International Journal of Heat and Mass Transfer 127 (2018) 126–137

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

A novel flux splitting scheme with robustness and low dissipation for hypersonic heating prediction

Shu-sheng Chen [a], Chao Yan [a,*], Kang Zhong [a], Hai-chao Xue [b], Er-long Li [a]

[a] School of Aeronautic Science and Engineering, Beihang University, Beijing 100191, China
[b] China Academy of Aerospace Aerodynamics, Beijing 100074, China

ARTICLE INFO

Article history:
Received 9 December 2017
Received in revised form 17 June 2018
Accepted 25 June 2018

Keywords:
Hypersonic heating prediction
Flux splitting
Shock-stable
Low-dissipation

ABSTRACT

In this paper, a novel flux splitting scheme is devised to overcome some difficulties in hypersonic heating prediction. Based on Zha-Bilgen splitting approach, the novel scheme integrates three key ingredients: (i) advection flux estimated by AUSM algorithm; (ii) pressure flux estimated by HLL algorithm; (iii) isentropic condition and low-Mach number fix applied in the difference diffusion term of pressure flux. Then, test problems are carefully selected for systematic assessment of the resulting scheme in terms of robustness and accuracy. The proposed scheme is shock-stable and low-dissipation; meanwhile it can exactly preserve contact discontinuity and eliminate numerical overshoots. A series of hypersonic viscous flow cases, such as 3D Mars Science Laboratory (MSL) reentry capsule, demonstrates its superior performance compared with existing upwind schemes, and is potentially a good candidate for hypersonic heating prediction.

1. Introduction

Hypersonic thermal protection is a bottleneck that restricts the development of hypersonic vehicles. With the rapid progress of aerospace technology, aircraft shapes are increasingly complex, and there have been mounting requirements for accurate aerodynamic heating prediction. Compared with other aerodynamic thermal prediction methods, Computational Fluid Dynamics (CFD) has obvious advantages of economy and effectiveness. However, the accurate prediction of surface heat transfer rate is still one of the most challenging problems in CFD [1]. Heat flux is dominated by the thermal conductivity of fluid and temperature gradient, the computational accuracy of which is closely related to computational grid, numerical scheme, physical model, post-processing [2], convergence process, etc. These factors combined lead to the complexity of hypersonic heating prediction.

In hypersonic vehicles, blunt body shape is widely applied and yields at least two flow patterns involving detached bow shock and compressible temperature boundary layer. Heat flux relies on the accurate calculation of temperature gradient on the wall. Moreover, during atmospheric re-entry, the chemical and vibrational non-equilibrium effects become remarkable and need detailed consideration for the accurate heating prediction [3]. Since there are large variable jumps at shock wave and strong-nonlinear temperature distribution in boundary layer, computational grid should be clustered at shock wave and boundary layer. Herein, heating prediction has a greater dependence on the grid. Klopfer et al. [4] initially pointed out that the first layer grid distance normal to the surface in boundary layer has a significant influence on the accurate simulation of heat flux. For blunt cone model, he introduced an important concept called the cell Reynolds number Re_{cell}, and proposed a method to obtain more accurate heat flux by reducing this grid size. Lee et al. [5] showed that when the cell Reynolds number is doubled, aerodynamic heating values produce 20% float in some cases. Hoffmann et al. [2] presented that the first layer grid distance off the wall varies greatly with changes in the free stream conditions, mainly Mach number and Reynolds number. Thivet et al. [6] argued that the accurate simulations of wall friction and heat flux in hypersonic flow require that computational grid satisfies good orthogonality. In addition, Henderson et al. [7] revealed that the grid should be orthogonally clustered and simultaneously aligned at shock wave for achieving accurate aerodynamic heating prediction. Otherwise, low-quality grid can easily give rise to the oscillation resolution of shock wave and anomalous distribution of surface heat transfer rates.

On the other hand, the robustness and accuracy of numerical scheme have important implications for accurate heating prediction. Currently, the widely-used numerical schemes fall into two categories: central schemes [8] and upwind schemes. Central

---

* Corresponding author.
E-mail address: yanchao@buaa.edu.cn (C. Yan).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.06.121
0017-9310/

Nomenclature

ρ	density $(\mathrm{kg/m^3})$
p	pressure (Pa)
T	temperature (K)
$\boldsymbol{u} = (u, v, w)$	velocity components (m/s)
M	Mach number
c	speed of sound (m/s)
E	total energy (J/kg)
H	total enthalpy (J/kg)
$\boldsymbol{\tau}$	shear stress tensor $(\mathrm{N/m^2})$
$\boldsymbol{q}$	heat transfer rate $(\mathrm{W/m^2})$
μ	molecular viscosity $(\mathrm{Pa \cdot s})$
γ	specific heat ratio, 1.4
R	gas constant $(\mathrm{J/(kg \cdot K)})$
Pr	Prandtl number, 0.72
Re	Reynolds number
α	angle of attack (deg)
r	radius of cylinder (m)
$\boldsymbol{Q}$	conservative state vector
$\boldsymbol{F}(\boldsymbol{Q})$	inviscid flux
$\boldsymbol{A}(\boldsymbol{Q})$	advection flux
$\boldsymbol{P}(\boldsymbol{Q})$	pressure flux
λ	eigenvalue

Subscripts

∞	freestream value
w	value on the wall
$cell$	value based on the minimum cell size
L/R	left and right states
$i + 1/2$	Interface value
δ	difference value

schemes [8] have a simple logical relationship and a small amount of computation, but the resolution discontinuity is achieved by artificial viscosity, leading to more difficulty in numerical dissipation control. Moreover, central schemes include undesirable empirical parameters. Upwind schemes have prevailed over central schemes in the simulation of high speed flows. Representatives of upwind schemes are Flux Vector Splitting (FVS) and Flux Difference Splitting (FDS) methods. Among FDS methods, Roe scheme [9] has found wide application as a result of its excellent performance in simulating constant shock, contact discontinuities and boundary layer. FVS scheme proposed by van Leer [10] also has been widely accepted and promoted due to its high efficiency and simplicity, especially the ability to capture strong shocks. A simple two-wave approximate Riemann solver developed by Harten et al. [11] has similar characteristics as van Leer's FVS scheme. The approximate solver HLLC [12] improved from HLL can restore the missing contact and shear waves. In the meantime, the hybrid methods combining the merits of FVS and FDS methods have been extensively studied. Hybrid flux splitting methods divide inviscid flux into convective and pressure systems to identify shock and contact waves. Based on different rules, there are mainly three splitting approaches: Liou-Steffen splitting [13], Toro-Vázquez splitting [14] and Zha-Bilgen splitting [15]. Liou and Steffen [13] proposed AUSM (Advection Upstream Splitting Method). This is gaining acclaim for its superior performance such as less numerical dissipation and better stability, and continues to evolve with many new variants such as AUSM+ [16], AUSMPW+ [17], AUSM + UP [18], SLAU [19,20], and so forth. Zha et al. [15] developed an improved low diffusion E-CUSP scheme.

Nevertheless, recent studies have found that these above-mentioned schemes are far from the perfect scheme due to the defects in the respective constructs. Kitamura et al. [21] proposed that numerical scheme suitable for hypersonic heating prediction should meet three basic properties: shock stability/robustness, total enthalpy conservation, and accurate boundary-layer resolution. Through the classification and comparison of several common numerical schemes, it is found that none of the investigated numerical schemes can completely satisfy three requirements. Among them, shock stability/robustness and accurate boundary-layer resolution have significant influence on heat flux, while total enthalpy conservation produces a relatively small effect. In particular, two-wave approximation Riemann solvers, such as van Leer's FVS and HLL, have good shock stability but fail to accurately capture contact discontinuity, resulting in poor viscous resolution and anomalous heating value of stagnation point. Three-wave approximate Riemann solvers, such as Roe and HLLC, can accurately resolve contact discontinuity but suffer from carbuncle phenomenon [22] or shock instability. The entropy correction is widely applied in Roe scheme to overcome carbuncle phenomenon and nonphysical expansion shock, but it introduces more numerical dissipation at low speed and may deteriorate boundary-layer resolution [23]. Moreover, the need to set artificial parameters to ensure better performance in entropy correction also restricts its application. For AUSM-family schemes, there are still some problems. AUSM+ is considered as light carbuncle prone scheme and some modifications of AUSM-type scheme are assigned to strong carbuncle prone schemes [24]. AUSM+ easily yields numerical overshoots behind strong shock waves and numerical wiggles near the wall [17]. Moreover, if the computational grid near shock waves is of low-quality, AUSM-family scheme may generate the oscillation of shock wave and give out unreasonable heat flux distribution.

In addition, flow velocities in different regions vary greatly in complex flow engineering applications. For example, there is large low-speed flow region near the wall for hypersonic flows. The simulation of these regions directly affects the predicted accuracy and efficiency of surface heat flux. Many current upwind schemes are designed for compressible flow. They have the following two deficiencies in solving low Mach number flow [18,25]: deteriorated accuracy and difficult convergence. Through theoretical analysis, Wessi [26] and Turkel [27], etc. developed preconditioning techniques to change mathematical properties of governing equations. Previous numerical experiments showed that preconditioned methods somewhat improve the accuracy and efficiency of low-speed flow simulation. However, such methods sacrifice time accuracy and encounter the global cut-off problems [27]. They also need problem-dependent parameters that greatly affect computational efficiency and accuracy. Herein, preconditioned methods are less robust in the flow field with large velocity span. Meanwhile, many researchers have obtained a series of improved Roe scheme [28–30], which can accurately calculate low-speed flows. But the above methods also inherit the shortcomings of the original method in high Mach number regimes. For all Mach number flows, Liou proposed AUSM + UP [18] and Edwards presented LDFSS2001 [31]. AUSM + UP has insufficient robustness and requires empirical artificial parameters. Thereafter, in order to avoid problem-dependent parameters, Shima et al. [19] developed a parameter-free simple low-dissipation AUSM-family scheme called SLAU. SLAU is not robust enough for hypersonic flows [20]. Kitamura et al. [20] further put forward SLAU2, AUSM + UP2, LDFSS2001-2