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Computational Study of Roughness-Induced Transition

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Laminar-to-turbulent transition in hypersonic flows may increase heat transfer rates significantly. Detached Eddy and Direct Numerical Simulations have been performed to study the complex physics of transition triggered by an isolated roughness in hypersonic flows. Both frozen and reacting flow solutions have been obtained for a hemisphere with a disk-like surface roughness element and compared to experiments done in a ballistic range at Mach 12 in air. The effects of high-enthalpy chemical reactions on roughness-induced transition will be investigated. Also, simulations will be performed for CO_2 gas to study the effect of a Mars-like atmosphere on heating augmentation.

I. Introduction

The design of hypersonic vehicles is challenging in several critical technology areas. The severe heating environment encountered during hypersonic flight dictates the shape of the vehicle. Boundary-layer transition at hypersonic speeds poses an especially significant challenge. Prediction and control of boundary layer transition in hypersonic flows are of crucial importance for the design of planetary entry vehicles as well as two-stage-to-orbit airbreathing access-to-space systems. Since turbulent heat transfer rates can be significantly higher than laminar heating rates, reductions in the weight of thermal protection systems can be realized with an improved understanding of the physics of transition from laminar to turbulent flow. The hypersonic heating environment, coupled with the emphasis on reusability, creates additional severe technology challenges for materials, material coatings, and structures that not only carry aerodynamic loads but also repeatedly sustain high thermal loads requiring long-life and durability while minimizing weight. The gap-filler incident of the Space Shuttle mission STS-114 in 2005 was a potent reminder of the importance of accurate prediction of roughness-induced boundary layer transition and subsequent increase in surface heating[1].

Direct Numerical Simulation (DNS) solves the Navier-Stokes equations by resolving a wide range of spatial and temporal scales of turbulence. Since DNS requires a number of grid points to resolve the Kolmogorov dissipative scales, it is not feasible for high Reynolds number flow simulations even with today's most powerful supercomputers. Large Eddy Simulation (LES) requires less computational resources than DNS by modeling small eddies using sub-grid scale models while still resolving large eddies. However, even with this improvement, the grid requirements for high Reynolds number LES calculations are still impractical. Implicit Large Eddy Simulation (ILES) is a turbulent flow simulation method without a sub-grid scale model but not a fully resolved DNS. Since the high cost of computation for LES comes from the near-wall region, hybrid models like Detached Eddy Simulation (DES) have been developed which alleviate the difficulty by using a Reynolds-Averaged Navier-Stokes (RANS) model in the boundary layer, while behaving like Smagorinsky's LES model away from the wall. Among several applications, DES has been used to study high-speed reentry base flows with favorable results.[2]

A study has been performed to determine the feasibility of using computational fluid dynamics as a tool for predicting hypersonic boundary layer transition to turbulence and the resulting increase in heat transfer. Of particular interest is whether DES can be used to overcome the scaling problems associated with DNS and LES of boundary layers. Numerical simulations for a boundary layer trip oriented at 45 degrees to the flow inside a Mach 10 wind tunnel have indicated that DES can predict perfect-gas flow transition.[3] Also, it has been shown that DES and ILES results are comparable when the grid is fine enough to resolve some of the small length scales.[3]

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Recently high-enthalpy flow transition experiments have been conducted in the NASA Ames Ballistic Range for blunt bodies with isolated roughness elements.[4] The objective of the present paper is to simulate selected cases of the Ballistic Range experiments to validate the CFD code against the test data for a hemisphere with an isolated roughness element.

II. Preliminary Results

The high-enthalpy experiments[4] were performed in the Hypervelocity Free Flight Aerodynamic Facility, part of the Ballistic Range complex at NASA's Ames Research Center. The Ballistic Range employs a two-stage light-gas gun to launch individual models on trajectories through a controlled-atmosphere test section. The largest gun has an inner diameter of 38.1 mm (1.5 in), and the test section is approximately 1 m across and 23 m long, measured from the first optical measurement station to the last. The models are in flight for an additional 10 m from the exit of the gun barrel to the first optical measurement station, during which time the launch sabot separates from the model and is trapped in the receiver tank. There are 16 optical measurement stations, spaced 1.524 m (5 ft) apart, along the length of the test section. Each station is equipped with orthogonal-viewing parallel-light shadowgraph cameras and high-speed timers for recording the flight trajectories.

The hemispheres were made from commercially available titanium alloy ball bearings with a diameter of 2.86 cm, which were cut in half using an electrical discharge machining wire. The arithmetical average surface roughness was 0.2 μm, giving an aerodynamically smooth surface finish. Isolated, disk-like surface roughness elements were created by drilling holes perpendicular to the model surface at parametrically varied locations of 10^o, 20^o and 30^o of arc length from the stagnation point, then press fitting cylindrical silicon carbide pins of diameter 762 μm into each hole, leaving exposed heights that were systematically varied to cover a wide range of Re_{kk} values. Four such pins were located on each model, all at the same arc length from the stagnation point, and separated by 90^o circumferentially. Roughness element heights were measured using greatly magnified silhouette images generated with an optical comparator. Figure 1 shows a shadowgraph picture of a model in hypersonic free flight.[4]

Our first test case is the flow in air over a high trip element (58 μm) located at 20^o. The freestream pressure level is 0.175 atm, and the freestream temperature of the quiescent test gas is at 294.16K. Model/sabot packages are launched from a two-stage light gas gun at a nominal muzzle velocity of 4.22 km/s, yielding a freestream velocity of 4.08 km/s at a mid-range location. The corresponding nominal freestream Mach number is approximately 12. Figure 2 shows a thermal image of the shot. The wake appears to be shorter than the actual because of the camera angle.

Results have been obtained on an unstructured grid that consists of approximately 40 million cells covering a quarter hemisphere. First, the effects of chemical reactions on hypersonic flows were investigated using the modified Steger-Warming flux vector splitting scheme. At hypersonic speeds, the perfect-gas assumption is no longer valid because molecular species dissociate due to the high temperatures resulting from aerodynamic heating. Vibrational and electronic excitation, dissociation, and ionization processes absorb energy, and hence result in lower temperatures than in a perfect gas. The decrease in temperature accompanies a rise in density, which in turn causes a thinner shock layer. A reacting flow solution in Fig. 3a, compared to a frozen flow in Fig. 3b, clearly shows that the bow shock is closer to the body and hence temperatures are lower in the shock layer. Since the bow shock is closer to the edge of the boundary layer, the transition is further affected by the production of an entropy layer.

III. References

[1]Yoon, S., Gnoffo, P.A., White, J.A., and Thomas, J.L.,"Computational Challenges in Hypersonic Flow Simulations," AIAA Paper 2007-4265, June 2007.

[2]Barnhardt, M.D. and Candler, G.V., "Detached Eddy Simulation of the Reentry-F Flight Experiment," AIAA Paper 2008-625, Jan. 2008.

[3]Yoon, S., Barnhardt, M.D. and Candler, G.V., "Simulations of High-Speed Flow over an Isolated Roughness," AIAA Paper 2010-1573, Jan. 2010.

[4]Reda, D. C., Wilder, M. C., and Prabhu, D.K., "Transition Experiments on Blunt Bodies with Isolated Rough ness Elements in Hypersonic Free Flight," AIAA Paper 2010-0367, 48th Aerospace Sciences Meeting, Jan. 2010.

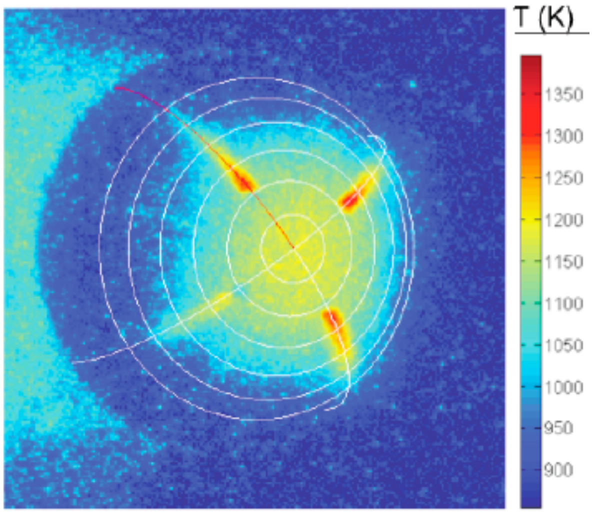


Fig. 1. An example thermal image of the hemisphere in flight with four trips at $\phi = 20°$ (Reda, Wilder, and Prabhu)

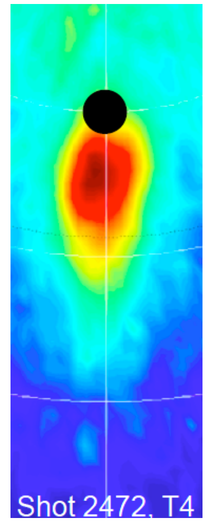
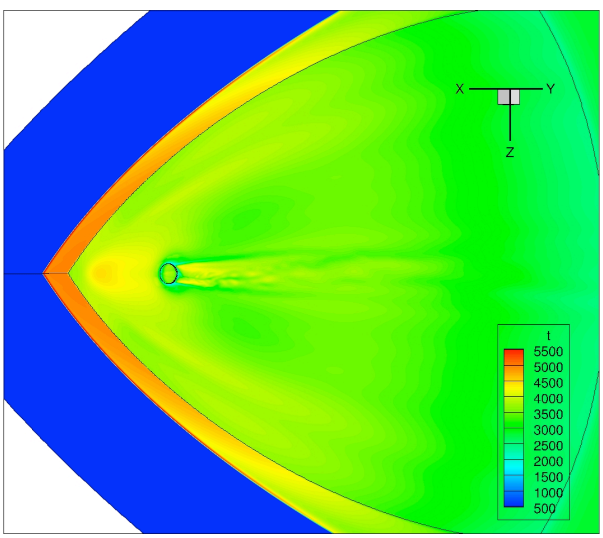


Fig. 2. Thermal image of the trip in air (Mach 11.87, P_∞= 0.175 atm and T_∞= 294.16 K)



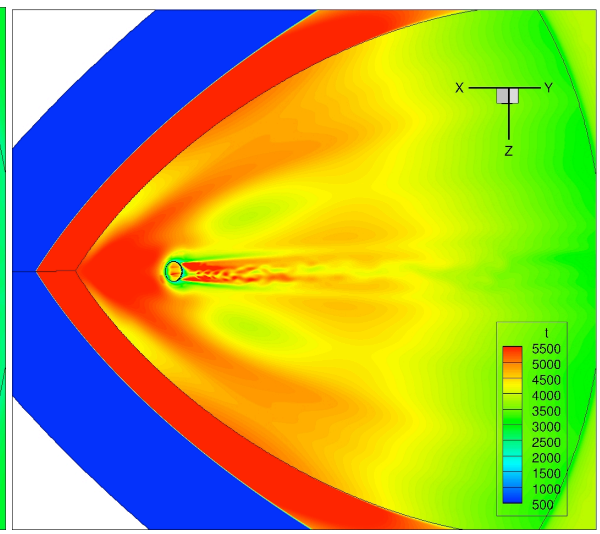


Fig. 3a. Chemically reacting flow solution using DES and a nonequilibrium chemistry model (temperature)

Fig. 3b. Non-reacting flow solution using DES (temperature)