Thermodynamic Properties of Air and Nitrogen to 15,000° K with Application

Clark H. Lewis* and Ernest G. Burgess III†
ARO Inc., Arnold Air Force Station, Tenn.

Empirical equations were obtained for equilibrium dissociating and ionizing air and nitrogen for temperatures to 15,000°K and in the entropy range $1.40 \leq \log(S/R) \leq 2.06$. The corresponding density range is approximately 10^{-6} to 10^2. The density $\rho(p,S)$, enthalpy $H(p,S)$, compressibility factor $Z(p,S)$, and speed of sound $a(p,S)$ for air are given, and the errors in each empirical surface for these properties are indicated. The results were used to compute the sphere stagnation point heat-transfer rate at hypervelocity conditions based upon the Fay and Riddell equilibrium theory.

To facilitate high-speed computer calculations, the data of Hilsenrath, Klein, and Woolley[4] for dissociating and ionizing air were interpolated at constant entropy, and the density ρ, enthalpy H, and compressibility factor Z were fitted empirically as functions of p and S. The results of the interpolation were differentiated numerically to obtain the isentropic exponent $\gamma_E = (\partial \ln p/\partial \ln \rho)_S$, and then the speed of sound $a = (\gamma_E ZRT)^{1/2}$ was computed. These latter quantities for $T \geq 1800°$K were compared with the data of Landis and Nilson,[5] and the results were in agreement within five significant figures. The results for ρ, H, Z, and a are shown on Figs. 1–4 where all logarithms are to the base 10 and the symbols denote errors in the empirical surface-fit equations. The data shown extend from 90° to 15,000°K. Below 1500°K, the data of Humphrey and Neel[6] neglecting the intermolecular force effects in those data were used. These data were fitted as those above 1500°K except the speed of sound which was fitted in the form $a = f(T)^{1/2}$.

The data of Hilsenrath[7] for equilibrium dissociating and ionizing nitrogen for $2000 \leq T \leq 15{,}000°$K were interpolated similarly and differentiated at constant entropy. For $400 \leq T \leq 2000°$K, the data of Hilsenrath et al.[8] were interpolated and fitted; however, those results are not shown here. Lewis and Burgess[1] give the results of the thermodynamic surface fits for air and nitrogen in the form of equations and an IBM Fortran subroutine listing. Source decks for the Fortran program can be obtained from the authors.

The surface-fit results were used by Lewis and Burgess[2] to compute the sphere stagnation heat-transfer rate in equilibrium air and nitrogen based upon the Fay and Riddell theory.[3] The formula used was

$$\dot{q}(r_n)^{1/2} = K(\bar{\rho}_w\mu_w)^{0.1}(\bar{\rho}_0\mu_0)^{0.4}(H_0 - H_w)(\bar{p}_0/\bar{\rho}_0)^{0.25}$$

in Btu (in.)$^{1/2}$/ft^2-sec where $\dot{q}$ is the heat-transfer rate, r_n the sphere radius in inches, μ the coefficient of viscosity in lbf-sec/ft^2, H the enthalpy in ft^2/sec^2, $\bar{\rho} = \rho/\rho_a$ the density in amagats, $\bar{p} = p/p_a$ the pressure in atmospheres with $p_a = 2116.22$ lbf/ft^2, and $T_a = 273.15°$K. The remaining quantities are given in Table 1.

Subscript w denotes wall conditions (here assumed $T_w = 300°$K), and 0 denotes stagnation conditions downstream of

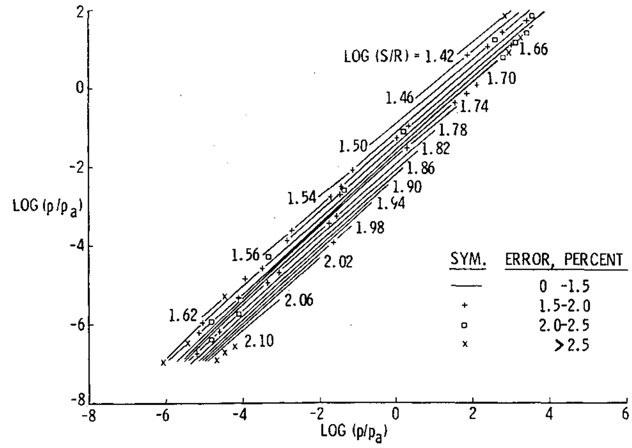

Fig. 1 Dimensionless density function $\log_{10}(\rho/\rho_a)$ as a function of pressure and entropy for $90 \leq T \leq 15{,}000°$K, where $\rho_a = 2.5075 \times 10^{-3}$ lbf-sec^2/ft^4 at 1 atm and 273.15°K in air.

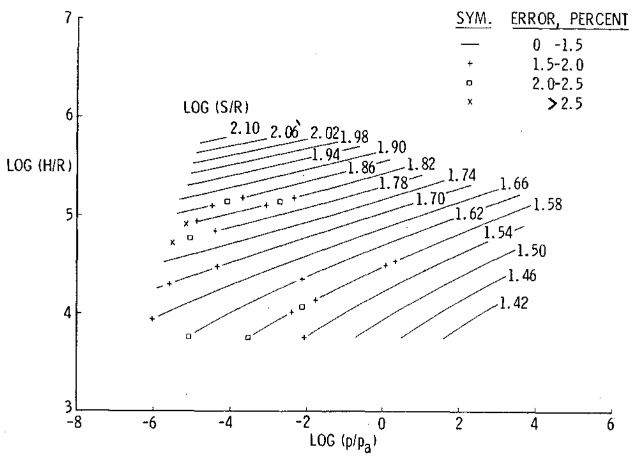

Fig. 2 Enthalpy function $\log(H/R)$ as a function of pressure and entropy for $90 \leq T \leq 15{,}000°$K. The gas constant $R = 3089.67$ ft^2/sec^{2}K for air.

a normal shock. The data of Hansen[9] were used for the coefficient of viscosity in air and those of Ahtye and Peng[10] in nitrogen. The Lewis number was taken to be unity. The heat-transfer parameter

$$\frac{Nu}{(Re)^{1/2}} \equiv \frac{(-\dot{q}_w)C_{pw}}{k_w(H_0 - H_w)}\left(\frac{\rho_w\, ux}{\mu_w}\right)^{-1/2} = 0.67\left(\frac{\rho_0\mu_0}{\rho_w\mu_w}\right)^{0.4}$$

was computed and is shown on Fig. 5. The recent theory of Fay and Kemp[11] and shock-tube measurements of Rose and Stankevics[12] are shown also. If the Fay and Riddell results are multiplied by the factor 1.15, the results are in reasonable agreement with the Fay and Kemp results. Because of the large scatter in the experimental data and the neglect of radiation at the high flight speeds, this simple modification of the Fay and Riddell formula may be useful for engineering estimates.

References

[1] Lewis, C. H. and Burgess, E. G., "Empirical equations for the thermodynamic properties of air and nitrogen to 15,000°K," Arnold Eng. Dev. Center TDR-63-138 (1963).

[2] Lewis, C. H. and Burgess, E. G., "Charts of sphere stagna-

Table 1 Reference density and constant in stagnation heat-transfer equation

	Air	Nitrogen
ρ_a, lbf-sec^2/ft^4	2.507542×10^{-3}	2.423609×10^{-3}
K	7.55274×10^{-3}	7.48873×10^{-3}

Received May 27, 1963. This work was sponsored by the Arnold Engineering Development Center, Air Force Systems Command, U. S. Air Force under Contract AF 40(600)-1000 with ARO Inc.

* Engineer, Hypervelocity Branch, von Karman Gas Dynamics Facility. Member AIAA.

† Member, Scientific Computing Services.

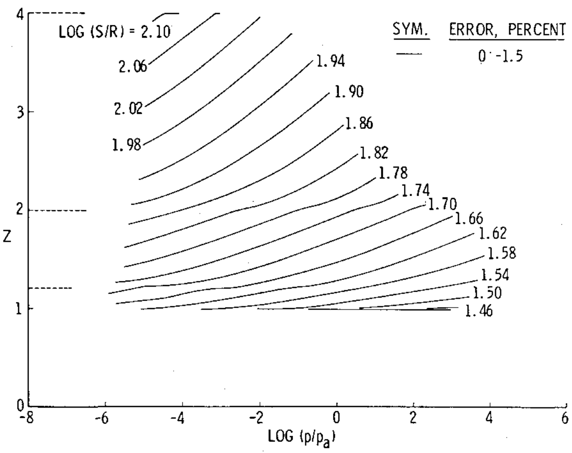

Fig. 3 Compressibility factor Z as a function of pressure and entropy for $T \leq 15{,}000°K$ in air.

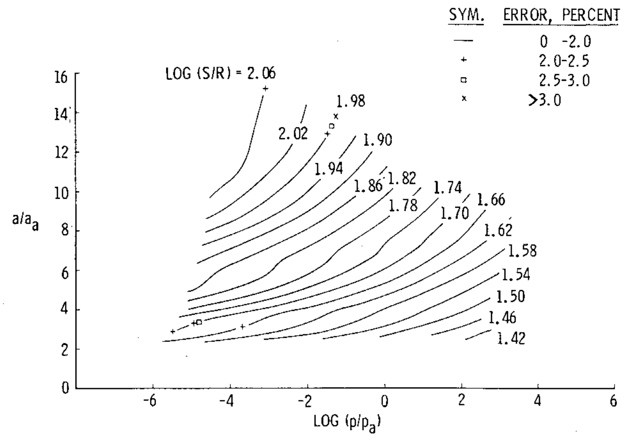

Fig. 4 Dimensionless speed of sound a/a_a as a function of pressure and entropy for $2000 \leq T \leq 15{,}000°K$, where a_a = 1086.98 fps at 1 atm and 273.15°K in air.

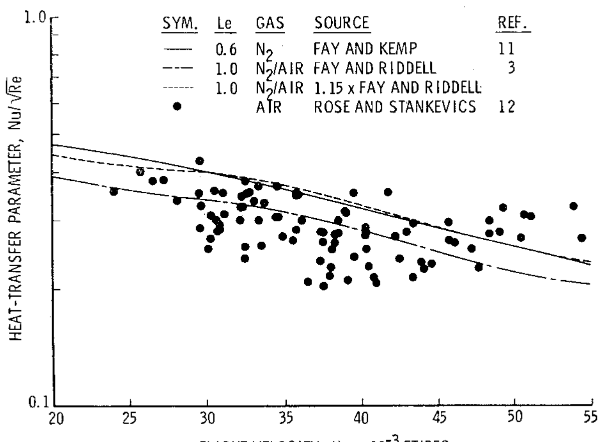

Fig. 5 Comparison between theory and experiment for equilibrium stagnation point heat-transfer at hypervelocity conditions (T_w = 300°K).

tion heat-transfer rate in air and nitrogen at high-temperatures," Arnold Eng. Dev. Center TDR-63-139 (1963).

[3] Fay, J. and Riddell, F. R., "Theory of stagnation point heat transfer in dissociated air," J. Aeronaut. Sci. **25**, 73–85, 121 (1958).

[4] Hilsenrath, J., Klein, M., and Woolley, H. W., "Tables of thermodynamic properties of air including dissociation and ionization from 1500°K to 15,000°K," Arnold Eng. Dev. Center TR-59-20 (1959).

[5] Landis, F. and Nilson, E. N., "Thermodynamic properties of ionized and dissociated air from 1500°K to 15,000°K," Pratt and Whitney Aircraft Rept. 1921 (1961).

[6] Humphrey, R. L. and Neel, C. A., "Tables of thermodynamic properties of air from 90 to 1500°K," Arnold Eng. Dev. Center TN-61-103 (1961).

[7] Hilsenrath, J., private communication, Natl. Bur. Standards (1959).

[8] Hilsenrath, J., Beckett, C. W., Benedict, W. S., Fano, L., Hoge, H. J., Masi, J. F., Nutall, R. L., Touloukian, Y. S., and Woolley, H. W., "Tables of thermal properties of gases," Natl. Bur. Standards Circular 564 (1955).

[9] Hansen, C. F., "Approximations for the thermodynamic and transport properties of high-temperature air," NACA TN 4150 (1958).

[10] Ahtye, W. F. and Peng, T. C., "Approximations for the thermodynamic and transport properties of high-temperature nitrogen with shock-tube applications," NASA TN D-1303 (1962).

[11] Fay, J. and Kemp, N., "Theory of stagnation point heat transfer in a partially ionized diatomic gas," Inst. Aerospace Sci. Paper 63-60 (1963).

[12] Rose, P. H. and Stankevics, J. O., "Stagnation point heat transfer measurements in partially ionized air," Inst. Aerospace Sci. Paper 63-61 (1963).

Nose Bluntness Effects on Cone Pressure and Shock Shape at M = 8.5 to 12.9

NIGEL B. WOOD
The War Office, Royal Armament Research and Development Establishment, Fort Halstead, England

Measurements of pressure distribution and shock shape were made on 15°-semiangle, spherically blunted cones in the Royal Armament Research and Development Establishment 10-in. hypersonic gun tunnel. The overexpansion in the pressure distribution increased with increasing Mach number, and good agreement with other experimental and theoretical results was obtained for similar values of $M\theta$. If $M\theta$ is greater than about 5, complete correlation of pressure distributions may be expected. The shock shape showed good agreement with Cheng's theory.

SINCE it was realized that a blunted cone, in certain circumstances, may have a lower drag than a corresponding sharp one, a number of investigators have focused their attention on the subject. In particular, the theoretical analyses of Chernyi[1] and Cheng,[2] together with the experimental results of Bertram,[3] have been the subject of considerable interest.

The present note compares the results on a 15°-semiangle spherically blunted cone at three Mach numbers in the Royal Armament Research and Development Establishment 10-in. hypersonic gun tunnel with already available experimental and theoretical results. The tests were made at nominally zero incidence and Mach numbers of 8.5, 10.4, and 12.9, with tip Reynolds numbers based on freestream conditions of 3.1 to 6.2 $\times$ 10^5, 1.3 to 2.6 $\times$ 10^5, and 0.6 to 1.2 $\times$ 10^5, respectively. Figures 1a and 1b* show typical schlieren photographs of the cone at small incidence at M = 8.5 and 10.4. It seems possible that the light and dark regions on the upper surface behind the shock represent approximately the entropy and shock layers considered by Cheng, and Fig. 1a appears to show the shock layer impinging and then skipping along the surface. Bertram suggested that the light region on the blunt cone represented a thick boundary

Received May 22, 1963.