[2] Belotserkovskii, O. M., "Flow with a Detached Shock Wave about a Symmetrical Profile," *Journal of Applied Mathematics and Mechanics (PMM)*, Vol. 22, 1958, pp. 279–296.

[3] Belotserkovskii, O. M., "Supersonic Gas Flow around Blunt Bodies," TT F-453, 1967, NASA.

[4] Traugott, S. C., "An Approximate Solution of the Direct Supersonic Blunt-Body Problem for Arbitrary Axisymmetric Shapes," *Journal of the Aerospace Sciences*, Vol. 27, 1960, pp. 361–370.

[5] Gummer, J. H. and Hunt, B. L., "The Impingement of a Uniform, Axisymmetric Supersonic Jet on a Perpendicular Flat Plate," *The Aeronautical Quarterly*, Vol. 22, 1971, pp. 403–420.

[6] Fox, L., *Numerical Solution of Ordinary and Partial Differential Equations*, Pergamon Press, Oxford, England, 1962, Chap. 4.

[7] Hunt, B. L., "An Attempted Improvement of the Method of Integral Relations for a Blunt Body in a Supersonic Flow," BLH/7301, 1973, Dept. of Aeronautical Engineering, Bristol Univ., Bristol, England.

# Heat Flux Probe as a Flowfield Diagnostic

IRWIN E. VAS*
*Princeton University, Princeton, N.J.*

IN recent years, several new developments have been made in the area of flowfield diagnostics. A few years ago, a new technique was developed which appeared ideally suited for measurements in a hot gas stream.[1] The "heat flux probe," as it is called, is small in size and can be used with good spatial resolution. The purpose of the present Note is to indicate that some published results obtained with this probe are quite inaccurate even though the probe technique and calibration appear very reasonable.

The heat flux probe operates on the same principle as a constant temperature hot wire. The sensor is a glass tube 0.006 in. o.d. with a wall thickness of 0.001 in. A thin platinum film is deposited on the tube to a length of 0.05 in. In a hot gas stream a balance is made between the convective heating of the sensor by the gas, cooling of the sensor by passing cold gas (or liquid) through it, and resistive heating of the sensor. The electronic circuitry is the same as required for a constant temperature hot wire. The probe and electronic circuitry was purchased from Thermo-Systems.

The initial concept, design and use of the heat flux probe was published in a thesis by Fingerson[1] in 1961. Since that time several other investigators have used this technique.[2–5] It is the results from McCroskey, Horstman, and Vas using this probing technique which will be discussed, and compared with results using other techniques.

A brief review of the three particular studies will initially be made. McCroskey examined the flow about a sharp flat plate in nitrogen at a freestream Mach number ($M_\infty$) of 25, Reynolds number ($Re_\infty$) of $10^4$/in. and stagnation temperature ($T_{t_\infty}$) of 2000°K. Flowfield measurements of pitot pressure ($p_t$) and heat flux ($\dot{q}$) were made. Horstman determined the flowfield about a 3° half-angle cone at $M_\infty \sim 41$, $Re_\infty/\text{in.} \sim 5.6\times10^4$ and $T_{t_\infty} \sim$ 900°K using helium as the test gas. The measurements in the flowfield included pitot pressure and heat flux. Detailed flowfield measurements were made by Vas on a 10° half-angle cone at two conditions: a) $M_\infty \sim 19$, $Re_\infty/\text{in.} \sim 4.0\times10^4$ and $T_{t_\infty} =$ 1700°K; b) $M_\infty \sim 25$, $Re_\infty/\text{in.} \sim 10^4$ and $T_{t_\infty} = 1850$°K. The traverses were made using four measuring techniques: pitot pressure, heat flux, total temperature ($T_t$) and density ($\rho$).

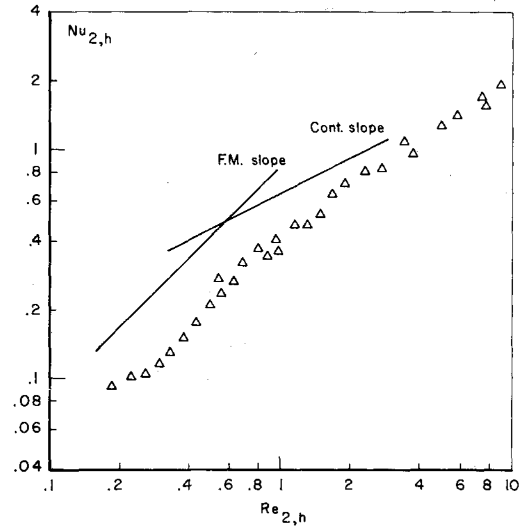


**Fig. 1 Heat flux probe calibration.**

In addition to the previous measurements on a flat plate in the hypersonic nitrogen gas flow, direct density measurements were performed by Harbour and Lewis[6] at conditions similar to Ref. 2. Recent flowfield measurements were made by Petraites[7] on a flat plate at these same conditions using a pitot probe and total temperature probe. Density and velocity ($u$) profiles were derived from the measurements of McCroskey and Petraites. The density profiles can be compared with the direct measurements of Harbour and Lewis.

In using the heat flux probe, a calibration was performed by each of the research workers. McCroskey carried out a calibration in the hypersonic helium and nitrogen facilities at Reynolds numbers $Re_{2,h}$ (based on conditions behind the shock and probe diameter) from 1 to 10. To obtain a larger range of Reynolds number a calibration was performed by Vas at $M_\infty \sim 2$ and 6 and stagnation temperatures between 550°K and 1150°K to give Reynolds numbers from 0.15 to 10. This was in addition to calibrations carried out in the hypersonic nitrogen facility. Over a range of Reynolds number the heat transfer to the sensor was measured ($Nu_{2,h}$) and is shown in Fig. 1. The slope of the measurements at the low and high Reynolds number ends approach the free molecule and continuum values, respectively. These measurements give the same trend as a hot wire.[8]

The flowfield characteristics were determined in Ref. 2 using measured pitot pressure and heat flux profiles and the wall static pressure. From these measurements, density and velocity profiles were calculated and are shown in dimensionless form ($\bar{\rho} \equiv \rho/\rho_\infty$, $\bar{u} \equiv u/u_\infty$) in Figs. 2 and 3 for the value of the rarefaction parameter, $[\bar{V} \equiv M_\infty (C)^{1/2}/(Re_{\infty,x})^{1/2}]$, of about 0.12. These profiles are not all made at identical distances $x$ from the leading edge. The height above the surface $y$ is nondimensionalized by the shock layer thickness $y_s$. Included in Fig. 2 is a direct measurement of density by the electron beam technique.[6] Behind the shock the density obtained by the electron beam technique is higher than that obtained by the other two methods. The profiles obtained by these methods are in agreement in the outer portion of the shock layer, but the results using the heat flux method deviate considerably from those obtained by the total temperature method, as well as the direct measurement, in the inner portion of the shock layer. In the shear layer, the

Received April 26, 1973; revision received June 12, 1973. This work was supported jointly by the Aerospace Research Laboratory, Office of Aerospace Research under contract AF33615-70-C-1244 and the U.S. Air Force Office of Scientific Research under contract AF44620-71-C-0032.

Index category: Research Facilities and Instrumentation.

* Senior Research Engineer and Lecturer, Department of Aerospace and Mechanical Sciences, Gas Dynamics Laboratory. Associate Fellow AIAA.

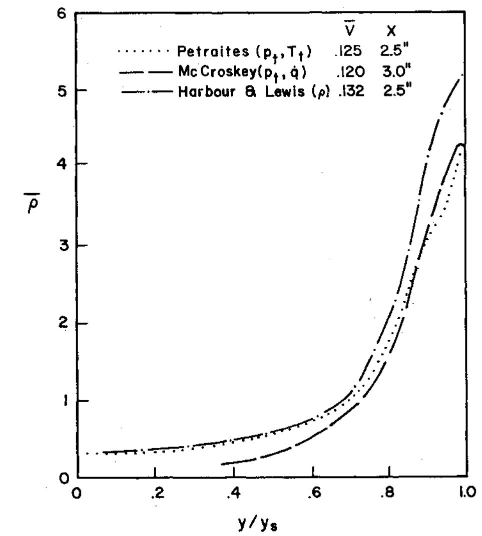


Fig. 2 Density profile on a flat plate at $M_\infty \sim 25$.

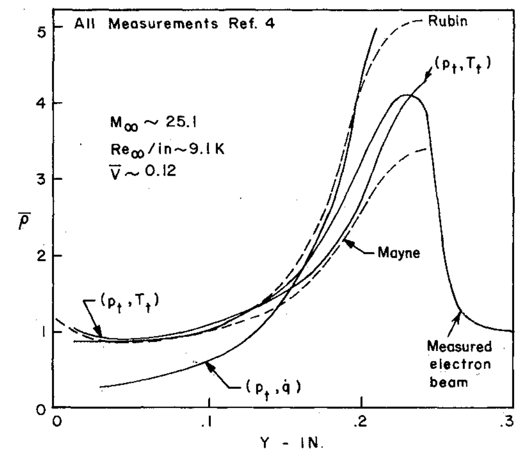


Fig. 4 Density profile on a sharp cone at $M_\infty \sim 25$.

velocity profile obtained using the heat flux probe is considerably fuller than that obtained using the total temperature probe. The simple laminar van Driest calculation is shown for reference purposes only for $M_\delta$ (the Mach number at the edge of the viscous region) of 12.

In a study on a 10° half-angle cone at $M_\infty \sim 25$ in nitrogen, the density distributions are shown in Fig. 4 at $\bar{V} \sim 0.12$ (Ref. 4). All of these measurements are made at identically the same location on the body at the same test conditions. The density obtained by the heat flux probe ($p_t$, $\dot{q}$) is higher in the outer portion of the shock layer and lower near the wall than obtained by the direct density measurement. Using the total temperature probe ($p_t$, $T_t$) the density is in good agreement with the direct density measurement. Also shown in the figure are theoretical calculations carried out by Rubin[9] and Mayne[10] for these particular test conditions. The calculations agree with each other in the inner portion of the shock layer but disagree considerably in the region behind the shock.

The velocity profiles show more clearly the effect of using the heat flux probe (Fig. 5). The velocity obtained by the heat flux probe in the outer portion of the shock layer is somewhat lower than the freestream value. It increases going towards the body (in the viscous region) then decreases, but reaches a minimum value of about 0.5. The velocity obtained using the total temperature probe gives the right value in the inviscid region of the flow and tends to a small slip when extrapolated to the wall. The profile is in reasonable agreement with the predicted velocity profiles of Mayne and Rubin.

Velocity profiles obtained, using pitot and heat flux profiles with the wall static pressure, gave high values of velocity (higher than freestream) in the viscous region on a 3° cone at $M_\infty \sim 41$ in helium flow.[3] No verification of these profiles was made by an alternate scheme.

The trend shown by the flowfield measurements indicates that the heat flux probe gives a) a density which is lower than the true density in a major portion of the boundary layer, and b) a velocity which is higher than the true velocity in a major portion of the boundary layer. The low value of the density and high value of velocity which occur when the heat flux probe is used in the inner portion of the shock layer imply a total temperature which is higher than the real value. It appears that even though the calibration of the heat flux probe is normal, the use of the probe in a viscous region (with varying stagnation temperature) is extremely doubtful. At the time that the measurements were performed by both McCroskey and Horstman only pitot and heat flux measuring techniques were available. Since that time, with the availability of a small total temperature probe and direct density measurements, a check can be made on the accuracy and dependability of the various techniques.

From the studies considered, the heat flux probe gives results which differ extensively from those obtained by other measuring techniques and also from theoretical predictions. In using this

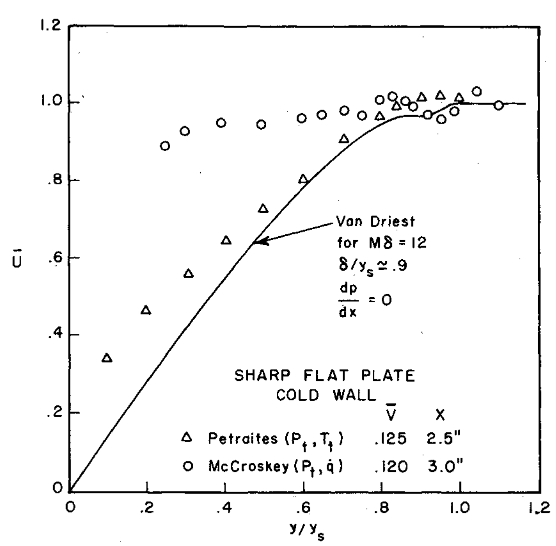


Fig. 3 Velocity profile on a flat plate at $M_\infty \sim 25$.

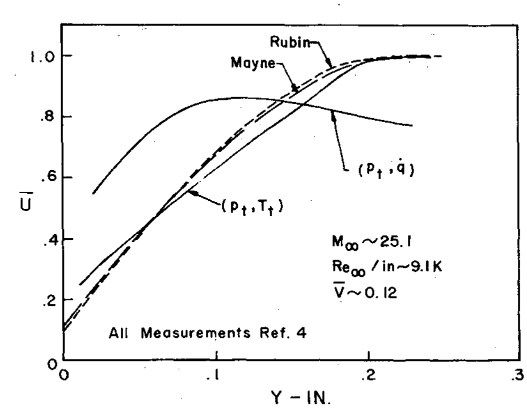


Fig. 5 Velocity profile on a sharp cone at $M_\infty \sim 25$.

particular technique, it would be advisable to verify its reliability by an additional measuring method.

## References


[1] Fingerson, L. M., "A Heat Flux Probe for Transient Measurements in High Temperature Gases," Ph.D. thesis, 1961, Univ. of Minnesota, Minneapolis, Minn.; also *ARS Journal*, Vol. 13, No. 11, Nov. 1962, p. 1709.

[2] McCroskey, W. J., "Density and Velocity Measurements in High-Speed Flows," *AIAA Journal*, Vol. 6, No. 9, Sept. 1968, pp. 1805–1808.

[3] Horstman, C. C. and Kussoy, M. I., "Hypersonic Viscous Interaction on Slender Cones," AIAA Paper 68-2, New York, 1968.

[4] Vas, I. E., "An Experimental Investigation of the Flow About a Slender Cone at Hypersonic Speeds," Ph.D. thesis, 1970, New York Univ., New York.

[5] Becker, M., Papanikas, D. G., and Schweiger, G., "Experimental Study of the Flow Field in Front of Hemispheres in the Transition and Shock Formation Regime," presented at the 7th RGDS, July 1970, Deutsche Forschungs- und Versuchsanstalt fur Luft- und Raumfahrt, (DFVLR) Porz-Wahn, W. Germany.

[6] Harbour, P. J. and Lewis, J. H., "Preliminary Measurements of the Hypersonic Rarefield Flow Field on a Sharp Flat Plate Using an Electron Beam Probe," *Rarefied Gas Dynamics*, Supp. 4, Vol. 1, Academic Press, New York, 1967.

[7] Petraites, R. J., "An Experimental Investigation of the Effects of Three-Dimensionality on the Flow Over a Flat Plate at $M \sim 25$," MSE thesis, Aug. 1972, Dept. of Aerospace and Mechanical Sciences, Princeton Univ., Princeton, N.J.

[8] Dewey, C. F., Jr., "A Correlation of Convective Heat Transfer and Recovery Temperature Data for Cylinders in Compressible Flow," *International Journal of Heat and Mass Transfer*, Vol. 8, 1965, pp. 245–252.

[9] Rubin, S. G., Rudman, S., Lin, T. C., and Pierucci, M., "Hypersonic Viscous-Inviscid Interaction by a New Type of Analysis," AGARD CP 30, Hypersonic Boundary Layers and Flow Fields, May 1968.

[10] Mayne, A. W., Jr., Gilley, G. E., and Lewis, C. H., "Binary Boundary Layers on Sharp Cones in Low-Density Supersonic and Hypersonic Flow," *AIAA Journal*, Vol. 7, No. 4, April 1969, pp. 699–706.


# A Simple Correlation for Incipient Turbulent Boundary-Layer Separation due to a Skewed Shock Wave


R. H. Korkegi*

*Aerospace Research Laboratories, Wright-Patterson Air Force Base, Ohio*


## Introduction

A frequently encountered form of three-dimensional shock wave-turbulent boundary-layer interaction is that due to a wedge mounted normal to a surface in a supersonic stream. Such a configuration is representative of a sharp-edged fin on a flying vehicle, an axial compression corner in an air breathing engine inlet or a wind-tunnel diffuser, and end wall conditions for a row of blades in turbomachinery.

The configuration is illustrated in Fig. 1. $\Theta$ is the wedge half angle or flow deflection angle and $\beta$ is the wedge shock wave angle. The shock wave is skewed to the turbulent boundary layer on the flat plate on which the wedge is mounted. Of particular interest for practical applications is the condition of incipient separation of the turbulent boundary layer, defined by the deflection angle $\Theta_i$.

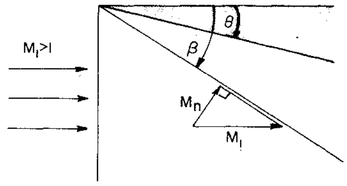


**Fig. 1 Skewed shock wave on flat plate.**

## Theory

McCabe[1] develops a simple approximate theory for conditions across the skewed shock wave, which relates the deflection of the flow at the surface to the flow at the edge of the turbulent boundary layer, based on the assumption that all the vorticity in the boundary layer upstream of the shock wave is convected with the freestream velocity. He obtains

$$\tan \varepsilon = \frac{\cos^2(\beta - \Theta) - \cos^2 \beta}{\cos^2 \beta \tan(\beta - \Theta)} \tag{1}$$

where $\varepsilon$ is the angle between the surface flow and the edge flow.

McCabe makes the reasonable assumption that incipient separation occurs when the surface flow becomes aligned with the shock wave, i.e. when $\varepsilon = \beta - \Theta_i$, for which condition Eq. (1) becomes

$$\cos \beta = \cos^2(\beta - \Theta_i) \tag{2}$$

With the assumption of small angles corresponding to $M_1 \gg 1$, Eq. (2) can be approximated to a first order by

$$\Theta_i \simeq (1 - 2^{1/2}/2)\beta = 0.293\beta \tag{3}$$

For practical purposes it is useful to relate the incipient deflection angle $\Theta_i$ to the freestream Mach number $M_1$. From oblique shock wave theory, the relationship between deflection angle, shock wave angle and Mach number is

$$\cot \Theta = \tan \beta \left[ \frac{[(\gamma+1)/2]M_1^2}{M_1^2 \sin^2 \beta - 1} - 1 \right] \tag{4}$$

which, for small angles and $\gamma = 1.4$, approximates to

$$M_1^2\beta^2 - 1 = 1.2M_1^2\Phi\beta - (M_1^2\beta^2 - 1)\Theta\beta \tag{5}$$

Substituting Eq. (3) for the incipient condition into Eq. (5) results in

$$M_1\Theta_i = 0.364[1 + 0(\Theta_i^2)] \simeq 0.364 \tag{6}$$

Thus, from McCabe's theory for $M_1 \gg 1$ the incipient separation angle $\Theta_i$ is inversely proportional to Mach number. Now, the component of Mach number normal to the oblique shock wave is $M_n = M_1 \sin \beta \simeq M_1\beta$. For the incipient condition, by substitution of Eqs. (3) and (6) one obtains

$$M_n = 3.42 M_1 \Theta_i = 1.24$$

for which the pressure rise is $P_i/P_1 = 1.63$, a constant value independent of Mach number.

## Comparison with Experiment

Incipient separation data by McCabe[1] and Lowrie[2] are given in Table 1 along with the corresponding shock-wave angles, normal Mach number components, and pressure rises.

The data, although over a limited Mach number range, bear out the near constancy of the pressure rise and of $M_1\Theta_i$ although the values are somewhat lower than that of Eq. (6). Better agreement with experiment is given by

$$M_1\Theta_i = 0.30 \tag{7}$$

This correlation along with the experimental values from Table 1 are shown in Fig. 2 in which the bars across the


Received May 3, 1973.

Index categories: Boundary Layers and Convective Heat Transfer—Turbulent; Jets, Wakes, and Viscid-Inviscid Flow Interactions; Supersonic and Hypersonic Flow.


* Director, Hypersonic Research Laboratory. Associate Fellow AIAA.