



Resistivity and heat transfer characteristics of high temperature film anemometers
by Scott Gerald Anders

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science
Mechanical Engineering
Montana State University
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Abstract:

The resistivity and heat transfer characteristics of a wedge-shaped high temperature film anemometer probe are studied here. These film anemometers were designed specifically for flows with stagnation temperatures up to 760 C and dynamic pressures of around 20 psia. The necessary theory was first developed from low speed applications of film anemometers and from hot-wire theory. The proper calibration equipment and procedures were selected so that the required raw data could be collected. The theory was used to reduce the data to the variables of interest. Oven calibration data were taken for the temperature range 20 C to 500 C. The resulting data were fit with a second degree polynomial in order to give the correct reference resistance and resistivity coefficients which were unique for each probe. Flow data were taken for Mach numbers 0, 0.5, 1, 2, and 3. Data for Mach 0.5, 1, 2, and 3 were taken at stagnation temperatures of 15 C and 65 C. The resulting dimensional Reynolds number range covered by these various flows was from zero to 120,000 1/cm. Small amounts of data were also collected at Mach 6 and Mach 8. For the flows investigated the Nusselt number was found to be a function of the square root of the Reynolds number with no apparent Mach number dependence. In order to obtain this Nusselt number the measured Nusselt number must be corrected for its conduction contribution as the developed theory indicates. The temperature recovery factor was found to have a maximum at a value of approximately one and it was found to decrease with increasing Mach number to a minimum of about .8 at Mach 8. It also exhibited a Reynolds number dependence for Mach numbers of 3 and higher.

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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NOMENCLATURE

<u>Symbol</u>	<u>Description</u>
A	Cross sectional area
A_s	Surface area
c	Constant
d	Diameter
G	Grashof number
g	Gravitational constant
h	Convective heat transfer coefficient
i	Current
k	Thermal conductivity
L_c	Conduction loss term
l	Length of sensor
LVT	Low velocity tunnel
M	Mach number
N	Nusselt number
N_{cd}	Conduction contribution to measured Nusselt number
N_m	Measured Nusselt number
P	Perimeter
PCS	Programmable Current Supply
Pr	Prandtl number

NOMENCLATURE-Continued

<u>Symbol</u>	<u>Description</u>
Q_{rad}	Heat transfer due to radiation
q	Heat transfer rate
R	Resistance
R_C	Resistance of cable connecting probe to current supply
R_{LW}	Resistance of platinum wire leads
R_T	Total line resistance
Re	Reynolds number
r	Radius
SWT	Supersonic wind tunnel
T	Temperature
V	Velocity
W	Power
y	Differential height of manometer
α	First coefficient of resistivity
β	Second coefficient of resistivity
γ	Specific weight
ϵ	Emissivity
η	Temperature recovery factor
ξ	Third coefficient of resistivity
σ	Stefan-Boltzmann constant
τ	Temperature loading factor

NOMENCLATURE-Continued

<u>Symbol</u>	<u>Description</u>
$()_e$	At recovery temperature
$()_f$	Based on film
$()_r$	At reference condition (0 C)
$()_s$	At supports
$()_w$	Based on wire
$()_\infty$	At free-stream temperature

ABSTRACT

The resistivity and heat transfer characteristics of a wedge-shaped high temperature film anemometer probe are studied here. These film anemometers were designed specifically for flows with stagnation temperatures up to 760 C and dynamic pressures of around 20 psia. The necessary theory was first developed from low speed applications of film anemometers and from hot-wire theory. The proper calibration equipment and procedures were selected so that the required raw data could be collected. The theory was used to reduce the data to the variables of interest. Oven calibration data were taken for the temperature range 20 C to 500 C. The resulting data were fit with a second degree polynomial in order to give the correct reference resistance and resistivity coefficients which were unique for each probe. Flow data were taken for Mach numbers 0, 0.5, 1, 2, and 3. Data for Mach 0.5, 1, 2, and 3 were taken at stagnation temperatures of 15 C and 65 C. The resulting dimensional Reynolds number range covered by these various flows was from zero to 120,000 1/cm. Small amounts of data were also collected at Mach 6 and Mach 8. For the flows investigated the Nusselt number was found to be a function of the square root of the Reynolds number with no apparent Mach number dependence. In order to obtain this Nusselt number the measured Nusselt number must be corrected for its conduction contribution as the developed theory indicates. The temperature recovery factor was found to have a maximum at a value of approximately one and it was found to decrease with increasing Mach number to a minimum of about .8 at Mach 8. It also exhibited a Reynolds number dependence for Mach numbers of 3 and higher.

CHAPTER 1

INTRODUCTION

As the area of supersonic and hypersonic research expands, the need for improved instrumentation to measure both mean flow properties and turbulent fluctuations becomes increasingly important. The majority of information in the area of turbulence fluctuation measurement has been gathered by the hot-wire anemometer. The hot-wire consists of a very fine wire mounted perpendicular to the flow on two small supports. By monitoring the resistance and power dissipation of the wire, the recovery temperature and the Nusselt number can be determined. If these are then investigated for different flow regimes their dependence on Mach number, Reynolds number, and temperature can be determined. These dependencies can then be used in the measurement of turbulent fluctuations. Further discussion on the hot-wire method can be found in References [1-4].

Though hot-wires have proven themselves useful, they are limited to flows where the temperatures and dynamic pressures are moderate. They also retain some undesirable characteristics such as a Mach number dependence at low Reynolds numbers due to restrictions on spatial resolution. Since high Mach number and high dynamic pressure facilities are usually small in order to be economically justifiable, the areas of interest in a particular flow to be studied require instrumentation that has high spatial resolution. A high spatial resolution is also

required if high turbulence frequencies (responses of around 300 kHz) are going to be measured. These requirements in turn put limitations on the magnitude of hot-wire diameters. These small diameter wires bring the instrument into the low Reynolds number range where the Nusselt number becomes Mach number dependent. Also, when flow dynamic pressures or stagnation temperatures become high the mechanical strength of the hot-wire is found insufficient to prevent wire breakage. To make the situation even more severe, many facilities are not adequately filtered to remove tiny particles which can destroy the small unsupported wire. These requirements for a high structural endurance, high frequency response, and high spatial resolution have given rise to the film anemometer probe.

Film anemometer probes have been used in the past mainly for measurement in liquids such as water and blood where hot-wires would be impractical [2,5,6]. The use of a film anemometer probe in a supersonic flow has received limited attention however, resulting in limited sources on their calibration methods, resistivity, and heat transfer characteristics. Now that more severe requirements have been placed on this type of instrumentation, use of the film anemometer has become more promising and the need for knowing its characteristics increasingly important. The requirements for the film anemometer probes investigated here were that the probes must be able to be used for high temperature (760 C), high dynamic pressure flows [7]. For these probes, the films are deposited on the stagnation line of a wedge-shaped probe tip. This film, being supported by the hard probe body tip, is much less subject to failure due to mechanical stresses as compared to the hot-wire yet still will be able to maintain the required frequency response and spatial resolution.

The theory developed for the films is drawn from low speed applications of film anemometers and from hot-wire anemometer theory which shares many points of

similarity. Much of the theory has also been previously established by Ling [8] and Demetriades [7]. The calibration methods used here are developed on the basis of this theory, the results of which show that the heat transfer characteristics of hot-films are quite similar to hot-wires. The most noticeable deviation is the large conduction loss to the substrate for the film.

Much time was spent investigating the hot-film probe resistivity and heat transfer characteristics since they must be understood in order to move on to the measurement of turbulence fluctuations. In order to make proper measurement of turbulence one must know accurately: the resistance and resistivity coefficients; the temperature recovery factor dependence on Mach number, stagnation temperature, Reynolds number; and the Nusselt number dependence on Mach number, stagnation temperature, Reynolds number, and temperature loading (power). The following is an account of how all of these are determined and the results of each. For information on the use of these characteristics for turbulent flow measurements see Demetriades [9].

CHAPTER 2

FILM ANEMOMETER PRINCIPLE AND RESEARCH GOALS

The principle of operation of the hot-film anemometer probe is the following: If an object is placed in a moving medium and then heated, heat will be exchanged between the object and the medium. The rate at which the heat is exchanged depends on the characteristics of the object, the physical characteristics of the medium, and the flow characteristics of the medium. The heat is introduced by a constant electrical current and the corresponding resistance of the object is monitored. By first observing and recording the behavior of the object for a variety of flow conditions, the object can later be used to determine unknown flow characteristics. This is the general method described and used by Laufer and McClellan [10].

The two aims of this research were to determine (a) the resistivity characteristics and (b) the heat transfer characteristics for film anemometers designed for high temperature hypersonic research. These film anemometers were designed to be able to withstand continuous exposure to 760 C stagnation temperatures and dynamic pressure loads exceeding 140 kPa (20 psia). This placed serious restrictions on probe design and development. Despite the design problems the two aims of this research were carried out while the probes were being developed. The determination of the resistance and resistivity characteristics included selection of the proper calibration equipment and procedures and the determination of the proper handling of the calibration data. The determination of the heat transfer

characteristics of the film anemometer probe also included selection of the proper calibration equipment, procedures and data handling. In addition to these the second aim included determination of the proper theory of measurement, relating the film anemometer probe electrical output to flow dependence variables by theory, and relating these variables to the flow characteristics such as the temperature recovery factor, Reynolds number, Mach number, and flow temperature.

CHAPTER 3

HEAT BALANCE FOR THERMAL SENSORS

As briefly mentioned in Chapter 2, the rate at which heat is exchanged from the object to the medium depends on the characteristics of the object, the physical characteristics of the medium, and the flow characteristics of the medium. In order to measure these flow characteristics by the method described, the rate at which heat is exchanged to the medium must be known. This requires analysis of the heat loss for the object of interest. The approach taken here is to start with the simplest model and work towards the desired but more complicated model.

Cylinder With No Conduction Loss

An electrically heated cylinder in a cross flow with no end losses can lose heat only by radiation and convection. If it is assumed that radiation losses are negligible the power balance is

$$(1) \quad i^2 R = h A_s (T - T_{\infty})$$

where

$i^2 R$ = power input

h = convective heat transfer coefficient

A_s = surface area

T = temperature of film

T_{∞} = temperature of surroundings

See pages xii–xiv for list of nomenclature used throughout the text. For a cylinder immersed in a compressible flow the temperature of the fluid nearest the sensor will not be the free stream stagnation temperature but instead some fraction of that temperature. In order to better satisfy the physics of the situation, (1) will be rewritten as

$$(2) \quad i^2 R = h 2 \pi r \ell (T - T_e) \quad .$$

The recovery temperature, T_e , is the temperature of the wire at zero current. In terms of the Nusselt number, (2) is

$$(3) \quad i^2 R = \pi \ell k_e N (T - T_e) \quad .$$

Again by arguments of the physical situation the thermal conductivity, k_e , is based on the recovery temperature.

Cylinder With Conduction Loss

For the above situation with added conduction losses, the form of the equation remains approximately the same by the following argument developed by Demetriades [7]. The heat balance is now

$$(4) \quad i^2 R = \pi \ell k_e N (T - T_e) + L_C \quad .$$

The added conduction loss term, L_C , must be roughly proportional to the thermal conductivity of the wire, k_w , the temperature difference between the wire and the support, $(T - T_s)$, and the wire cross sectional area. It must also be roughly inversely proportional to the length, ℓ , of the wire. Combining these arguments gives

$$(5) \quad L_C = C_1 \frac{\pi d^2 k_w}{4 \ell} (T - T_s) \quad , \quad C_1 = \text{constant} \quad .$$

Since the supports are many times larger than the wire and are wetted by the flow at temperature T_e , the supports can be assumed to be approximately at the recovery temperature also (lack of knowing the actual temperature leads the experimentalist to make some kind of assumption and the one assumed here is as appropriate as any). Equation (4) can now be written as

$$(6) \quad i^2 R = \pi \ell k_e N (T - T_e) + C_1 \frac{\pi d^2 k_w}{4 \ell} (T - T_e) .$$

This new conduction term can now be absorbed into a new Nusselt number which will include both conduction and convection losses so that

$$(7) \quad i^2 R = \pi \ell k_e N m (T - T_e)$$

where

$$(8) \quad Nm = N + \left(\frac{d^2}{\ell^2} \frac{C_1}{4} \frac{k_w}{k_e} \right)$$

or

$$(9) \quad Nm = N \left(1 + \frac{C}{S^2} \right) , \quad S^2 = \frac{\ell^2}{d^2} \frac{k_e}{k_w} N .$$

If the term appearing in parenthesis in (8) or (9) is large then the conduction term is significant.

Kovaszny [11] and Dewey [12] have performed a more detailed calculation of the end losses. Their results are

$$(10) \quad Nm = N / \psi(S)$$

where $\psi(S)$ is the correction. The dimensional argument indicates that S depends on the Nusselt number and the temperature loading. Therefore (10) can be written as

$$(11) \quad Nm = \frac{N}{f(N, \tau)} = Nm(N, \tau)$$

or

$$(12) \quad i^2 R = \pi \ell k_e N m(N, \tau) (T - T_e) \quad .$$

Kovaszny [11] and Dewey [12] give the exact solution as

$$(13) \quad \psi(S) = 1 - \frac{\tanh S}{S} \quad .$$

By comparing the exact solution given by (13) to the approximate solution given by (9) Demetriades [7] gives

$$(14) \quad \psi(S) = \frac{1}{1 + \frac{C}{S^2}} \quad .$$

This is satisfactorily close to (13) if the constant C is about four according to Demetriades [7].

Film Anemometer With No Substrate

For an electrically heated film with negligible radiation losses (see Appendix A) and no conduction losses the heat balance is

$$(15) \quad i^2 R = h A_s (T - T_e)$$

or, in terms of the Nusselt number,

$$(16) \quad i^2 R = k_e N A_s / w (T - T_e) \quad .$$

For the "homemade" films used, the area and characteristic length are not physically defined well enough to measure with acceptable accuracy. To accommodate this difficulty a new dimensional Nusselt number is defined as

$$(17) \quad N' = N A_s / w$$

so that (16) is now

$$(18) \quad i^2 R = k_e N' (T - T_e) \quad .$$

Film Anemometer With Substrate

Assuming that the heat balance equation is of the same form as (18), the heat balance can be written

$$(19) \quad i^2 R = k_e N' (T - T_e) + L_C \quad .$$

Using the same argument as that used for the wire the conduction loss can be written as

$$(20) \quad L_C = C k_s \frac{A_s}{L} (T - T_e) \quad .$$

Yet another Nusselt number will be defined that is dimensional and includes both conduction and convection losses as

$$(21) \quad Nm' = N' + C_1 \frac{k_s}{k_e} \frac{A_s}{L} \quad .$$

Equation (19) can now be written in the form of convection losses only as shown in the following equation:

$$(22) \quad i^2 R = k_e Nm' (T - T_e) \quad .$$

It is known analytically and experimentally that the heat loss due to conduction to the supports is quite small for wires. Experimental results have shown that this is not so for films. In order to look more closely at this heat loss, a "thin-rod" model of the heat loss to the substrate will be examined. Figure 1

shows this model. This model assumes a constant cross sectional area and a constant thermal conductivity. It also assumes that the only temperature gradient is along the axis (no radial temperature distribution), that the face is held at a constant temperature, that the cylinder approaches the surrounding temperature as it extends to infinity, and that the surrounding temperature is the recovery temperature of the film. The differential equation describing the heat loss is

$$(23) \quad \frac{d^2 T}{dx^2} - \frac{h_B P}{k_S A} (T - T_e) = 0$$

where

h_B = heat transfer coefficient for probe body

P = perimeter of probe body

k_S = thermal conductivity of substrate

A = body cross sectional area .

Solving this equation gives the temperature distribution as

$$(24) \quad T = T_e + (T_f - T_e) e^{-\sqrt{\frac{h_B P}{k_S A}} x} .$$

For a circular rod this may be written as

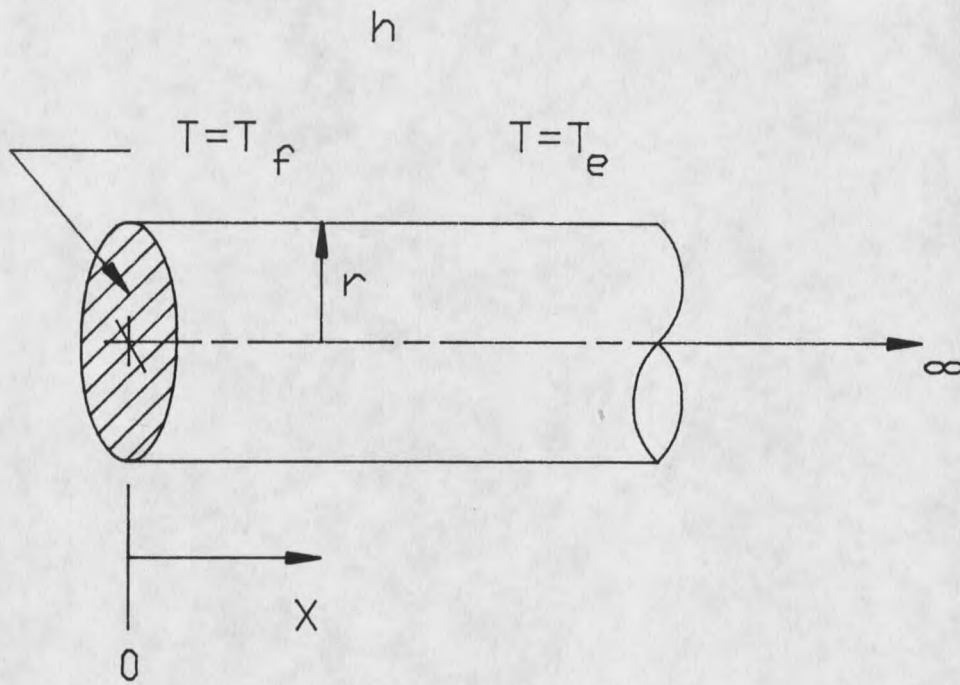
$$(25) \quad T = T_e + (T_f - T_e) e^{-\sqrt{\frac{2 h_B}{k_S r}} x} .$$

From (25) L in (21) can be approximated by taking the slope at $x = 0$ of (25) and extending a line formed by this slope to the point where the temperature is equal to the fluid temperature as in Figure 2. If this is done it is found that

$$(26) \quad L = \sqrt{\frac{k_S r}{2 h_B}}$$

or in terms of the Nusselt number of the rod near the film

$$(27) \quad L = r \sqrt{\frac{k_S}{k_e} \frac{1}{2 N_B}} .$$



B.C.

$$\begin{aligned} \text{At } x=0 \quad T &= T_f \\ \text{As } x \rightarrow \infty \quad T &\rightarrow T_e \\ A &= \text{constant} \\ k_s &= \text{constant} \end{aligned}$$

Figure 1. One-Dimensional Model for Heat Loss to Substrate.

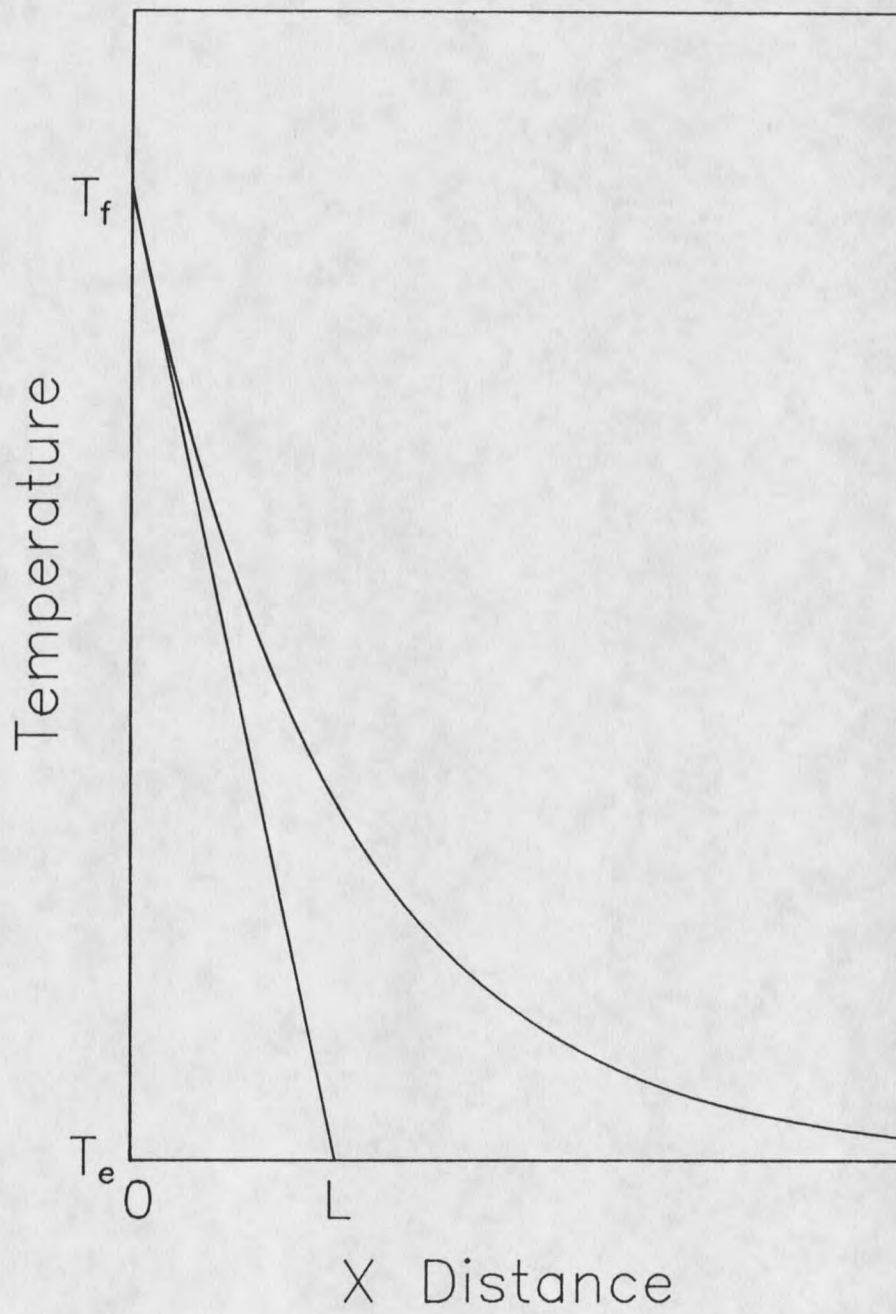


Figure 2. Approximation of Distance L for "Thin-Rod" Model.

Substituting (27) into (21) gives

$$(28) \quad Nm' = N' + C_1 \frac{A_f}{r} \sqrt{\frac{k_s}{k_e}} 2N_B$$

This equation says that for a low conduction loss the thermal conductivity of the substrate must be minimized. It can also be seen that since the thermal conductivity of the air is temperature dependent, the conduction loss term will also be temperature dependent. The thermal conductivity of the substrate material may also be temperature dependent. This dependence can not easily be found since the substrate can come in a truly infinite number of compositions and therefore tabulated data is likely unavailable. It is known by looking at [13] that some glasses vary as much as 10% in conductivity in the temperature range from zero to 100 C and that the amount by which the thermal conductivity changes will depend on the particular temperature range investigated. All other terms in (28) affect the convection loss as well as the conduction loss. The magnitude of these effects cannot be determined easily theoretically. It is known experimentally that this conduction loss term can amount to over 50% of the magnitude of the measured Nusselt number, Nm' , for Reynolds numbers ranging up to 100,000 1/cm.

Unfortunately the variable found from experiment is the measured Nusselt number, Nm' , in (28) which is dimensional and includes conduction effects. The variable of interest however is the convective Nusselt number, N . In order to extract this variable from the measured quantity additional work has to be done when reducing the data. This will be described later in Chapter 4.

General Heat Balance Equation

Regardless of the sensors examined or the boundary conditions applied, all of the heat balance equations developed so far have had the same general form. By

examining equations (3), (7), (18) and (22) it can be seen that the general form is

$$(29) \quad i^2 R = k_e \overline{N} (T - T_e)$$

where $\overline{N}$ may include dimensions or conduction losses and is a function of Mach number, Reynolds number, and Temperature Loading (power). For films, $\overline{N}$, is dimensional and includes conduction losses. This general heat balance equation was originally noted by Demetriades [7].

CHAPTER 4

THEORY OF MEASUREMENT

From the theory of heat transfer from a film anemometer, the measured Nusselt number can be found by (22):

$$(30) \quad Nm' = \frac{i^2 R}{k_e (T - T_e)}$$

This expression is not nearly as simple as it first appears. The Nusselt number cannot be determined for the following reasons:

1. The recovery temperature, T_e , is not known.
2. Since the thermal conductivity is a function of the recovery temperature it is also an unknown.
3. The value of the measured Nusselt number, Nm' , is known through experimental work to be a function of power.
4. The Nusselt number found includes both convection and conduction effects (it is desired to find the "real" Nusselt number which includes convection effects only).

Resistance-Temperature Relations

In order to determine the recovery temperature, a relation between the resistance of the film and the surrounding temperature must be known. It is known that (reference [14]) resistance type sensors can be described by

$$(31) \quad R = R_r (1 + \alpha(T - T_r) + \beta(T - T_r)^2 + \xi(T - T_r)^3 + \dots)$$

For the film anemometer probes studied for the targeted temperature range this equation does not include terms past the quadratic. The number of terms retained is effected by the operation range of the instrument and its physical properties. For instance, hot-wires were typically operated from 10–200 C and used a linear fit but the films here were targeted for 10–760 C where a linear fit was found inadequate, as will be shown in Chapter 8. This will give the resistance at the recovery temperature as

$$(32) \quad R_e = R_r (1 + \alpha(T_e - T_r) + \beta(T_e - T_r)^2) \quad .$$

The recovery temperature can now be found if the reference resistance, R_r , the resistivity coefficients, α and β , and the resistance at zero current, R_e , in the above equation are known. The equation will yield two solutions for the recovery temperature, only one of which will make sense physically. From (32) the recovery temperature is

$$(33) \quad T_e = \frac{-\alpha + \sqrt{\alpha^2 + 4\beta(R_e/R_r - 1)}}{2\beta} + T_r \quad .$$

As mentioned above, in order to determine the recovery temperature the reference resistance and the resistivity coefficients, α and β , must be determined. This is done by performing an “oven calibration”. This calibration is done by finding the resistance at zero current for each known film temperature over a range of temperatures (see Chapter 7 for further detail on oven calibration procedures). The resulting set of resistance-temperature points can then be approximated by a second degree polynomial to obtain the coefficients in (32). Making the measurements of this needed resistance at zero current for each known temperature requires additional procedures. Points must be collected over a range of different powers and the resulting resistance versus power data fit to a second degree

polynomial as in Figure 3. This fit is then used to extrapolate to zero power to find the resistance at zero current. A second degree polynomial fit is chosen as the correct form of the relation by examining the theory of the dependence of the measured Nusselt number on power and by previous experimental results, as will be shown next.

Nusselt Number Dependence On Power

The dependence of the measured Nusselt number on power cannot be determined directly from theory but it is known that such a dependence exists by looking at past experimental work. A simple relation will be assumed by expanding one over the measured Nusselt number in a Taylor series expansion and retaining only the first two terms, which is sufficient according to Demetriades [7]:

$$(34) \quad \frac{1}{Nm'} = \frac{1}{Nm'_e} - \frac{1}{Nm_e'^2} \left(\frac{\partial Nm'}{\partial W} \right)_e W ; \quad \left(\frac{\partial Nm'}{\partial W} \right)_e = \text{constant}$$

After manipulation of (30), (32), and (34) and then letting the reference temperature be 0 C it can be found that

$$(35) \quad \begin{aligned} R = R_e + W & \left[\frac{\alpha R_r}{k_e Nm'_e} + \frac{R_r 2\beta T_e}{k_e Nm'_e} \right] \\ & - CW^2 \left[\frac{\alpha R_r}{k_e Nm'_e} + \frac{R_r 2\beta T_e}{k_e Nm'_e} - \frac{R_r \beta}{Ck_e^2 Nm_e'^2} \right] \\ & - C^2 W^3 \left[\frac{R_r \beta 2}{Ck_e^2 Nm_e'^2} \right] + C_3 W^4 \left[\frac{R_r \beta}{k_e^2 C Nm_e'^2} \right] \end{aligned}$$

where

$$(36) \quad C = \frac{1}{Nm'_e} \left(\frac{\partial Nm'}{\partial W} \right)_e$$

Equation (35) is in the following form:

$$(37) \quad R = R_e + AW + BW^2 + EW^3 + FW^4$$

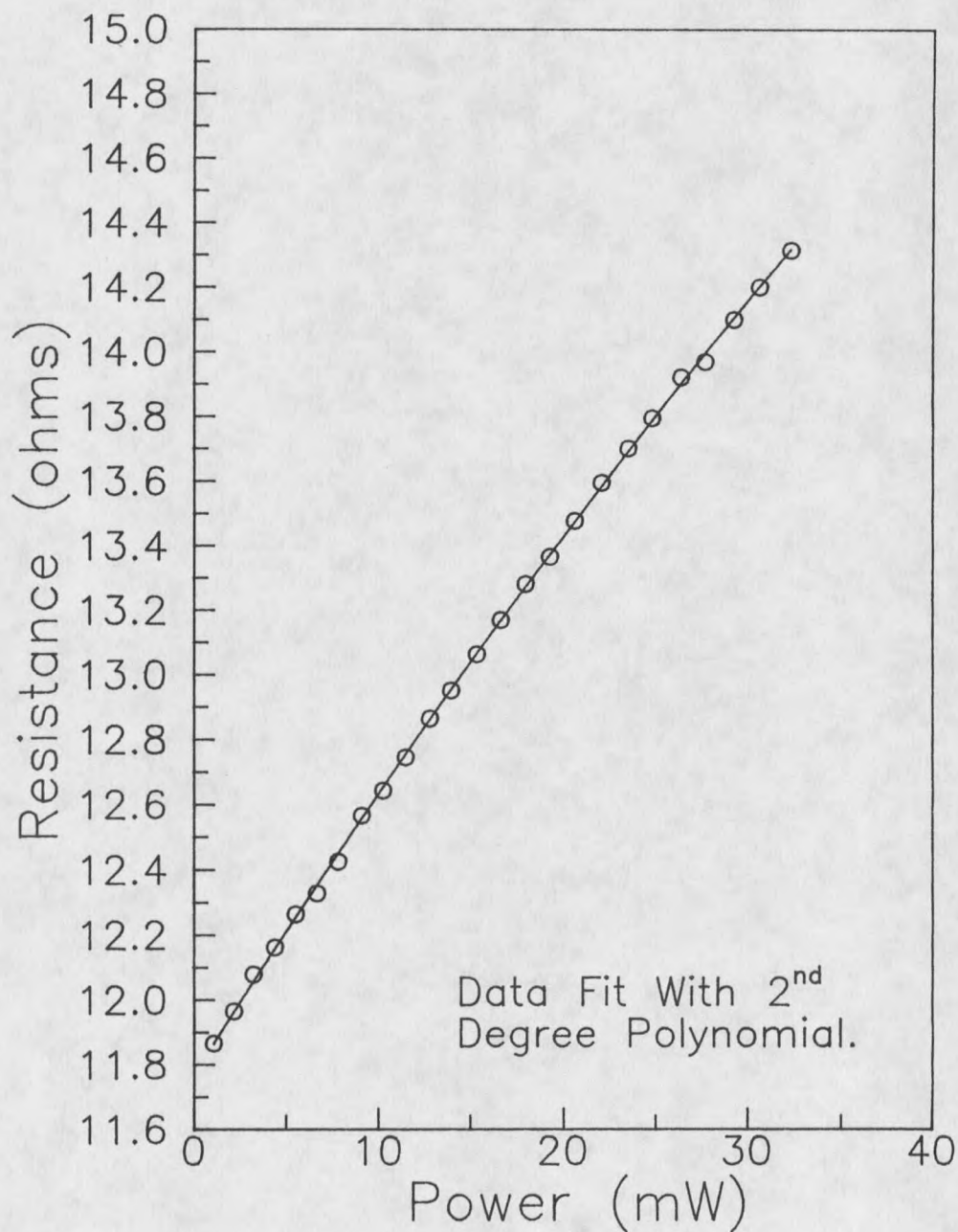


Figure 3. Film Resistance Dependence on Power Fit with a Second Degree Polynomial.

Equations (35) and (37) indicate that if the resistance versus power data are fit to a fourth order polynomial the measured Nusselt number at zero current can be found by relating the constant A in (37) to the corresponding term in (35) so that

$$(38) \quad Nm'_e = \frac{\alpha R_r}{Ak_e} \left(1 + \frac{2\beta T_e}{\alpha} \right)$$

However, it is known experimentally that the coefficients E and F in (37) are close to zero, making a second degree polynomial fit sufficient. In (38) all variables can now be determined. The recovery temperature is now known from (33). The thermal conductivity can be found knowing the recovery temperature by using a textbook relation such as found in Irvine and Liley [15]. The resistivity coefficients and the reference resistance can be found by performing an oven calibration and finally, by making a second degree fit of the power versus resistance data the variable A can be determined. This will give the measured Nusselt number at zero current which still needs to be corrected so that the Nusselt number which is controlled only by convection can be found.

The Nusselt number dependence on power can more easily be examined if (35) is put in non-dimensional form. Since the coefficients E and F are zero, (35) can be written more simply as

$$(39) \quad R = R_e + W \left[\frac{\alpha R_r}{k_e Nm'_e} + \frac{R_r 2\beta T_e}{k_e Nm'_e} \right] + CW^2 \left[\frac{\alpha R_r}{k_e Nm'_e} + \frac{R_r 2\beta T_e}{k_e Nm'_e} - \frac{R_r \beta}{Ck_e^2 Nm'^2_e} \right]$$

Rewriting (39) in the form of (37) gives

$$(40) \quad R = R_e + AW + BW^2$$

where

$$(41) \quad B = C \left[\frac{\alpha R_r}{k_e Nm'_e} + \frac{R_r^2 \beta T_e}{k_e Nm'_e} - \frac{R_r \beta}{Ck_e^2 Nm'^2_e} \right]$$

Now let

$$(42) \quad G = \frac{B}{C}$$

and

$$(43) \quad r = \frac{R - R_e}{R_e} \quad .$$

Substituting the above three equations into (39) will yield

$$(44) \quad r = \frac{AW}{R_e} + \frac{A^2}{A^2} \frac{R_e}{R_e} B \frac{W^2}{R_e} \quad .$$

Let

$$(45) \quad i_C^2 = 1/A$$

and

$$(46) \quad w = W/W_C \quad ; \quad W_C = i_C^2 R_e$$

so that

$$(47) \quad r = w - \frac{BR_e}{A^2} w^2 = w - \frac{CGR_e}{A^2} w^2 \quad .$$

Substitute (36) into (47):

$$(48) \quad r = w - \frac{G}{A^2} R_e \frac{1}{Nm'_e} \left(\frac{2Nm'}{2W} \right)_e w^2 \quad .$$

Define a new variable D as

$$(49) \quad D = \frac{G}{A^2} \frac{R_e}{Nm'_e} \quad .$$

Equation (48) is now written as

$$(50) \quad r = w - Dw^2 \quad .$$

According to (49) the constant D indicates how the Nusselt number depends on power. This can more easily be seen if, for purposes of clarity, the effect of the β term (from the oven calibration) on the Nusselt number dependence on power is assumed to be negligible. This simplifies (49) to

$$(51) \quad D = \frac{k_e R_e}{\alpha R_r} \left(\frac{\partial N m'}{\partial W} \right)_e$$

Though (51) is not the true definition of the constant D it draws the same conclusion as (49) and can more easily be understood. By looking at (50) it can be seen that the constant D can simply be found by curve-fitting the non-dimensional power versus resistance points and extracting the second coefficient. The value of D found will indicate the dimensional Nusselt number dependence on power. A value of zero would indicate no dependence and a value different than zero would indicate the magnitude of the dependence. The variables w , r , and the constant D can also be used to determine if the number of terms in the Taylor Series expansion was sufficient by plotting $(1 - r/w)/D$ versus w . Demetriades [7] has done this and concluded that the number of terms retained in the expansion is sufficient.

Conduction Term Correction

The loss due to conduction should be able to be determined experimentally despite theoretical difficulties if it is assumed that the loss is solely a function of the thermal conductivity of the surrounding fluid (see (28)). By theory it was determined that the conduction contribution to the measured Nusselt number depends linearly on the inverse square root of the thermal conductivity of the surrounding fluid (see (28)).

Since the thermal conductivity is a function of temperature the conduction contribution can also be written as a function of temperature. This temperature dependent conduction contribution will show up in the measured Nusselt number versus Reynolds number data. Each set of data taken at a different stagnation temperature will lie on its own line as shown hypothetically in Figure 4 by the symbolic squares and circles on the graph. By taking the data found for the relation between the measured Nusselt number and Reynolds number for each set and extrapolating to zero Reynolds number a measured Nusselt number without a convection term can be found for that particular set of data (labeled as N_{cnd1} and N_{cnd2} on Figure 4). The resulting extrapolated value should approximately include only conduction losses. This method assumes that the Nusselt number will be zero at zero Reynolds number. This is not strictly true due to natural convection currents. Given a different extrapolated measured Nusselt number for each stagnation temperature over a range of temperatures, a relation that connects the conduction loss to the fluid temperature can be found. Each conduction loss can then be subtracted from its corresponding set of measured Nusselt number - Reynolds number points so that the resulting data would be as in Figure 5 where the Nusselt number is now the desired variable of interest. Unfortunately extensive Nusselt number - Reynolds number data may not be available, and were not available for the measurements made in this study, for a large number of different temperatures. The alternative solution would be to use the oven calibration data. For each point taken during the oven calibration there is a corresponding Nusselt number at that temperature. This can be estimated as the measured Nusselt number at zero Reynolds number (referred to as the extrapolated measured Nusselt number above) by neglecting convection currents (see Appendix B). Assuming the absence of convection and radiation leaves conduction to be the only contribution

to the measured Nusselt number in the enclosed oven chamber. By using the oven calibration data this way a relation that connects the conduction contribution of the measured Nusselt number to the surrounding temperature can be found. This conduction contribution can then be subtracted from the measured Nusselt number found in a flow so that the convection Nusselt number can be obtained, which is the desired parameter. The results of this procedure should be as shown in Figure 5.

Much effort has been expended in arriving at the convective Nusselt number. This Nusselt number is the variable through which the heat transfer characteristics will be studied, which is the desired point of investigation.

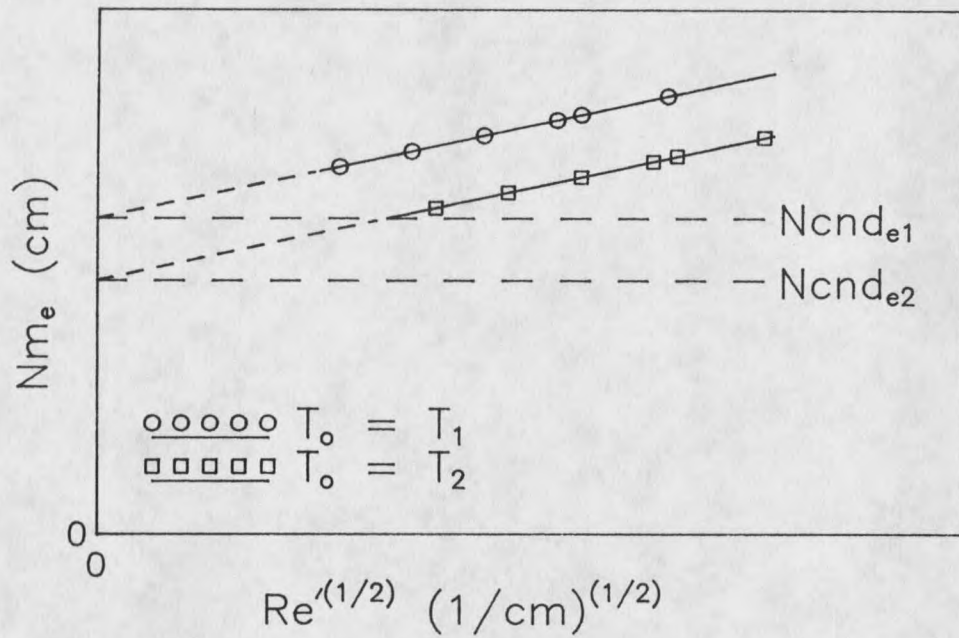


Figure 4. Hypothetical Case of Measured Nusselt Number Dependence on Flow Properties.

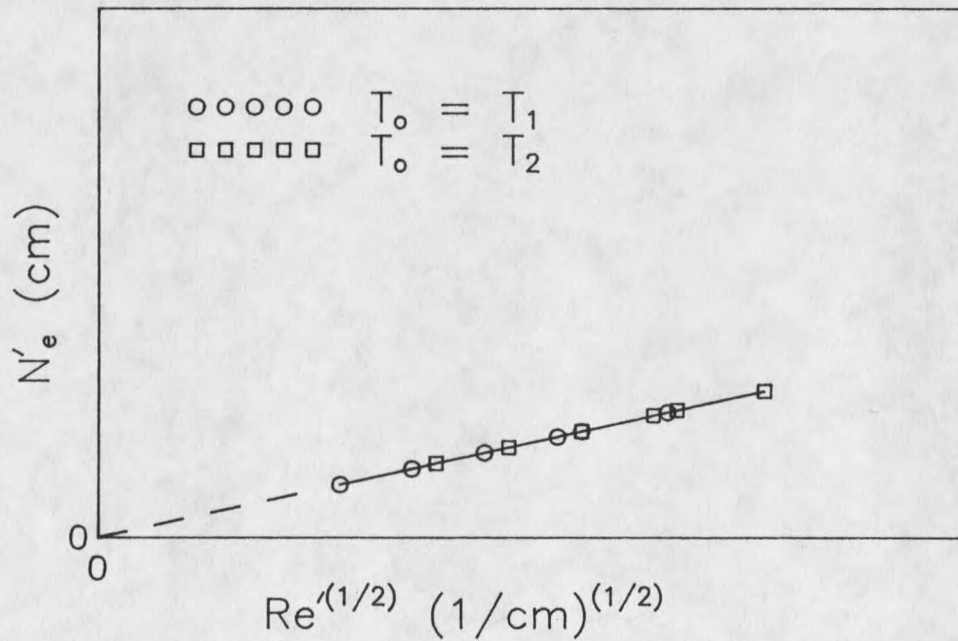


Figure 5. Hypothetical Case of "Actual" Nusselt Number Dependence on Flow Properties.

CHAPTER 5

HEAT TRANSFER FROM STAGNATION POINT SENSORS

Determining the Nusselt number is of no use unless it is somehow related to the flow characteristics. This is done by examining the heat transfer from stagnation point sensors and then drawing from hot-wire theory.

The local heat transfer rate of a sensor immersed in a flow is generally the highest at the stagnation line (Dewey [12], Sandborn [16], White [17]). Figure 6, originally presented by White [17], shows the local heat transfer rate from the surface of a hemisphere in a hypersonic laminar flow where $q_w(0)$ is the heat transfer at the stagnation line. The correlation shown agrees closely with experimental data [17]. Figure 6 clearly shows that the heat transfer rate is the greatest at the stagnation line as compared to the other positions investigated.

This conclusion can also be arrived at by examining the fact that the driving parameter for heat transfer is the temperature gradient between the heat transfer surface and the surrounding flow. This gradient depends heavily on the boundary layer thickness which is thinnest at the stagnation line, resulting in the highest gradient in this region [19]. Since a higher gradient results in a higher heat transfer rate one would expect that the heat transfer rate would be the greatest at the stagnation line.

From this conclusion it can be said that hot-wires exchange much of their total heat transferred at the stagnation line. Similarly, since films are deposited on the stagnation line, the film anemometer heat transfer theory should conform

closely with that of the hot-wire heat transfer theory; the theory which connects the Nusselt number to the various flow parameters such as the Reynolds number, Grashof number, Mach number, the temperature loading, etc. as follows [10]:

$$(52) \quad N = N(Re, M, G, Pr, \tau, \dots)$$

Note that only forced convection is being considered. Also, for air in the range considered the Prandtl number will be taken as constant. This simplifies the above expression so that

$$(53) \quad N = N(Re, M, \tau)$$

This relation is shown by Dewey [12] in Figure 7. This figure indicates that the Nusselt number depends on Mach number for low Reynolds numbers where free-molecular effects are important [12]. From this and the previous conclusions regarding the similarities between film anemometers and hot-wires, film anemometers should follow the same general trends as found for hot-wires. The primary difference being that, since the hot-films are physically much larger than the hot-wires, the Reynolds number range shown in Figure 7 will be displaced to the right into the higher Reynolds number range for the hot-films. This would be of great advantage as it will eliminate the Mach number dependence of the Nusselt number on the Reynolds number. It is also expected that hot-films will show a Nusselt number dependence on the square root of the Reynolds number as is given by Kings Law [11] and as is found for hot-wires in the high Reynolds number range ($Re > 20$) ([12],[20]).

In addition to knowing the hot-wire and film Nusselt number dependence on the Reynolds number, it is also required to know the temperature recovery factor dependence on the Reynolds number before either instrument can be used

as a tool for measuring flow properties. Comparisons of hot-wires and hot-films are difficult here due to the effects of the different geometries and supporting methods of each type of sensor. It can only be predicted that the temperature recovery factor should be one at Mach number zero and remain fairly close to one (within about 10%) as the Mach number varies. Exact values can be found only by experiment since they will depend, at a minimum, on individual probe geometry and supporting method.

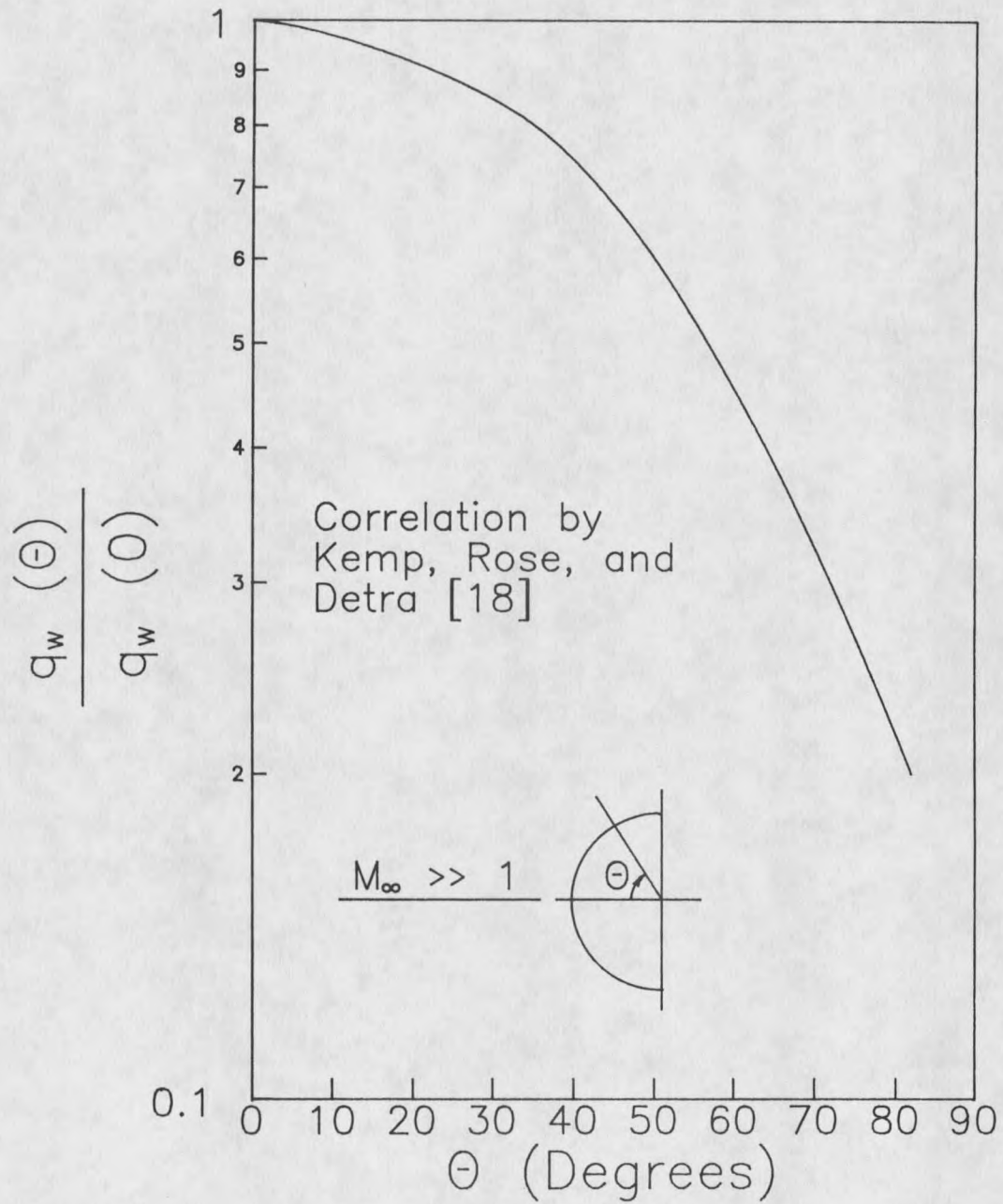


Figure 6. Local Heat Transfer Rate from the Surface of a Hemisphere in Hypersonic Flow.

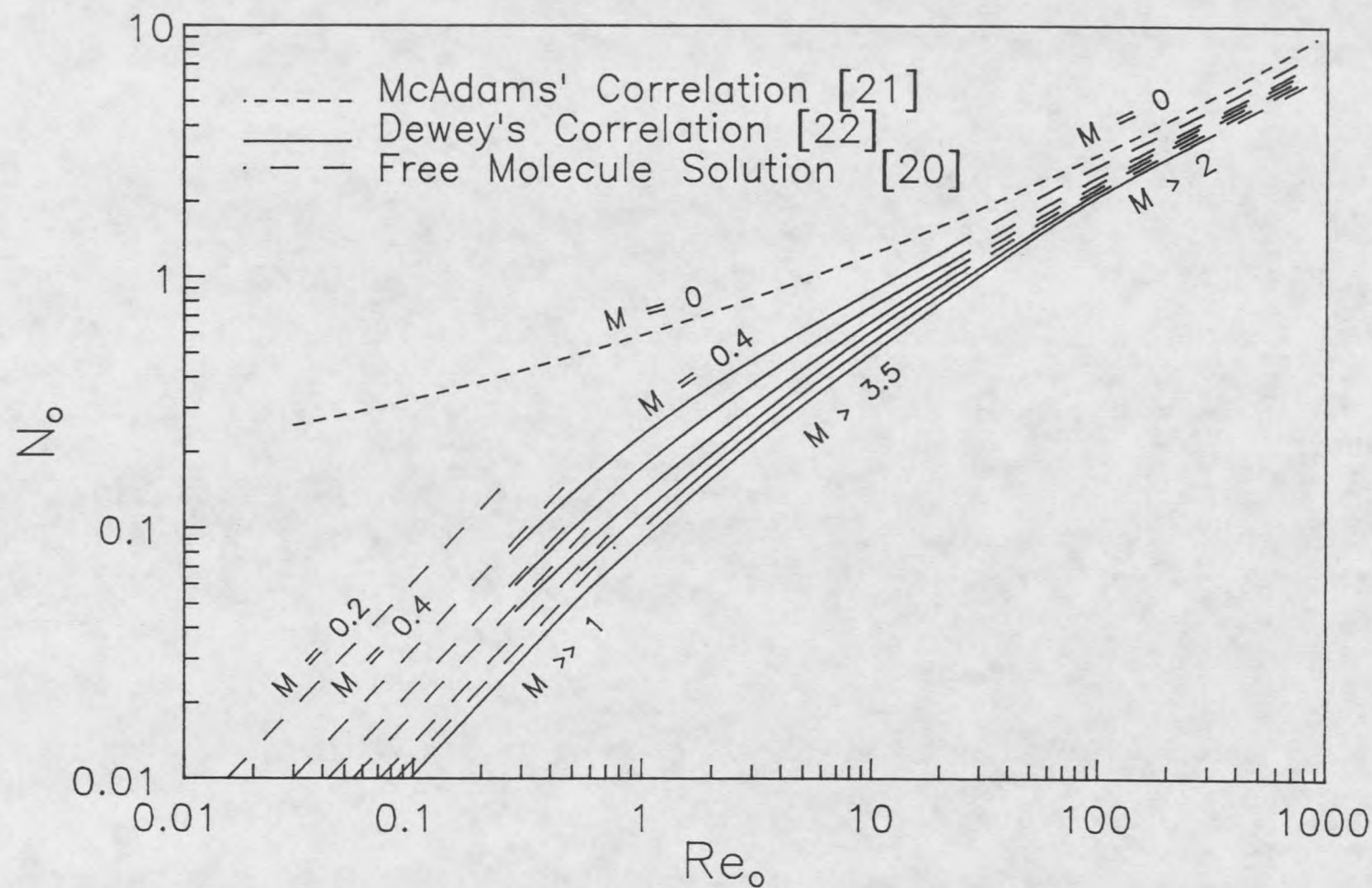


Figure 7. Correlation of Hot-Wire Heat Transfer at Low Reynolds Numbers.
Nusselt and Reynolds Number Evaluated at Stagnation Temperature.

CHAPTER 6

EXPERIMENTAL APPARATUS

Film Anemometer Probes

The film anemometer probes studied were of the design shown in Figure 8. All of the hot-film probes studied were built at Montana State University by Dr. A. Demetriades. The probes were designed specifically for high temperature hypersonic flows. These particular flows are extremely restrictive for the probe design. The probes consist of four basic components which are the body, the leads, the glaze substrate, and the film. The main body is a 0.25 cm diameter 10 cm long twin-bore alumina tube. This was selected because it can easily withstand the temperature requirement and because of its availability. Two 24 gauge (0.05 cm diameter) 15 cm platinum lead wires extend through the alumina. These allow connection at one end to the electrical circuit and the other end to the film. Platinum was selected as the wire material since it is commercially available, is resistant to oxidation, and can withstand high temperatures. It is also chemically identical to the platinum film itself, resulting in a better film-leadwire joint. Possibly the most important component is the glaze substrate which supports the film. The glaze used was Amaco HF-10. A liquid platinum resinate was then used for the film. The film is deposited on the stagnation line of the probe tip and cured. The finished probes have resistances ranging from 5 to 25 ohms. The film area is about 0.18 cm by 0.05 cm and approximately .0000013 cm thick [9].

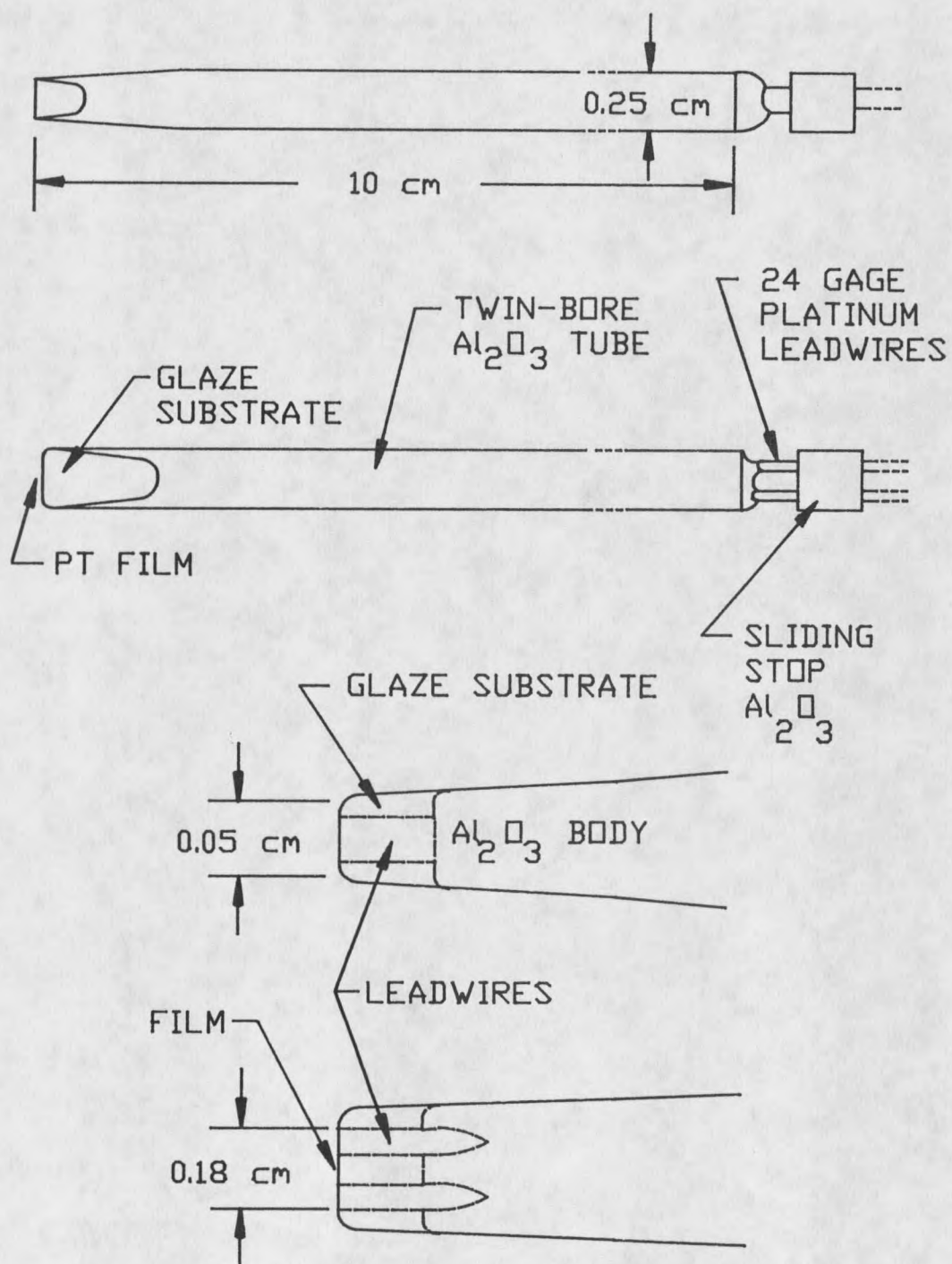


Figure 8. Film Probe Design.

As a part of the fabrication process the probes underwent preliminary tests consisting of stability checks at room temperature and high temperature soaks. For more information on the probe design and fabrication see [7].

Programmable Current Supply (PCS)

The electronic equipment used for making the necessary calibrations was a programmable current supply referred to as a PCS. The PCS is made up of a Zenith-100 microcomputer, a digital thermometer, and a computer controlled current supply. Figure 9 shows a diagram of the system components. The PCS is indispensable in making oven calibrations, flow calibrations, and single sets of current-increasing steps which will be referred to as "overheat traverses". The PCS allows several modes of operation ranging from manual to fully automatic. For example, for a single overheat traverse the PCS can be programmed to pass a specified number of sequential increasing currents through the film, stopping at a specified maximum current that can be up to 100 mA. Each temperature, voltage, current, and resistance is recorded by the computer. This data can then be stored in a data file for later data reduction. The PCS can also be programmed to monitor the temperature of the probe surroundings via a digital thermocouple and make overheat traverses at predetermined temperatures. By doing this the PCS can be set up to do complete oven calibrations without constant user supervision.

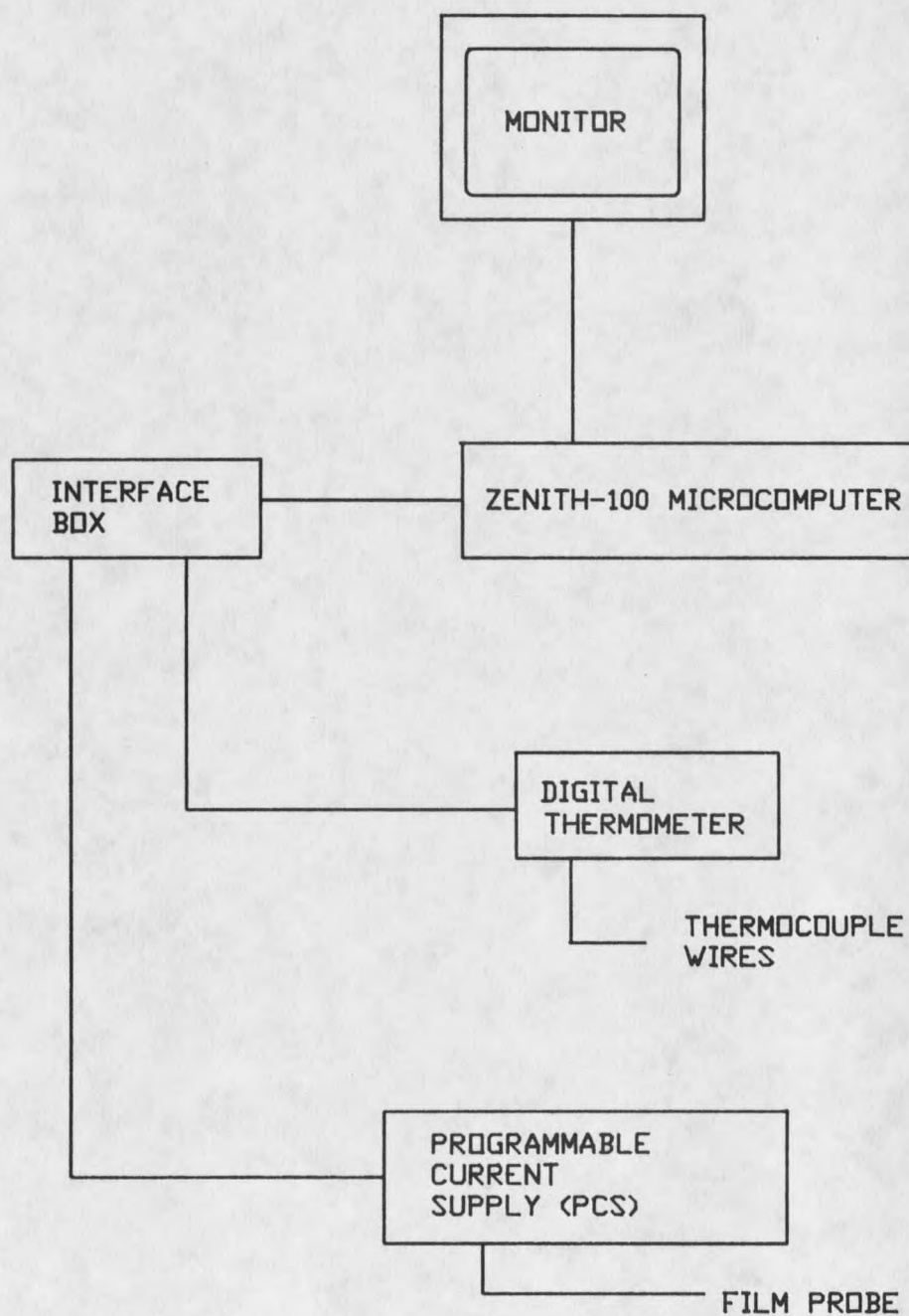


Figure 9. System Components Used to Collect Raw Data.

Oven Calibration Hardware

In order to find the reference resistance at 0 C and the resistivity coefficients for each probe, it is necessary to find the probe resistance at zero current for a range of temperatures. This must be done in a surrounding where the temperature can be measured accurately and independently of the film. This can be conveniently done by using a controlled oven. With the probe completely immersed in the oven with an accompanying thermocouple, the film temperature can be monitored. See Figure 10 for a schematic of the oven with the probe in place. Figure 11 shows the probe mounted in the oven probe holder. Once the probe is mounted on the holder and connected to the PCS the holder can be completely inserted into the oven chamber.

The oven is a Hevi-Duty Electronic Co. Model M-3012-S. It is a 30 cm outside diameter 45 cm long cylinder with a 5.7 cm diameter coaxially located insulated heating chamber lined with alumina. The heating chamber is accessible at one end by a sliding steel door. The probe holder is a ceramic plug which is made to slide completely into the heating chamber of the oven leaving only lead-wires and thermocouple leads protruding from a small opening in the door. The oven is rated at 1650 Watts and 1000 C. It is powered by a variable transformer with a 140 Volt maximum. The oven is capable of reaching 500 C in about 1 hour and cools to room temperature in about 12 hours.

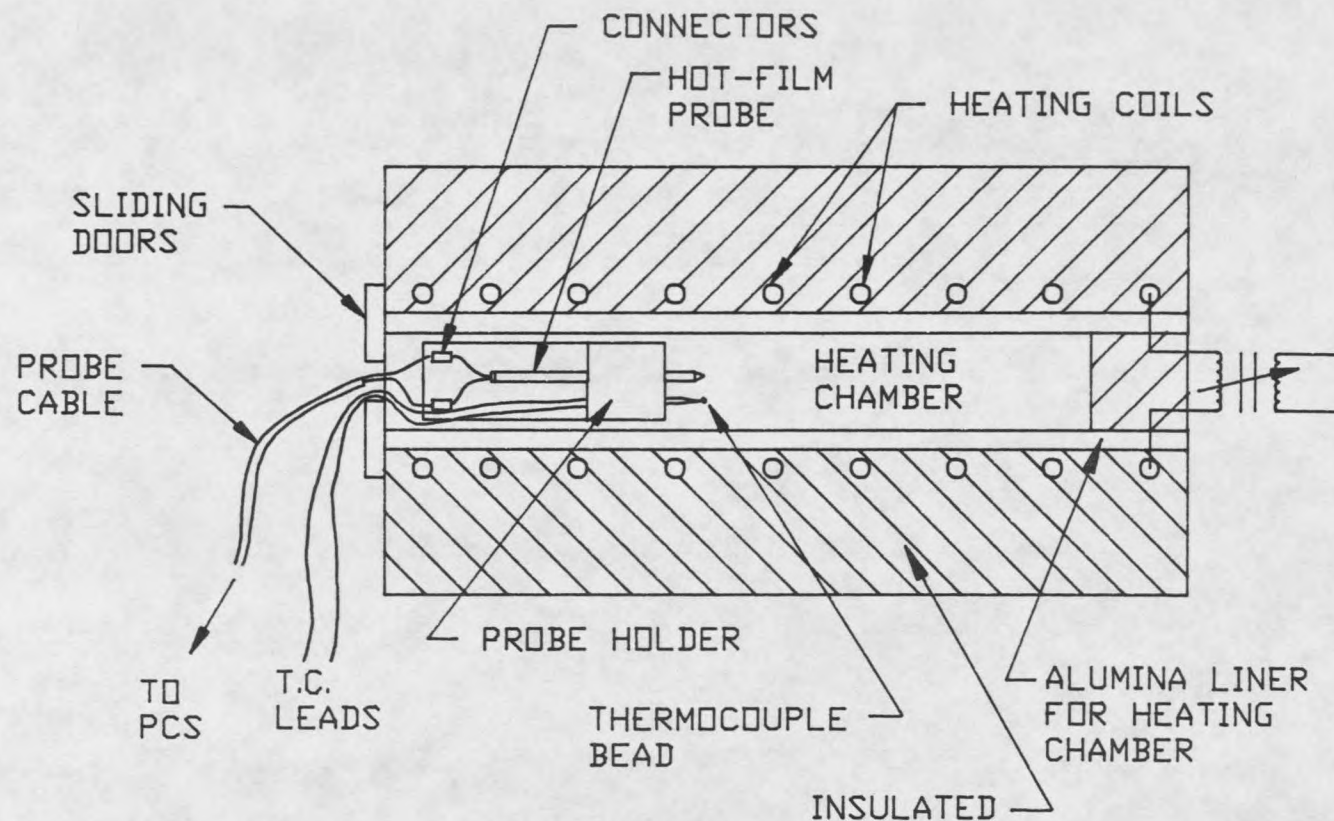


Figure 10. Top Cut-Away View of Oven Calibration Hardware with Probe in Place.

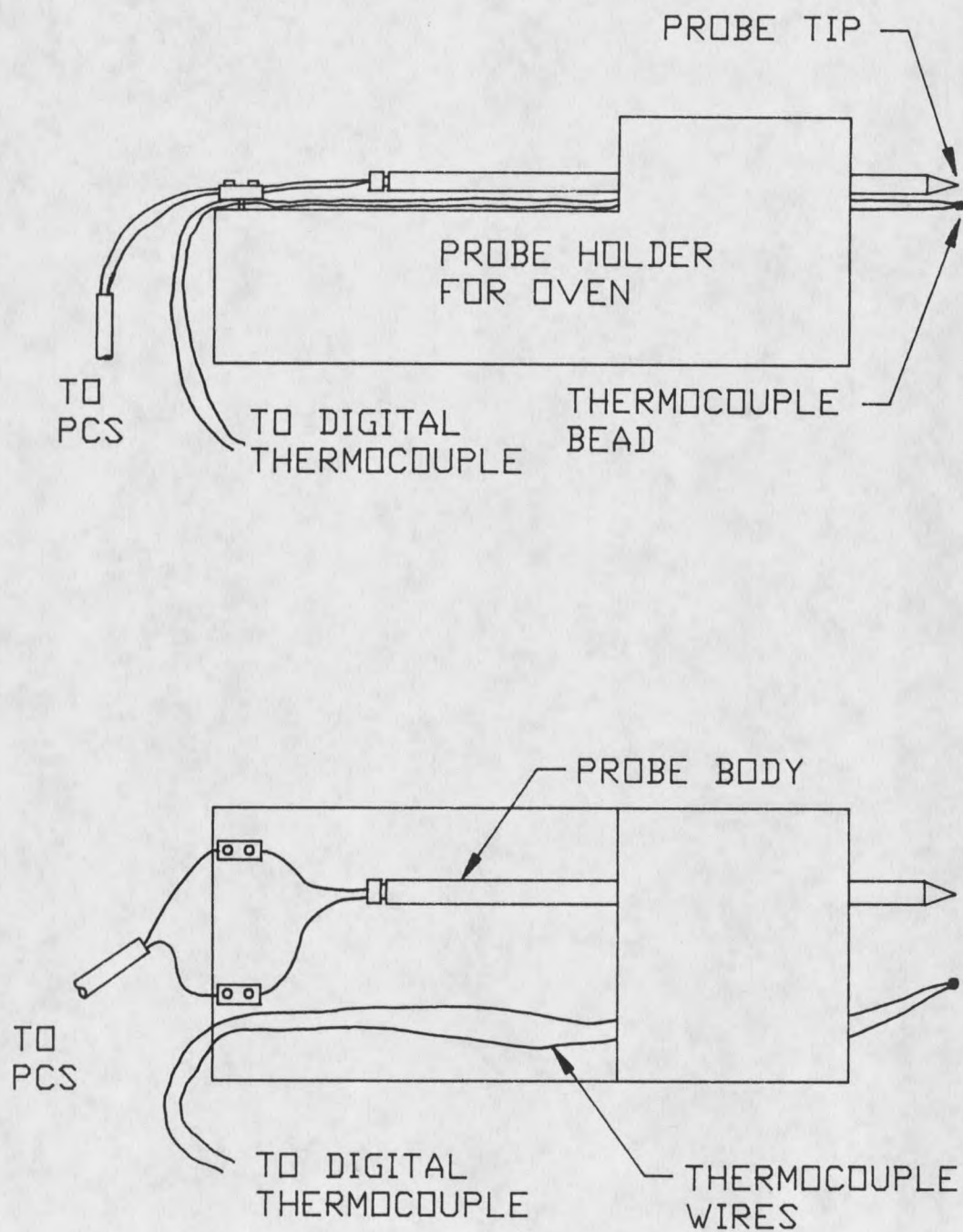


Figure 11. Probe and Accompanying Thermocouple in Probe Holder.

Low Velocity Tunnel (LVT)

The low velocity tunnel (LVT), shown in Figure 12, is a fan-operated venturi manufactured by Aerolab Supply Company. Air flows through the tunnel by suction induced by the fan at the exit of the tunnel. The amount of mass passing through the test section is controlled by letting air enter behind the test section through the gap in a cylindrical shroud enclosing the test section, thereby decreasing the mass flow entering ahead of the test section. By controlling the gap width one can change the velocity in the test section and thereby obtain a Reynolds number range of about 1700–9000 per cm.

The probes were mounted on a holder, shown in Figure 13. The holder positioned the probe on the centerline of the LVT directly facing into the flow.

The LVT was calibrated with a pitot-static tube and a vertical manometer using water as the working fluid. Incompressible flow was assumed in calculating the velocity yielding the following formula for velocity:

$$(54) \quad V = \left[2gy \left(\frac{\gamma_{H_2O}}{\gamma_{AIR}} - 1 \right) \right]^{1/2} \quad (\text{m/s})$$

The calibration measurements were made at the tunnel centerline, where probes would be positioned, with the probe holder stand in place. Results were cross checked by using a separate manometer, static, and dynamic pressure taps. The range of velocities for the LVT were found to be from about 2.6 m/s to 16.0 m/s at the maximum with an error of about 0.1 m/s. The calibration of test section velocity versus gap width is shown in Figure 14.

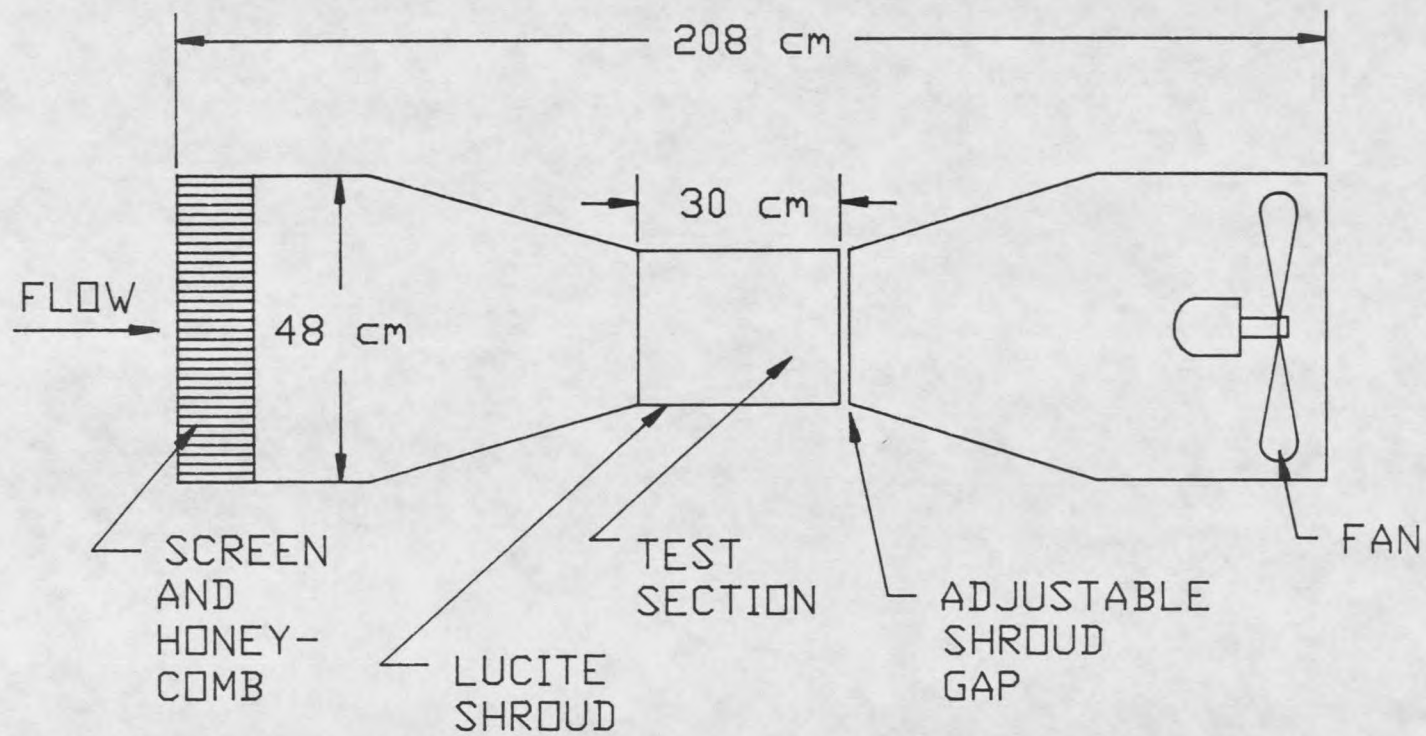


Figure 12. Low Velocity Tunnel.

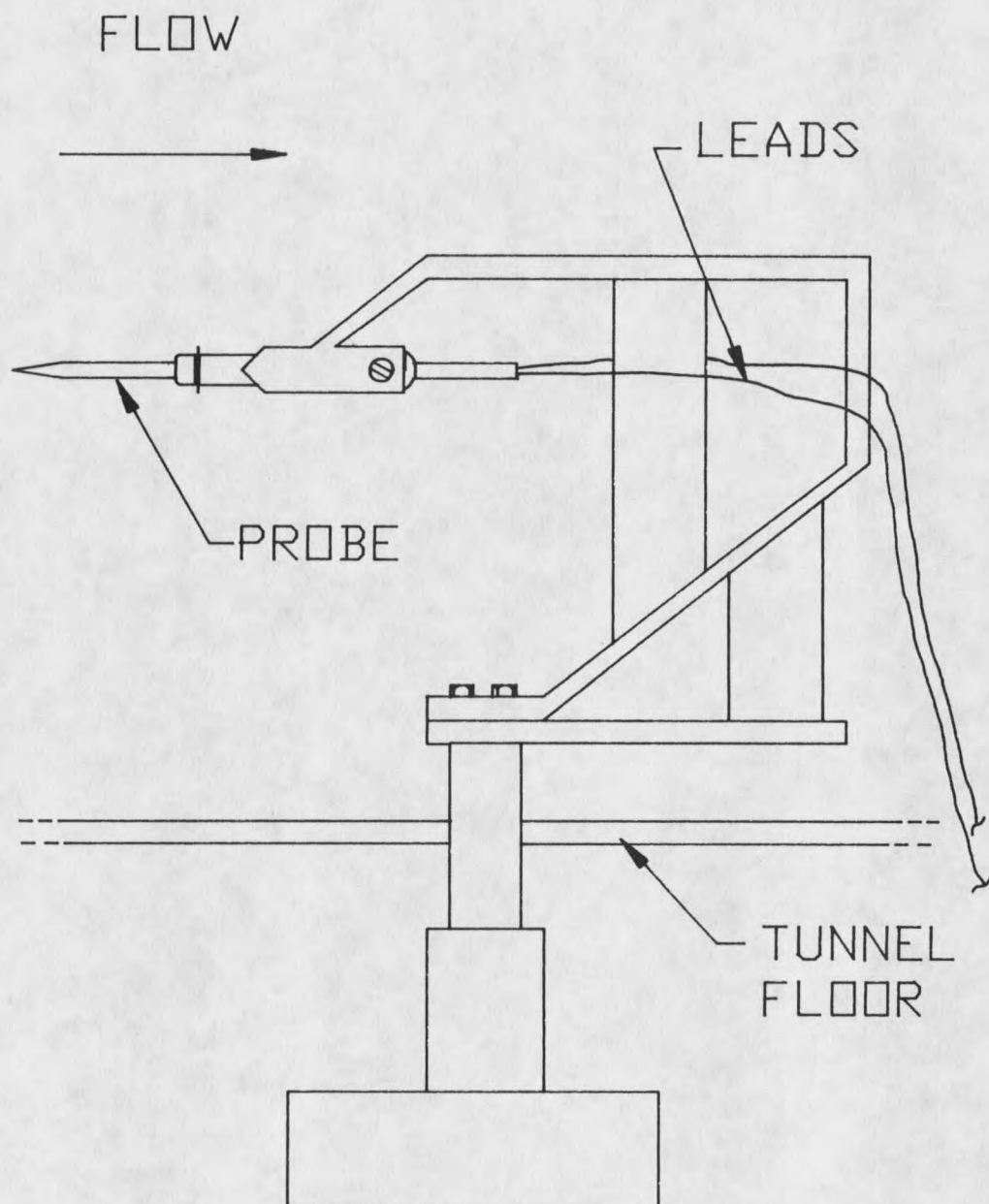


Figure 13. Probe Holder for Low Velocity Tunnel.

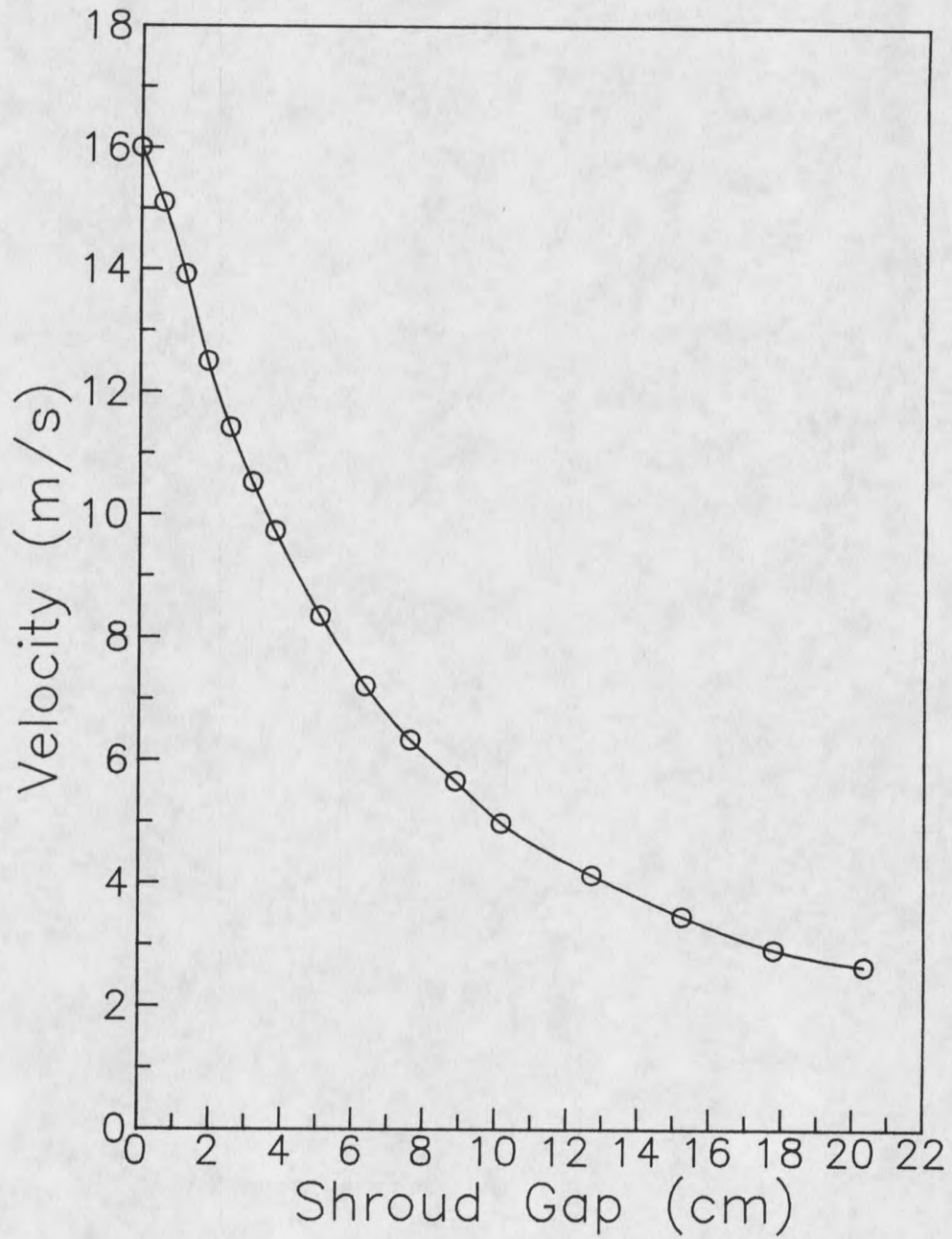


Figure 14. Calibration Results of Low Velocity Tunnel.

Supersonic Wind Tunnel (SWT)

The Montana State University Supersonic Wind Tunnel is of an open circuit type, using air as the working fluid. The flow is continuous for a period of several hours, being limited by the ability of the silica-gel air dryer to maintain a dew point of about -34 C. The present setup allows for Mach numbers as high as 3 and Reynolds numbers from about 19,000 per centimeter to about 120,000 per centimeter. These flows are obtained by a two-dimensional Mach 3 nozzle block. Also, stagnation temperatures can be obtained between about 10 C to 65 C. The geometry of the test section itself is about 7.9 cm $\times$ 8.1 cm $\times$ 40.6 cm.

The general circuit and its components are shown in Figure 15. Atmospheric air first enters and passes through a silica-gel air dryer in order to remove as much moisture as possible. It then passes through a throttling valve, which controls the stagnation pressure, and then goes into a stilling tank before entering the test section. The air then passes through the supersonic nozzle, through the test section, and into the supersonic diffuser. From there, it flows through a subsonic diffuser, two pumping stages and a large silencer after which it is exhausted to the atmosphere.

The Supersonic Wind Tunnel is controlled from a console located near the test section. The console allows the operator to adjust the temperature and the inlet pressure. These settings can be controlled automatically or manually. For more information on the SWT see [23].

The hot-film probes were mounted on the center line of the SWT. The local Mach number was changed by moving the hot-film probe to different positions along the tunnel axis. The Mach numbers greater than one were found by using a transducer calibrated to obtain the pitot pressure as in Figure 16, the SWT control

gauge to obtain the stagnation pressure, and the isentropic charts to determine the Mach number at that corresponding pressure ratio. The pitot probe was arranged to be at the same axial position as the probe at about 1.25 cm to one side. Figure 17 shows the film probe holder with accompanying pitot probe. The pitot probe also allowed the operator to determine if the flow near the probe tip was unsteady or not. The position at Mach 1 was simply at the throat and for Mach numbers less than one the position was determined by using Figure 18.

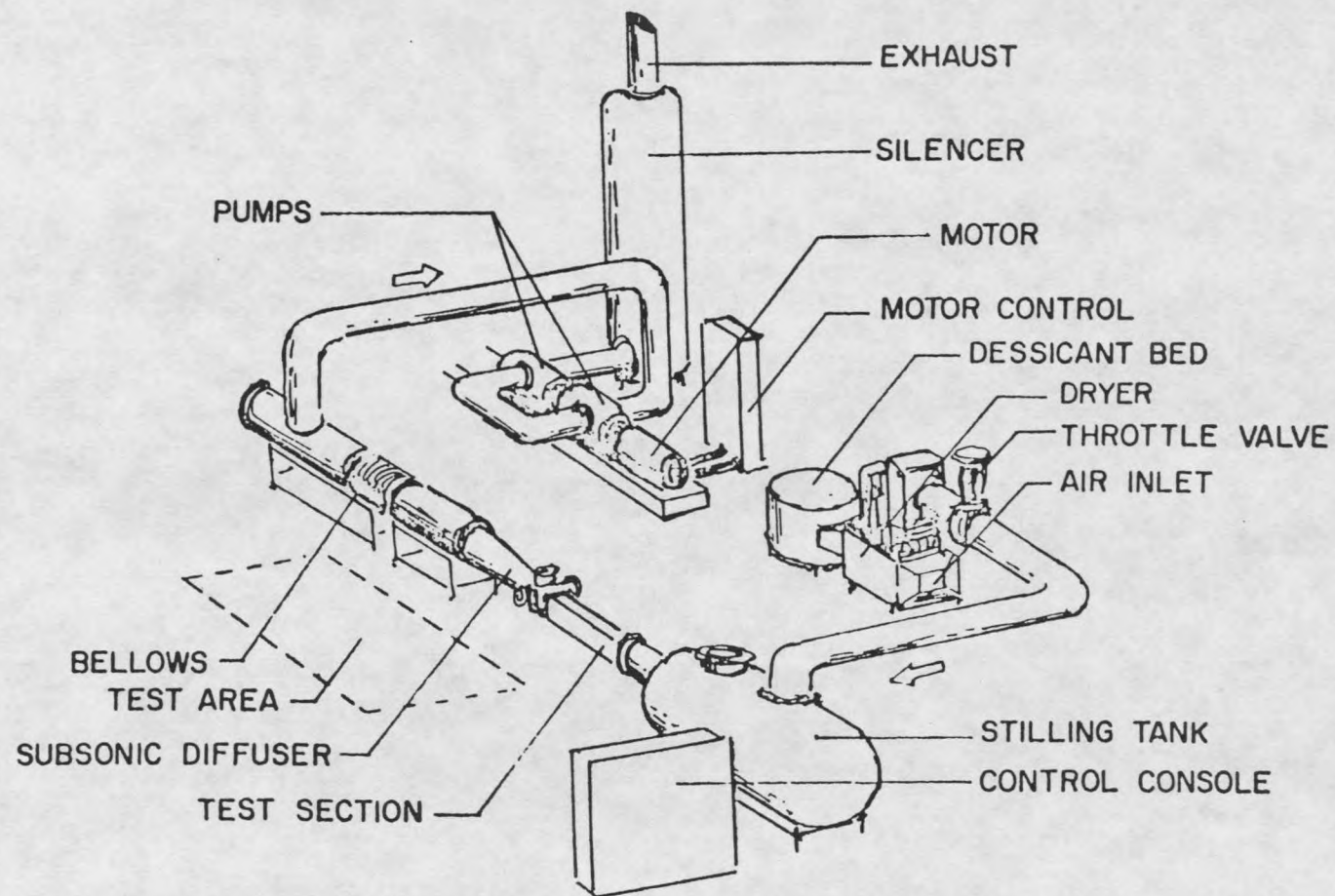


Figure 15. General Circuit of Supersonic Wind Tunnel.

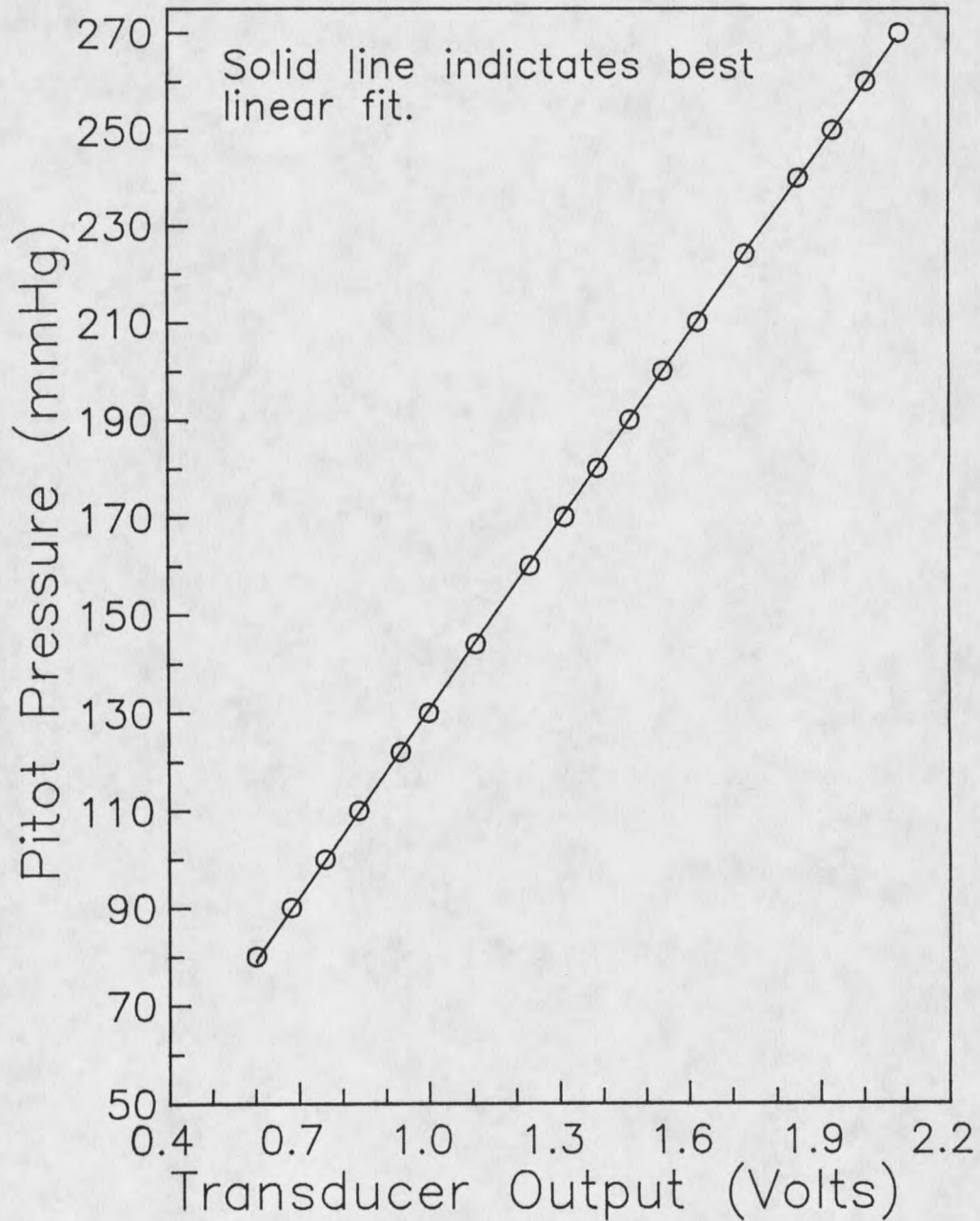


Figure 16. Transducer Calibration for Measurement of Pitot Pressure in Supersonic Wind Tunnel.

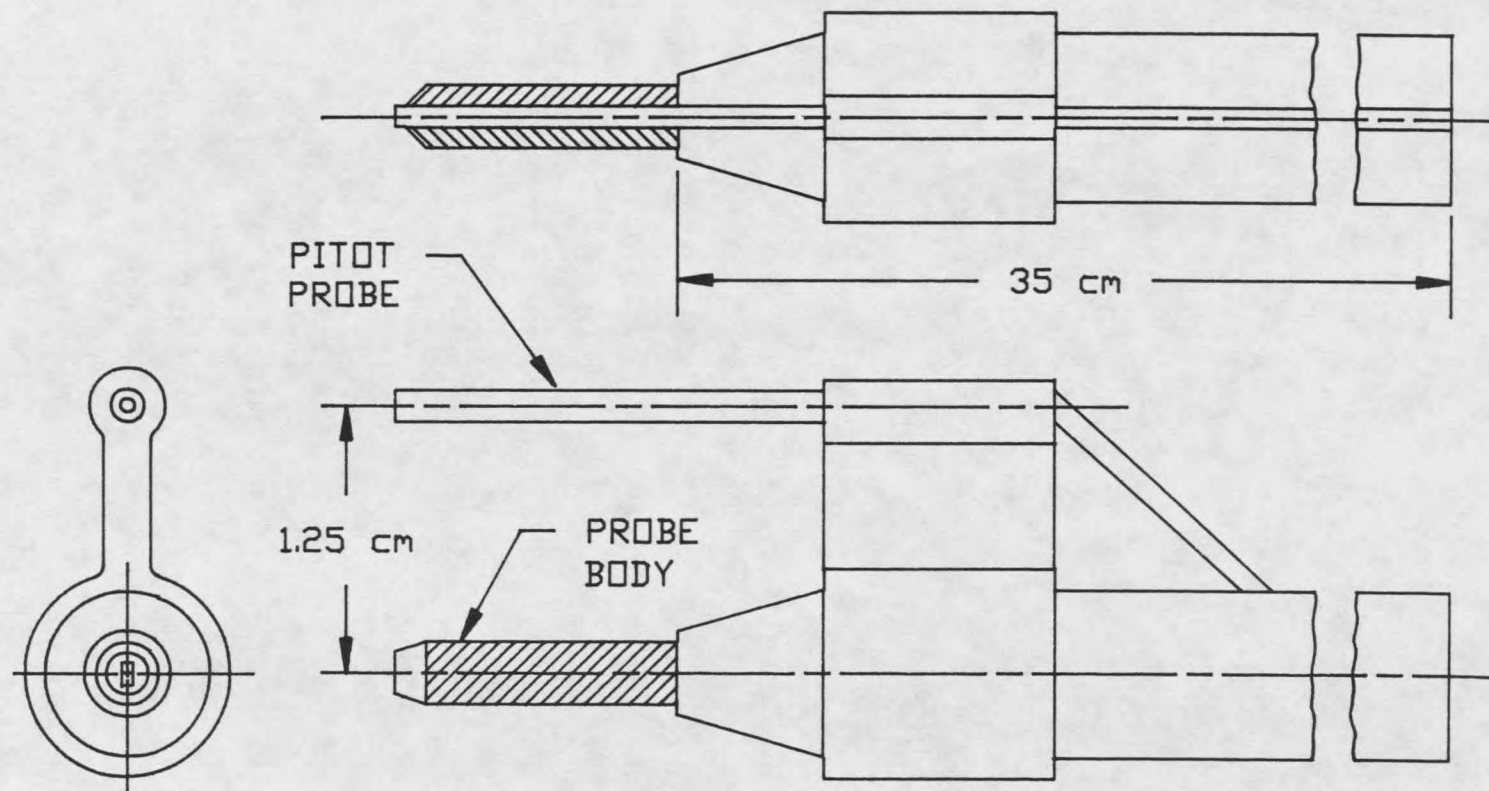


Figure 17. Supersonic Wind Tunnel Film Probe Holder with Accompanying Pitot Probe.

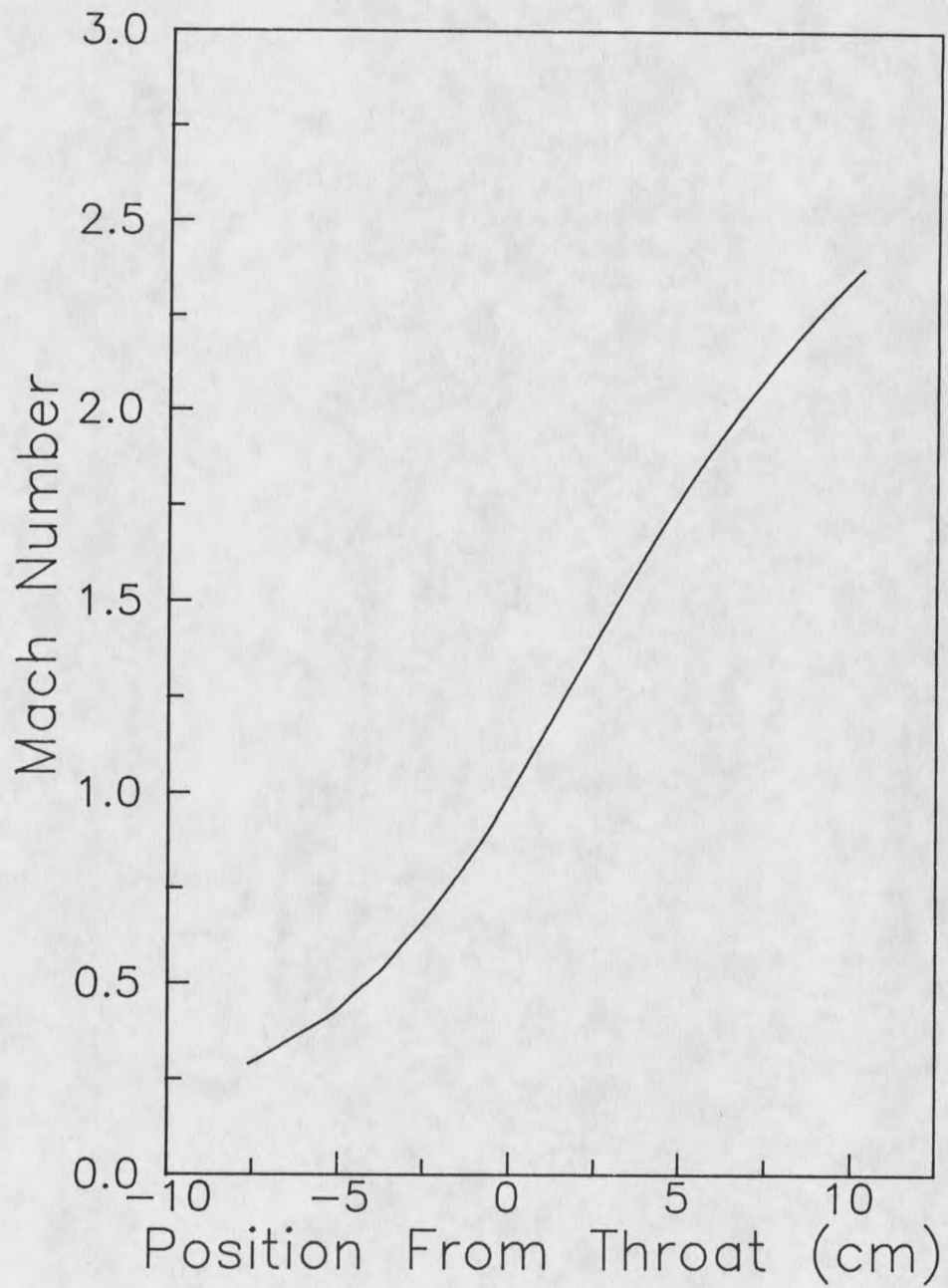


Figure 18. Mach Number Variation With Position.

CHAPTER 7

CALIBRATION PROCEDURES

Oven Calibration Procedures

In order to determine the resistance-temperature relation of each probe it is necessary to perform an oven calibration. This calibration is performed using the PCS and oven calibration hardware described in Chapter 6. The desired results of this calibration are the reference resistance at 0 C and the resistivity coefficients α and β . These variables are used to find the probe temperature at zero current and to find the measured Nusselt number. In order for the probe to be of any use these variables must be known accurately. The following is an outline of the procedure. For detailed step-by-step instructions see Demetriades [7].

After mounting the probe and thermocouple in the oven probe holder as previously shown in Figure 10 the oven is activated. The oven is then allowed to reach a temperature of 500 C which takes about one hour. At this point the cable linking the probe lead wires to the PCS is connected. The PCS is then programmed to take an overheat traverse of specified magnitude and length at several temperatures (20 currents, 100 mA maximum current, and 17 different temperatures at 30 C steps, for instance). Upon finishing the programming, the oven power source was shut off so that the oven would begin cooling. The calibration is then started by the operator so that the first overheat traverse is taken at 500 C. After this data set is taken the operator names the file to be written to. The PCS can now be left to finish the calibration automatically. After about a 12 hour period the

calibration is complete with the data stored in the specified file. The probe is then withdrawn from the oven and the PCS deactivated.

The program to be used with the PCS is named WIRECAL. Having the data from the oven calibration on disk, the data are then reduced using a program named NEWOVEN.BAS (see Appendix C). This program can produce either a detailed or a summarized view of the oven calibration results. A typical summarized view is the one-page output of Figure 19. As shown in this figure, the output gives a table of oven temperature versus hot-film resistance and these important results: probe resistance at zero current and zero degrees C, the first resistivity coefficient (α), and the second resistivity coefficient (β). The program also prepares a summary file that is used to produce graphical results of temperature versus resistance as will be presented in Chapter 8. In order to produce this graph the overheat traverse at each oven temperature was fit with a second degree polynomial to find the resistance at zero current for that temperature. This results in a set of data containing zero current resistances versus the corresponding temperatures. These data are also fit with a second degree polynomial to find the reference resistance and the coefficients of resistivity.

The calibration is done in order to find how the resistance of the film increases with temperature. Unless compensation is made, the actual relation found includes the resistance of the film, its corresponding platinum lead wire, and possibly its connecting cable increases with temperature. This is true for both oven and flow calibrations. For probes operating over wide temperature ranges this may become very important as it may otherwise give erroneous results of the probe measurements. In order to avoid this, the values of the resistance of the cable and lead wires at their corresponding temperatures are subtracted from the measured resistance so that the resulting value is the film resistance alone.

NEWOVEN DATA REDUCTION PROGRAM

DATE 3-07-90
 PROBE NUMBER 50
 CALIBRATION FILE NAME a:5030790.ov9

CABLE RESISTANCE RECORDED .166
 LINE RESISTANCE (OHMS) = $.166 + .1381497 * (1 + .003927 * T)$

THE MAXIMUM SET CURRENT WAS 100 mA
 THE MAXIMUM CURRENT ACHIEVED WAS 97.715 mA
 THE NUMBER OF CURRENTS USED WAS 20

TEMP DEG. C	R OHMS	D	CRIT. C mA
498	15.28	-.219	289.22
466	14.87	-.128	292.12
436	14.38	-.271	284.91
406	13.88	-.334	276.87
377	13.4	-.197	277.9
347	12.93	-.042	277.42
317	12.38	-.174	267.09
287	11.85	-.098	265.46
257	11.31	.123	266.63
229	10.86	-.069	259.17
199	10.35	.103	260.25
169	9.82	-.138	252.43
139	9.28	.133	254.19
109	8.74	.104	249.28
79	8.18	-.104	242.04
50	7.62	.015	239.88
27	7.17	-.207	230

THE MAXIMUM RESISTANCE FOR THIS PROBE (OHMS)= 17.17468
 THE LARGEST PERCENT OVERHEAT ACHIEVED = 20.91941
 THE LARGEST POWER DISSIPATION (mW) = 163.9876
 MAXIMUM PROBE TEMPERATURE ACHIEVED = 596.5743

RO (OHMS, AT 0 DEG. C)= 6.842243
 ARO (OHMS/DEG C)= 1.731961E-02
 AVERAGE RESISTANCE-CURRENT DEVIATION. (OHMS)= 3.010654E-03
 OVERALL RMS DEVIATION OF R FROM R-T CURVE (OHMS)= 1.716214E-02
 THE AVERAGE VALUE OF THE CONSTANT D = -8.790911E-02
 ALPHA (REFERRED TO RO ABOVE, PER DEG. C)= 2.531277E-03

QUADRATIC FIT OF RESISTANCE -VS- TEMP.
 RESISTANCE AT ZERO DEG. = 6.678555
 QUADRATIC ALPHA = 2.867842E-03
 QUADRATIC BETA = -5.285644E-07

Figure 19. Summarized Output for Oven Calibration for Probe Number 50.

This total line resistance is given as

$$(55) \quad R_T = R_{LW} + R_C$$

Using the known resistance and resistivity of 24-gauge platinum wire the platinum lead wire resistance is approximately

$$(56) \quad R_{LW} = 0.138(1 + 0.003927 * T)$$

The cable resistance can be measured directly. For the oven calibrations the cable remains at room temperature the entire time so that no temperature compensation is needed. If the cable was subject to heating an equation similar to that for the platinum lead wires could be written.

Flow Calibration Procedures

The flow calibration procedures are explained in [7] as they are written here. The procedure for flow calibration in the LVT consists of first mounting the probe along the center-line of the LVT and then connecting it to the PCS. One overheat traverse is performed at zero velocity. The LVT is then started and a shroud gap is chosen. An overheat traverse is performed, the data is stored, and the velocity is noted. The velocity of the LVT is then changed and another overheat traverse is performed. This cycle continues until approximately fifteen overheats have been performed at known velocities. The flow properties are determined using atmospheric pressure and the temperature measured at the LVT inlet. The data is then reduced using the program FLOWRDCT.BAS (see Appendix D).

The procedure for flow calibration for the SWT is similar to the procedure for the LVT except that for the LVT only the velocity is changed for each overheat traverse while for the SWT the temperature, pressure, and Mach number are

varied for each traverse. The SWT flow calibration procedure begins with first mounting the probe in the SWT and then starting the tunnel and bringing it to the appropriate temperature. The probe is then moved to the position of the desired Mach number at the tunnel center-line. The connection to the PCS is made at this time. Having recorded the Mach number, total temperature, and stagnation pressure an overheat traverse is made. This file is then saved for later reduction. The stagnation pressure of the SWT is then changed by about 20 mm Hg and another overheat traverse is made. This cycle of recording the flow parameters and making overheat traverses continues until the lowest pressure obtainable without flow "break-down" is reached. After reaching the lowest pressure, the pressure is returned to its maximum and another Mach number is selected. The cycle begins again and continues for each Mach number. After taking data for each desired Mach number the tunnel stagnation temperature is changed and the entire routine is repeated. The calibration routine used included Mach numbers 3, 2, 1, and 0.5 and stagnation temperatures of about 15 C and 65 C. The pressure ranges were from about 615 mm Hg to 100 mm Hg at a minimum. The resulting unit Reynolds number range was from 25,000 to 120,000 per centimeter.

This process results in about 4000 points of data. The program FLOWRDCT.BAS (Appendix D) was written and used to reduce this data.

CHAPTER 8

RESULTS

Temperature Endurance and Stability

For the film anemometer probes to be of any use in high temperature hypersonic flows it had to be determined through experimental testing if they could withstand the high temperatures and remain stable.

In order to test the temperature endurance of the film anemometer probes they were placed in a high temperature environment. The maximum temperature was typically around 700 C. The resistance was then monitored for a period of over two hours. A constant resistance over time for several high temperatures indicated that the film was stable under these conditions. It was found that probes that failed to maintain a constant resistance were most likely to be the probes that failed in future tests. The stability could also be monitored by noting the difference between the resistance before and after the soak. Typical changes were 0.2 ohms.

In order to further test the stability and endurance of the film anemometer probes, several destructive tests were performed. Four probes were used to determine the highest survivable operating temperature of the probe and to see if probes could remain stable over time. Note that "operating temperature" refers to the film temperature upon applying the heating current and not to the temperature of the medium surrounding the film alone. These tests revealed several significant findings. One finding was that probes could be pushed to at least a

90% overheat (percent increase in resistance). This overheat resulted in a film temperature of 356 C above room temperature. Limitation on the maximum current of the programmable current supply restricted any higher overheats. Other tests which were performed were aimed at finding the maximum operating temperature of the hot-film probe. Previous to these test the maximum film operating temperature obtained in a successful oven calibration was 665 C. High operating temperatures can be achieved by either raising the temperature of the medium and keeping the overheat approximately constant (about 25%) or by raising the overheat at a constant but relatively high surrounding temperature (500 C in this case). The highest film temperature achieved by the first method (raising the oven temperature) was 765 C. The probe characteristics shifted slightly at this temperature indicating that the temperature limit had been exceeded. The next highest film temperature achieved by this method without a resistance shift was 725 C. This indicated that the maximum operating temperature for this probe was about 750 C. The second method of reaching high operating temperatures (by increasing the overheat) found the highest film temperature achievable to be 800 C. The film's resistance shifted at this temperature and then failed, indicating that the maximum operating temperature had obviously been exceeded. However, before failing, the film anemometer indicated a temperature of 765 C without any apparent shifting of the film's resistance. This was considered the maximum operating temperature of this film anemometer as it previously existed. Though the two methods for reaching high operating temperatures differed, the results of both tests agree fairly closely. It appears that the maximum operating temperatures of the particular probes studied here are around 760 C. High temperature survivability is very important for the application being sought but is not the only criterion the probes must meet. The probes must also be stable.

Stability of the films was examined by constant room checks and repeated oven calibrations. Probes demonstrated a tendency to drift to a higher resistance as they aged and underwent repeated calibrations (about 0.2 ohms or 2% was typical). Probes that were unstable (changed more than 2 ohms) typically failed in later testing.

Probes incapable of surviving high temperatures or remaining stable were eventually destroyed and rebuilt. If they could not successfully endure these tests they were determined to be of no use since the rest of the film's history would rely on them.

Dynamic Pressure Endurance

If probes were to be used in hypersonic flows they must be able to endure high dynamic pressure loads inherent in these types of environments. A select few of the probes used were placed in a Mach 6 high dynamic pressure facility in order to find out if the films could survive. The probes were found to survive dynamic pressure loads of 160 kPa (23 psia) before failing (hot-wires are typically limited to dynamic loads of about 30 kPa (4 psia)). Though the films did finally fail at these loads it is believed that failure occurred due to particle impact combined with high dynamic pressure and not due to high dynamic pressure alone. This would make sense physically since the film has a hard backing, unlike the hot-wire probe, and should therefore be able to withstand very high "clean" dynamic pressure flows. Microscopic inspection of the films indicated that particle impact had caused the failure.

Resistance and Resistivity Coefficients

The reference resistance and the coefficients of resistivity were obtained as outlined in Chapter 7. Since every probe had different physical characteristics, each had to be oven calibrated. It is not sufficient to determine the reference resistance alone and then apply the tabulated values for the resistivity coefficients of platinum. Resistivity coefficients are often quoted for the bulk material and are likely to be different (Lomas [3]) for very thin samples (films were about .0000013 cm thick according to Demetriades [9]). Also, the platinum film resistor could easily contain impurities that would be reflected in the value of the resistivity coefficients. For these reasons each film is oven calibrated. Table 1 shows results of 39 oven calibrations. The average α value is $.00293 \frac{1}{C}$ and the average β value is $-.00000071 \frac{1}{C^2}$ with standard deviations of $.00014 \frac{1}{C}$ and $.00000020 \frac{1}{C^2}$, respectively. These standard deviations of 5% and 28% speak of the predictability of the resistivity coefficients for these sensors. These values are reasonably close to those quoted by Perry [1] and Hinze [14] of $.0035 \frac{1}{C}$ for α and $-.00000055 \frac{1}{C^2}$ for β for platinum. Note that for the film anemometer probes studied the oven calibration is fit with a second degree polynomial to find α and β . Typical oven calibration results are presented on a summary page as in Figure 19 and in graphical form as in Figure 20. Hot-wires were typically fit with a best linear fit ($\beta = 0$). For the targeted temperature range a linear fit was found insufficient for the films, as will be demonstrated.

The effect of the proper type of fit of the oven calibration data was found to be very significant for the film anemometers studied. Figures 21 through 23 show this effect. Originally a linear fit was thought sufficient and flow calibration data were reduced as shown in Figures 21 and 23.

OVEN CALIBRATION RESULTS SUMMARY

PROBE TEST	R_r	$\alpha \times 10^3$	$\beta \times 10^7$
59OV1	6.614	3.053	-10.36
59OV2	6.745	2.961	-9.898
58OV1	8.090	2.824	-6.712
58AOV1	10.087	2.946	-9.544
57OV1	11.465	3.190	-7.151
57OV2	12.164	3.214	-7.379
56OV1	14.362	2.973	-7.084
56OV2	15.358	2.837	-6.532
55OV1	14.151	2.866	-10.94
55OV2	14.487	2.749	-7.458
54OV1	22.315	2.648	-6.522
53SOV1	13.471	2.697	-8.046
53OV1	6.587	3.007	-8.276
53OV2	6.637	3.021	-8.149
52OV1	8.765	3.202	-12.17
52OV2	9.322	3.031	-12.52
51OV1	12.407	2.870	-6.428
51AOV1	7.902	3.278	-8.614
50OV1	6.852	2.985	-6.439
50OV2	6.836	2.939	-5.984
50OV3	6.845	2.864	-4.867
50OV4	6.757	2.912	-5.236
50OV5	6.746	2.952	-6.004
50OV6	6.526	2.821	-3.265
50OV7	6.416	3.038	-6.990
50OV8	6.400	3.074	-7.655
50OV9	6.679	2.868	-5.285
49OV1	15.611	3.026	-6.393
49OV2	16.955	2.927	-6.469
49OV3	17.086	2.905	-6.071
49AOV1	8.843	2.876	-5.306
48OV1	7.177	3.007	-6.287
47OV1	14.862	2.791	-5.403
46OV1	9.315	2.850	-6.215
45OV1	12.252	2.753	-4.841
44OV1	13.073	2.833	-6.324
43OV1	15.250	2.799	-5.077
43AOV1	12.305	2.813	-6.227
42AOV1	26.009	2.734	-5.840
AVERAGE		2.926	-7.076
STANDARD DEVIATION		0.144	2.005

Table 1. Resistivity Coefficients for 39 Oven Calibrations.

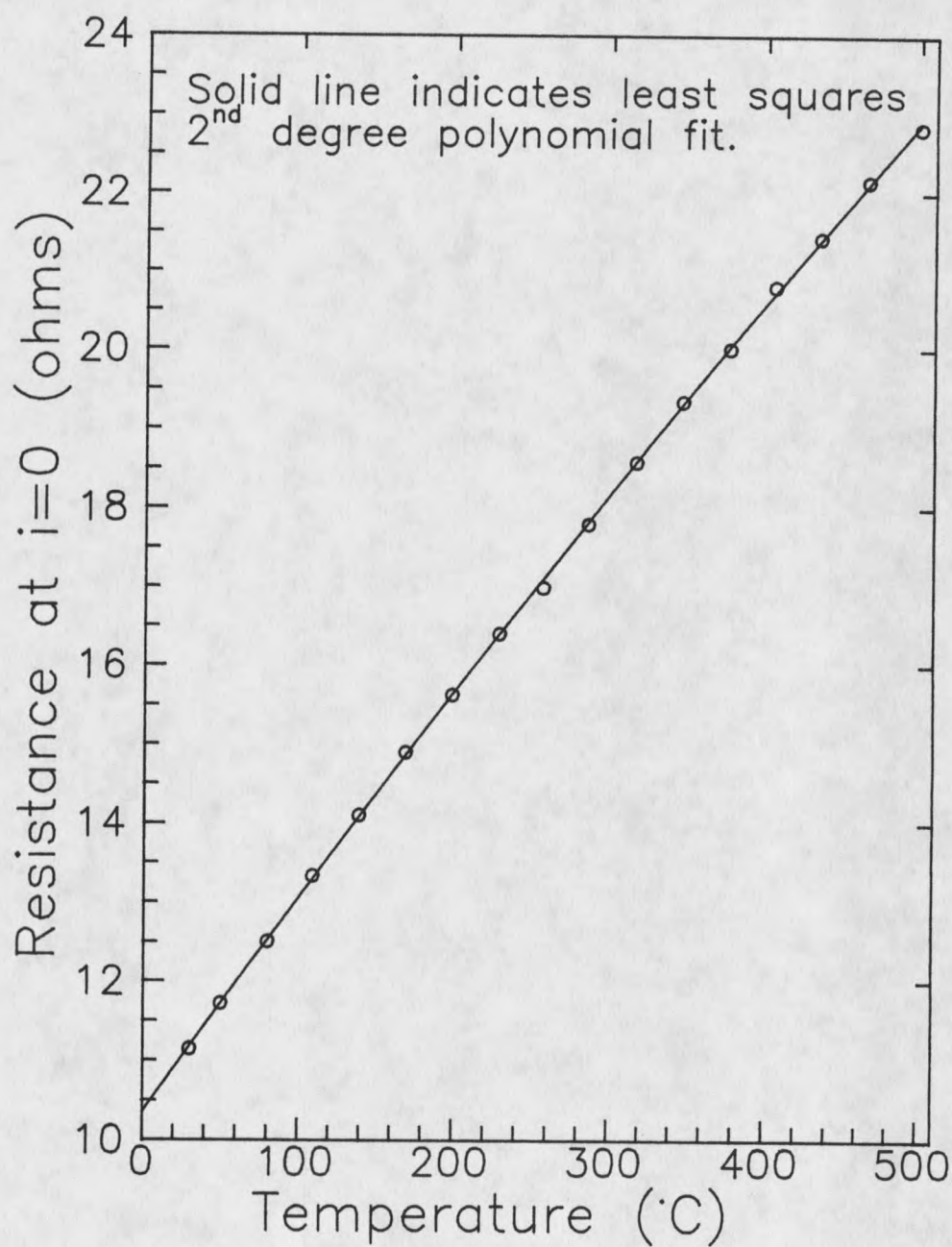


Figure 20. Graphical Presentation of Oven Calibration Results for Probe 48.

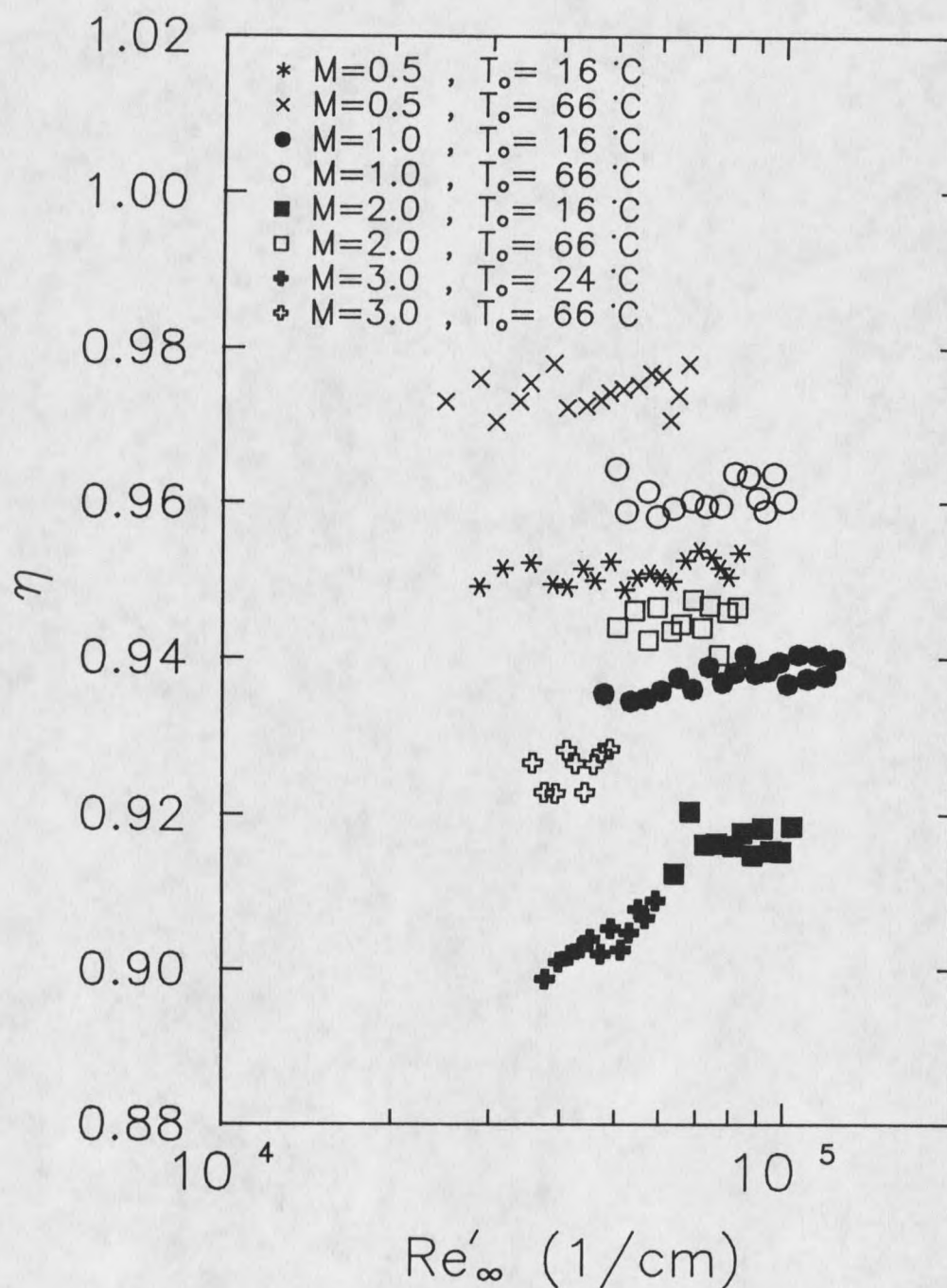


Figure 21. Temperature Recovery Factor Variation for a Typical Probe. Resistivity Calibration with $\beta = 0$. Resistance versus Power Data Fit with a Second Degree Polynomial.

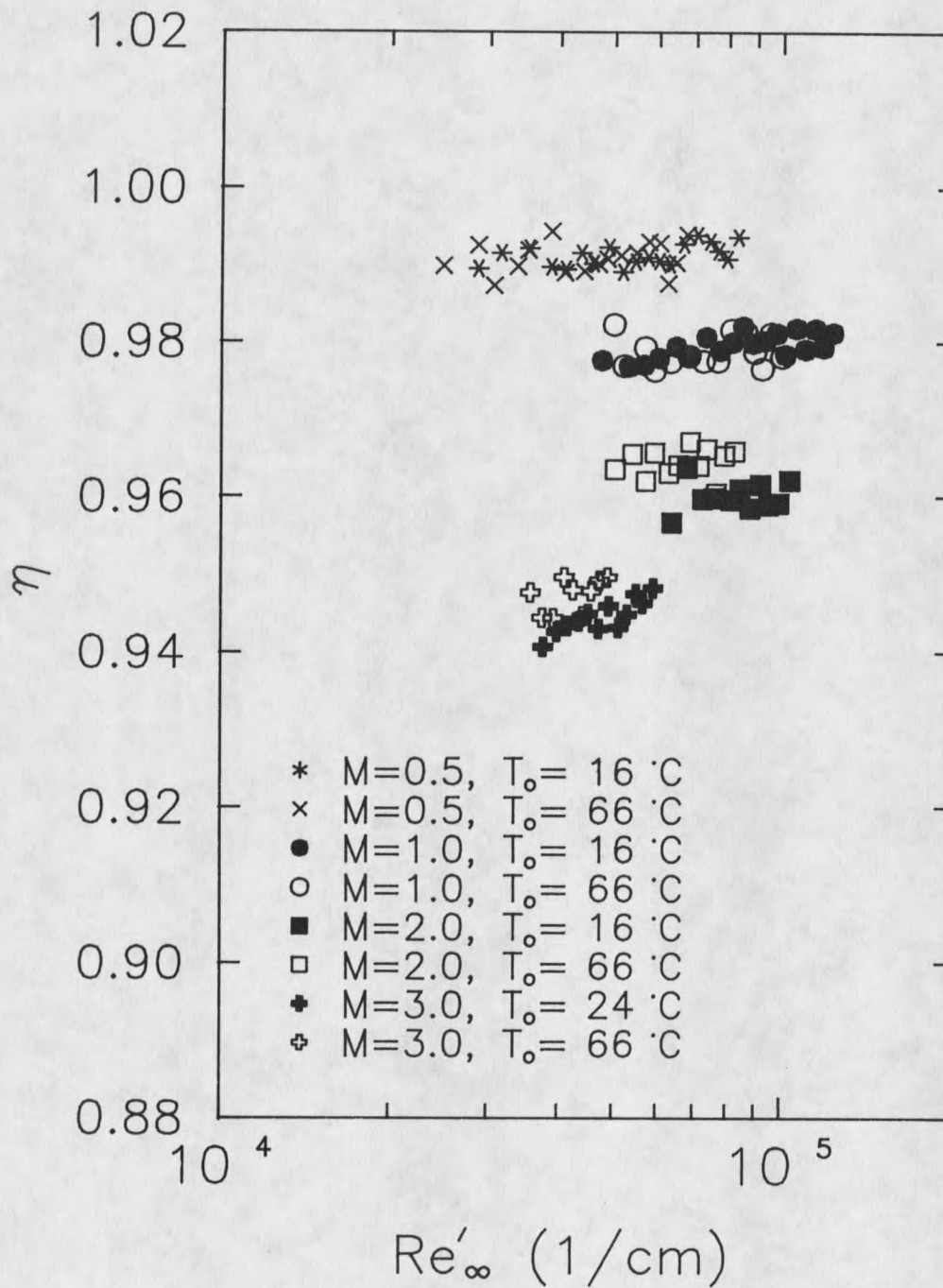


Figure 22. Temperature Recovery Factor Variation for a Typical Probe. Resistivity Calibration with $\beta \neq 0$. Resistance versus Power Data Fit with a Second Degree Polynomial.

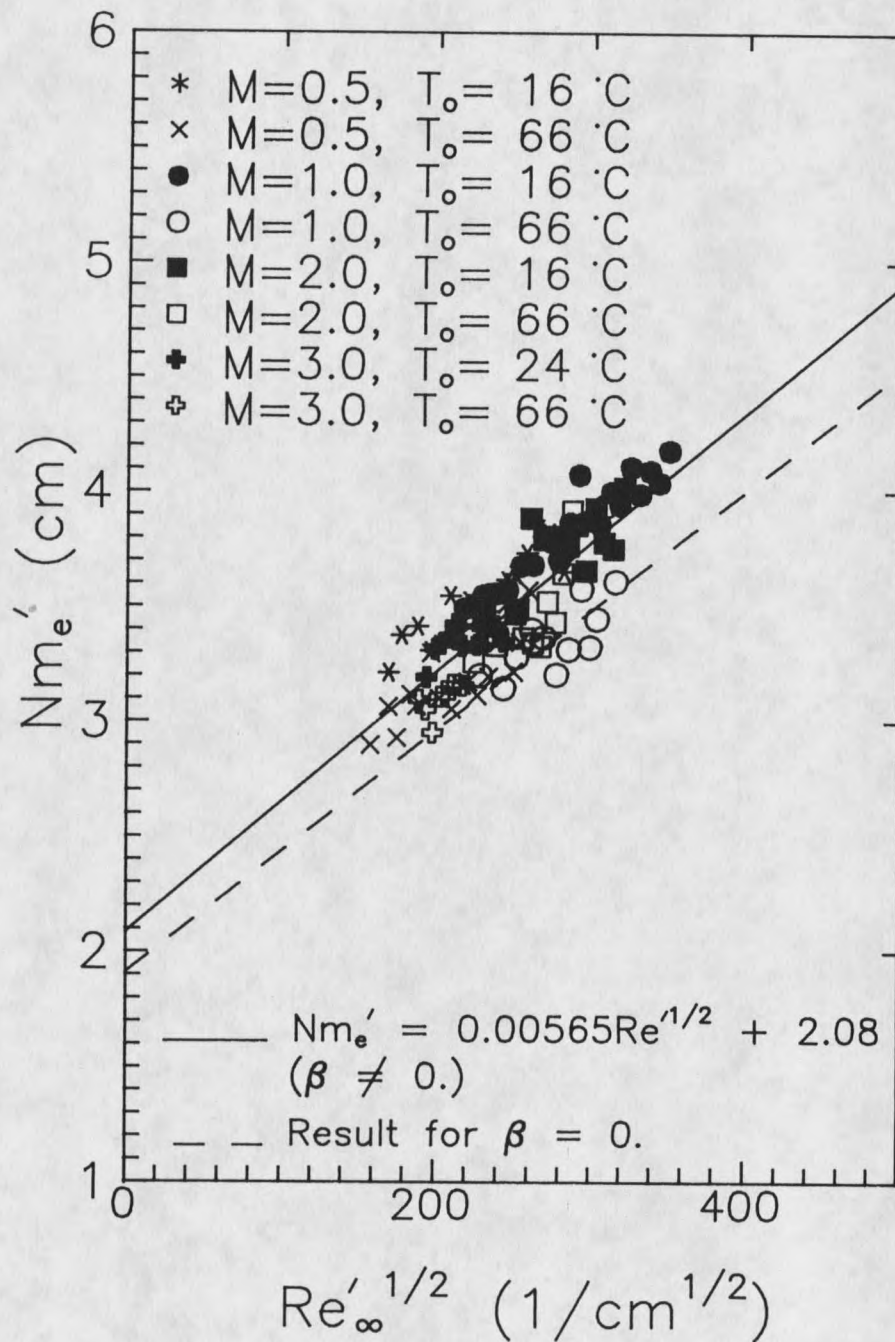


Figure 23. Heat Transfer Characteristics for a Typical Probe.
Resistance versus Power Data Fit with a
Second Degree Polynomial.

The temperature recovery factor is shown to be a function of both stagnation temperature and Mach number. Upon using a second degree fit of the oven calibration data instead of a linear fit the same flow calibration data were found as shown in Figure 22 and 23. Figure 23 shows a definite shift in the Nusselt number results. The dotted line represents the best linear fit of the data reduced using the linear oven calibration results ($\beta = 0$). Figure 22 shows that the temperature recovery factor is not a function of stagnation temperature as compared with the same data in Figure 21 reduced with a linear oven calibration. The data presented in Figure 22 indicated that the temperature recovery factor is a function of Mach number and slightly of Reynolds number for Mach 3.

Dependence of The Nusselt Number On Power

In Chapter 5 it was noted that the Nusselt number was dependent on power. A constant D was then defined that would give indication of how the Nusselt number depends on power. This constant D was plotted against the flow Reynolds number in order to investigate this power dependence. The list of variables in Figure 19 also includes the constant D . This list gives typical results of how the probes behaved and shows that the absolute value of the constant D generally increases as the surrounding medium increases with temperature. Figures 24, 25 and 26 show how the constant D is related to Mach number, Reynolds number, and stagnation temperature. The value of D generally remains unaffected by all variables except the stagnation temperature for the entire range investigated.

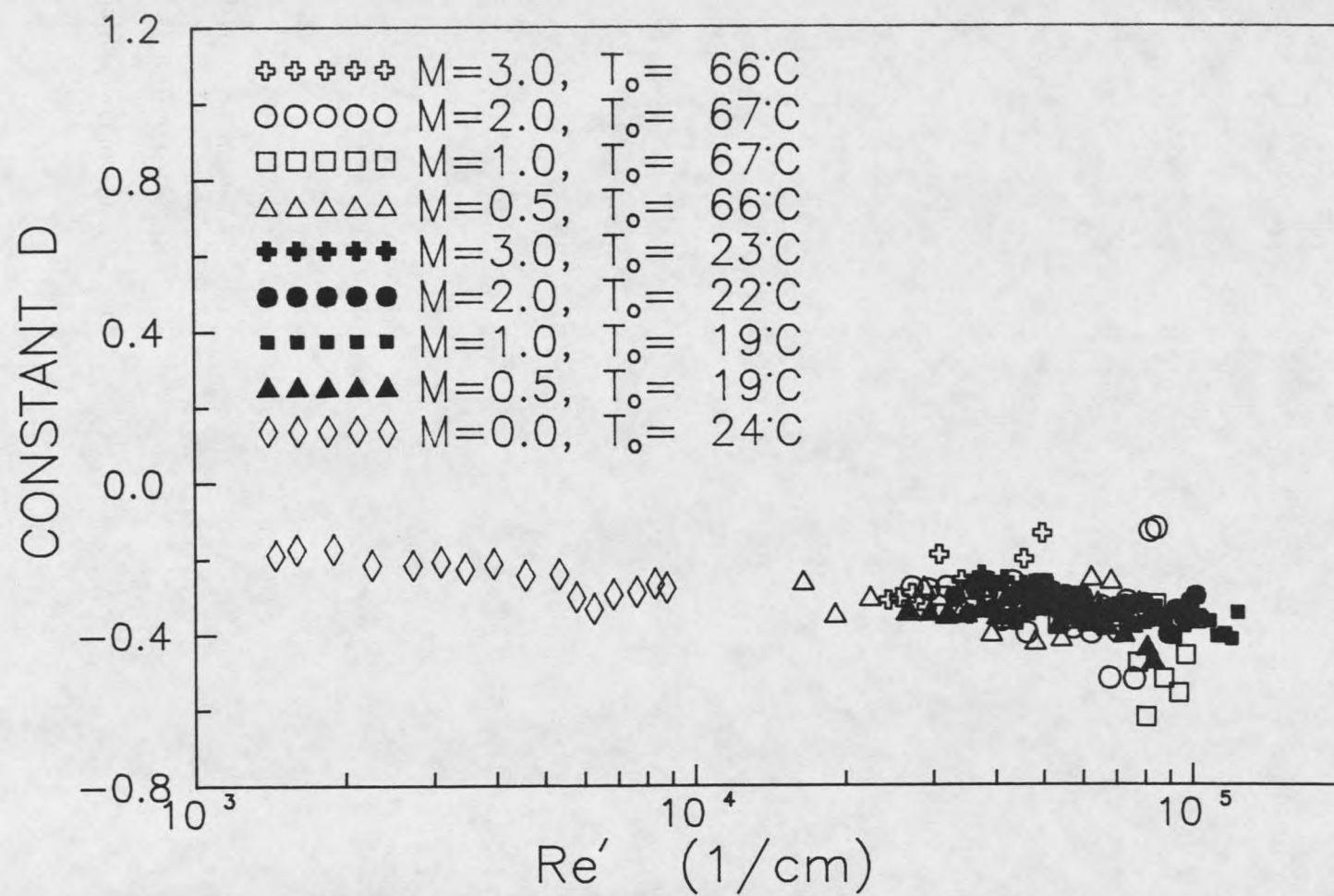


Figure 24. Characteristics of the Constant D for Probe 48.

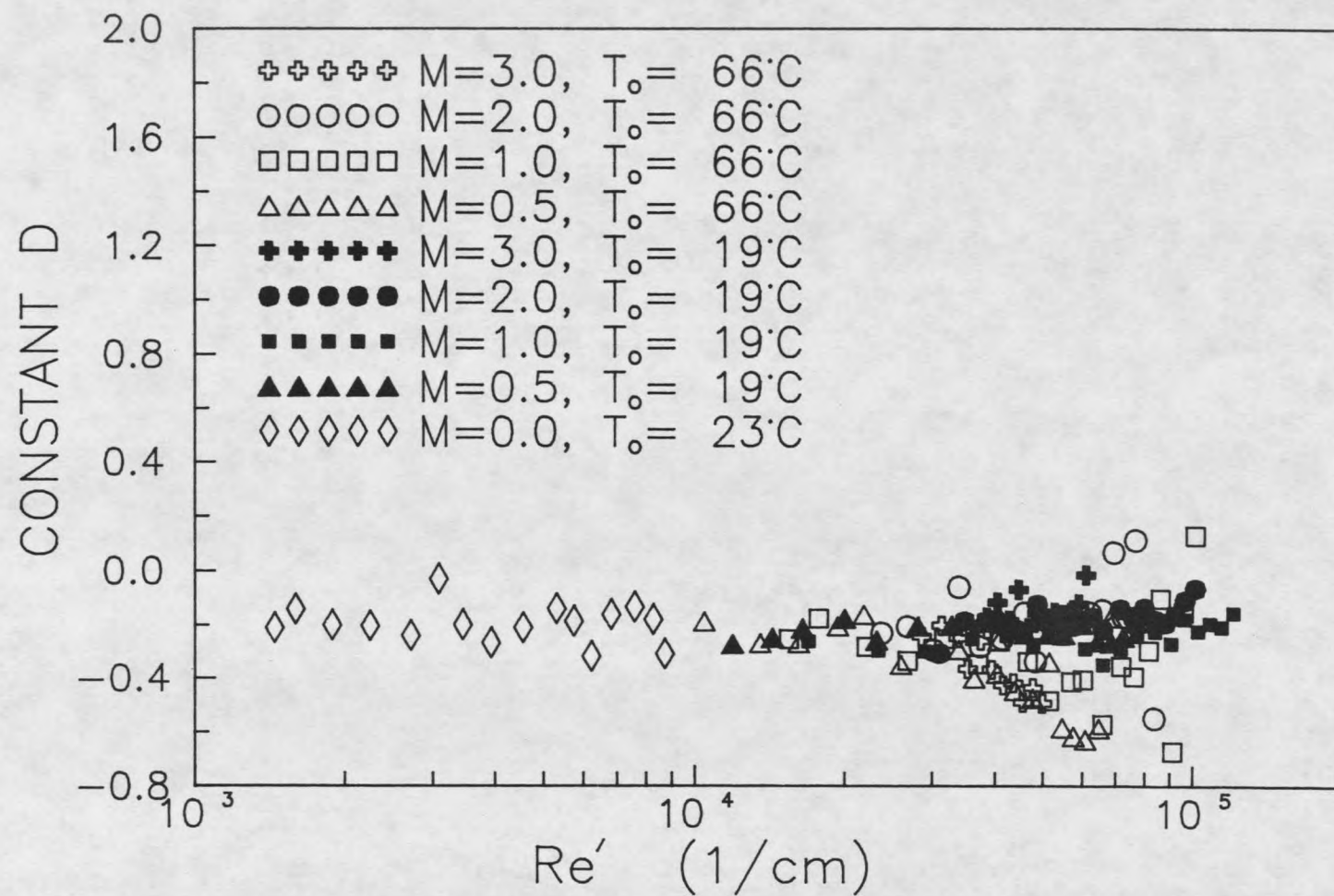


Figure 25. Characteristics of the Constant D for Probe 50.

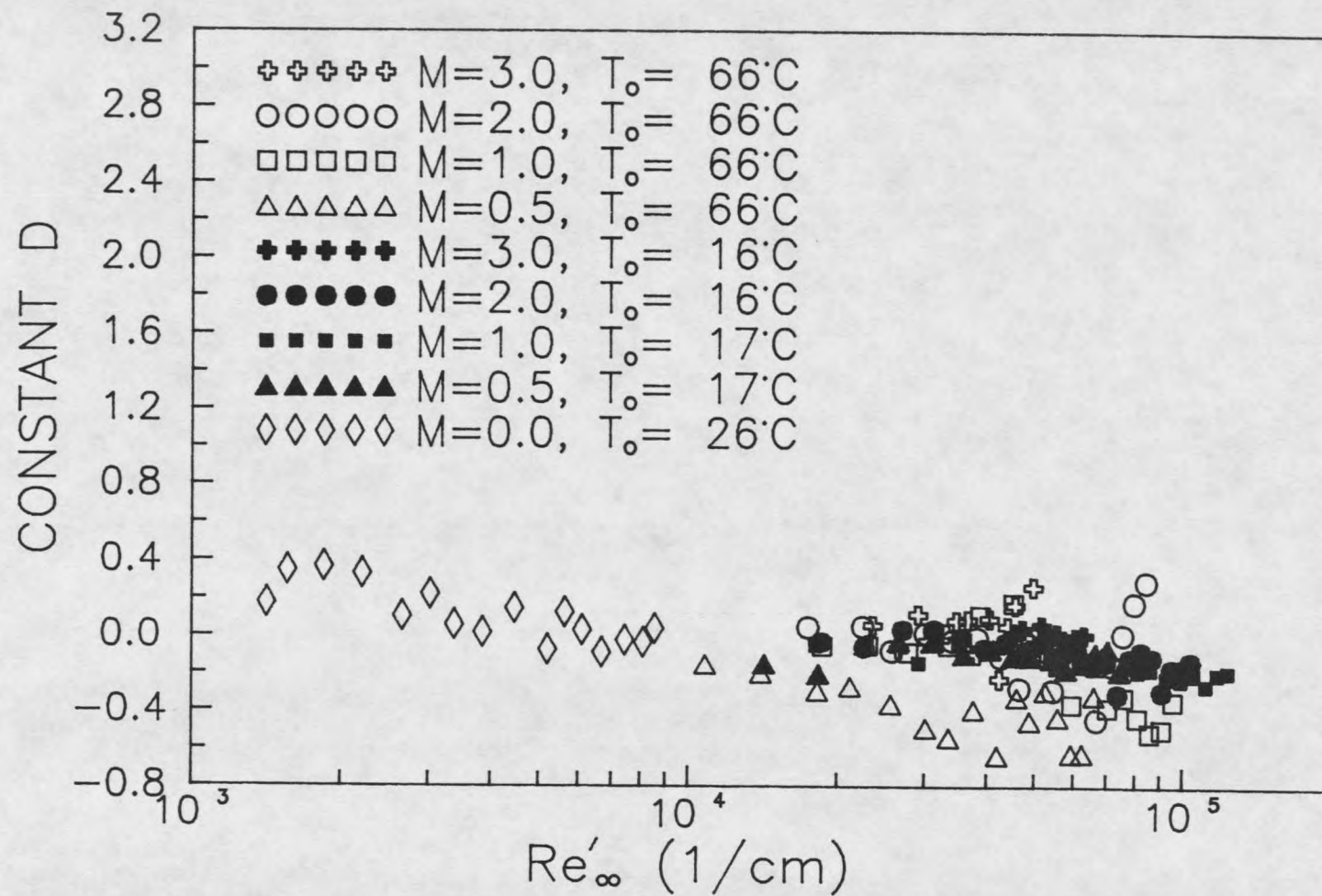


Figure 26. Characteristics of the Constant D for Probe 56.

Temperature Recovery Factor Dependence on Flow Properties

If calibrated correctly the film anemometer probes could be used to determine certain flow properties such as the stagnation temperature and the unit Reynolds number as well as the relations necessary to make turbulence measurements. The correct calibrations are those which give these necessary heat transfer characteristics of the film anemometer. By knowing and understanding these, the calibration data can be used most effectively.

Through constant experimental work over a period expanding approximately three years both oven and flow calibration data have been taken and reduced in order to determine the hot-film probe characteristics. The two most telling parameters found from a flow calibration are the temperature recovery factor and the Nusselt number. Together they can be used to find information about the flow. The temperature recovery factor can ideally be related to the stagnation temperature of the flow knowing the Mach number or to the Mach number knowing the stagnation temperature. The Nusselt number can be related to the free-stream Reynolds number. Obtaining these relations is also the first step necessary in order to make turbulence measurements.

The temperature recovery factor is found by relating the film resistance at zero current to the recovery temperature of the flow by an oven calibration and then dividing this result by the stagnation temperature of the flow. Its value depends on the local free-stream Mach number and the frictional dissipation of the kinetic energy in the boundary layer (Kovasznay [11]). For the film anemometers studied here the temperature recovery factor was typically close to 1.02 at a Mach number of 0. This indicates that the probe is not a very good instrument for measuring the temperature of the surrounding medium. A temperature recovery

factor of 1.02 indicates that the probe will measure a temperature 2% higher than the actual absolute temperature. This would result in an error of 6 C for a measurement taken at room temperature. This poor temperature measurement capability is most likely caused by shifts in the probe resistance. Even small shifts (about 0.2 ohms) will cause poor results such as the ones found. From a value of about 1.02 for a Mach number of 0 the temperature recovery factor decreased with increasing Mach number to about 0.8 at Mach 8. Figures 27, 28 and 29 show typical results of how the temperature recovery factor varied with the various flow parameters for Mach numbers of 0, 0.5, 1, 2 and 3. Figures 30 and 31 show results of a Mach 8 calibration. Figure 32 is a plot of Mach number versus the normalized temperature recovery factor. The temperature recovery factor was normalized by dividing the results for each probe by its value at Mach 0. This was done so that different probes could be compared on the same plot. The figure shows clearly that the temperature recovery factor decreases with increasing Mach number. It is expected that this Mach number dependence will disappear as the Mach number approaches infinity. The data appear to draw this conclusion. This data of Figure 32 should be looked upon as a general trend only since there is only one point for Mach numbers greater than 3. That one point is also placed on the graph with some amount of uncertainty about its exact location since the temperature recovery factor at Mach 0 for this data was not available and had to be assumed as one. The probe could have easily shifted in resistance between its oven and flow calibrations. Also, the data came from five different probes. Though each probe will show the same trend, they will have their own unique characteristics. In addition to the above findings, it is found that the temperature recovery factor is a function of the Reynolds number in the higher Mach number range ($M \geq 3$).

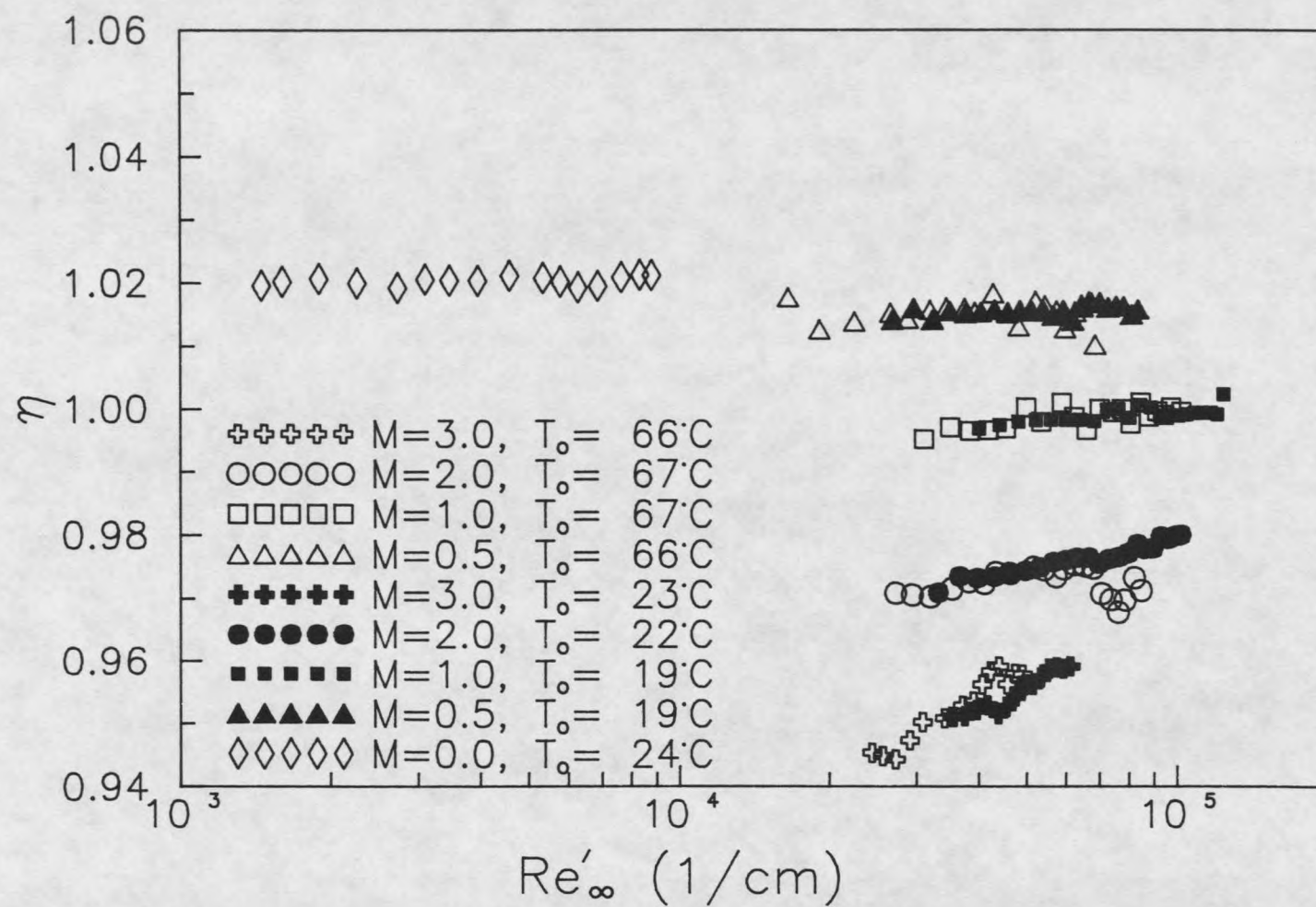


Figure 27. Temperature Recovery Factor Dependence on Flow Properties for Probe 48.

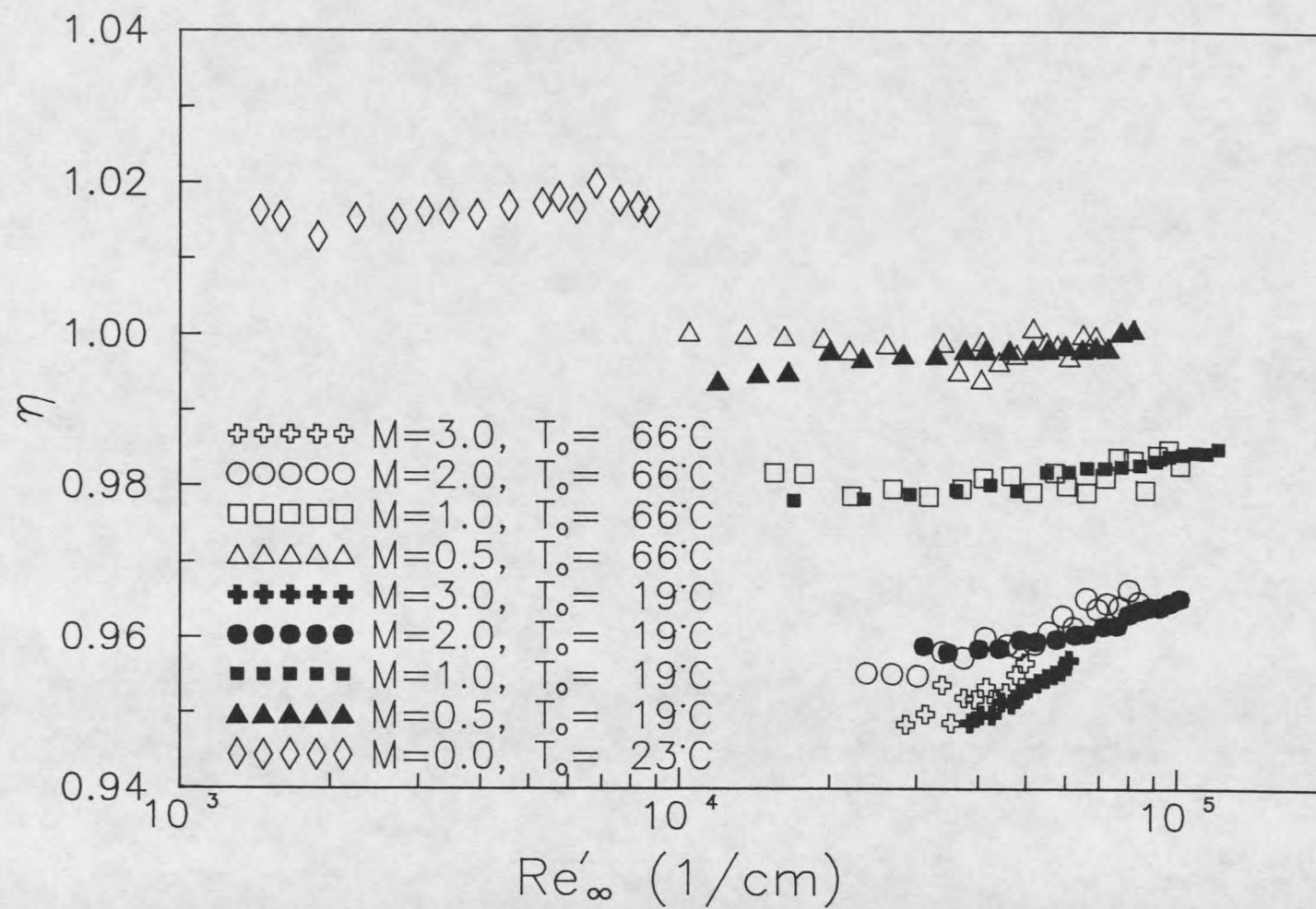


Figure 28. Temperature Recovery Factor Dependence on Flow Properties for Probe 50.

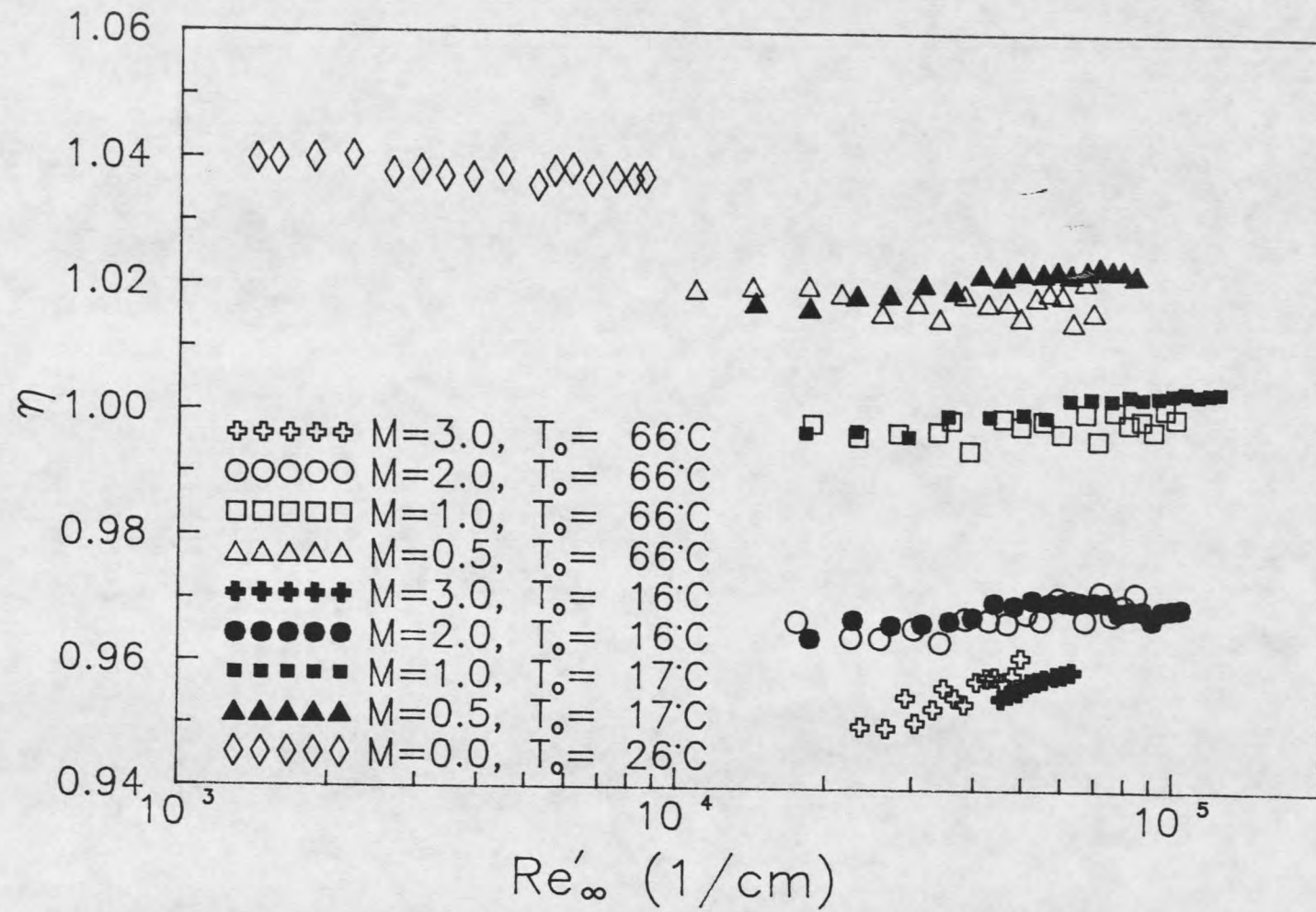


Figure 29. Temperature Recovery Factor Dependence on Flow Properties for Probe 56.

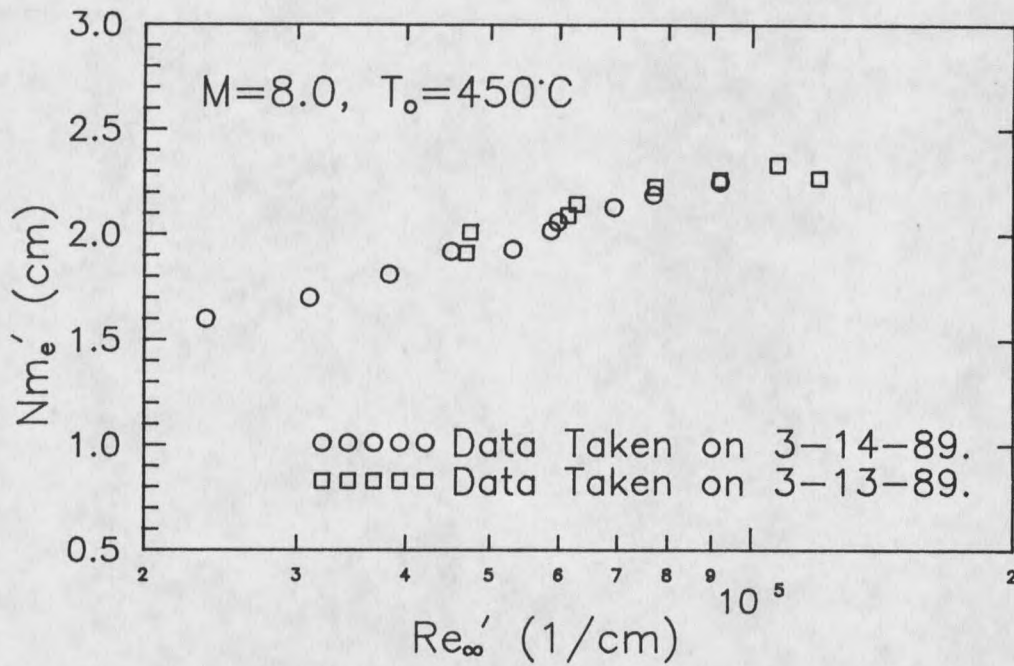


Figure 30. Measured Nusselt Number Characteristics in a Mach 8 Flow.

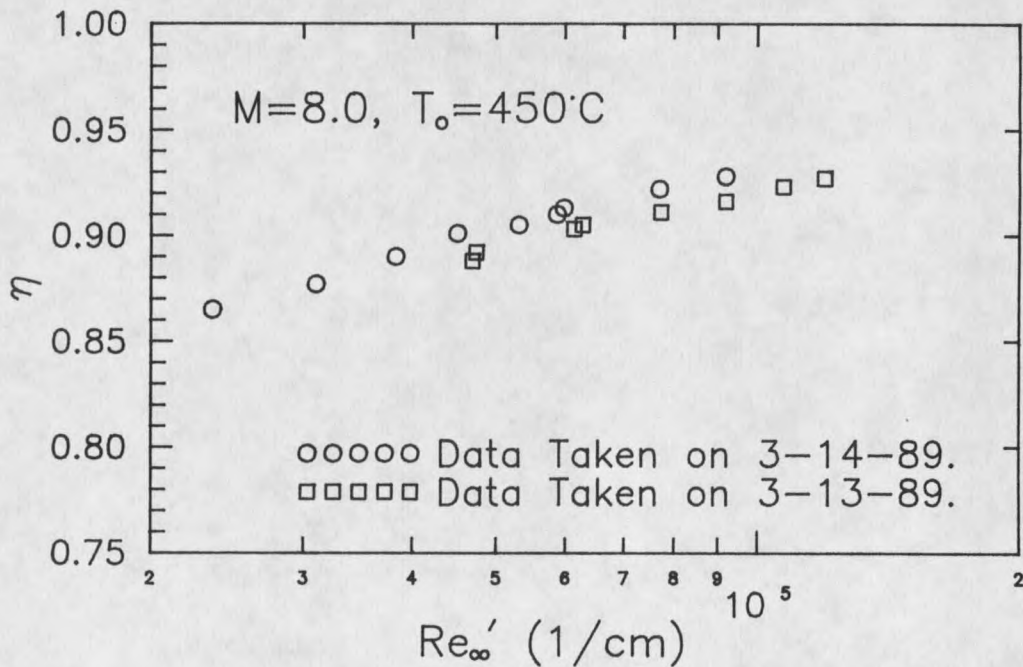


Figure 31. Temperature Recovery Factor Dependence in a Mach 8 Flow.

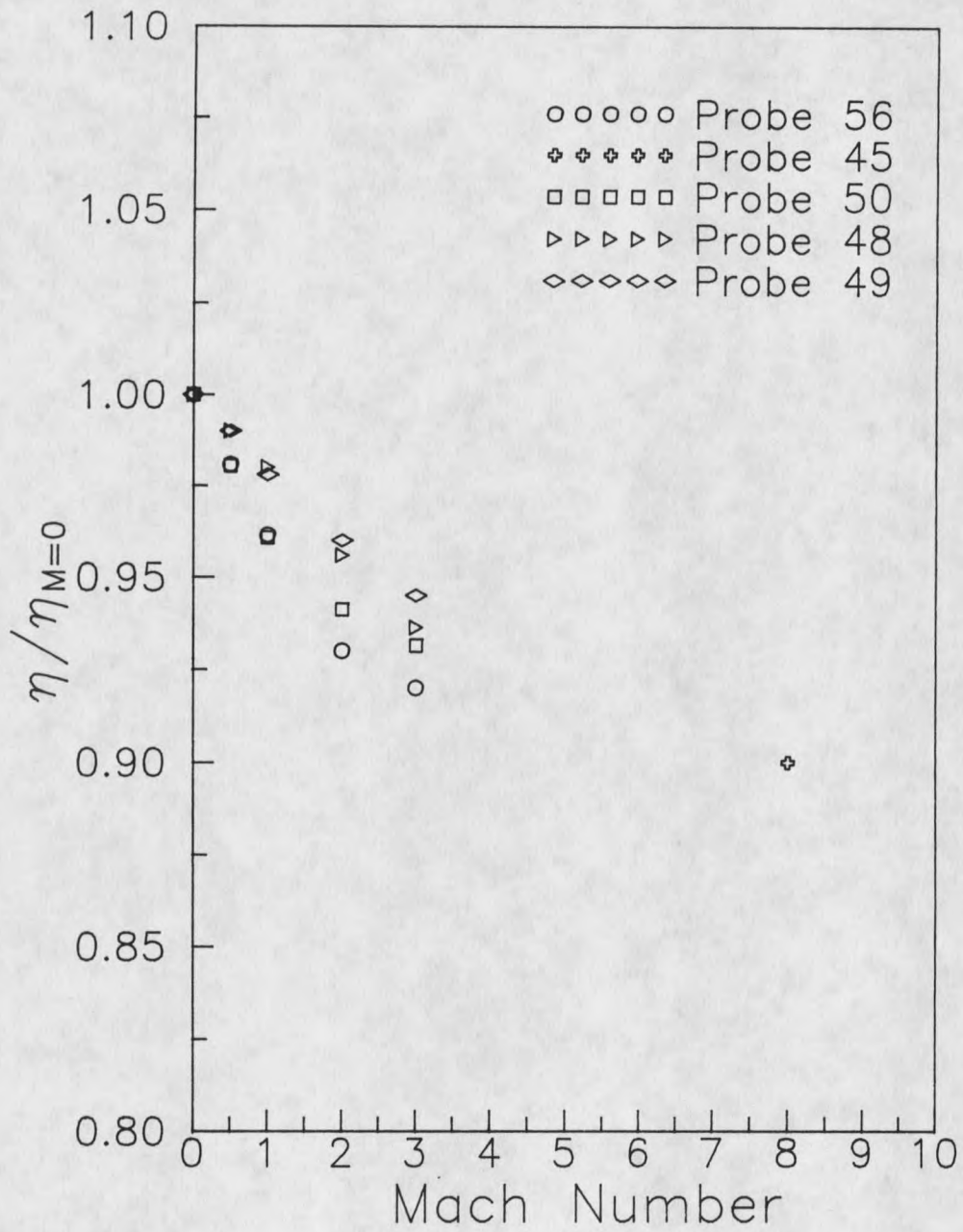


Figure 32. Normalized Temperature Recovery Factor Variation with Mach Number.

Nusselt Number Dependence On Flow Properties

The Nusselt number is found to be a more complicated function and even more complicated to obtain. By the method described in Chapter 4, the Nusselt number can be determined as a function of the flow properties. The results of the measured Nusselt number versus dimensional Reynolds number are shown in Figures 30, 33, 34, and 35. According to Kings Law the data should plot as a straight line, which they do, if plotted against the square root of the Reynolds number as is done in Figures 36, 37, and 38. Notice that the measured Nusselt number, which contains conduction and convection effects, is a function of Reynolds number, stagnation temperature, and Mach number. However, this measured Nusselt number is not the variable of interest. The variable of interest is the "convective" or "actual" Nusselt number which can be obtained from the measured Nusselt number if it is corrected for conduction effects (refer to (28)).

It was estimated in Chapter 3 that the conduction contribution term should be a linear function of the form

$$(57) \quad N_{cnd} = c \sqrt{\frac{k_s}{k_e}} .$$

As can be seen in Figure 39, this predicted linear dependence on the inverse square root of the thermal conductivity of the air surrounding the probe is quite good. This conduction contribution to the measured Nusselt number can more readily be used if it is plotted against the recovery temperature, as in Figure 40, since the recovery temperature is readily found. Knowing both the measured Nusselt number and the contribution to the measured Nusselt number by conduction, the "actual" unit Nusselt number can be determined. By simply subtracting the conduction contribution the "actual" Nusselt number is found. Typical results of this procedure are shown in Figures 41, 42, and 43.

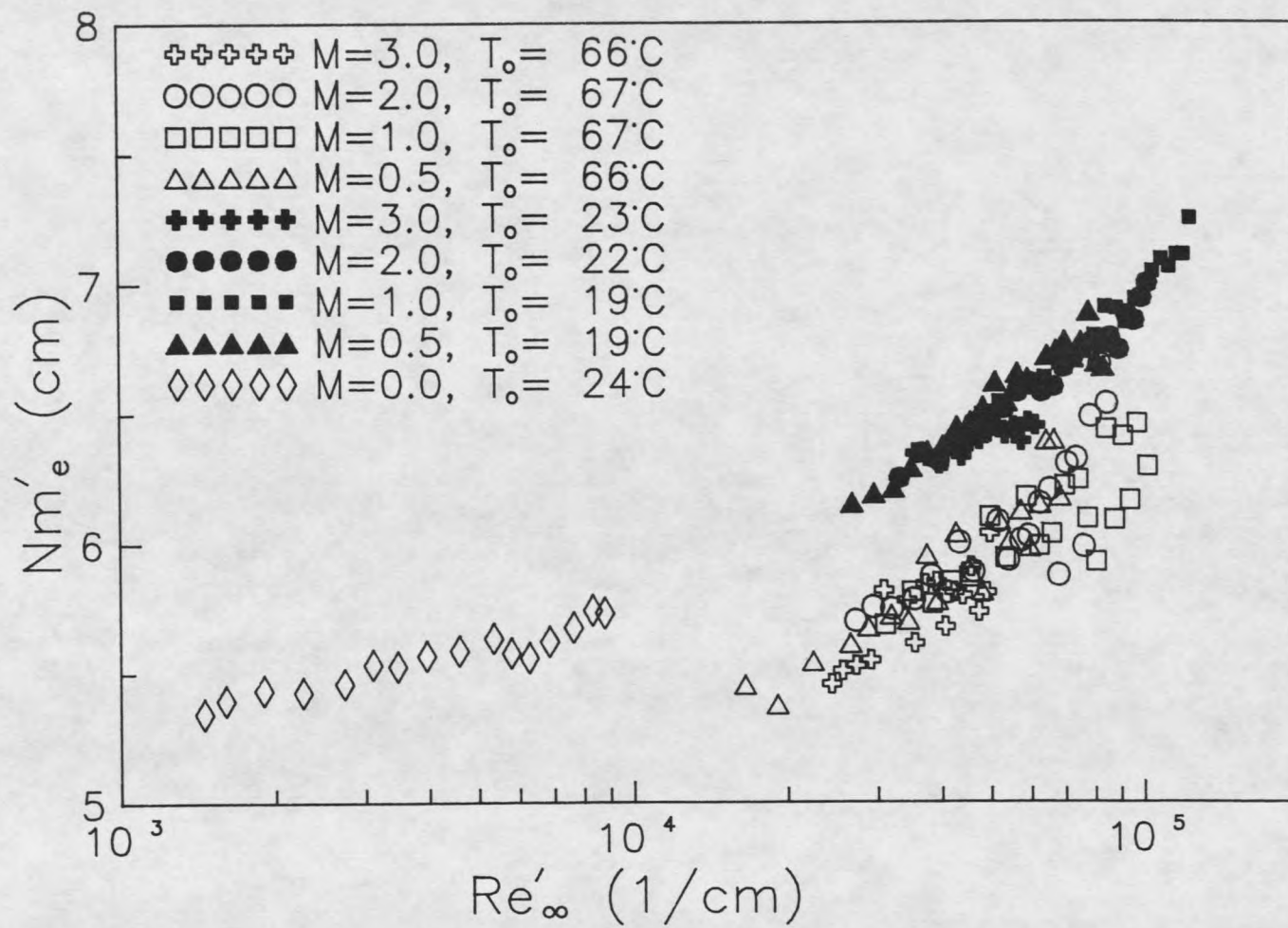


Figure 33. Measured Nusselt Number Characteristics for Probe 48.

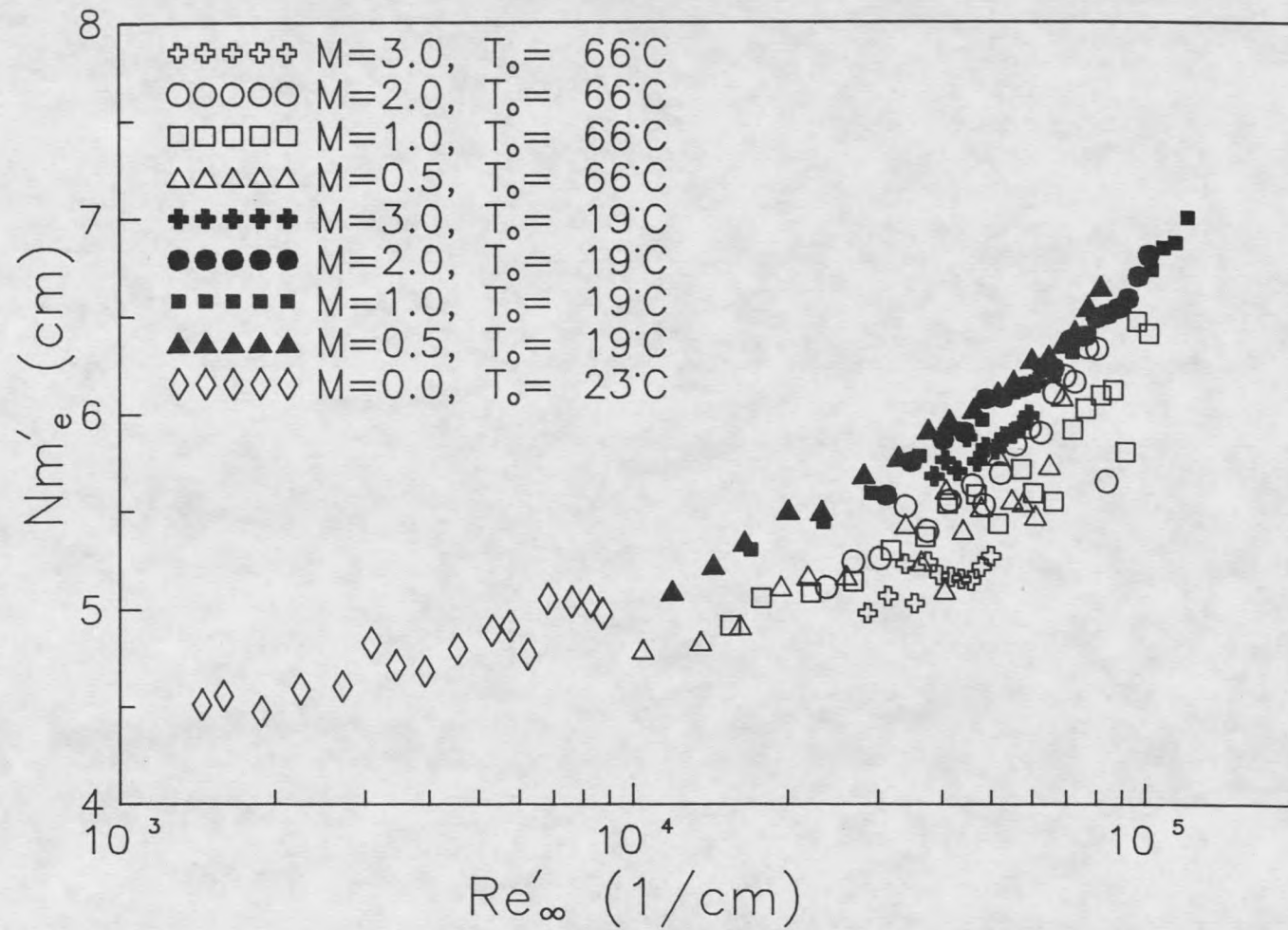


Figure 34. Measured Nusselt Number Characteristics for Probe 50.

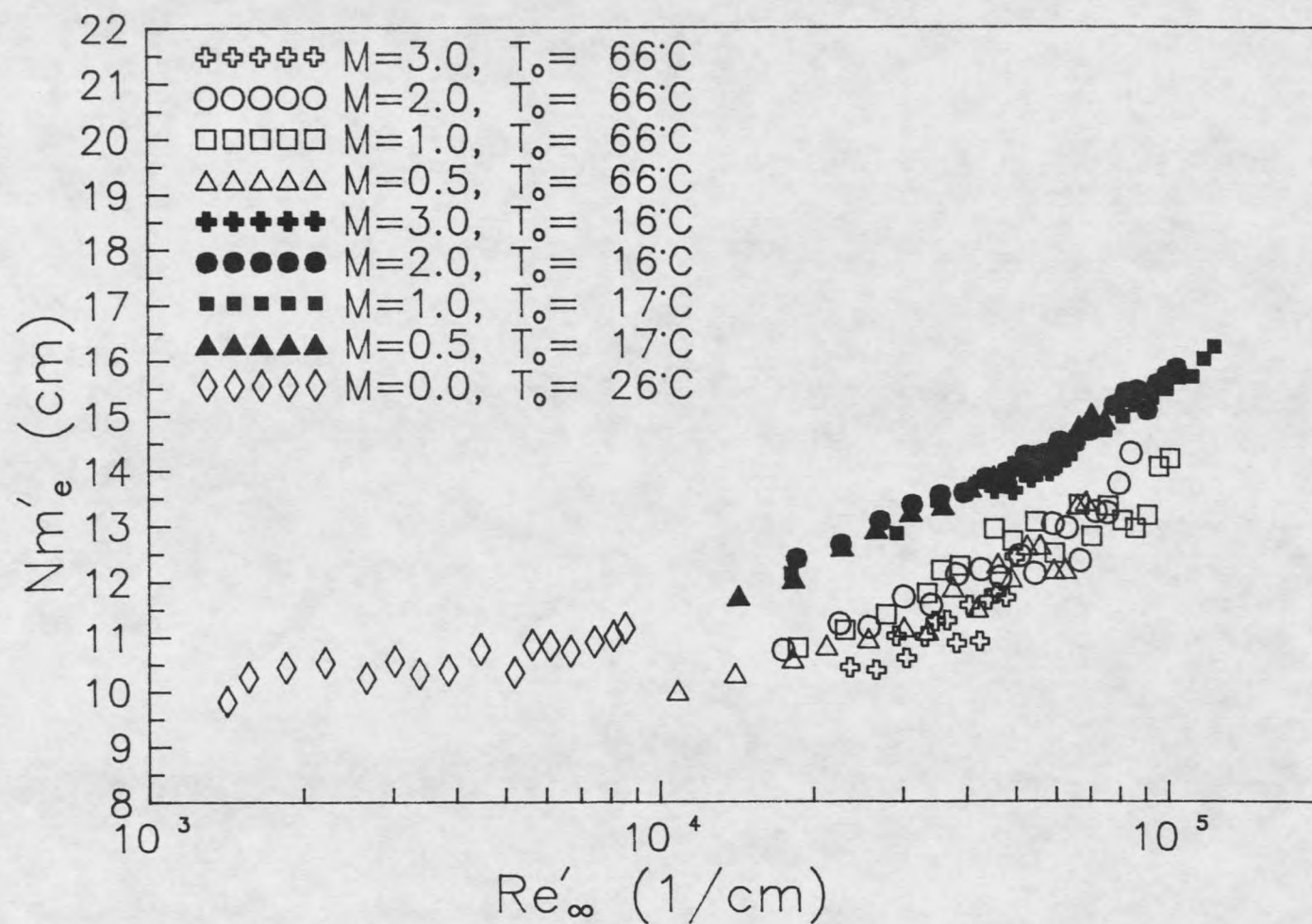


Figure 35. Measured Nusselt Number Characteristics for Probe 56.

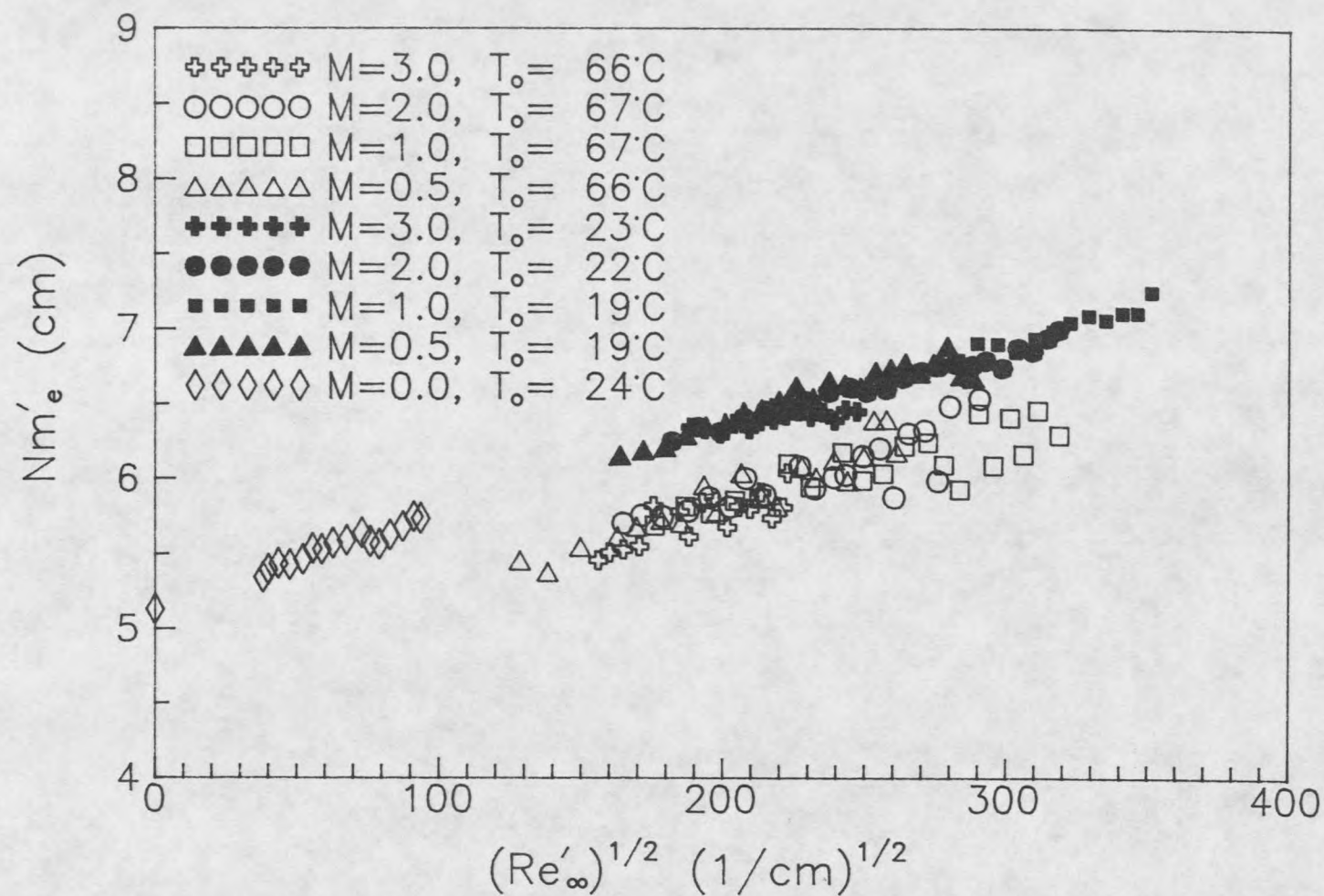


Figure 36. Measured Nusselt Number Characteristics for Probe 48 in Terms of the Square Root of the Reynolds Number.

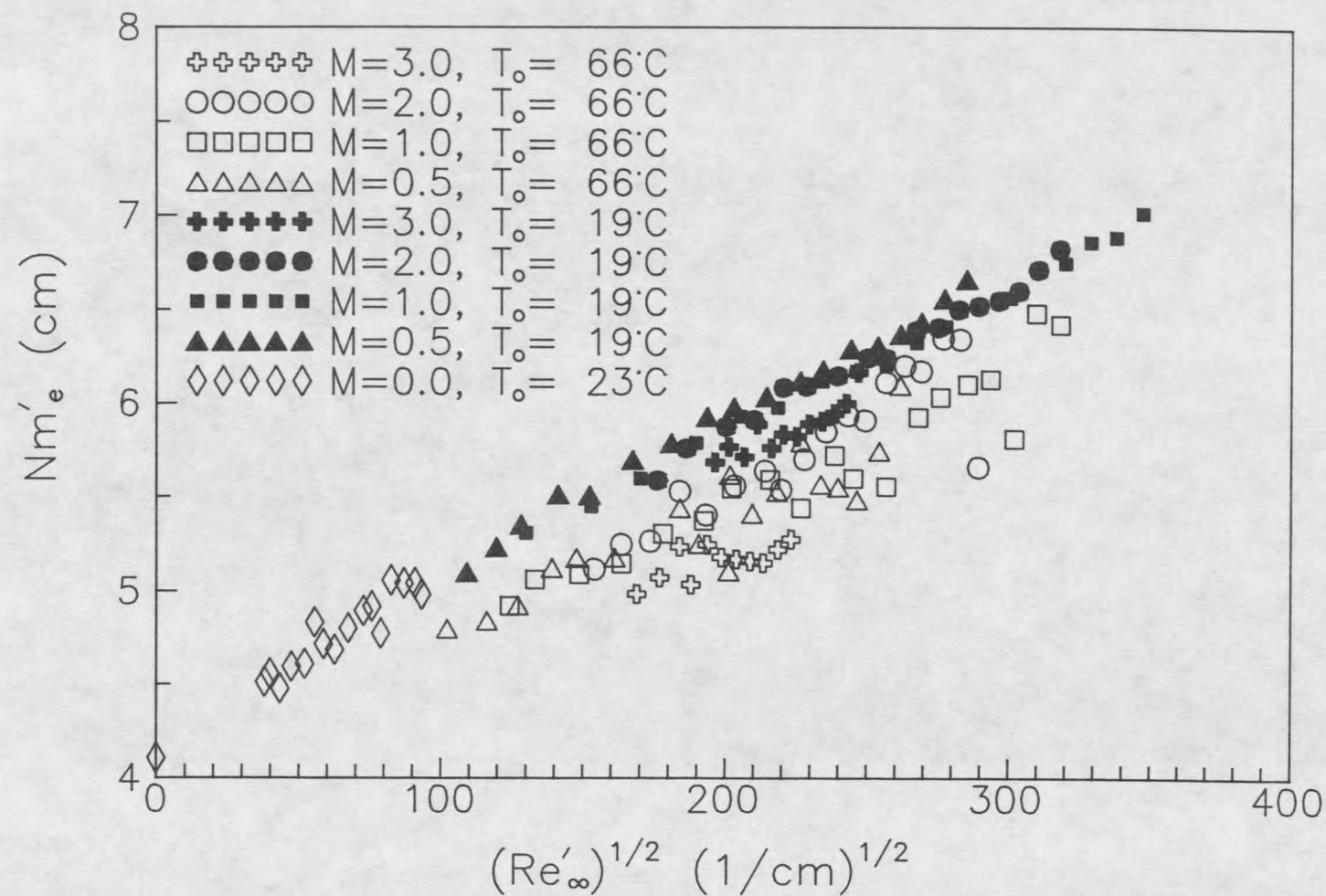


Figure 37. Measured Nusselt Number Characteristics for Probe 50 in Terms of the Square Root of the Reynolds Number.

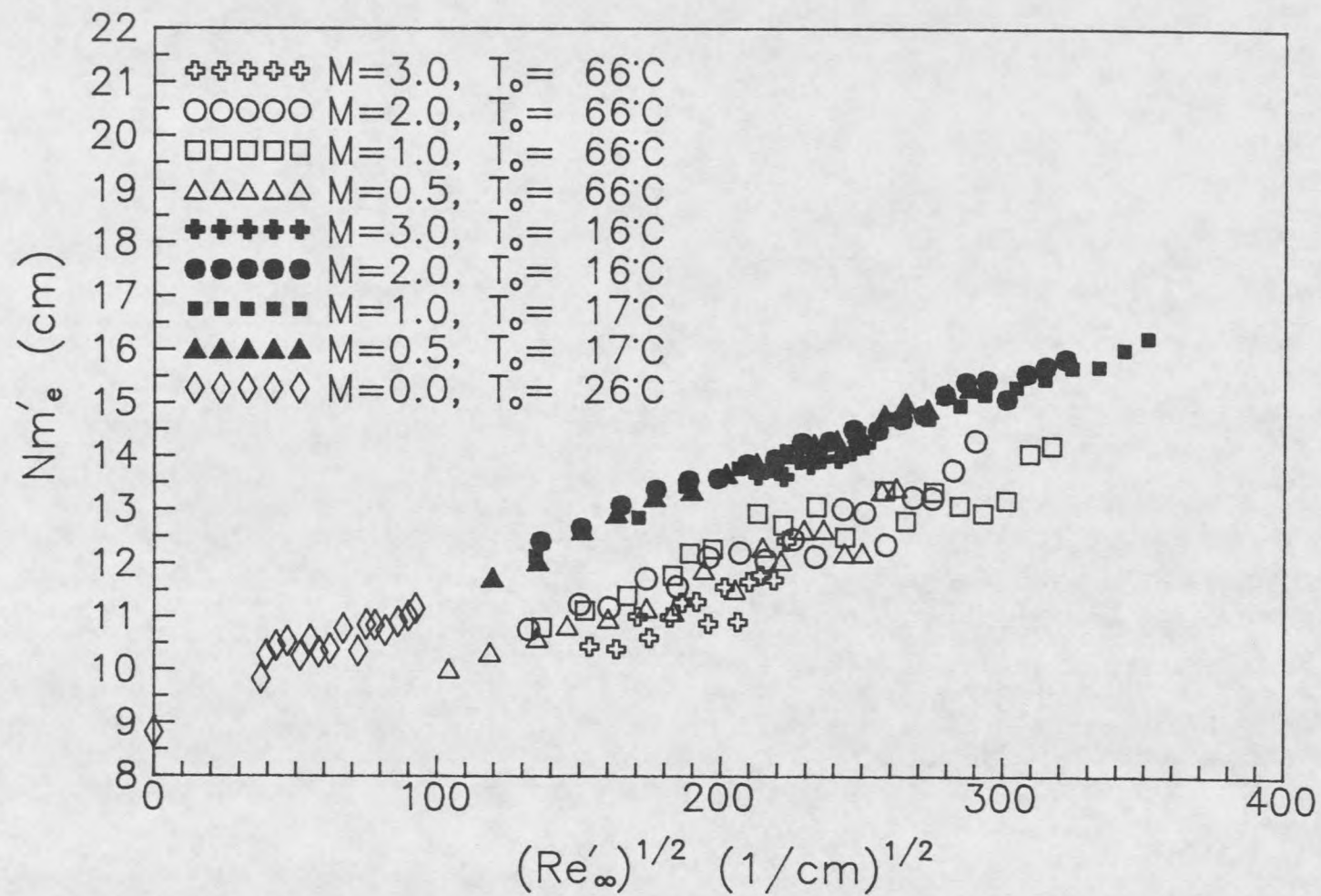


Figure 38. Measured Nusselt Number Characteristics for Probe 56 in Terms of the Square Root of the Reynolds Number.

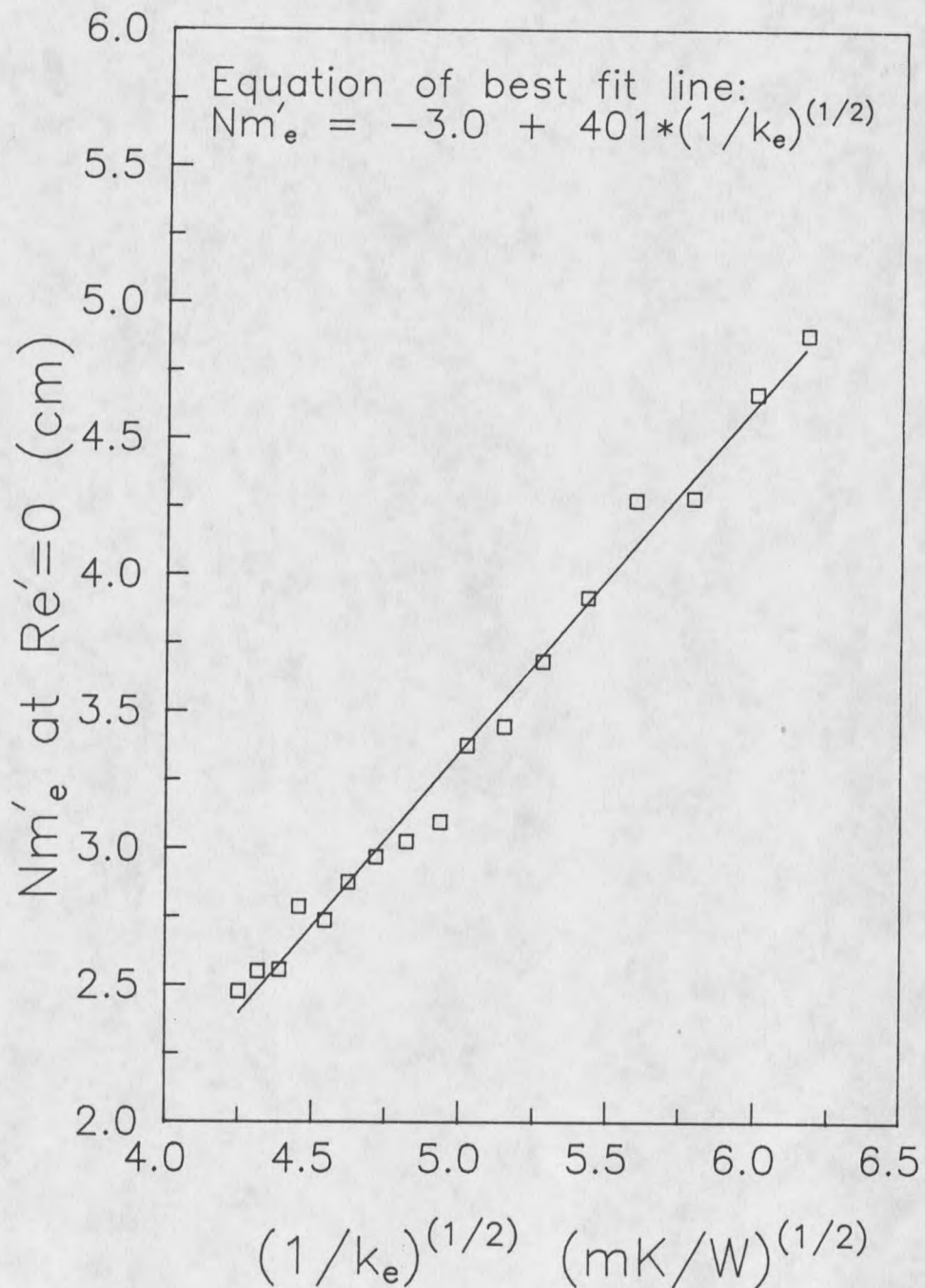


Figure 39. Measured Nusselt Number Dependence on the Inverse Square Root of the Thermal Conductivity in the Absence of Forced Convection.

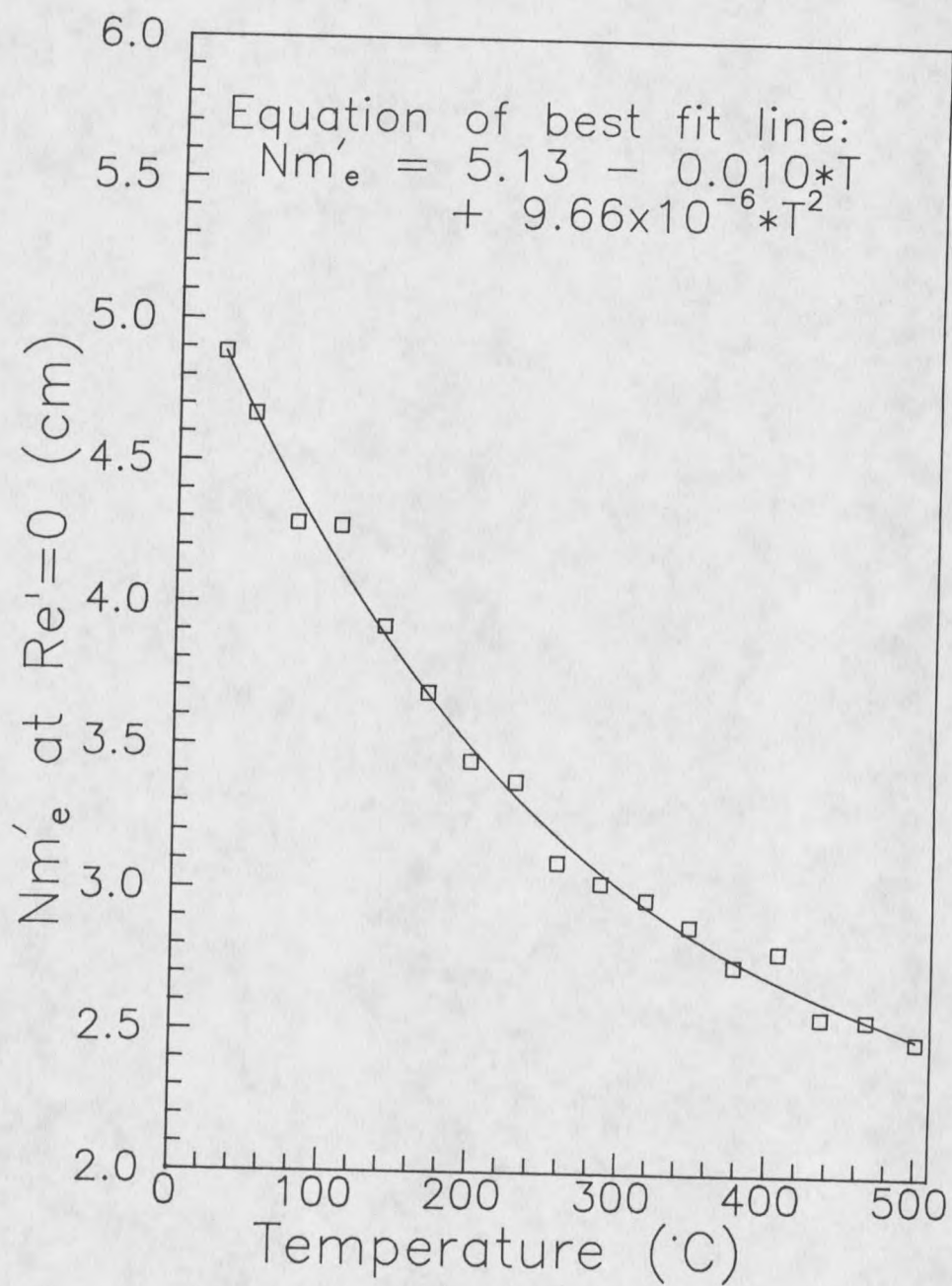


Figure 40. Temperature Dependence of the Measured Nusselt Number in the Absence of Forced Convection.

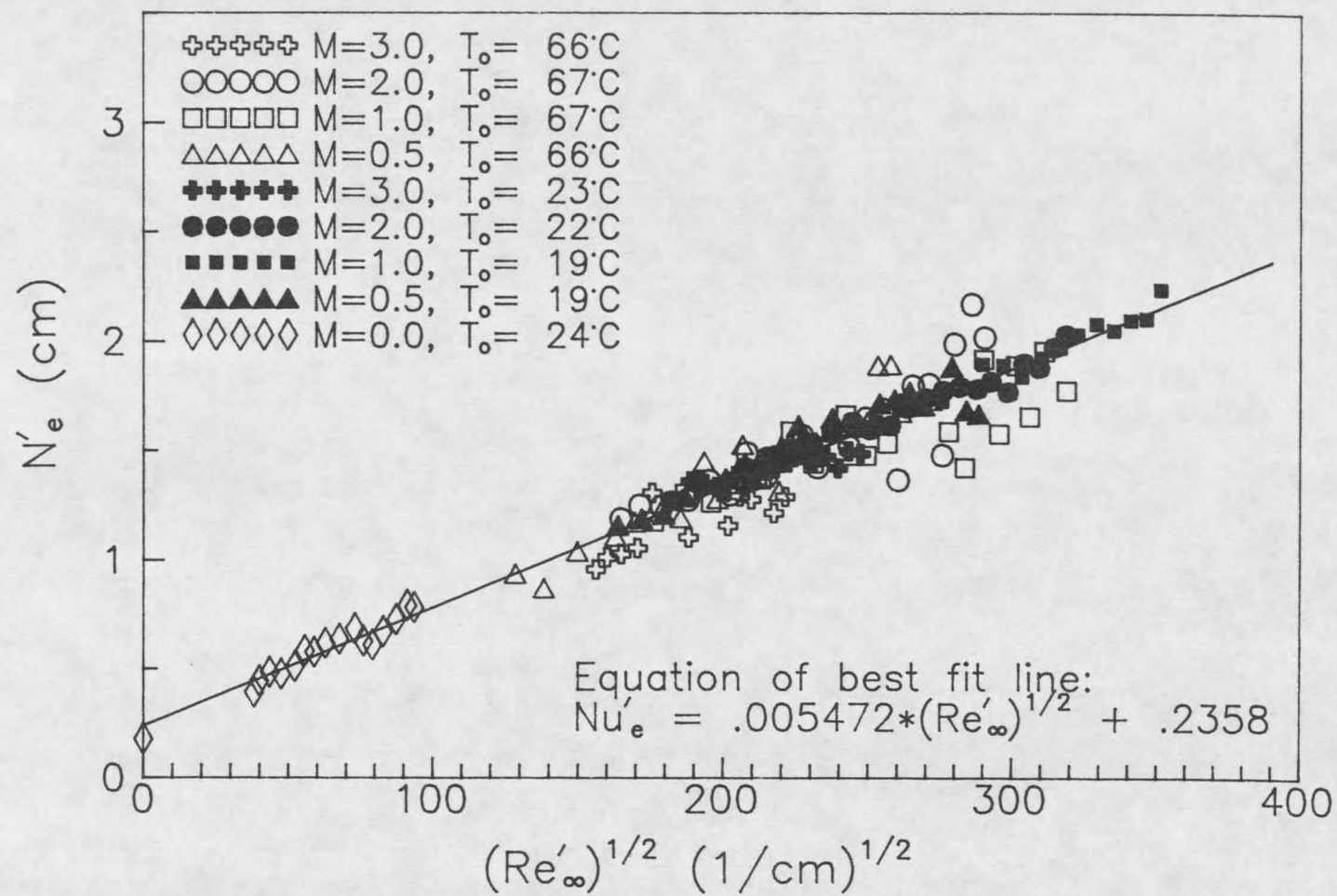


Figure 41. Convective Nusselt Number Characteristics for Probe 48.

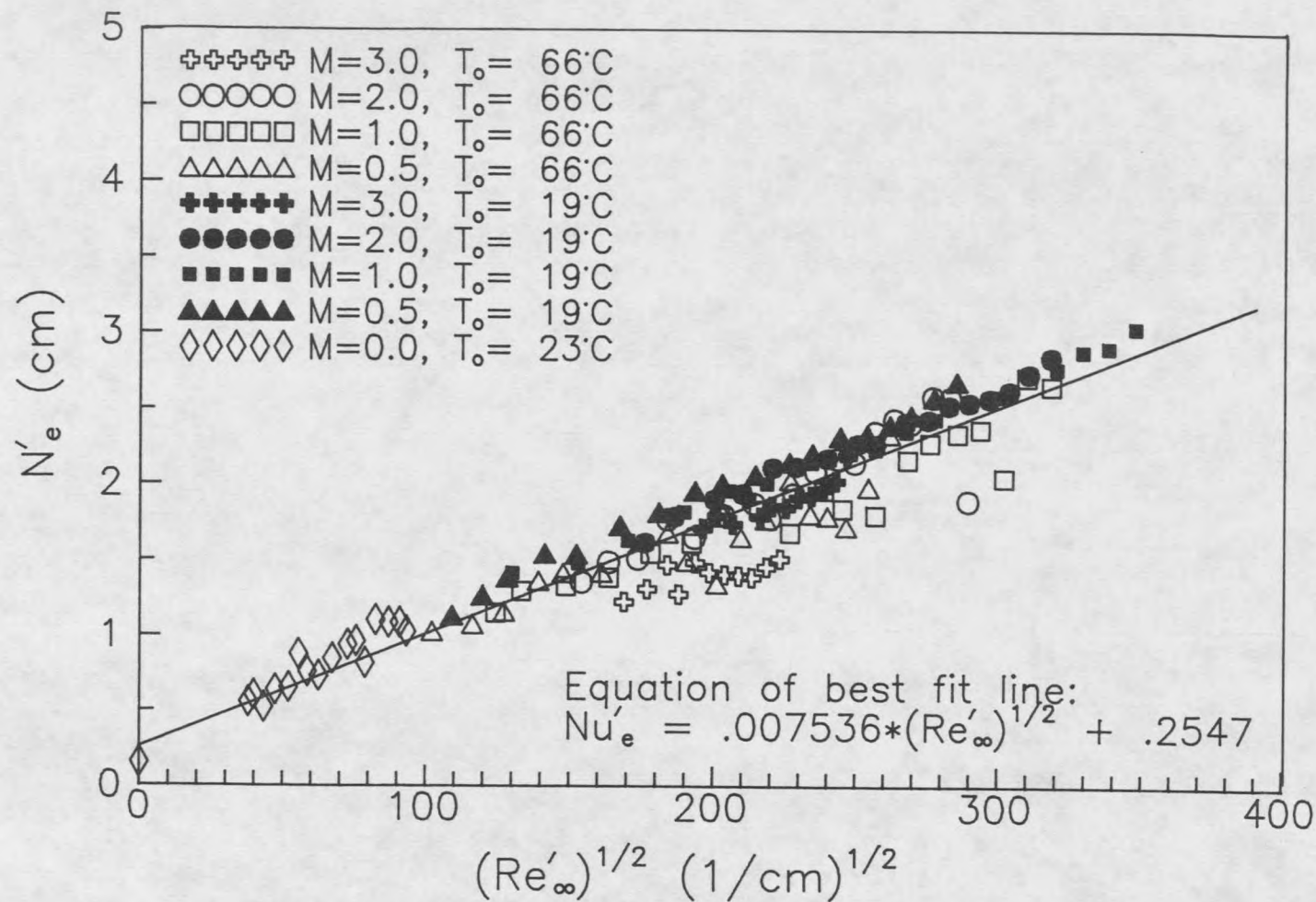


Figure 42. Convective Nusselt Number Characteristics for Probe 50.

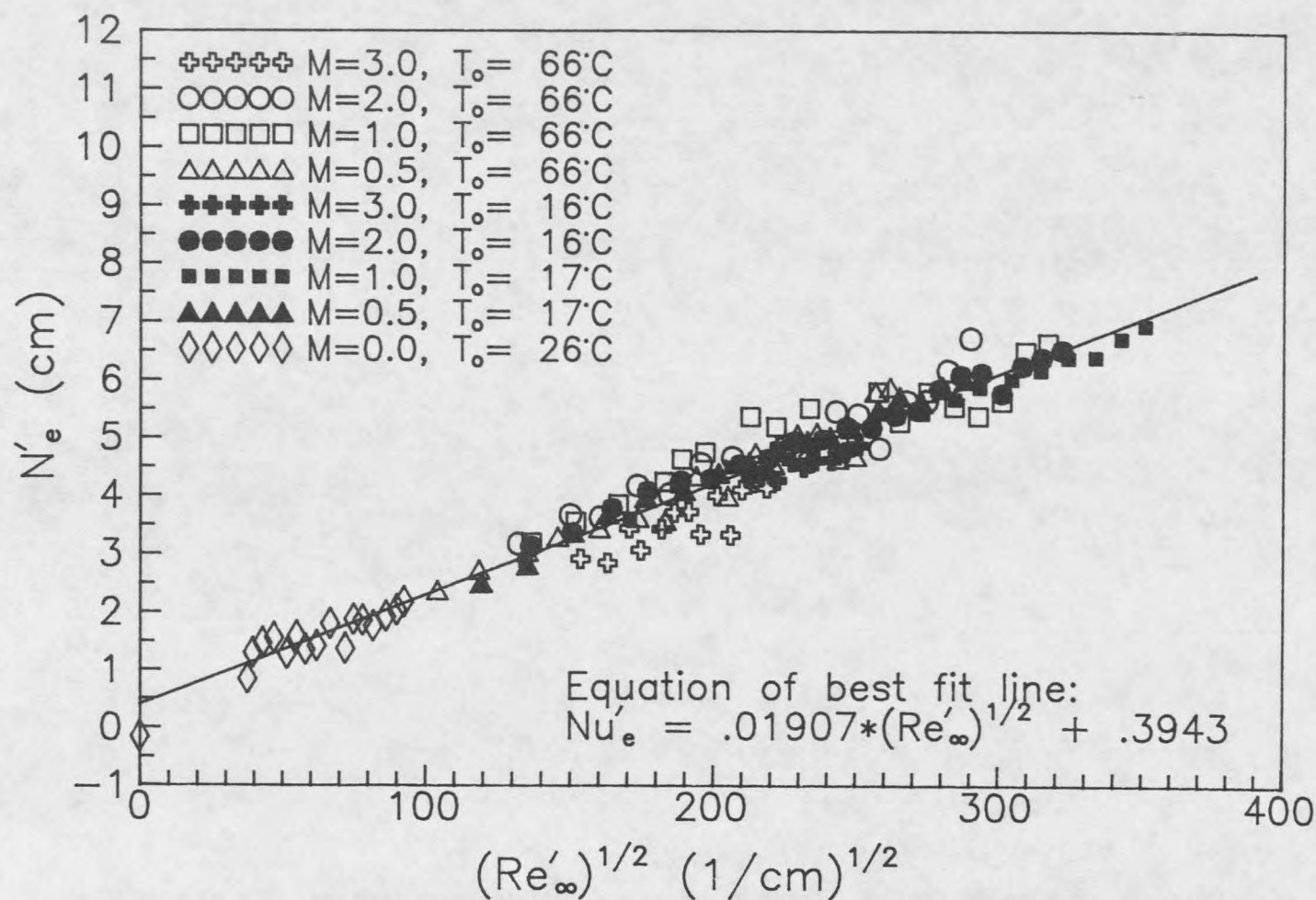


Figure 43. Convective Nusselt Number Characteristics for Probe 56.

The figures indicate that the Nusselt number is dependent on the square root of the unit Reynolds number as predicted. The Nusselt number plot also demonstrates that the Mach number dependence found for hot-wires in the low Reynolds number range is very weak, if existent at all, for the film anemometer. By correction of the conduction loss the stagnation temperature dependence has been eliminated. Note that, as with the temperature recovery data there is some scatter in the data points. This is primarily due to the resolution of the electronic equipment used and somewhat due to the inability to maintain 65 C in the Supersonic Wind Tunnel without the stagnation temperature varying about 1 C. Regardless of the scatter, significant conclusions can be drawn.

The theory developed in Chapter 4 indicated that the Nusselt number should be evaluated at the recovery temperature (refer to (38)). This Nusselt number has been plotted against the Reynolds number evaluated at the free-stream temperature. The Nusselt number could have been based on the flow stagnation temperature as was done by Seiner [24]. The study done here is in disagreement with Seiner [24] on this point but is in agreement with the temperature at which the Reynolds number should be evaluated. If the Reynolds number is based on the free-stream temperature and the Nusselt number on the stagnation temperature as Seiner [24] indicates should be done the data would plot as in Figure 44. If the Reynolds number is based on the free-stream temperature and the Nusselt number on the recovery temperature as done in this study the same data would plot as in Figure 45. However if either the Nusselt number evaluated at the stagnation temperature or at the recovery temperature is plotted against the Reynolds number based on the stagnation temperature the plots would look as in Figure 46 and 47. These plots seem to support that the temperatures used for evaluating the flow properties should be either the recovery temperature for the Nusselt number and

the free-stream temperature for the Reynolds number or the stagnation temperature for the Nusselt number and the stagnation temperature for the Reynolds number. The plots are not very conclusive but do support that the temperatures at which the variables used here were evaluated were as appropriate as any.

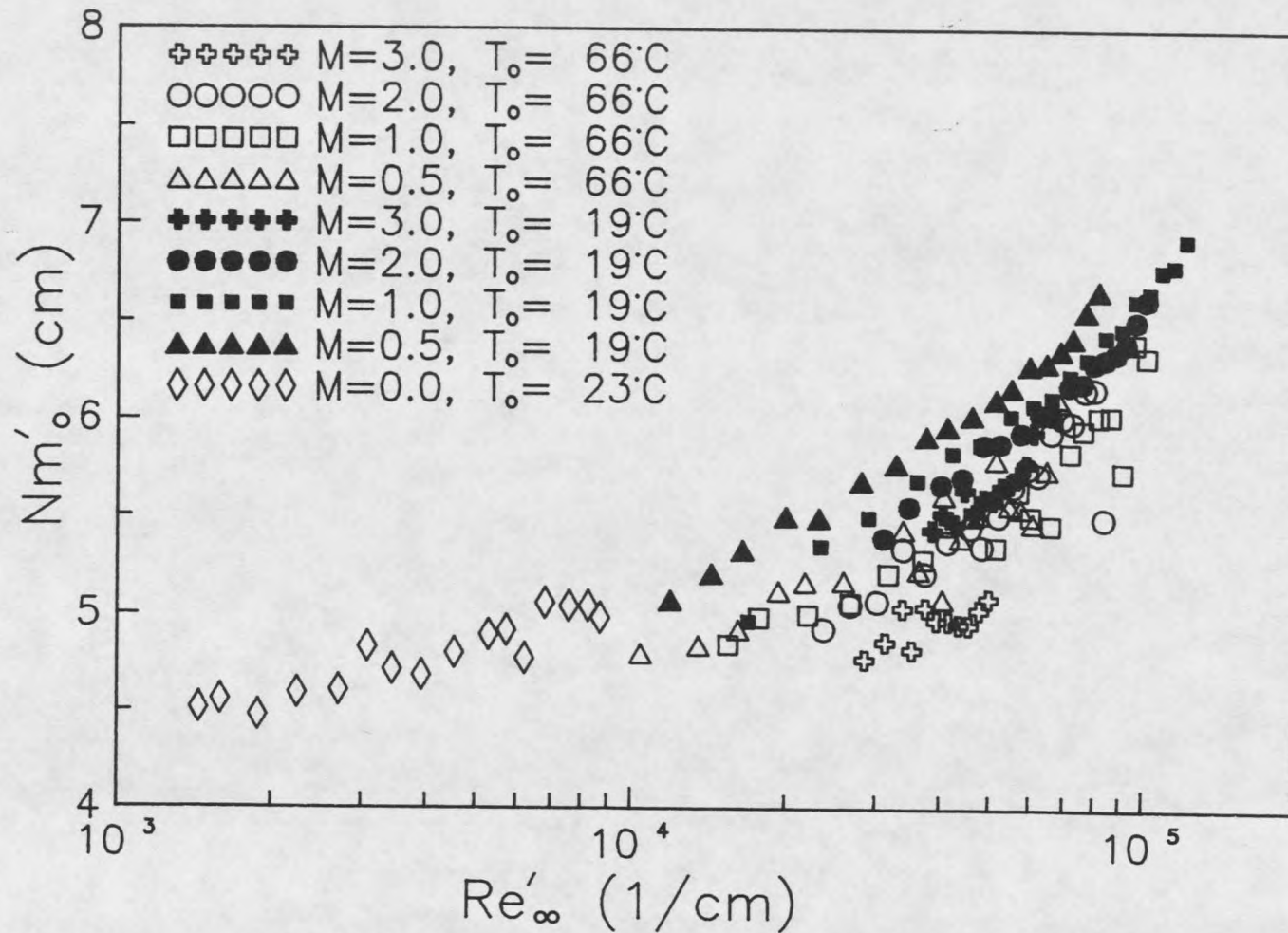


Figure 44. Measured Nusselt Number Characteristics for Probe 50.
 Nusselt Number Evaluated at the Stagnation Temperature.
 Reynolds Number Evaluated at the Free-Stream Temperature.

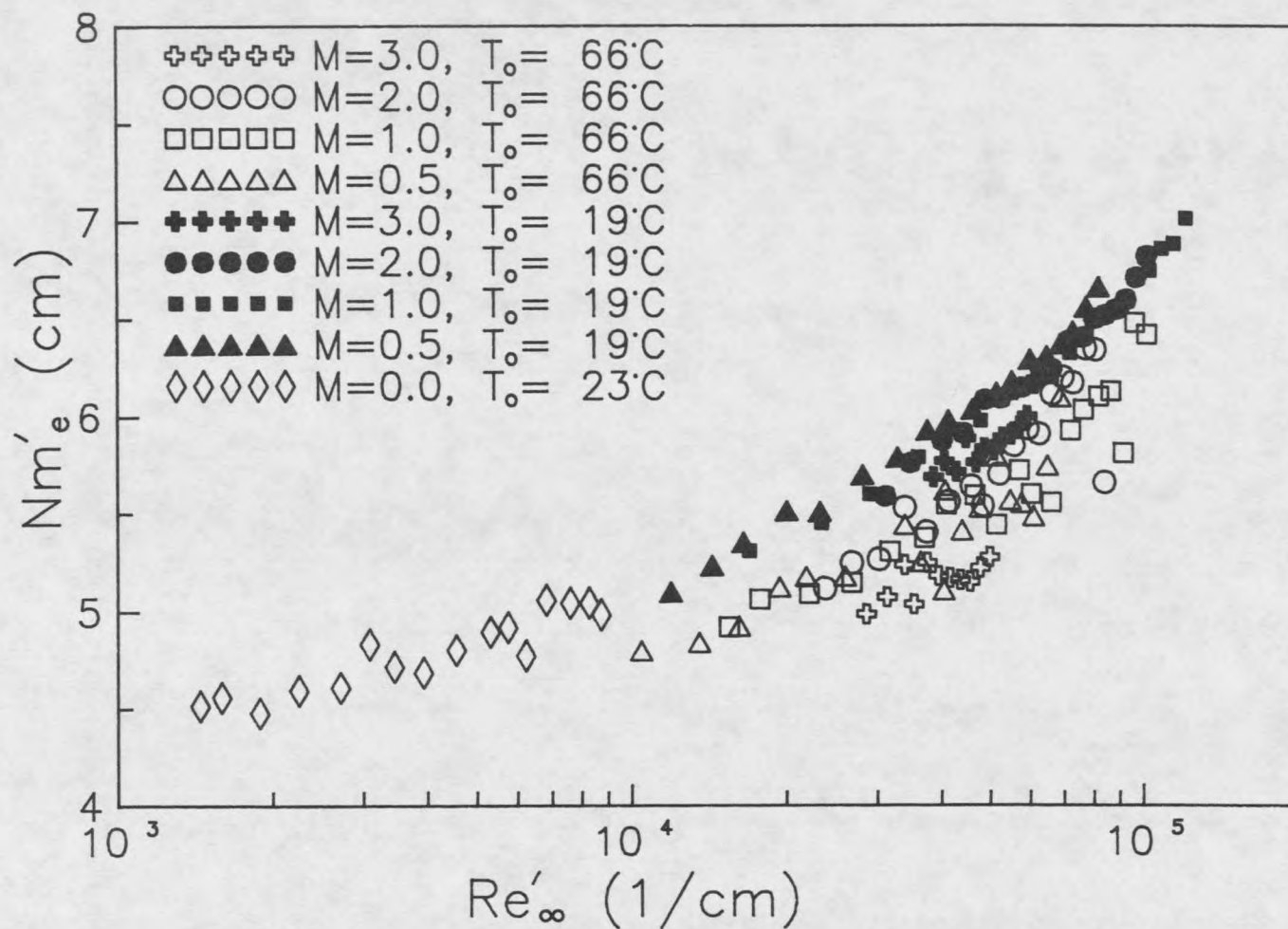


Figure 45. Measured Nusselt Number Characteristics for Probe 50.
 Nusselt Number Evaluated at the Recovery Temperature.
 Reynolds Number Evaluated at the Free-Stream Temperature.

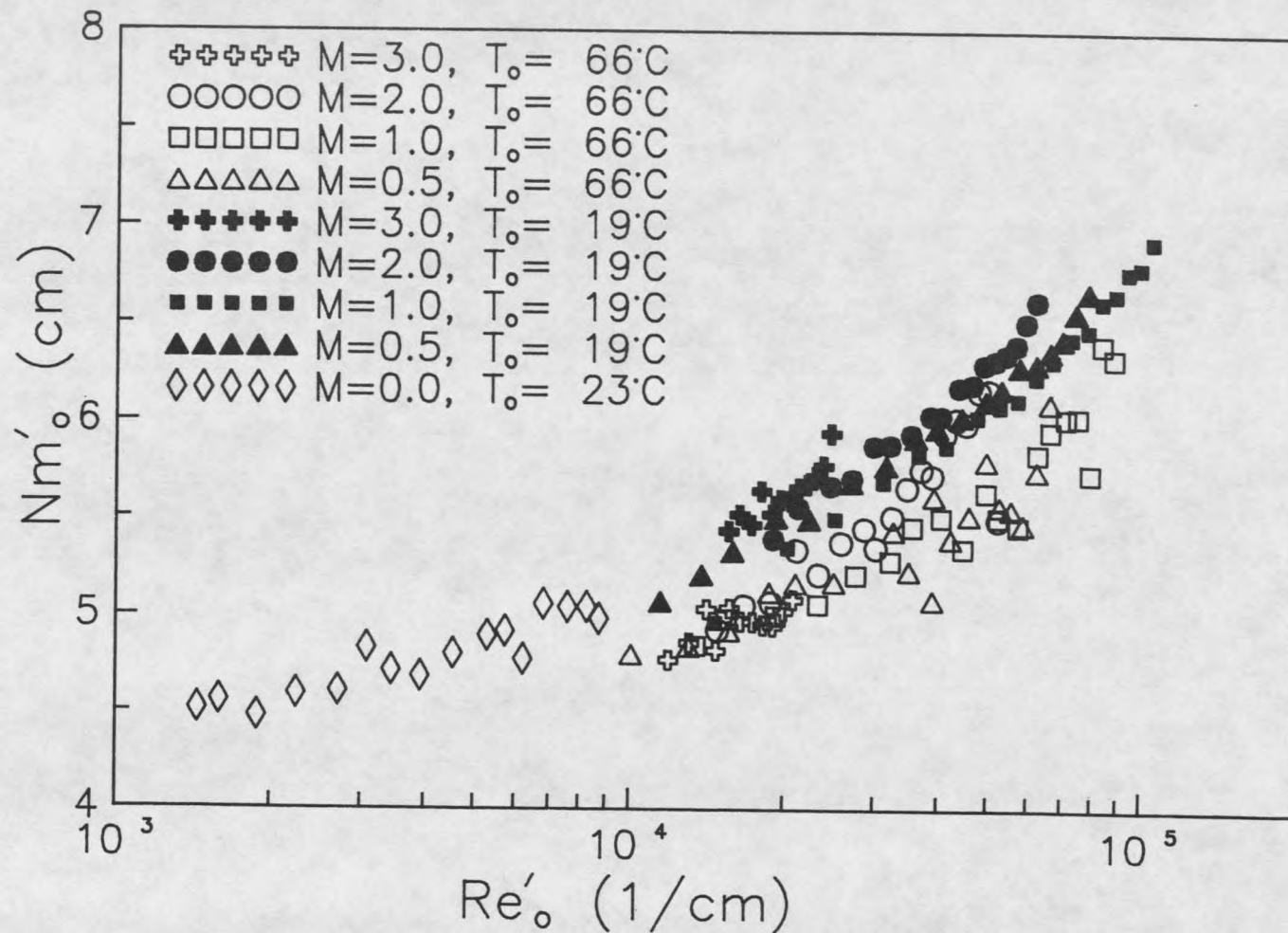


Figure 46. Measured Nusselt Number Characteristics for Probe 50.
 Nusselt Number Evaluated at the Stagnation Temperature.
 Reynolds Number Evaluated at the Stagnation Temperature.

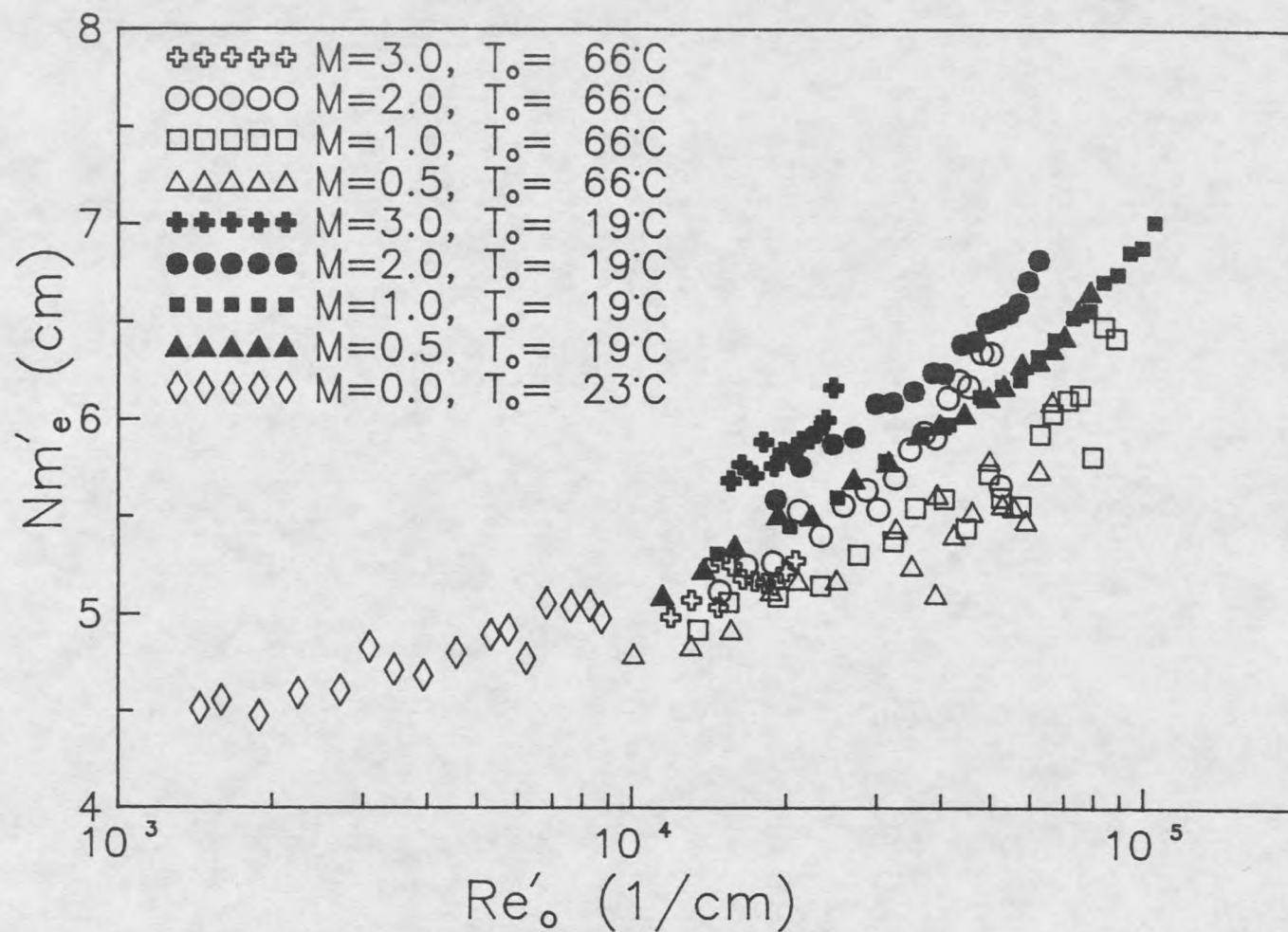


Figure 47. Measured Nusselt Number Characteristics for Probe 50.
 Nusselt Number Evaluated at the Recovery Temperature.
 Reynolds Number Evaluated at the Stagnation Temperature.

CHAPTER 9

CONCLUSIONS

The theoretical and experimental work done here lead to several conclusions in each area. Theoretical conclusions can be drawn about the heat transfer model for hot-film anemometers, the relation for writing the resistance in terms of power, the second degree fit of the oven calibration data, and the theory for correcting for the conduction loss so that the "actual" Nusselt number can be found. Experimental conclusions can be drawn concerning the importance of the β term from the oven calibrations, the predictability of α and β , and the dependence of the constant D , temperature recovery factor, measured Nusselt number, and "convective" or "actual" Nusselt number on the characteristics of the flow.

Theoretical Conclusions

The theory of measurement developed here allows the heat transfer loss from a hot-film to be modeled in the form of convection losses only. This was done by defining a new Nusselt number referred to as the measured Nusselt number. This model allows this measured Nusselt number to be found by conventional methods without introducing complicated conduction loss effects while making the measurement. This modeling also agrees with the hot-wire heat transfer model, making similar methods of measurement applicable and making comparisons easier.

The theory has shown that the resistance can be written in terms of the power by using a best fit second degree polynomial. The first term of the polynomial is found to be controlled by the recovery temperature. The second term is controlled by the Nusselt number at zero current. The third term is controlled by the effect of the temperature loading (power) on the Nusselt number. This second degree polynomial fit of the resistance-power data was determined to be the proper relation by assuming the Nusselt number dependence on power, by using a second degree fit of the oven calibration data, and by looking at past experimental results.

As mentioned above, the theory uses a second degree polynomial to find the resistance and resistivity coefficients for each probe in an oven calibration. This second degree polynomial fit of the oven calibration data is necessary due to the operating range for which the probes were to be used for. A linear fit would not represent the data satisfactorily.

Theory also gives insight and direction for dealing with the conduction contribution to the measured Nusselt number. Theory shows that the loss depends on the quantity

$$(58) \quad c \sqrt{\frac{k_s}{k_e}} .$$

This relation says that to minimize the conduction loss the thermal conductivity of the substrate must be minimized. It also says that the loss will depend on the recovery temperature via the air thermal conductivity term. If the probe is placed in an environment with negligible forced convection the conduction contribution can be closely estimated. This can be done for several temperatures in order to write this conduction contribution in terms of the temperature recovery factor. This function can then be used so that the conduction contribution can be found

and subtracted from the measured Nusselt number found in a flow, yielding the desired Nusselt number.

Experimental Conclusions

The resistivity characteristics of hot-film anemometers prepared for hypersonic research have been shown to be found accurately by making an oven calibration for each probe and fitting the data to a second degree polynomial. The resistivity characteristics of each film are different due to the uniqueness in their physical characteristics. However, the resistivity coefficients for 39 oven calibrations have shown that the film resistivity coefficients are predictable. The films have resistances from 5 to 25 ohms, have an average α value of $.00293 \frac{1}{C}$ with a 5% standard deviation, and have an average β value of $.00000071 \frac{1}{C^2}$ with a 28% standard deviation.

The resistivity characteristics of the films were described by a second degree polynomial instead of the more typical linear representation used for this type of resistance thermal sensor. The data have shown that a second degree fit must be used in order to get proper flow calibration results for both the temperature recovery factor and the Nusselt number.

How the Nusselt number dependence on power depends on the flow characteristics and properties has been investigated by looking at the non-dimensional constant D . The absolute value of the constant D is found to increase slightly with temperature and to remain independent of all other variables investigated. Typical values for the constant D were -0.2.

The temperature recovery factor was found to be dependent on the Mach number, and on the Reynolds number only for Mach numbers of three or higher.

The temperature recovery factor decreases with Mach number with a maximum value of around 1.0 for Mach 0 and a minimum value of around 0.9 for Mach 8. The data show that the temperature recovery factor increases as the Reynolds number increases starting at a Mach number of about 3.

The measured Nusselt number, which is dimensional and includes conduction effects, depends on all of the flow parameters investigated except the Mach number. It depends indirectly on the stagnation temperature because of its conduction loss. It depends on the square root of the Reynolds number as predicted by Kings Law. The data do not allow a conclusion of a Mach number dependence. The magnitude of the measured Nusselt number depends heavily on the conduction loss to the substrate. This loss may contribute to as much as 75% of the measured value or as little as 25%. This loss is directly dependent on the substrate material and is a function of temperature.

The characteristics of the "actual" Nusselt number were found to agree well with those of the hot-wire in the higher Reynolds number range ($Re > 50$). The Nusselt number was found to be dependent on the square root of the Reynolds number, it was found to be stagnation temperature independent, and it was not found to be Mach number dependent. It was also found that the temperatures used in this study for evaluating the flow properties and Nusselt number were appropriate. These were the recovery temperature for the Nusselt number and the free-stream static temperature for the Reynolds number.

Though the film anemometers have high mechanical strength, their ability to make flow measurements has not been fully investigated. No attempt to make mean flow measurements has been made. The film anemometers' ability to make measurements of turbulence fluctuations has not been examined either. Therefore,

the film anemometers' ability to make flow measurements cannot be evaluated at this point.

Continued research on the resistivity and heat transfer characteristics of hot-film probes is essential to the proper use of these sensors in the future. As the development of these sensors advances their characteristics should be investigated since complete understanding of these is vital in applying the hot-film for use in turbulent measurements. The hot-films should be investigated over a wider range of stagnation temperatures, Mach numbers, and Reynolds numbers so that these characteristics can be more completely found. Upon completing the investigation of these characteristics the film's capability of making turbulent measurements should be fully investigated.

APPENDICES

APPENDIX A
RADIATION LOSS FROM FILM ANEMOMETER

RADIATION LOSS FROM FILM ANEMOMETER

If it assumed that the surface of the film has a constant emissivity and that the area of the surface it emits to is much greater than itself, the rate of energy loss by radiation is given in Karlekar and Desmond [25] as

$$(59) \quad Q = A\sigma\epsilon(T^4 - T_e^4)$$

where

A = film surface area

$$\sigma = 5.668 \times 10^{-8} \text{ W/m}^2 \text{ K}^4 \quad [25]$$

$$\epsilon = 0.1 \text{ for platinum} \quad [25]$$

T = temperature of film

T_e = temperature of film at zero current

T_e = temperature of surrounding surfaces .

As can be seen, it has been assumed that the surface that the film is emitting to is at the same temperature as the film at zero current. This should be correct within a few degrees. For a typical "worst case" for when the radiation losses would be greatest, let the following variables be defined:

$$R = 10\Omega$$

$$i = 100 \text{ mA}$$

$$A = 0.05 \text{ cm} \times 0.18 \text{ cm}$$

$$T = 600 \text{ C}$$

$$T_e = 500 \text{ C} .$$

Using these values and substituting into (59) will yield

$$(60) \quad Q = 0.0011 \text{ Watts}$$

The total heat loss from the film is equal to the electrical power input to the film which is, using the given values, 0.1 Watts. The value found for radiation loss is only 1% of the total heat loss for this case. A 1% loss for the "worst case" leads to the conclusion that radiation losses can be neglected for the work done in this investigation.

APPENDIX B
CONVECTION LOSS IN CALIBRATION OVEN

CONVECTION LOSS IN CALIBRATION OVEN

The convection loss from the film surface inside the oven chamber can be examined by looking at the magnitude of the Nusselt number due to natural convection. In order to do this the hot-film will be modeled as a constant temperature vertical wall. For a vertical wall, the Nusselt number is given in Karlekar and Desmond [25] as

$$(61) \quad N = 0.68 + \frac{0.67 Ra_L^{1/4}}{\left[1 + \left(\frac{0.492}{Pr}\right)^{9/16}\right]^{4/9}}$$

where

$$(62) \quad Ra_L = \frac{g(\Delta T)L^3}{T_\infty \nu^3} Pr$$

Let the variables in the above equations be defined as follows:

$$g = 9.81 \text{ m/s}$$

$$\Delta T = 100 \text{ C}$$

$$L = 0.05 \text{ cm}$$

$$T_\infty = 500 \text{ C}$$

$$\nu = 37.9 \times 10^{-6} \text{ m}^2/\text{s} \quad [23]$$

$$Pr = 0.7$$

If these values are substituted into (62) they will result in a value of about 0.08. If the result of (62) is then substituted into (61) the resulting Nusselt number is about one (the case where $T = 100 \text{ C}$ will yield a value of 1.2 for (61)). This value corresponds to the non-dimensional Nusselt number and must be put in

dimensional form in order to compare with the magnitudes of the Nusselt numbers found in this investigation. The proper dimension to use according to theory is the length of the film. The following equations show where the dimension comes from for the Nusselt number found in this study:

$$(63) \quad Q = hA(T - T_e) = \frac{kN}{w} A(T - T_e) \quad .$$

By solving for N ,

$$(64) \quad N = \frac{Qw}{kA(T - T_e)}$$

where the area A is the film surface area (height times length) and w is the film height. Therefore the dimension comes from the length of the film. With this length, the non-dimensional value of one found from (61) becomes 0.177 cm in dimensional form. This value is typically about 2% of the total measured Nusselt number found in the oven and varies little (from .21 at 25 C to .177 at 500 C) from this value over the oven temperature range. The remaining 98% of the Nusselt number must then be due to radiation, which has been previously shown negligible, and conduction to the substrate.

Note that the method of correcting the measured Nusselt number for conduction effects actually corrects for the radiation effects also, even though the radiation was first assumed negligible.

APPENDIX C
NEWOVEN PROGRAM

```

10 ' ..... VARIABLE LIBRARY .....
20 '
30 '
40 ' A$= DUMMY INPUT IN MOST OF PROGRAM
50 ' ALPHA2= ALPHA OF QUADRATIC FIT
60 ' ALPHAR= ALPHA TIMES RZERO
70 ' AR()= r
80 ' AW()= w
90 ' BETA2= BETA OF QUADRATIC FIT (SQUARED TERM)
100 ' C()= CRITICAL CURRENT
110 ' CURRENT()= INDIVIDUAL CURRENTS FROM WIRECAL
120 ' CURRENTS= NUMBER OF CURRENTS PROGRAMMED INTO WIRECAL
130 ' DAVE= AVERAGE VALUE OF D
140 ' D()-D2()= CURVEFIT RELATED
150 ' DD= D
160 ' DTS$= DATE OF THE CALIBRATION
170 ' FILE$= INPUT FILE NAME FROM WIRECAL PROGRAM
180 ' G1-G7= CURVEFIT RELATED
190 ' G6= GRAPHICS FILE OUTPUT SELECTION
200 ' HH= PRINTER OUTPUT OPTIONS
210 ' LABEL$= TEMP LABEL FOR GRAPHER
220 ' LRINT= XX
230 ' LRSLP= YY
240 ' NAM$= PROBE NAME OR NUMBER
250 ' OHMAX= MAXIMUM OVERHEAT ACHIEVED BY THE PROBE
260 ' PP= SCREEN OUTPUT OPTION
270 ' PRBTEMP()= TEMPERATURE OF THE FILM SURFACE
280 ' PROBES= # OF PROBES IN CALIBRATION ASSIGNED TO BE ONE
290 ' PWR()= POWER DISSIPATION
300 ' PWRMAX= MAXIMUM POWER DISSIPATION IN THE PROBE
310 ' RES()= RESISTANCE OF PROBE-LINE RESISTANCE
320 ' RIZERO= RESISTANCE WITH NO CURRENT FLOWING IN THE PROBE
330 ' RMAX= MAXIMUM RESISTANCE ACHIEVED BY THE PROBE
340 ' RPLUSLR()= RESISTANCE INCLUDING LINE FROM WIRECAL
350 ' RZERO= RES. AT ZERO DEG. C AND NO CURRENT
360 ' SET= THE MAXIMUM CURRENT THAT WIRECAL WAS PROGRAMMED TO.
370 ' T()=INDIVIDUAL INPUT TEMPERATURES FROM WIRECAL
380 ' TEMP()= AVERAGE TEMPERATURE AT EACH READING T()/CURRENTS
390 ' TEMPMAX= MAXIMUM TEMPERATURE ACHIEVED BY THE PROBE
400 ' TEMPS= NUMBER OF TEMPERATURES IN CALIBRATION
410 ' VOLTAGE()= INPUT VOLTAGE FROM WIRECAL
420 ' WW= RESISTANCE OF CONNECTING CHORD IN THE CALIBRATION
430 ' XX= RESISTANCE OF Pt AT ZERO DEGREES C
440 ' YY= TEMPERATURE DEPENDENT RESISTANCE OF Pt
450 ' Z$= DUMMY VARIABLE FOR INPUTS
460 '

```

Figure 48. NEWOVEN Program.

```

470 '
480 '..... DIMENSIONS AND DECLARATIONS .....
490 '
500 DIM CURRENT(500), VOLTAGE(500), RES(500), TEMP(25)
510 DIM D0(100), D1(100), D2(100), RIZERO(100), A1(100), A2(100)
520 DIM G9(100), PWR(500), PRBTEMP(100), C(100), AW(1000)
530 DIM RPLUSLR(1081), D(100), T(1000), AR(1000), DD(200)
540 '
550 Q = 1: K = 1: DAVE = 0: OHMAX = 0: PWRMAX = 0: RMAX = 0
560 A$ = "z": SET = 0: PP = 0
570 PROBES = 1
580 '
590 '..... TITLE PAGE .....
600 '
610 CLS
620 PRINT "....."
630 PRINT ". "
640 PRINT ". "
650 PRINT ". "
660 PRINT ". "
670 PRINT ". "
680 PRINT ". NEWOVEN "
690 PRINT ". "
700 PRINT ". WRITTEN BY; Cary Munger "
710 PRINT ". WRITTEN FOR; Dr. A. Demetriades "
720 PRINT ". Montana State University "
730 PRINT ". Supersonic Wind Tunnel "
740 PRINT ". "
750 PRINT ". DATE; SPRING 1989 "
760 PRINT ". "
770 PRINT ". "
780 PRINT ". "
790 PRINT ". "
800 PRINT ". "
810 PRINT ". "
820 PRINT ". "
830 PRINT "....."
840 PRINT "press return to continue"
850 INPUT A$
860 CLS
870 PRINT : PRINT : PRINT : PRINT : PRINT
880 PRINT "INPUT A (?) FOR PROGRAM "
890 PRINT "LIMITATIONS AND DESCRIPTION"
900 PRINT "- OR -"
910 PRINT "RETURN TO EXECUTE NEWOVEN"
920 INPUT A$

```

Figure 48 (continued). NEWOVEN Program.

```

930 IF A$ <> "?" THEN 1560
940 CLS
950 PRINT "          NEWOVEN DESCRIPTION AND LIMITATIONS"
960 PRINT "    The purpose of Newoven.bas is to create one data reduction"
970 PRINT "program that can meet the needs of both the Zenith 159 data"
980 PRINT "reduction programs and those used on the Zenith 100 series"
990 PRINT "computers."
1000 PRINT "    This program is designed to take data files that have been"
1010 PRINT "created using the Wirecal data aquisition program and reduce"
1020 PRINT "the files by performing curvefits to first determine the "
1030 PRINT "resistance of the hot-film/hot-wire annemometers with no "
1040 PRINT "current passing through the probe. These resistances are"
1050 PRINT "curvefitted to the temperature at which they occurred to "
1060 PRINT "determine the resistance of the probes at zero degrees C "
1070 PRINT "and no current passing through the probe. This final fit"
1080 PRINT "is performed both with the best linear and the best quadratic"
1090 PRINT "fit. This is the primary improvement found in the newoven"
1100 PRINT "program over its predecessors the 'Ovenal 1-9' series of"
1110 PRINT "programs."
1120 PRINT "    The general form of the input file is a series of arrays"
1130 PRINT "that contain the following information;"
1140 PRINT "    Temperature, Voltage, Current, Resistance"
1150 PRINT "Only one data file is to be read in so all temperatures are"
1160 PRINT "to be contained in a single file starting with the largest "
1170 PRINT "temperature and proceeding to the smallest."
1180 INPUT "press return to continue"; Q$
1190 CLS
1200 PRINT "          PROGRAM RESTRICTIONS"
1210 PRINT "    The input file must be in the form mentioned on the "
1220 PRINT "preceeding page and must be named with an OV1...OV2 etc. "
1230 PRINT "as an extension. This extension tells the program which "
1240 PRINT "calibration the probe is undergoing. This information is "
1250 PRINT "used by the program in bookkeeping."
1260 PRINT "    The line resistance calculation found in this program"
1270 PRINT "was calculated by Cary Munger and Scott Anders in the spring"
1280 PRINT "of 1989 based on one foot of platinum wire for the probe leads"
1290 PRINT "and handbook values found as such. The connecting chord line"
1300 PRINT "resistance was measured using Wirecal and should be repeated"
1310 PRINT "from time to time."
1320 PRINT "    The screen and printer output prompts ask if the user"
1330 PRINT "would like the output of the entire set of results or "
1340 PRINT "simply the summary results. The entire set of results involves"
1350 PRINT "the output of the current, power, resistance, w, overheat"
1360 PRINT "w/r, and (1-r/w)/D for each current in the run at each temp."
1370 PRINT "in the run. In addition zero current resistance, critical"
1380 PRINT "current, D, and the line resistance is output at each temp."

```

Figure 48 (continued). NEWOVEN Program.

```

1390 PRINT "thus the printing of the entire set of results is very time"
1400 PRINT "consuming and involves about a page of output per temperature."
1410 PRINT : PRINT
1420 INPUT "press return to continue"; Q$
1430 CLS
1440 PRINT " The summary only outputs involves the output of a single"
1450 PRINT "page of the most pertinent data. This includes the "
1460 PRINT "temperatures with their corresponding values of D, probe"
1470 PRINT "temperature, and zero current resistance. In addition"
1480 PRINT "this output contains the final goal of the program, that being,"
1490 PRINT "the value of the r zero value (resistance at zero Deg. C) "
1500 PRINT "and the value of alpha obtained using both a linear and a "
1510 PRINT "quadratic fit."
1520 INPUT "press return to continue"; Q$
1530 '
1540 '
1550 '..... BEGIN INPUTS .....
1560 CLS
1570 PRINT : PRINT : PRINT
1580 INPUT "INPUT OVEN CALIBRATION DATA FILE:"; FILE$
1590 OPEN "I", #1, FILE$
1600 INPUT "INPUT THE DATE OF THE CALIBRATION "; DTS$
1610 INPUT "INPUT THE PROBE NAME/NUMBER BEING CALIBRATED "; NAM$
1620 INPUT "INPUT THE NUMBER OF CURRENTS PER PROBE PER TEMPERATURE "; CURRENTS
1630 INPUT "INPUT THE MAXIMUM CURRENT PASSED THROUGH THE PROBE"; SET
1640 INPUT "INPUT THE NUMBERS OF TEMPERATURES USED "; TEMPS
1650 PRINT : PRINT : PRINT "PRESS RETURN TO CONTINUE OR (1) TO REENTER PARAMETERS"
1660 INPUT Z$
1670 IF Z$ <> "1" THEN 1700
1680 CLOSE
1690 GOTO 1560
1700 CLS
1710 PRINT : PRINT : PRINT
1720 '
1730 '..... LINE RESISTANCE SECTION .....
1740 '
1750 PRINT "LINE RESISTANCE CALIBRATION": PRINT
1760 PRINT " LINE RESISTANCE= WW+XX( 1 + YY*(TEMP. DEGREES C))"
1770 PRINT : PRINT
1780 PRINT "WW-CONNECTING CHORD LINE RESISTANCE = 0.166 OHMS"
1790 WW = .166
1800 PRINT "XX-REFERENCE RESISTANCE AT ZERO DEGREES C = 0.1381497"
1810 LRINT = .1381497
1820 PRINT "YY-TEMPERATURE DEPENDENT RESISTANCE OF PLATINUM = 0.003927"
1830 LRSPL = .003927
1840 PRINT : PRINT "DO YOU WISH TO REENTER ANY OF THE ABOVE VALUES"

```

Figure 48 (continued). NEWOVEN Program.

```

1850 PRINT "      ENTER 'Y' FOR YES OR RETURN TO CONTINUE"
1860 INPUT A$
1870 IF A$ = "Y" OR A$ = "y" THEN 1890
1880 GOTO 1920
1890 INPUT "INPUT THE INTERCEPT (XX) "; LRINT
1895 GOTO 1920
1900 INPUT "INPUT THE SLOPE (YY) "; LRSLP
1910 INPUT "PLEASE ENTER THE CHORD RESISTANCE VALUE"; WW
1920 '
1930 '..... data input .....
1940 '
1950 CLS
1960 PRINT : PRINT : PRINT : PRINT : PRINT : PRINT : PRINT : PRINT : PRINT : PRINT
1970 PRINT "      READING DATA "
1980 FOR I = 1 TO CURRENTS * PROBES * TEMPS
1990 INPUT #1, T(I), VOLTAGE(I), CURRENT(I), RPLUSLR(I)
2000 NEXT I
2010 '..... temp. ave. and storage .....
2020 '
2030 CLS
2040 PRINT : PRINT : PRINT : PRINT : PRINT : PRINT : PRINT : PRINT : PRINT : PRINT
2050 PRINT "      DETERMINING TEMPERATURES"
2060 FOR H = 1 TO TEMPS
2070 TEMP = 0
2080 FOR J = 1 TO CURRENTS * PROBES
2090 TEMP = TEMP + T(J + CURRENTS * PROBES * (H - 1))
2100 NEXT J
2110 TEMP(H) = INT(TEMP / (CURRENTS * PROBES))
2120 NEXT H
2130 '
2140 '..... curvefitting .....
2150 '
2160 FOR J = 1 TO TEMPS
2170 CLS
2180 PRINT : PRINT : PRINT : PRINT : PRINT : PRINT : PRINT : PRINT : PRINT : PRINT
2190 PRINT "      EVALUATING @ T= "; TEMP(J)
2200 G1 = 0: G2 = 0: G3 = 0: G4 = 0
2210 G5 = 0: G6 = 0: G7 = 0: G8 = 0
2220 FOR N = (J - 1) * CURRENTS + 1 TO J * CURRENTS
2230 RES(N) = RPLUSLR(N) - (WW + LRINT + LRSLP * LRINT * TEMP(J))
2240 PWR(N) = (CURRENT(N) / 1000) ^ 2 * RES(N)
2250 G1 = G1 + PWR(N)
2260 G2 = G2 + PWR(N) ^ 2
2270 G3 = G3 + PWR(N) ^ 3
2280 G4 = G4 + PWR(N) ^ 4
2290 G5 = G5 + RES(N)

```

Figure 48 (continued). NEWOVEN Program.

```

2300 G6 = G6 + RES(N) * PWR(N)
2310 G7 = G7 + (PWR(N) ^ 2) * RES(N)
2320 NEXT N
2330 D(J) = CURRENTS * G2 * G4 + 2 * G1 * G2 * G3 - G2 ^ 3
2331 D(J) = D(J) - CURRENTS * (G3 ^ 2) - (G1 ^ 2) * G4
2340 D0(J) = G5 * G2 * G4 + G2 * G3 * G6 + G1 * G3 * G7
2341 D0(J) = D0(J) - (G2 ^ 2) * G7 - (G3 ^ 2) * G5 - G1 * G4 * G6
2350 D1(J) = CURRENTS * G4 * G6 + G1 * G2 * G7 + G2 * G3 * G5
2351 D1(J) = D1(J) - (G2 ^ 2) * G6 - CURRENTS * G3 * G7
2360 D1(J) = D1(J) - G1 * G4 * G5
2370 D2(J) = CURRENTS * G2 * G7 + G1 * G3 * G5 + G1 * G2 * G6
2371 D2(J) = D2(J) - (G2 ^ 2) * G5 - CURRENTS * G3 * G6
2380 D2(J) = D2(J) - (G1 ^ 2) * G7
2390 RIZERO(J) = D0(J) / D(J)
2400 A1(J) = D1(J) / D(J)
2410 A2(J) = D2(J) / D(J)
2420 FOR N = (J - 1) * CURRENTS + 1 TO J * CURRENTS
2430 G8 = G8 + (RES(N) - RIZERO(J) - A1(J) * PWR(N) - A2(J) * (PWR(N) ^ 2)) ^ 2
2440 NEXT N
2450 G9(J) = SQR(G8) / CURRENTS
2460 IF A1(J) > 0 THEN 2480
2470 A1(J) = A1(J) * (-1)
2480 C(J) = SQR(1 / A1(J)) * 1000
2490 DD(J) = (RIZERO(J) * A2(J)) / A1(J) ^ 2
2500 DAVE = DAVE + DD(J)
2510 REM ***** ADDITIONAL CHART SUBROUTINE *****
2520 YU$ = STR$(Q)
2530 F3$ = "OV" + YU$ + ".DAT"
2540 YUA$ = MID$(F3$, 4)
2550 F3$ = "OV" + YUA$
2560 Q = Q + 1
2570 REM OPEN "Q",#2,F3$
2580 FOR N = (J - 1) * CURRENTS + 1 TO J * CURRENTS
2590 AR = RES(N) - RIZERO(J)
2600 AR(N) = AR / RIZERO(J)
2610 AW = RES(N) * CURRENT(N) ^ 2 / 1000
2620 PWR = AW
2630 AD = 1 / A1(J) * RIZERO(J)
2640 AW(N) = AW / (AD * 1000)
2650 PWR(N) = PWR
2660 LABEL$ = " "
2670 IF INT(N / CURRENTS) = N / CURRENTS THEN LABEL$ = STR$(INT(TEMP(J))) + " C"
2680 REM WRITE #2,PWR(N),RES(N),AW(N)/1000,AR(N),LABEL$
2690 NEXT N
2700 REM CLOSE #2
2710 NEXT J

```

Figure 48 (continued). NEWOVEN Program.

```

2720 F = 0: F1 = 0: F2 = 0: F3 = 0: F4 = 0: F5 = 0: Q = 0
2730 FF = 0: FF1 = 0: FF2 = 0: FF3 = 0: FF4 = 0: FF5 = 0: QB = 0
2740 FOR J = 1 TO TEMPS
2750 F1 = F1 + TEMP(J)
2760 F2 = F2 + (TEMP(J) ^ 2)
2770 F3 = F3 + TEMP(J) ^ 3
2780 F4 = F4 + TEMP(J) ^ 4
2790 F5 = F5 + RIZERO(J)
2800 F6 = F6 + RIZERO(J) * TEMP(J)
2810 F7 = F7 + TEMP(J) ^ 2 * RIZERO(J)
2820 FF = FF + TEMP(J)
2830 FF1 = FF1 + RIZERO(J)
2840 FF2 = FF2 + TEMP(J) * RIZERO(J)
2850 FF3 = FF3 + TEMP(J) ^ 2
2860 NEXT J
2870 H = TEMPS * F2 * F4 + 2 * F1 * F2 * F3 - F2 - F2 ^ 3
2871 H = H - TEMPS * F3 ^ 2 - F1 ^ 2 * F4
2880 H0 = F5 * F2 * F4 + F2 * F3 * F6 + F1 * F3 * F7 - F2 ^ 2 * F7
2881 H0 = H0 - F3 ^ 2 * F5 - F1 * F4 * F6
2890 H1 = TEMPS * F4 * F6 + F1 * F2 * F7 + F2 * F3 * F5 - F2 ^ 2 * F6
2891 H1 = H1 - TEMPS * F3 * F7 - F1 * F4 * F5
2900
H2 = TEMPS * F2 * F7 + F1 * F3 * F5 + F1 * F2 * F6 - F2 ^ 2 * F5
H2 = H2 - TEMPS * F3 * F6 - F1 ^ 2 * F7
2910 H3 = H0 / H
2920 H4 = H1 / H
2930 H5 = H2 / H
2940 REM      R = H3 + H4*TEMP + H5*T^2
2950 RZERO2 = H3
2960 ALPHA2 = H4 / H3
2970 BETA2 = H5 / H3
2980 ALPHAR = (FF * FF1 - TEMPS * FF2) / (FF ^ 2 - TEMPS * FF3)
2990 RZERO = (FF1 - ALPHAR * FF) / TEMPS
3000 F2$ = "tempvsr.dat"
3010 REM open "a",#2,F2$
3020 FOR J = 1 TO TEMPS
3030 Q = Q + CURRENTS
3040 TE1 = (RES(Q) / RZERO) - 1
3050 PRBTEMP(J) = TE1 * (RZERO / ALPHAR)
3060 REM WRITE #2,TEMP(J),RIZERO(J),PRBTEMP(J)
3070 FF4 = FF4 + (RIZERO(J) - RZERO - ALPHAR * TEMP(J)) ^ 2
3080 FF5 = FF5 + 69(J)
3090 NEXT J
3100 REM CLOSE #2
3110 R7 = (SQR(FF4)) / TEMPS
3120 R8 = FF5 / TEMPS

```

Figure 48 (continued). NEWOVEN Program.

```

3130 REM CLOSE #1
3140 '.....DETERMINATION OF MAXIMUMS.....
3150 FOR N = 1 TO CURRENTS * TEMPS
3160 IF OHMAX < AR(N) THEN OHMAX = AR(N)
3170 IF PWRMAX < PWR(N) THEN PWRMAX = PWR(N)
3180 IF RMAX < RES(N) THEN RMAX = RES(N)
3190 NEXT N
3200 FOR J = 1 TO TEMPS
3210 IF TEMPMAX < PRBTEMP(J) THEN TEMPMAX = PRBTEMP(J)
3220 NEXT J
3230 '.....
3240 CLS
3250 '..... SCREEN OUTPUT OPTIONS .....
3260 PRINT : PRINT : PRINT "SCREEN OUTPUT OPTIONS"
3270 PRINT "PLEASE INPUT YOUR CHOICE"
3280 PRINT "      (1) SCREEN DISPLAY OF ENTIRE SET OF RESULTS"
3290 PRINT "      (2) SCREEN DISPLAY OF SUMMARY ONLY"
3300 PRINT "      (3) NO SCREEN DISPLAY"
3310 INPUT PP
3320 IF PP = 3 THEN 3890
3330 IF PP = 2 THEN 3550
3340 CLS
3350 FOR J = 1 TO TEMPS
3360 PRINT : PRINT : PRINT "RESULTS FOR PROBE "; NAM$; " AT "; TEMP(J); " DEG. C"
3370 PRINT
3380 PRINT " I(mA) ", "W(mW)", "R(OHMS)", "w", "r"
3390 FOR N = CURRENTS * J + 1 - CURRENTS TO CURRENTS * J
3400 PRINT CURRENT(N), INT(PWR(N) * 100) / 100, INT(RES(N) * 100) / 100,
      INT(AW(N) * 1000) / 1000, INT(AR(N) * 1000) / 1000
3410 NEXT N
3420 PRINT
3430 PRINT "ZERO CURRENT RESISTANCE (ohms)= "; RIZERO(J)
3440 PRINT "CRITICAL CURRENT      ( mA )= "; C(J)
3450 PRINT "VALUE OF D              = "; DD(J)
3460 PRINT "LINE RESISTANCE          (ohms)= "; WW + LRINT + LRINT * LRSPL * TEMP(J)
3470 PRINT : PRINT : PRINT
3480 PRINT " I(mA) ", " w/r ", "(1-r/w)/D"
3490 FOR N = CURRENTS * J + 1 - CURRENTS TO CURRENTS * J
3500 PRINT CURRENT(N), AW(N) / AR(N), (1 - AR(N) / AW(N)) / DD(J)
3510 NEXT N
3520 '
3530 '
3540 NEXT J
3550 PRINT "PRESS RETURN FOR THE SUMMARY OUTPUT"
3560 INPUT Z$
3570 CLS

```

Figure 48 (continued). NEWOVEN Program.

```

3580 PRINT "----- SUMMARY OUTPUT -----"
3590 PRINT " DATE "; DTS$
3600 PRINT " PROBE NUMBER "; NAM$
3610 PRINT " CALIBRATION FILE NAME "; FILE$
3620 PRINT " LINE RESISTANCE "
3630 PRINT " RESISTANCE (ohms) = "; LRINT + WW; "+"; LRSPL * LRINT; " * TEMP (DEG C)"
3640 PRINT
3650 PRINT "MAXIMUM CURRENT WAS SET AT "; SET
3660 PRINT " TEMP ", " RES. ", " CRIT. CURRENT", "D"
3670 PRINT "(deg C)", "(ohms)", " (mA)"
3680 FOR J = 1 TO TEMPS
3690 PRINT TEMP(J), INT(RZERO(J) * 100) / 100, INT(C(J) * 100) / 100, ;
3700 PRINT " ", INT(DD(J) * 100) / 100
3710 NEXT J
3720 PRINT
3730 PRINT "MAXIMUM RESISTANCE ACHIEVED (OHMS) = "; RMAX
3740 PRINT "MAXIMUM OVERHEAT RECORDED = "; OHMAX * 100
3750 PRINT "MAXIMUM POWER DISSIPATION ( mW ) = "; PWRMAX
3760 PRINT "MAXIMUM PROBE TEMPERATURE (DEG. C) = "; TEMPMAX
3770 PRINT : PRINT " RES. ( AT ZERO CURRENT, ZERO DEG. C) = "; RZERO
3780 PRINT " ARO (DEGREES/DEG. C) = "; ALPHAR
3790 PRINT " ALPHA ( REFEREED TO RD ABOVE PER DEG. C) = "; ALPHAR / RZERO
3800 PRINT "QUADRATIC FIT OF RESISTANCE -VS- TEMP."
3810 PRINT " RESISTANCE AT ZERO DEG. = "; RZERO2
3820 PRINT " QUADRATIC ALPHA = "; ALPHA2
3830 PRINT " QUADRATIC BETA = "; BETA2
3840 PRINT
3850 PRINT "PRESS RETURN TO CONTINUE"
3860 INPUT J$
3870 PRINT " "
3880 ..... PRINTER OUTPUT OPTIONS .....
3890 CLS
3900 PRINT "----- PRINTER OUTPUT OPTIONS -----"
3910 PRINT " PLEASE INPUT YOUR CHOICE"
3920 PRINT " (1) HARD COPY THE ENTIRE RESULTS"
3930 PRINT " (2) HARD COPY A ONE PAGE DATA OUTPUT"
3940 PRINT " (3) NO HARD COPIES"
3950 INPUT HH
3960 IF HH = 3 THEN 4630
3970 IF HH = 2 THEN 4210
3980 PRINT " READY THE PRINTER AND THEN PRESS RETURN"
3990 INPUT Z$
4000 CLS
4010 FOR J = 1 TO TEMPS
4020 LPRINT : LPRINT : LPRINT "RESULTS FOR PROBE "; NAM$; " AT "; TEMP(J); " DEG. C"
4030 LPRINT

```

Figure 48 (continued). NEWOVEN Program.

```

4040 LPRINT " I(mA) ", "W(mW)", "R(OHMS)", "w", "r"
4050 FOR N = CURRENTS * J + 1 - CURRENTS TO CURRENTS * J
4060 LPRINT CURRENT(N), INT(PWR(N) * 100) / 100, INT(RES(N) * 100) / 100,
      INT(AW(N) * 1000) / 1000, INT(AR(N) * 1000) / 1000
4070 NEXT N
4080 LPRINT
4090 LPRINT "ZERO CURRENT RESISTANCE (ohms)= "; RIZERD(J)
4100 LPRINT "CRITICAL CURRENT      ( mA )= "; C(J)
4110 LPRINT "VALUE OF D              = "; DD(J)
4120 LPRINT "LINE RESISTANCE        (ohms)= "; WW + LRINT + LRINT * LRSLP * TEMP(J)
4130 LPRINT : LPRINT : LPRINT
4140 LPRINT " I(mA) ", " w/r ", "(1-r/w)/D"
4150 FOR N = CURRENTS * J + 1 - CURRENTS TO CURRENTS * J
4160 LPRINT CURRENT(N), AW(N) / AR(N), (1 - AR(N) / AW(N)) / DD(J)
4170 NEXT N
4180 '
4190 '
4200 NEXT J
4210 PRINT " READY THE PRINTER FOR SUMMARY OUTPUT AND THEN PRESS RETURN"
4220 INPUT Z$
4230 LPRINT "                                NEWOVEN DATA REDUCTION PROGRAM"
4240 LPRINT "                                ....."
4250 LPRINT
4260 LPRINT "          DATE "; DTS$
4270 LPRINT "          PROBE NUMBER "; NAM$
4280 LPRINT "          CALIBRATION FILE NAME "; FILE$
4290 LPRINT
4300 LPRINT "          CABLE RESISTANCE RECORDED "; WW
4310 LPRINT "          LINE RESISTANCE (OHMS) = "; WW; "+"; LRINT;
      " * ( 1 +"; LRSLP; " * T) "
4320 LPRINT : LPRINT "          THE MAXIMUM SET CURRENT WAS "; SET; " mA "
4330 LPRINT "          THE MAXIMUM CURRENT ACHIEVED WAS "; CURRENT(CURRENTS); " mA"
4340 LPRINT "          THE NUMBER OF CURRENTS USED WAS "; CURRENTS
4350 LPRINT : LPRINT : LPRINT
4360 LPRINT " ", "TEMP", "R", " D ", "CRIT. C"
4370 LPRINT " ", "DEG. C", "OHMS", " ", "mA"
4380 LPRINT " ", " ", " ", " ", " "
4390 LPRINT " -----"
4400 FOR J = 1 TO TEMPS
4410 LPRINT " ", TEMP(J), INT(RIZERD(J) * 100) / 100, ;
4420 LPRINT INT(DD(J) * 1000) / 1000, INT(C(J) * 100) / 100
4430 NEXT J
4440 LPRINT : LPRINT
4450 LPRINT "          THE MAXIMUM RESISTANCE FOR THIS PROBE (OHMS)= "; RMAX
4460 LPRINT "          THE LARGEST PERCENT OVERHEAT ACHIEVED = "; OHMAX * 100
4470 LPRINT "          THE LARGEST POWER DISSIPATION (mW) = "; PWRMAX

```

Figure 48 (continued). NEWOVEN Program.

```

4480 LPRINT "          MAXIMUM PROBE TEMPERATURE ACHIEVED =" ; TEMPMAX
4490 LPRINT
4500 LPRINT "          RO (OHMS, AT 0 DEG. C) =" ; RZERO
4510 LPRINT "          ARO (OHMS/DEG C) =" ; ALPHAR
4520 LPRINT "          AVERAGE RESISTANCE-CURRENT DEVIATION. (OHMS) =" ; R8
4530 LPRINT "          OVERALL RMS DEVIATION OF R FROM R-T CURVE (OHMS) =" ; R7
4540 LPRINT "          THE AVERAGE VALUE OF THE CONSTANT D = " ; DAVE / TEMPS
4550 LPRINT "          ALPHA (REFERRED TO RO ABOVE, PER DEG. C) =" ; ALPHAR / RZERO
4560 LPRINT
4570 LPRINT "          QUADRATIC FIT OF RESISTANCE -VS- TEMP."
4580 LPRINT "          RESISTANCE AT ZERO DEG. = " ; RZERO2
4590 LPRINT "          QUADRATIC ALPHA          = " ; ALPHA2
4600 LPRINT "          QUADRATIC BETA           = " ; BETA2
4610 '
4620 '
4630 CLS
4640 PRINT " GRAPHICS FILE OUTPUT."
4650 PRINT "          (0) EXPLANATION OF OUTPUT FORMAT"
4660 PRINT "          (1) FULL GRAPHICS FILE OUTPUTS "
4670 PRINT "          (2) SUMMARY ONLY DATA OUTPUT"
4680 PRINT "          (3) NO GRAPHICS FILES"
4690 INPUT G6
4700 IF G6 = 3 THEN 5180
4710 IF G6 = 2 THEN 4850
4720 IF G6 = 0 THEN 4920
4730 FOR J = 1 TO TEMPS
4740 IF TEMP(J) > 99.9999 THEN A$ = RIGHT$(STR$(TEMP(J)), 3)
4750 IF TEMP(J) < 100 THEN A$ = RIGHT$(STR$(TEMP(J)), 2)
4760 B$ = "T" + A$ + ".ov"
4770 C$ = RIGHT$(FILE$, 1)
4780 D$ = B$ + C$
4790 OPEN "o", #2, D$
4800 FOR N = CURRENTS * J + 1 - CURRENTS TO CURRENTS * J
4810 WRITE #2, CURRENT(N), PWR(N), RES(N), AW(N), AR(N), AW(N) / AR(N),
      (1 - AR(N) / AW(N)) / DD(J)
4820 NEXT N
4830 CLOSE #2
4840 NEXT J
4850 D$ = "summary.ov" + C$
4860 OPEN "o", #2, D$
4870 FOR J = 1 TO TEMPS
4880 WRITE #2, TEMP(J), RZERO(J), C(J), DD(J)
4890 NEXT J
4900 CLOSE #2
4910 GOTO 5180
4920 CLS

```

Figure 48 (continued). NEWOVEN Program.

```

4930 PRINT "          EXPLANATION OF FILE OUTPUT"
4940 PRINT ">>> INDIVIDUAL TEMP. FILES"
4950 PRINT "          File names are predecided and yet are original so no"
4960 PRINT "over-writting, and therefore loss of data, will be encountered."
4970 PRINT "The individual file output is named by a first letter 'T'"
4980 PRINT "implying temperature followed by the temperature at which"
4990 PRINT "that data was gathered. The extension is the same extension"
5000 PRINT "as that found on the original input data file that is, ovl,"
5010 PRINT "ov2 etc. Thus, the data for the first oven calibration of a"
5020 PRINT "probe at a temperature of 400 deg. C would be saved as;"
5030 PRINT "          T400.ov1"
5040 PRINT "This general file contains all the following information"
5050 PRINT " current, power, resistance, w, r, w/r, (1-r/w)/D"
5060 PRINT
5070 PRINT ">>> SUMMARY FILE"
5080 PRINT "          The summary output file is called, simply enough,"
5090 PRINT "'SUMMARY' with the 'OV' extension being the parameter"
5100 PRINT "that will distinguish between different summary outputs"
5110 PRINT "Thus, the summary output for the third calibration of a"
5120 PRINT "particular probe is named;"
5130 PRINT "          SUMMARY.OV3"
5140 PRINT " The summary file contains the following information."
5150 PRINT " Temperature, Resistance(@ no current), Critical Current, D"
5160 INPUT "press return to make selection"; Q$
5170 GOTO 4630
5180 CLS
5190 PRINT : PRINT : PRINT : PRINT : PRINT : PRINT :
      PRINT "          DATA REDUCTION COMPLETE"
5200 PRINT : PRINT : PRINT : PRINT : PRINT : PRINT : PRINT
5210 END

```

Figure 48 (continued). NEWOVEN Program.

APPENDIX D
FLWRDCT PROGRAM

```

CLS

' Beta not equal to zero.
' 2nd degree fit of flow data.
' Improved thermal conductivity fit also.
' Thermal conductivity evaluated at recovery temperature of film.
' Reynolds number calculated using static temperature of fluid.
'
' *****
'
'   Dimension all variable arrays to be used
'
' *****

DIM J(100), J1(100), C(100), R1(100), R(100), W(100), W1(100), R2(100)
DIM NUSLT(100), CONSTD(100), RECOV(100), REY(100), SP(100), CRITCUR(100)
DIM fil$(100), GRAPH$(100), TYPE$(100), K$(100), TFIL$(100)
DIM PD$(100), P$(100), RE$(100), TT$(100), TTD$(100)
DIM TR(100)
DIM C$(100)
RECOV(0) = .95

' *****
'
'   Explain data file order and see
'   if user wants them.
'
' *****

PRINT "THIS PROGRAM REDUCES ALL OF THE FILES FOR ONE PROBE"
PRINT "THAT HAVE BEEN COLLECTED AND CAN PRODUCE A HARDCOPY"
PRINT "SUMMARY OF THE RESULTS OF EACH FILE. OUTPUT FILES"
PRINT "CAN ALSO BE MADE THAT CONTAIN VARIOUS PARAMETERS"
PRINT "SUCH AS THE DIMENSIONAL REYNOLDS NUMBER, THE DIMENSIONAL"
PRINT "NUSSELT NUMBER, THE TEMPERATURE RECOVERY FACTOR, THE "
PRINT "CONSTANT D, THE CURRENT, THE RESISTANCE, THE POWER, AND"
PRINT "THE OVERHEAT."
PRINT
PRINT "SELECT REDUCTION FOR THE LOW"
PRINT "VELOCITY WIND TUNNEL OR THE SUPERSONIC WIND TUNNEL BY "
INPUT "ENTERING '1' FOR LVT OR '2' FOR SWT HERE; ", TUNNEL$
CLS
PRINT
IF TUNNEL$ = "2" GOTO 390
PRINT "THIS PROGRAM ASSUMES THE USER IS FOLLOWING THE"
PRINT "FORMAT DESCRIBED BELOW FOR NAMING DATA FILES;"

```

Figure 49. FLWRDCT Program.

```

PRINT
PRINT "      DATA FILE NAME -      PNDDVV.VV"
PRINT "      Where PN = Probe Number"
PRINT "      DDD = Data Acquisition Date"
PRINT "      NOTE: The first D = Month;"
PRINT "      1-9 for Jan. - Sept,"
PRINT "      0,N,D for Oct., Nov., Dec."
PRINT "      VV.VV = Velocity of Tunnel in M/S"
PRINT "      NOTE: If vel.=2.65 m/s enter"
PRINT "      02.65 for vv.vv"
GOTO 560
390 PRINT "THIS PROGRAM WORKS ON THE BASIS THAT THE OPERATOR"
PRINT "HAS RESTRICTED HIMSELF TO NAMING HIS DATA FILES"
PRINT "IN THE FOLLOWING MANNER;"
PRINT "      "
PRINT "      FILENAME -      DDDNNTTM.PPP"
PRINT "      Where DDD = Date (month and day)"
PRINT "      Note : Months are numbered"
PRINT "      1-9 for Jan.-Sept. and"
PRINT "      0 for October, N for November,"
PRINT "      and D for December"
PRINT "      Where NN = Probe number"
PRINT "      Where TT = Last two digits of temperature(F)"
PRINT "      Where M = Mach Number"
PRINT "      THIS MUST BE M=1,2,3 OR 5 FOR"
PRINT "      FOR M < 1.0 ONE SHOULD ENTER THE"
PRINT "      NUMBER AFTER THE DECIMAL."
PRINT "      Where PPP= Pressure (mm Hg)"
560 PRINT
INPUT "DO YOU WANT HARD COPIES?(Y/N) ", F$
CLS
PRINT "YOU CAN MAKE A GRAPHICS FILE THAT STORES"
PRINT "RESULTS IN THE FOLLOWING ORDER:"
PRINT
PRINT "      VARIABLE #1 : I (MA)"
PRINT "      #2 : W (MILLIWATTS)"
PRINT "      #3 : R (OHMS)"
PRINT "      #4 : w (NON-DIM. POWER)"
PRINT "      #5 : r (NON-DIM. OVERHEAT)"
PRINT "      #6 : 1-r/w (NON-DIM.)"
PRINT
PRINT "THE GRAPHICS FILES WILL BE NAMED FOR YOU."
IF TUNNEL$ = "2" GOTO 850
PRINT "THEY WILL HAVE THE FOLLOWING FORMAT: PPDDVVV.DAT"
PRINT "      PP = PROBE NUMBER"
PRINT "      DDD = DATE"

```

Figure 49 (continued). FLWRDCT Program.

```

PRINT "          VVV = THE FIRST THREE NUMBERS OF VELOCITY"
PRINT "          EXAMPLE -   VEL.=15.16 M/S THEN VVV=151"
PRINT "          .DAT = THIS IS ASSIGNED TO THE END OF THE FILE NAME"
PRINT "OR THEY WILL HAVE THIS FORMAT: VVVV.DAT"
PRINT "          VVVV = VELOCITY(DECIMAL OMITTED)"
PRINT "          .DAT = THIS IS ASSIGNED"
PRINT
PRINT "DO YOU WANT GRAPHIC FILES?(ENTER '1' FOR FIRST FORMAT"
PRINT "          ENTER '2' FOR SECOND FORMAT"
INPUT "          AND 'N' FOR NONE)", G$
GOTO 930
850 PRINT "THEY WILL HAVE THE FOLLOWING FORMAT: NNTTMPPP.DAT"
PRINT "          NN = PROBE NUMBER"
PRINT "          TT = LAST TWO DIGITS OF TEMPERATURE"
PRINT "          M = MACH NUMBER DESIGNATION"
PRINT "          PPP = PRESSURE IN mm Hg"
PRINT "          .DAT = THIS IS ASSIGNED TO THE END OF THE FILE NAME"
PRINT
INPUT "WOULD YOU LIKE GRAPHICS FILES?", G$
930 CLS
PRINT "FINALLY YOU CAN MAKE A 'THEORETICAL' GRAPHICS FILE STORING THE"
PRINT "NON-DIMENSIONAL VARIBALS IN THE POLYNOMIAL;  $r=w+Dw^2$ ."
PRINT
PRINT "  VARIABLE #1: w (NON-DIM. POWER)"
PRINT "          #2: r (NON-DIM. OVERHEAT)"
PRINT "          #3: w/r"
PRINT "          #4: (1-w/r)/D"
PRINT
PRINT "THE THEORETICAL GRAPHICS FILE WILL BE NAMED FOR YOU."
IF TUNNEL$ = "2" GOTO 1120
PRINT "THE FOLLOWING FORMAT WILL BE USED: TPDDVVV.DAT"
PRINT "          TP = 'T' PLUS THE LAST NUMBER OF THE PROBE"
PRINT "          DDD = DATE"
PRINT "          VVV = THE FIRST THREE NUMBERS OF VELOCITY"
PRINT "          EXAMPLE -   VEL.=15.16 M/S"
PRINT "          THEN VVV=151"
PRINT "          .DAT = THIS IS ASSIGNED TO THE END OF THE FILE NAME"
GOTO 1180
1120 PRINT "THE FOLLOWING FORMAT WILL BE USED: TNTTMPPP.DAT"
PRINT "          TN = 'T' PLUS THE LAST NUMBER OF THE PROBE"
PRINT "          TT = LAST TWO DIGITS OF TEMPERATURE"
PRINT "          M = MACH NUMBER DESIGNATION"
PRINT "          PPP = PRESSURE IN mm Hg"
PRINT "          .DAT = THIS IS ASSIGNED TO THE END OF THE FILE NAME"
1180 PRINT
INPUT "DO YOU WANT THIS FILE PREPARED (Y/N)", J$

```

Figure 49 (continued). FLWRDCT Program.

```

CLS
PRINT "YOU CAN HAVE A REYNOLDS NUMBER FILE CREATED IF DESIRED."
PRINT " FIVE VARIABLES ARE STORED IN THIS FILE IN THE"
PRINT " FOLLOWING ORDER;"
PRINT " "
PRINT "      DIMENSIONAL REYNOLDS NUMBER (1/CM)"
PRINT "      DIMENSIONAL NUSSELT NUMBER MEASURED (CM)"
PRINT "      TEMPERATURE RECOVERY FACTOR"
PRINT "      CONSTANT D"
PRINT "      CRITICAL CURRENT (mA)"
PRINT "      SQUARE ROOT OF THE REYNOLDS NUMBER"
PRINT "      CONVECTION NUSSELT NUMBER (CM)"
PRINT " "
INPUT "DO YOU WANT REYNOLDS NUMBER FILE?(Y/N) ", REYFILE$
IF REYFILE$ = "N" OR REYFILE$ = "n" GOTO 1360
PRINT
INPUT "ENTER NAME OF REYNOLDS NUMBER FILE:", FINAL$
INPUT "ENTER SECOND REYNOLDS NUMBER FILENAME: ", FINAL2$
1360 CLS
PRINT
PRINT
PRINT
' *****
'      Input file information
' *****
'
IF F$ = "N" OR F$ = "n" GOTO 1430
INPUT "ENTER NAME OF OPERATOR WHO ACQUIRED THE DATA:", B$
INPUT "ENTER DATA ACQUISITION DATE:", C$
1430 INPUT "ENTER LEAD RESISTANCE (OHMS): ", RL
INPUT "ENTER NO. OF CURRENTS: ", N
INPUT "RESISTANCE AT ZERO DEG. C, OHMS =", RR
INPUT "TEMP. COEFF. OF RESISTANCE ALPHA R, PER DEG. C =", AL
INPUT "BETA FROM SECOND DEGREE FIT OF OVEN CALIBRATION =", BTA
IF TUNNEL$ = "2" GOTO 1500
INPUT "ENTER ATMOSPHERIC PRESSURE HERE PLEASE(mm Hg) ", ATMP
INPUT "IS TEMPERATURE IN FILE? ", INFILE$
IF INFILE$ = "Y" OR INFILE$ = "y" GOTO 1500
INPUT "WHAT WAS ROOM TEMPERATURE? ", ROOMTMP
1500 PRINT
PRINT
' *****
'
Enter names of data files

```

Figure 49 (continued). FLWRDCT Program.

```

*****

CLS
PRINT
PRINT
PRINT
PRINT
tempspec$ = "DUMMY.FIL"
INPUT " What directory is data from"; dirr$
INPUT " Enter beginning part of data files wanted ", df$
SHELL "DIR " + dirr$ + df$ + ".*" + ">" + tempspec$
OPEN tempspec$ FOR INPUT AS #3
DIM new$(80)
i = 0
DO UNTIL EOF(3)
LINE INPUT #3, entryline$
    IF entryline$ <> "" THEN
        TestCh$ = LEFT$(entryline$, 1)
        IF TestCh$ <> " " THEN
            EntryName$ = RTRIM$(LEFT$(entryline$, 8))
            EntryExt$ = RTRIM$(MID$(entryline$, 10, 3))
            IF EntryExt$ <> "" THEN
                GetEntry$ = EntryName$ + "." + EntryExt$
            ELSE
                GetEntry$ = EntryName$
            END IF
            i = i + 1
            fil$(i) = dirr$ + GetEntry$
        END IF
    END IF
LOOP
CLOSE #3
KILL "DUMMY.FIL"
nf = i
1550 PRINT " "
PRINT "THESE ARE THE FILES YOU ENTERED;"
PRINT
FOR COUNT = 1 TO nf
COUNT$ = STR$(COUNT)
PRINT COUNT$; " ..... "; fil$(COUNT)
NEXT COUNT
PRINT
INPUT "DO YOU WISH TO RE-ENTER ANY OF THESE?(Y/N)", RENTER$
IF RENTER$ = "N" OR RENTER$ = "n" GOTO 1690
PRINT "WHAT IS THE NUMBER OF THE FILE NAME TO"

```

Figure 49 (continued). FLWRDCT Program.

```

INPUT "BE RE-ENTERED? ", KJH
INPUT "WHAT IS NEW NAME OF FILE? ", fil$(KJH)
GOTO 1550
REM
REM *****
REM
REM   Extract information from data file name
REM
REM *****
REM
1690 IF TUNNEL$ = "2" GOTO 1910
'
'   Routine for low velocity tunnel
'
FOR II = 1 TO nf
  CHQ$ = LEFT$(fil$(II), 2)
  IF CHQ$ = "A:" THEN QHC$ = RIGHT$(fil$(II), 10) ELSE QHC$ = fil$(II)
  TMPOA$ = LEFT$(QHC$, 7)
  TMPOB$ = RIGHT$(QHC$, 2)
  TMPOC$ = LEFT$(TMPOB$, 1)
  TMPO$ = TMPOA$ + TMPOC$ + ".DAT"
  TMPOD$ = RIGHT$(TMPOA$, 2)
  TMPOE$ = TMPOD$ + TMPOB$ + ".DAT"
  GRAPH$(II) = TMPO$
  IF G$ = "2" THEN GRAPH$(II) = TMPOE$
  RTHEO$ = RIGHT$(TMPO$, 11)
  K$(II) = "T" + RTHEO$
NEXT II
PN = VAL(LEFT$(QHC$(1), 2))
FOR i = 1 TO nf
  SPCHK$ = RIGHT$(fil$(i), 5)
  SP(i) = VAL(RIGHT$(fil$(i), 5))
  TYPE$(i) = STR$(SP(i)) + " M/S"
NEXT i
GOTO 2250
'
'   Routine for SWT
'
1910 FOR II = 1 TO nf
  CHKFIL$ = LEFT$(fil$(II), 2)
  TFIL$(II) = fil$(II)
  IF CHKFIL$ = "A:" THEN TFIL$(II) = RIGHT$(fil$(II), 12)
  TMPO$ = RIGHT$(TFIL$(II), 9)
  TMPOA$ = RIGHT$(TFIL$(II), 3)
  TMPOB$ = LEFT$(TMPO$, 5)
  GRAPH$(II) = TMPOB$ + TMPOA$ + ".DAT"

```

Figure 49 (continued). FLWRDCT Program.

```

      TMPOC$ = RIGHT$(GRAPH$(II), 11)
      K$(II) = "T" + TMPOC$
      PO$(II) = VAL(RIGHT$(TFIL$(II), 3))
      P$ = STR$(PO$(II))
      C$(II) = LEFT$(TFIL$(II), 3)
      SRSR$ = LEFT$(TFIL$(II), 5)
      PN = VAL(LEFT$(SRSR$, 2))
      SRSR$ = RIGHT$(TFIL$(II), 5)
      MACH$ = VAL(LEFT$(SRSR$, 1))
      IF MACH$ < 4 GOTO 2100
      MACH$ = .5
2100  MACH$ = STR$(MACH$)
      SRSR$ = LEFT$(TFIL$(II), 7)
      TEMP = VAL(RIGHT$(SRSR$, 2))
      IF TEMP < 57 THEN TEMP = TEMP + 100
      TEMP$ = STR$(TEMP)
      TIO$(II) = TEMP
      TR(II) = 5 / 9 * (TEMP - 32)
      TYPE$(II) = "M=" + MACH$ + ", TO=" + TEMP$ + ", PO=" + P$
NEXT II
REM
REM *****
REM
REM **** BEGIN MAIN LOOP ****
REM
REM *****
REM
REM      II is the counter for file number 1 to file number NF
REM
2250 FOR II = 1 TO nf
  REM
  REM      Initialize all variables, that need to be, to zero
  REM
  REM      I is the counter for each current in file II
  REM
  FOR i = 1 TO 50
    R(i) = 0
    W(i) = 0
  NEXT i
  T = 0
  REM      INPUT RAW DATA FROM FILE
  OPEN "I", #1, fil$(II)
  FOR i = 1 TO N
    INPUT #1, J(i), J1(i), C(i), R1(i)
    T = T + J(i)
  NEXT i

```

Figure 49 (continued). FLWRDCT Program.

```

CLOSE #1
REM   Compute average temperature (TR(II)) for file II
IF TUNNEL$ = "2" GOTO 2570
TR(II) = T / N
IF INFILE$ = "Y" OR INFILE$ = "y" GOTO 2570
TR(II) = ROOHTMP
REM
REM   CORRECT RAW DATA FOR LINE RESISTANCE
REM   AND CALCULATE POWER.
REM   ALSO GENERATE SUMS FOR LEAST SQUARES FIT ROUTINE
REM
2570 RECOV(II) = RECOV(II - 1)
DUMMY = .01
2590 ACTUALT = (TR(II) + 273.15) * RECOV(II) - 273.15
RLINE = RL + .138 * (1 + .003927 * ACTUALT)
G1 = 0: G2 = 0: G3 = 0: G4 = 0: G5 = 0: G6 = 0: G7 = 0
REM
REM   Check to see if line resistance value has converged.
REM   (recall, line res. depends on temp. and the temp.
REM   calculations depends on the line resistance.)
REM
IF ABS(DUMMY - RLINE) < .0001 THEN GOTO 3000
DUMMY = RLINE
REM
REM   Start with least squares routine.
REM
FOR i = 1 TO N
R(i) = R1(i) - RLINE
W(i) = (C(i) ^ 2) * R(i)
LET G1 = G1 + W(i)
LET G2 = G2 + (W(i) ^ 2)
G3 = G3 + (W(i) ^ 3)
G4 = G4 + (W(i) ^ 4)
G5 = G5 + R(i)
G6 = G6 + R(i) * W(i)
G7 = G7 + (W(i) ^ 2) * R(i)
NEXT i
REM   Continue with least squares routine.
D = N * G2 * G4 + 2 * G1 * G2 * G3 - G2 - G2 ^ 3 - N * (G3 ^ 2)
D = D - (G1 ^ 2) * G4
D0 = G5 * G2 * G4 + G2 * G3 * G6 + G1 * G3 * G7 - (G2 ^ 2) * G7
D0 = D0 - (G3 ^ 2) * G5 - G1 * G4 * G6
D1 = N * G4 * G6 + G1 * G2 * G7 + G2 * G3 * G5 - (G2 ^ 2) * G6
D1 = D1 - N * G3 * G7 - G1 * G4 * G5
D2 = N * G2 * G7 + G1 * G3 * G5 + G1 * G2 * G6 - (G2 ^ 2) * G5
D2 = D2 - N * G3 * G6 - (G1 ^ 2) * G7

```

Figure 49 (continued). FLWRDCT Program.

```

A0 = D0 / D
A1 = D1 / D
A2 = D2 / D
REM
REM      Compute temperature measured by probe and the
REM      temperature recovery factor.
REM
te = (-AL + (AL ^ 2 + 4 * BTA * (A0 / RR - 1)) ^ .5) / (2 * BTA)
RECOV(II) = (te + 273.15) / (TR(II) + 273.15)
REM
REM      Now go back to where the line resistance was
REM      last calculated and calculate it again with the
REM      new temperature recovery factor.
REM
GOTO 2590
3000 FOR i = 1 TO N
  G8 = G8 + (1 - (A0 + A1 * W(i) + A2 * (W(i) ^ 2)) / R(i)) ^ 2
NEXT i
G9 = SQR(G8) / N
IF TUNNEL$ = "2" GOTO 3200
REM
REM      Compute Reynolds numbers for low speed tunnel
REM
TACT = TR(II) + 273.15
TTEMP = TACT
TACT = TACT * (9 / 5)
PRES = 133.3356 * ATMP
R = 287
RHO = PRES / (TTEMP * R)
VISC = 1.09E-06 * (((TACT ^ 1.5)) / (TACT + 198.6))
REY(II) = (RHO * SP(II) / VISC) / 100
GOTO 3320
REM
REM      Compute Reynolds numbers for supersonic wind tunnel
REM
3200 TT(II) = (TT0(II) + 459.67) / (1 + .2 * MACH# ^ 2)
TT(II) = TT(II) * 5# / 9#
P(II) = P0(II) * (1 + .2 * MACH# ^ 2) ^ (-3.5)
MU# = (-5.7971299D-11 * TT(II) + .00000012349703) * TT(II)
MU# = (MU# - .000117635575) * TT(II)
MU# = (MU# + 9.080124000000001D-02) * TT(II) - .9860100000000001#
MU# = MU# * 10# ^ (-6#)
V# = MACH# * SQR(1.4# * 287# * TT(II))
RE#(II) = P(II) * (133.322368421# / 28700#) * V# / TT(II) / MU#
REY(II) = (INT(RE#(II) * 1000)) / 1000
3320 FOR i = 1 TO N

```

Figure 49 (continued). FLWRDCT Program.

```

      W1(i) = (W(i) * A1) / A0
      R2(i) = (R(i) / A0) - 1
    NEXT i
    CRITCUR(II) = SQR(1 / A1)
    REM "CONSTANT C IN R=Re+W/Ic2+CW2/Ic2 (PER HILLIWATT)=";1000*(A2/A1)
    te# = te + 273.15
    ke# = -.002276501# + .00012598485# * te#
    ke# = ke# - .00000014815235# * te# ^ 2 + 1.73550646D-10 * te# ^ 3
    ke# = ke# - 1.066657D-13 * te# ^ 4 + 2.47663035D-17 * te# ^ 5
    ke = ke# * 100000
    NU = 10 * AL * RR * (1 + 2 * BTA * te / AL) / (ke * A1)
    NUSLT(II) = NU
    TM = (-AL + (AL ^ 2 + 4 * BTA * (R(N) / RR - 1)) ^ .5) / (2 * BTA)
    D = (A0 * A2) / (A1 ^ 2)
    CRITCUR(II) = SQR(1 / A1)
    CONSTD(II) = D
    REM *****
    REM      Routine for hard copy print-out
    REM *****
    IF F$ = "N" OR F$ = "n" GOTO 3910
    LPRINT "RESULTS USING THE ONESHOT1 PROGRAM"
    LPRINT "-----"
    LPRINT
    LPRINT "ONE-SHOT CALIBRATION OF PROBE NO. "; PN
    LPRINT "PROBE CALIBRATION DONE ON "; C$; " BY "; B$
    LPRINT "CALIBRATION FILENAME:"; fil$(II)
    LPRINT "TYPE OF CALIBRATION:"; TYPE$(II)
    LPRINT "LINE RESISTANCE (OHMS) WAS "; RL
    LPRINT "NUMBER OF CURRENTS USED WERE "; N
    LPRINT "INPUTED TEMPERATURE COEFF. OF RESISTANCE (PER C): "; AL
    LPRINT "RESISTANCE AT 0 DEG. C WAS "; RR; " OHMS"
    LPRINT "AMBIENT TEMPERATURE (DEG C) WAS: "; TR
    LPRINT
    LPRINT "TABLE I OF RESULTS"
    LPRINT "-----"
    LPRINT
    LPRINT "I(MA)", "W(MWATTS)", "R(OHMS)", "w(N/D POWER)", "r(OVERHEAT)"
    FOR i = 1 TO N
    LPRINT C(i), W(i) / 1000, R(i), W1(i), R2(i)
    NEXT i
    LPRINT
    LPRINT "SUMMARY OF RESULTS"
    LPRINT "-----"
    LPRINT
    LPRINT "RESISTANCE AT ZERO CURRENT (OHMS)= "; A0
    LPRINT "CRITICAL CURRENT Ic (MA)= "; SQR(1 / A1)

```

Figure 49 (continued). FLWRDCT Program.

```

CRITCUR(II) = SQR(1 / A1)
LPRINT "CONTANT C IN R=Re+W/Ic2+CW2/Ic2 (PER MILLIWATT)= "; 1000 * (A2 / A1)
LPRINT "FRACTIONAL STANDARD DEVIATION OF R-W CURVE-FIT= "; G9
LPRINT "FILM TEMPERATURE AT ZERO CURRENT TE (DEG C)= "; te
LPRINT "THERMAL CONDUCTIVITY AT ZERO CURRENT KE (CGS PER C)= "; ke
LPRINT "TEMPERATURE RECOVERY FACTOR ETA=TE/TR= "; (te + 273) / (TR(II) + 273)
LPRINT "COMPOUND NUSSELT NUMBER AT ZERO CURRENT NU (PER CM)= "; NU
LPRINT "CONSTANT D IN r=w+Dw2= "; D
LPRINT
LPRINT "FILM TEMPERATURE REACHED AT MAXIMUM POWER WAS (DEG C)=", TM
LPRINT "Note: maximum allowed Pt film temperature is 1200 C"
3910 IF G$ = "N" OR G$ = "n" GOTO 4040
OPEN "D", #2, GRAPH$(II)
L$ = " "
FOR i = 1 TO N
IF TUNNEL$ = "2" GOTO 3990
IF i = N THEN L$ = TYPE$(II)
WRITE #2, L$, W(i) / 1000, R(i), W1(i), R2(i), 1 - (R2(i) / W1(i))
GOTO 4000
3990 WRITE #2, C(i), W(i) / 1000, R(i), W1(i), R2(i), 1 - (R2(i) / W1(i))
4000 NEXT i
CLOSE #2
PRINT
PRINT "GRAPHICS FILE "; GRAPH$(II); " HAS BEEN LOADED"
4040 IF J$ = "N" OR J$ = "n" GOTO 4120
OPEN "D", #3, K$(II)
FOR IN = 1 TO N
DUMMY = 1 - W1(IN) / R2(IN)
WRITE #3, W1(IN), R2(IN), W1(IN) / R2(IN), DUMMY / CONSTD(II)
NEXT IN
CLOSE #3
PRINT "THEORETICAL FILE "; K$(II); " HAS BEEN LOADED"
4120 NEXT II
IF REYFILE$ = "N" OR REYFILE$ = "n" GOTO 4220
OPEN "D", #1, FINAL$
OPEN "D", #2, FINAL2$
FOR II = 1 TO nf
NBCOND = 4.1 - .00569 * TR(II) + 4.61E-06 * TR(II) ^ 2
NUCONV = NUSLT(II) - NBCOND
WRITE #1, REY(II), NUSLT(II), RECOV(II), CONSTD(II), CRITCUR(II), SQR(REY(II)), NUCONV
WRITE #2, REY(II), NUSLT(II), RECOV(II), CONSTD(II), CRITCUR(II), SQR(REY(II)), NUCONV
NEXT II
CLOSE
4220 END

```

Figure 49 (continued). FLWRDCT Program.

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REFERENCES CITED

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