AIAA 94-2478
The Method of Heat Flux Simulating in Hypersonic Aerothermodynamics

V. V. Riabov
Worcester Polytechnic Institute
Worcester, MA

18th AIAA Aerospace Ground Testing Conference

June 20-23, 1994 / Colorado Springs, CO

THE METHOD OF HEAT FLUX SIMULATING IN HYPERSONIC AEROTHERMODYNAMICS

Vladimir V. Riabov*
Worcester Polytechnic Institute
Worcester, Massachusetts 01609

Abstract

A new method is offered to simulate heat transfer processes in nonequilibrium viscous shock layers near the catalytic body surface at hypersonic wind tunnel and free natural flight conditions. The method is based on computations of nonequilibrium parameters in thin viscous shock layers, and on an analogy with flows that arise behind normal shock waves. The obtained simplified relationships between the linear scales of the vehicle and the model, velocities of the flows and their densities determine the similar structures of the viscous layers and heat fluxes at hypersonic wind tunnel and flight conditions.

Nomenclature

C_h = heat-transfer coefficient
c_m = mass concentration of molecules
$\langle E_v \rangle$ = average vibrational energy of a unit volume of gas
H_0 = total enthalpy
K = Cheng' similarity parameter
k = Boltzmann constant
L = vehicle nose radius
l = model nose radius
q = heat flux
Re_{of} = $\rho_\infty V_\infty L/\mu(T_{of})$, Reynolds number
St = Stanton number
T = temperature
T_{of} = stagnation temperature
V_∞ = free stream velocity
γ = specific heat ratio in perfect gas
ε = $(\gamma-1)/2\gamma$, hypersonic perturbation parameter
μ = viscosity coefficient
ρ_∞ = free stream density

subscripts
a = index for atomic components
c = characteristic parameter
e = equilibrium conditions
f = "frozen" conditions
m = index for molecular component
O_2 = molecular oxygen
N_2 = molecular nitrogen
v = index for vibrational degrees of freedom
w = wall conditions
∞ = freestream conditions
o = stagnation conditions
2 = parameter behind the normal shock wave

superscript
* = wind-tunnel conditions

*Visiting Associate Professor
Mechanical Engineering Department
Member AIAA

Introduction

The possibility of simulating the heat flux and aerodynamic characteristics of hypersonic vehicles at natural flight conditions in a wind tunnel was examined by Gibson,[1] Agafonov et al.,[2] Gusev et al.,[3-4] and Artamonov et al.[5] Because of the nonequilibrium character of physical and chemical processes in a flowfield near the vehicle, there is a major distinction between two typical situations: the streamlining of a model in an aerodynamic hypersonic wind tunnel and the streamlining of a body under the conditions of free flight. In the first case the upstream flow is vibrationally "frozen-in" and an atomic fraction is far from zero.[6] In the second case the approaching stream under the conditions of free flight is in an equilibrium state. To analyze the structure of the flows in both cases, we used a model of a thin viscous shock layer (TVSL) developed by Cheng.[7] Nonequilibrium processes were studied within the framework of the CVDV model[8] which allows to consider the major relationship between the molecular vibrations and dissociation. In the above mentioned cases the structures of TVSL, heat transfer coefficients at catalytic surfaces of vehicle and testing models are significantly different.

In the present study the different methods of heat flux simulating techniques are examined for modelling the free flight conditions in a hypersonic wind tunnel.

In the following sections we first present the method, physical and chemical concepts. Then we demonstrate the main features of the structure of the TVSL for two cases and obtain the system of the similarity criteria for the hypersonic flight and wind-tunnel conditions.

The TVSL-Approximation

The flow of a vibrational-nonequilibrium dissociated gas in the vicinity of the deceleration line near the blunt body was described in terms of a model of a thin viscous shock layer.[7] An analysis of the equations and the boundary conditions was done, for example, by Cheng,[7] Gusev et al.,[4] Tirskii[9] and others. The TVSL equations were written in general orthogonal curvilinear coordinates. The main variables are defined by ratios of gas-dynamic functions to the density ρ_∞ and velocity V_∞ of the upstream flow, the stagnation temperature T_{of}, the nose radius of a blunt body L (or a model l), and the viscosity coefficient $\mu(T_{of})$. We suggested that the total enthalpy can be approximated as $H_o \approx V_\infty^2/2$. After this procedure, the equations contain two major hypersonic parameters: the Reynolds number[3,4] $Re_{of} = \rho_\infty V_\infty L/\mu(T_{of})$ and the perturbation parameter[7] $\varepsilon = \rho_\infty/\rho_2 \approx R_g T_e/(M_m V_\infty^2)$. In a perfect gas at $T_e = T_{of}$, parameter ε is equal to $(\gamma-1)/2\gamma$, where γ is a specific heat ratio. These parameters can be considered together as the hypersonic similarity criterion first introduced by Cheng[7] as

$$K = \varepsilon Re_{of}. \quad (1)$$

The generalized Rankine-Hugoniot equations[4,9] are considered as the external boundary conditions for the thin viscous shock layer. At the surface of the body, the set of boundary conditions was applied such as the "no-slip" condition for the velocity, the condition of equilibrium-radiation heat exchange, the equilibrium of the vibrational energy, and mass component balance at the catalytic wall.

The undisturbed conditions are assumed for a free flight: $\langle E_v \rangle_\infty = \langle E_v \rangle_e(T_\infty)$, $c_{m,\infty} = 1$, $T = T_\infty$, where $\langle E_v \rangle$ is the average vibrational energy of a unit volume of gas, $c_{m,\infty}$ is the mass concentration of the molecules in the upstream flow.

The conditions in the hypersonic wind tunnel can be simulated by the values of $\langle E_v \rangle_\infty$, $c_{m,\infty}$ and T_∞, which are significantly different from the equilibrium magnitudes.[6] These values are correspondent to the conditions of the "frozen" expanded flow of dissociated gas from a nozzle into a vacuum. The physical flow model was developed by Apolonskii et al.[10] in the framework of the CVDV model.[8]

Numerical Method

The flow in a nonequilibrium thin viscous shock layer near the stagnation stream-line was analized by the numerical method of the solution of the one-dimensional boundary-value problem. A universal numerical procedure[10] for the solution of the systems of nonlinear ordinary algebraic-differential equations with a small parameter for the higher derivatives was used. The approximation of the differential equations with respect to the two-point second-order Keller scheme was realized. The algorithm of an adaptive computation grid was based on the procedure[11] of minimizing the integral approximation error norm. The numerical method was originally developed by Babikov,[12] and Apolonskii et al.[10]

Simulation Parameters for Wind-Tunnel Conditions

Agafonov et al.[2], and Gusev et al.[3,4] have shown, that nonequilibrium chemical processes are binary in the inviscid and viscous shock layers near the blunt body, and the reactions of recombination can be neglected. It is only in the immediate vicinity of the catalytic surface of the body, there is necessary to take into consideration the triple character of the collisions between the gas components. Using binary approximation, Gibson[1] studied a nonequilibrium inviscid flow on the stagnation streamline near a blunt body. He considered this flow as the correspondent flow behind the normal shock wave at the same magnitudes of the stagnation enthalpy. The linear character of a function of the enthalpy from atomic concentration $c^*_{a,\infty}$ was assumed. This assumption made it possible to find the simple rule of calculation of the upstream velocity V^*_∞ at experimental conditions, when the dissociation exists, and the upstream velocity V_∞ at free flight conditions:

$$V^*_\infty = (V_\infty^2 - 2c^*_{a,\infty} R_g T_d / M_m)^{1/2} \qquad (2)$$

The index (*) refers to the parameters at the wind-tunnel conditions.

Let us assume additionally that the values of dynamic pressure are the same in the experiment and in the free flight. As a result, we find the relation between the densities at these conditions:

$$\rho^*_\infty = \rho_\infty V_\infty^2 / V^{*2}_\infty \qquad (3)$$

Gibson[1] found, that the structures of these flows (i.e., the values of density, temperature, atomic concentration, etc.) are very similar even at short distances after the shock, and at the condition $c^*_{a,\infty} \leq 0.3$.

In simulating the viscous flow parameters in a nonequilibrium thin shock layer, additionally to the conditions (2)-(3) it is necessary to satisfy the Cheng' criterion[5,7] (see also Eq.(1)):

$$K = \varepsilon \rho_\infty V_\infty L / \mu(T_c) = \varepsilon^* \rho^*_\infty V^*_\infty l / \mu(T^*_c) \qquad (4)$$

We choose the stagnation temperature of a "frozen" flow (without dissociation) as a characteristic gas temperature T_c:

$$T_c = T^*_c = T_{of} \qquad (5)$$

If the condition (5) is correct, than from Eqs. (3)-(4) we can find a relation between the linear scale of the model l and of the vehicle L:

$$l/L = (V^*_\infty / V_\infty)^3 \qquad (6)$$

Thus, under the certain conditions, which are described by Eqs. (2), (3), (5), and (6), the nonequilibrium flow of a viscous gas near the model in a wind-tunnel is similar to the flow around the vehicle. The detailed analysis of these flows was done by Apolonskii et al.[10]

Heat Flux Calculations

The study of heat flux on the surface of a model in an aerodynamic experiment or of a vehicle under the flight conditions is the most important task of the hypersonic aircraft design.

In present study, the computational values for the heat-transfer coefficient $C_h = 2q/\rho_\infty V_\infty^3$ at flight conditions are compared with the values $C_h^* = 2q^*/\rho^*_\infty V^{*3}_\infty$ under the wind-tunnel conditions. Using recommendations of Agafonov et al.[2], and Gusev et al.,[3-4] Reynolds number Re_{of} (or Re^*_{of}) is chosen to correlate the computation data.

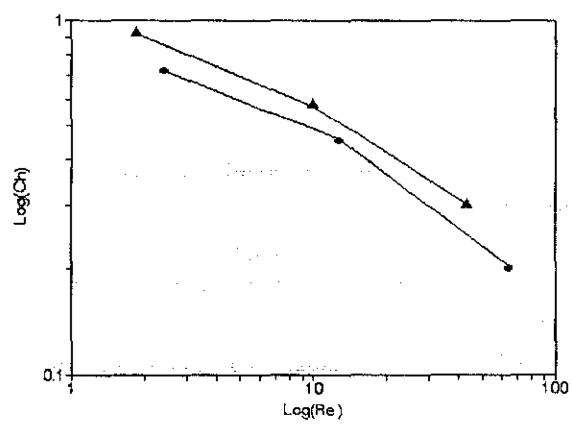

Fig. 1. The Heat-Transfer Coefficient C_h vs Reynolds Number Re_{of} for Nitrogen (+ - $c^*_{N,\infty}=0$, ▲ - $c^*_{N,\infty}=0.2$).

Figure 1 shows the correlations $C_h(Re_{of})$ and $C_h^*(Re^*_{of})$ for nitrogen. The choice of nitrogen as the working gas in the wind tunnel was done because of its molecular properties (i.e., Riabov[13]): nitrogen is the major component of air, and according to Mitra et al.,[6] this gas has a low level of dissociated molecules (or atomic concentration $c^{*}_{N,\infty}$) in the high-temperature jet, where the model is placed. In the calculations we used $c^{*}_{N,\infty} = 0.2$, $6400 \leq V_{\infty} \leq 7900$ km/s, L = 0.1 m, $2.4 \leq Re_{of} \leq 64.2$.

Figure 1 shows that the values of C_h^{*} (triangles) are significantly more than the values of C_h (plus, $c_{N,\infty} = 0$) under the free flight conditions. Also we have the relationship: $Re^{*}_{of} < Re_{of}$. This analysis indicates that the Reynolds number Re_{of} (or Re^{*}_{of}) couldn't be considered as the correlation parameter at the discussed conditions.

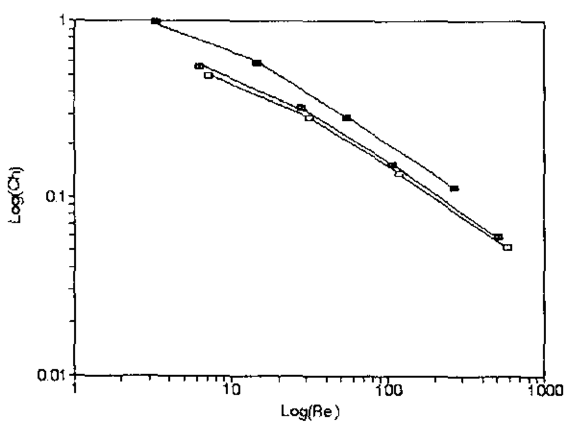

Fig. 2. The Heat-Transfer Coefficient C_h vs Reynolds Number Re_{of} for Oxygen (□ - $c^{*}_{O,\infty}=0$, ⊠ - $c^{*}_{O,\infty}=0.2$, ▪ - $c^{*}_{O,\infty}=0.95$).

The same conclusion could be done from the comparison of heat-transfer coefficients C_h and C_h^{*} for the case, at which the working gas is oxygen. Figure 2 compares the correlation curve $C_h(Re_{of})$ at $c_{O,\infty} = 0$ (empty squares) and $C_h^{*}(Re^{*}_{of})$ for two different magnitudes of oxygen-atom concentrations in upstream jet-flow: $c^{*}_{O,\infty} = 0.2$ (squares with x) and 0.95 (filled squares). The case of the large value of the oxygen-atom concentration ($c^{*}_{O,\infty} = 0.95$) is the most typical one under the wind-tunnel experimental conditions. In the calculations we used $7.08 \leq Re_{of} \leq 575$, $V_{\infty} = 7900$ km/s, L = 0.06 m.

Using the recommendations of Cheng,[7] Artamonov et al.,[5] and Apolonskii et al.,[10] let us try to find the correlation of the heat fluxes in terms of the Stanton number $St = q/(\rho_{\infty} V_{\infty}(H_o - H_w))$ and the Cheng' parameter K.

Figure 3 shows the correlations St(K) for nitrogen (triangles) and for oxygen (squares). It was found that the values of the Stanton number St (or St^{*}) are independent in fact from the upstream concentrations of the atomic component $c^{*}_{a,\infty}$, if the conditions (2)-(6) are realized. The small difference between the values of the Stanton number for various gases can be explained by the difference in the transfer properties of nitrogen and oxygen, which were analyzed by Riabov.[13]

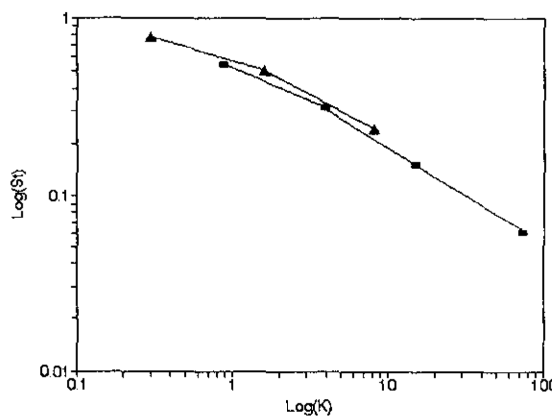

Fig. 3. The Stanton Number S_t vs the Cheng' Parameter K (▲ - Nitrogen, ▪ - Oxygen).

The discovered correlation, that is $St \approx St^{*}$ at $K = K^{*}$, indicates the useful correlation between the heat-transfer coefficients:

$$C_h^{*} = C_h(V_{\infty}/V^{*}_{\infty})(1 - t^{*}_w)/(1 - t_w) \qquad (7)$$

Here parameter $t_w = T_w/T_{of}$ is the temperature factor.

In the case that $t_w \ll 1$ or $t^{*}_w \approx t_w$, from Eq. (7) it is possible to find the simple relationship between the value of heat flux q under the free-flight conditions and the value of q^{*} in aerodynamic wind-tunnel experiment:

$$q/q^{*} \approx V^{*}_{\infty}/V_{\infty} \qquad (8)$$

The obtained correlations for the Stanton numbers, heat-transfer coefficients, and for heat fluxes could be helpful in the simulating of the nonequilibrium viscous flowfield parameters near the hypersonic vehicles.

Concluding Remarks

The present study indicates the principle possibility to use simple rules for simulation of heat-flux values under natural flight conditions in the wind tunnel. The more complex analysis of the dissociation processes in air and the Martian atmosphere could be considered in the future.

Acknowledgments

The advice and assistance of O. Yu. Apolonskii and I. V. Lebed' were instrumental to this research effort.

References

[1]Gibson, W., "The Effect of Ambient Dissociation and Species Diffusion on Nonequilibrium Shock Layer", Paper No. 63-70, IAS, New York, 1963.

[2]Agafonov, V. P., Vertushkin, V. K., Gladkov, A. A., and Polyanskii, O. Yu., *Nonequilibrium Physicochemical Processes in Aerodynamics* (in Russian), Mashinostroyeniye, Moscow, 1972.

[3]Gusev, V. N., Kogan, M. N., and Perepukhov, V. A., "Similarity and Changes in the Aerodynamic Characteristics in the Transition Region for Hypersonic Flow Velocities" (in Russian), *Uchenye Zapiski TsAGI*, Vol. 1, No. 1, 1970, pp. 24-31.

[4]Gusev, V. N., Provotorov, V. P., and Riabov, V. V., "Effect of Physical and Chemical Nonequilibrium on Simulation of Hypersonic Rarefied Gas Flows," *Fluid Mechanics - Soviet Research*, Vol. 10, No. 5, Sept.-Oct. 1981, pp. 123-135.

[5]Artamonov, A. K., Arkhipov, V. N., and Farafonov, V. G., "Similarity Criteria in the Rarefied Gas Aerodynamics," *Fluid Dynamics*, Vol. 16, No.1, Jan.-Feb. 1981.

[6]Mitra, N. K., and Fiebig, M., "Low Reynolds Number Nozzle Flows with Vibrational Dissociational Nonequilibrium," *Proceedings of the Eleventh International Symposium on Rarefied Gas Dynamics*, Vol. 2, Cannes, 1979 pp. 857-868.

[7]Cheng, H. K., "The Blunt-Body Problem in Hypersonic Flow at low Reynolds Number," Paper No. 63-92, IAS, New York, 1963.

[8]Marrone, P. V., and Treanor, C. E. "Chemical Relaxation with Preferential Dissociation from Excited Vibrational Levels," *Physics of Fluids*, Vol. 6, No. 10, 1963, pp.1215-1221.

[9]Tirskii, G. A., "Up-To-Date Gasdynamical Models of Hypersonic Aerodynamics and Heat Transfer with Real Gas Properties," *Annual Review of Fluid Mechanics*, Vol. 25, 1993, pp. 151-181.

[10]Apolonskii, O. Yu., Babikov, P. E., Lebed', I. V., and Riabov, V. V. "Studying the Streamlining of a Blunted Body by a Vibrational-Nonequilibrium Dissociated Gas," *Journal of Applied Mechanics and Technical Physics*, Vol. 30, No. 6, Nov.-Dec. 1989, pp. 970-976.

[11]Ablow, C. M., Schechter, S., and Zwisler, W. H., "Node selection for two-point boundary-value problems," *Transactions of ASME, Journal of Fluids Engineering*, Vol. 107, No. 3, 1985.

[12]Babikov, P. E., and Egorow, I. V., "On the Version of the Method of the Adaptive Grid Generation to Solve Evolution Problems," *Proceedings of the Soviet Union - Japan Symposium on Computational Fluid Dynamics*, Khabarovsk, 1988, p. 15.

[13]Riabov, V. V., "Approximate Calculation of Transport Coefficients in Multicomponent Mixtures," *Journal of Engineering Physics*, Vol. 44, No. 2, February 1983, pp. 183-189.