A High-Altitude Base Pressure Experiment

J. M. Cassanto*
General Electric Co., Phila., Pa.
and
J. W. Lane†
NASA Ames Research Center, Mountain View, Calif.

A high-altitude base pressure experiment has been successfully conducted by GE-RESD and NASA Ames on a high performance Air Force re-entry vehicle. Low Reynolds number laminar flow flight data were obtained at an altitude of ~248,000 ft. The experiment utilized the NASA Ames vibrating diaphragm transducer specifically designed to measure base pressure at altitudes in excess of 200,000 ft with a threshold sensitivity level of 0.0002 psia. The flight data has provided needed low Reynolds number information from $Re_L \approx 7\times10^4$ to 1×10^7. These new data verify that a "maximum" exists in the base pressure ratio versus Reynolds number curve at low Reynolds numbers and hypersonic Mach numbers ($M_\infty > 20$) in qualitative agreement with the theory of Crocco and Lees.

Introduction

RE-ENTRY vehicle (R/V) flight test base pressure data have been unavailable at high altitudes (low Reynolds number) in moderately rarefied laminar flow due to limitations on commercially available low range flight pressure transducers. The lowest range flight pressure sensors generally available have been 0 to 0.10 psia sensors operating on the capacitance and reluctance principles. The highest altitude that these sensors have provided base pressure data on slender cones is believed to be ~180,000 ft ($R_{e_L} \sim 4\times10^5$) where the sensors were registering ~10% of full scale of the sensor range. The purpose of this paper is to describe the results of a joint GE/NASA high-altitude base pressure experiment[1,2] which consisted of flying the NASA Ames low range vibrating diaphragm pressure transducer on a GE/USAF high performance re-entry vehicle to extend the existing laminar flow data base to higher altitudes and low Reynolds number. The NASA pressure transducer utilized in this flight experiment had a threshold sensitivity level of ~0.0002 psia which resulted in data being obtained at an altitude of ~248,000 ft. ($R_{e_L} \approx 7\times10^4$).

Instrumentation and Preflight Calibration

The vibrating diaphragm pressure transducer was developed by the Instrument Division of the NASA Ames Research Center and operates on the gas damping principle.[3,4] The transducer can measure pressures over a wide range, and tests have been conducted under laboratory conditions in which the sensor has measured pressures from 10^{-4} to 10^4 torr (~2×10^{-6} to 50 psia), eight orders of magnitude. The vibrating diaphragm transducer is considered to be extremely accurate and is characterized by a small error which is proportional to the pressure being measured, rather than the full scale of the instrument which is the case of commerically available flight pressure sensors.

The sensor was located in the aft portion of the re-entry vehicle and was connected to the base pressure port by metallic tubing designed and fabricated by NASA Ames to minimize time lag effects. Theoretical calculations using the tubing geometry indicated that time lag effects would be negligible. Subsequent re-entry pressure simulations during the preflight calibration tests of the sensor with a quick response pressure sensor "T" taped to the base pressure port showed that time lag effects due to the tubing were, in fact, negligible.

The transducer flown on the present flight experiment was sized to provide a range from 0.0002 to 0.05 psia and 0.0002 to 2.0 psia on two independent channels providing 0–5.0 V outputs. The present flight experiment utilized only the low range channel to obtain laminar flow data at high altitudes. The flight prototype transducer was subjected to a detailed series of flight qualification environmental tests. The prime flight unit was calibrated several times at NASA Ames thoughout the range of the sensor $P = 0.0002$ to 2.0 psia at various temperatures. The prime sensor was found to be extremely stable and repeatable. A nominal calibration curve through the component test data (open symbols) is shown in Fig. 1.

In keeping with good flight test procedures, the sensor was subjected to a detailed preflight calibration through the R/V telemetry system at the GE field site to insure accurate, reliable flight data. Results of the preflight calibration field test (closed symbols) are compared with the component test (open symbols) in Fig. 1 and show excellent agreement. Details of the NASA vibrating diaphragm transducer, internal tubing geometry and port details of the R/V, and preflight calibration procedures can be found in Refs. 1 to 4.

Flight Vehicle/Flight Conditions

The present experiment was conducted on a high performance re-entry vehicle slender cone having a flat base. The base pressure port for the experiment was located at the center of the base. An ablative type forebody heat shield was utilized which had low mass addition rates during the data taking period (average $\dot{m}/\rho A V \approx 0.007$). Onboard thermal instrumentation established that the R/V had a laminar boundary layer during the experiment. The R/V had a slight angle of attack at the initiation of the first base pressure data point, $R_{e_L} \approx 7\times10^4$; however, the α damped down to very small values (<0.5°) during the higher Reynolds number portion of

Presented as Paper 75-151 at the AIAA 13th Aerospace Sciences Meeting, Pasadena, Calif., Jan. 20-22, 1975; submitted Feb. 20, 1975; revision received Dec. 8, 1975. The authors would like to gratefully acknowledge the assistance of A. Seiff and J. Dimeff of NASA Ames and T. Blanco and F. Giantforte of GE RESD for their support of this flight experiment.

Index categories: Jets, Wakes, and Viscid-Inviscid Flow Interactions; LV/M Flight Testing.

*Project Engineer, Re-entry Systems Dept. Member AIAA.

†Instrumentation Engineer, NASA Ames Instrument Division.

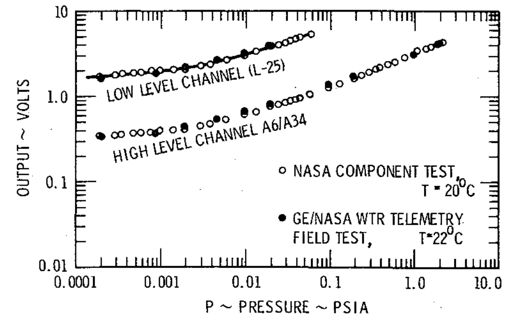

Fig. 1 Calibration data for NASA AMES vibrating diaphragm pressure transducer.

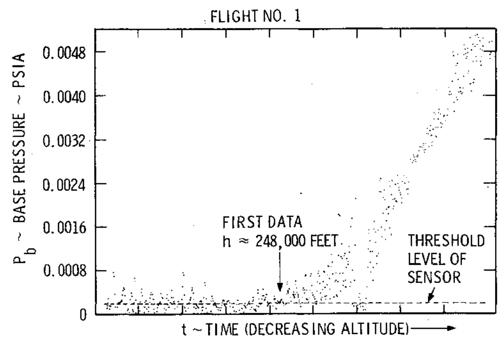

Fig. 2 Raw base pressure data history showing first indication of high altitude data.

the flight $R_{e_L} \approx 4 \times 10^6$. The Mach number during the laminar data period was in excess of $M_\infty = 20$.

R/V Flight Data Results

First Data

A detailed time history of the high-altitude pressure data was plotted (Fig. 2) to determine the altitude of "first data." The dashed line represents the threshold sensitivity level of the pressure sensor and the flight data can be seen to diverge from this level at an altitude of approximately 248,000 ft.

It is significant to note that the pressure transducer indicated its lowest threshold sensitivity level ($P = 0.0002$ psia) prior to re-entry ($h \sim 248{,}000$ ft) thus providing an "over the top" vacuum reference check point. This reference check is a standard R/V flight test evaluation technique procedure that provides a good indication that the pressure measurement system is operating properly and will provide valid data. The high altitude data point obtained at 248,000 ft is unique, and is believed to represent the highest altitude base pressure data ever obtained on a slender cone re-entry vehicle.

Data Reduction Technique

The reduced flight data to be presented are based on a representative sampling of the raw pressure data. In choosing a typical data point, the authors tried to utilize the criterion of choosing data points where the pressure stayed relatively constant at some nominal value for several data samples. The spread on the data reflects the maximum and minimum pressure oscillation values around the data point. Many of the data points are biased to the upper or lower levels of the spreader bars.

The reduced data points in the form of base pressure ratio (P_b/P_∞) plotted vs freestream Reynolds numbers are shown in Fig. 3 with uncertainty bars which reflect pressure oscillations of the raw data. Note that at low Reynolds numbers, $Re_L \sim 1 \times 10^5$ (high altitude), the spreader bars are large and encompass factors of two on the data points. However, at higher Reynolds numbers $Re_L \sim 1 \times 10^6$ to 1×10^7, the oscillations of the pressure data damp down, consequently, the uncertainty spreader bars are smaller.

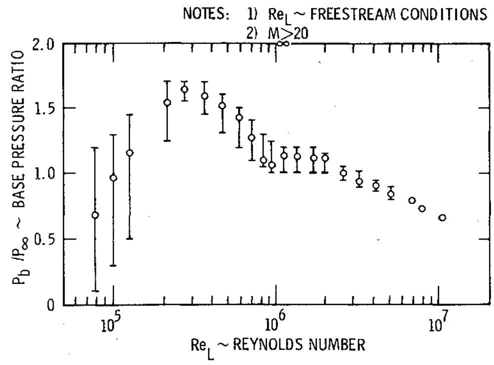

Fig. 3 Reduced base pressure ratio data plotted vs. Reynolds number with uncertainty limits.

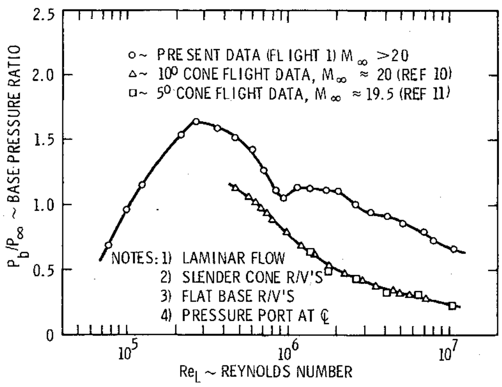

Fig. 4 Flight data comparison: Base pressure ratio vs Reynolds number.

Data Trends

The most striking feature of the data presentation of Fig. 3 is the maximum in base pressure ratio (P_b/P_∞) at $Re_L \sim 2.6 \times 10^5$ with a decreasing pressure ratio for higher or lower Reynolds numbers. This "maximum" trend was qualitatively predicted many years ago by Crocco and Lees[5] and has been verified by low Mach number ($M_\infty \approx 3$) ground test data by Kavanau[6] and Van Hise[7]. However, the present data represent the first verification of this maximum, to the author's knowledge, at truly hypersonic Mach numbers ($M_\infty > 20$). It should be noted that the "maximum" trend at low Reynolds numbers evident in the present data has a high degree of confidence due to the accuracy/repeatability of the flight pressure transducer and the preflight calibration procedures. The maximum which occurs at $Re_L \sim 2.6 \times 10^6$ represents an absolute base pressure level ($\sim 10^{-3}$ psia) which is an order of magnitude greater than the threshold sensitivity level ($\sim 10^{-4}$ psia) of the flight pressure transducer. In addition, the base pressure maximum observed in the flight data was obtained by utilizing approximately $\sim 1/2$ the range of the low level telemetry channel calibration curve (Fig. 1), which also increases the confidence level of the flight measurement.

Another interesting feature of the present data (Fig. 3) is that they contain a "flat" region between $Re_L \sim 1 \times 10^6$ to 2×10^6. This region is characterized by the only trajectory regime where the freestream Mach number is a constant. Since base pressure is a strong function of both Mach number and Reynolds number in laminar flow, the "flat" portion of the base pressure data is believed to be related to the fact that the Mach number reaches a constant minimum during this time period. The difference in slope of the P_b/P_∞ vs Re_L curve prior to, and subsequent to, the "flat" (at $Re_L \sim 1 \times 10^6$) is believed to be due to combined effects of Mach and Reynolds numbers. This "flat," or plateau, region has not been observed previously by the senior author in GE R/V flight data, or by other active investigators such as Bulmer.[8] with the exception of recent TRW flight data by Batt[9] which have indicated a discontinuity in the Pb/P_∞ vs Re_L curve in the same approximate Reynolds number range ($\sim 1 \times 10^6$).

Flight Data Comparisons

The present flight results are compared with two other sets of flight data. Although a large amount of flight test base pressure data are available, much of the data are classified and are for configurations and/or heat shields basically different than the present experiment. The criteria utilized for the present comparison were simply: a slender cone R/V forebody configuration, a base pressure measurement at the centerline of the base, a flat base configuration having no dome aft body or rounded shoulder, trajectory flight conditions which insured laminar flow and low angles of attack, and finally, low mass addition rates ($<1\%$) from the heat shield.

The two sets of R/V flight data[10,11] available for comparison (shown in Fig. 4) are for 5° and 10° sharp cones. Both of these R/V's employed a nonablative heat sink/heat shield resulting in zero mass addition during the data taking period. Both R/V's utilized 0 to 0.1 psia low range variable reluctance pressure transducers with ports at the center of the base (flat base). The Mach number histories for these two flights were very similar ($M_\infty \approx 20$). The 5° and 10° cone flight data are in excellent agreement with each other, indicating negligible cone angle effects in laminar flow for these two sets of flight data. The present flight data: a) extend to a lower Reynolds number (10^4) than the baseline 5° and 10° cone flight data, and b) show the existence of the maximum in base pressure ratio at $Re_L \approx 2.6 \times 10^6$.

It is clear from the comparison plot of Fig. 4 that the present flight results are higher than both the 5° and 10° cone baseline data. This is the expected trend and may be due solely to Mach number effects or a combination of Mach numbers, nose bluntness ratio, and mass addition effects. First, the Mach numbers history for the present flight experiment is significantly higher than the base line data. It has been shown from both flight data[12] and data correlations[13] that base pressure ratio increases significantly with increasing Mach numbers in supersonic flow. In addition, NASA flight test data from the Project FIRE program[14] show a drastic increase in base pressure ratio for $M_\infty > 15$. These NASA data show in creases in Pb/P_∞ from a factor of three to a factor of ten by doubling the Mach number to $M_\infty \approx 30$. The NASA data are for a blunt Apollo forebody configuration, but the trend of the present flight experiment is substantiated.

Second, the R/V in the present experiment has a higher bluntness ratio (approximately twice) than that of the base line R/V data. The ground test data and correlations of Cassanto,[15,16] Martellucci,[17,18] Softley,[19,20] and Lochman[21] all show the same trend of increasing base pressure ratio with increasing bluntness in laminar flow.

Third, the R/V in the present flight experiment utilized an ablative heat shield while the base line data are for R/V's that utilized heat/sink heat shields and produced no mass addition. The ablative heat shield in the present experiment produced mass addition to the boundary layer and tends to increase the base pressure slightly in laminar flow. The preceding three effects: Mach number, bluntness ratio, and mass addition, qualitatively explain why the present flight data are higher than the base line data. The differences in the slopes of the P_b/P_∞ vs Re_L curves between the present experiment and the base line data can be explained by the fact that the base line data have a constant Mach number ($M_\infty \approx 20$) and the decreasing base pressure ratio with increasing Reynolds number reflects Reynolds number effects only. The present R/V flight experiment data have a varying Mach number history and, hence, a varying slope (and discontinuities) of the P_b/P_∞ curve as explained in the previous section.

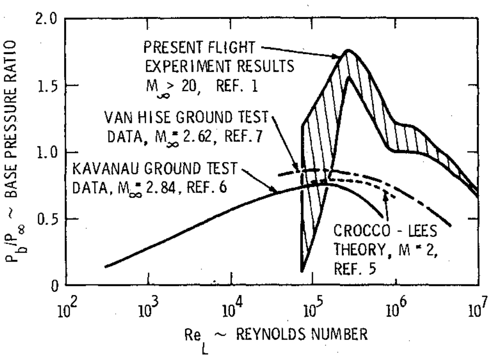

Fig. 5 Ground data comparison: Base pressure ratio vs Reynolds number.

Ground Data Comparisons

The present flight data envelope is compared with the low Reynolds number base pressure theory/data by Crocco and Lees,[5] Kavanau,[6] and Van Hise[7] in Fig. 5. Although more recent sharp cone ground test base pressure data are available for $Re_L \approx 10^5 \sim 10^6$, none are available for extremely low Reynolds number, $Re_L \sim 10^4$ to 10^5, the regime in which the Pb/P_∞ maximum occurs.

The data from the present flight experiment clearly show that the hypersonic ($M_\infty > 20$) low Reynolds number trend is to reach a maximum at $Re_L \approx 2.6 \times 10^5$ and then decrease with decreasing Reynolds number in qualitative agreement with the theory of Crocco and Lees[5] and the ground test data of Kavanau[6] and Van Hise.[7] It is also significant to note that the maximum in the present flight data occurs very close to the values of $Re_L \sim 1$ to 2.5×10^5 observed in earlier works.

The "maximum" in low Reynolds number base flow has been suggested by Crocco and Lees[5] to be the result of a "critical point" in the wake flowfield. The basic mechanism has to do with the transition point. As the transition point (between laminar and turbulent flow) moves from the far wake to the critical point, the base pressure ratio increases with increasing Reynolds number. When transition lies between the "critical point" and the base of the R/V, the base pressure ratio decreases with increasing Reynolds number as a direct result of differences in the mixing rates between laminar and turbulent flow. Accordingly, a "maximum" would exist between these two flow regimes.

Kavanau[6] suggested in his paper that the maximum might be due to the transition from free molecular flow to continued flow but later discarded this hypothesis. *Sufficient data do not exist from the present flight experiment to evaluate the precise cause of the maximum in the P_b/P_∞ vs Re_L curve.* This flight experiment has clearly established that the base pressure ratio "maximum" does indeed exist at low Reynolds numbers. Subsequent experiments will be required to establish the mechanism.

Conclusions

A high altitude base pressure experiment has been conducted and low Reynolds number laminar flow flight data were obtained at an altitude of $\sim 248{,}000$ ft. This extended the range of the available laminar flow low Reynolds number data bank to $Re_L \sim 7 \times 10^4$. The flight experiment utilized a high accuracy vibrating diaphragm pressure transducer specifically designed by NASA Ames to measure base pressures at altitudes in excess of 200,000 ft with a threshold sensitivity level of 0.0002 psia. Laminar flow base pressure ratio data were obtained at hypersonic Mach numbers ($M_\infty > 20$) from a Reynolds number range from $Re_L \sim 7 \times 10^4$ to 1×10^7.

Low Reynolds number base pressure characteristics from the flight experiment were found to exhibit a "maximum" in the base pressure ratio vs Reynolds number curve (at $Re_L \sim 2.6 \times 10^5$) in qualitative agreement with the theory of Crocco and Lees[5] and the low Mach number data ($M_\infty \approx 3.0$) of Kavanau[6] and Van Hise.[7] The base pressure ratio then decreases with decreasing Reynolds number ($Re_L < 2.6 \times 10^5$) and decreases with increasing Reynolds number ($Re_L > 2.6 \times 10^5$). The present flight experiment represents the first hypersonic ($M_\infty > 20$) data to verify the existence of the P_b/P_∞ "maximum" trend in flight at low Reynolds numbers based on an ultra low range, highly accurate flight pressure measurement system.

References

[1]Cassanto, J. M., "The GE/NASA High Altitude Base Pressure Experiment: A Progress Report, Flight 1," General Electric Co., Re-Entry and Environmental Systems Division, Phila. Pa., ALDM No. 71-111, Aug. 1971.

[2]Cassanto, J.M. and Lane, J.W., "A High Altitude Base Pressure Experiment" AIAA Paper 75-151, Pasadena, Calif. Jan. 20-22, 1975.

[3]Dimeff, J., Lane, J. W., and Coon, G. W., "New Wide Range Pressure Transducer," *Review of Scientific Instruments,* Vol. 33, 1962, p. 804.

[4]Dimeff, J., Lane, J. W., Deboo, G. J., and Hedlund, R.C., "A Vibrating Diaphragm Pressure Measurement System," *ISA Proceedings 15th National Aerospace Symposium,* May 1969.

[5]Crocco, L., and Lees, L., "A Mixing Theory for the Interaction Between Dissipative Flows and Nearly Isentropic Streams," *Journal of the Aeronautical Sciences,* Vol. 19, Oct. 1952, pp. 649-676.

[6]Kavanau, L. L., "Base Pressure Studies in Rarefield Supersonic Flows," *Journal of the Aeronautical Sciences,* Vol. 23, March 1956, pp. 193-207.

[7]Van Hise, V., "Investigation of Variation in Base Pressure Over the Reynolds Number Range in Whick Wake Transition Occurs for Nonlifting Bodies of Revolution at Mach Number from 1.62 to 2.62," NACA TN 3942, Jan. 1967.

[8]Batt, R. G., "Flight Test Base Pressure Results for Sharp 8° Cones," *AIAA Journal,* Vol. 12, April 1974, pp. 555-557.

[9]Bulmer, B. M., "Correlation of Re-entry Base Pressure in Laminar Hypersonic Flow," Sandia Laboratories, Alburquerque, N.M., Report SLA-74-0169, Aug. 1974.

[10]Cassanto, J. M., "Radial Base Pressure Gradients in Laminar Flow," *AIAA Journal,* Vol. 5, Dec. 1967, p. 2278-2279.

[11]Dillon, J. L., "Analysis of Base Pressure and Base Heating on a 5 Deg. Half-Angle Cone in Free Flight Near Mach 20 (Re-entry F)," NASA TMX-2468, Jan. 1972.

[12]Cassanto, J. M., "Flight Test Base Pressure Results at Hypersonic Mach Numbers and High Reynolds Numbers in Turbulent Flow: Implications to Ground Test Simulation Requirements," General Electric Co., Philadelphia, Pa., GE RESD TIS 71SD200, Jan. 1971.

[13]Cassanto, J. M., "The Effect of Cone Angle and Bluntness Ratio on Base Pressure," *AIAA Journal,* Vol. 3, Dec. 1965, pp. 2351-2352.

[14]Slocumb, T. H., Jr., "Project FIRE Flight II Afterbody Temperatures and Pressures at 11.35 Kilometers per second (37,200 feet per second)," NASA TMX-1319, Dec. 1966.

[15]Cassanto, J. M., "Base Pressure Results at $M=4$ Using Free Flight and String-Supported Models," *AIAA Journal,* Vol. 6, July 1968, pp. 1411-1414.

[16]Cassanto, J. M., "A Semi Empirical Technique for Approximating the Base Pressure of Sphere Cone Configuration in Laminar Flow at Hypersonic Mach Numbers," General Electric Co., Philadelphia, Pa., GE ATFM 67-06, Feb. 1967.

[17]Martellucci A. and Raulet J., "Experimental Study of Near Wakes: Data Presentation," General Applied Science Labs., N.Y.C., GASL TR 641, March 1967.

[18]Martellucci, A., "Laminar Base Pressure Correlation," General Electric Co., Philadelphia, Pa., GE ATC 67-13, March 1967.

[19]Softley, E. J., et. al. "Techniques for Low Level Pressure and Heat Transfer Measurements and Their Application to Base Flow," General Electric Co., King of Prussia, Pa., GE TIS 67SD2, March 1967.

[20]Muntz, P. and Softley E. "A Study of Laminar Near Wakes," *AIAA Journal,* Vol. 4, June 1966, pp. 961-975.

[21]Lockman, W. K., "Free Flight Base Pressure and Heating Measurements on Sharp and Blunt Cones in a Shock Tunnel," *AIAA Journal,* Vol. 5, Oct. 1967, pp. 1898-1900.