극초음속 유동의 열전달 예측에 관한 수치해석적 연구

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Computational Study on the Heat Transfer Prediction in Hypersonic Flows

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ABSTRACT

In recent years, scientific community has found renewed interest in hypersonic flight research. These hypersonic vehicles undergo severe aero-thermal environments during their flight regimes. 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. Hyperbolic system of equations with stiff relaxation method are being identified in recent literature as a novel method of predicting long time behavior of systems such as gas at high temperatures. In present work, Energy Relaxation Method (ERM) has been considered to simulate the real gas flow over a 2-D cylinder. Present heat flux results over the cylinder compared well with the experiment. Thus, real gas effects in hypersonic flows can be modeled through energy relaxation method.

Key Words: Hypersonic Flows, Energy Relaxation Method, Heat Transfer, AUSM, Real Gas

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

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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 $p_1(\rho, e_1)$ 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. Governing Equations

Navier Stokes (NS) equation for a real compressible flow can be expressed as conservation laws for mass, momentum (three in number) and energy. The Navier Stokes equations are closed by a thermodynamic model which provides pressure and temperature as a function of the conservative variables. The simplest and most often used thermodynamic model is that of thermally perfect and calorically perfect (TPCP) gas model $p = p(\rho, e)$. As the temperature varies over a wide range, the gas will not be in local thermodynamic equilibrium. At this condition, pressure p becomes non-linear which is considered as a function of only a part of e, while other part of e is governed by a rate equation. Coquel and Perthame, in their Energy Relaxation Method solve the nonlinearity in pressure law by relaxing the energy. Further, Bongiovanni er al. [3] have decomposed the diffusive flux for the Navier Stokes (NS) equation keeping same energy splitting and stability condition occur in Euler equation.

3. 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 (Fig. 1). 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.

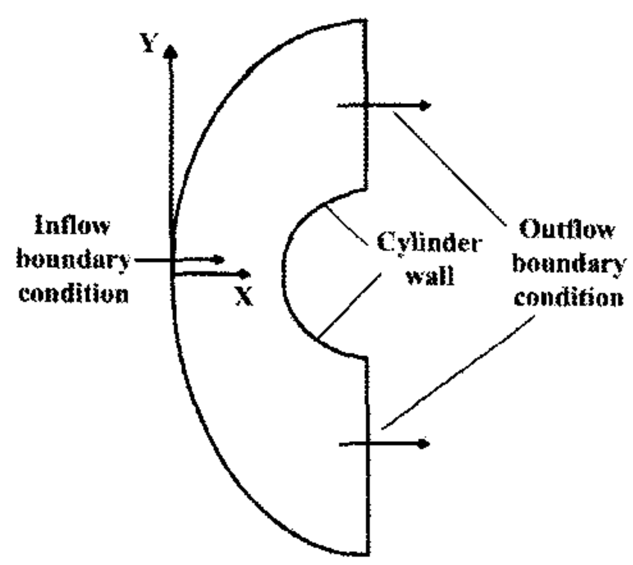

Fig. 1. Computational domain for 2-D Cylinder.

Grid convergence study has been carried out with 121x121, 161x181 and 200x181. Experiment values are available till the cylinder angle of 50. Figure 2 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. 3. 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.

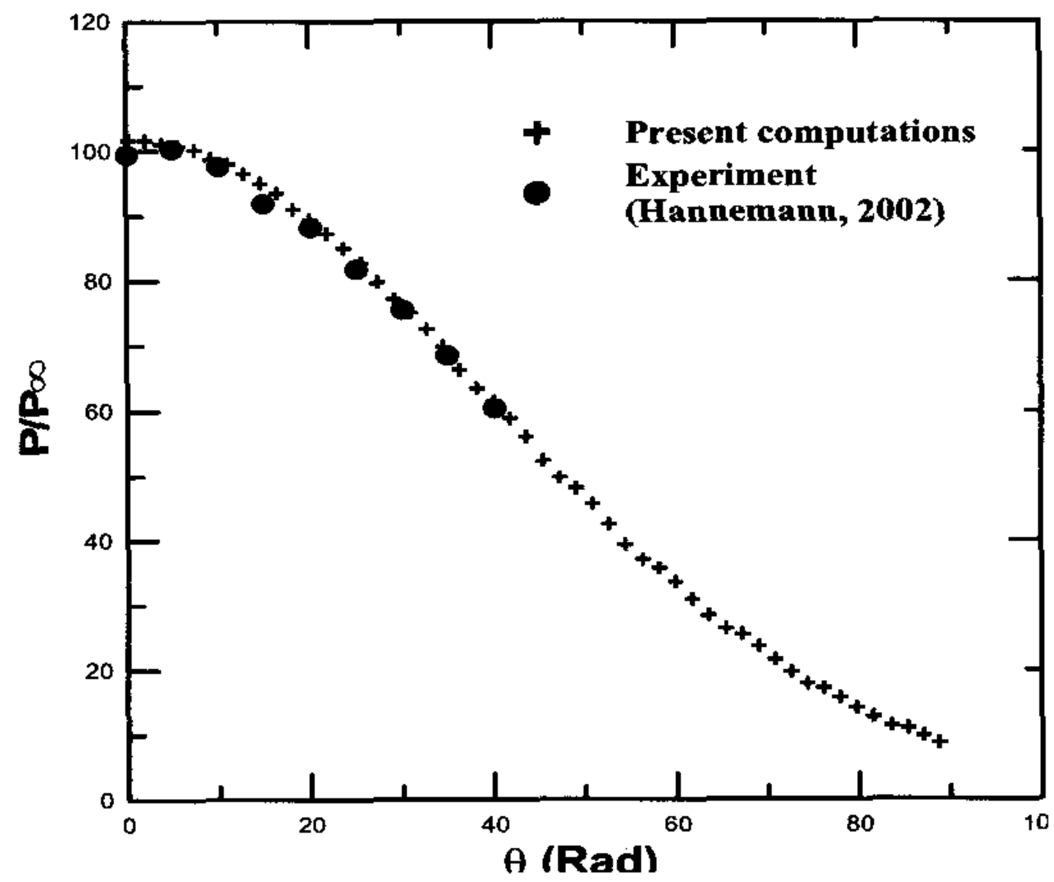

Fig. 2 Comparison of surface pressure with experimental data

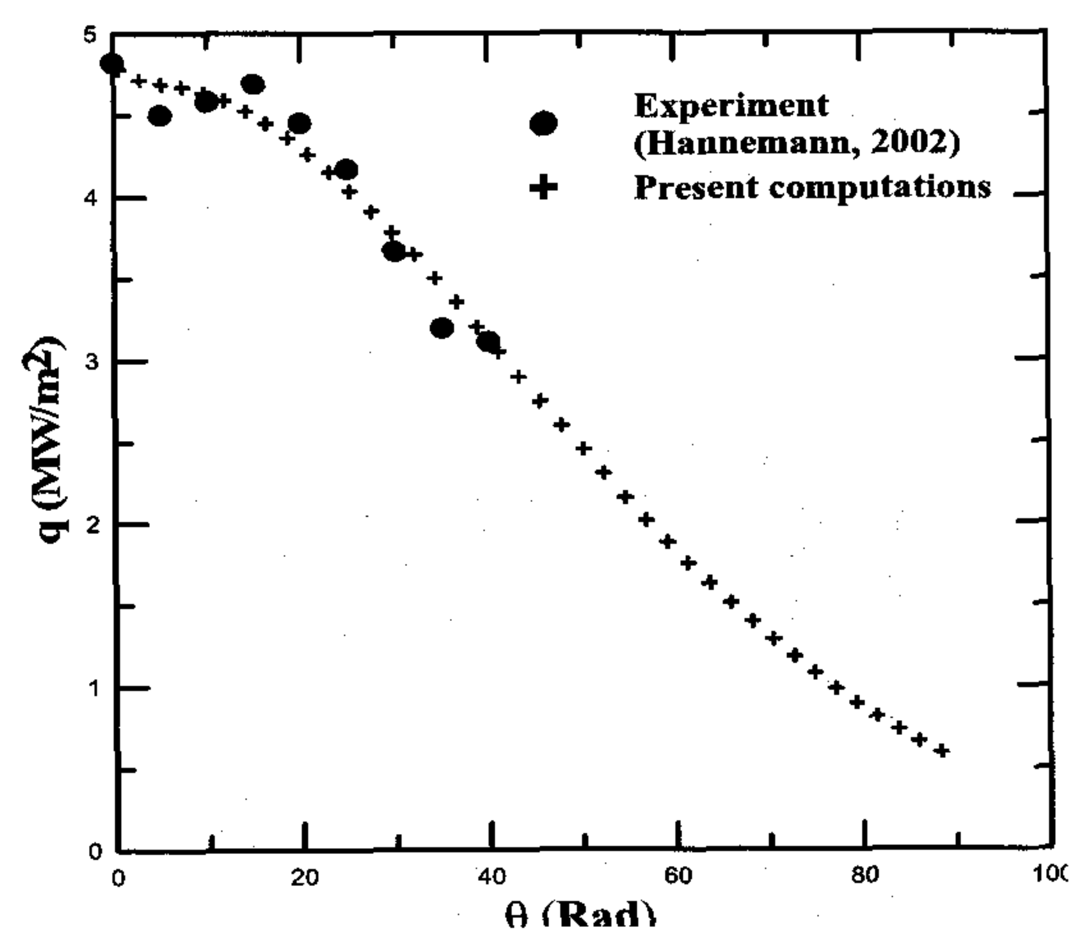

Fig. 3 Comparison of surface heat flux with experimental data

Present computation could not predict the second peak of heat flux which occur because of entropy layer attachment. However, temperature distribution over the cylinder surface has shown the rise in temperature away from the stagnation point as shown in Fig. 4. The temperature distribution has shown that the present computations could capture the entropy layer attachment on the cylinder. Figure 5 shows the Mach contour plot over the cylinder. Mach number contour plot clearly shows the shock and boundary layer close to the cylinder.

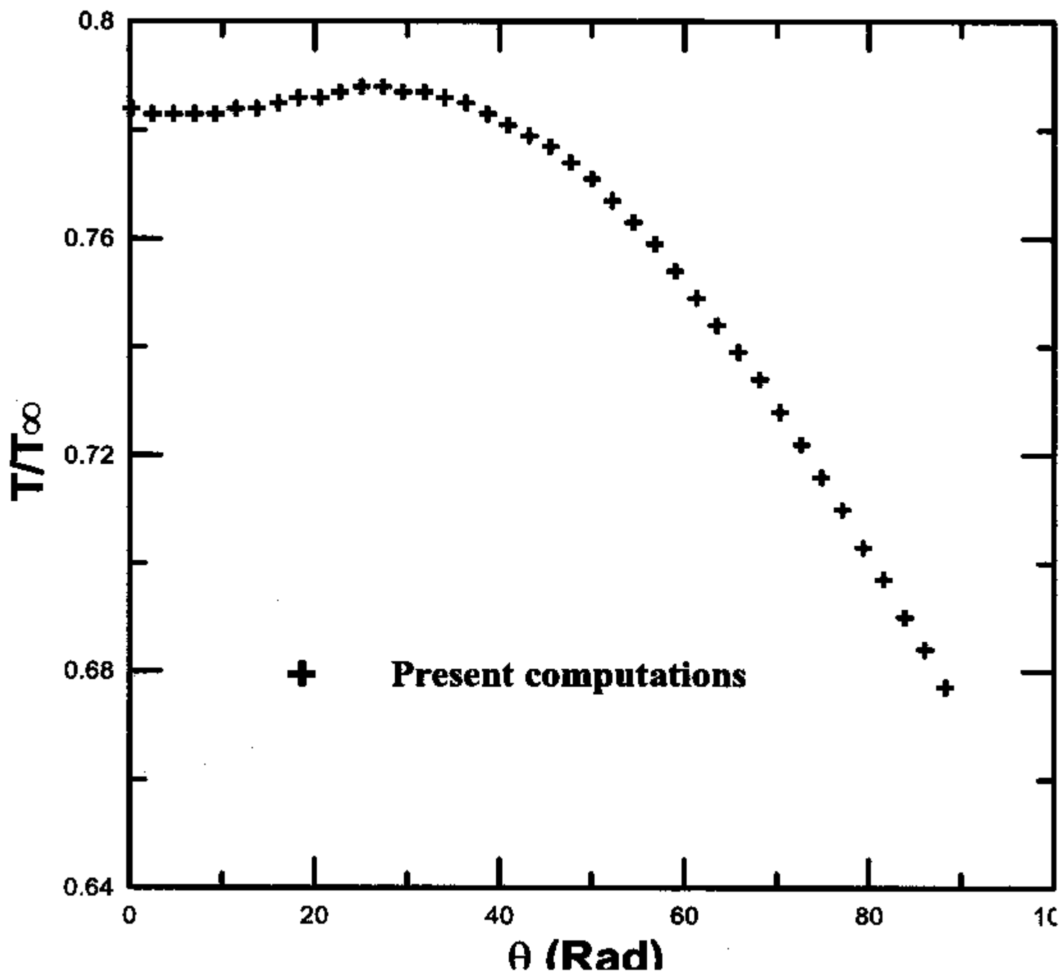

Fig. 4 Distribution of temperature over the surface of 2-D cylinder

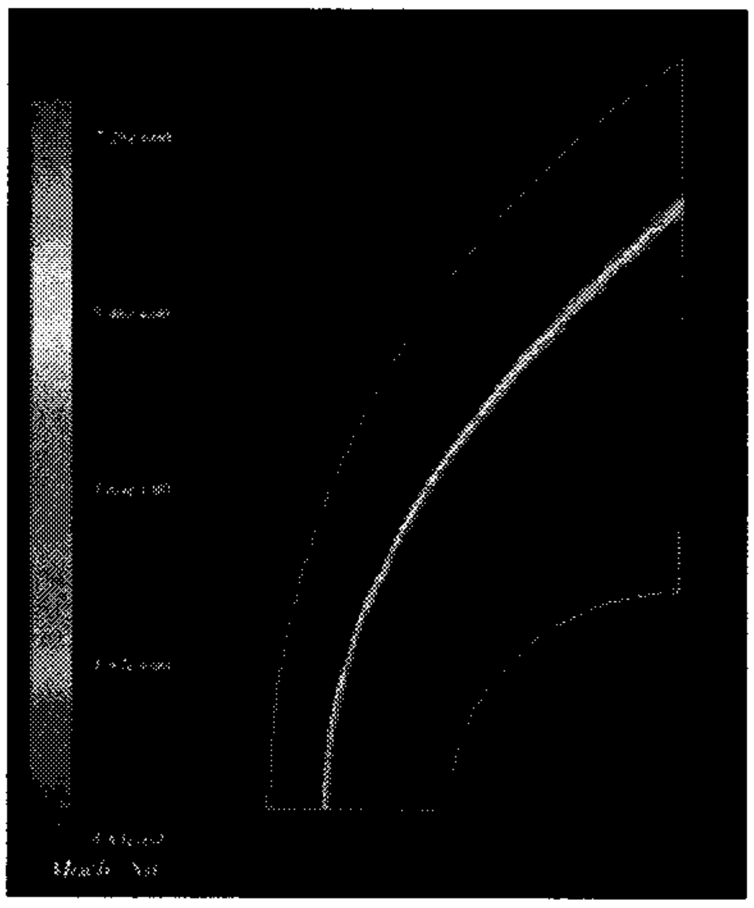
Fig. 4 Mach number distribution

4. 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 2-D circular cylinder test case shows reasonably good comparison with experimental data.

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