Flow-Angle Measurements in a Rarefied Nozzle Plume

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A rotary pitot probe configuration has been developed to make measurements of the local flow angle in the plume that results from the expansion of a nozzle flow into a wholly cryopumped vacuum chamber. This probe has been used to make measurements inside the nozzle and in the backflow region upstream of the nozzle exit plane. These experimental measurements show that 1) in the nozzle boundary layer close to the nozzle exit the local flow is directed toward the nozzle wall rather than being parallel to it, and 2) in the backflow region local flow angles up to 140 deg to the nozzle axis have been measured and there are indications that local flow angles can approach 180 deg. The experimental measurements also show that the flow in the backflow can be affected by small changes in the cryopumping in this region of the flow.

Introduction

EXPERIMENTAL studies of nitrogen and carbon dioxide expansions from a small-scale, high-area-ratio nozzle into a hard vacuum[1] have shown that the nozzle boundary layer is affected by nozzle wall temperature, nozzle lip geometry, condensation in the expanding core flow,[2] and chamber background pressure.[3] Furthermore, electron beam fluorescence measurements of rotational temperature in the expansion of the nozzle boundary layer into the hard vacuum have shown regions of rotational nonequilibrium. It was also found that computations of the nozzle boundary-layer characteristics in the nozzle exit plane using a code developed by Whitfield,[4] did not agree with the measured characteristics. This was an unexpected result because a review of nozzle boundary-layer codes by Edwards[5] indicated that Whitfield's technique should have been an appropriate approach. This inability to accurately predict the boundary-layer characteristics of an ideal-gas nozzle expansion (nitrogen with no condensation) into a hard vacuum, suggests that the techniques used to predict the flow characteristics of more complex nozzle expansions, e.g., monopropellant, bipropellant, and solid-propellant rocket motors, may be of questionable validity. As a result of these studies[1] it was concluded that additional basic studies of the properties of nozzle expansions into a hard vacuum are needed to provide a more complete and accurate experimental data base against which the validity of computational codes may be checked. In light of this requirement, an experimental program was established to make accurate flowfield measurements in the plumes generated by pure-gas nozzle expansions into a hard vacuum. This paper presents the results of one phase of this experimental program in which attempts have been made to measure the value of the local flow angle using conventional pitot and free-molecular pressure probes.

Present Tests

The experimental measurements to be discussed herein were obtained in the 4×10 ft research vacuum chamber (RVC) located at the Arnold Engineering Development Center. The RVC is a stainless-steel, cylindrical vacuum chamber with an internal diameter of approximately 3.5 ft (1.07 m) and an overall length of approximately 14 ft (4.27 m). Vacuum conditions within the RVC are achieved through the use of mechanical, oil diffusion, and LN_2 cryopumps (77 K). In the present application the LN_2 cryopumps were used to pump the nozzle test gas, CO_2, whereas the oil diffusion and mechanical pumps removed the small quantities of N_2 and O_2 that were present as contaminants in the CO_2. It should also be noted that the innermost surfaces of the chamber were maintained at 77 K in order to minimize the scattering of plume gases by the test chamber walls.

At the onset of this investigation, nozzle flow conditions were established which precluded the possibility of condensation occurring at or upstream of the nozzle exit plane. This was accomplished by expanding the heated carbon dioxide through two 15-deg half-angle conical nozzles with throat diameters of 0.6 and 1.0 in. (1.53 and 2.54 cm), exit diameters of 4.0 in. (10.16 cm), and lip thicknesses of 1×10^{-3} and 0.25 in. (2.5×10^{-3} and 0.63 cm).

Each nozzle was welded directly to a stilling chamber, which consisted of an 8.5-in. long (21.6 cm), 4.0-in. diam (10.2 cm) schedule 10 pipe. Provision was made to measure the total temperature of the gas within the stilling chamber with a shielded Chromel®-Alumel® thermocouple. Nozzle and stilling chamber wall temperatures were monitored with Chromel-Alumel thermocouples attached to their outer walls. Stilling chamber pressure was measured with an absolute 5-psia Taber® pressure transducer.

A gas and stilling chamber heating system, comprised of an 800 W in-line serpentine heater positioned upstream of the stilling chamber and four 750 W band heaters strapped to the stilling chamber, was capable of raising the gas and stilling chamber to temperatures on the order of 1000 K. The nozzle and stilling chamber assembly was mounted on a traversing table located in the movable section of the RVC (Fig. 1). This table provided 6 in. (15.2 cm) of motion in both the lateral and axial directions to an accuracy of $\pm5\times10^{-4}$ in. (1.3×10^{-3} cm). This degree of motion and positioning accuracy was accomplished through the use of two Aerotech® stepping motor-driven, positioning tables. The nozzle positioning tables and the various flow-diagnostic probes were mounted to a common support structure (cf. Fig. 1) which allowed for the accurate positioning of a particular probe configuration with respect to the nozzle prior to the evacuation of the chamber.

One of the objectives of the present program was to investigate the flow of gas into the nozzle backflow region. To minimize the effect that the nozzle, stilling chamber, and the support structure have upon the flow in this region, a liquid-nitrogen-cooled plate, having internal and external diameters of 4.5 and 9.5 in. (11.4 and 24.2 cm), respectively, was positioned in the region of the nozzle throat (Fig. 1).

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At the beginning of this investigation it was anticipated that pitot pressure measurements would be made in the 1) central isentropic core flow, 2) the nozzle boundary layer, 3) forward flow area, 4) regions of steep density and flow-angle gradients, e.g., the lip region of the nozzle, and 5) nozzle backflow region. To make measurements in these widely different flowfields four basic probes were constructed having diameters of 0.03, 0.05, 0.125, and 0.25 in. (0.076, 0.129, 0.318, and 0.635 cm). Each of these probes was approximately 20 diameters in length with a sensing orifice not less than 80% of the probe diameter.

Wide variations in the angle of the flow velocity vector to the nozzle centerline, i.e., $0 \leq \Theta \leq 180$ deg, make it impossible to make accurate pitot pressure measurements with a fixed-angle probe. Accurate measurements of this type require that the probe be aligned with the local velocity vector. In the present study this was accomplished by mounting the pitot probe directly to an MKS® Type 370 absolute pressure transducer which was mounted on an Accudex® ARS 304 rotary positioning table in such a manner that the vertical axis through the front face of the probe was positioned over the center-of-rotation of the table (Fig. 1). With this arrangement the probe could be aligned with the velocity vector at a fixed position in the plume flowfield.

In those regions of the nozzle plume flowfield where the mean free path is large, i.e., greater than 1 cm, local values of flow angle and speed ratio can be determined from measurements made with a free-molecule pressure probe. A theoretical basis for the analysis of measurements of this type has been developed by Patterson[6] and Hughes.[7] The free-molecule pressure probe consists of a cylindrical tube with an orifice in its side which can be positioned in any direction relative to that of the velocity vector and which is so small, compared with the local mean free path, that it can be considered to be in free-molecule flow. It is assumed that the angle of the velocity vector is defined by the angle at which the peak pressure occurs.

In the present study the cylindrical probe and its pressure-measuring system were mounted to the Accudex ARS 304 rotary position table in such a manner that the longitudinal axis of the probe was positioned over the center-of-rotation of the rotary table. Two pressure-measurement systems were selected for use with the free-molecule pressure probe: 1) Schultz-Phelps ion gage tube which operates in the pressure range from 5×10^{-6} to 5×10^{-1} Torr, and 2) MKS Type 370 absolute-pressure transducers with ranges 0–1 and 0–10 Torr. Both systems are capable of accurate pressure measurements to as low as 10^{-5} Torr. The probe system using the Schultz-Phelps ion gage is more compact and for this reason is better suited to measurements in the nozzle backflow region. However, it suffers from the fact that, being an ion gage, it is sensitive to the type of gas under test and cannot make absolute pressure measurements unless it has been calibrated for the test gas. The MKS system on the other hand measures absolute pressure directly, and its accuracy is independent of gas composition.

The background pressure in the 4×10 ft RVC was continuously monitored with 1) a nude Bayard-Alpert ionization gage positioned behind and above the nozzle throat and 2) a Schultz-Phelps ionization gage positioned behind and to the side of the nozzle mount and a traversing mechanism within the LN_2-cooled cryoliner, with the sensing element facing in the direction of the flow on the nozzle centerline.

Results

Measurements of centerline pitot pressure as a function of axial distance were made for each of the nozzles to establish the flow characteristics of these nozzles. The values of the flowfield properties on the nozzle centerline for the sharp-lipped nozzle, e.g., M_∞, p_∞, T_∞, etc., derived from the measured values of pitot pressure, stagnation pressure, and stagnation temperature with the assumption that the flow is isentropic, are presented in Fig. 2. The expansion of gas from an axisymmetric nozzle into a hard vacuum should result in the symmetrical distribution of flowfield properties about the centerline of the nozzle. For a variety of reasons, possibly associated with probe/plume/chamber pumping interactions, radial profiles of flow properties downstream of the exit have been found in some (e.g., Ref. 8) to be asymmetrical. An earlier study of nozzle plumes in the 4×10 ft RVC has shown that radial profiles of pitot pressure are symmetrical. The difference between the present investigation and that discussed in Ref. 1 is that the probe support structure presents a larger nonpumping area to the incident

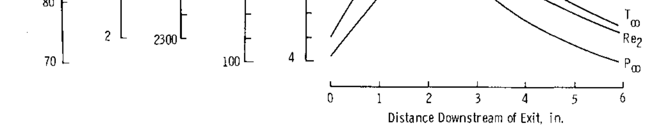


Fig. 2 Centerline flowfield properties as a function of axial distance ($A/A^* = 16$, $P_0 = 10.8$ Torr, $T_0 = 487$ K).

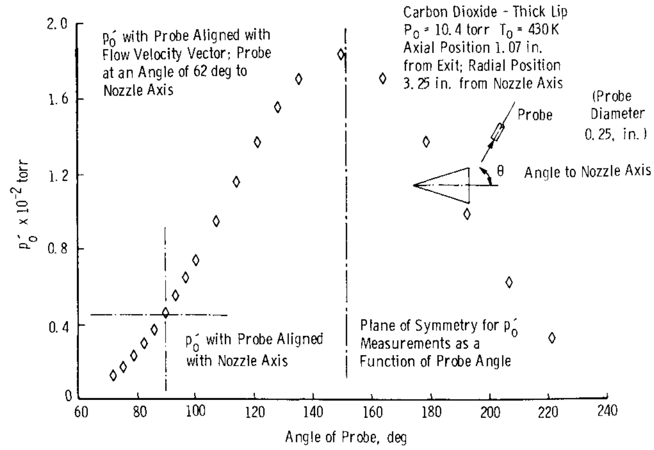


Fig. 3 Variation of pitot pressure with angle of probe to flow.

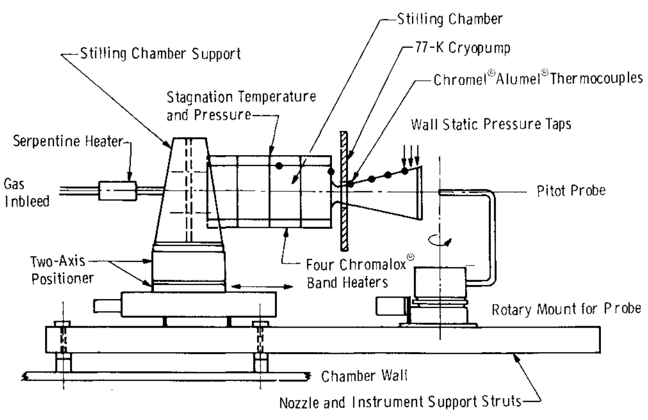


Fig. 1 Schematic of the nozzle, stilling chamber, and transverse assembly.

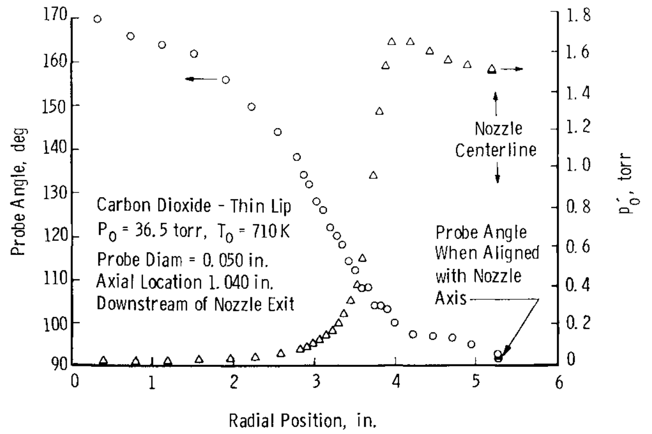


Fig. 4 Pitot pressure measured with probe aligned with velocity vector, raw data.

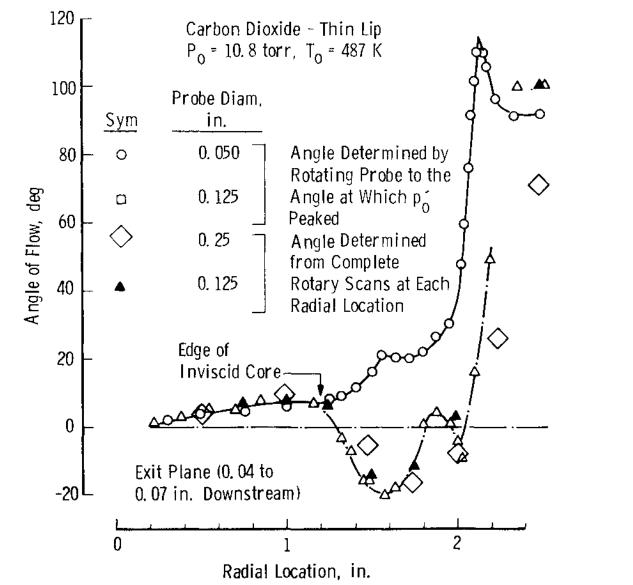
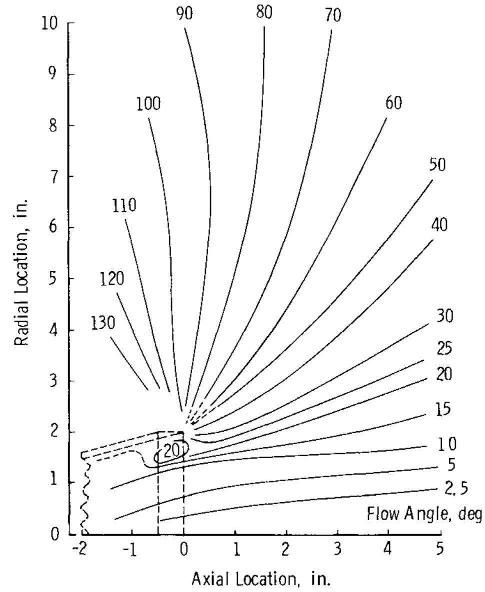
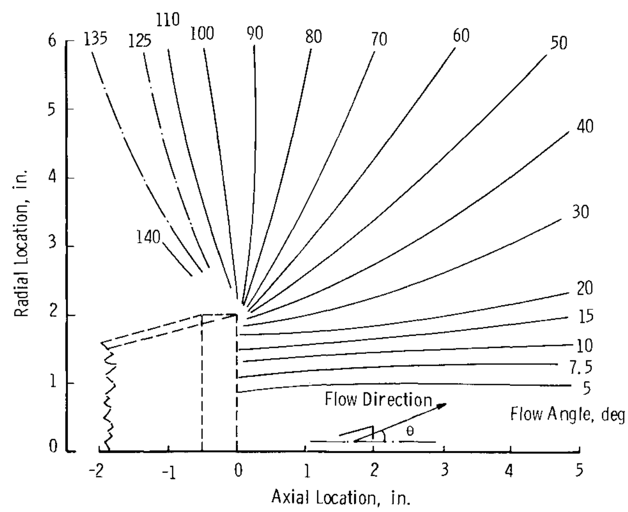


Fig. 5 Effect of pitot probe size on flow-angle measurements.



a) **Carbon dioxide, $P_0 = 10.8$ Torr, $T_0 = 487$ K.**



b) **Carbon dioxide, $P_0 = 36.5$ Torr, $T_0 = 710$ K.**

Fig. 6 Spatial map of constant CO_2 flow-angle values.

flow and thus an increased potential for interaction with the nozzle plume. To determine whether the presence of the probe mechanism within the chamber resulted in a distortion of the nozzle plume, complete radial profiles were obtained at a number of axial stations at, and downstream of, the nozzle exit plane. Having established the basic symmetry of the flow it was considered to be unnecessary to obtain full radial scans; subsequent radial scans were made with respect to the nozzle centerline only.

The variation of pitot pressure with pitot probe angle to the flow (Fig. 3) demonstrates that well-resolved pressure measurements can be made to pressures as low as 1×10^{-3} Torr. The degree of symmetry of these pressure vs angle measurements is good (see Fig. 3), and the angle at which $(p_0')_{max}$ occurs is clearly defined. It is assumed that the angle at which this maximum occurs is the angle of the flow velocity vector at that position in the nozzle plume.

At the outset of this investigation it was intended that measurements of the local flow angle would be derived from measurements of the type presented in Fig. 3. Fortunately, in the course of some preliminary measurements, it was found that the response time of the probe/transducer was short enough to allow the identification of $(p_0')_{max}$, and the angle at which it occurred, as the probe angle was changed with the rotary mechanism. Measurements of local flow angle, and $(p_0')_{max}$ as a function of radial distance at a fixed axial station are presented in Fig. 4. These measurements show that the local flow angle changes rapidly at the edge of the inviscid core region. Flow angle measurements in this region of the flow were found to be dependent upon the size of the probe. The flow-angle dependence on probe size is illustrated in Fig. 5. It is shown that at the outer edge of the inviscid core the apparent local angle, as determined by the 0.125- and the 0.25-in. (0.318 and 0.635-cm)-diam probes, is toward the nozzle axis rather than away from it. These anomalous flow angle values were observed with both flow-angle measuring techniques, i.e., full rotary scans or derived from the determination of $(p_0')_{max}$. In the present study it has been found that more believable values of flow angle were obtained with a 0.05-in. (0.127 cm)-diam probe (Fig. 5). As a result of similar measurements downstream of the nozzle exit plane it is suggested that the probe interaction effect, identified in Fig. 5, is related to the pressure gradient in this flow regime. The apparently anomalous flow-angle values are not observed far downstream of the nozzle exit where the pressure gradients are considerably less.

Local flow-angle measurements have been made as a function of radial distance from the nozzle centerline at nine ax-

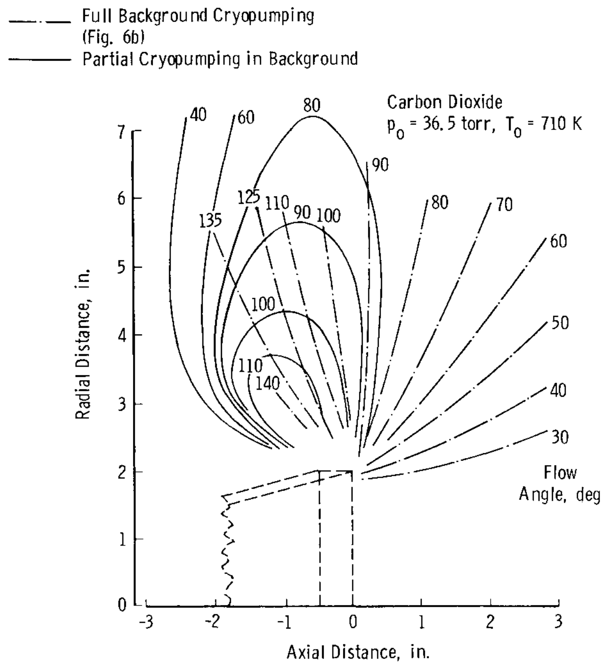


Fig. 7 Effect of partial cryopumping in backflow region on local flow angle.

ial stations. Constant flow-angle values at each of these axial stations have been derived from smooth curves that have been drawn through the experimental measurements, e.g., Fig. 5. The variation of local flow angle with axial and radial location in the nozzle plume is presented in Fig. 6.

It should not be concluded on the basis of these measurements that the maximum flow turning angle for these test conditions is 140 deg. Rather, it may be representative of a physical limitation associated with the probe/rotary-mechanism configuration. The physical size of this mechanism was such that measurements could not be made closer to the nozzle axis and further behind the nozzle exit plane. There are other indications in this study that suggest that the maximum flow angle was greater than 140 deg. This suggestion is based on the fact that after several hours of continuous operation (greater than 4 hr), a thin layer of CO_2 frost could be seen on the LN_2-cooled plate which was positioned slightly upstream of the nozzle throat section (Fig. 1). The inner and outer diameters of this 0.5-in. (1.27 cm)-thick aluminum plate were 4.5 and 9.5 in. (11.4 and 21.4 cm), respectively. Since the exit diameter of the nozzle was 4 in. (10 cm), an inference that may be drawn from the observed frost layer on this plate is that the boundary-layer flow expands through an angle approaching 180 deg in the region of the nozzle lip. Although it is possible that the gas condensed on this plate was a result of the development of a recirculatory flow region upstream of the nozzle exit, other measurements [the free-molecule pressure probe and Quartz Crystal Microbalance (QCM)] indicated that this was not so when this plate was cold enough to pump CO_2.

Local flow angle measurements in the backflow region have been made with cryocooled surface in the region of the throat operating at 80 and 90 K. For an increase in temperature of this magnitude there will be an increase in backscatter from the surface. This increase in backscatter results in the development of what appears to be a recirculatory flow in the backflow region, Fig. 7, as opposed to the source-like flow which exists for the lower temperature surface.

Concluding Remarks

By combining conventional pitot and free-molecule pressure probes with a low-range absolute-pressure transducer and a remotely controlled rotary-positioning device, it has been possible to make measurements of flow angle inside, downstream, and upstream of the nozzle exit plane. The successful development and implementation of this rotary probe demonstrate that meaningful flowfield measurements can be made effectively and efficiently in the nozzle backflow region. Suitably designed probe/transducer configurations of this type could be used to make measurements in the plumes generated by rocket motors in other ground-based test facilities.

Detailed studies of flow angle in the region of the lip have shown that the local flow angle in the boundary layer is not parallel to the local nozzle wall angle but is directed toward the wall. This provides the first experimental support for Bird's[9] theoretical predictions of flow angle in the nozzle lip region. From these flow-angle measurements it can be concluded that boundary-layer codes which do not account for this flow-angle effect cannot be used to make accurate predictions of the flow into the nozzle backflow region. These same flow-angle studies also suggest that a source of the flow into the backflow region is a very thin layer of the boundary layer close to the nozzle wall.

The experimentally observed dependence of local flow angle in the backflow region on small changes in the scattering from a cryocooled plate in this region has implications, with regard to local mass flux measurements, that have been made in this area. Typically, measurements of this type are made with QCM's that are positioned at a fixed orientation with respect to the nozzle axis. Provided there is no backscattering from surfaces in the nozzle backflow region, QCM measurements of this type will be valid since the QCM will not be at a large angle to the local velocity vector. If there is backscatter, the QCM can be at a large angle to the velocity vector and errors in the determination of the local mass flux can occur. On the basis of the present study it is suggested that measurements of the local flow angle in the nozzle backflow region can provide an indication of the presence (or otherwise) of plume/chamber interaction effects.

Acknowledgments

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