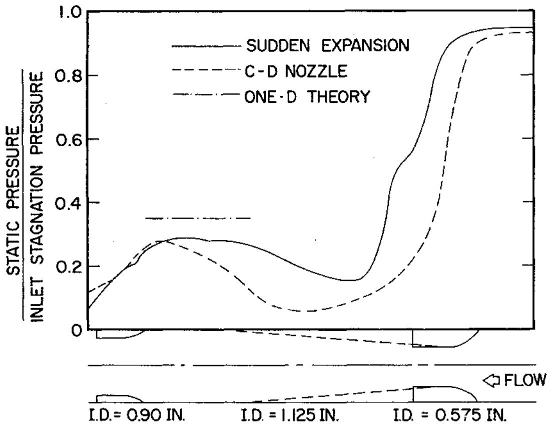

Fig. 2 Comparison of a sudden expansion and a convergent-divergent nozzle with a medium back pressure.

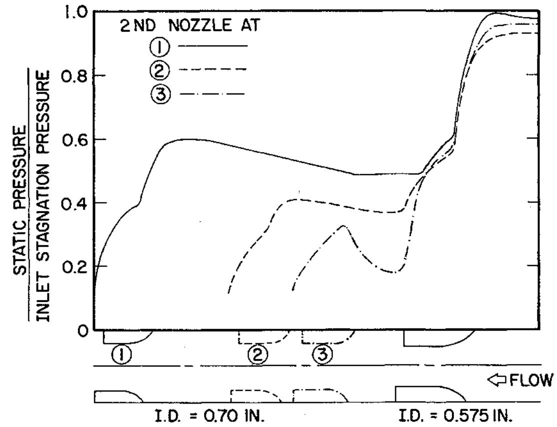

Fig. 4 Effect of the location of the second nozzle.

nozzle. This corresponds to the flow field that one computes by applying the method of characteristics to the sudden expansion.

The resemblance of the flow behind a sudden expansion to a convergent-divergent nozzle is further illustrated in Figs. 2 and 3. To increase the back pressure, a second nozzle was placed approximately 8 diam downstream from the primary nozzle. Simple one-dimensional theory postulates that, to maintain choked flow in both nozzles, the product of nozzle area and stagnation pressure must remain a constant. Both the convergent-divergent nozzle and the sudden expansion approximate this simple rule as illustrated by the measured centerline pressures taken far downstream from the exit plane. The convergent-divergent nozzle follows the theoretically predicted characteristic. In the divergent portion, the flow is initially supersonic, it passes through a series of normal shock waves which take the place of a single normal shock because of boundary-layer interaction,[2] and the shock waves are followed by a subsonic diffusion. The strength and position of the normal shock are determined by the stagnation pressure loss necessary to match the choked flow conditions at the downstream throat. The flow field behind the sudden expansion achieves the same pressure level prior to the second nozzle. Near the exit plane, the expansion and recompression by expansion and compression waves are evident. The expansion characteristics of the wave pattern are determined by the back pressure so that the over-all stagnation pressure loss is identical to the stagnation pressure loss that is achieved by the normal shock wave pattern in the convergent-divergent nozzle.

The second nozzle must be located downstream well beyond the first expansion wave and wall reflection pattern. If the second nozzle is moved closer, for example, within 2 to 4 nozzle diam, then the second nozzle interferes with the primary expansion wave pattern and produces a significantly different flow field. This phenomena is illustrated in Fig. 4 where the centerline pressure is plotted for tests with the second nozzle at different locations relative to the exit plane of the first nozzle.

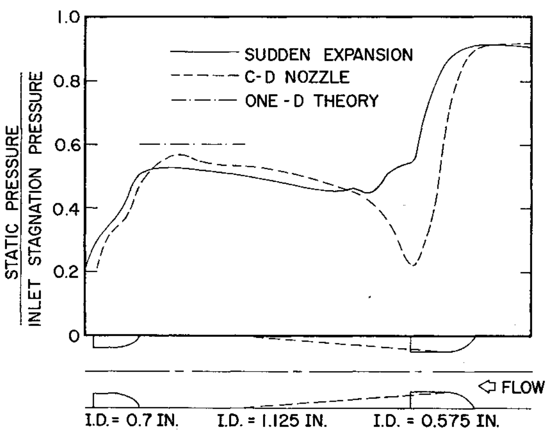

Fig. 3 Comparison of a sudden expansion and a convergent-divergent nozzle with a high back pressure.

These experiments confirm that the sudden expansion of a bounded jet achieves approximately the same pressure level and, therefore, Mach number, as if the jet were expanded in a convergent-divergent nozzle. A longitudinal distance of 8 nozzle diam is sufficient to establish a relatively uniform flow field. The flow field immediately behind the sudden expansion from the nozzle diameter to the duct diameter resembles the flow field immediately behind an underexpanded nozzle in free air.

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Condensation Studies in Hotshot Tunnels

B. J. Griffith,* H. Eugene Deskins,† and H. R. Little‡
ARO, Inc., Arnold Air Force Station, Tenn.

Introduction

A NUMBER of studies has been made to determine the influence of air condensation on the stream-pressure characteristics and to establish the degree of supersaturation which may be obtained. The most recent work, reported by Daum[1] and Dayman,[2] extends the earlier studies into the

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* Supervisor, Aerodynamics Section, Hypervelocity Branch, von Karman Gas Dynamics. Facility Member AIAA.

† Project Engineer, Aerodynamics Section, Hypervelocity Branch, von Karman Gas Dynamics Facility.

‡ Project Engineer, Aerodynamics Section, Hypervelocity Branch, von Karman Gas Dynamics Facility Associate. Member AIAA.

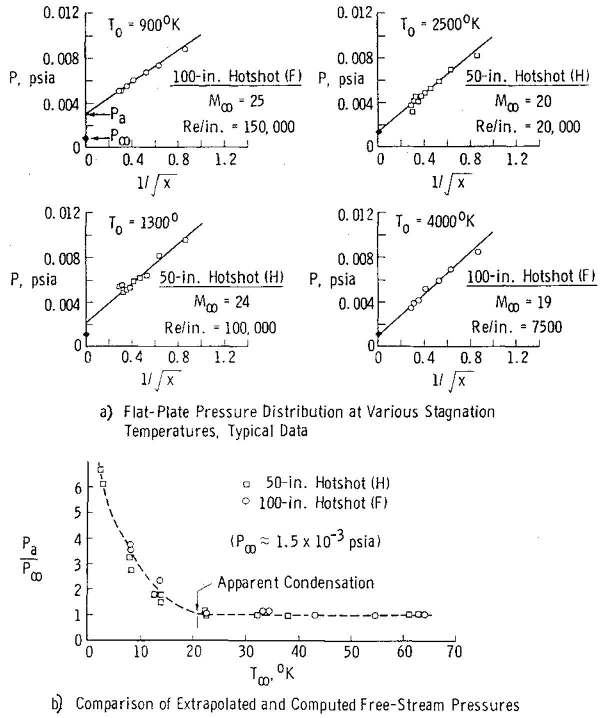

Fig. 1 Effect of condensation on flat plate pressures.

Mach 9 to 17 regime. Clark,[3] of the College of Aeronautics in Cranfield, has published a theoretical treatment of the flow of a condensing diatomic vapor. The present experimental study conducted in the von Karman Gas Dynamics Facility (VKF), Arnold Engineering Development Center (AEDC), was undertaken for the purpose of extending the work of Dayman and Daum to include nitrogen as the test gas at free-flight Mach numbers up to 22.

In this note, an experimental method of determining the onset of condensation is presented along with the amount of apparent supersaturation obtainable in hotshot tunnels using nitrogen as the test gas.

Test Procedure

The experiments were conducted with a sharp flat plate at zero angle of attack in the 50- and 100-in. VKF tunnels *H* and *F*, respectively. A complete description of the apparatus and procedure of testing is given in Ref. 4.

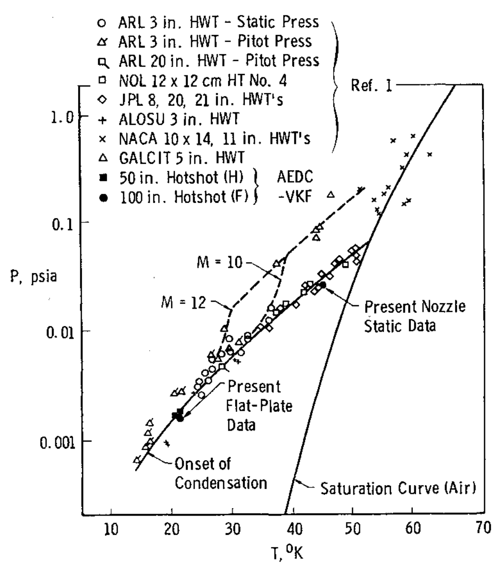

Fig. 2 Phase diagram.

The pressure distribution on a sharp flat plate at large Mach numbers in low-density continuum flow has been shown[5] to be a linear function of the viscous interaction parameter $\bar{\chi}$; explicitly,

$$(p - p_\infty)/p_\infty = m[(C_\infty)^{1/2}(M_\infty)^3/(Re_{\infty x})^{1/2}] \qquad (1)$$

or, in another form,

$$(p - p_\infty)/p_\infty \propto 1/x^{1/2} \text{ (for a given tunnel run)}$$

where x is the distance from the sharp leading edge. Taking the limit as $x \to \infty$, we see that the pressure tends to the freestream value as follows:

$$\lim_{x\to\infty} \frac{p - p_\infty}{p_\infty} = \lim_{x\to\infty} \frac{\text{(const)}}{x^{1/2}} = 0$$

or

$$p/p_\infty = 1 \text{ at } 1/x^{1/2} = 0$$

Using the preceding relationship, the freestream pressure can be determined experimentally by plotting the flat plate pressure distribution as a function of $1/x^{1/2}$ and extrapolating the data linearly to $1/x^{1/2} = 0$. With a method of measuring the test section static pressure, the effects due to low-temperature operation can be evaluated.

Results

Figure 1a presents a number of individual run distributions for the 50- and 100-in. hotshot tunnels. Note the linearity of the data plotted vs $1/x^{1/2}$. A linear line, drawn through the data with stagnation temperatures of 2500° and 4000° K, passes through the computed static pressure at $1/x^{1/2} = 0$; hence, $p/p_\infty = 1$, and good tunnel flow in the test section should exist. For stagnation temperatures of 900° and 1300° K, a linear line through the test data gives an extrapolated freestream pressure (p_a) at $1/x^{1/2} = 0$ greater than the computed pressure; thus $p/p_\infty > 1$ (note the departure of the extrapolated pressure from the computed pressure as the tunnel stagnation temperature is decreased). With a method of measuring the test section static pressure, the general rise in static pressure due to the latent heat of condensation and nonisentropic flow can be evaluated. Data are presented from both tunnels (Fig. 1) to show the consistency of the tunnels and the measured data.

Figure 1b is a summary of the pressure data plotted in such a way to indicate the onset of condensation. Note that the ratio of the extrapolated to computed static pressure rapidly increases below about 20° K. In fact, $p_a/p_\infty > 6$ at the lowest freestream static temperature tested ($T_\infty \approx 3°$), whereas $p_a/p_\infty \approx 1$ between $T_\infty \approx 22°$ and 63° K.

Summary

The present data were found to agree well with the recent data of Daum[1] and Dayman.[2] The large amounts of apparent supersaturation that can be achieved at high Mach numbers in air can also be obtained using nitrogen as the test gas. Figure 2 presents the pressure-temperature phase diagram of Ref. 1 with data from the present study included. Note the excellent agreement of the flat plate pressure data and the nozzle static pressure with the data of Ref. 1. A summary of the nozzle static data and the method of analysis are given in Ref. 4. Also presented in Ref. 4 are data from the test section pitot, hemisphere-cylinder heat probe, and heat-transfer rate data on the flat plate.

Using the onset of condensation curve as the lower temperature limit instead of the theoretical saturation curve, a half-an-order of magnitude increase can be realized in the freestream Reynolds number at a temperature of about 15° K (onset of condensation) instead of about 40° K (theoretical saturation).

It should be noted that the present or past studies of the apparent supersaturation obtainable in supersonic nozzle flows offer no proof of the general equivalence of this supersaturated flow to a subsaturated flow. Equivalence is shown here for the hypersonic viscous induced pressures on a flat plate. Equivalence must, at present, be assumed for general application of supersaturation to broaden the test regime of a given tunnel.

In conclusion: 1) the amount of supersaturation that can be achieved at high Mach numbers with air can also be obtained using nitrogen as the test gas, and 2) the flat plate proves to be a very useful tool in condensation studies.

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A Thin-Film Radiative Heat-Transfer Gage

Robert M. Nerem* and George H. Stickford†
The Ohio State University, Columbus, Ohio

In order to measure the total integrated radiative heat flux due to shock-layer radiative emission on aerodynamic configurations mounted in high-enthalpy, supersonic, shock-tube generated flows, a fast response thin-film total radiation heat-transfer gage has been developed at The Ohio State University Aerodynamic Laboratory. Standard thin-film resistance thermometer techniques have been applied in this gage because the use of such techniques in convective heating measurements in impulse devices is well understood and quite extensively documented in the literature.[1, 2]

A schematic of the thin-film radiative heat-transfer gage is shown in Fig. 1. It consists of a double-layer thin-film sensing element mounted on a Pyrex backing material. The bottom layer of the double-layer sensing element is a thin film of Bright Platinum no. 05-X, whereas the top layer is a thin film of Luster Black no. 4771. Both of these materials are liquid metal suspensions marketed by the Hanovia Liquid Gold Division, Engelhard Industries, East Newark, N. J. The Bright Platinum material is an electrical conductor and serves as the resistive element in the d.c.-powered, constant current circuit designed to measure the variation in the gage resistance. The Luster Black material is for all practical purposes nonelectrically conducting; however, it has a high absorptivity at wavelengths below 1 μ and thus provides the proper gage surface characteristics for re-entry heating investigations of current interest. The percent transmission and reflection of a Luster Black thin-film surface[3] is shown in Fig. 2, and it can be seen that, in the wavelength region below 1 μ, the absorptivity will be approximately 0.8. The lower spectral absorptivity of the Luster Black in the infrared is associated with its high transmissivity in this wavelength region. However, because of the low transmissivity of the Bright Platinum no. 05-X thin film, the absorptivity of the double-layer thin-film gage is actually much higher in the infrared than indicated by the surface characteristics shown in Fig. 2.

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* Instructor, Department of Aeronautical and Astronautical Engineering. Associate Member AIAA.

† Research Assistant, Aerodynamic Laboratory.

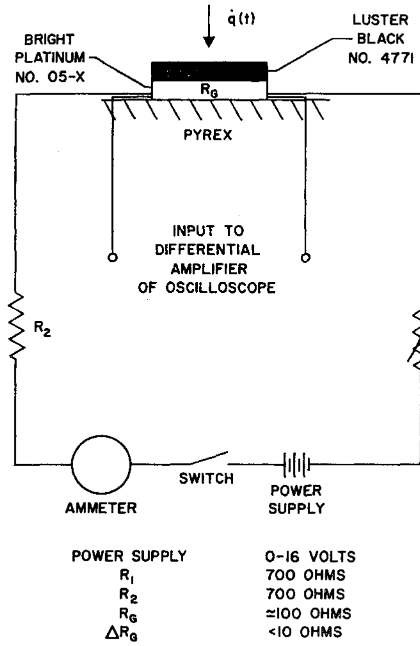

Fig. 1 Schematic of thin-film gage and electrical circuit.

It should be noted that the exact spectral characteristics of thin films depend on the thickness and uniformity of the film, and therefore the spectral characteristics of different thin-film heat-transfer gages will vary somewhat. However, such variations have a small effect on the absorptivity of gages of the present type. For example, an obviously extreme deviation of 50% in the reflectivity of the Luster Black thin film from that shown in Fig. 2 produces only about a 12% change in the gage absorptivity. It would thus appear that variations in gage surface characteristics will be small and can be neglected. This negligible difference between surface characteristics of different gages was borne out in a recent investigation of stagnation-point radiative heat transfer in which three different thin-film gages of the forementioned type were used to measure radiation heat transfer[4] over a wide range of flow conditions. Analysis of the results of this investigation showed any differences in surface spectral characteristics to have an indiscernible effect.

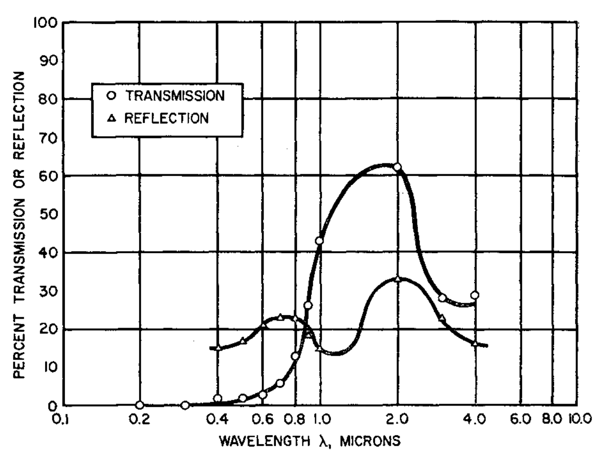

Fig. 2 Transmission and reflection characteristics of Luster Black no. 4771.