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A hybrid numerical scheme for aeroheating computation of hypersonic reentry vehicles

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ABSTRACT

Hypersonic aeroheating simulations were conducted for three-dimensional (3D) reentry capsule for the Mars Science Laboratory (MSL) using the AUSM and the Roe schemes. The study confirms that AUSM family of schemes generate unphysical oscillations in the wall heat flux distributions due to the unstable simulation of the shock wave. And the wall heat flux is underpredicted by the Roe scheme due to excess dissipation, even though captures the shock wave accurately. In order to overcome these limitations, we develop a numerical scheme that can capture the shock wave stably and still maintain an accurate prediction of the heat flux. We propose a novel hybrid scheme that combines both the AUSM+ and Roe schemes. Two different hybrid techniques are proposed for switching between the two schemes, one based on the shock wave detection and other utilizing a criterion based on the distance from the wall. The implementation of the two hybrid schemes for the 3D MSL reentry capsule was studied for prediction accuracy compared to experimental data. It is found that the second hybrid scheme (based on the criterion for switching based on distance from the wall) can eliminate the unphysical oscillations in the wall heat flux distributions and improve the aeroheating prediction accuracy.

1. Introduction

Space technology has been developing rapidly in recent years, and the problem of thermal protection for the hypersonic reentry vehicles is becoming increasingly prominent. High-precision prediction for the aerothermal environment is one of the crucial technologies for the design of a thermal protection system. With the advent of numerical methods and computational capability, computational fluid dynamics (CFD) gradually becomes an important tool for the hypersonic aeroheating prediction. However, it is still very difficult to achieve a robust and accurate wall heat flux prediction for hypersonic reentry vehicles using CFD.

Previous research revealed that the grid-point distribution and numerical schemes are the two important factors influencing the accuracy of the heat flux prediction in CFD [1–11] for a hypersonic laminar flow. As early as 1990s, a series of numerical experiments were conducted by Hoffmann et al. [1] based on the studies of Klopfer and Yee [2] and Blottner and Larson [3], and the results showed that the computed wall heat flux depends highly on the density of the grid points near the wall. Subsequently, some researchers studied in detail the effects of the first grid point spacing off the wall on the accuracy of the computed heat flux, resulting in several grid generation criterions proposed to estimate an appropriate first grid point spacing off the wall for an accurate heat flux computation [5,6]. However, for a high Mach number flow over a blunt body where a strong detached shock wave exists, the accuracy of the computed wall heat flux depends not only on the near-wall grid spacing, but also the grid quality in the vicinity of the shock wave. By numerical experiments, Henderson and Menart [7] showed that, in order to achieve a reasonable aeroheating prediction, the shape of the mesh needs to be in accordance to the shock wave and grid points should also be clustered normal to the shock wave. A low-quality grid-point distribution near the shock wave is easy to lead to an oscillating resolution of the shock wave which would cause an anomalous distribution of the wall heat flux. While for the numerical schemes, Kitamura et al. [8,9] argued that a numerical scheme suitable for hypersonic wall heat flux computation should be equipped with the following three properties: shock stability/robustness, conservation of total enthalpy and accurate resolution of boundary layer. In Ref. [9], 15 kinds of numerical schemes were evaluated according to the above three properties, and it was found that no numerical scheme investigated in [9] possessed all the three properties, while the

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Nomenclature

Ma	free-stream Mach number
ρ	density (kg/m^3)
T	temperature (K)
p	pressure (pa)
u_j	velocity (m/s)
H	total enthalpy (J/kg)
λ	molecular thermal conductivity (W/(m K))
μ	molecular viscosity (N s/m^2)
τ_{ij}	shear stress (N/m^2)
e	internal energy (J/kg)
E	total energy (J/kg)
R	gas constant (J/(kg K))
α	the angle of attack (deg)
Q_w	local heat flux (W/m^2)
Re	Reynolds number
R	radius of cylinder (m)
f_D	damping function
C_{am}	amplification factor of damping function
d	the distance of the local grid point from the wall (m)
δ_0	empirical parameter
L	the characteristic length (m)

Subscripts

∞	free-stream
w	at the wall

AUSM family schemes [12–16] and Roe [17] scheme appeared to be promising. However, these two kinds of numerical schemes have different characteristics for the aeroheating prediction. The AUSM family schemes do not have tunable factors in their scheme design and generally have low numerical dissipation, and thus they could resolve the near-wall temperature gradient more precisely within the boundary layer. Hence, with the same grid spacing near the wall, AUSM family schemes could give a more accurate heat flux result than Roe scheme [10,11]. However, for a flow with strong shock wave, if the shape of the mesh is not in accordance to the shock wave or the grid points are not dense enough across the shock wave, the AUSM family schemes may resolve the shock wave with obvious oscillations [10], which would further generate an unphysical distribution of heat flux on the wall. While for the Roe scheme, an entropy correction function with a tunable factor is incorporated, which could help to control the added numerical dissipation and guarantee a stable shock wave resolution even with a low-quality mesh near the shock wave, but would also bring in additional numerical dissipation inside the boundary layer and thus decrease the prediction accuracy of the wall heat flux. Generally, a small value of the tunable factor in the entropy correction function could lead to relative accurate heat flux predictions for the Roe scheme. However, for a three-dimensional (3D) complicated case with high Mach number, this tunable factor needs to be taken as a large value to ensure a stable resolution of the shock wave and then the numerical resolution inside the boundary layer by the Roe scheme would be significantly reduced.

In practical hypersonic aeroheating computations, for a two-dimensional (2D) problem, it is still feasible to keep the mesh aligned with the shape of the shock wave and then maintain a stable resolution of the shock wave, so the AUSM family schemes could be adopted to enhance the accuracy of the wall heat flux computation. While for 3D complex flows, it would be difficult to adjust the computational mesh to achieve an accordance of the grid shape and shock wave. Even if it could be realized, the mesh will have to be re-generated for different free-stream conditions because the shape of the shock wave would change, thereby increasing the work for the mesh generation. To remove the above restriction on the grid generation for stable resolution of the shock wave, the Roe scheme is a better choice than the AUSM family schemes. However, the high-dissipation characteristic of Roe scheme in boundary layer is likely to introduce errors in the wall heat flux prediction. Thus Roe scheme generally needs more dense grid points near the wall than the AUSM schemes in order to obtain reasonable heat flux, which would severely limit the computational time step and thus dramatically increase the computational consumption especially for 3D complicated cases. The above dilemma indicates that more efforts should be put on the development of a reliable numerical scheme which could guarantee a stable resolution of strong shock wave without strict restriction on the grid generation while in the meantime maintain an accurate computation of the wall heat flux for hypersonic vehicles.

The objective of the present paper is to develop a hybrid numerical scheme combining the Roe and AUSM schemes, which would adopt the Roe scheme around the shock wave to guarantee a stable resolution of the shock wave without strict restriction on the grid generation while utilize the AUSM scheme within the boundary layer to maintain low numerical dissipation and high accuracy of the wall heat flux computation. First, we introduce the governing equations and numerical methodology used in the present study. Secondly, hypersonic aeroheating computations for a 3D reentry capsule from the Mars Science Laboratory (MSL) are performed using the Roe and AUSM family schemes respectively, and the aeroheating accuracy is examined independently for each of the two schemes. Then, new hybrid schemes combining the Roe and AUSM family schemes are proposed following two different techniques, and the performance of the new hybrid schemes is evaluated. Finally, by applying the hybrid schemes to the 3D reentry capsule case, improvements in aeroheating prediction accuracy of the hybrid schemes are examined in detail.

2. Governing equations and numerical methodology

The compressible Navier-Stokes (N-S) equations can be written as follow:

$$\begin{aligned}&\frac{\partial(\rho)}{\partial t}+\frac{\partial}{\partial x_j}(\rho u_j)=0\\&\frac{\partial(\rho u_i)}{\partial t}+\frac{\partial}{\partial x_j}(\rho u_i u_j+\delta_{ij}p)=\frac{\partial\tau_{ij}}{\partial x_j}\\&\frac{\partial(\rho E)}{\partial t}+\frac{\partial}{\partial x_j}(\rho H u_j)=\frac{\partial}{\partial x_j}\left(\tau_{ij}u_i+\lambda\frac{\partial T}{\partial x_j}\right)\end{aligned}\tag{1}$$

where τ_{ij} is the shear stress given as:

$$\tau_{ij}=\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)-\frac{2}{3}\mu\frac{\partial u_i}{\partial x_j}\delta_{ij}\tag{2}$$

E is the total energy defined as:

$$E=e+\frac{1}{2}u_iu_i\tag{3}$$

The equation of state is

$$p=\rho RT\tag{4}$$

All the numerical simulations are carried out using a finite difference code, ACANS (Aerodynamic, Combustion and Aerothermodynamic Numerical Simulation), developed by the authors. The reliability of ACANS code has been validated by a variety of simu-