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Computational Study of Hypersonic Real Gas Flows Over Cylinder Using Energy Relaxation Method

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에너지 완화법을 이용한 실린더 주위의 극초음속 실제기체 유동에 관한 수치해석적 연구

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Key Words : *Hypersonic flows, Energy Relaxation Method (ERM), Heat Transfer, Real Gas, AUSM*

Abstract

In recent years, scientific community has found renewed interest in hypersonic flight research. These hypersonic vehicles undergo severe aero-thermal environment during their flight regimes. During reentry and hypersonic flight of these vehicles through atmosphere real gas effects come into play. The analysis of such hypersonic flows is critical for proper aero-thermal design of these vehicles. The numerical simulation of hypersonic real gas flows is a very challenging task. The present work emphasizes numerical simulation of hypersonic flows with thermal non-equilibrium. Hyperbolic system of equations with stiff relaxation method are identified in recent literature as a novel method of predicting long time behaviour of systems such as gas at high temperature. In present work, Energy Relaxation Method (ERM) has been considered to simulate the real gas flows. Navier-Stokes equations A numerical scheme Advection Upstream Splitting Method (AUSM) has been selected. Navier-Stokes solver along with relaxation method has been used for the simulation of real flow over a circular cylinder. Pressure distribution and heat flux over the surface of cylinder has been compared with experiment results of Hannemann. Present heat flux results over the cylinder compared well with experiment. Thus, real gas effects in hypersonic flows can be modeled through energy relaxation method.

1. Introduction

At hypersonic speed, most of the kinetic energy of the flow surrounding the object is converted to internal energy through a strong shock. Thus, temperature increases enormously and air can neither be considered as a calorically perfect gas nor thermally perfect gas. The reason is the activation of vibrational energy which depends non-linearly on temperature. A gas can be considered to be in thermodynamic equilibrium, if all the modes of internal energies are in equilibrium with each other. The modes of internal energy are associated with translational motion, rotational motion, vibration, dissociation, electronic excitation, and finally ionization. At hypersonic velocities, the time available for changes in thermodynamic variables are so small that internal energies can not be in equilibrium even though they change from point to point. In fact, in general, these modes are in non-equilibrium and trying to attend the equilibrium.

There are various numerical methods that model non-equilibrium flow as equilibrium flows locally. These methods use flux vector or flux difference splitting upwind schemes (Grossmann, Vinokur, Glaister, Liou). The most popular method amongst these methods has been Roe's scheme which was originally proposed for a perfect gas. All the numerical methods either require computation of the pressure law and its derivative or a Riemann solver. This makes these methods not only costly but also difficult to implement especially when there is no expression for the pressure law [1].

Relaxation method seems to be an appealing approach for non-equilibrium flows. Coquel and Perthame [2] introduced a numerical scheme called Energy Relaxation Method (ERM), which does not require an expression for pressure law. It uses two energy model of gas. The method assumes that energy associated with translation and rotation attends equilibrium almost instantaneously, where as energy associated with vibration requires finite time to reach the equilibrium and is modeled as an additional hyperbolic equation. Coquel and Perthame accordingly relax the nonlinear pressure law using internal energy splitting such as e = e_1 + e_2, where internal energy e_1 is function of pressure law

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p_1(r, e_1) and the energy e_2 advected by the flow. This method has advantages over other conventional methods, such as (a) Neither derivative of the pressure law nor Riemann solvers are required in the implementation. (b) It uses a single call to the pressure law per grid point per time step. (c) Coding of the solvers does not depend on the expression for the equation of state of the gas. Recently Bongiovanni [3] has modified energy relaxation method for the viscous flow. They have distributed (weighted) the diffusive flux and splitted the heat flux for the non-equilibrium equation.

One of the most important topics of research in hypersonic aerodynamics is to find a reasonable way of calculating either the surface temperature or the heat flux to surface when its temperature is held fixed. This requires modeling of physical and chemical processes. In the present work, chemical processes has not considered. Present work aims the prediction of heat transfer at hypersonic speed considering the relaxation method.

2. Results and Discussion

Numerical algorithm based on finite volume method with explicit time marching scheme for simulation of three dimensional fluid equations has been used for the analysis. The present investigation uses numerical scheme proposed by AUSM (Advection Upstream Splitting Method). Second order accuracy is achieved by calculating variables reconstructed by using MUSCL approach and limiting fluxes by min-mod limiter. Gradients are calculated using Greens theorem.

A circular cylinder with diameter 90mm is considered for the present simulation [4]. Freestream flow properties selected are P = 687 Pa, T = 694 K, u = 4776, density = 0.00326, Temp. at wall = 300 K and Mach number as 8.78. Inflow boundary is considered in front of a cylinder at a distance of radius. Present numerical results are compared with the experiment data for the pressure and heat transfer on the surface of cylinder. Present computations has been performed with relaxation time as speed of sound divided by 10000.

Figure 1 shows comparison of predicted pressure with the experiment data over the cylinder surface. Present calculated pressure compared well with the experiment values [4] over the cylinder surface. Heat flux distribution over the cylinder surface is shown in Fig. 2. Predicted value of heat flux at the stagnation point compared well with experiment data. Moreover, present heat flux has shown good agreement for heat flux over the surface of cylinder except near the stagnation region.

3. Conclusions

In the present work, thermo-nonequilibrium effects are modeled through Energy relaxation method introduced for Euler, later modified by Bongiovanni for Navier-Stokes equations. The governing equations are cast in hyperbolic equation with stiff relaxation source term. AUSM numerical scheme has been modified to incorporate the non-equilibrium equation of relaxation method. Modified code has captured all the critical flow field over the circular cylinder satisfactorily. The computations of hypersonic flow over a 3-D circular cylinder test case shows reasonably good comparison with experimental data.

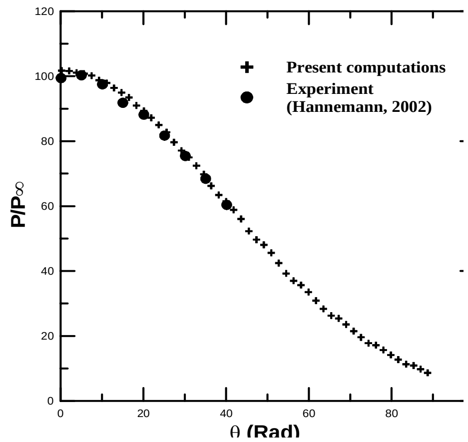

Fig. 1 Comparison of surface pressure with experimental data

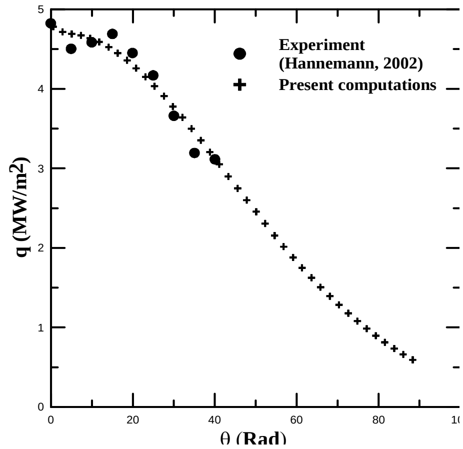

Fig. 2 Comparison of surface heat flux with experimental data

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