Wind-Tunnel Simulation of High-Altitude Rocket Plumes

James Stark Draper* and James P. Moran†
Aerodyne Research, Inc., Bedford, Mass.

Abstract

ROCKET plumes at altitudes above 150 km are among the largest man-made phenomena. As rocket speed and altitude increase, the description of plume features systematically varies from continuum through transitional to rarefied flow. Despite the vast size of these structures, this progressive rarefaction of high-altitude plumes can be reasonably simulated in the wind tunnel. The high-altitude regime is that region where the rocket body dimensions are small relative to the plume scale. In this region, vehicle Mach numbers are usually very supersonic. The fully continuum, high-altitude plume flowfield has been summarized in a model by Jarvinen and Hill.[1] The plume dimensional analysis has been developed by Moran.[2] The Jarvinen and Hill plume scaling has been put into nomogram form by Draper and Sutton.[3] Jarvinen and Hill based the scaling of their plume model upon the hypersonic plume scale L and the engine drag to thrust ratio D/F. Here, $L=\sqrt{F/q_\infty}$ where q_∞ is freestream dynamic pressure. In the Jarvinen and Hill model inviscid limit, freestream and exhaust gases would be separated by a contact surface. At high altitudes, a laminar mixing layer exists in which transport phenomena are important. The parameter controlling viscous plume features is a Knudsen number Kn_L based on plume scale L. The Kn_L values also indicate the extent to which the plume is in the transitional flow regime. Consequently, this Knudsen number is the major parameter in the wind-tunnel fluid-mechanical simulation of high-altitude rocket plumes.

Contents

The dominant simulation parameter for hypersonic rocket plumes at high altitudes is a Knudsen number based on the ratio of ambient gas mean free path to hypersonic plume scale, $Kn_L=\lambda_\infty/L$. Parameters of lesser importance are the engine drag to thrust ratio D/F, and ratios of rocket dimensions to plume scale.

Inviscid aerodynamic theory may accurately predict plume characteristics if the viscous shear layer, between exhaust and ambient gas, is thin compared to the distance from this layer to inner or outer shocks. Order-of-magnitude arguments of Hayes and Probstein[4] show that the thickness of this shear layer at the plume boundary is ordered as

$$\delta \doteq [\mu L/(\epsilon^{1/2}\rho u_\infty)]^{1/2}$$
$$= [(\mu/\mu_\infty)(\theta/\theta_\infty)(p_\infty/p)(L^2/\epsilon^{1/2})(Re_L)^{-1}]^{1/2} \quad (1)$$

where $\epsilon=(\gamma_\infty-1)/(\gamma_\infty+1)$ and μ, θ, and p are representative values of viscosity, temperature, and pressure in the shear layer. The plume Reynolds number Re_L is based on stream conditions and hypersonic plume sclae. The distance from the shear layer to the plume outer shock is typically

$$\Delta \doteq \epsilon L \quad (2)$$

By simple arguments based on the kinetic theory, Knudsen number is related to stream Reynolds number as

$$Kn_L \equiv \lambda_\infty/L \doteq M_\infty (Re_L)^{-1} \quad (3)$$

If the temperature dependence of viscosity is approximated by $\mu \propto \theta^{3/4}$ and if hypersonic shock relations are used to order pressure and temperature as

$$p/p_\infty \doteq M_\infty^2 \qquad \theta/\theta_\infty \doteq \epsilon M_\infty^2 \quad (4)$$

then the ratio of shear layer thickness to shock layer thickness becomes

$$\delta/\Delta \doteq \epsilon^{-3/8} Kn_L^{1/2} M_\infty^{1/4} \quad (5)$$

Continuum flow is assured if the ratio of plume mean free path λ to relevant flow dimensions is sufficiently small in all disturbed parts of the flowfield. Here, we consider the region between the bow shock and the shear layer where the appropriate ratio is λ/Δ. However, λ/λ_∞ is of the order of $\epsilon M_\infty^{1/2}$. Thus, with the preceding relations we obtain

$$\lambda/\Delta \doteq Kn_L M_\infty^{1/2} \quad (6)$$

For rockets climbing out of the atmosphere, it can be shown that M_∞ is not itself a major simulation parameter if it is sufficiently large to represent hypersonic flight. Typical flight Mach number profiles were derived for large rockets on climbing trajectories in the thermosphere. There results a relatively narrow range in Mach number (6 to 10) for the altitude range of interest. Consequently, the $M_\infty^{1/2}$ dependence of Eq. (6) can be ignored by comparison with the extremely broad range of variation of Kn_L through variation in ambient density.

Complete aerodynamic simulation of full-scale missile plumes requires equality in each nondimensional parameter which characterizes the flow. For hypersonic plumes, the freestream Mach numbers should exceed values of 6 to 8. For the D/F effects, nozzle thermodynamic efficiencies must be approximately matched. Nozzle boundary-layer effects must be simulated by matching the exit plane Knudsen number. Further rocket body size effects must be included and are discussed by Draper and Moran.[5,6]

A wind-tunnel test program designed to provide information on the viscous interaction between the freestream and the exhaust species has been carried out using the von Karman Facility's hypersonic tunnels, M and D, and 10V aerospace chamber. The measurements are reported by Smithson, Price, and Whitfield,[7] Price, Power, and Moskalik[8] for the 10V chamber, and by Norman, Kinslow, and Lewis[9] for tunnels M and D. The wind tunnel provided a supersonic freestream in which a coparallel secondary plume flow was introduced by a model rocket. The interaction

Received June 17, 1977; synoptic received Dec. 29, 1977; revision received Jan. 30, 1978. Full paper available from National Technical Information Service, Springfield, Va., 22151 as N78-17146 at the standard price (available upon request).

Index categories: Jets, Wakes, and Viscid-Inviscid Flow Interactions; LV/M Simulation; Environmental Effects.

*Principal Research Scientist, Applied Sciences Division. Member AIAA.

†Principal Research Scientist, Applied Sciences Division.

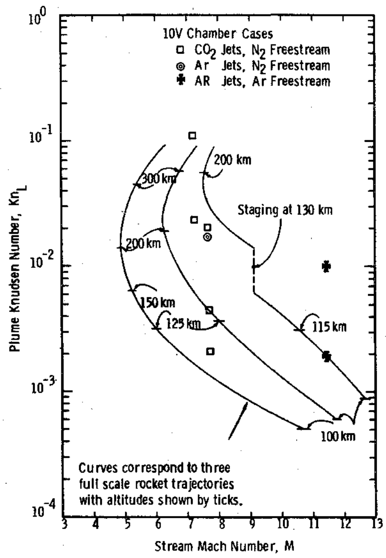

Fig. 1 Plume Knudsen numbers for rocket flight in the thermosphere and wind-tunnel tests.[7,8]

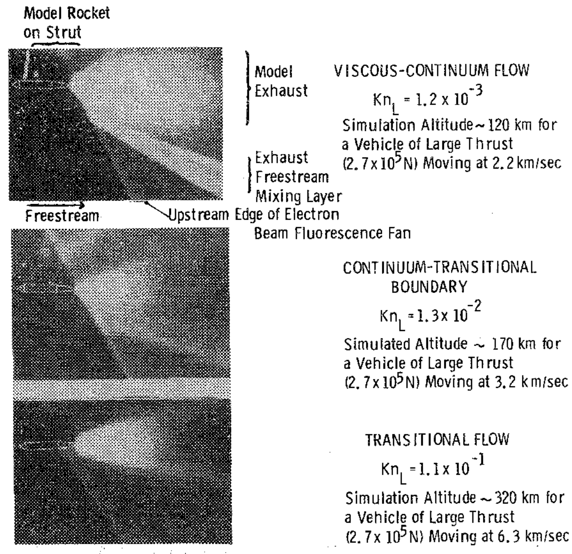

Fig. 2 Flow visualization photographs of model plumes in continuum and transitional flow regimes corresponding to a full-scale rocket of 2.68×10^5 N (6×10^4 lb) thrust, climbing an accelerating trajectory in the 1962 U.S. standard atmosphere.[10]

between the two flows was studied by pitot probe surveys and by electron beam fluorescence. Fluorescence was studied qualitatively with flow visualization photography and quantitatively with a filtered photomultiplier.

To examine the Kn_L simulation provided in these wind-tunnel tests, consider the range of Kn_L representative of rockets on climbing trajectories. For fixed thrust, this parameter varies as $\rho_\infty^{-1/2}$, where ρ_∞ is stream density. Over the altitude range from 100 to 300 km, Kn_L varies by a factor of 10^2. Flight plume Knudsen numbers are shown in Fig. 1 as a function of M_∞ for typical trajectories. A sampling of the wind-tunnel simulations[7-9] shows Knudsen numbers covering the range of interest for full-scale rocket flight.

It is significant that the entire Kn_L range of interest is covered by a single wind-tunnel facility (the 10V chamber) and a single model rocket.[7] By appropriate variations in model rocket pressure and tunnel pressure and temperature, a variation in Kn_L of a factor of 60 was achieved which corresponds to an altitude range from 125 to 330 km for representative vehicle and flight conditions. High Mach number flight at lower altitudes was achieved by use of Ar as the freestream gas. The strength and weaknesses of the various test simulations are discussed by Draper and Moran.[5,6]

An electron beam fluorescence technique was used for both flow visualization and density profile measurements.[8] Representative fluorescence photographs of the simulated plume cross sections are shown in Fig. 2. Photographs were selected to illustrate progressive stages of rarefaction in a simulation of a 2.7×10^5N thrust vehicle at progressively higher altitudes. The upper photograph corresponds to an altitude of 120 km and a plume Knudsen number of 1.2×10^{-3} and shows distinct outer and inner plume shocks. Associated density measurements show that viscous effects are important throughout the region between shocks. The middle photograph corresponds to an altitude of 170 km and a plume Knudsen number of 1.3×10^{-2}, and shocks are evident but less distinct. Density measurements show that these shocks do not satisfy Rankine-Hugoniot conditions. It is important to note that the geometrical features of the continuum-transitional plume are reasonably represented by the Jarvinen and Hill plume model,[1] even though the inviscid flow equations upon which that model is based are invalid for this range of Kn_L. The lower photograph corresponds to an altitude of 320 km and a plume Knudsen number of 1.1×10^{-1}. No shock waves are evident. Associated species density measurements show no discontinuities and a monotonic decrease in jet species density with increasing distance from the plume axis.

Measurements of this type can provide important information on the detailed nature of rarefaction in full-scale rocket plumes at high altitudes. Such measurements cannot practically be obtained in actual rocket flight. Furthermore, current calculational techniques are inadequate for describing such flows. Indeed, such measurements can provide tests of new calculation techniques. Therefore, it is important to realize the potential of such wind-tunnel simulation and of the precise degree of simulation achievable.

Acknowledgment

This work was sponsored by the Air Force Rocket Propulsion Laboratory under Contract No. F04611-72-C-0063, monitored by S. B. Thompson. The authors acknowledge valuable discussions with J. L. Kerrebrock of the Massachusetts Institute of Technology and Howard Baum of the National Bureau of Standards.

References

[1] Jarvin, P. O. and Hill, J.A.F., "Universal Model for Underexpanded Rocket Plumes in Hypersonic Flow," *Proceedings of the 12th JANNAF Liquid Propulsion Meeting*, Las Vegas, Nev., Nov. 1970.

[2] Moran, J. P., "Similarity in High Altitude Jets," *AIAA Journal*, Vol. 5, July 1967, pp. 1343-1345.

[3] Draper, J. S. and Sutton, E. S., "Nomogram for High Altitude Plume Structures," *Journal of Spacecraft and Rockets*, Vol. 10, Oct. 1973, pp. 682-684.

[4] Hayes, W. D. and Probstein, R. F., *Hypersonic Flow Theory*, Academic Press, New York, 1959.

[5] Draper, J. S. and Moran, J. P., "A Study of Wind Tunnel Simulation of High Altitude Rocket Plumes," Air Force Rocket Propulsion Lab., Director of Science and Technology, Air Force Systems Command, Edwards AFB, Calif., Tech. Rept. AFRPL-TR-111, Feb. 1973.

[6] Draper, J. S. and Moran, J. P., "Wind Tunnel Simulation of High Altitude Rocket Plumes," Aerodyne Research, Inc., Bedford Research Park, Bedford, Mass., ARI-RR-88, June 1977.

[7] Smithson, H. D., Price, L. L., and Whitfield, D. S., "Wind Tunnel Testing of Interactions of High Altitude Rocket Plumes with the Freestream," AEDC-TR-71-118, July 1971.

[8] Price, L. L., Powell, H. M., and Moskalik, R. S., "Species Number Density Measurements in Plume Interactions with Freestream Using an Electron Beam Technique," AEDC-TR-71-226, Nov. 1971.

[9] Norman, W., Kinslow, M., and Lewis, J. W., "Experimental Study of Simulated High Altitude Rocket Exhaust Plumes," AEDC-TR-71-25, July 1971.

[10] *1962 U.S. Standard Atmosphere*, Washington, D. C., 1962.