generality of the proposed function and the acceleration effects on the coefficients.

References

[1] Brinich, P. F. and Neumann, H. E., "Some Effects of Acceleration on the Turbulent Boundary Layer," *AIAA Journal*, Vol. 8, No. 5, May 1970, pp. 987–989.

[2] Boldman, D. R., Schmidt, J. F., and Gallagher, A. K., "Laminarization of a Turbulent Boundary Layer as Observed from Heat-Transfer and Boundary-Layer Measurements in Conical Nozzles," TN D-4788, 1968, NASA.

[3] Boldman, D. R., Neumann, H. E., and Ehlers, R. C., "Velocity, Intermittency, and Turbulence Intensity Measurements in the Boundary Layer of an Accelerated Flow," proposed TN, NASA.

[4] Bradbury, L. J. S., "A Simple Circuit for the Measurement of the Intermittency Factor in a Turbulent Flow," *The Aeronautical Quarterly*, Vol. 15, No. 3, pp. 281–284.

[5] Corrsin, S. and Kistler, A. L., "Free-Stream Boundaries of Turbulent Flows," TN 3133, 1954, NACA.

Condensation in a Contoured-Nozzle Shock Tunnel

R. L. Varwig* and S. B. Mason†
The Aerospace Corporation, El Segundo, Calif.

I. Introduction

ONE of the limiting conditions for a wind tunnel is established by the phenomenon of condensation. This occurs when the decreasing pressure and temperature of the expanding flow reach or exceed the air saturation "values." Therefore, for a given reservoir pressure there exists a minimum reservoir temperature necessary to prevent condensation and, hence, preserve the isentropic relationship required to obtain meaningful data. This required temperature has been shown to be somewhat below the theoretical prediction[1] for high Mach number because of an apparent supersaturation.[2–4]

Daum and Gyarmathy[3] have presented extensive data and empirical predictions for the degree of supersaturation possible in a blow-down type wind tunnel. They have shown that condensation at low pressures (<0.1 mm Hg) follows the predictions based on spontaneous nitrogen condensation, and that at higher pressures the seeding effects of small amounts of H_2O and CO_2 condensing earlier influence the onset of condensation. On the basis of these results Daum and Gyarmathy have devised a conservative formula for predicting the occurrence of condensation in wind-tunnel nozzles. The difficulty with using the formula is that in the pressure range where seeding is dominant, the experimental data are quite scattered. Therefore, although the work of Daum and Gyarmathy may serve as a reliable guide, the condensation measurements must be made in order to accurately determine the extent to which one may supercool the flow in a particular nozzle that lies in the above pressure range.

In this study the condensation point in a contoured nozzle shock tunnel was sought. Static and Pitot pressure, which have been shown to be sensitive to the onset of condensation were measured at constant reservoir pressure, while the reservoir temperature was decreased to obtain freestream temperatures below the theoretical saturation curve of Ref. 4. This report describes these measurements and their interpretation, which indicate that only little supercooling can be obtained.

II. Facility and Measurements

The Aerospace Corporation contoured nozzle shock tunnel with throat sized to produce Mach number 14.5 was used in these tests. Reservoir pressure and shock Mach number were measured with two model 601H piezoelectric pressure gages (Kistler Instrument Corporation, Clarence, New York) positioned near the end of the 24-ft driven section. The test section measurements were made with two Pitot probes positioned on each side of a static pressure probe (Fig. 1). The static pressure probe was instrumented with two Aerospace Corporation piezoelectric pressure gages‡ mounted in tandem 29 in. and 31.5 in. aft of the sharp nose. The Pitot probes were instrumented with model LC 60 piezoelectric pressure gages (Atlantic Research Corporation, Alexandria, Va.).

Two reservoir pressure ranges were studied—the lower obtained with 5000 psi in the driver and the higher with 10,000 psi in the driver.

The requirement that the shock tube remain tailored while the reservoir temperature was varied placed constraints on the driver gas sound velocity, which was, therefore, altered by adding argon to the helium driver gas. Thus as shock Mach number M_s was reduced from 3.98 to 2.49, the diaphragm pressure ratio p_4/p_1 was reduced from 340 with pure helium to 57 with the helium diluted with 7.5% argon. Some "equi-

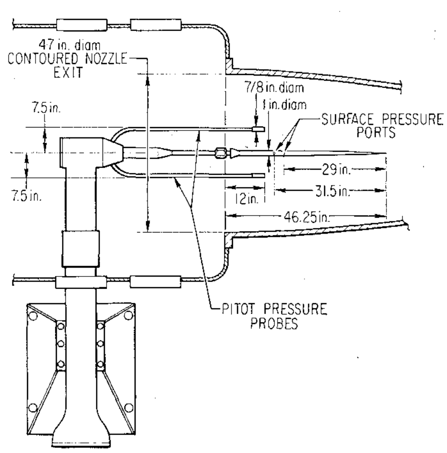

Fig. 1 Instrument installation.

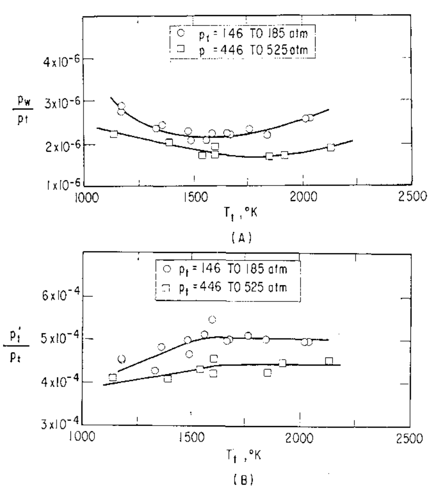

Fig. 2 Effect of condensation on measured pressure; A) static pressure, B) Pitot pressure.

Received June 1, 1970.

* Member of the Technical Staff. Member AIAA.

† Member of the Administrative Staff.

‡ L. Rosenman, U.S. Patent 3-181-016 (April 1965).

librium interface" conditions were tolerated in order to obtain the desired range of reservoir temperatures.

The wall pressure measurements p_w for the two positions on the static probe were equal (±3%), as were the two Pitot pressures p_t'. p_w was taken as the average value between the two static pressure measurements; p_t' was taken as the average value between the Pitot measurements. The reservoir pressure p_t was measured over the same time interval as the Pitot and static measurements. M_s was determined from a measurement of the time interval between passage of the shock wave past the two shock tube gages positioned 0.8225 ft apart. The arrival signals were recorded through a differential amplifier on a single trace to eliminate scope chopping error. A time-mark generator was used to record the time history to eliminate any error caused by distortion in the camera or oscilloscope sweep.

The reservoir temperature was calculated from the shock Mach number. Adiabatic corrections were made where off-tailoring caused a slight increase in reservoir pressure above the initial reflected shock pressure. All calculated flow conditions were made from the ratio p_t'/p_t, with appropriate corrections for caloric and compression imperfections.[1]

The measured Pitot and static pressure are normalized with respect to the reservoir pressure in Figs. 2 and 3. The onset of condensation was considered to be the point at which the measured pressure departed from its trend as the reservoir temperature was decreased.

III. Results and Conclusions

From Fig. 2a it is seen that as the reservoir temperature is decreased the measured wall pressure decreases steadily until the temperature reaches about 1570°K for $p_t \sim 170$ atm and 1770°K for $p_t \sim 500$ atm. The point where a clear reversal in the trend is noted is considered to be the point where condensation begins. The observed downtrend in p_w is a viscous effect that can be predicted by considering the effect of decreasing temperature on the tunnel wall boundary-layer thickness and the boundary-layer growth, and hence, the effect of pressure interaction on the static pressure probe. For decreasing temperature, the tunnel wall boundary layer, calculated from Ref. 5, decreases, resulting in increased M_∞, for which the pressure decreases. The pressure interaction on the slender pressure probe[6] decreases as the temperature decreases. Therefore, the pressure on the wall of the probe also decreases. For a reservoir temperature decreasing from 2040°K to 1560°K at a reservoir pressure of 170 atm, the effect of the tunnel wall boundary-layer change and the effect of the change in the pressure interaction on the slender probe are −9% and −7% respectively. The sum of these two effects equals the 16% pressure drop observed. The trend for the higher reservoir pressure range is similarly well predicted.

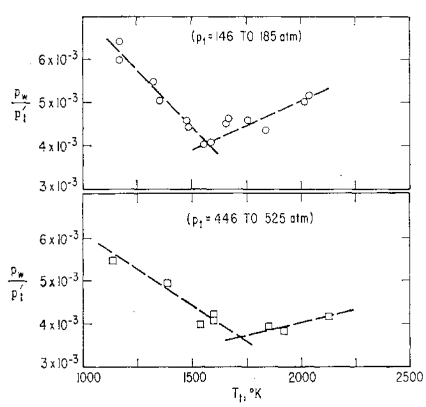

Fig. 3 Effect of condensation on p_w/p'_t.

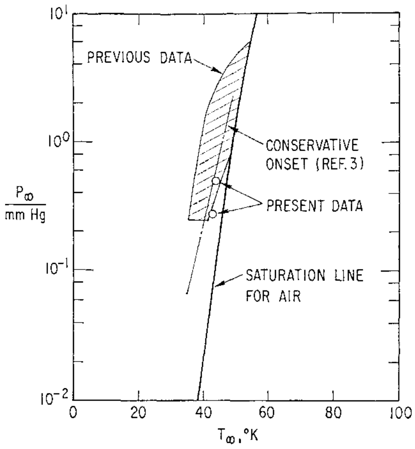

Fig. 4 Comparison of prediction from Ref. 3 with measurements.

The Pitot pressure in Fig. 2b also indicates a change in the trend as reservoir temperature is reduced, however, it is not as apparent nor in the same direction as that indicated by Daum.[4] When the ratio of measured pressures p_w/p_t' is plotted vs the reservoir temperature (Fig. 3), the point at which condensation begins is very marked. The difference between the Pitot pressures observed in this study and in that of Ref. 4 may be attributed to the shape of the Pitot probe body. In the present study, the Pitot probe consists of a large-diameter body relative to the diameter of the port (9/1 ratio) leading to the pressure sensing device. Hence, a strong normal shock exists forward of the port and significant re-evaporation may occur, as indicated by Pope,[7] rendering the Pitot measurement relatively less sensitive to the presence of condensation.

By calculating the freestream temperature, including caloric and compressive imperfection, a plot of p_∞ as a function of T_∞ can be obtained (Fig. 4) to be compared with the measurements and predictions of Daum and Gyamarthy.[3] This figure shows that the data representing the onset of condensation for the two driver pressure conditions of this study fall between the theoretical saturation curve for air and the anticipated supercooling. This difference is small, however. The shaded region of the figure represents the spread in data previously reported for contoured nozzles.[3] This scatter in data made it necessary to perform the measurement. The conservative temperature predictions were actually only 1 to 2° different from those measured.

References

[1] Erickson, W. D. and Creekmore, H. S., "A Study of Equilibrium Real-Gas Effects in Hypersonic Air Nozzles, Including Charts of Thermodynamic Properties for Equilibrium Air," TN D-231, April 1960, NASA.

[2] Stever, H. G., "Condensation Phenomena in High Speed Flows," *Fundamental of Gas Dynamics, Vol. III, High Speed Aerodynamics and Jet Propulsion*, edited by H. W. Emmons, Princeton Univ. Press, Princeton, N. J., 1958, pp. 526–572.

[3] Daum, F. L. and Gyarmathy, G., "Condensation of Air and Nitrogen in Hypersonic Wind Tunnels," *AIAA Journal*, Vol. 6, No. 3, March 1968, pp. 458–465.

[4] Daum, F. L., "Air Condensation in a Hypersonic Wind Tunnel," *AIAA Journal*, Vol. 1, No. 5, May 1963, pp. 1043–1046.

[5] Burke, A. F. and Bird, K. D., "The Use of Conical and Contoured Nozzles in the Hypervelocity Facilities," *Proceedings of the 2nd Symposium on Hypervelocity Techniques*, Univ. of Denver, Denver, Colo., March 1962, pp. 379–390.

[6] Ellinwood, J. W. and Varwig, R. L., "A Pressure-Interaction Theory for Axisymmetric, Hypersonic, Laminar, Unseparated Flows," *AIAA Paper 70-183*, New York, Jan. 1970.

[7] Pope, A., *Wind Tunnel Testing*, 2nd ed., Wiley, New York, 1954, p. 493.