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Numerical Simulations of Shock Wave Induced Unsteady Aerodynamic Heating Phenomena with Chemical Nonequilibrium

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Abstract

In the present study the full two-dimensional Navier-Stokes equations are solved in order to investigate unsteady aerodynamic heating phenomena induced by the shock impingement on a ramp surface. The effects of chemical reactions to aerodynamic heating are investigated. The results show the effects of chemical reactions to shock induced aerodynamic heating phenomena are quite significant at high temperature.

1. Introduction

Recently high speed winged vehicles have been studied. One of the most important problems for designs of such vehicles is the severe aerodynamic heating and pressure rise caused by the impingement of shock waves on the surfaces. Especially the unsteady aerodynamic heating caused by shock wave reflections at a higher shock Mach number has been investigated and the peak heating due to a Mach stem and the second peak heating due to a slip layer have been observed by the present authors[1,2].

In the present study the full two-dimensional Navier-Stokes equations are solved in order to investigate unsteady aerodynamic heating phenomena induced by the shock impingement on a ramp surface. When the shock is much strong, nonequilibrium chemical reactions are occurred in the flows. The effects of chemical reactions to aerodynamic heating are investigated and the results are compared with experiments and calculated results without reactions.

2. Numerical Methods

In the numerical caluculations nonequilibrium chemically reacting flows are considered. The governing equations are two-dimensional full Navier-Stokes equations. Two-dimensional full Navier-Stokes equations in conservation form is as follows:

$$\frac{\partial U}{\partial t} + \frac{\partial E}{\partial x} + \frac{\partial F}{\partial y} = J$$

where each vector is expressed as follows:

$$U = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ \rho(E + \frac{V^2}{2}) \\ \rho c_i \end{bmatrix}, E = \begin{bmatrix} \rho u \\ \rho u^2 + p - \tau_{xx} \\ \rho uv - \tau_{xy} \\ \rho(E + \frac{V^2}{2})u + pu - q_x - u\tau_{x_{xy}} \\ \rho c_i u - \rho D_{im} \frac{\partial c_i}{\partial x} \end{bmatrix}$$

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$$F = \begin{bmatrix} \rho v \\ \rho uv - \tau_{yx} \\ \rho v^2 + p - \tau_{yy} \\ \rho(E + \frac{V^2}{2})v + pv - q_y - u\tau_{yx} - v\tau_{yy} \\ \rho c_i v - \rho D_{im}\frac{\partial c_i}{\partial y} \end{bmatrix}, J = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \dot{w}_i \end{bmatrix}$$

Heat conductionterms are expressed as follows:

$$q_x = k\frac{\partial T}{\partial x} + \sum_i \rho D_{im}\frac{\partial c_i}{\partial x}h_i, \quad q_y = k\frac{\partial T}{\partial y} + \sum_i \rho D_{im}\frac{\partial c_i}{\partial y}h_i$$

For chemical reactions of oxygen gas the 6 elementary reactions are assumed.

Forward rate constant, k_f, and backward rate constant, k_b, are obtained from Arrhenius equation as follows:

$$k_f = A_f T^{B_f} e^{-\frac{C_f}{T}}, \quad k_b = A_b T^{B_b} e^{-\frac{C_b}{T}}$$

For convective terms a Harten and Yee's upwind TVD scheme is used and for viscous terms a conventional central difference is used. For boundary conditions non-slip conditions are applied for the ramp surface and zero derivatives along freestream are assumed at incoming and downstream boundaries. Since in the flows with nonequilibrium chemical reactions the density, temperature and chemical compositions behind shock are changed along the distance from shock front, one-dimensional steady Euler equations for nonequilibrium chemically reacting flows are solved at first in order to obtain the initial conditions for incident shock wave. Also zero physical derivatives normal to incoming flow are imposed for the upper boundary in order to keep the incident shock wave normal. For the energy equation a constant wall temperature condition is assumed. Both fully catalytic wall case and non catalytic wall case are considered. Thermally equilibrium is assumed.

3. Numerical Results and Discussions

Calculated results of shock reflection processes in air at M_s=10.37, θ=10^0, p_∞=50 Torr and T_∞=299.0 K is shown in Fig.1 (a) and (b) with experiments[3]. At this testing conditions O_2 is fully dissociated and N_2 gas is slightly dissociated. The calculated results assuming chemically frozen gas and chemically non-equilibrium gas also show quite good agreements with experiments. In this flow conditions oxygen gas is fully dissociated and nitrogen is slightly dissociated. Since oxygen gas is only 20 % of total gas, total dissociation rate is quite small and almost no change is observed in the shock patterns and heat flux distribution as shown in Fig.1(b).

4. Conclusions

In the present study the full two-dimensional Navier-Stokes equations are solved in order to investigate unsteady aerodynamic heating phenomena induced by the shock impingement on a ramp surface. When the shock is much strong, chemically and thermally nonequilibrium reactions are occurred in the flows. The effects of chemical reactions to aerodynamic heating are investigated. The results show the effects of chemical reactions to shock induced aerodynamic heating phenomena are quite significant at high temperature.

References

[1] S. Aso et. al.: Proc. of 17th ISSWST, 1989, pp.777-782.
[2] K. Ohyama, S. Aso and M. Hayashi: Proc. of 19th ISSW, 1993.(to be published)
[3] R.R. Weynabts: UTIAS TN No.126 (1968).

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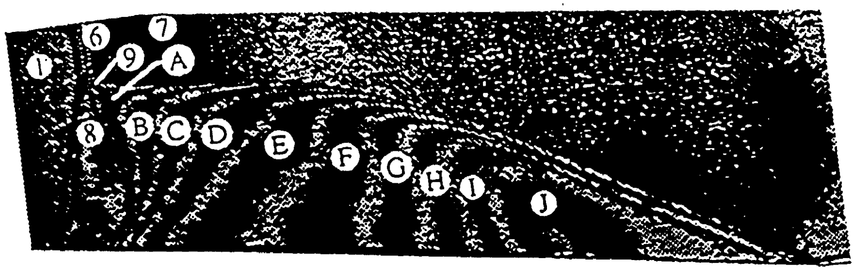
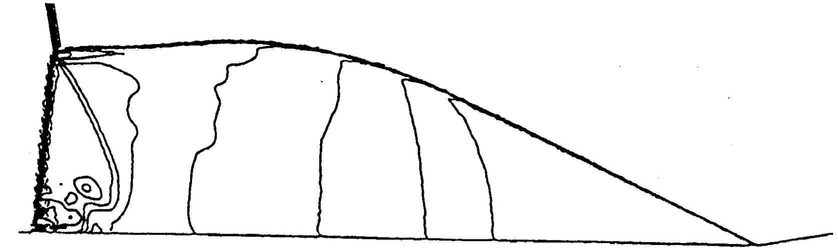
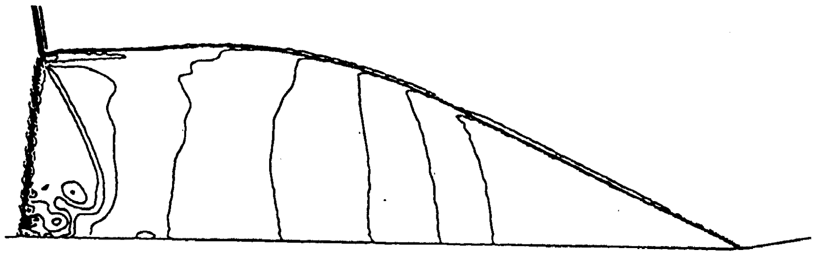


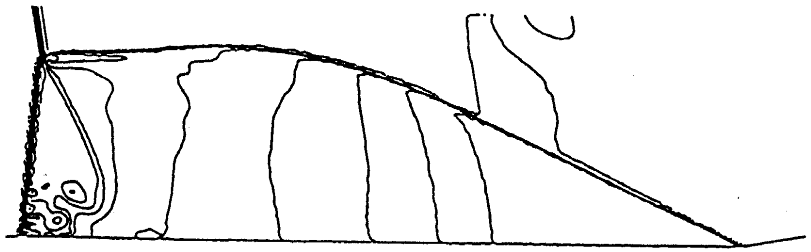
Experiment by R. L. Deschambault and I. I. Glass
Air, θ_w=10, Ms=10.37, P_0=50(torr), T_0=299.0(K)



Computational result (Chemically frozen flow)

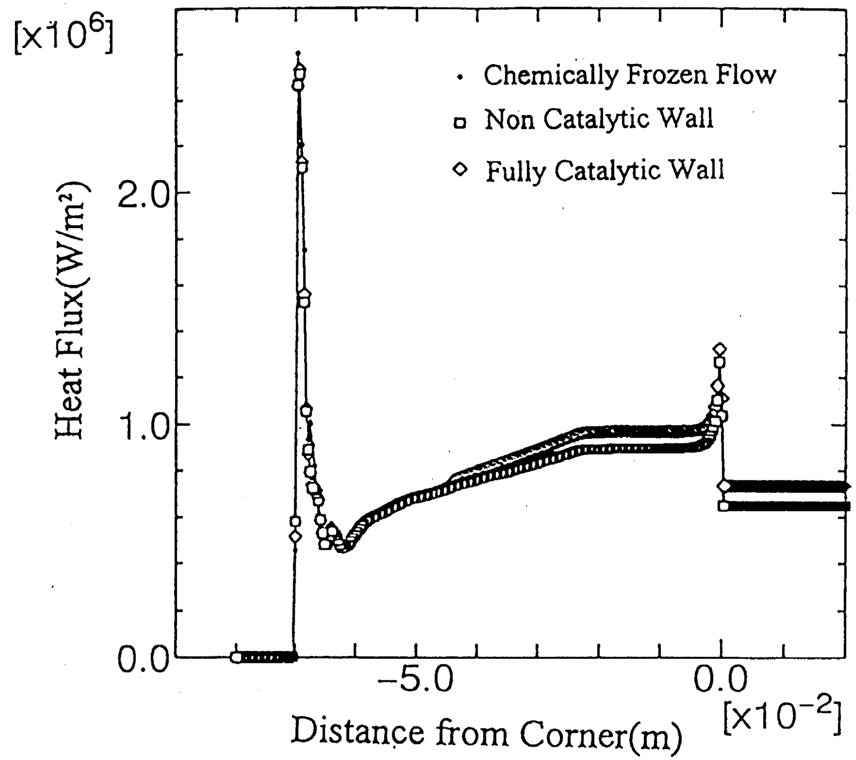


Computational result (Fully catalytic wall)



Computational result (Non catalytic wall)

(a) Shock wave patterns



(b) Surface heat flux distributions

Fig.1 Comparison of calculated results with experiments
(Air, M_s=10.37, θ=10^0, p_∞=50 Torr and T_∞=299.0 K)

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