Comparison and Uncertainty Assessment of CFD Codes for Hypersonic Flow Modeling

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1 Abstract

The study of hypersonic flows is limited by the lack of reliable experimental data. As such, the use of Computational Fluid Dynamics (CFD) is critical for the prediction of hypersonic flows. There are a myriad of CFD software options that a user may select. In this paper, we give an overview of and compare various codes to establish their usefulness, limitations, and accuracy. For this study we evaluate state of the art codes that span a range of fidelities, turbulence models, chemistry models, and computational implementations with the aim of assessing the contribution to modeling uncertainty in the system response quantities (SRQs) due to each. This paper compares four codes: US3D, SANS, EXASIM, and BuBL.

First, the codes will be compared by running the Holden flat plate case in Table 1 at very high resolution as a two-dimensional(2D) simulation (1). Surface pressure and heat flux outputs will give a benchmark comparison between the codes for solving the 2D laminar Navier-Stokes (NS) equations in the hypersonic regime. Next, different levels of chemical modeling will be tested on the laminar case to identify how modeling assumptions such as assuming a calorically perfect gas, thermally perfect gas, or a real gas assumptions impact the solution for a flat plate. We then will compare each code to see how they predict SRQs over the hypersonic flat plate with a turbulent boundary layer. This will be completed using Reynolds-Averaged Navier-Stokes (RANS) simulations with the SA-CatrisCons turbulence model (2), along with a comparison to 3D wall-resolved Large Eddy Simulations (LES) done in both a finite element and finite volume solver. This turbulent boundary layer study will focus on quantifying the uncertainty in the heat flux to the surface when comparing to experimental data, but will also investigate the meshing and simulation time requirements of the solvers.

1.1 US3D

UnStructured 3D or (US3D) is a tool that was developed by the University of Minnesota and the NASA AMES Research Center for the simulation of compressible and reacting flows (3). US3D has been extensively studied and as such, it is one of the most frequently referenced Hypersonic CFD tools in literature. US3D is a highly parallelizable code that uses a finite volume method capable of explicit and implicit time integration schemes. It uses low-dissipation (4^{th}- and 6^{th}-order) numerical flux schemes for unsteady simulations. US3D is capable of thermo-chemical modeling of finite-rate chemistry and vibrational relaxation. US3D is still actively being developed and can be customized with plugins and user-implemented subroutines. US3D will be used to run steady laminar and RANS simulations, along with unsteady LES simulations while including chemical modeling modifications.

1.2 SANS

SANS is a high-order unstructured finite element flow solver which utilizes Variational Multi-Scale with Discontinous subscales (VMSD) discretization (4). VMSD combines continuous Galerkin (CG) and discontinuous Galerkin (DG) methods while staying adjoint consistent. The adjoint consistency allows for accurate numerical error estimates. SANS uses output-based adaptation which updates the mesh until the discretization error estimate in an integral output quantity, such as drag or heat flux, has reached a minimum for a target DOF (5; 6). SANS is able to adapt grids to reduce discretization error orders of magnitude lower than what is generally achievable using manually-generated grids. SANS will be used to run steady laminar and RANS simulations while including finite-rate chemistry in the former by incorporating thermochemical non-equilibrium (TCNE) models (7).

1.3 EXASIM

EXASIM is matrix-free implicit Discontinuous Galerkin (DG) solver. It uses a Local DG method to solve the compressible Navier-Stokes equation. The DG method allows for high-order discretications on unstructured meshes and complex 3D geometries. EXASIM is capable of producing time-accurate solutions of both transitional and turbulent flows. EXASIM is able to run simulations at mesh resolutions consistent with Direct Numerical Simulations (DNS). This code uses robust physics-based artificial viscosity for shock-capturing in hypersonic flows. EXASIM's formulation also lends well to error estimation and mesh adaptation, and suitable for emerging computer architectures such as GPUs (8). EXASIM will be used to run 2D laminar and 3D turbulent cases using wall-resolved LES with very fine meshes to minimize numerical error.

1.4 BuBL

BuBL is a steady,laminar, compressible Boundary Layer code developed in the MIT Hypersonics Research Lab using the methodology described in detail in (9). BuBL uses a Non-linear Newton Raphson Solver to evaluate a 2nd order finite-difference discretization of the Lees-Dorodnitsyn Boundary Layer (LDBL) Equations (10) paired with the Euler equations for the external flow. BuBL is capable of modeling temperature-dependence in flow properties namely viscosity, specific heat, Prandtl number, and thermal conductivity; and can treat calorically and thermally perfect gases. BuBL will be used to run 2D laminar simulations both with and without temperature dependent gas properties.

Table 1: Test Case Conditions from Holden Experiment (1; 11)

Description	M_∞	$\rho_\infty(kg/m^3)$	$T_\infty(K)$	$T_{\text{stag}}(K)$	T_w	Fluid
Holden Flat Plate	11.2	0.09483	64	1670	300	Air

1.5 Summary

In summary, we plan to simulate a standard set of inflow conditions using various numerical and modeling methods in order to quantify uncertainty in hypersonic heat flux pressure coefficient prediction over a simple flat plate geometry. This study will evaluate modeling uncertainty due to the treatment of governing equations, turbulence and chemical reactivity.The uncertainty in these SRQs will be quantified using a verification framework outlined in (12; 13).

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