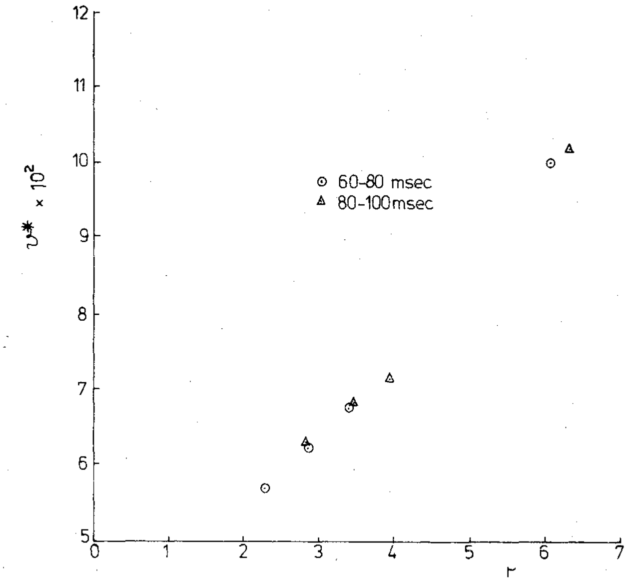

Fig. 4 Kovasznay mode diagram of the hot-wire signal; $P_0 = 610$ psia, $T = 20$ msec.

periods at frequencies ≥1.6 KHz within the run time, but for the frequency of 0.8 KHz the standard deviation is greater than 1 dB throughout the run. It is also observed that, for frequencies ≥1.6 KHz, the variation of standard deviation with frequency is small. If, however, the sampling commences at the 40 msec instant, then the standard deviation, in general, decreases to those shown in Fig. 3b, and it is possible to analyze the 0.8 KHz case within the specified limit of 1 dB. This implies that the nonstationarity decreases as the run progresses, and it would be more appropriate to sample toward the end of the run.

The overall sampling period of 20 msec used on the results of Fig. 3b would result in a total temperature, density, and velocity changes of 3%, 3%, and 1½%, respectively, for the interval of the run 40-60 msec. For changes of these magnitudes it would prove possible to assign meaningful values to the mean flow conditions.

A Kovasznay mode analysis[7] of the hot-wire signals was made with a sampling period of $T = 20$ msec. The results for sampling commencing at the 60 and 80 msec instants are shown in Fig. 4. The results include only the frequencies > 1600 HZ. The mode diagrams are linear with a positive slope. This means that the correlation between the mean flow (the slope of the line) and total temperature fluctuations (the intercept on the v^* axis) is −1. A correlation of −1 has two possibilities: 1) entropy fluctuations for which the straight line would have an intercept of $r = -[1+(\gamma-1)/2)M_\infty^2]^{-1}$ on the r axis, which is not the case here; or 2) a pure sound field with a finite total temperature fluctuation implying that sound originates from a moving source. Construction of a mode diagram from the data taken from different runs may be questionable. Nevertheless, the data indicate that the differences in the magnitude of the fluctuations between 60 and 100 msec is negligible and the disturbance field appears to be essentially a sound made of disturbance as in supersonic wind tunnel flows.[8,9]

Conclusion

It appears that the nonstationary flows encountered in short duration test facilities can be used for the study of unsteady flow problems, provided care is taken in selecting the sampling period and the instant from which the sampling commences.

The present tests show that an optimum sampling period of 20 msec toward the end of the run results in a total standard deviation of less than 1 dB and a meaningful mean flow condition can be assigned for this sampling period.

Acknowledgment

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Flow Characteristics in an Expansion Tunnel as Inferred from Velocity Measurements

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Introduction

An experimental study[1,2] was undertaken recently to determine if predicted[3] advantages of operating the Langley expansion tube[1,4] as an expansion tunnel exist in real life. (The Langley expansion tunnel is simply an expansion tube with a conical nozzle positioned at the exit of the acceleration section; hence, nozzle entrance flow conditions are hypersonic and hypervelocity.) Heretofore, the only flow diagnostic used to deduce flow characteristics in the vicinity of the nozzle exit was vertical surveys and time histories of the pitot pressure. As discussed in Ref. 1, additional measurements are required to define nozzle flow characteristics and determine if nozzle flow conditions are satisfactory for aerodynamic testing. To provide this information, a photoionization technique[5] was employed to measure vertical surveys of the axial component of flow velocity just downstream of the nozzle exit. Preliminary results from these velocity measurements are presented herein, along with estimates of freestream density inferred from the velocity measurement technique. These data are compared to measured pitot pressure; thus, two in-

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dependent measurements are used to determine the diameter and uniformity of the test core at the nozzle exit and the duration of the quasisteady flow period.

Apparatus and Tests

A detailed description of the Langley expansion tube is presented in Ref. 4. The expansion tunnel is simply an expansion tube with a nozzle positioned at the exit of the acceleration section.[1] The present tests were performed with an unheated helium driver pressure of approximately 33 MN/m^2 and air and CO_2 test gases at a quiescent pressure of 3.45 kN/m^2. The acceleration gas was the same as the test gas, and the quiescent pressures for air and CO_2 were 3.2 and 2.1 N/m^2, respectively. Because no tertiary diaphragm[2] was used to separate the nozzle and acceleration section, the initial nozzle pressure was equal to the quiescent acceleration gas pressure. The nozzle was conical, having a 10° half-angle, and the entrance and exit diameters were 8.9 and 63.5 cm, corresponding to a geometric nozzle area ratio of 51. Flow conditions at the nozzle entrance for the present study are tabulated in Ref. 1.

The axial component of the flow velocity was obtained using two windowless, collimated ultraviolet light sources[5] spaced 3.81 cm apart. These light sources were pulsed simultaneously to produce two parallel ionized columns in the flow, which were detected downstream of the light sources by ion probes. The axial component of flow velocity was inferred from the time interval between the arrival of the two ionized columns (which were swept downstream with a velocity equal to the flow velocity) at the ion probe. Thus, the velocity represents an average value over the 3.81-cm interval between the two light sources. These light sources were of the capillary discharge type,[5] and the pulse duration of the light was approximately 0.2 μsec. The ion probe consisted of a 15° half-angle cone forebody, with a base diameter equal to 1.015 cm, followed by a cylindrical afterbody having a diameter of 0.95 cm. The cone was fabricated from stainless steel, and the ion sensor was a brass ring sandwiched between nylon insulators; the center of the sensor was 2.78 mm downstream of the cone-cylinder junction. Sixteen ion probes were installed in a survey rake having a probe spacing of 3.81 cm and mounted vertically. The ion sensors were 20.3 cm downstream of the nozzle exit. The most upstream light source was located 11.82 cm downstream of the nozzle exit.

Output signals from the ion probes were recorded from oscilloscopes with a camera. Oscilloscope time sweeps were calibrated before, during, and after the test series, and corrections were applied to the data if necessary. Based on estimated uncertainties in time and distance measurements, the inferred velocity is believed accurate to within 2%. These oscilloscopes were triggered by the output signal from an ion sensor mounted flush with the nozzle wall and at the nozzle exit. This signal was fed into a three-channel time-delay generator, and the output from this generator was used to pulse the two light sources simultaneously, as well as trigger the oscilloscopes. This arrangement permitted the axial component of the flow velocity between the two light sources to be measured at different times in the flow sequence.

The incident shock velocity in the acceleration gas was measured using a microwave technique.[1] For the conditions of this study, the test-gas/acceleration-gas interface velocity was essentially equal to the measured incident shock velocity. This test-gas velocity at the nozzle entrance is used to normalize the measured velocity downstream of the exit.

On occasion, the ion probe 7.62 cm below the nozzle centerline was replaced by a pitot pressure probe[1] to provide a simultaneous pitot-pressure time history measurement with the flow velocity measurement. Pitot pressure was measured with commercially available miniature quartz transducers.

Vertical density profiles, normalized by the nozzle centerline density, were estimated by comparing the charge collected at the ion probes. The charge acquired by a fluid element (and hence transferred to a given ion probe) is proportional to the density of the fluid element and to the dose of photoionizing radiation received from the ultraviolet light source. Since the variation of the radiation dose across the flow depends on the distribution of the fluid density and the optical properties of the fluid, the distribution of the fluid density can be deduced approximately from the charge collected by the various ion probes. In carrying out this analysis, it was assumed that 1) the density profile is symmetrical about the nozzle centerline, 2) the effective photoionization cross section is constant along the light path, and 3) all ion probes sample equal segments of the ionized column. According to this analysis, the density varies as the geometric mean of charges collected at symmetric (about the flow centerline) pairs of ion probes. The magnitude of the density was obtained by equating the integral of the density distribution just downstream of the nozzle exit to the integrated density of a constant property gas column which produced the same transmission of ultraviolet light as the nozzle flow. The optical transmission of the nozzle flow was measured by two windowless, nickel photodiodes positioned opposite the ultraviolet light sources and near the edge of the flow. The optical transmission of the reference gas column was obtained from a static calibration carried out in the nozzle dump tank over a range of pressures.

Results and Discussion

The average axial component of flow velocity over the interval 11.82 to 15.63 cm downstream of the nozzle exit, nondimensionalized by the velocity measured at the nozzle entrance, is shown in Fig. 1 as a function of time for air and CO_2 test gases. These values of flow velocity represent an average of the velocities obtained from the center five ion probes for a given test and the average of two tests. Also shown are pitot-pressure time histories. The pitot pressure for both test gases is characterized by an initial, sharp increase, then decrease, in pressure, followed by a period of essentially constant pressure. (The results of Ref. 2 demonstrate that the present pitot-pressure measurements are essentially free of a pressure lag effect at the low Reynolds numbers of this study.) Around 400 μsec after flow arrival, the pitot pressure begins to decrease, and high-frequency variations in pitot pressure appear. The initial spike in pitot pressure is attributed to the relatively strong starting shock formed within the nozzle when the initial nozzle pressure is equal to the quiescent acceleration gas pressure.[2] Duration of the period of quasisteady pitot pressure is 300 to 350 μsec for both test gases, thereby exceeding that observed for the expansion tube mode of

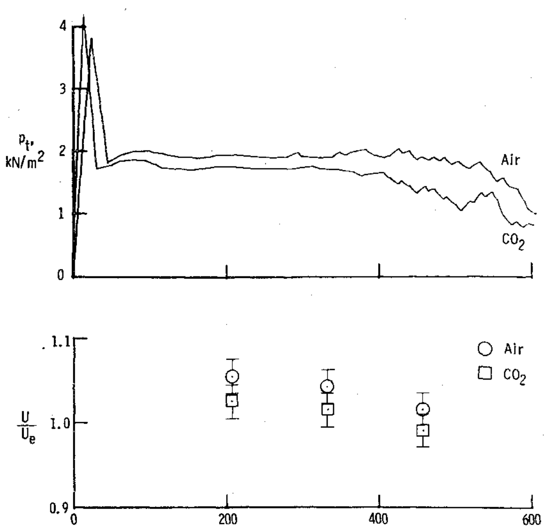

Fig. 1 Measured pitot pressure and average axial component of velocity as a function of time for air and CO_2 test gases.

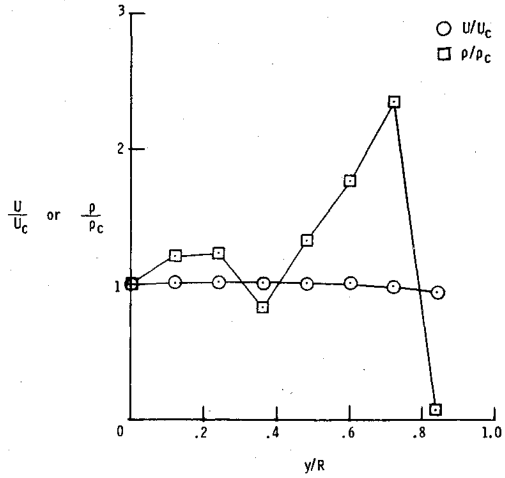

Fig. 2 Vertical velocity and static density profiles at the nozzle exit for CO_2 test gas ($R = 31.75$ cm).

operation.[1,2] Values of flow velocity at the two earliest times agree within the experimental uncertainty (denoted by barred symbols), whereby a decrease in velocity occurs between the earliest and the latest times for both test gases. Thus, the flow velocity is essentially constant during the later half of the quasisteady pitot-pressure period and decreases during the period of decreasing pitot pressure and high-frequency variation in pitot pressure. The flow velocity increases as it traverses the distance between the nozzle entrance and exit, this increase being 4 to 5% for air and 2% for CO_2. For hypersonic flow, the pitot pressure is approximately equal to ρU^2; hence, the results of Fig. 1 imply that freestream density and velocity are essentially invariant with time just downstream of the nozzle exit for about 300 μsec following the initial peak in pitot pressure. These results also confirm that the flow density undergoes an appreciable decrease in magnitude as the flow traverses the nozzle, with the density at the nozzle exit being about 0.02 times that at the nozzle entrance for both air and CO_2 test gases. (Inversely, the ratio of density at the nozzle entrance to that at the nozzle exit is approximately equal to the nozzle geometric area ratio.) The relatively small increase in flow velocity and large decrease in density as the flow traverses the nozzle is expected, since most of the flow energy is kinetic at the nozzle entrance, and the continuity of mass and energy relations show that the density will decrease as the nozzle area ratio increases.

The vertical profile of the axial component of flow velocity and the density is shown in Fig. 2 for CO_2 test gas. The velocity is nondimensionalized by measured velocity on the nozzle centerline over the interval 11.82 to 15.63 cm downstream of the nozzle exit, and the density also is nondimensionalized by the nozzle centerline value downstream of the nozzle exit. Velocity and density profiles were obtained during the period of quasisteady pitot pressure. A uniform core of the flow velocity (within 2%) exists about the nozzle centerline, the diameter of which is approximately 0.7 times the nozzle exit diameter. Outside of this core of uniform velocity, the flow velocity was observed to decrease rapidly in the direction of the nozzle wall. Values of freestream density are within 20% in a region about the nozzle centerline, and the diameter of this region is about half the nozzle exit diameter. A toroid of high-density flow surrounds this inner region of relatively uniform density, but the flow velocity is constant across this region and the toroid. Outside the toroid, the density diminishes rapidly in the direction of the nozzle wall. Vertical profiles of flow velocity and density for air were similar to those observed for CO_2. These findings are in agreement with previously measured pitot-pressure profiles,[1] which showed a relatively uniform pitot-pressure inner-core region surrounded by a region of higher pitot pressure. The diameter of this uniform pitot-pressure region was approximately 0.5 times the nozzle exit diameter for CO_2 and air test gases. A similar expansion tunnel flow model was observed in the Langley pilot model expansion tunnel.[5] The toroid of high-density flow is believed to be caused by shocks (weak disturbances), as predicted for hypersonic flow in conical nozzles.[6] As a point of interest, the value of centerline density obtained from measuring the charge collected by the ion probe is about twice the density inferred from the measured velocity and pitot pressure. In view of the assumptions required to obtain a value of density from the measured charge, this difference in centerline density of a factor of 2 is believed to be quite reasonable.

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Cooling Effectiveness of Slot Injection into a Turbulent Boundary Layer

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Introduction

SYSTEMS studies show that lighter and less expensive structural materials can be used if the operational surface temperature of a high-speed vehicle can be reduced below the normal radiation equilibrium temperature. Transpiration cooling, which is the process of releasing a coolant gas through a porous surface material, has been demonstrated as an effective means of maintaining the surface temperature below a required level.[1,2] However, a porous material may not be structurally practical for the skin of high-speed vehicles. A second technique for cooling a surface is to inject coolant gas through a discrete slot into the boundary layer. A considerable number of investigations[3-5] having been conducted on the cooling effectiveness ϵ for a single slot. Cooling effectiveness for high-speed flow usually is defined as

$$\epsilon = (T_t - T_{eq})/(T_t - T_j)$$

where T_t, T_{eq}, and T_j are the stream stagnation temperature,

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