Flowfield Measurements Using a Total Temperature Probe at Hypersonic Speeds

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A "fine wire" total temperature probe has been constructed, calibrated, and used at hypersonic speeds. The calibration was performed at Mach numbers of 2, 6, and 25, stagnation temperatures from 300°K–2500°K and Reynolds number (based on conditions behind the shock and wire diameter) from 10^{-2} to 10. Calculating the conduction, convection and radiation losses by the equations developed for the hot wire, the probe gave the gas temperature to within 10% of the calculated adiabatic wire temperature over a major portion of the Reynolds number range. The probe was then used to provide the total temperature in the shock layer of a sharp 10° half-angle cone at $M_\infty \sim 19$, $T_o \sim 1700$°K and Re_∞/in. ~ 40,000. With the additional measurements of the wall static pressure and Pitot profile, the flowfield characteristics were determined and compared with some available theoretical predictions.

Nomenclature

d = wire diameter
h = heat-transfer coefficient
k = thermal conductivity
Kn = Knudsen number
L = wire span
M = Mach number
Nu = Nusselt number
q = heat-transfer rate
Re = Reynolds number
T = temperature
U = velocity
y = distance from the model surface
ε = emissivity
σ = Stefan-Boltzmann constant

Subscripts

a or 1 = before shock
b or 2 = after shock
∞ = freestream
o or t = stagnation condition
g = local gas condition
ad = adiabatic condition
w = wire condition
d = wire diameter
tc = thermocouple condition
j = surroundings
n = needle (support) conditions

Superscript

— = nondimensionalized by freestream conditions

Introduction

TOTAL temperature probes have normally been used in the freestream with no stringent requirements on size. The ideal probe was considered one in which the recorded temperature from a thermocouple was identically the value of the stagnation temperature. As the stagnation temperature increased, the losses due to radiation and conduction also increased. To reduce these losses, shielded probes were designed; the larger the number of shields, the higher the efficiency of the probe. A small vented probe, with a high recovery factor, was made by Winkler[1] in 1954. This probe used a single shield of silica, plated with platinum or gold in order to reduce both the conduction and radiation errors (Fig. 1). Even though this probe was smaller than others, it could not be used to make measurements close to the wall or in a thin boundary layer. The parameters that influenced the probe reading were the stagnation temperature, Mach number, Reynolds number, and vent-to-inlet areas. Further improvements in this type of probe were made by Wood,[2] however, in this case, the probe was more complicated than suggested

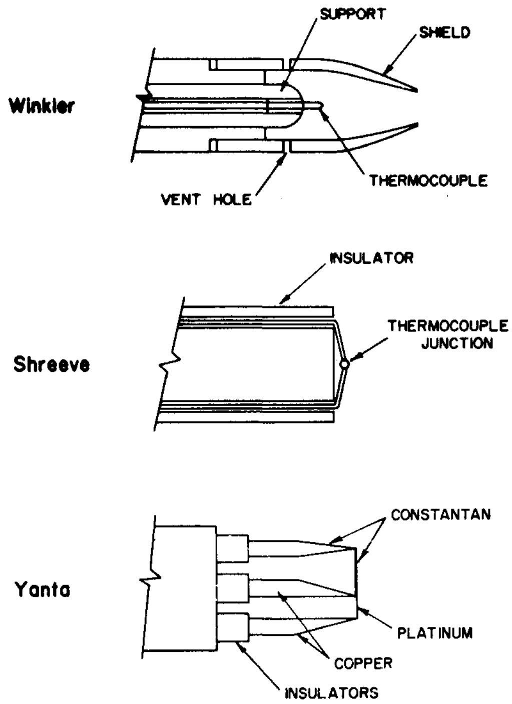

Fig. 1 Sketches of shielded (Winkler), small bare wire (Shreeve), and fine-wire type (Yanta) probes.

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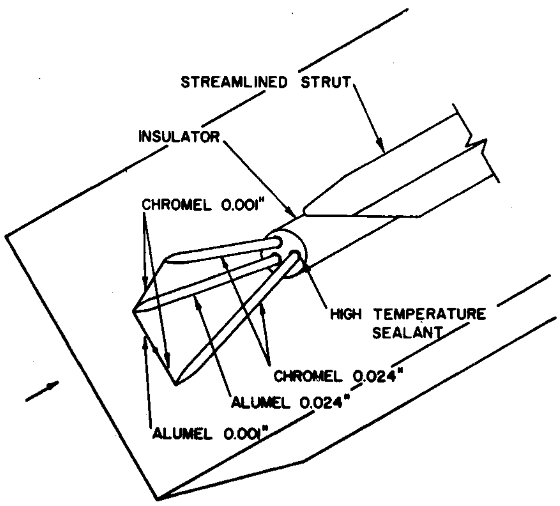

Fig. 2 Sketch of the "fine-wire" type thermocouple probe.

by Winkler. To reduce the radiation losses from the thermocouple, the outside of the shield was electrically heated. This extra complication in the design did not drastically change the size of the probe, which could still be used fairly close to the wall. The over-all diameter of the probe was about 0.06 in. This probe was also affected by changes in Reynolds and Mach numbers. For measurements close to the wall, the tip of the probe was flattened to a dimension of about 0.03 in. Both of these probes were intended to achieve a recovery factor close to unity, so that in use, the value of the measured temperature and recovery temperature would be identical.

An unshielded probe was recently made by Shreeve[3] using very fine thermocouple wires to form a junction at the front of the holder (Fig. 1). Chromel and alumel wires were employed with the wire diameters varying from 0.002 in.–0.0005 in. The results from this probe at temperatures up to about 700°K indicated that in using the finer wires the recovery factor of the probe approached unity. These tests were performed at $M_\infty \sim 6$ and Re_∞/in. greater than 5×10^5. The outside size of the probe holder was 0.063 in. with an insulator diameter of 0.031 in. which is similar in dimensions to the small vented probes.

A different approach was used by Yanta,[4] who designed a probe using hot wire concepts (Fig. 1). He used a thin platinum wire across two copper supports and read the resistance of the wire. A third support of constantan was used and a constantan wire strung between the tip of the copper support and constantan support. This gave the temperature at the copper support. From the known resistance of the wire (platinum) and the temperature of the copper support, using the solution of the one-dimensional heat conduction equation and relationships available for convective heat transfer to a fine wire, the local stagnation temperature was inferred. This probe has the capability of being used close to the wall due to its small size. For this particular probe, the platinum wire diameter was 0.0001 in. and constantan wire was 0.001 in. The probe has been used at a Mach number of 5, at a stagnation temperature up to approximately 400°K at Re_∞/in. about 5×10^4.

Using hot-wire principles, a more advanced probe was constructured[5] to operate in a region where not only conduction losses but also radiation losses could be significant. However, it differed from the preceding in that a thermocouple junction was made midway between the supports (Fig. 2). A third support was used, with a wire going between one of the main supports and the auxiliary support, to measure the main support temperature. From the temperature measured midway between the main supports, the support temperature and freestream flow conditions, the corrections in the gas temperature due to conduction and radiation losses could be calculated. A calibration was performed over an extended Mach number, Reynolds number and stagnation temperature range for several wire diameters and spans. One of the limits in the conditions of the calibration minimized either the conduction or radiation loss thus verifying the calculation technique. This method of calculating the corrections was then applied to the probe when it was used in the shock layer of a sharp cone at a Mach number of about 19 and Reynolds number per inch of about 40,000.[5]

A similar probe was recently made by Yanta[6] and calibrated at $M \sim 5$, $T_0 \sim 430$°K and Reynolds numbers based on aftershock and wire diameter larger than 0.8. For these conditions, no radiation losses were considered.

Probe Design

The fine wire thermocouple probe, because of its construction and geometry, can be used close to the wall. Three supports are used, all with a diameter of 0.024 in. The tips of the supports are streamlined (conical). Three different sizes of sensing wire are used in the work reported here—0.001, 0.002, and 0.005 in. in diameter. The sensing wire is held between two main supports, one of chromel and one of alumel. Midway in the sensing wire is the chromel-alumel junction, the chromel end of the wire going to the chromel support and the alumel end of the wire going to the alumel support. A fine wire of chromel joins the main alumel support (at the tip) to the auxiliary chromel support. The support temperature, as well as the temperature midway between the supports, can thus be measured. As the probe is intended to be used at elevated temperatures, all joints are welded.

The three supports pass through a ceramic insulator which is held in a streamlined stainless steel strut. The supports are rigidly held at the front of the insulator by a high-temperature cement. To reduce conduction losses, the ratio of the span between the main supports and the diameter of the sensing wire should be kept relatively large. Two different span lengths were used, 0.16 and 0.38 in., resulting in six different aspect ratios, from a minimum of 32 to a maximum of 380. When making flowfield measurements, the strut was placed at an angle to the body surface with the sensitive wire parallel to the model surface and normal to the flow direction. In the present shear layer measurements, the angle between the probe and the surface of the body was about 10°.

An advantage of this type of probe is that the wire diameter may be made large (the aspect ratio may be made small). This permits its use in a region where the dynamic loads may be large. A sketch of the probe is shown in Fig. 2.

Calculation of the Heat Losses

For a wire placed in a hot gas stream, there are three means by which energy transfer occurs: a) the wire is heated by the oncoming gas stream by convection; b) the wire loses energy to its surroundings by radiation; and c) the wire transfers energy to its supports by conduction.

One advantage of the fine wire probe is that the analysis for a standard hot wire has been quite well detailed in subsonic and supersonic flows and in regimes that extend from continuum to free molecular. Heat transfer and recovery factor measurements for a cylinder in cross flow have been amply verified. Empirical relationships have been derived by Dewey[7] to correlate the available data up to a Mach number of approximately 6. The radiation and conduction corrections for a cylinder have also been shown previously[4,8,9]; however, for completeness the corrections will be indicated in the present paper.

For steady state, the sum of the heat-transfer rates due to convection, conduction and radiation must be identically zero. The convective heat transfer per unit length is given as

$$q]_{\text{conv}} = (Nu\, k_g/d)(T_g - T_w)\pi d$$

where T_g is the adiabatic wire temperature which is obtained by using the measured wire and support temperatures. The conductive heat transfer through the ends of a wire per unit length is

$$q]_{\text{cond}} = k_w(\partial^2 T_w/\partial x^2)\pi d^2/4$$

The amount of radiation emitted by the wire of unit length is given by $\sigma\varepsilon_w T_w^4 \pi d$. The amount of energy received from the surrounding is given as $\sigma\varepsilon_w T_j^4 \pi d$. If the gas temperature is not sufficiently high to radiate, the radiative heat transfer becomes

$$q]_{\text{rad}} = \sigma\varepsilon_w \pi d(T_j^4 - T_w^4)$$

The heat-transfer balance is then given by

$$\left[\frac{Nu k_g}{d}(T_g - T_w)\pi d\right] + \left(k_w \frac{\partial^2 T_w}{\partial x^2}\frac{\pi d^2}{4}\right) + [\sigma\varepsilon_w(T_j^4 - T_w^4)\pi d] = 0$$

This can be rewritten as

$$T_g - T_w + (k_w/Nu k_g)(\partial^2 T_w/\partial x^2)d^2/4 + \bar{\beta}_1[(T_j/T_w)^4 - 1]\varepsilon_w = 0$$

where

$$\bar{\beta}_1 = \sigma d T_w^4/Nu k_g$$

The gas temperature is then given as

$$T_g = T_w - \bar{\beta}_1[(T_j/T_w)^4 - 1]\varepsilon_w - (1/\eta^2)\partial^2 T_w/\partial x^2$$

where

$$\eta^2 = 4Nu k_g/d^2 k_w$$

The resulting differential equation is

$$(1/\eta^2)\partial^2 T_w/\partial x^2 - T_w + T_f = 0$$

where T_f is the temperature the wire would reach if no conduction losses existed, and

$$T_f = T_g + \bar{\beta}_1[(T_j/T_w)^4 - 1]\varepsilon_w$$

Solving the differential equation with the boundary conditions

$$T_w = T_n \quad \text{at} \quad x = 0 \quad \text{and} \quad x = L$$

gives the solution

$$T_w = T_f + (T_n - T_f)\psi$$

where the temperature distribution function ψ is

$$\psi = [\sinh x + \sinh(\eta L - \eta x)]/\sinh \eta L$$

At the midpoint of the wire $T_w = T_{tc}$, $\psi = \psi_m$ and ψ_m simplifies to

$$\psi_m = \text{sech}(\eta L/2)$$

Then

$$T_{tc} = T_f + (T_n - T_f)\psi_m$$

and the gas temperature is given by

$$T_g = T_{tc} - \bar{\beta}_1[(T_j/T_{tc})^4 - 1]\varepsilon_w - [(T_n - T_{tc})/(1 - \psi_m)]\psi_m$$

The correction in the temperature due to radiative effects is

$$\Delta T]_{\text{rad}} = \bar{\beta}_1\{(T_j/T_{tc})^4 - 1\}\varepsilon_w$$

and that due to conductive effects

$$\Delta T]_{\text{cond}} = [(T_n - T_{tc})/(1 - \psi_m)]\psi_m$$

with the gas temperature given as

$$T_g = T_{tc} - \Delta T]_{\text{rad}} - \Delta T]_{\text{cond}}$$

Hence, for a nonradiating gas the temperature changes due to conduction and radiation effects can be determined if the Nusselt number and gas thermal conductivity are known.

For nitrogen with a temperature above 300°K the thermal conductivity[10] is given as

$$k_g = k_o(1 + 3.13\times10^{-3}t - 1.33\times10^{-6}t^2 + 2.63\times10^{-10}t^3)$$

where

$$k_o = 4.5227\times10^{-4} \text{ ft lbf/in. sec °K}$$

and t is in °C.

The thermal conductivity of the chromel and alumel wires vary with temperature.[15] To simplify the calculation, a fixed value of the wire thermal conductivity was used equal to 0.47 ft-lbf/in. sec °K.

The Nusselt number is calculated following the method outlined by Dewey[7] where a corrective term is involved to account for Mach and Reynolds number effects, namely

$$Nu_{b,d}(Re_{b,d}, M) = Nu_{b,d}(Re_{b,d}, \infty)[\phi(Re_{b,d}, M)]$$

where

$$Nu_{b,d}(Re_{b,d}, \infty) = Re_{b,d}^{\,n}\left[0.14 + (0.2302)\left(\frac{Re_{b,d}^{\,0.7114}}{15.44 + Re_{b,d}^{\,0.7114}}\right) + \left(\frac{0.01569}{2.571 + Re_{b,d}^{\,0.7378}}\right)\left(\frac{15}{15 + Re_{b,d}^{\,3}}\right)\right]$$

$$n = 1 - \tfrac{1}{2}\left(\frac{Re_{b,d}^{\,0.6713}}{2.571 + Re_{b,d}^{\,0.6713}}\right)$$

$$\phi(Re_{b,d}, M) = 1 + \psi\omega Y$$

$$\psi = (0.6309/M) + 0.5701\{[M^{1.222}/(1 + M^{1.222})]^{1.569} - 1\}$$

$$\omega = 1 + [0.300 - (0.0650/M^{1.670})][Re_{b,d}/(4 + Re_{b,d})]$$

$$Y = 1.834 - 1.634[Re_{b,d}^{\,1.109}/(2.765 + Re_{b,d}^{\,1.109})]$$

At very low Reynolds numbers, n approaches unity and the Nusselt number varies directly as the Reynolds number (free molecule flows). At high Reynolds number, n approaches 0.5 and the Nusselt number varies as $Re^{1/2}$ (continuum flows). All quantities are now defined and the gas temperature can be obtained.

The gas temperature, T_g, is not the stagnation temperature, T_t, but is really the adiabatic wire temperature, T_{ad}. This in turn can be obtained from the local Mach number, Reynolds number and stagnation temperature. Using the empirical correlations[7] for measurements conducted over a wide range of Mach and Reynolds numbers at $\gamma = 1.4$ (Refs. 9 and 11–14), we can write the adiabatic temperature in terms of the continuum and free molecule recovery ratios.

$$T_{ad}/T_t = \bar{\eta}^*(\eta_f - \eta_c) + \eta_c$$

where

$$\bar{\eta}^* = Kn^{1.193}/(0.493 + Kn^{1.193})$$

$$\eta_c = 1 - 0.05[M^{3.5}/(1.175 + M^{3.5})]$$

$$\eta_f - \eta_c = 0.2167[M^{2.8}/(0.8521 + M^{2.8})]$$

with the Knudsen number based on conditions ahead of the shock and wire diameter

$$Kn_{a,d} = \lambda/d = 1.482\,M_a/Re_{a,d}$$

Other quantities necessary for the calculations are the Stefan-Boltzmann constant σ where

$$\sigma = 2.7272\times10^{-11} \text{ ft-lbf/sec in.}^2\text{ °K}^4$$

and the emissivity of the wire ε_{tc}. From the data available an averaged value was taken

$$\varepsilon_{tc} = 0.27 + 5\times10^{-4}(T_{tc} - 300)$$

with T_{tc} in °K. All quantities are thus known to calculate the conduction and radiation losses, to determine the gas temperature, and to obtain the adiabatic wire temperature if freestream (before shock) conditions are known.

Probe Calibration

A. Facility

An essential feature in using a probe is to have its calibration over a range of Mach number, Reynolds number and stagnation temperature. In general, all these parameters will affect the performance of a probe. To provide a variation of these parameters a special calibration facility was constructed. A brief description follows.

As the probe was to be used in a hypersonic nitrogen tunnel, nitrogen was also used in the calibration tunnel. The gas was passed through an inconel pipe which was electrically heated by a motor generator set. The inconel pipe was approximately 25 ft long with a 1 in. outside diameter. As the gas traveled along the pipe, its temperature increased to a value close to the pipe temperature, at the pipe exit. At the stagnation chamber, the pressure and temperature were recorded. The stagnation temperature which can be taken to about 1200°K was measured by a chromel-alumel shielded thermocouple constructed from 0.010 in. wire. Simple converging-diverging (conical) nozzles were used to

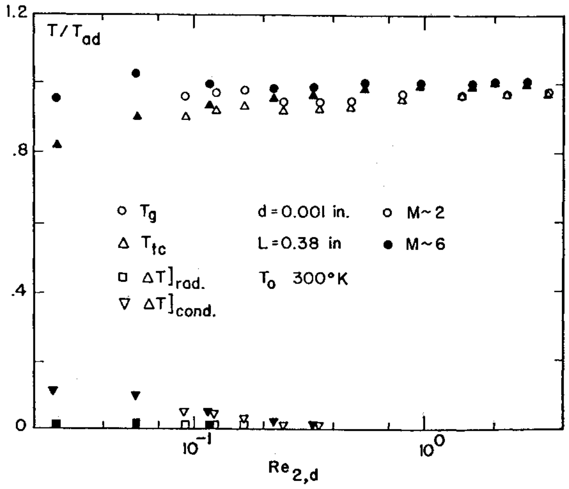

Fig. 3 Probe calibration $M \sim 2$ and 6, $d = 0.001$ in., $T_o \sim 300°K$.

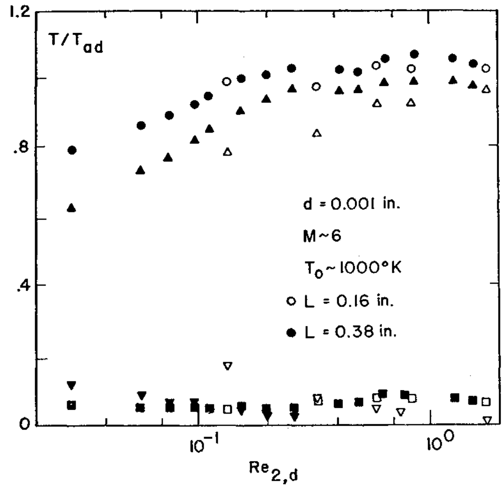

Fig. 4 Probe calibration $M \sim 6$, $d = 0.001$ in., $T_o \sim 1000°K$.

provide test section Mach numbers of approximately 2 and 6. These nozzles were water cooled downstream of the throat. The exit diameter of the nozzles varied from $1\frac{1}{2}$ to $2\frac{1}{2}$ in.

The measurements were conducted just downstream of the exit of the nozzle in an open-jet test section. A drive section held probes that were to be calibrated. Downstream of the drive section was a gate valve which isolated the calibration tunnel from a manifold which was directly connected to a five stage steam ejector. This ejector provided a back pressure which ranged from 10 μ to 110 μ.

A calibration was also performed in the hypersonic nitrogen tunnels N-3 and N-4 at Mach number of about 25 and stagnation temperature up to about 2500°K. Details of these facilities are found in Refs. 16 and 17.

B. Probe Calibration

The nozzles in the calibration facility were surveyed with a Pitot probe downstream of their exits in order to determine the size of the test core. To calibrate the total temperature probe, the stagnation pressure, stagnation temperature and Pitot pressure were measured to define the freestream conditions, and the wire and support temperatures. The pressures were determined by variable reluctance, differential transducers and the temperatures by a Rubicon potentiometer. The calibration was performed at three nominal values of stagnation temperature, 300°K, 700°K, and 1000°K, at Mach numbers about 2 and 6 over a range of Reynolds numbers. For these measurements the Reynolds number variation was obtained primarily by changing the stagnation pressure.

In the hypersonic facilities, the stagnation pressure was held constant and the stagnation temperature was changed to give a variation in the Reynolds number. This method was repeated at $M \sim 25$, stagnation pressures from 1000 psia to 5000 psia at stagnation temperatures from 2500°K to 900°K with Reynolds numbers from 4000 to 40,000 per in. in the N-3 facility; and at $M \sim 26.5$, stagnation pressure of 350 psia from 1500°K to 900°K with Reynolds numbers from 1500–3000 per in. in the N-4 facility.

With the measurements of the probe, that is, the wire temperature midway between the supports, and the support temperature, and the known freestream conditions, using the equations given previously, the gas and the adiabatic wire temperatures can be determined. For perfect agreement, the ratio T_g/T_{ad} should be unity. Checks can be made of the validity of the conduction calculation (with negligible radiation losses) at low temperature, and of the radiation calculation (with negligible conduction losses).

Some of the calibration results are shown in Figs. 3–7. The gas and wire temperatures as well as the temperature corrections for radiation and conduction losses are nondimensionalized by the adiabatic wire temperature in these figures. At approximately room temperature using a wire with a diameter of 0.001 in. and length of 0.38 in., at Mach numbers of 2 and 6, the gas temperature is within 5% of the adiabatic wire temperature over the Reynolds number range 0.025–4 (Fig. 3). At $Re_{2,d} \sim 0.1$, the conduction losses amount to about 5% and at $Re_{2,d} \sim 1.0$ they are less than 1%. At Reynolds numbers in excess of 0.5 the conduction correction is so small that for all practical purposes the measured temperature and the adiabatic wire temperature are the same.

For the wire diameter of 0.001 in. and the stagnation temperature of about 1000°K, the gas and adiabatic wire temperatures were approximately equal to unity for $Re_{2,d} > 0.1$ (Fig. 4). For $L = 0.16$ in., the conduction correction decreased from about 16% at $Re_{2,d} = 0.15$ to about 1% at $Re_{2,d} > 1.0$. The radiation correction, on the other hand, increased to a value of about 8% at the higher values of $Re_{2,d}$. When the span was increased to 0.38 in., the conduction correction which had a maximum value of about 12% at $Re_{2,d} = 0.028$ decreased to a value less than 1% at $Re_{2,d} \sim 0.3$. The radiation correction had a maximum value of about 10%.

For $d = 0.005$ in., and $L = 0.16$ in., there is a reasonable amount of scatter in the data. In general, the gas temperature is higher than the adiabatic wire temperature. For the larger aspect ratio the data is more consistent, and for $Re_{2,d}$ less than approximately 1.0, the gas temperature falls below the adiabatic wire temperature. For the lower aspect ratio, at $Re_{2,d} \sim 0.2$, the conduction losses contribute 40% to the gas temperature. These losses decrease to about 6% at the maximum value of $Re_{2,d} = 7$. For the larger aspect ratio, the conduction correction decreases

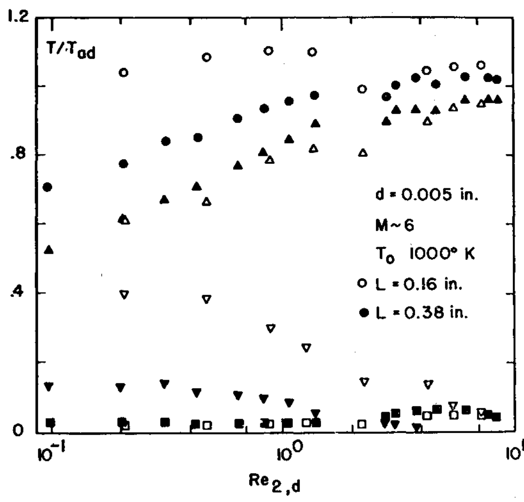

Fig. 5 Probe calibration $M \sim 6$, $d = 0.005$ in., $T_o \sim 1000°K$.

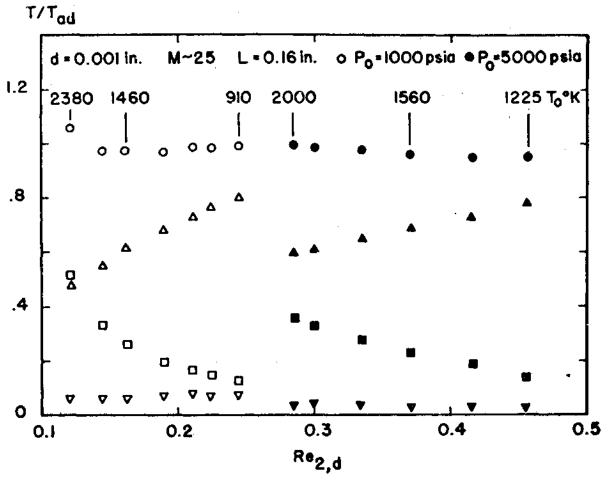

Fig. 6 Probe calibration $M \sim 25$, $d = 0.001$ in., $2400 > T_o$°K > 900.

from approximately 14% at $Re_{2,d} \sim 0.1$ to under 1% at $Re_{2,d} > 4.0$ (Fig. 5).

In general, these tests which have been done at Mach numbers of about 2 and 6 and temperatures up to 1000°K, show that the radiation corrections are relatively small, less than 10%. The conduction correction at $Re_{2,d} \sim 0.1$ is greater than 10% when the aspect ratio is less than 200. When $Re_{2,d} \sim 1$ the conduction correction is less than 5% when the aspect ratio is greater than 100.

At higher temperatures, in the N-3 and N-4 facilities $T_0 \sim$ 2500°K max), the radiation correction would become more important. It was not possible to get results with the 0.001 in. wire for $L = 0.38$ in. as the wire repeatedly broke. Some of the results are now presented. For $d = 0.001$ in. the results are shown in Fig. 6 for stagnation temperatures that varied between 2400°K and 900°K. For all cases, the gas temperature is within 5% of the adiabatic wire temperature. At the lower value of the stagnation pressure ($Re_{2,d} \sim 0.12$), the radiation correction at the highest temperature exceeds the wire temperature and decreases from a value of approximately 50% to a value of approximately 10% at a stagnation temperature of 900°K. The conduction correction for all cases is under 10%. For the higher value of the stagnation pressure ($Re_{2,d} \sim 0.29$), the radiation correction decreases from approximately 35% at a temperature of about 2000°K to a value of about 15% at a temperature of 1200°K. The conduction correction is about 5%. The Reynolds numbers covered by these conditions range from 0.1–0.5. Similar measurements were made with wire sizes of 0.002 in. and 0.005 in. with $Re_{2,d}$ going as high as 3. As the wire diameter increased, the conduction correction increased with small changes in the measured wire temperature and radiation correction.

Measurements made in the N-4 facility at lower Reynolds numbers are shown in Fig. 7. For $d = 0.001$ in., $L = 0.16$ in., $Re_{2,d}$ changed from 0.02 to 0.03 as T_o went from 1520°K to 910°K. Over this range of Reynolds numbers, the wire temperature changed from 40% to 55%, the radiation losses decreased from approximately 28% to 15% and the conduction losses from 35% to 28%. The final gas temperature was close to the adiabatic wire temperature over the entire range of the Reynolds numbers. For the higher aspect ratio, the conduction losses were about 10% over the entire range of Reynolds numbers, considerably lower than for the smaller aspect ratio probe. Even though the conduction and radiation corrections are large, the calculated gas temperature was close to the adiabatic wire temperature. Similar results were obtained for wire diameters of 0.002 and 0.005 in.

The measurements that have been performed at $M \sim 25$ with stagnation temperatures between 2400°K and 900°K and Reynolds numbers varying from 0.02 to 3.0 have given a gas temperature approximately equal to the adiabatic wire temperature. It is important to note that under certain test conditions, the temperature measured by the wire was less than either the temperature correction due to radiation (at high temperature) or the temperature correction due to conduction (at low Reynolds numbers) but yet the calculated gas temperature was in reasonable agreement with the adiabatic wire temperature.

A portion of the present calibration has been performed in the same Mach number range as previous hot wire measurements,[7] that is up to about 7. However, the stagnation temperature range is considerably larger than any of the previous studies, the present measurements going as high as 1200°K. The Reynolds numbers in the present study are considerably lower than those presented by Dewey. It is important to note that the hot wire method to calculate convection, conduction and radiation losses, works quite adequately for Reynolds numbers down to 0.1 for $d = 0.001$ in. However, for Reynolds numbers less than 0.1, there is a deviation of the gas temperature (determined from the measurements of the wire itself) and the adiabatic wire temperature. As the wire diameter increased to 0.005 in., the gas temperature agreed with the adiabatic wire temperature for Reynolds numbers greater than 1.0. At lower values of Reynolds numbers, the gas temperature was less than the adiabatic wire temperature. To the author's knowledge, there appear to be no similar measurements performed at hypersonic conditions at elevated temperatures and low Reynolds numbers. This technique will now be used to provide a flowfield measurement in the shock layer of a cone.

Flowfield Profiles Using the Probe

Flowfield measurements were made with the total temperature probe in the shock layer of a 10° half-angle cone over a wide range of freestream Reynolds number (40,000, 10,000, and 1,500 per in.).[5] To illustrate the techniques we will consider only the measurements made at $M_\infty \sim 19$, $T_o \sim 1700$°K and Re_∞/in. $\sim$ 40,000. The shock layer thickness varied from about 0.08 in. near the front of the body to 0.16 in. at the rear. At the rear, the viscous region was approximately $\frac{1}{2}$ the shock layer thickness. For the cold wall condition of the body, the local total temperature should range from approximately 300°K near the wall to approximately 1700°K at the edge of the boundary layer, should remain at this value through the inviscid portion of the shock layer, and should give a value of approximately 1700°K in the freestream outside the shock.

It was shown previously that it is necessary to know the freestream conditions (conditions ahead of the probe) in order to determine the local stagnation temperature. However, these freestream conditions are usually unknown in many experiments. By initiating the calculation procedure with approximate values of these quantities, the gas temperature and ultimately a total temperature. To the author's knowledge, there appear to be no completely, it is necessary to be given three quantities. We will consider a Pitot measurement as the second flowfield quantity. For lack of a third flowfield measurement, we can, in some cases,

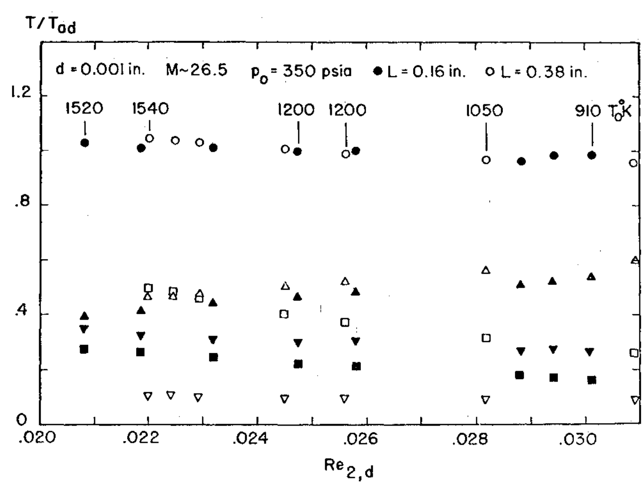

Fig. 7 Probe calibration $M \sim 26.5$, $d = 0.001$ in., $1540 > T_o$°K > 900.

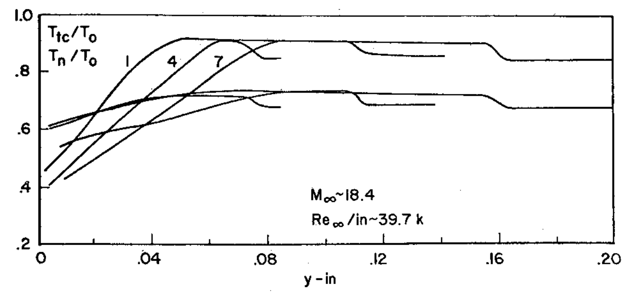

Fig. 8 Wire and support temperature profiles.

make the assumption of constant static pressure between the wall and the shock.

From the static and Pitot pressures, the local Mach number can be found. It is now assumed that the measured wire temperature is the stagnation temperature. The conduction and radiation losses are calculated, and the gas temperature evaluated. The adiabatic wire temperature is calculated from the assumed value of stagnation temperature. For the correct value of stagnation temperature, the gas and adiabatic wire temperatures will be equal. If these temperatures are not equal, then the difference is added to the initial assumed value of the stagnation temperature to get a new value of the stagnation temperature and the procedure repeated.

In using the Pitot pressure and wall static pressure with the wire and support temperatures, the calculation gives a gas temperature which is directly related to the stagnation temperature. The remaining flowfield characteristics are determined using standard isentropic relationships.

The measured wire and support temperatures are shown in Fig. 8, nondimensionalized by the freestream stagnation temperature for three locations on the model. There were a total of 8 measuring stations on the model (Table 1). The wire used had a diameter of 0.001 in. with a length of 0.16 in. The wire temperature in the external flow is about 0.85 and behind the shock about 0.90. The needle temperature in the freestream is about 0.65 and behind the shock about 0.70. At these conditions, the major cause of discrepancy between the measured wire temperature and gas temperature is due to radiation effects. For conditions behind the shock, the error due to radiation losses was calculated to be about $-120°$K and negligible for conduction losses for $Re_{b,d} \sim 5$.

The wire temperature dropped rapidly from the peak value measured behind the shock to the value measured near the body surface. The support temperature decreased, but not as rapidly as the wire temperature, with the result that the two profiles cross at a temperature ratio about 0.63. At lower values of y the support temperature is higher than the wire temperature and, as the Reynolds number is also decreasing, the conduction error now becomes a predominant correction to the measurement of the gas temperature. For a wire temperature of 720°K measured at $y \sim 0.01$ in. (station 7) the radiation error is $-40°$K and the conduction error $+60°$K for $Re_{b,d} = 0.54$.

Total temperature profiles calculated by three different theoretical methods are shown in Fig. 9 with the measured profiles for stations 1, 4 and 7. The van Driest calculation is valid for a

Table 1 Surface distance from model tip for the sharp cone

Station number	Distance, in.
1	0.895
2	1.195
3	1.495
4	1.895
5	2.295
6	2.695
7	3.205
8	3.700

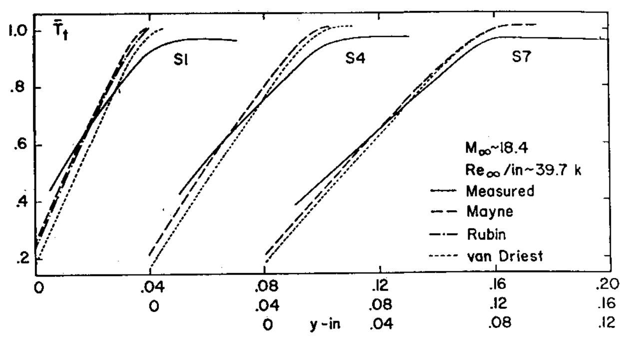

Fig. 9 Stagnation temperature and predicted profiles.

thin boundary layer, constant Prandtl number and zero pressure gradient, for the conditions where the edge Mach number is given. The numerical viscid-inviscid computations by Mayne[5] include the effects of transverse curvature and slip at the wall. The technique developed by Rubin[18] using a single set of equations valid between the freestream and wall was used to predict the flowfield near the front of the model only. The agreement between the different predicted profiles is good for these test conditions. The total temperature measurements agree quite well with the calculations. Close to the wall these measurements would be in error due to the erroneous Pitot pressure measurement. For $y > 0.2$ in., (where the values of Pitot pressure are reliable), the deviation between the measured and predicted values is considerably less than 10%. In the inviscid portion of the shock layer the measurements and calculations deviate by less than 5%.

From the three measured quantities, it is now possible to obtain the other characteristics of the flowfield. The density and velocity profiles are shown in Figs. 10 and 11. The density measurements agree well with the predicted curves in a major portion of the shock layer at station 4 but give a higher value in the region immediately behind the shock. This is true even at the last station where the density reaches a value of approximately $4\frac{1}{2}$ times the freestream density. The peak value of the density, which is measured behind the shock is higher than given by the Mayne calculation at the rear of the model. The measured value of the density is in good agreement with the density which is obtained using the freestream conditions and a knowledge of the shock shape. These measured density profiles indicate a slightly larger viscous region than predicted, at the front and rear of the model.

The velocity profiles reach a peak value of approximate 95% of the freestream value at the edge of the boundary layer and in the inviscid portion of the shock layer. In general the velocity profiles agree relatively well with the predicted curves. Variation between the measured velocity profiles and the predictions is less than 10% over the major portion of the profile.

Concluding Remarks

A "fine wire" total temperature probe has been constructed, calibrated and used at hypersonic speeds. At Mach numbers of

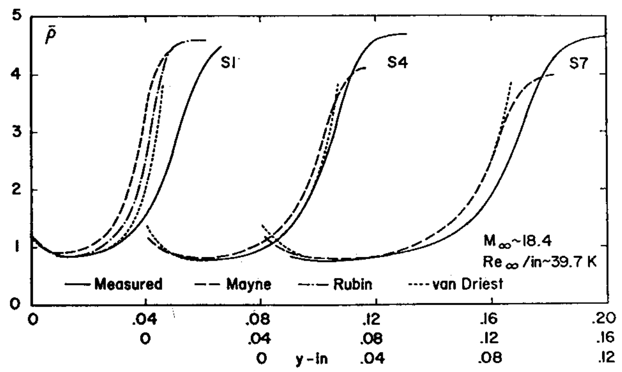

Fig. 10 Density and predicted profiles.

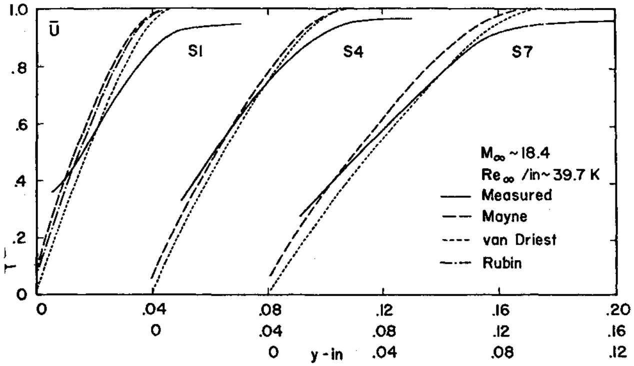

Fig. 11 Velocity and predicted profiles.

2, 6 and 25, stagnation temperatures from 300°K to 2500°K and Reynolds number from 10^{-2} to 10, the measured probe temperatures, when properly corrected for radiation and conduction losses, gave the correct value of the gas temperature to within 10%. At lower values of Reynolds number at supersonic speeds, it was found that the gas temperature was less than the adiabatic wire temperature.

This probe was used to survey the shock layer of a 10° half-angle cone at $M_\infty \sim 19$, $T_o \sim 1700$°K, Re_∞/in. ~ 40,000. Using the probe temperatures, the measured local Pitot pressure and wall static pressure, the local total temperature together with all other physical characteristics of the shock layer were determined. The agreement was good between the total temperature profile obtained by this method and the predicted profiles by the van Driest (thin boundary layer), Mayne and Rubin (numerical) methods.

This type probe has the advantage that it can be used to provide details of the flow near surfaces. As the wire diameter need not be small, it can be used in areas where the dynamic loading is significant. The present probe appears to be a sufficiently accurate and practical device to provide an additional flowfield measurement in a wide range of Mach number, Reynolds number and gas temperature, even where large radiation and conduction effects are present.

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