Study of Hypersonic Dissociating Flows over Spheres using the Space-Time CE/SE Method

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ABSTRACT

When a space vehicle enters the atmosphere at an orbital speed, a detached bow shock forms in front of its blunt nose and the temperature behind the shock, especially in the stagnation region, can reach to a very high level, due to the conversion of kinetic flow energy into thermal energy by strong shock compression. The important gas molecule dissociation and other real gas effects of hypersonic flows will occur, consequently. The air can no longer be treated as a perfect gas and the dissociative non-equilibrium phenomena complicate the flow physics. Due to the extreme flow conditions, experimental approaches are difficult in general, not to mention the expensive cost. Theoretical methods are also limited in exploring the global dissociative non-equilibrium flow physics. Only some simple analytical solutions can be obtained, such as the dimensionless shock-off distance as a function of dimensionless dissociation rate [1-3]. Therefore, to thoroughly understand the hypersonic dissociative non-equilibrium flows, developing an efficient and accurate code is essential. Variable numerical methods have been applied to simulating the hypersonic non-equilibrium flows. However, the conservation element and solution element (CE/SE) method is implemented to investigate such problems for the first time, to the best of the current authors' knowledge. The CE/SE method is a novel numerical framework, which is proposed by Chang and co-workers [4-7] to solve hyperbolic conservation equations. Nevertheless, the CE/SE scheme used in present study is that implemented on a hybrid mesh consisting of triangular elements and quadrilateral elements [8,9]. This hybrid-meshed scheme is proved to be accurate and robust in the shock propagating problems. It has several promising advantages for the simulation of hypersonic flows: (i) It keeps the conservation of physical quantities in both local and global space-time domains; (ii) Since a dimensional splitting method is not required, it's a genuinely multi-dimensional scheme; (iii) It can capture strong shocks sharply without using Riemann solver; (iv) Only information at the immediate neighboring nodes is needed to update the solutions at the new time level which is consistent with a fundamental physical reality, i.e., in the absence of body force, direct physical interaction occurs only among the immediate neighbors. In present study, the dissociating chemical reactions and the vibrational energy relaxation are added to the previous code to simulate the dissociating nitrogen and air flows over a blunt body. Some important experimental and theoretic results are used to validate the accuracy and robustness of present code. Furthermore, the flow features of hypersonic flows are analyzed in detail through the extensive numerical results.

REFERENCES

[1] C.Y. Wen, and H.G. Hornung, "Non-Equilibrium Dissociating Flow over Spheres," *Journal of Fluid Mechanics*, Vol. 299, 1995, pp. 389-405.

[2] H. Olivier., "A Theoretical Model for the Shock Stand-off Distance in Frozen and Equilibrium Flow," *Journal of Fluid Mechanics*, Vol. 413, 2000, pp. 345-353.

[3] N. Belouaggadia, H. Olivier and R. Brun, "Numerical and Theoretical Study of the Shock Stand-off Distance in Non-Equilibrium Flows," *Journal of Fluid Mechanics*, Vol. 607, 2008, pp. 167-197.

[4] S.C. Chang, "The Method of Space-Time Conservation Element and Solution Element-a New Approach for Solving the Navier-Stokes and Euler Equations," *Journal of Computational Physics*, Vol. 119, 1995, pp. 295-324.

[5] S.C. Chang, X.Y. Wang and C.Y. Chow, "The Space-Time Conservation Element and Solution Element Method: A New High-Resolution and Genuinely Multidimensional Paradigm for Solving Conservation Laws," *Journal of Computational Physics*, Vol. 156, 1999, pp. 89~136.

[6] Z.C. Zhang, S.T. John Yu, X.Y. Wang, S.C. Chang and C.E. Jorgenson, "The Space-Time CE/SE Method for the Navier-Stokes Equations in Three Spatial Dimensions," *AIAA paper*, 2000-2331.

[7] Z.C. Zhang, S.T. John Yu and S.C. Chang, "A Space-Time Conservation Element and Solution Element Method for Solving the Two- and Three-Dimensional Unsteady Euler Equations Using Quadrilateral and Hexahedral Meshes," *Journal of Computational Physics*, Vol. 175, 2002, pp. 168-199.

[8] H. Shen, K.X. Liu and D.L. Zhang, "Three-Dimensional Simulation of Detonation Propagation in a Rectangular Duct by an Improved CE/SE Scheme," *Chinese Physics Letters*, Vol. 28, 2011, 124705.

[9] H. Shen, C.Y. Wen, K.X. Liu and D.L. Zhang, "Robust high-order space–time conservative schemes for solving conservation laws on hybrid meshes", Journal of Computational Physics, Vol. 281, 2015, pp 375-402.