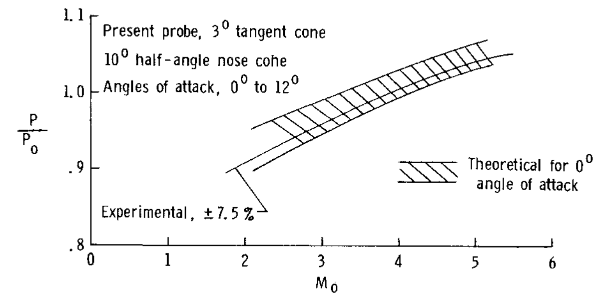

Fig. 6 Variation of measured static pressure with Mach number.

at some angles in Fig. 5 but this is not all attributable to the probe. The tunnels in which these preliminary tests were made are known to contain flow irregularities and at angle of attack, the location of the probe static holes does not exactly coincide with the point at which the reference pressure was measured. Also, since the probe was hand-made for expediency, it was not as precise as desired. The theoretical band shown in Fig. 6 is indicative of the variation in pressure due to expected changes in probe shape and static hole location resulting from construction inaccuracy. The over-all scatter in the present data, is about ±7.5% and this compares very favorably with conventional probes which exhibit at least 3 times this scatter under similar flow conditions. Figure 6 also shows that a given probe is fairly accurate over a reasonable range of Mach numbers; however, the probe design obviously should be tailored as closely as possible to the Mach number range of intended use, and perhaps be calibrated at several Mach numbers.

Conclusions

The new static probe design, in which the static holes are located much closer to the tip than in conventional probes, shows promise for use in certain flow situations where conventional probes become highly inaccurate. An additional advantage of the new probe design is that when used in static pressure survey rakes the probes can be located much closer together than in conventional designs and still ensure that disturbances from neighboring probe tips do not affect the static readings. A disadvantage of the new design is in the more difficult construction techniques required to provide accurately shaped tubes. However, this proved to be no great deterrent in construction of the present probes. Further study of the probe geometry is required in order to optimize the combination of cone angles, transition section length and hole location for application to any given flow situation.

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Flow Properties in Expansion Tube with Helium, Argon, Air, and CO_2

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Nomenclature

M_∞ = freestream Mach number
$N_{Re,\infty}$ = freestream unit Reynolds number, m^{-1}
p_∞ = freestream static pressure, kN/m^2
p_t = pitot pressure, kN/m^2
R = tube radius, m
T_∞ = freestream temperature, °K
T_t = stagnation-point temperature, °K
U_s = incident shock velocity in intermediate section, km/sec
U_∞ = freestream velocity, km/sec
y = vertical distance from tube centerline, m
Z_t = ratio of number of moles at stagnation point to number of moles of undissociated gas
ε = normal shock density ratio
ρ_∞ = freestream density, g/m^3

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Introduction

SEVERAL studies have been performed recently in the Langley 6-in. Expansion Tube, which were unique in the sense that hypersonic and hypervelocity real-gas flows were generated with several test gases in a single facility. The capability of employing arbitrary test gases resulted in a range of normal shock density ratio (an important parameter in the simulation of real-gas effects for entry vehicles) from 4 to 19. The purpose of this Note is to present results from a calibration study performed in conjunction with these investigations. Test flow velocities from 5 to 7 km/sec were generated using helium, argon, air, and CO_2 test gases. Pitot pressure profiles across the flow at the test section are presented for the four test gases, and measured flow quantities are compared to predicted values from Ref. 1.

Apparatus and Tests

A brief description of the Langley 6-in.-Diam Expansion Tube is presented in Ref. 1. For the present tests, the driver gas was unheated helium at a nominal pressure of 33 MN/m^2 and test gases were helium, argon, air, and CO_2 at an initial pressure of 3.45 kN/m^2. For a given test, the acceleration gas was the same as the test gas, but at a lower initial pressure.

Velocities were inferred from microwave interferometer measurements and from response of pressure, heat transfer, and photomultiplier instrumentation along the length of the tube. Pressures were measured using miniature piezoelectric (quartz) transducers in conjunction with charge amplifiers. Uncertainties in measured U_s and U_∞ are believed not to exceed 4.5% and 2.5%, respectively; uncertainties in p_∞ and p_t are believed to be less than 20% and 10%, respectively.

Vertical pitot pressure profiles were made with a 9-probe survey rake positioned 4.13 cm downstream of the tube exit. Probe spacing was 1.91 cm and the o.d. of each probe, at the sensing surface, was 7.87 mm. The centerline of the center probe was coincident with the tube centerline.

Employing nominal values of measured p_∞, p_t, and U_∞ as input to the thermochemical equilibrium program of Ref. 2 yields the following calculated values in Table 1.

Table 1 Test section flow conditions

Gas	p_∞	ρ_∞	T_∞	U_∞	M_∞	$N_{Re,\infty} \times 10^{-5}$	ε	p_t	T_t	Z_t
He	1.31	2.02	305	7.04	6.82	6.63	3.76	88.9	5077	1.00
Ar	2.24	10.47	1027	5.21	8.74	9.76	7.58	268.8	13140	1.16
Air	2.14	6.97	1068	5.40	8.45	8.62	11.35	196.5	6273	1.33
CO_2	1.17	4.74	1308	5.00	9.29	5.09	18.86	116.6	3858	1.75

Results and Discussion

Vertical pitot pressure profiles are shown in Fig. 1 for the four test gases. Test repeatability, often a problem with impulse facilities, is observed to be good for helium, argon, and air, and somewhat less satisfactory for CO_2. This poorer repeatability for CO_2 is due, in part, to the difficulty of repeating and maintaining the lower value of initial acceleration gas pressure (3.1 N/m^2) required for the CO_2 tests. The profiles of Fig. 1 show the existence of a uniform test core (that is, region of uniform p_t) for all test gases. The test core diameter, defined as

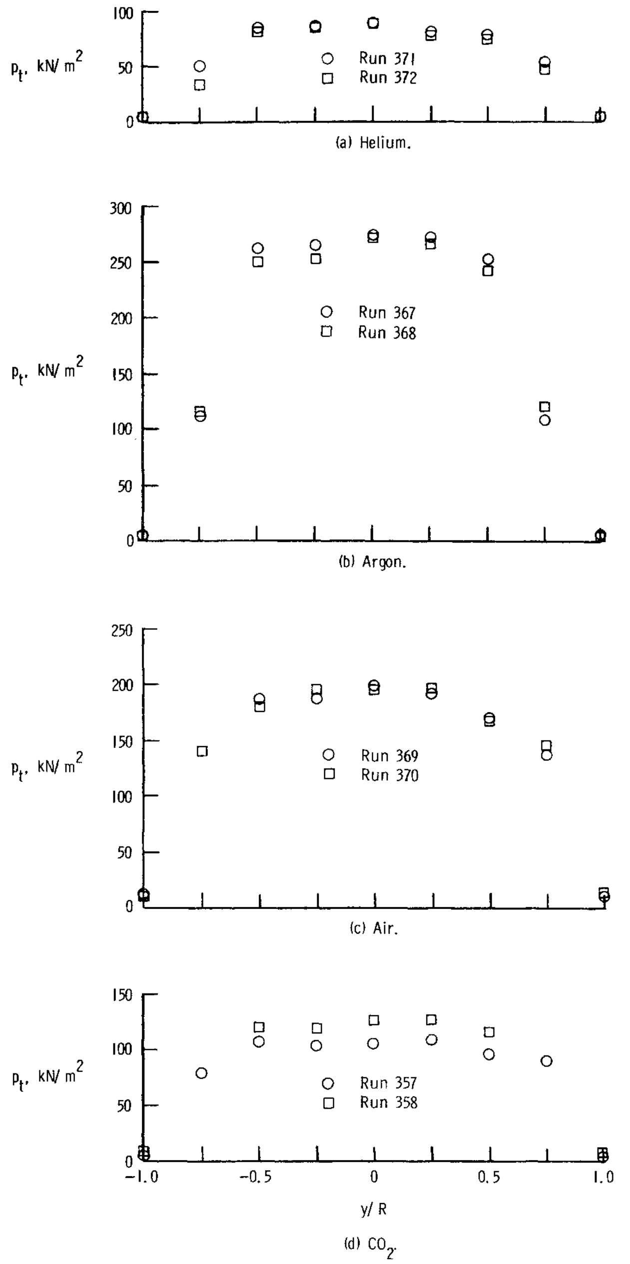

Fig. 1 Vertical pitot pressure profiles for helium, argon, air, and CO_2 test gases.

the diameter of the region for which p_t is within $\pm 10\%$ of the average of the center three values, is approximately 6.4 cm for air and 7.6 cm for helium, argon, and CO_2. In light of the fact that flow nonuniformity can severely alter flowfield characteristics about blunt bodies,[3] these results demonstrate the applicability of the expansion tube for studying flow conditions about small (4 to 5-cm-diam) models with these test gases. The quasi-steady test time varied from 200 to 250 μsec for all test gases.

The helium tests provide an approximate ideal-gas model of the expansion tube fluid mechanics. This model is approximate due to differences in viscous effects and wave characteristics between helium flow and the flow of other gases. For example, the flow energy lost in the rupture of the secondary diaphragm must result in an upstream-facing shock wave reflected from this diaphragm. When the diaphragm ruptures, the resulting expansion fan overtakes and weakens the reflected shock. It is sometimes assumed that the reflected shock has been weakened to a standing shock at the time it processes the flow which eventually becomes the test flow. The diaphragm opening time determines the rate at which the reflected shock is weakened by the expansion; thus a rapid diaphragm opening will minimize the effects of shock reflection. For the present test conditions, helium has a lower pressure behind the reflected shock and thus is expected to have the longest diaphragm opening time and show the most pronounced effects of shock reflection. Estimates indicate the diaphragm opening time for helium will be about 2.7 times that for air or argon and about four times that for CO_2. In Fig. 2, predicted[1] and measured p_∞ and p_t are compared for helium. The shaded region denotes the effect of a $\pm 4.5\%$ uncertainty in measured U_s for no shock reflection at the secondary diaphragm. It is interesting to note that small uncertainties in U_s result in much larger uncertainties in predicted p_∞ and p_t, thereby illustrating the need for an accurate determination of U_s. Since no ionization of helium occurred, predicted values for equilibrium and frozen flow expansions are the same. In the predictions illustrated in Fig. 2, the effect of a totally reflected shock at the secondary diaphragm is included. Predictions for a standing shock at the secondary diaphragm were very close to those for no shock reflection and thus are not presented. The results of Fig. 2 imply the existence of a totally reflected shock at the secondary diaphragm for helium.

Predicted and measured p_t are compared in Fig. 3 for CO_2 test gas. Included in Fig. 3 is the effect of flow attenuation on prediction[4] for an equilibrium expansion. The U_∞ for CO_2 was observed to decrease approximately 300 m/sec in traversing the acceleration section, which was 17 m long. Measured p_t agrees best with the two equilibrium predictions accounting for flow attenuation and no shock reflection and total shock reflection at the secondary diaphragm. Similar comparisons for argon and air, in which flow attenuation was also observed, showed

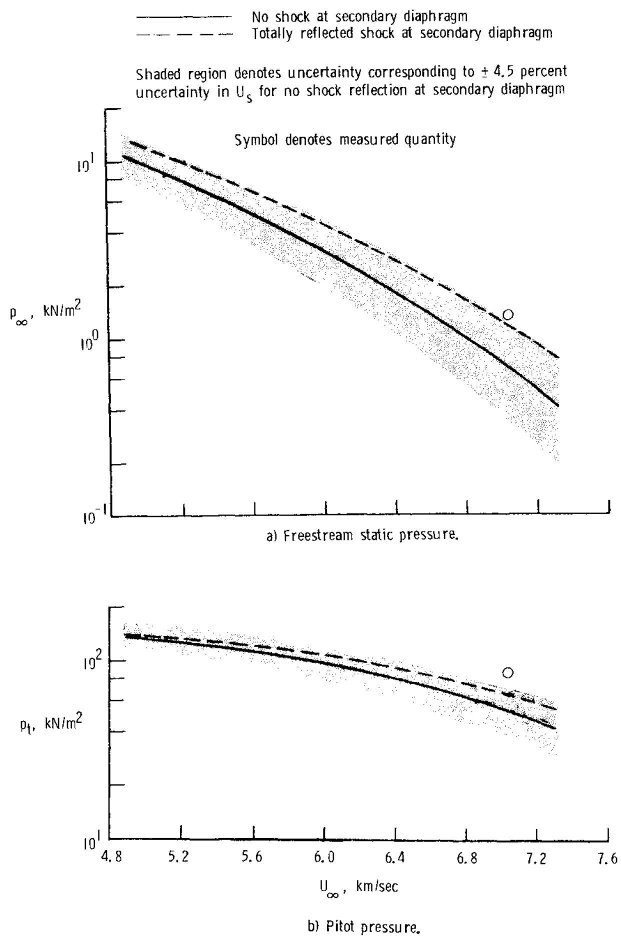

Fig. 2 Comparison of predicted and measured freestream static pressure and pitot pressure for helium test gas.

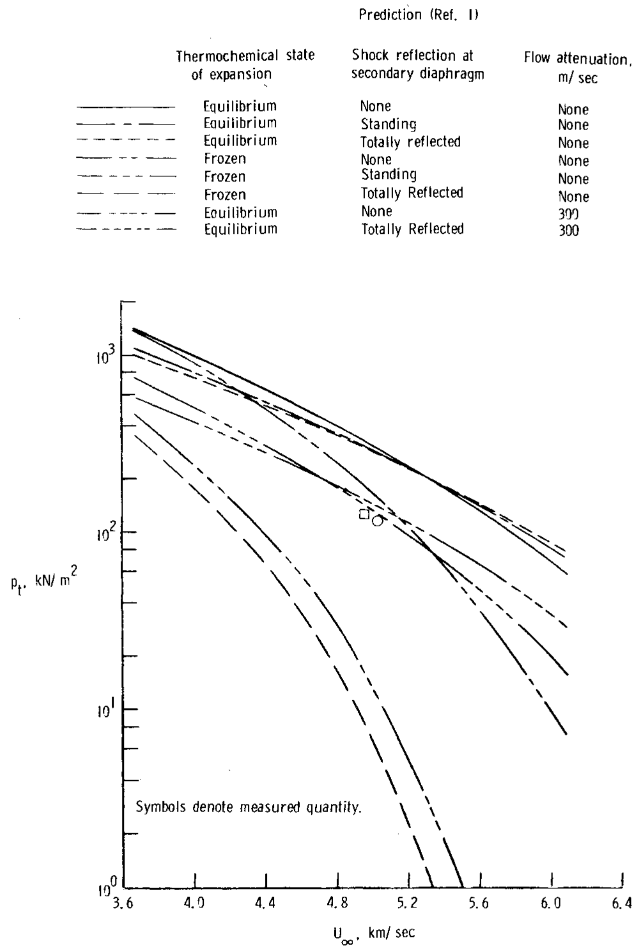

Fig. 3 Comparison of predicted and measured pitot pressure for CO_2 test gas.

measured flow quantities to agree best with equilibrium prediction accounting for flow attenuation and including a totally reflected shock at the secondary diaphragm. No flow attenuation was observed for the helium tests.

In conclusion, the present results show the existence of a uniform test core diameter of approximately half the expansion tube diameter for helium, argon, air, and CO_2 test gases. This test core diameter and duration of test flow are sufficient for model testing with current high response, miniaturized instrumentation techniques. Comparison of predicted and measured flow quantities suggest the expansion to be near thermochemical equilibrium for all gases and implies the existence of a totally reflected shock at the secondary diaphragm. Argon, air, and CO_2 flows were observed to attenuate while traversing the acceleration section, whereas no attenuation was observed for helium.

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Experimental Investigation of Gas Injection through a Transverse Slot into a Subsonic Cross Flow

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Introduction

EFFECTIVE fuel injectors for combustion chambers must produce rapid mixing of the fuel with the mainstream. Lateral injection offers the advantage of adding the effect of inertial penetration to turbulent diffusion. Penetration of laterally injected jets is of interest also for other situations, such as cooling of gas turbines or boundary-layer control.

In the experiments reported here, both the airstream and the jet were subsonic with the jet being injected through a long and narrow, transverse slot. Results of these experiments and comparison with other data are presented in the following. More details on the experimental techniques are described elsewhere.[1]

Many experiments on jet penetration in a cross flow have been reported in the literature.[2–15] Jets with various shapes of their cross section have been used, but the ratio of the longest to the shortest dimension (aspect ratio) did not exceed about four. An exception is the study by Vranos and Nolan[2] which included injection of helium through a circumferential slot (infinite aspect ratio) into supersonic flow. There is a lack of data on jet penetration for slots with aspect ratios considerably larger than four.

Experiments and Results

In the present experiments, the slot width was 0.01 in. (0.25 mm) and the length was 2.5 in. (64.5 mm), corresponding to an aspect ratio of 250. Air was supplied by a centrifugal blower through a plenum chamber into a square duct and test section of 4.25 in. (108 mm) width, and its velocity ranged from 26 to 259 fps (7.9–79 m/sec). The injected gases were helium, Freon 22, and Freon 116. The ratio of the jet density to the air density thus varied between about 0.14 and 4.8. Jet velocities ranged from 117 to 1820 fps (36–556 m/sec). The parallel section of the slot passage was 0.125 in. (3.2 mm) long, and the flow through it was supplied through a rounded inlet from a small plenum chamber to which the gas was fed from compressed-gas bottles through controls and flowmeters.

Photographs of the jets were obtained with a standard single-pass schlieren system, and Fig. 1 shows three photographs of a helium jet injected into different airflows. The reduced jet penetration with increased stream velocity and the tendency to early reattachment to the wall on the side of the injection slot are clearly noticeable. The black step in the lower right corner of each picture is a marker attached to the window of the test section to provide the reference scale needed for evaluation of the photographs in actual dimensions.

Penetration was defined by the leading edge of the jet visible in the photographs and was measured at 2.06 and 4.14 in. (52 and 105 mm) from the injection point. These measurements were correlated in terms of the momentum-flux ratio $J =$

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Index categories: Jets, Wakes, and Viscid-Inviscid Flow Interactions; Nozzle and Channel Flow; Subsonic and Transonic Flow.

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