codes and so the primary concern involves making sure that these models are consistent with one another within the MPC framework.

Acknowledgment / Disclaimer

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Publications

(1) Schwartzentruber, T.E. and Boyd, I.D., "A Hybrid Particle-Continuum Method Applied to Shock Waves," *Journal of Computational Physics*, Vol. 215, 2006, pp. 402.

(2) Lofthouse, A.J., Boyd, I.D. and Wright, M.J., "Effects of Continuum Breakdown on Hypersonic Aerothermodynamics," *Physics of Fluids*, Vol. 19, 2007, Article 027105.

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(4) Lofthouse, A.J., Scalabrin, L.C., and Boyd, I.D., "Hypersonic Aerothermodynamics Analysis Across Nonequilibrium Regimes Using Continuum and Particle Methods," AIAA Paper 2007-3903, June 2007.

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(6) Schwartzentruber, T.E., Scalabrin, L.C. and Boyd, I.D., "Modular Implementation of a Hybrid DSMC- NS Solver for Hypersonic Non- Equilibrium Flows," AIAA Paper 2007-0613, January 2007.

(7) Schwartzentruber, T.E., Scalabrin, L.C., and Boyd, I.D., "Hybrid Particle-Continuum Simulations of Low Knudsen Number Hypersonic Flows," AIAA-2007-3829, June 2007, Miami, FL.

Honors & Awards Received

AIAA Thermophysics Best Student Paper (with Jon Burt)-awarded June 2005.

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