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Modeling hypersonic entry with the fully-implicit Navier-Stokes (FIN-S) stabilized finite element flow solver. (English) Zbl 1391.76340

Comput. Fluids 92, 281-292 (2014).

Summary: In this paper, we present a novel scheme for modeling the hypersonic atmospheric entry of large vehicles with an ablative thermal protection system. The Favre-averaged thermochemical nonequilibrium Navier-Stokes equations with Spalart-Allmaras turbulence closure, thermodynamic, chemical kinetic, and quasi-steady ablation model are presented. The numerical method is based on a streamline upwind Petrov-Galerkin (SUPG) stabilized finite element formulation. The formulation and implementation of the finite element approximation are discussed in detail. The performance of the scheme is investigated through a series of increasingly complex applications, culminating in the simulation of a three-dimensional ablating heatshield in transitioning flow.

MSC:

76M10 Finite element methods applied to problems in fluid mechanics
76K05 Hypersonic flows
76D05 Navier-Stokes equations for incompressible viscous fluids

Keywords:

stabilized finite elements; compressible flow; hypersonic flow; reentry; surface ablation

Software:

Spalart-Allmaras; PETSc; MASA; libMesh

Full Text: DOI

References:

[1] Hassan B, Kuntz D, Potter DL. Coupled fluid/thermal prediction of ablating hypersonic vehicles. AIAA Paper 98-0168, AIAA; 1978.

[2] Kuntz, D.; Hassan, B.; Potter, D. L., Predictions of ablating hypersonic vehicles using an iterative coupled fluid/thermal approach, J Thermophys Heat Transfer, 15, 2, 129-139, (2001)

[3] Chen, Y.-K.; Milos, F., Navier-Stokes solutions with finite rate ablation for planetary mission Earth reentries, J Spacecraft Rockets, 42, 961-970, (2005)

[4] Gosse R, Candler G. Ablation modeling of electro-magnetic launched projectile for access to space. AIAA Paper 2007-1210.

[5] Sakai, T.; Sawada, K., Calculation of nonequilibrium radiation from a blunt-body shock layer, J Thermophys Heat Transfer, 15, 1, 99-105, (2001)

[6] Suzuki, T.; Furudate, M.; Sawada, K., Unified calculation of hypersonic flowfield for a reentry vehicle, J Thermophys Heat Transfer, 16, 1, 94-100, (2002)

[7] Matsuyama, S.; Ohnishi, N.; Sasoh, A.; Sawada, K., Numerical simulation of galileo probe entry flowfield with radiation and ablation, J Thermophys Heat Transfer, 19, 1, 28-35, (2005)

[8] Gnoffo PA, Johnston CO, Thompson RA. Implementation of radiation, ablation, and free energy minimization modules for coupled simulations of hypersonic flow. AIAA Paper 2009-1399, AIAA; 2009.

[9] Johnston, C. O.; Gnoffo, P. A.; Sutton, K., Influence of ablation on radiative heating for Earth entry, J Spacecraft Rockets, 46, 3, 481-491, (2009)

[10] Bauman, P. T.; Stogner, R.; Carey, G. F.; Schulz, K. W.; Upadhyay, R.; Maurente, A., Loose-coupling algorithm for simulating hypersonic flows with radiation and ablation, AIAA J Spacecraft Rockets, 48, 1, 72-80, (2011)

[11] Wright, M.; Candler, G. V.; Bose, D., Data-parallel line relaxation method for the Navier-Stokes equations, AIAA J, 36, 9, 1603-1609, (1998)

[12] Kirk BS, Bova SW, Bond RB. A streamline-upwind Petrov-Galerkin finite element scheme for non-ionized hypersonic flows in thermochemical nonequilibrium. AIAA Paper 2011-134; 2011.

[13] MacLean M, Marschall J, Driver DM. Finite-rate surface chemistry model, II: coupling to viscous Navier-Stokes code. AIAA 2011-3784; 2011.

[14] Upadhyay R, Bauman PT, Stogner R, Schulz KW, Ezekoye O. Steady-state ablation model coupling with hypersonic flow. AIAA Paper 2010-1176.

[15] Kirk, B. S.; Peterson, J. W.; Stogner, R. H.; Carey, G. F., Libmesh: a C++ library for parallel adaptive mesh refinement/coarsening simulations, Eng Comput, 22, 3, 237-254, (2006)

[16] Anderson, J. D., Hypersonic and high temperature gas dynamics, (2006), AIAA Reston, Virginia

[17] Gnoffo PA, Gupta RN, Shinn JL. Conservation equations and physical models for hypersonic air flows in thermal and chemical nonequilibrium. Tech rep, National Aeronautics and Space Administration, nASA TP-2867; 1989.

[18] Spalart, P. R.; Allmaras, S. A., A one-equation turbulence model for aerodynamic flows, La Rech Aerospatiale, 1, 5-21, (1994), [see also AIAA Paper 1992-439]

[19] Allmaras SR. Personal communication via email with T. Oliver; 2007.

[20] Oliver TA, Darmofal DL. Impact of turbulence model irregularity on high-order discretizations. AIAA Paper 2009-953.

[21] Tauber ME. A review of hgih-speed, convective, heat-transfer computation methods. Tech rep, National Aeronautics and Space Administration, nASA TP-2914; 1989.

[22] Campbell CH, King RA, Berry SA, Kegerise MA, Horvath TJ. Roles of engineering correlations in hypersonic entry boundary layer transition prediction. In: 48th AIAA aerospace sciences meeting, AIAA Paper 2010-247; 2010.

[23] Candler GV. The computation of weakly ionized hypersonic flows in thermochemical nonequilibrium. Ph.D. thesis, Stanford University; 1988.

[24] Park, C., Nonequilibrium hypersonic aerotherodynamics, (1990), John Wiley \& Sons

[25] Blottner FG, Johnson M, Ellis M. Chemically reacting viscous flow program for multi-component gas mixtures. Tech Rep Sandia Laboratories Report No. SC-RR-70-754, Sandia National Laboratories, Albuquerque, NM; 1971.

[26] Wright MJ. A family of data-parallel relaxation methods for the Navier-Stokes equations. Ph.D. thesis, The University of Minnesota; 1997.

[27] Vincenti, Kruger. Introduction to physical gas dynamics. Krieger; 1965.

[28] Barnhardt MD. Modeling and simulation of high-speed wake flows. Ph.D. thesis, University of Minnesota; 2009.

[29] Park, C., Assessment of two-temperature kinetic model for ionizing air, J Thermophys Heat Transfer, 3, 3, 233-244, (1989)

[30] Olejniczak J. Computational and experimental study of nonequilibrium chemsitry in hypersonic flows. Ph.D. thesis, The University of Minnesota; 1997.

[31] Millikan, R. C.; White, D. R., Systematics of vibrational relaxation, J Chem Phys, 39, 12, 3209-3213, (1963)

[32] Erwin T, Anderson WK, Kapadiaz S, Wang L. Three dimensional stabilized finite elements for compressible Navier-Stokes. In: 20th AIAA computational fluid dynamics conference, AIAA 2011-3411; 2011.

[33] Aliabadi SK. Parallel finite element computations in aerospace applications. Ph.D. thesis, The University of Minnesota; 1994.

[34] Aliabadi, S. K.; Tezduyar, T. E., Parallel fluid dynamics computations in aerospace applications, Int J Numer Methods Fluids, 21, 783-805, (1995) · Zbl 0862.76033

[35] LeBeau GJ. The finite element computation of compressible flows. Master's thesis, The University of Minnesota; 1990.

[36] Shakib, F.; Hughes, T. J.R.; Johan, Z., A new finite element formulation for computational fluid dynamics: X. the compressible Euler and Navier-Stokes equations, Comput Methods Appl Mech Eng, 89, 141-219, (1991)

[37] Hughes, T. J.R.; Mallet, M., A new finite element formulation for computational fluid dynamics: IV. A discontinuity operator for multidimensional advective-diffusive systems, Comput Methods Appl Mech Eng, 58, 329-336, (1986) · Zbl 0587.76120

[38] Chalot, F.; Hughes, T. J.R.; Shakib, F., Symmetrization of conservation laws with entropy for high-temperature hypersonic computations, Comp Syst Eng, 1, 2-4, 495-521, (1990)

[39] Upadhyay R, Bauman PT, Stogner R, Schulz KW, Ezekoye O. Steady-state ablation model coupling with hypersonic flow. AIAA Paper 2010-1176; 2010.

[40] Malaya N, Estacio-Hiroms K, Stogner RH, Schulz KW, Bauman PT, Carey GF. : a library for verification using manufactured and analytical solutions, engineering with computers; in press. doi: http://dx.doi.org/10.1007/s00366-012-0267-9.

[41] Oliver TA, Estacio-Hiroms KC, Malaya N, Carey GF. Manufactured solutions for the Favre-averaged Navier-Stokes equations with eddy-viscosity turbulence models. In: 50th AIAA aerospace sciences meeting. AIAA-2012-0080; 2012.

[42] Balay S, Buschelman K, Eijkhout V, Gropp WD, Kaushik D, Knepley MG, et al. PETSc users manual. Tech Rep ANL-95/11 - Revision 2.3.0, Argonne National Laboratory; 2004.

[43] Barrett, R.; Berry, M.; Chan, T. F.; Demmel, J.; Donato, J. M.; Dongarra, J., Templates for the solution of linear systems: building blocks for iterative methods, (1994), Society for Industrial and Applied Mathematics Philadelphia

[44] Golub, G. H.; Van Loan, C. F., Matrix computations, (1996), The Johns Hopkins University Press · Zbl 0865.65009

[45] Park, C.; Jaffe, R. L.; Partridge, H., Chemical-kinetic parameters of hyperbolic Earth entry, J Thermophys Heat Transfer, 15, 1, 76-90, (2001)