Abstract of paper for 42nd AIAA Fluid Dynamics Conference, New Orleans, June 2012

Gap Filler Induced Transition on the Mars Science Laboratory Heatshield

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Detached Eddy Simulations have been performed to investigate the effects of high-fidelity turbulence modeling on roughness-induced transition to turbulence during Mars entry. Chemically reacting flow solutions will be obtained for a gap filler of Mars Science Laboratory at the peak heating condition.

I.   Introduction

Inaccurate prediction of aerodynamic heating may lead to mission failures. For instance, vortices in turbulent boundary layers might cause uneven ablation of thermal protection materials and hence affect vehicle aerodynamics. Since turbulent heat transfer rates can be 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 gap-filler incident of 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.

Next generation NASA missions will rely on larger entry systems, which will place increased emphasis on improved understanding of turbulent heating, transition to turbulence, shock layer radiation, and complex surface-chemistry interactions. These phenomena must be modeled in the context of a hypersonic chemically reacting flow environment. Thermal protection system materials that are chemically designed to self-heal or affect boundary layer transition have the potential to significantly enhance future mission performance.

The Detached Eddy Simulation (DES) method, which employs a Reynolds-Averaged Navier-Stokes (RANS) turbulence model in the boundary layer while behaving like a Large Eddy Simulation (LES) model away from the wall, has been used to study hypersonic transition to turbulence in a perfect-gas wind tunnel test[1] and in real-gas ballistic range experiments,[2,3] as well as in high-speed reentry base flows, with favorable results.[4] High-enthalpy flow transition experiments were conducted in the NASA Ames Ballistic Range for blunt bodies with isolated roughness elements in CO_2 gas, simulating a Mars-like atmosphere.[5] It has been shown that DES can be used to overcome the scaling problems associated with Direct Numerical Simulations of boundary layers and can predict boundary layer transition in air.

Mars Science Laboratory (MSL) is scheduled for launch in late 2011 and is expected to land on the surface of Mars in August 2012. The MSL heatshield Thermal Protection System (TPS) is constructed of a Phenolic Impregnated Carbon Ablator (PICA), which was used successfully on the Stardust mission. Since the MSL

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aeroshell is quite large, as shown in Fig. 1, it is not possible to create a monolithic PICA heatshield. Instead, PICA is applied to the aeroshell in a tile pattern, and the tiles are bonded to the aeroshell structure using an adhesive material. A total of 113 tiles are used to form the heatshield, and gaps are left intentionally between the tiles to allow for thermal expansion. To prevent hot gases from flowing between the tiles, gaps are filled with liquid RTV-560, which is then cured to form solid gap fillers. Due to a difference in recession rates of PICA and RTV-560, it is possible that the gap fillers will recess less than the tiles during the probe's entry into Mars. This behavior could result in gap fillers protruding from the surface of the heatshield. These protuberances may induce the flowfield to transition earlier to turbulence and generate vortices downstream of the gap fillers. These phenomena could increase the heat loads on the TPS and increase the risks to the success of the mission.

A computational study was performed using steady-state RANS on relatively coarse grids to estimate the heating augmentation.[6] The objective of the present paper is to investigate the effects of unsteady turbulence modeling on roughness-induced transition in CO_2 by using DES on very fine grids.

II.   Turbulence Modeling

The default turbulence modeling options in US3D are RANS-based models. While RANS methods produce mostly inaccurate solutions for high-speed flows with large separation regions, the DES approach of Spalart has predicted unsteady separated flows with improved accuracy by modeling the dynamics of the dominant length scales.[7]

In this work, we have chosen to use the one-equation Spalart-Allmaras[8] model with the compressibility correction of Catris and Aupoix. The model consists of a transport equation for a variable $\tilde{v}$, which is related to the eddy viscosity v_t.

$$\frac{D\rho\tilde{v}}{Dt} = \nabla\cdot(\frac{1}{\sigma}\mu\nabla\tilde{v}) + \nabla\cdot(\frac{1}{\sigma}\sqrt{\rho}\tilde{v}\nabla\sqrt{\rho}\tilde{v}) + \frac{c_{b2}}{\sigma}\nabla\sqrt{\rho}\tilde{v}\cdot\nabla\sqrt{\rho}\tilde{v} + c_{b1}\tilde{S}\rho\tilde{v} - c_{w1}f_w\rho(\frac{\tilde{v}}{d})^2 \qquad (9)$$

Here ρ is the density, μ is the molecular viscosity, $\tilde{S}$ is related to the vorticity magnitude, f_w is a function of the local flow state, d is the distance to the nearest surface, and σ, c_{b1}, c_{b2}, and c_{w1} are constants. The form of this equation is derived largely from empirical arguments, and a detailed explanation of its development can be found in Ref. 11.

The first three terms on the right-hand side of the above equation represent diffusive transport of turbulent viscosity, the next-to-last term governs its production, and the final term is responsible for its destruction. Once the eddy viscosity is computed from this equation, it is used to augment the molecular viscosity. Thus, in regions of high turbulent viscosity the effective diffusive transport will be enhanced above the molecular level.

Note that the destruction term depends on the inverse distance to the nearest solid surface. Thus, when the model is used far from solid surfaces, there is very little destruction of turbulent viscosity, and high levels of $\tilde{v}$ persist. This is what causes the RANS approach to over-predict the turbulent dissipation levels in separated flow regions. The DES solution of this problem is to replace the length scale of the model with a new one, such that the model behaves as a subgrid scale model in regions where the flow is separated. Thus the new length scale should act as a filter, allowing the simulation to resolve eddies down to the grid scale while modeling those that are smaller. For the particular case of the Spalart-Allmaras model, this is accomplished in a straightforward manner by replacing d with a new variable that depends on some measure of the local grid cell size:

$$\tilde{d} = \min(d, C_{DES}\Delta) \qquad (10)$$

With this definition, the modified equation is equivalent to the unchanged Spalart-Allmaras RANS model near walls. Away from walls, if the filter width (i.e. cell size) is chosen to lie in the inertial subrange, the production and destruction terms are balanced and it is easy to show that the Spalart-Allmaras model reduces to the familiar Smagorinksy form. Indeed, in the context of the present study, it is perhaps more accurate to refer to our DES formulation as a Wall-Modeled LES because we are attempting to resolve the boundary layer itself, rather than simply allowing the model to operate entirely in RANS mode. C_{DES} is an adjustable parameter, conventionally set

to 0.65, determined by Shur *et al.*[9] using simulations of homogeneous turbulence.

III.   Chemistry Modeling

A five-species (CO_2, CO, O_2, C, and O) chemical and vibrational non-equilibrium model[10] for CO_2 has been used for the chemically reacting flow computations. Table 1 shows three dissociation and three exchange reactions for CO_2. Due to differences in the covalent bonding of the constituent molecules, more molecular dissociation is expected in CO_2 than in air. Since both O_2 and CO_2 have double bonds, they dissociate more easily through collisions than N_2, which has a triple bond.

Table 1. Chemical Reactions for CO_2

$$CO_2 + M \Leftrightarrow CO + O + M$$
$$CO + M \Leftrightarrow C + O + M$$
$$O_2 + M \Leftrightarrow O + O + M$$
$$CO + O \Leftrightarrow O_2 + C$$
$$CO_2 + O \Leftrightarrow O_2 + CO$$
$$CO + CO \Leftrightarrow CO_2 + C$$

IV. Preliminary Results

Although US3D[11,12] can handle both tetrahedral and hexahedral meshes, unstructured hexahedral-only grids have been used in the present study. All computations are three-dimensional unsteady DES unless stated otherwise. Fine-grid computations have been performed using 1024 cores on the Pleiades system (a supercomputer which currently has 112,896 cores and 191 TB memory) at the NASA Advanced Supercomputing Division. The speed of each six-core Intel Xeon Westmere processor is 3.06 GHz, and the available memory is 2 GB per core.

Our test case is a flow in CO_2 over a gap filler protrusion located at the leeward side of the heatshield, where we expect the boundary layer to be thick and the heat flux to be high. Figure 2 shows a partial view of the grid around the gap filler. At the peak heating, the freestream velocity is 5 km/s, and the freestream temperature is 176.45K. The angle of attack at the peak heating is 15.49 deg.

Three levels of grids have been generated. The number of nodes for coarse, medium, and fine grids are 6 million, 48 million, and 383 million, respectively. Figures 3a and 3b show temperature and Mach number contours in the shock layer. Surface density and pressure contours are shown in Fig. 4a and Fig. 4b. Pressure gradients in Fig. 4b between the capsule and the outer boundary indicate a bow shock. Fine-grid chemically-reacting unsteady flow DES computations will be performed to study the effect of high-fidelity turbulence modeling on the prediction of roughness-induced transition to turbulence in Mars entry.

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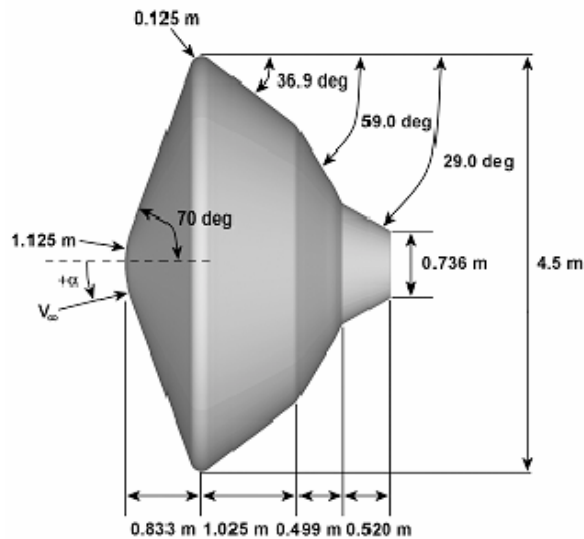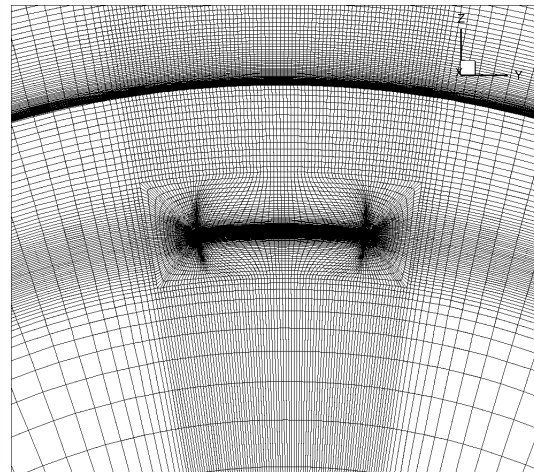
Fig. 1. MSL capsule geometry
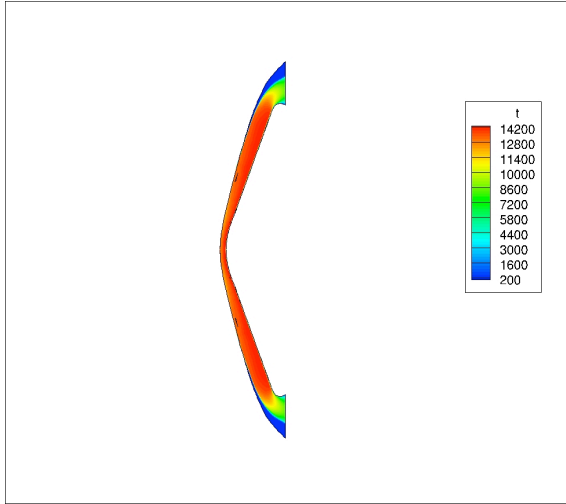

Fig. 2. Surface grid around the gap filler

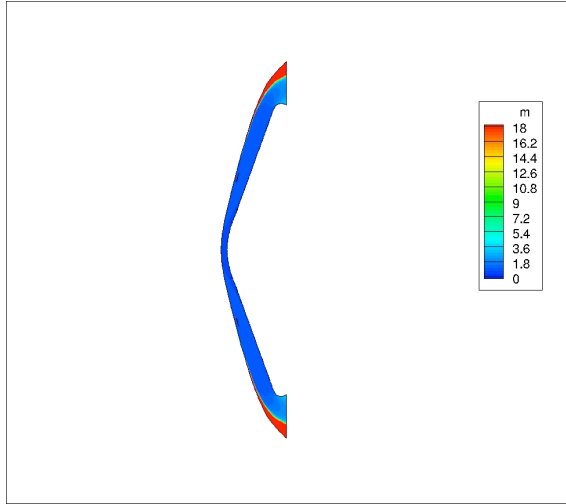Fig. 3a. Temperature contours in the shock layer
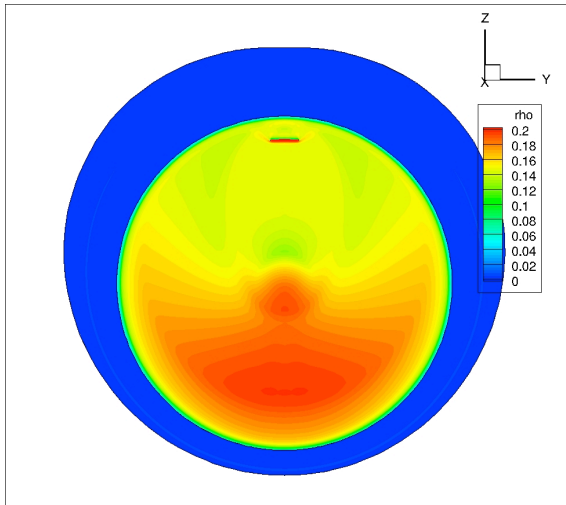

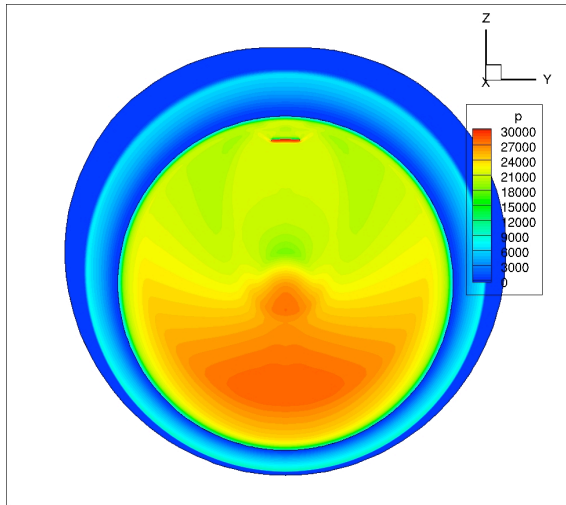
Fig. 3b. Mach number contours in the shock layer

Fig. 4a. Surface density contours

Fig. 4b. Surface pressure contours

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