Wind Tunnel Pressure Probes: New Calibrations for New Geometries and Flow Environments

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Theme

FOR many years, pitot probes, cone-static probes, and static probes have been successfully applied to supersonic flows at moderate pressures and temperatures, using well-known laws of inviscid continuum fluid mechanics to interpret the measurements. However, modern research and development programs in hypersonic flows require that these probes be exposed to test environments containing flow phenomena which are not taken into account by the inviscid continuum equations. To measure the difference between the actual probe response (subscript m) and the "ideal" predictions of the simplified governing equations (subscript i), calibrations must be made over the full range of flow conditions that will be encountered by the probes during subsequent usage. The purpose of this investigation is to present calibrations of various pitot probe geometries for viscous and rarefaction effects and calibrations of static and cone-static probes for viscous interaction effects so that these probes may be used accurately and confidently in high-speed, low-density flows.

Contents

Calibrations of pitot and cone-static probes were conducted in a small open-jet wind tunnel, using pure nitrogen as the test gas. The facility could operate continuously at Mach numbers (M) from 1.8 to 8.6, stagnation temperatures (T_0) between 300K and 650K, and freestream unit Reynolds numbers (Re/cm) between 40 and 30,000. Static pressure probes required a test environment with smaller axial flow gradients than could be obtained in the open-jet tunnel; consequently, these probes (and the cone-static probes) were calibrated in large contoured nozzles operating at $M=7.2$ with air and $M=14$ with nitrogen. Test conditions at $M=7.2$ were $T_0=710$K and $12{,}000 \leq Re/\text{cm} \leq 42{,}000$; at $M=14$, $T_0=1280$K and $16{,}000 \leq Re/\text{cm} \leq 33{,}000$. Measurements from all probes were corrected for thermal transpiration errors and the effect of any axial flow gradients in the nozzle before correlations of viscous and rarefaction phenomena were examined.

Round (circular-cross-section) pitot probes with no tip chamfer were calibrated *in situ* for viscous and rarefaction effects. Calibration results were in excellent agreement with the data of Potter and Baily[1] and Matthews[2] when correlated by the parameter $Re_{2,R}(\rho_2/\rho_1)^{1/2}$ ($Re_{2,R}$ is the Reynolds number based upon probe tip radius and flow conditions behind the normal shock; ρ_2/ρ_1 is the density ratio across the normal shock.). These probes were used as reference probes during the calibration experiments, and a polynomial fit of the correlation curve was used to correct the reference probe measurements so that true freestream flow conditions could be determined.

To minimize errors due to finite probe height, flat-tipped (rectangular-cross-section) pitot probes with no tip chamfer are often used in flows with large gradients in mean flow properties. Since corrections for viscous and rarefaction effects have not been measured for this probe geometry, nine pitot probes with different tip widths (W) and half-heights (H) were tested in the open-jet facility in inviscid, viscous, and rarefied flow regimes. Correlations of the data using the parameter $Re_{2,H}(\rho_2/\rho_1)^{1/2}$ resulted in considerable scatter due to differences in tip aspect ratio ($W/2H$). Furthermore, none of the flat-tipped probe data coincided with round pitot probe results in the merged layer regime ($Re_{2,H}(\rho_2/\rho_1)^{1/2} < 10$). These observations lead to the conclusion that separate calibrations must be performed for probes with different tip geometries unless the correlation parameter could be modified to include variations in tip shape. With this objective in mind, the probe half-height was replaced in the correlation parameter by a length scale $\bar{H}$ which takes into account both characteristic dimensions (H and W) of the flat-tipped pitot probe. $\bar{H}$ was defined by equating the rectangular-cross-sectional area of the flat-tipped probes to an equivalent area of a circular-cross-section probe with radius $\bar{H}$:

$$\bar{H} = (2KHW/\pi)^{1/2} \tag{1}$$

The parameter K is a measure of the relative effectiveness of the probe width compared to the probe height in determining the extent of rarefaction effects. Values of K were determined by requiring that data from each flat-tipped probe match the round probe data at one point in the merged-layer regime. Figure 1 shows that all other flat-probe data fall on the round probe results, implying that the fundamental viscous and rarefaction phenomena at the probe tip are similar even though the shapes of the probe tips differ significantly.

To achieve the correlation shown in Fig. 1, the free-parameter K was allowed to vary with $W/2H$ (Fig. 2). Correlations involving free parameters should be used only if the behavior of the free parameter can be shown to be

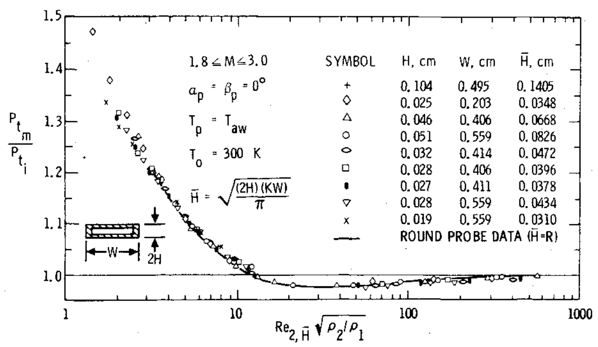

Fig. 1 Flat-tipped pitot probe corrections correlated to round pitot probe data

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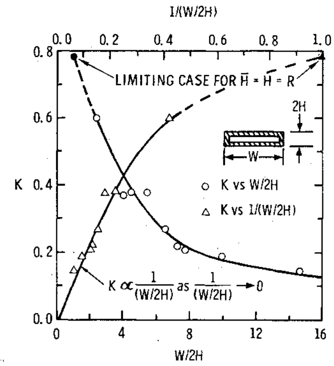

Fig. 2 Variation of K with tip aspect ratio.

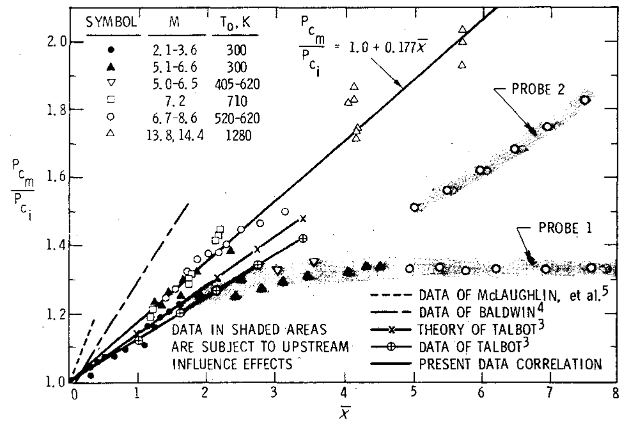

Fig. 3 Cone-static probe corrections for viscous interaction.

physically reasonable. Two checks on the free parameter K were applied for the limiting cases of a square tip and an arbitrarily wide (two-dimensional) tip. The data in Fig. 2 support the trends expected in these limiting cases, and therefore encourage the use of Figs. 1 and 2 in correcting flat-tipped pitot probe measurements for viscous and rarefaction errors.

Three flat-tipped probes with aspect ratios of 2.4, 4.2, and 9.7 were calibrated for the effects of pitch and yaw misalignments in inviscid, viscous, and rarefied flow regimes. The results showed that flat-tipped pitot probes are more sensitive to flow misalignment than circular-cross-section probes. Errors in measured pitot pressure began to appear at a yaw angle of 11°, independent of the flow regime. At larger yaw angles, the magnitude of the error increased with aspect ratio. For pitch misalignments, both the onset and magnitude of measurement errors were a function of flow regime, but the effect of aspect ratio was not as strong as it was in yaw.

Static and cone-static pressure measurements must be corrected for induced pressures caused by the interaction of the probe boundary layer and the inviscid flow. This phenomenon is called hypersonic viscous interaction, and is described by the parameter $\bar{\chi} = M^3(C/Re_\ell)^{1/2}$, where C and Re_ℓ are the Chapman-Rubesin constant and Reynolds number based upon the distance to the pressure orifices. Two cone-static probes with 10° half-angles were calibrated for values of $\bar{\chi}$ (based upon inviscid cone properties and measured wall temperature) between 0.3 and 5.8. Figure 3 shows that both the present results and previous empirical data[3-5] suffer from appreciable scatter which cannot be explained by differences in the values of wall temperature ratio or the hypersonic similarity parameter among the experiments. A separate experiment, conducted in the open-jet wind tunnel, proved that all data in the shaded regions of Fig. 3 were affected by the upstream influence of the cone-shoulder expansion fan. Other possible sources of scatter in Fig. 3 include rarefaction and transverse curvature effects. Since none of these effects can be correlated by $\bar{\chi}$, the cone-static probe may be of little use under test conditions which give rise to any of these phenomena. In the absense of such effects, the ratio of measured cone-static pressure to "ideal" pressure for the 10° half-angle probes was satisfactorily correlated by

$$P_{c_m}/P_{c_i} = 1.0 + 0.177\bar{\chi} \tag{2}$$

The static probe geometry tested in this and other experiments was a 10° half-angle cone-cylinder, with pressure orifices located sixteen cylinder-diameters downstream of the cone-cylinder junction. It was originally tested in the open-jet facility at values of $\bar{\chi}$ (based upon freestream conditions) below 1.0. The results of this experiment showed that static probes should not be used in flows with strong axial or radial pressure gradients. Calibrations at $M = 7.2$ and $M = 14$, where axial gradients were negligible, indicated that the static probe was much less susceptible to rarefaction and transverse curvature effects than the cone-static probe. The ratio of measured static pressure to "ideal" static pressure is adequately correlated by the linear relationship first suggested by Williams[6]

$$P_m/P_i = 1.0 + 0.080\bar{\chi} \tag{3}$$

even though the range of calibration has been extended to much larger values of $\bar{\chi}$ (8.3) than in Ref. 6.

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