



Heat transfer characteristics of small configuration hot-wires in low Reynolds number subsonic and supersonic air flows
by Peter Sean Hertel

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering
Montana State University
© Copyright by Peter Sean Hertel (1985)

Abstract:

Heat loss measurements from 20 gin. and 50 gin. hot-wires with aspect ratios between 95 and 420 were obtained in air flows in the range $0 < 3.0$ and $0.1 < 10$. Measurements in compressible flows were obtained in the throat region and test section of the Montana State University Supersonic Wind Tunnel. An alternative theory suggested by Demetriades is used for determination of the Nusselt number and recovery temperature of the hot-wire. The heat loss measurements were corrected for conductive end losses to the hot-wire supports and compared to the correlations of Dewey and Collis and Williams. The results indicate that flow conditions in the vicinity of lower aspect ratio wires are altered so that heat loss from the wire may not be correctly determined from theory. High aspect ratio hot-wires converge toward Dewey's correlation for $M > 2$; however, similar hot-wires may behave differently and individual flow calibration for each wire is necessary for quantitative flow measurements. Nusselt number measurements in low velocity flow fall below the correlation of Collis and Williams by 5 to 20 percent. Recovery temperature measurements in $M=3$ flows vary considerably (30 %) for probes under similar flow conditions and show no distinct dependence on either SI/d or Kn . Recovery temperatures of the hot-wires in low velocity flows indicated the stagnation temperature within 2.5 %.

HEAT TRANSFER CHARACTERISTICS OF SMALL CONFIGURATION HOT-WIRES
IN LOW REYNOLDS NUMBER SUBSONIC AND SUPERSONIC AIR FLOWS

by

Peter Sean Hertel

A thesis submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Mechanical Engineering

MONTANA STATE UNIVERSITY
Bozeman, Montana

March 1985

MAIN LIB.
N378
H442
cop. 2

ii

APPROVAL

of a thesis submitted by

Peter Sean Hertel

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.

2/26/85
Date

A. K. Kmetz
Chairperson, Graduate Committee

Approved for the Major Department

2-27-85
Date

Samuel K. Kmetz
Head, Major Department

Approved for the College of Graduate Studies

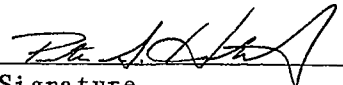
~~2-27-85~~
Date

M. J. Wake
Graduate Dean

STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a master's degree at Montana State University, I agree that the Library shall make it available to borrowers under rules of the Library. Brief quotations from this thesis are allowable without special permission, provided that accurate acknowledgement of source is made.

Permission for extensive quotation from or reproduction of this thesis may be granted by my major professor, or in his absence, by the Director of Libraries when, in the opinion of either, the proposed use of the material is for scholarly purposes. Any copying or use of the material in this thesis for financial gain shall not be allowed without my written permission.


Signature

19 FEB, 1985
Date

ACKNOWLEDGEMENT

The author is indebted to the following for their contributions to this investigation.

His advisor, Dr. Anthony Demetriades, for his able guidance throughout the investigation.

Glenn McCullough and John Rompel for their technical assistance with the laboratory equipment.

Pat Vowell and Gordon Williamson of the machine shop for their assistance with fabrication of equipment used in this investigation.

Drs. Ron Mussulman and Harry Townes for their support as committee members.

The Department of Mechanical Engineering and the Engineering Experimental Station for financial assistance.

Special thanks to family and friends for their support and encouragement throughout the course of this graduate program.

TABLE OF CONTENTS

	page
LIST OF FIGURES	viii
NOMENCLATURE	x
ABSTRACT	xiii
1. INTRODUCTION	7
2. THEORETICAL REVIEW	7
Incompressible Flows	10
Compressible Flows	11
Free-Molecule Theory	14
End loss correction	17
Recovery temperature	21
3. EXPERIMENTAL APPARATUS AND PROCEDURE	22
Hot-Wire Probes	22
Supersonic Wind Tunnel	24
Low Velocity Tunnel	27
Flow Measurement Apparatus	28
Calibration Oven	30
Data Acquisition	32
Experimental Procedure	34
4. RESULTS	40
General	40
Nusselt Number	40
End Loss Correction	52
Recovery Temperature	52
5. CONCLUSION	64
APPENDICES	66
APPENDIX A - OVEN CALIBRATION DATA REDUCTION CODE	67
APPENDIX B - FLOW CALIBRATION DATA REDUCTION CODE: INCOMPRESSIBLE FLOW	70
APPENDIX C - FLOW CALIBRATION DATA REDUCTION CODE: COMPRESSIBLE FLOWS	73
APPENDIX D - HOT-WIRE RESISTANCE-TEMPERATURE COEFFICIENTS	77

TABLE OF CONTENTS--Continued

APPENDIX E - FLOW CALIBRATION RESULTS	79
REFERENCES CITED	96

LIST OF FIGURES

	Page
1. Correlation of end loss corrected hot-wire characteristics (reproduced from {3})	3
2. End loss corrected heat transfer data, MSU/SWT catalog data ($M > 3.0$)	5
3. Hot-wire characteristic data, incompressible flow (reproduced from {15})	12
4. Hot-wire characteristics, supersonic flow	13
5. Hot-wire characteristics, subsonic flow (reproduced from {15}).	15
6. Normalized recovery factor data (reproduced from {3})	21
7. Hot-wire probe configuration	23
8. Photographs of hot-wire element	23
9. Major components of MSU/SWT (reproduced from {25}).	25
10. Test area of MSU/SWT (reproduced from {25})	25
11. Variation of M with axial location in MSU/SWT nozzle	26
12. Low velocity tunnel (LVT)	27
13. Probe configuration, MSU/SWT ($M=3$).	28
14. Probe configuration, MSU/SWT ($.18 < M < 2.2$).	29
15. Probe configuration, LVT ($M=0$).	30
16. Oven calibration equipment.	31
17. Data acquisition equipment diagram	33
18. Oven calibration overheat traverse data	35
19. Resistance-temperature correlation obtained from intercept data ($R(W=0)$) of figure 18.	36
20. Typical flow calibration overheat traverse data	38

LIST OF FIGURES---Continued

21.	End loss corrected heat transfer data; $M=3$, $d=20 \mu\text{in.}$	42
22.	End loss corrected heat transfer data; MSU/SWT catalog data; $M=3$, $d=20 \mu\text{in.}$	43
23.	End loss corrected heat transfer data; $M=3$, $d=50 \mu\text{in.}$	44
24.	Support prong proximity effect on Nusselt number (normalized with Dewey's correlation)	47
25.	End loss corrected heat transfer data; $.2 < M < 1$, $d=20 \mu\text{in.}$	48
26.	End loss corrected heat transfer data; Probe 29/8	49
27.	End loss corrected heat transfer data; $M=0$, $d=20 \mu\text{in.}$	50
28.	End loss corrected heat transfer data; $M=0$, $d=50 \mu\text{in.}$	51
29.	Summary of heat transfer data	53
30.	Theoretical end loss correction correlation	54
31.	Typical end loss correction data; $M=3$, $d=20 \mu\text{in.}$	55
32.	Typical end loss correction data; $M=3$, $d=50 \mu\text{in.}$	56
33.	Typical end loss correction data; $M=0$, $d=20 \mu\text{in.}$	57
34.	Typical end loss correction data; $M=0$, $d=50 \mu\text{in.}$	58
35.	Recovery temperature data; $M=3$, $d=20 \mu\text{in.}$	60
36.	Recovery temperature data; $M=3$, $d=50 \mu\text{in.}$	61
37.	Recovery temperature data; $M=0$, $d=50 \mu\text{in.}$	62
38.	Recovery temperature data; $M=0$, $d=20 \mu\text{in.}$	63

NOMENCLATURE

<u>Symbol</u>	<u>Description</u>
C_D	Drag coefficient
d, D	Wire diameter
$f(s_1), g(s_1)$	Functions of molecular speed ratio s_1
Gr	Grashoff Number
h	Heat transfer coefficient
i	Current (amps)
k	Thermal conductivity
k_b	Boltzmann constant, 5.66×10^{-26} ft-lbs/°F per molecule
Kn	Knudsen number
ℓ, L	Wire length
LVT	Low velocity tunnel
M	Mach number
MSU	Montana State University
Nu	Nusselt number
Nu_m	Measured Nusselt number (not corrected for end loss)
P	Static pressure
P_d	Dynamic pressure ($\gamma PM^2/2$)
Pe'	Peclet' number
P_o	Stagnation pressure
P_{o2}	Pitot pressure
Pr	Prandlt number
q_c	Convective heat transfer

NOMENCLATURE--Continued

<u>Symbol</u>	<u>Description</u>
R	Wire resistance
Re	Reynolds number
s_1	Molecular speed ratio ($\sqrt{\gamma/2} M$)
S	Dimensionless end loss parameter
SWT	Supersonic wind tunnel
T	Temperature
W	Power (Watts)
α	Thermal accomodation coefficient
α_r	Temperature-resistance coefficient
γ	Ratio of specific heats
γ_e	Euler's constant (.577)
η	Recovery factor (T_{aw}/T_o)
η_c	Experimental continuum recovery factor
η_f	Theoretical free-molecule recovery factor
η_w	Measured wire recovery factor
η	Nondimensional recovery factor
σ_{yp}	Yield stress of hot-wire material
τ	Dimensionless overheat temperature $(T-T_{aw})/T_{aw}$
ψ_N	Nusselt number end loss correction factor
$()_a$	air property
$()_{aw}$	evaluated at equilibrium temperature ($i=0$)
$()_m$	measured value
$()_r$	evaluated at arbitrary reference temperature

NOMENCLATURE--Continued

<u>Symbol</u>	<u>Description</u>
$()_o$	evaluated at stagnation conditions
$()_{o2}$	evaluated at conditions behind a normal shock
$()_\infty$	free stream property
$()_s$	pertaining to the hot-wire supports

ABSTRACT

Heat loss measurements from 20 μ in. and 50 μ in. hot-wires with aspect ratios between 95 and 420 were obtained in air flows in the range $0 < M < 3.0$ and $0.1 < Re < 10$. Measurements in compressible flows were obtained in the throat region and test section of the Montana State University Supersonic Wind Tunnel. An alternative theory suggested by Demetriades is used for determination of the Nusselt number and recovery temperature of the hot-wire. The heat loss measurements were corrected for conductive end losses to the hot-wire supports and compared to the correlations of Dewey and Collis and Williams. The results indicate that flow conditions in the vicinity of lower aspect ratio wires are altered so that heat loss from the wire may not be correctly determined from theory. High aspect ratio hot-wires converge toward Dewey's correlation for $M > 2$; however, similar hot-wires may behave differently and individual flow calibration for each wire is necessary for quantitative flow measurements. Nusselt number measurements in low velocity flow fall below the correlation of Collis and Williams by 5 to 20 percent. Recovery temperature measurements in $M=3$ flows vary considerably (30 %) for probes under similar flow conditions and show no distinct dependence on either ℓ/d or Kn . Recovery temperatures of the hot-wires in low velocity flows indicated the stagnation temperature within 2.5 %.

CHAPTER 1

INTRODUCTION

Hot-wire anemometers have become an important instrument for the determination of flow properties and are especially suitable for measuring turbulence. This application utilizes the relation between heat-loss from the hot-wire and the mean properties of flow and therefore requires the measurement of the Nusselt number, Nu .

In general, the Nusselt number dependence for an infinite cylinder in a transverse flow may be expressed in terms of dimensionless parameters as

$$Nu = Nu(Re, M, Pr, Gr, \tau_w) \quad (1)$$

where Re , M , Pr , and Gr are the Reynolds number, Mach number, Prandlt number, and Grashoff number and $\tau_w = (T_w - T_{aw})/T_{aw}$ is the temperature loading. Equation (1) neglects radiation effects which have been shown to be negligible up to high temperature loading. The complexity of (1) has prevented the establishment of a universal relation, however, for special applications (1) may be simplified. For measurements in air flows the dependence of Nu on Prandlt number may be eliminated ($Pr = \text{constant}$). Further, if we consider only forced convection for zero overheat ($\tau_w = 0$), equation (1) may be expressed as

$$Nu = Nu(Re, M) \quad (2)$$

In actual applications, the length of the hot-wire must be restricted for greater resolution and to prevent wire breakage. For these wires, the infinite wire solution is no longer valid. For a finite hot-wire, a

percentage of heat is lost by axial conduction to the supports and the Nusselt number is dependent on an additional parameter, S , such that

$$Nu_m = Nu(Re, M, S) \quad (3)$$

where

$$S = \frac{\lambda}{d} \left(\frac{k_a Nu}{k_w} \right)^{1/2}$$

The standard practice is to evaluate the Nusselt number assuming all heat transfer from the hot-wire to be convective and applying a correction factor, $\psi_N(S)$, to account for the losses by conduction. Thus a measured Nusselt number is evaluated from

$$\lambda \pi k_a Nu_m \Delta T = i^2 R_w \quad (4)$$

and $Nu_m(Re, M, S)$ is then corrected to obtain the actual Nusselt number $Nu(Re, M, S=\infty)$ from

$$Nu(Re, M, S=\infty) = \psi_N(S) Nu_m(Re, M, S) \quad (5)$$

The early work of Betchov [1] and more recently studies by Kovasznyai and Tormark [2], Dewey [3], and Behrens [4] addressed the heat transfer from finite wires using the above procedure. The heat loss correlation presented by Dewey for the special case

$$Nu_o = Nu_o(Re_o, M, S=\infty, \tau=0) \quad (6)$$

where the subscript "o" refers to the evaluation of the air properties μ and k at the stagnation temperature, was determined utilizing (4) and (5) and remains the state-of-the-art for low Reynolds number air flows. Dewey's correlation, shown in figure 1, is based on his measurements from 100 μ in. (.00254 mm) hot-wires and on supplemental data of Laufer and McClellan [5], Cybulski and Baldwin [6], Vrebalovich [7], and others, and the theory of Stalder, Goodwin, and Creager [8] and Cole and Roshko [9]. An outstanding feature of Dewey's correlation is an

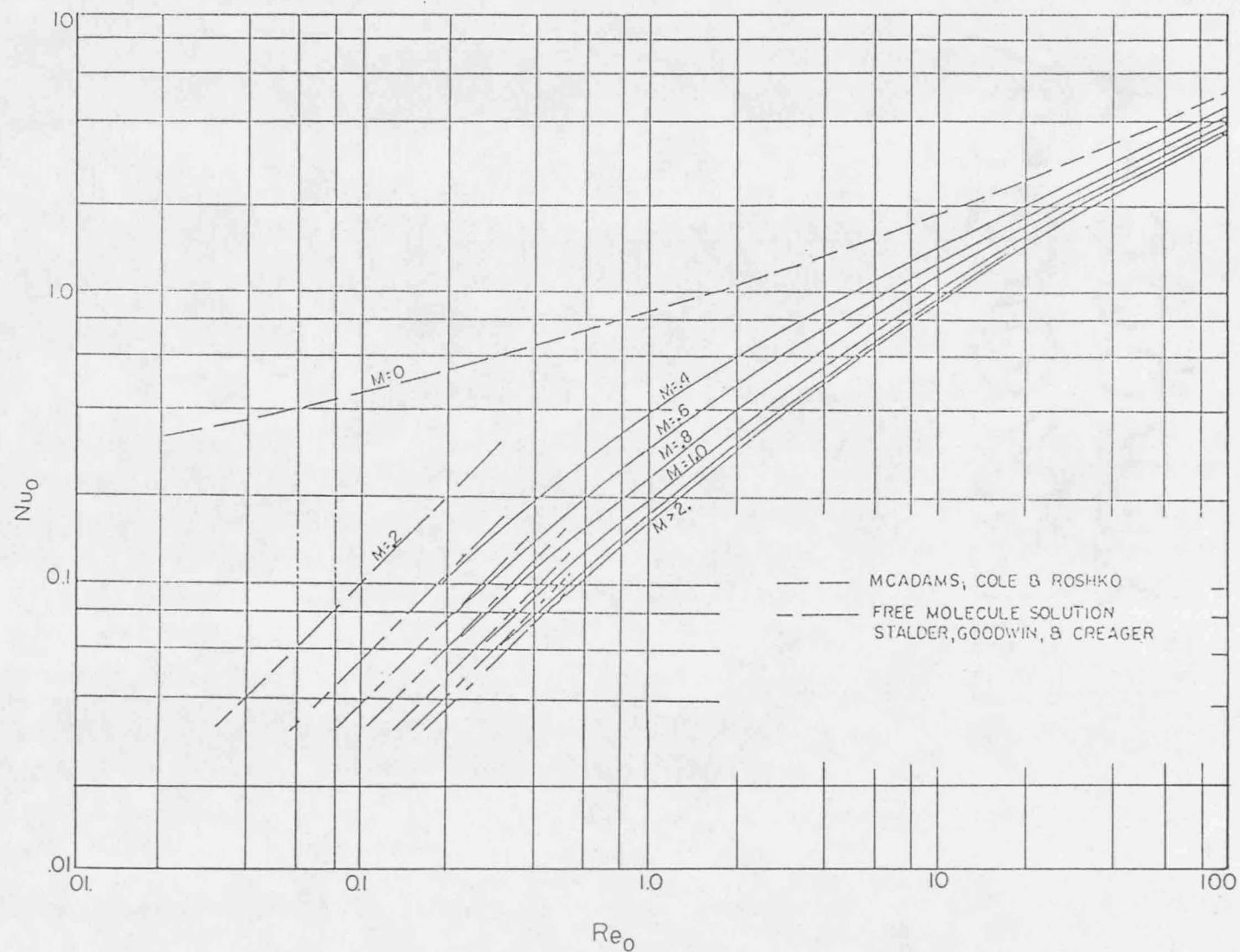


Figure 1. Correlation of end loss corrected hot-wire characteristics (reproduced from {3}).

independence of Nu_0 on M for $M > 2.0$.

For actual applications, it is desirable to utilize the above heat transfer correlation to predict properties of flow. If (5) and (6) are known, the flow Reynolds Number may then be predicted using Dewey's correlation. (note that additional measurements of flow properties are required for the determination of the mean velocity.)

Figure 1 is in some ways restrictive in that (1) the data are from hot-wires of relatively large diameter alleviating problems of quality control associated with smaller configuration probes, (2) the data are limited to larger aspect ratios where the correction $\psi_N(S)$ was relatively small, and (3) there is insufficient data to guarantee the correlation over the entire range of Re_0 and M . Therefore, additional data are needed for smaller diameter wires of a wide range of aspect ratios in low Reynolds number flows in the range $M < 3$.

Finite hot-wire data ($Nu_m(Re_0, M > 3.0, S)$) obtained from a number of sources and compiled by Demetriades [10] (hereafter referred to as MSU/SWT Catalog data) were corrected using (5) in an attempt to verify Dewey's correlation for $M > 2.0$. These data, shown in figure 2, differ from the data of Dewey's correlation in that (1) the heat loss measurements were not the focus of investigation and the data were obtained under more severe conditions, and (2) the hot-wires were of smaller diameter and aspect ratio. Figure 2 shows that a fit of these data to Dewey's correlation is non-existent for $Re_0 < 1.5$ leading to the conclusion that (5) is invalid or that some additional factor has been overlooked such as the proper measurement of $Nu_0(Re_0, M, S)$ or the aerodynamics of the miniature probe configurations of the hot-wires used

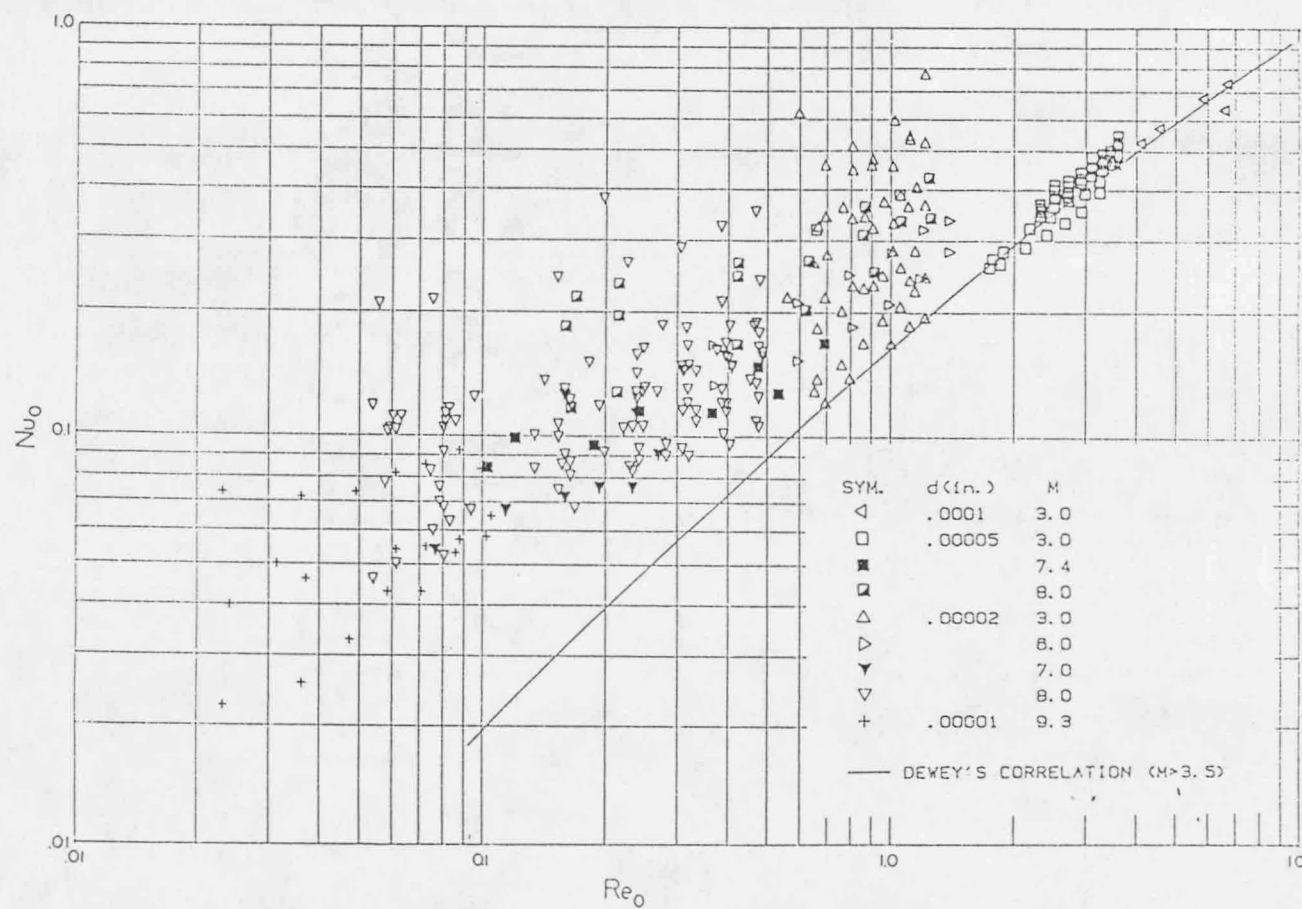


Figure 2. End loss corrected heat transfer data; MSU/SWT catalog data ($M > 3$).

in {10}.

Considering the preceding discussion, the problem of predicting fluid properties from the heat transfer characteristics, $Nu_0(Re_0, M, S)$, of finite hot-wires of the type used in {10} is relevant for actual applications in steady and unsteady flows but has not yet been fully examined. This investigation, conducted at the Montana State University Supersonic Wind Tunnel Laboratory, was undertaken to provide additional heat loss data for smaller diameter hot-wires over a wide range of ℓ/d for low Reynolds numbers in the range $0 < M < 3$ and to present an alternative technique for the actual measurement of the Nusselt number and recovery temperature.

CHAPTER 2

THEORETICAL REVIEW

This investigation is concerned with the heat transfer characteristics of fine wires and, therefore, requires the evaluation of the Nusselt number and recovery temperature of the hot wire. Assuming negligible heat loss by radiation and natural convection, the Nusselt number may be expressed as

$$Nu = Nu(Re, M, S, \tau) \quad (7)$$

Flow measurement based on the characteristics of an unheated wire ($\tau=0$) further simplifies the correlation as does the use of (5) which theoretically eliminates the dependence on S . Thus, in order to utilize figure 1 in actual applications, the correction factor $\psi_N(S)$ must be accurately predicted.

Consider the lumped evaluation of the heat loss from the hot-wire

$$i^2 R_w = \pi \ell k_a Nu_o \Delta T - \frac{\pi d^2}{2} k_w \left. \frac{dT}{dx} \right|_{x=\ell/2} \quad (8)$$

where $\Delta T = T_w - T_{aw}$. Equation (8) may be simplified using a rough approximation of $dT/dx = -(T_w - T_{aw})/(\ell/2)$ where the support temperature is assumed equal to the equilibrium temperature. This is a valid assumption considering the relative size of the supports with respect to the hot-wire. Equation (8) then reduces to

$$i^2 R = \ell \pi k_a Nu_m \Delta T \quad (9)$$

where

$$Nu_m = Nu_o (1 + 1/S^2)$$

Although the above analysis provides only a poor estimate of the

magnitude of conductive losses, it is useful in that it provides justification for equation (4) (i.e. measurement of both convection and conduction losses using a single convective type relation) and presents the parameter S on which the correction factor $\psi_N(S)$ is dependent. Axial conduction and the end loss correction factor are addressed in more detail later in this chapter.

The mechanisms of energy transfer between the hot-wire and the gas vary depending on the physical characteristics of the fluid and are generally separated according to the continuum, slip, and free-molecule flow regions.

In continuum flow the heat transfer is, for the most part, a function of the Reynolds number (indicating viscous effects) and the Mach number (indicating effects due to compressibility). Thus, the transfer of energy is related to the drag on the wire surface due to viscosity and the conversion of kinetic energy into thermal energy. At low velocities (incompressible flow) the energy associated with the velocity is less influential. As the velocity increases, the compressible effects become more dominant and a large Mach number dependence is evident. At $M=1$, a bow shock forms ahead of the wire, and the flow field in the vicinity of the wire again becomes subsonic. Depending on the strength of this shock, we expect the hot-wire to behave as in the subsonic case. An unheated cylinder placed in a low velocity incompressible continuum flow will attain a temperature equal to the static temperature of the fluid while at high velocities the recovery temperature of the cylinder will approach or equal the stagnation temperature of the flow.

For smaller diameter wires and low density (rarefied) gasses, the flow field in the vicinity of the wire no longer behaves as a continuum and the thermal behavior of the hot-wire is dependent on the molecular structure of the fluid. The approach to free-molecule flow is indicated by the Knudsen number; the ratio of the mean free molecular path of the fluid molecules to the cylinder diameter ($Kn=\lambda/d$). Fully developed free molecule flow has been shown by Stalder et al. to exist at $Kn=2.0$. The energy transferred between the hot-wire and the fluid is in the form of molecular energy incident to and re-emitted from the surface of the cylinder. In free-molecule flow, the Reynolds number dependency reflects density effects rather than viscosity effects of continuum flow while the Mach number reflects effects due to free stream velocity rather than compressibility effects. Experimental evidence and theory have shown that the recovery temperature of an unheated wire in free-molecule flow will exceed the stagnation temperature of the wire. The theory of hot-wire behavior in free-molecule flow is addressed later in this chapter.

Most supersonic and compressible subsonic hot-wire data falls in the slip flow region, that is, the region between continuum and free-molecule flow. In this region, the boundary layer associated with fully developed continuum flow is altered so that a non-zero velocity occurs at the surface of the hot-wire. In slip flow, the fluid retains some of its continuum characteristics while also exhibiting free-molecular behavior. The heat transfer behavior of the hot-wire in the slip flow region will therefore show dependencies both on Mach number and Reynolds number, the magnitude of which are dependent on the magnitude of the

Knudsen number.

Evaluation of (4) is non-restrictive as to the type of flow (i.e. continuum, slip, free-molecule, compressible, or incompressible flows) as long as the heat transfer coefficient is defined by $q_c = h\Delta T$ where q_c is the convective heat transfer. The value of h , however, is heavily dependent on the flow parameters Re , M , and Kn .

Incompressible Flows

The heat transfer from cylinders in low velocity incompressible air flow is well represented at high Re (see McAdams [11]), however, hot-wire data at low Re ($Re < 10$) has been obtained only by few investigations.

There is some disagreement among researchers as to what conditions the Reynolds number and Nusselt number should be evaluated. The most common practice is to evaluate the air viscosity and thermal conductivity at the free stream temperature or the mean (film) temperature between the free stream and the hot-wire. For an unheated wire, the film temperature is equal to the free stream temperature.

One of the first and most widely applied relations used in incompressible hot-wire anemometry was developed by King [12]. King's law,

$$Nu = 0.318 + 0.690(Re)^{1/2} \quad (9)$$

was determined theoretically assuming two-dimensional inviscid incompressible flow and constant heat flux over the boundary. King's relation has been used by many in slightly modified forms retaining the square-root dependence on Reynolds number with empirically determined

constants. Cole and Roshko obtained the relation

$$2/\text{Nu} = \ln(8/\text{Pe}') - \gamma_e \quad \text{Pe}' = \text{Re} \cdot \text{Pr} \quad (10)$$

based on the Oseen viscous flow theory valid for the limit as $\text{Re} \rightarrow 0$ ($\gamma_e = \text{Euler's constant} = 0.577$). Hilpert [13] investigated the heat transfer from fine wires in the Reynolds number range from 2.6 to 3×10^5 . Hilpert's data in the range of Reynolds numbers between 2.6 and 4.0 may be expressed as

$$\text{Nu} = .891 [\text{Re}(T_w/T_\infty)^{1/4}]^{.330} \quad (11)$$

where the conductivity and viscosity are evaluated at the film temperature. Measurements in low Reynolds number incompressible flows by Collis and Williams [14] were best expressed by the relation:

$$\text{Nu} = \left(\frac{T_w + T_\infty}{2T_\infty} \right)^{-.17} [.24 + .56 \text{Re}^{.45}] \quad .1 < \text{Re} < 44 \quad (12)$$

Again, the fluid properties were evaluated at the film temperature. Baldwin, Sandborn, and Laurence [15] have summarized the data of Cole and Roshko, Hilpert, Collis and Williams, and others in the Reynolds number range between .01 and 1×10^6 . This summary is compared with Dewey's correlation for $M=0$ in figure 3.

Compressible Flow

A considerable volume of research in the 1950's and 1960's was directed toward hot-wire behavior in compressible flows. Investigations in supersonic flows at higher Reynolds numbers ($\text{Re} > 20$) by Kovasznay [16], Laufer and McClellan, and Spangenberg [17] have shown a dependence of the Nusselt number on the square-root of the Reynolds number as was seen in the incompressible flows. Kovasznay's data in the range of Mach numbers from 1.15 to 2.05 also showed that for small temperature

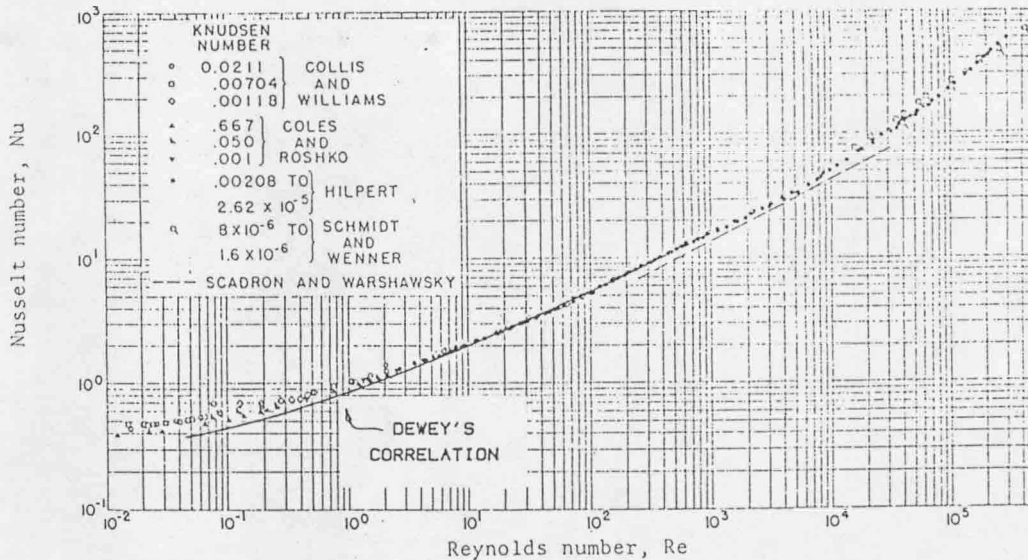


Figure 3. Heat loss characteristics; incompressible air flow (reproduced from [15]).

differences between the hot-wire and air, the hot-wire behaves independently of the Mach number. This Mach number independence for supersonic flows has been varified many times and is generally accepted for Mach numbers greater than 2. Baldwin et al. summarized the supersonic data of Kovasznay and Tormark, Winovich and Stine [18], Lowell [19], Sandborn and Domitz [20], Laufer and McClellan, Stalder et al., Weltmam and Kuhns [21], and Wong [22] for air flows in the range of Mach numbers from 1.155 to 6.083. A portion of the data for $Re < 10$ is shown in figure 4. Data obtained by Dewey in air at $M=5.8$ was in close agreement to the data of Laufer and McClellan and is also shown in figure 4.

As with the incompressible case, the choices for the evaluation of the flow properties in compressible flow vary widely among researchers. In addition to evaluation of properties at the free stream

conditions or film temperature, μ and k may also be evaluated at the stagnation temperature or, in the case of supersonic flow, at conditions behind the shock. As with the more recent investigations, in this study, μ and k were evaluated at the stagnation conditions.

The MSU/SWT Catalog data shown in figure 2 merit further discussion. These data were collected under the following conditions distinguishing them from the data presented above.

1. The data were not the focus of investigation but were a consequence of turbulence, boundary layer, and wake studies. As such, the data were obtained under conditions more severe than normally encountered in hot-wire heat transfer studies.

2. Most of the data were from hot-wires of 10 μ in. (.000254 mm), 20 μ in. (.000508 mm), and 50 μ in. (.00127 mm) diameter with aspect ratios much lower than encountered in previous hot-wire investigations

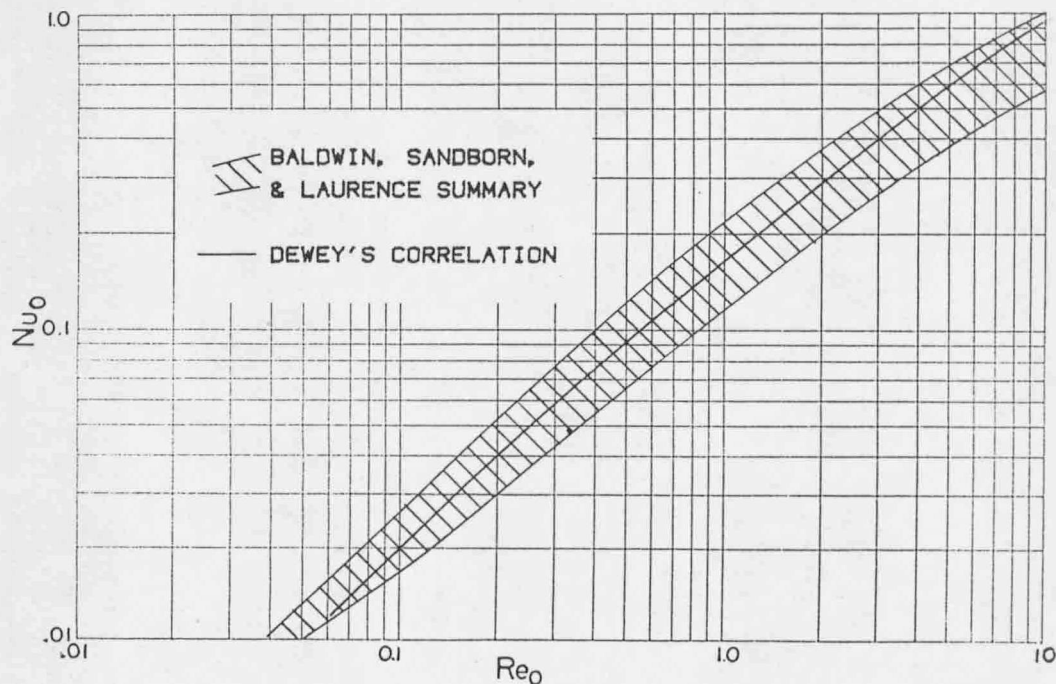


Figure 4. Hot-wire characteristics; supersonic flow.

(ℓ/d as low as 120). Some scatter is expected for these smaller configuration probes because of fabrication difficulties resulting in poor quality control. This scatter is evident in figure 2 in which the data for larger hot-wires ($Re_o > 1.5$) show less scatter and approach Dewey's correlation. Data collected by Dewey for 50 μ in. hot-wires (not included in his correlation) were also scattered and in poor agreement with the 100 μ in. hot-wire data shown in figure 1.

3. The small aspect ratios result in greater conductive heat losses than for wires of previous investigations, thus resulting in larger errors associated with (5).

Subsonic compressible flows have been investigated by Cybulski and Baldwin, Baldwin [23], Spangenberg, and Vrebalovich. Baldwin, Sandborn, and Laurence suggested the relations shown in figure 5. The data of figure 5 is qualitatively similar to the relations presented by Dewey (figure 1) however the values of Nu_o in figure 5 are considerably lower than the data by Vrebalovich (Dewey's correlation for $M < 1$) shown in figure 1. This discrepancy and the limited amount of available data in low Re compressible subsonic flows suggests the need for further research in this area. Measurements in subsonic compressible flows were made in this investigation and will be discussed in chapter 4.

Free-Molecule Theory

Stalder et al. have theoretically determined the Nusselt number and recovery temperature relationships for a hot-wire in free-molecule flow. The infinite wire Nusselt number may be expressed as

$$Nu_o = \frac{(\gamma-1)}{2(\pi)^{3/2}} a Re_o Pr \frac{g(s_1)}{s_1} \quad (13)$$

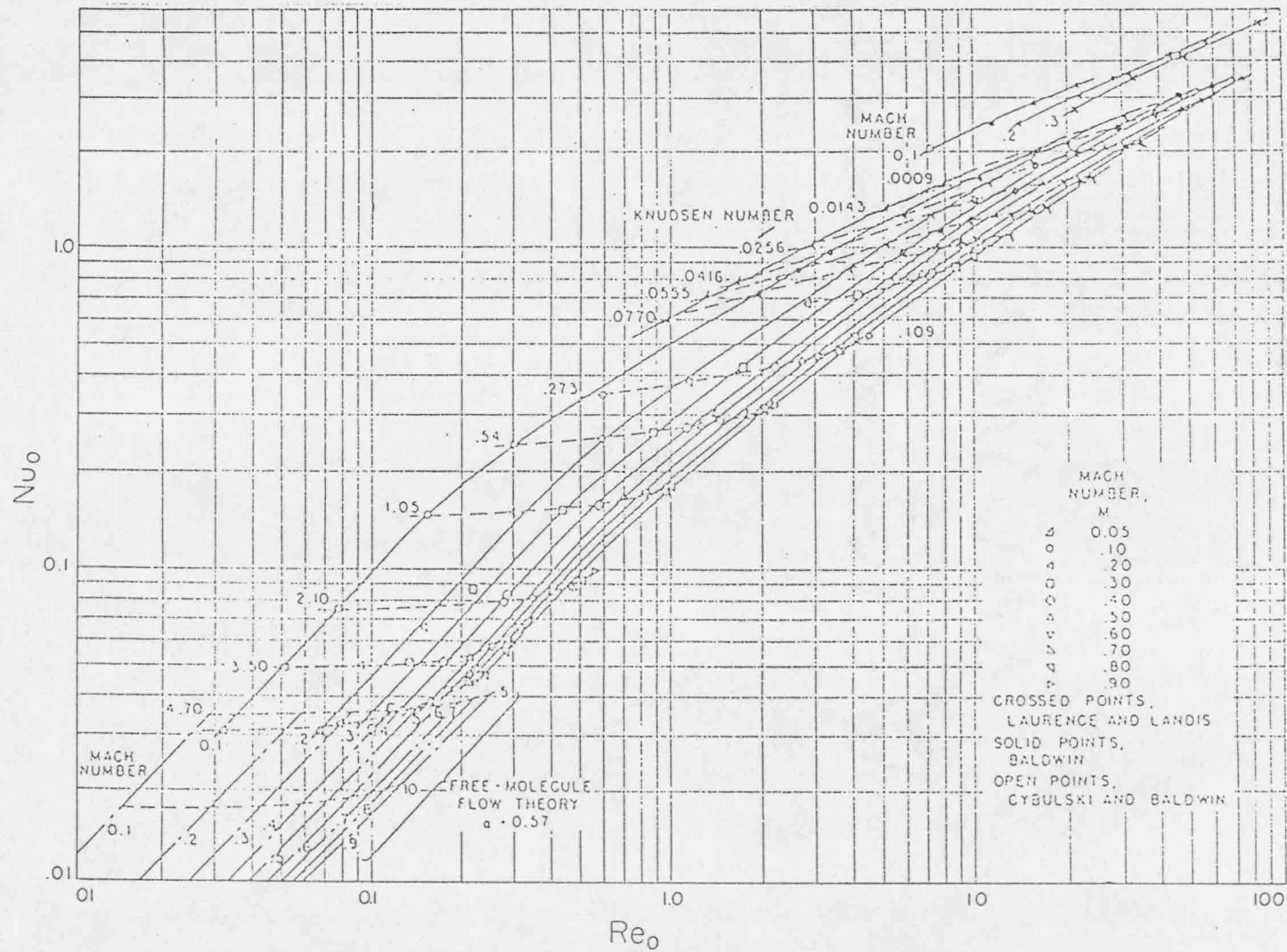


Figure 5. Hot-wire characteristics; subsonic flow (reproduced from {5}).

and the recovery factor as

$$\eta_f = \frac{T_{aw}}{T_o} = \left(1 - \frac{\gamma-1}{2} M^2\right) \frac{f(s_1)}{g(s_1)} \quad (14)$$

where α is the thermal accommodation coefficient, s_1 is the molecular speed ratio ($s_1 = \sqrt{\gamma/2} M$) and $f(s_1)$ and $g(s_1)$ are functions dependent only on s_1 and the number of excited degrees of freedom of the gas. The thermal accommodation coefficient is an indication of the efficiency with which energy is exchanged between the solid hot-wire surface and the impinging air stream molecules and is determined experimentally. The above relation applies to infinite unheated wires and excludes radiation. Equations (13) and (14) were formulated by equating the joule heating ($i^2 R$) to the molecular energy (both translational and rotational for a diatomic gas) incident on and re-emitted from the surface of the cylinder using a simplified kinetic theory assuming classical Maxwellian velocity distribution. A detailed analysis and tabulated values of s_1 , $f(s_1)$ and $g(s_1)$ may be found in reference [8]. Equation (13) is shown in figure 1.

As was indicated earlier, the recovery temperature of a unheated wire immersed in a free-molecule flow exceeds the stagnation temperature. Stalder et al. explained this phenomenon by comparing the magnitudes of incident and re-emitted molecular energies. The translational component of the incident molecular energy is the total of the free stream kinetic energy superimposed on the random thermal translational molecular kinetic energy. The incident energy per molecule has a value ranging from $2k_b T$ to $5/2 k_b T$ (depending on the speed and orientation of the flow) as opposed to a value of $3/2 k_b T$ per

molecule for continuum flow. Similarly, the energy of the re-emitted stream is $2k_b T_{aw}$ for free-molecule flow and $5/2 k_b T_{aw}$ for continuum flow. Thus, under steady state conditions, if the re-emitted energy equals the energy incident in each case, the temperature of the body, T_{aw} , must be higher in the case of free-molecule flow.

As in the continuum flow case, the Nusselt number and recovery ratio are nearly independent of Mach number for $M > 2.0$. This effect can be seen in figure 1.

End Loss Correction

If the term for axial conduction is included, the steady state heat equation for the hot-wire is:

$$\pi k_a N u_o \Delta T = \frac{\pi d^2 k_w}{4} \frac{d^2 T_w}{dx^2} + \frac{i^2 R_w}{\ell} \quad (15)$$

The average wire resistance is determined by calibration and may be expressed as a linear function of temperature as

$$R_w = R_r [1 + \alpha_r (T_w - T_r)] \quad (16)$$

where R_r is the resistance at some arbitrary reference temperature T_r (usually 0°C). The solution to (15), expressed in terms of the average wire temperature is:

$$\tau_w = \frac{c}{b} + (\tau_s - \frac{c}{b}) \frac{\tanh \beta}{\beta} \quad \beta = \sqrt{b/a} \quad (17)$$

where

$$a = \frac{k_w}{k_a} \left(\frac{d}{\ell} \right)^2 \quad b = Nu_o - \frac{i^2 R_r \alpha_r}{\ell \pi k_a} \quad c = \frac{i^2 R_r}{\ell \pi k_a T_{aw}} [1 + \alpha_r (T_{aw} - T_r)]$$

In a similar manner, equation (4) can be nondimensionalized to obtain:

$$Nu_m (\tau_w - \tau_{aw}) = c + z \tau_w \quad (18)$$

where

$$z = \frac{i^2 R_r \alpha_r}{\ell \pi k_a}$$

Substituting (18) into (5), the Nusselt number correction factor becomes:

$$\psi_N = \frac{Nu_0 (\tau_w - \tau_{aw})}{c + z\tau_w} \quad (19)$$

The nondimensional recovery temperature, τ_{aw} , may be obtained by substituting $i=0$ into (17) to obtain:

$$\tau_{aw} = \frac{\tau_s \tanh S}{S} \quad (20)$$

Then equation (19) becomes:

$$\psi_N = \frac{Nu_0 \left[\frac{c}{b} + \frac{(\tau_s - c) \tanh \beta}{b} - \frac{\tau_s \tanh S}{S} \right]}{c + z \left[\frac{c}{b} + \frac{(\tau_s - c) \tanh \beta}{b} \right]} \quad (21)$$

For the limiting case of $i \rightarrow 0$, equation (21) may be simplified and linearized in i^2 to obtain:

$$\psi_N = 1 - \frac{\tanh S}{S} \quad (22)$$

The above analysis was first presented by Dewey.

Nusselt Number Measurements

Consider now the actual measurement of Nu_m in (4). Using (16), the temperature difference in (4) may be expressed as:

$$T_w - T_{aw} = \frac{R_w - R_{aw}}{R_r \alpha_r} \quad (23)$$

The heat loss equation for the infinite wire becomes:

$$Nu_m = \frac{i^2 R_m \left(\frac{R_r \alpha_r}{R_m - R_{aw}} \right)}{2\pi k_a} \quad (24)$$

The usual technique used in many earlier investigations involves linearizing (24) in the limit as $i \rightarrow 0$. Then:

$$\left(\alpha_r R_r \right) \lim_{i \rightarrow 0} \frac{i^2 R_m}{(R_m - R_{aw})} \approx \left(\frac{\alpha_r R_r R_{aw}}{dR_w/di^2} \right)_{i=0} \quad (25)$$

Substituting, we then obtain:

$$Nu_m = \frac{\alpha_r}{2\pi k_a} \frac{R_{aw} R_r}{(dR_w/di^2)} \Big|_{i=0} \quad (26)$$

In order to determine the Nusselt number in this manner, measurements of R_w are necessary at very low values of i . Accurate measurements of i and R_w at small i are difficult and invite error.

Demetriades [24] suggests an alternative procedure that eliminates the need to restrict measurements of Nu_m at low values of current. Equation (24) may be written as:

$$R = R_{aw} + \frac{W}{i_b^2}, \quad i_b^2 = \frac{2\pi k_a Nu_m}{\alpha_r R_r}, \quad W = i^2 R_m \quad (27)$$

A linear fit of R vs. W may therefore be used to obtain R_{aw} and Nu_m if kNu is assumed constant. This method offers an advantage over (26) in that (27) is exact and the range of i is limited only by the melting temperature of the wire. Since k is a function of temperature, however, the actual relation between R and W should not be linear. However, Demetriades points out that the dependence of kNu on temperature must be weak for the following reasons.

- (a) Conduction, k , is not a strong function of T .
- (b) The temperature controlling k is only partially due to the wire temperature (e.g. film temperature $= (T_w + T_{aw})/2$.)
- (c) It is known from earlier works that Nu is affected by T_w in a way balancing changes in k .

Based on the above observations, the variation of kNu with W may be written as:

$$\begin{aligned} \frac{1}{kNu} &= \frac{1}{kNu}(W=0) + \left. \frac{\partial(1/kNu)}{\partial W} \right|_{i=0} W \\ &= \frac{1}{(kNu)_{i=0}} - \frac{1}{(kNu)^2} \left[\frac{k \partial Nu}{\partial W} + \frac{Nu \partial k}{\partial W} \right] \Big|_{i=0} W \end{aligned} \quad (28)$$

Substituting into (27), the wire resistance becomes:

$$R_w = R_{aw} + \left(\frac{\alpha_r R_r}{2\pi k_a Nu} \right) W - \left(\frac{\alpha_r R_r}{2\pi k_a Nu} \right) CW^2 \quad (29)$$

Where

$$C = \left[\frac{1}{Nu} \frac{\partial Nu}{\partial W} + \frac{1}{k_a} \frac{\partial k_a}{\partial W} \right]_{i=0} \quad (30)$$

Thus, if we measure R_w and W and fit the data to a second order polynomial

$$R = A_0 + A_1 W + A_2 W^2 \quad (31)$$

then the hot wire heat loss characteristics (Nu_m) may be determined from the known coefficients A_0 , A_1 , A_2 and (29). The recovery temperature is obtained from the intercept $A_0 = R_{awm}$ and the resistance-temperature relation (16). From the coefficient A_1 and the evaluation of k_{aw} using T_{aw} , the Nusselt number at $\tau=0$ is determined from:

$$Nu_{aw} = \frac{\alpha_r R_r}{2\pi k_a A_1} \quad (32)$$

The coefficient A_2 provides the coefficient $C = -A_2/A_1$ and integration of (30) provides the Nusselt number for $W \neq 0$. Performing the integration of (30) results in:

$$\frac{Nu(T)}{Nu_{aw}} = \frac{k_{aw}}{k(T)} \exp[-(A_2/A_1)W] \quad (33)$$

The above analysis was used in the present investigation. The data were fitted to a second order polynomial using the method of least squares in computer codes LOFLOW02 and HIFLOW02 written by Demetriades and modified for this investigation to include the end loss correction procedure presented by Dewey (eqn (21)). These codes are included in the appendices.

Recovery Temperature

As noted earlier in this chapter, the hot-wire recovery temperature may vary from a value equal to the free stream temperature in incompressible continuum flow to a value greater than the stagnation temperature in free-molecule flow. In continuum flow, the recovery temperature is mainly a function of the Mach number. In slip flow and free-molecule flow, the recovery temperature is also dependent on the Knudsen number as well as the Mach number. Vrebalovich proposed a normalized recovery ratio given by

$$\bar{\eta} = \frac{\eta_w - \eta_c}{\eta_f - \eta_c} \quad (34)$$

where η_c is the experimental continuum recovery factor and η_f is the theoretical free-molecule recovery factor. The normalized recovery factor minimizes the Mach number effect as was shown by Vrebalovich for $M > 4$. Normalized recovery temperature data compiled by Dewey from several sources is shown in figure 6.

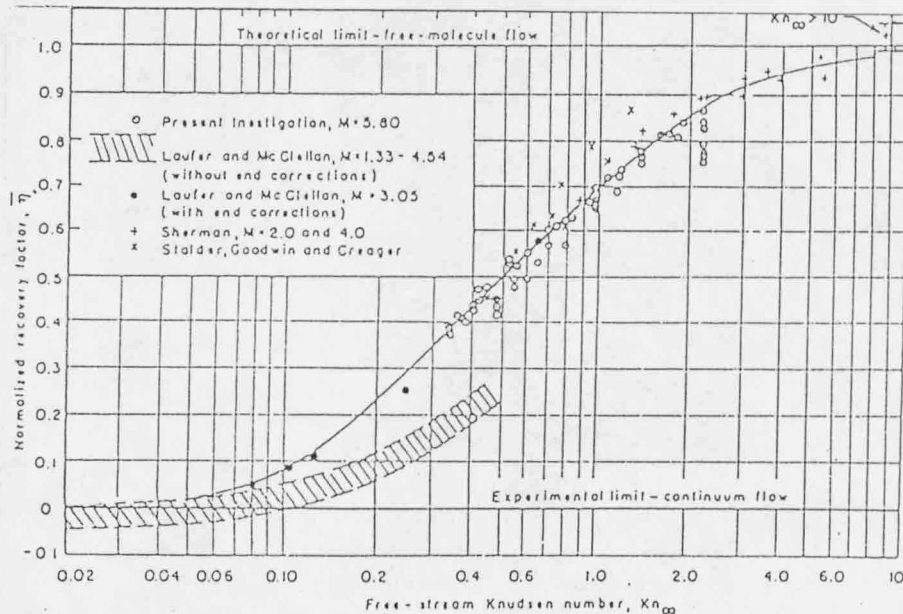


Figure 6. Normalized recovery factor data (reproduced from [3]).

CHAPTER 3

EXPERIMENTAL APPARATUS AND PROCEDURE

Hot-wire Probes

The hot-wire probes, shown in figures 7-8, were fabricated at the MSU/SWT lab. The primary probe body is a 2 inch length of 1/16 inch diameter 2-hole alumina tubing. The secondary body is a 1/2 inch length of 1/32 inch diameter 2-hole alumina tubing. Pyrocera glass cement, manufactured by Corning Glass Works, is used to attach the secondary body to the primary body. Current is supplied to the hot-wire through .012 inch diameter armoured polythermaleze copper leads arc welded (using a thermocouple welder) to the .003 inch diameter nickel hot-wire supports. The supports are shaped with an acid etch and fine sandpaper to provide a suitable contact surface for the hot-wires. Pyrocera is applied to the forward end of the probe to provide a smooth rounded tip. Silicon rubber applied at the end of the primary body where the leads enter helps to prolong the life of the lead wires through continued use.

Hot-wires used in this experiment were 90% Platinum-10% Rhodium with diameters of 20 μ in. and 50 μ in. A liquid gold resinate was used to attach the hot-wires to the support prongs. After mounting, the hot-wires were baked at 1000°F to burn off the organic vehicle of the liquid gold as well as to anneal the hot-wire in an effort to eliminate the strain gage effects reported by previous researchers.

A constant current control fabricated especially for

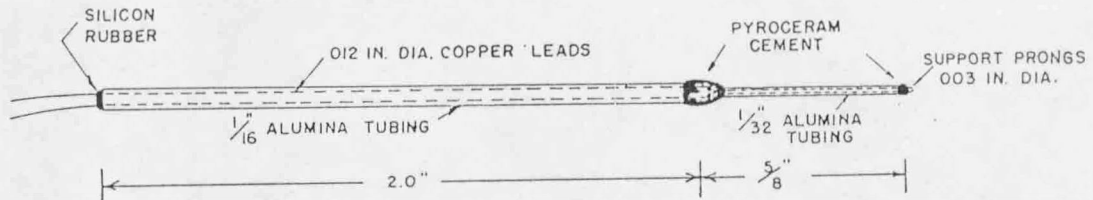


Figure 7. Hot-wire probe configuration.

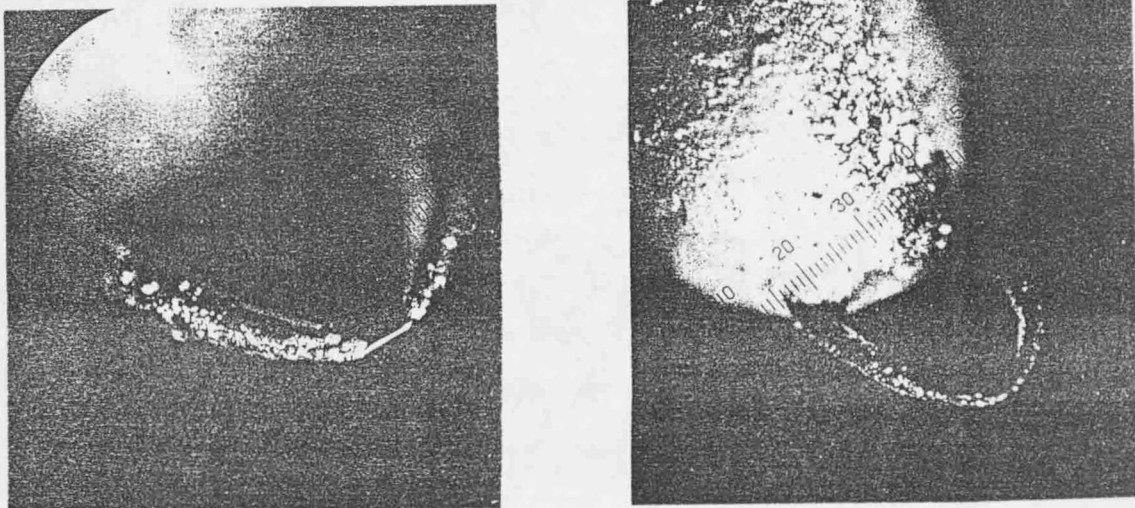


Figure 8. Photographs of hot-wire element and supports.

turbulence research at Philco-Ford Aeronutronic was used to heat the hot-wire. The constant current control system (model ADP-13) provides 15 individually adjustable pushbutton current settings. Pushbutton operation is designed for quick disconnect current change and is ideally suitable for automated data recording with switching transients of only a fraction of a second. Power is supplied to the heating circuit through ten 10,000 milliamp-hour mercury batteries or three 12V 350 amp automotive batteries. The mean voltage and current outputs may be simultaneously recorded from jacks located on the rear of the unit. The voltage and current signals were amplified as much as 10 times before recording. The digital conversion and data recording are discussed later in this chapter.

Supersonic Wind Tunnel

The Montana State University Supersonic Wind Tunnel, shown in figures 9 and 10 is an open circuit continuous flow facility, using air as the working fluid and producing Mach numbers of 3.0 over a Reynolds number range of 48500-145000 per in. (19000-57000 per cm.). Under normal operating conditions, the SWT is capable of stagnation temperatures as high as 145°F (62°C) and stagnation pressures as low as 300 mm Hg absolute. Automatic or manual control of the flow conditions is maintained from the control console located in the test area. The rectangular test section has a cross sectional area of 3.1x3.2 inches (7.87x8.13 cm.). For this investigation, the entire length of the Laval nozzle was utilized. The variation of the Mach number with axial position is shown in figure 11. The test section is accessed through

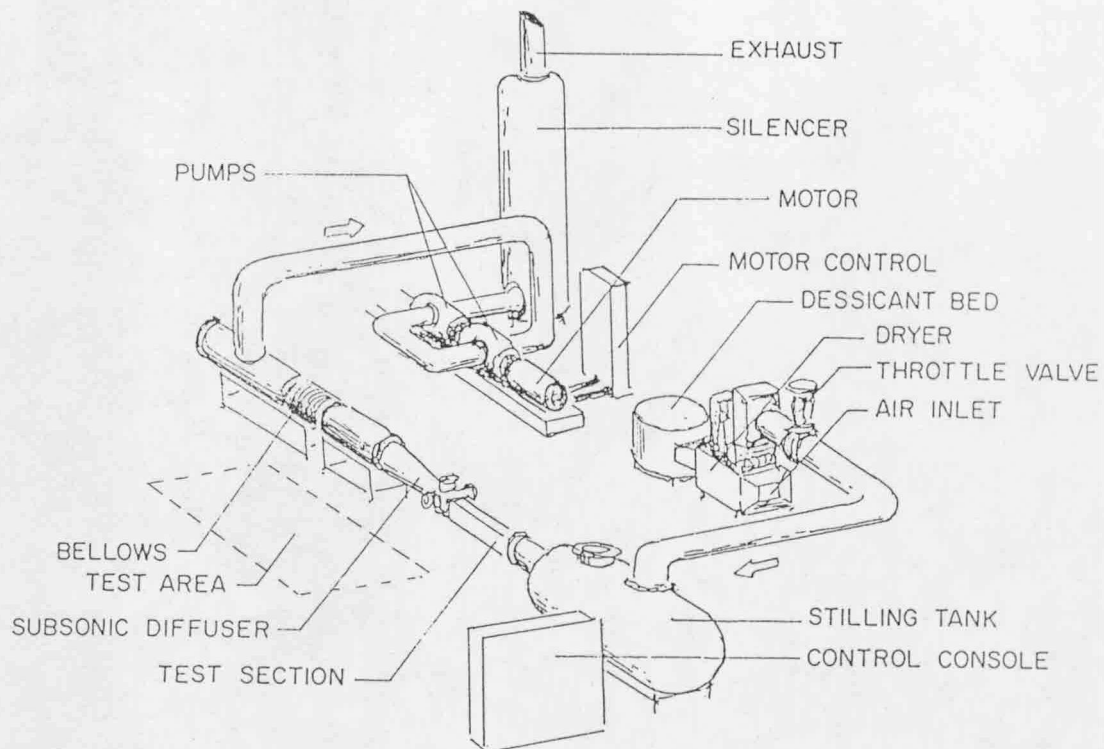


Figure 9. Major components of MSU/SWT. (reproduced from [25]).

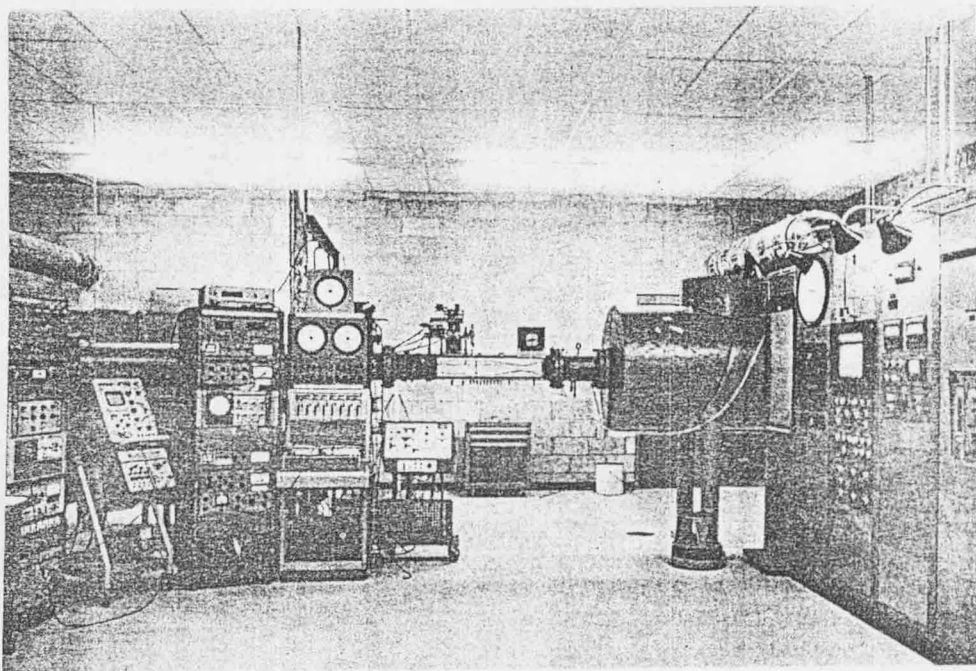


Figure 10. Test area of MSU/SWT laboratory.

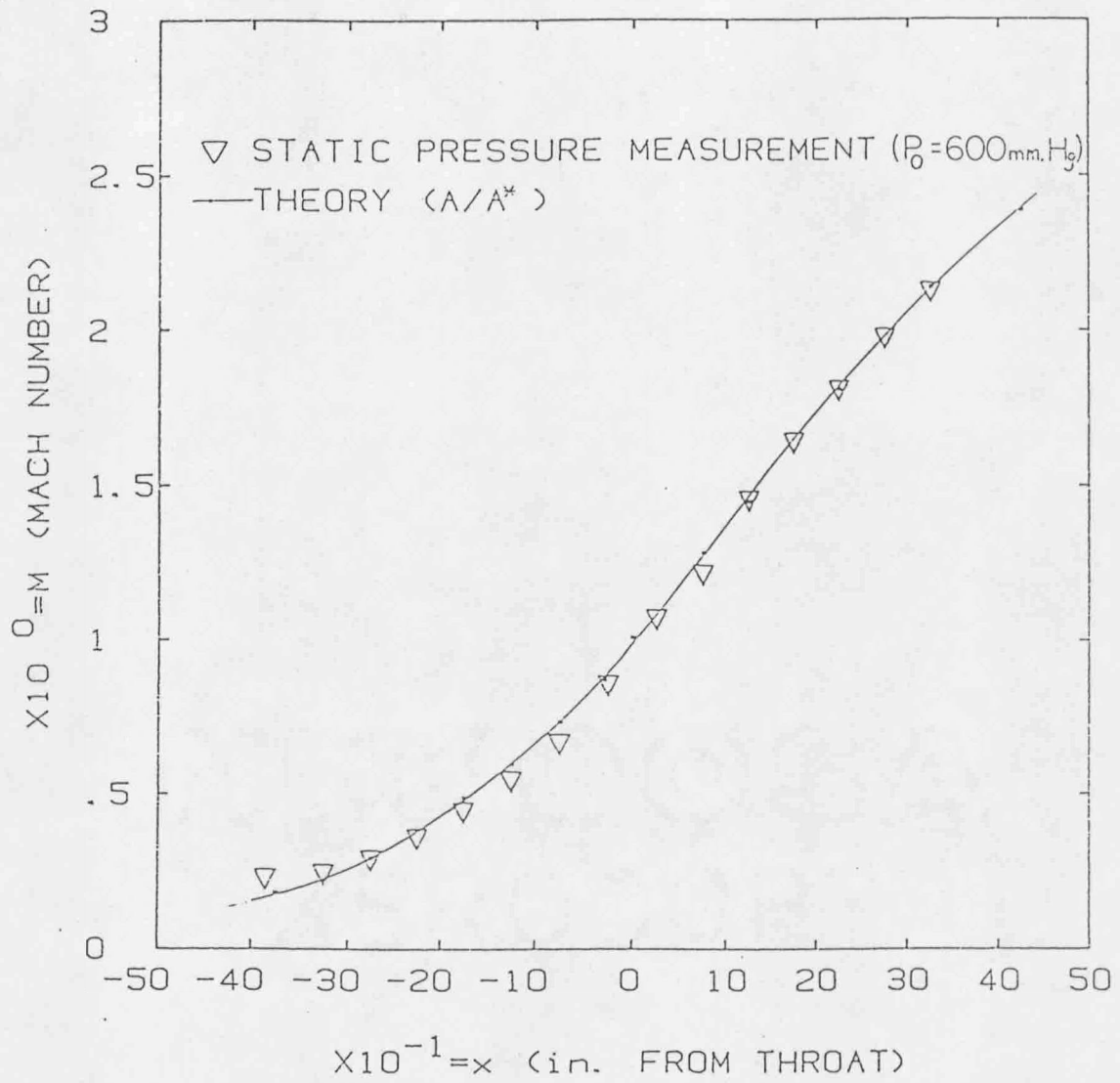


Figure 11. Variation of Mach number with axial location in MSU/SWT nozzle.

removable optical-quality glass panels extending the length of the nozzle. A detailed description of the SWT may be found in [25].

Low Velocity Tunnel

The Low Velocity Apparatus (LVT), Shown in figure 13, is a fan operated suction venturi manufactured by Aerolab Supply Company. The LVT has a 12 inch (30.48 cm) diameter plexiglas test section capable of operating over a Reynolds number range of 4300-23000 per in. (1700-9000 per cm) at room temperature with a maximum velocity of 56 ft/s (1700 cm/s). This corresponds to a Mach number range of $.007 < M < .05$. The mass flow in the test section is controlled by allowing air to enter the diffuser behind the test section thereby decreasing mass flow entering ahead of the test section at the intake manifold.

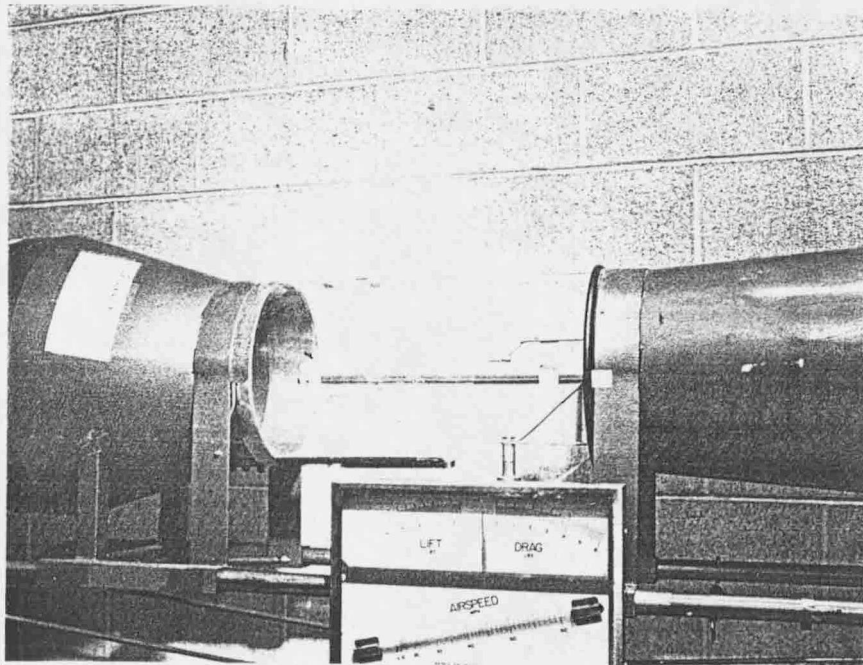


Figure 12. Low velocity tunnel (LVT)

Flow Measurement Apparatus

Flow conditions for tests conducted in the SWT were determined from two separate sets of measured flow properties. For tests conducted at $M=3$, the flow conditions were determined by measuring the stagnation temperature and pressure (T_0, P_0) and the pressure ratio across a normal shock P_{02}/P_0 . The stagnation conditions were measured upstream of the nozzle using a type J thermocouple for temperature measurement, and a pitot tube for the determination of the stagnation pressure. The pressure P_{02} was measured using a .029 inch i.d.-.063 inch o.d. pitot tube positioned in the same vertical plane as the hot-wire as shown in figure 13.

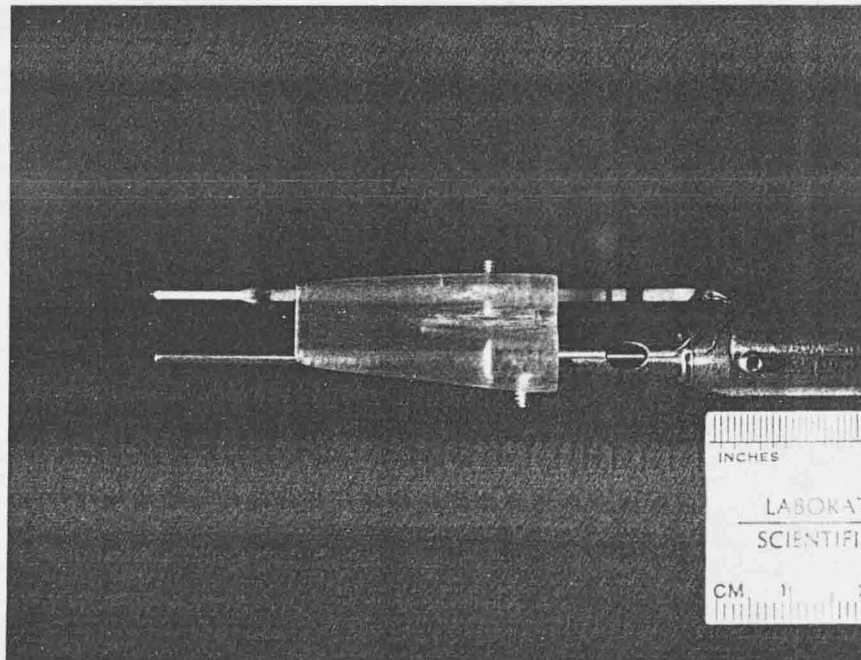


Figure 13. Probe configuration; MSU/SWT ($M=3.0$).

For tests conducted in the range $.18 < M < 2.2$, where the hot-wire was traversed through the throat, the flow conditions were determined by measuring the total pressure ratio and the static pressure-stagnation pressure ratio P/P_0 . The stagnation properties were measured in the same manner as in the $M=3$ tests while the static pressure was determined using a static pressure probe attached in the same horizontal plane and parallel to the hot-wire probe and shown in figure 14. The separation distance between the static probe and the hot-wire was .90 inches. The probe was fabricated from a .032 in o.d. hollow tube tapered to a point and sealed at the tip. Four .0145 inch static pressure taps were drilled around the perimeter a distance of .25 inches from the tip. The hot-wire was aligned such that the element was at the same upstream location as the static pressure taps. The pressure transducers were

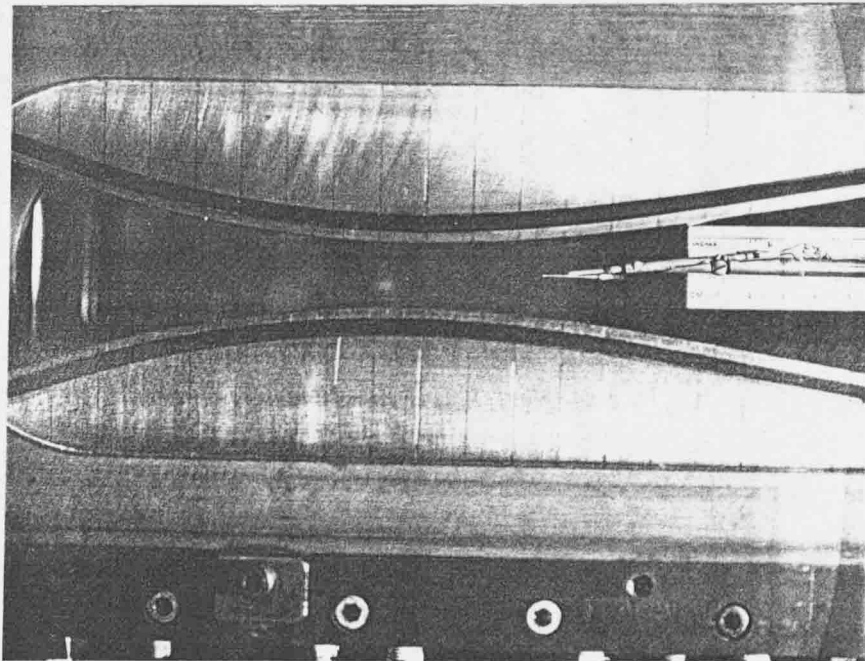


Figure 14. Probe configuration; MSU/SWT ($.18 < M < 2.2$).

located outside the tunnel and were connected to the total and static pressure probes by flexible tubing extending through the hollow sting and exiting the tunnel through ports located in the diffuser. The pressure transducers consisted of a Dynisco 0-15 psi transducer energized by 5 vdc and a Kulite 0-15 psi transducer energized by 10 vdc. The signals were amplified 30 and 100 times and were dynamically damped before recording. The probes were axially and vertically positioned using an electromechanical actuating system located above the test and diffuser sections of the tunnel as seen in figure 10.

The flow conditions in the vicinity of the hot-wire for tests conducted in the LVT ($M=0$) were determined using the ambient temperature and a pitot-static probe positioned in the same vertical plane and below the hot-wire as shown in figure 15. The pitot-static tube consisted of

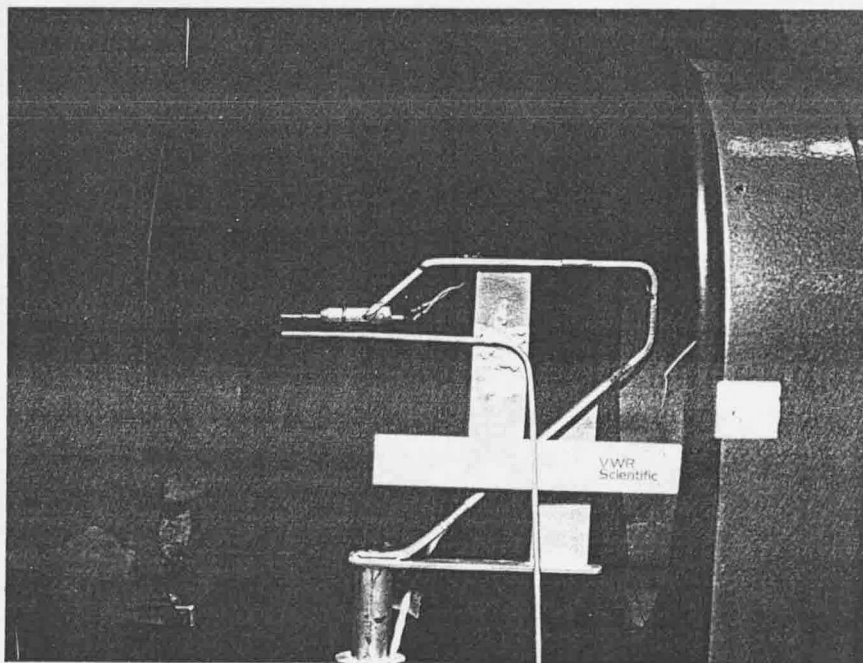


Figure 15. Probe configuration; LVT ($M=0$).

concentric tubes, the smaller of which was a .04 inch i.d. tube open at the tip for total pressure measurement and the outer tube, a .120 inch o.d. tube with eight .0145 inch static pressure taps drilled around the perimeter a distance of .6 inches from the probe tip. The static and dynamic pressures were indicated on an inclined micromanometer with a scale to .6 inches of H_2O and accuracy to .001 inch H_2O using alcohol as the working fluid.

Calibration Oven

The temperature-resistance characteristics of the hot-wires were calibrated in the calibration oven. The oven, manufactured by Sigma Systems, measures 1000 in³ and is regulated to maintain constant temperature. A six-position probe holder, shown in figure 16, allows

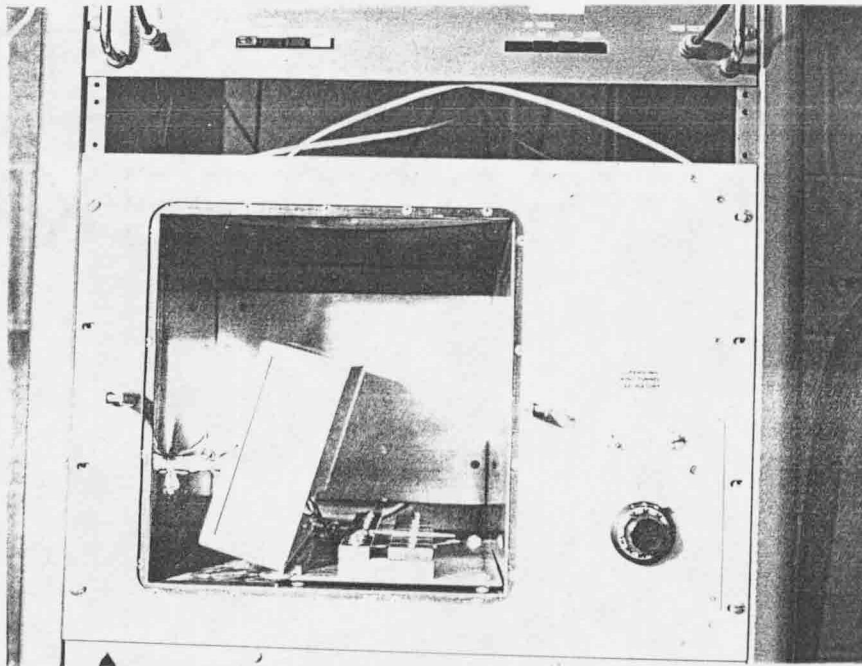


Figure 16. Oven calibration equipment.

the simultaneous calibration of six hot-wires. A seventh position on the holder allows for the calibration of a shorted hot-wire probe which was used to account for resistances in the probe other than the hot-wire element. The holder is enclosed within a tin box to isolate the hot-wires from the light air currents caused by a small circulation fan in the oven. A type J thermocouple monitors the oven temperature in the vicinity of the hot wire. The hot-wires are heated by the ADP-13 described on page 23 with voltage and current recorded in the same manner as in the flow calibrations.

Data Acquisition

The block diagram of figure 17 shows the electronic components used in data acquisition. The hot-wire signals from the constant current control panel were amplified before conversion to a digital signal for storage. The signals from the static and total pressure transducers were likewise amplified and dynamically suppressed with a resistor-capacitor (R/C) circuit prior to digital conversion. The analog to digital (A/D) converter (a Spectral Dynamics model SD-133) linearly converts the analog input signal to a digital signal proportional to the voltage range of the specified input channel. The SD-133 is accurate to 1 part per 1000 over the input channel voltage range. The output from the SD-133 was then recorded directly to 5 inch disk using the Intertek Superbrain microcomputer and also to a Texas Instruments Silent 700 ASR computer terminal which provided temporary back-up storage on cassette tape as well as a hard copy of the data. The above procedure was applied to oven calibrations, LVT flow

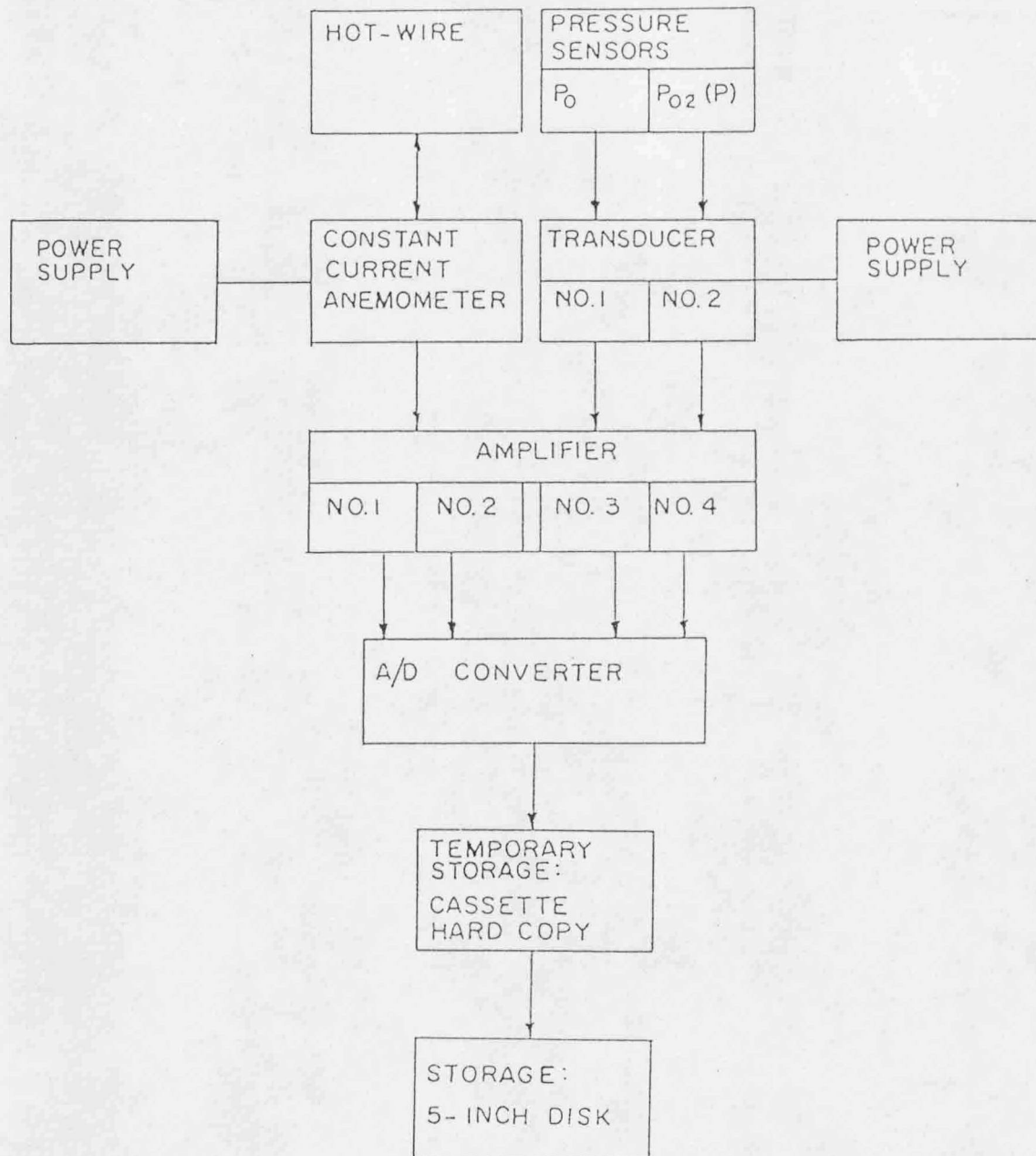


Figure 17. Data Acquisition equipment diagram.

calibrations, and SWT flow calibrations.

Experimental Procedure

The procedure for preparing the hot-wire probes is described in detail in [26]. The Pt-10% Rh Wollastin wires were first etched to remove the silver coating, then mounted on the probe with the aid of a microscope, and annealed to remove the thermal stress effects that occur at high overheat. Each wire was checked under the microscope and any wires showing obvious imperfections or improper mounting were discarded.

The wires were then oven calibrated to determine the temperature-resistance characteristics from equation (16). This method of calibration utilized an "overheat traverse". The wires were placed in the calibration oven and the resistance measured at fifteen pre-set current settings. Using the ADP-13 as described on page 23, voltage and current measurements were obtained at twelve constant temperatures in 15° C increments ranging from room temperature to 190° C. At each temperature, the R vs. W data were fitted to a quadratic. Figure 18 shows typical $R(W)$ vs. T oven calibration data. The intercept ($W=0$) of each polynomial provides the resistance of the wire at the temperature of that particular overheat traverse. The $R(W=0)$ vs. T data were then linearly fit to obtain the coefficients R_T (Ω) and α_T ($1/^\circ\text{C}$) of equation (16). Figure 19 shows the resistance-temperature correlation using the intercept data of figure 18. Calibrations showing rms deviations of $R(W)$ greater than .1 in the quadratic fit were discarded. A summary of coefficients R_T and α_T for hot-wires used in this investigation is

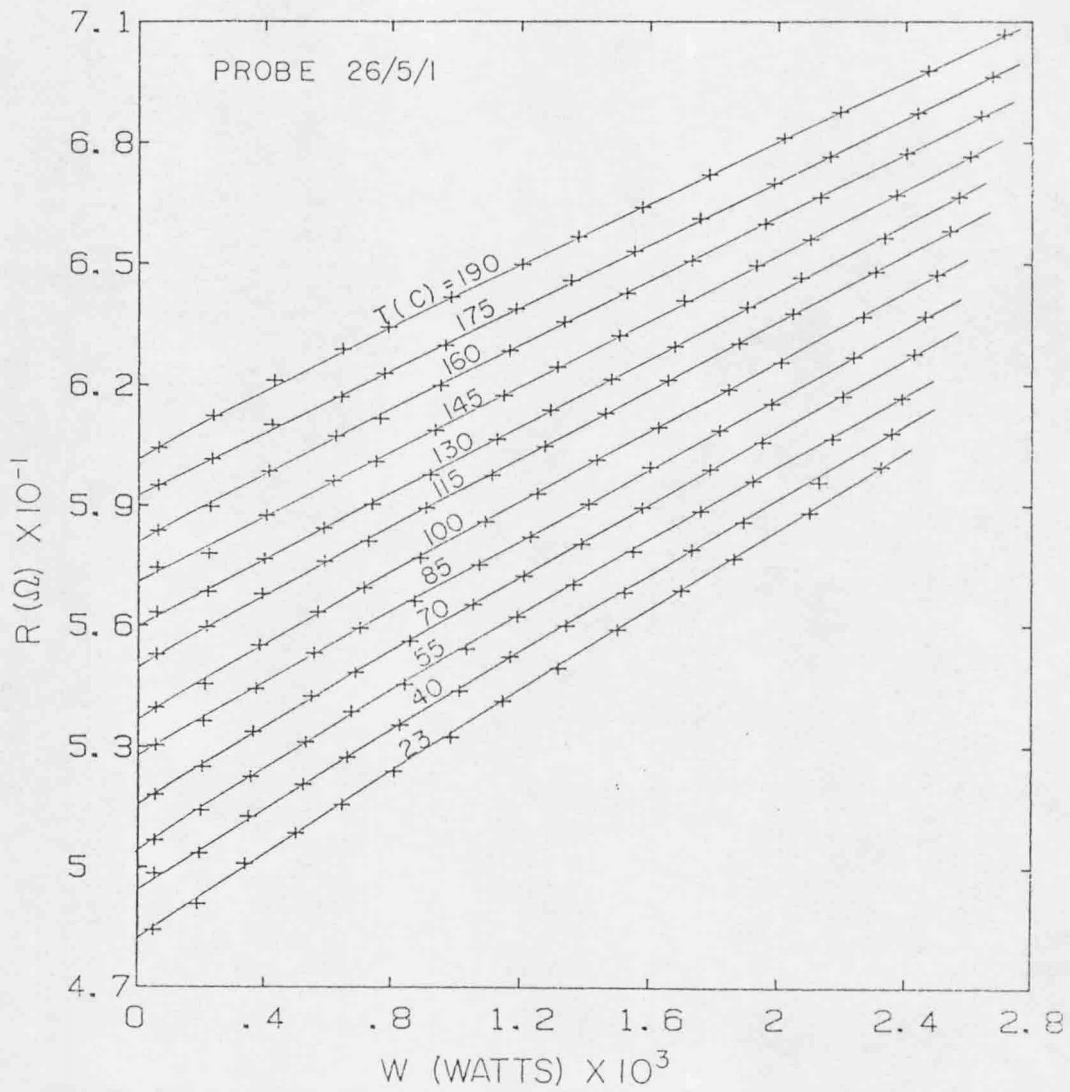


Figure 18. Oven calibration overheat traverse data.

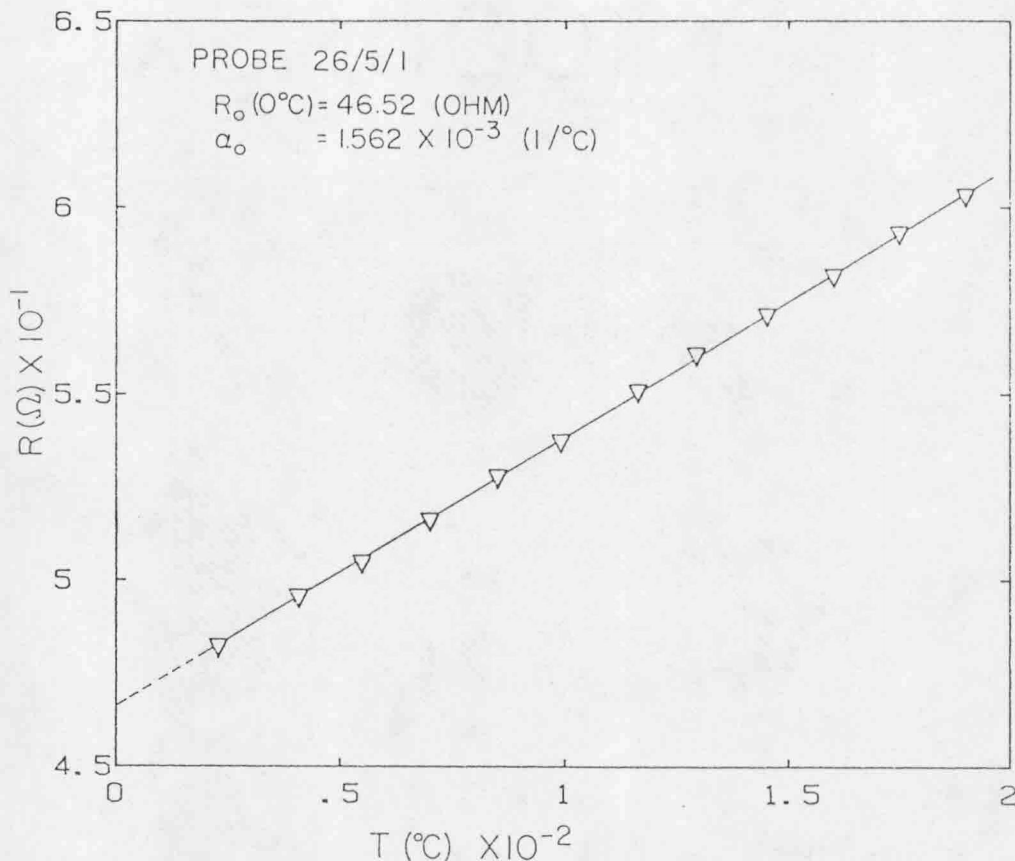


Figure 19. Resistance-temperature correlation obtained from the intercept data ($R(W=0)$) of figure 18.

given in the appendices. The reduction of data was accomplished using the OVENCAL5 code written by Demetriades and Fishbaugher. The code is included in the appendices.

The flow calibration process is similar to the oven calibration described above. The purpose of the flow calibration is to obtain the heat transfer and flow data for the determination of $Nu_0(Re_0, M, S=\infty)$. The flow calibration, like the oven calibration, utilizes the overheat traverse. For calibrations in the LVT, overheat traverse measurements were recorded along with P , T , and P_0 for the determination of the mean flow properties. In the LVT tests, the Reynolds number was varied by

regulating the velocity in the test section. The heat transfer characteristics were then determined using a quadratic fit of the R vs. W data and equations (29)-(33). The end-loss correction factor, $\psi_N(S)$ was determined from equation (18) using an interval halving iteration procedure. Data reduction was facilitated using the code LOFLOW02 listed in the appendices.

The procedure for the SWT calibrations was identical to the LVT calibration except that variation of Reynolds number was accomplished by regulating the total pressure in the tunnel. The data recorded for the $M=3.0$ tests included i , R , P_o , P_{o2} , and T_o while i , R , P_o , P , and T_o were recorded for calibrations in the throat region ($.18 < M < 2.2$). Typical flow calibration overheat traverse data is shown in figure 20. Data for the SWT calibrations were reduced using the code HIFLOW02 listed in the appendices.

Measurements using hot-wires of 10 μ in. were attempted, however, consistent wire breakage in the SWT prevented the collection of data. Wire failure has been a persistent problem in research using fine hot-wires and is caused by a number of factors including high pressure loading and collisions with the hot-wire element by dust particles.

Fishbaugher [27] approximated the hot-wire stress loading using simplified beam and cable theories. He determined that the maximum aspect ratio for each theory may be obtained from :

$$\text{beam theory} \quad \frac{l}{d} = \left[\frac{3 \cdot \pi}{4 \cdot C_D P_d} \frac{\sigma_{yp}}{d} \right]^{\frac{1}{2}} \quad (35)$$

or

$$\text{cable theory} \quad \frac{l}{d} = \frac{\pi}{2} \frac{\sigma_{yp} \sin \theta}{C_D P_d} \quad (36)$$

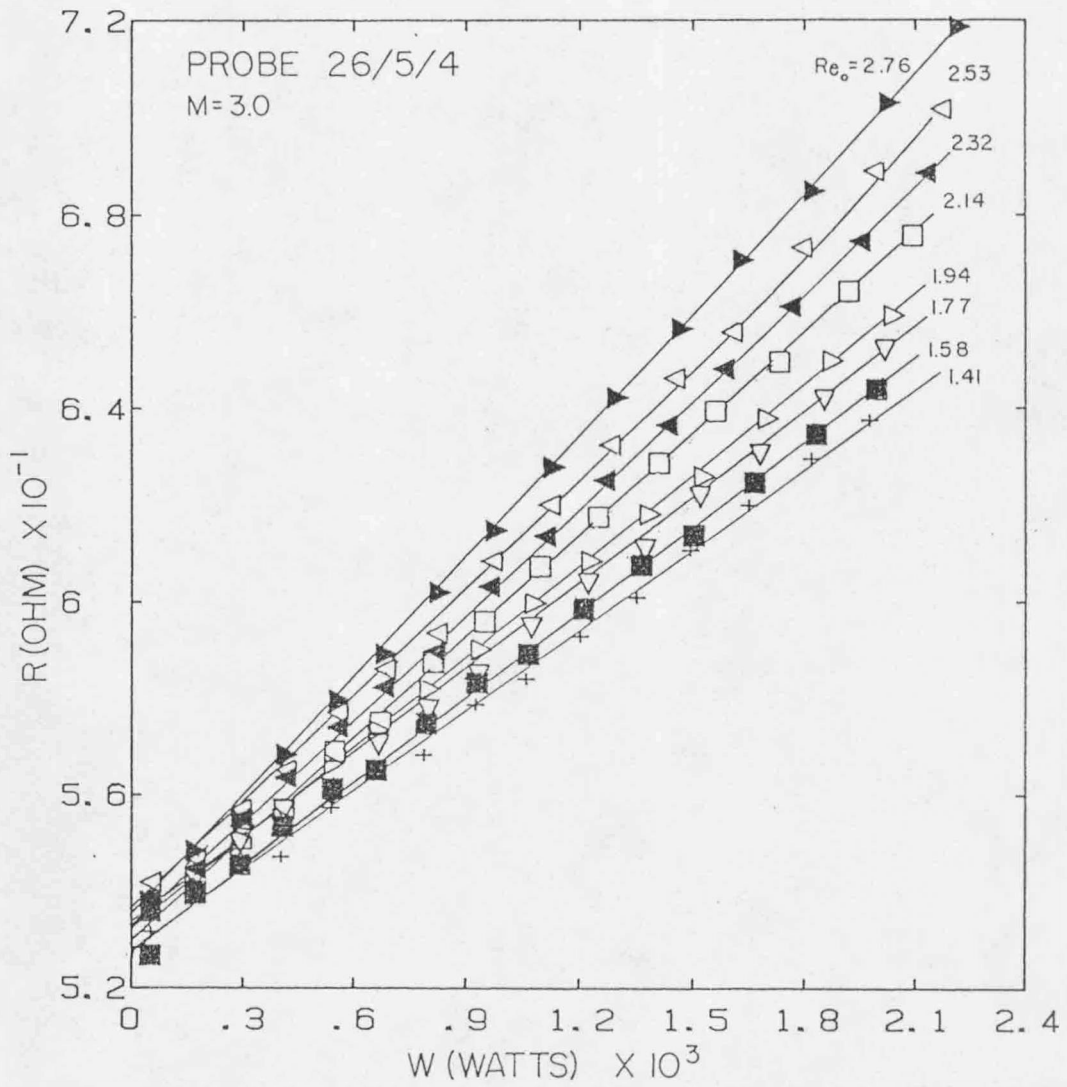


Figure 20. Typical flow calibration overheat traverse data.

where σ_{yp} is the maximum yield stress (48000 psi for Pt-10% Rh wire), C_D is the drag coefficient, P_d is the dynamic pressure and θ is the angle of deflection due to loading. The beam theory models the hot-wire as a uniformly loaded beam with fixed supports while the cable theory uses small angle approximation and a uniform load distribution model.

A comparison of the above theory with actual conditions encountered in this investigation showed the following.

Conditions: $M=3.0$ $Re_o=1.2$
 $P_d=2$ psi (min. dynamic pressure of $M=3$ tests)
 C_D (free-molecule)=4 (from {8})
 C_D (continuum)=9 (from {28})

Results: ℓ/d

	Beam	Cable ($\theta=.1$)	($\theta=1$)
continuum	80	7	73
free-molecule	120	16	164

The beam theory gives a better approximation, however, the predicted ℓ/d is quite conservative for these conditions. In the $M=3$ SWT calibrations, wires of $\ell/d < 250$ had a good survivability rate and unavoidable wire failure for 20 min. wires generally occurred for wires greater than about 350. In order for the cable theory to predict a maximum wire ℓ/d of 350, the value of θ is greater than unity, thus violating the assumption of small angles in the development of (36). Note that (35) and (36) do not depend on the diameter of the hot-wire. In practice, however, higher aspect ratio wires show better survivability for larger diameter wires.

CHAPTER 4

RESULTS

General

The purpose of this investigation was to determine the heat transfer characteristics of small configuration hot-wires in low Reynolds number air flows. In particular, it was desired to evaluate Nusselt number and recovery temperature data in low Reynolds air flows of Mach number less than 3. The results, which are tabulated in the appendices, are discussed under the subheadings of

1. End loss corrected Nusselt number $Nu_0(Re_0, M, S=\infty)$
2. End loss correction $\psi_N(S)$
3. Recovery Temperature $\eta_{aw}=(T_{aw}/T_0)$

The following discussion presents the results of this experiment in comparative form with previous investigations. The correlations presented by Dewey have been verified by data from several sources and are used as a basis for comparison of the compressible flow data of this study. The correlation of Collis and Williams for incompressible low velocity flows was used for comparison of data obtained in the LVT ($M=0$).

Nusselt Number $Nu_0(Re_0, M, S=\infty)$

The variation of the end-loss-corrected zero-current Nusselt number, Nu_0 , with Reynolds number, Re_0 , is shown in figures 21-29. Nusselt number data collected in the $M=3.0$ test section of the MSU/SWT

is shown in figures 21 and 23. Several distinct characteristics are immediately apparent in these data.

1. Nu_0 varies inversely with ℓ/d even though axial conductive end losses have been theoretically eliminated from the total heat loss.
2. Data for very low aspect ratios ($\ell/d < 130$) are more scattered than data for wires of larger ℓ/d .
3. Data for high aspect ratio wires converge toward Dewey's correlation.

Possible causes for the observations 1 and 2 may be found in the assumptions used in the solution of the heat loss equation (15) and the end loss correction factor equation (19). The assumptions used in the solution of (15) were: (1) the heat transfer coefficient, h , is constant along the length of the wire, (2) Both hot-wire supports are maintained at a temperature T_s , (3) the thermal conductivity of the wire, k_w , is constant, and (4) a uniform temperature exists at any cross section of the wire. For this study, assumption (2) was further restricted to $T_s = T_{aw}$ ($\tau_s = 0$).

Assumption (1) requires that the flow be uniform over the length of the wire. If the flow near the supports is affected by their presence, the resulting effect on the measurement of Nu_0 would be more pronounced for smaller ℓ .

The assumption $\tau_s = 0$ may be questionable especially for small aspect ratio wires. Because of their relative size, the flow in the vicinity of the hot-wire supports behaves as a continuum, and therefore, the temperature of the support tips should be equal to or less than the

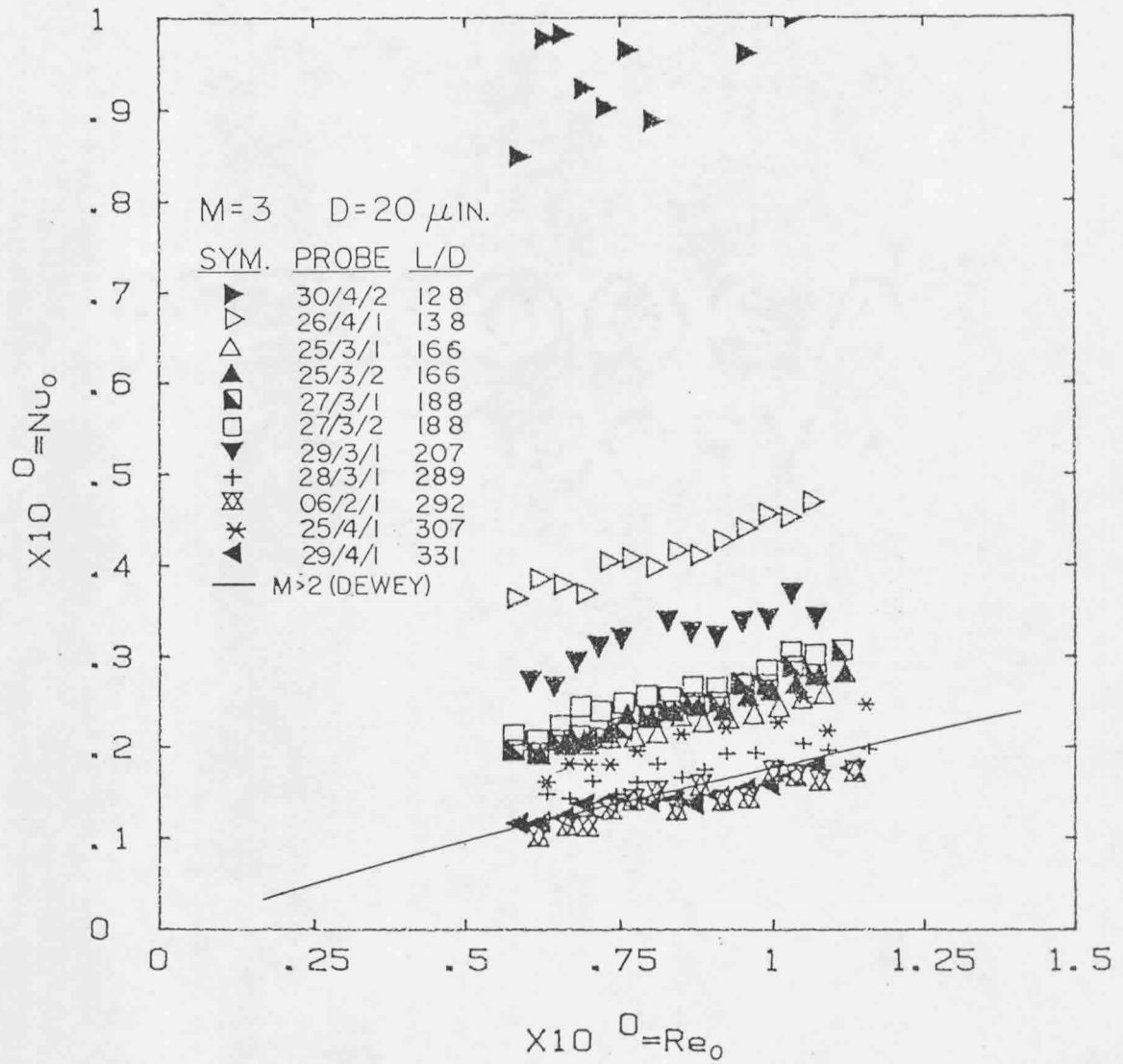


Figure 21. End loss corrected heat transfer data; $M=3$, $d=20\mu\text{in.}$

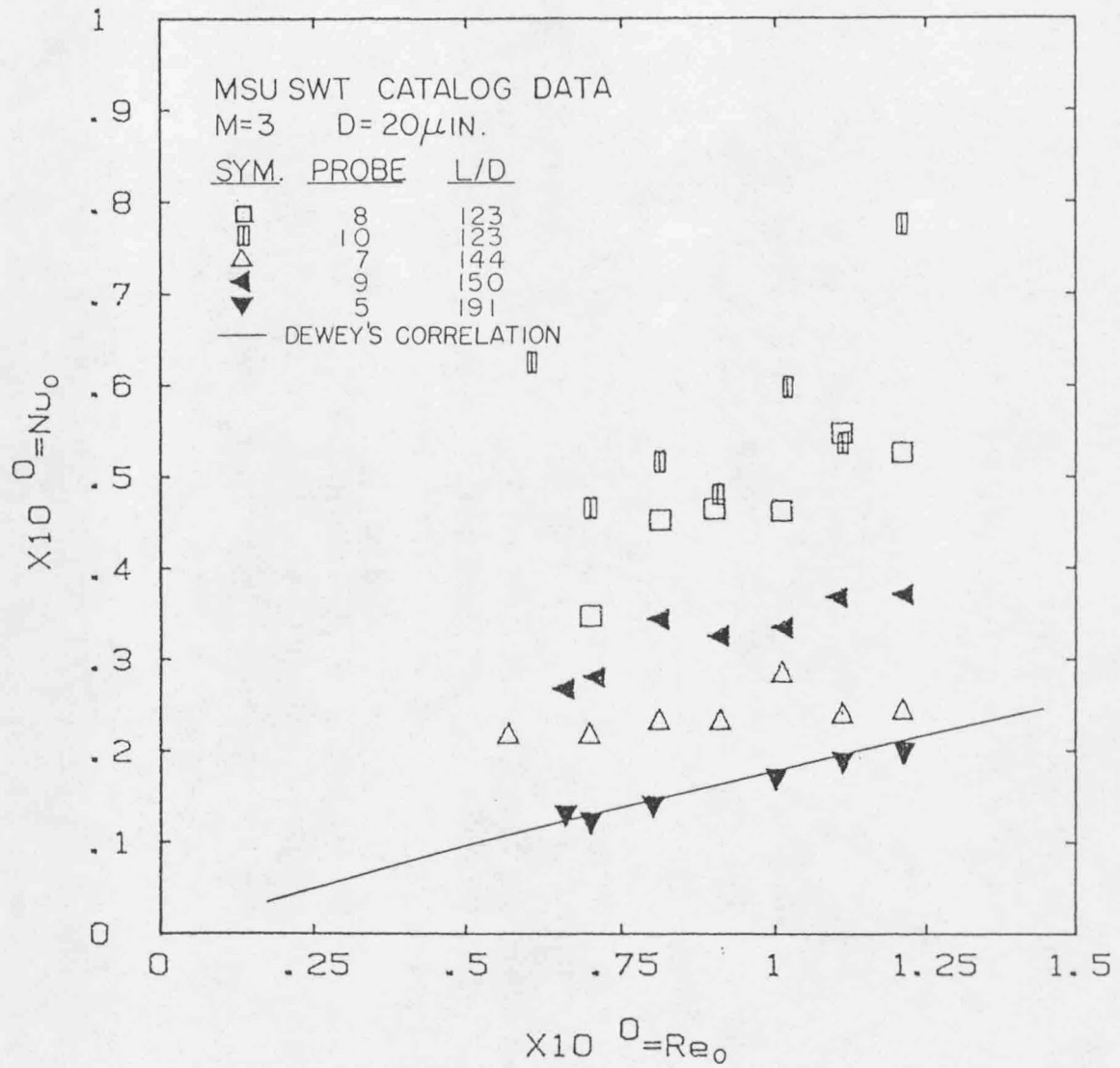


Figure 22. End loss corrected heat transfer data; MSU/SWT catalog data
 $M=3$, $d=20\mu\text{in.}$

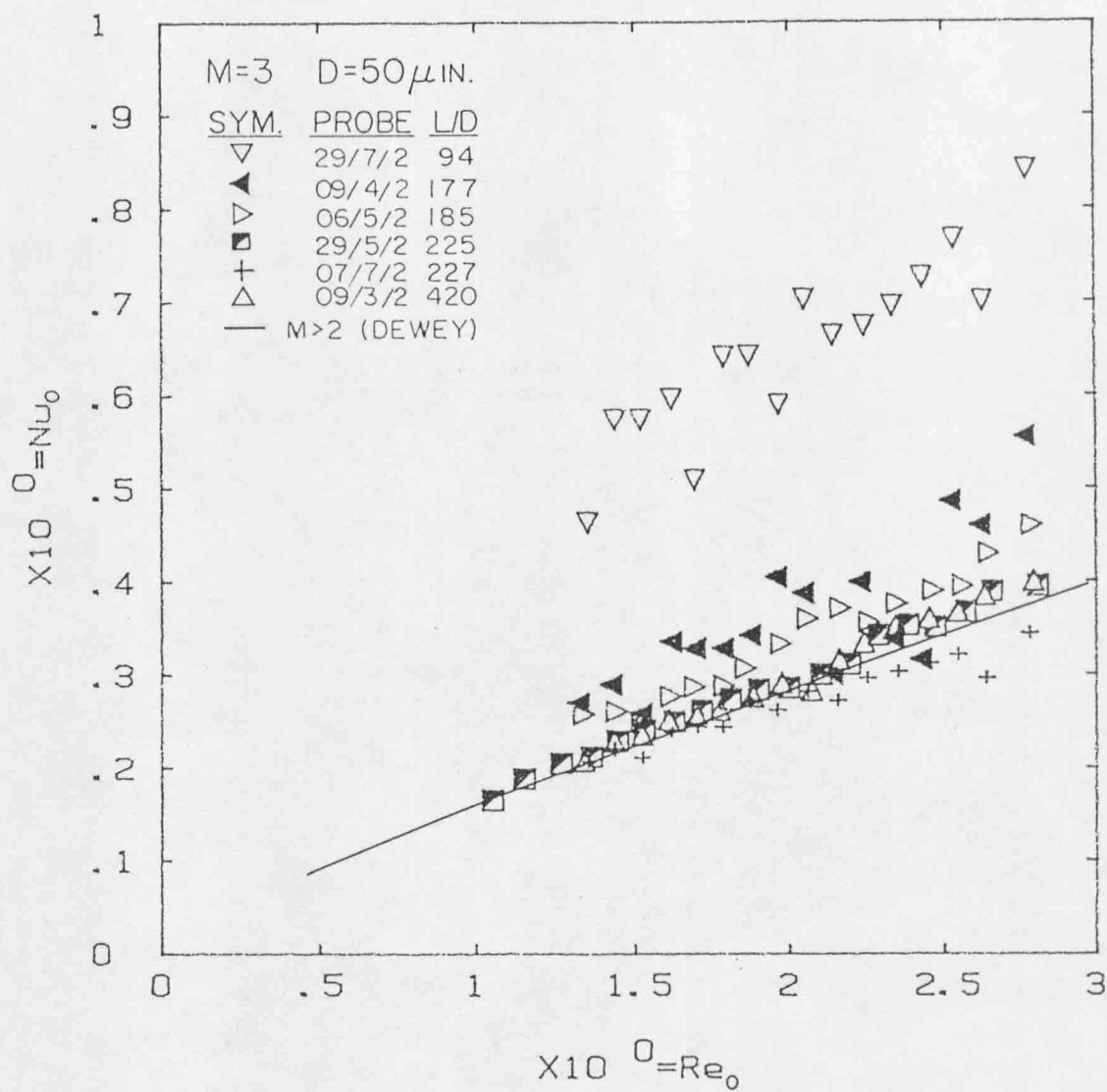


Figure 23. End loss corrected heat transfer data; $M=3$, $d=50\mu\text{in.}$

stagnation temperature of the air stream, T_o . For hot-wires in free-molecule flow, theory and results from previous investigations indicate $T_o < T_{aw}$. Thus, the evaluation of ψ_N assuming $T_s = T_o$ would result in a lower calculated value of Nu_o . Note, however, that a higher proportion of heat is conducted to the supports for smaller aspect ratio hot-wires, tending to raise the support temperature, decreasing ψ_N and resulting in an increase in the calculated value of Nu_o . The sensitivity of Nu_o to the support temperature was calculated and resulted in deviations less than 2 % for $\tau_s = \pm 1.0$. The codes HIFLOW02 and LOFLOW02 provide for input of specified values of τ_s .

The 20 μ m. data ($M=3$.) are shown in figure 21. The observations (1-3) noted on page 41 are clearly visible in these data. This behavior was verified (in figure 22) by 20 μ m. MSU/SWT catalog data in Mach 3 flow. All corrected MSU/SWT catalog data show a general ℓ/d dependence. Although figure 22 indicates that end loss correction satisfies Dewey's correlation for a hot-wire of $\ell/d=200$, the data of the present investigation show a much higher limit on ℓ/d for a fit to Dewey's correlation. The 50 μ m. data ($M=3$) of figure 23 show similar behavior although the approach to Dewey's correlation occur at a lower value of ℓ/d ($\ell/d=185$).

The corrected Nusselt number data presented in figure 24 clearly shows the effect of wire length on the measured Nusselt number. The fact that the 50 μ m. data converge to Dewey's correlation at a lower ℓ/d than the 20 μ m. data leads to the conclusion that the separation distance between the supports affects the flow distribution over the hot-wire resulting in a higher heat loss than that measured by longer

wires. It is interesting to note that an increase in the heat loss indicates a lower local Mach number or higher Reynolds number. If we assume $\ell/d = 180$ as the limit for 50 μ in wires where the support effect dissipates then we would expect a limit of $\ell/d = 450$ for the 20 μ in. wires in order to maintain the same separation between prongs (.0093 in./ .235 mm). However, figure 24 indicates a limit of approximately 300 at which point the prongs no longer affect the measured Nusselt number for 20 μ in hot-wires.

Verification of Dewey's correlation for $M < 2$ and 20 μ in. hot-wires is shown in figures 25 and 26. Data for two longer hot-wires ($\ell/d > 280$) are shown in figure 25. These data agree with Dewey's correlation within 18 % at $M = .4$ and 14 % at $M = 1$. The data collected at $M = .2$ agree to 13 % with the empirical correlation shown. Data for a shorter wire ($\ell/d = 207$) are shown in figure 26. The higher heat loss that was evident for low aspect ratio wires in the $M = 3$ measurements is clearly evident. Qualitatively, the data of figure 26 agree with Dewey's correlations, showing a decrease in Mach number dependence of Nu_0 with increasing M .

The hot-wire heat-loss behavior in low velocity incompressible flows ($M = 0$) is presented in figures 27 and 28. The support proximity effect which was evident in the compressible flow calibrations appears to exist in the $M = 0$ calibrations, although it is of lower magnitude. All the 20 μ in. data deviate from Collis and Williams' correlation by less than 23 %. Although the 50 μ in. data of figure 28 agree within 26 %, the data are extremely scattered with the exception of one wire (probe 29/6/1). The origin of this scatter is unknown, however, considering the uniformity of data from probe 29/6/1 and the

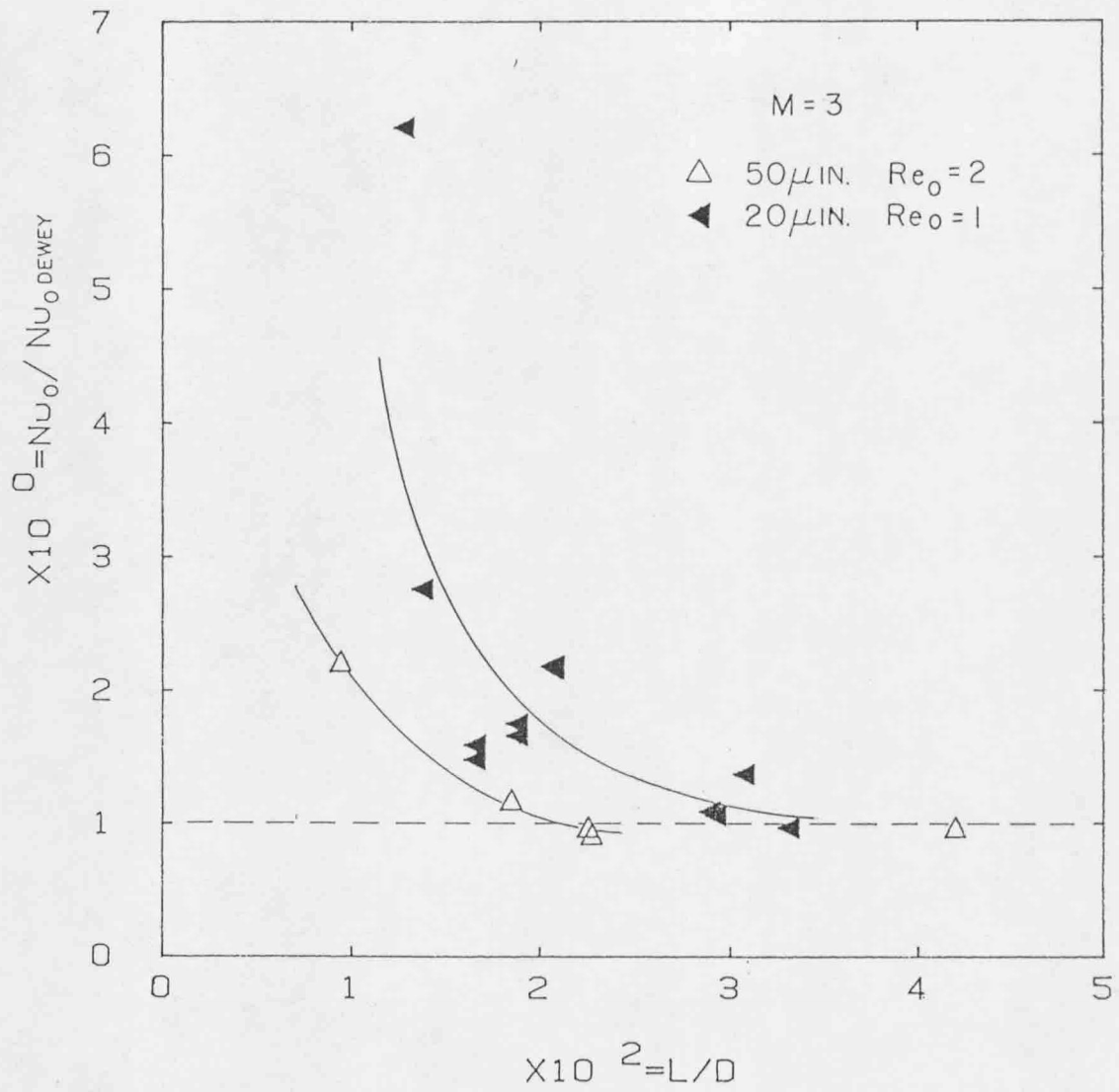


Figure 24. Support prong proximity effect on Nusselt number (normalized with Dewey's correlation).

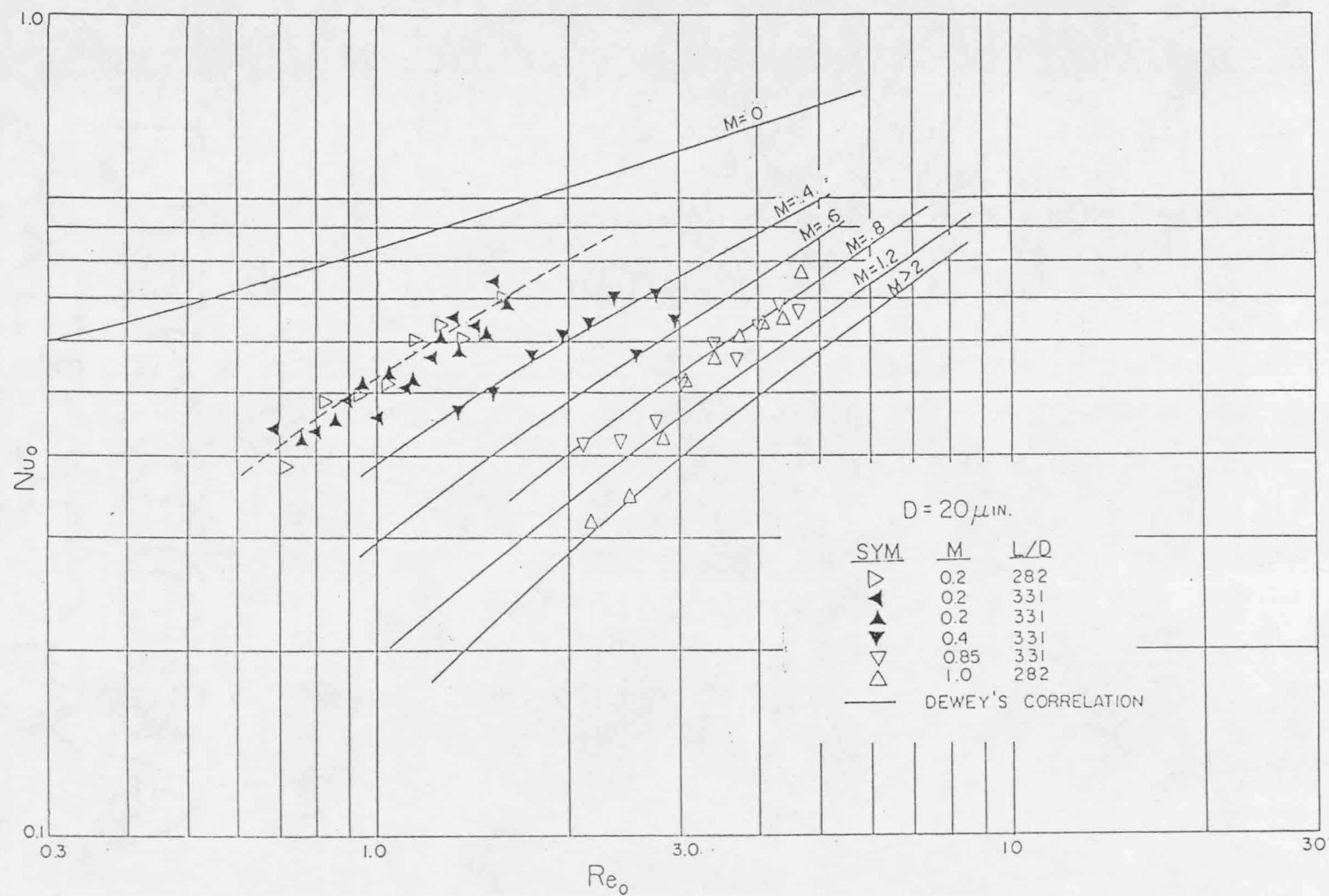


Figure 25. End loss corrected heat transfer data; $.2 < M < 1.$, $d = 20 \mu\text{in.}$

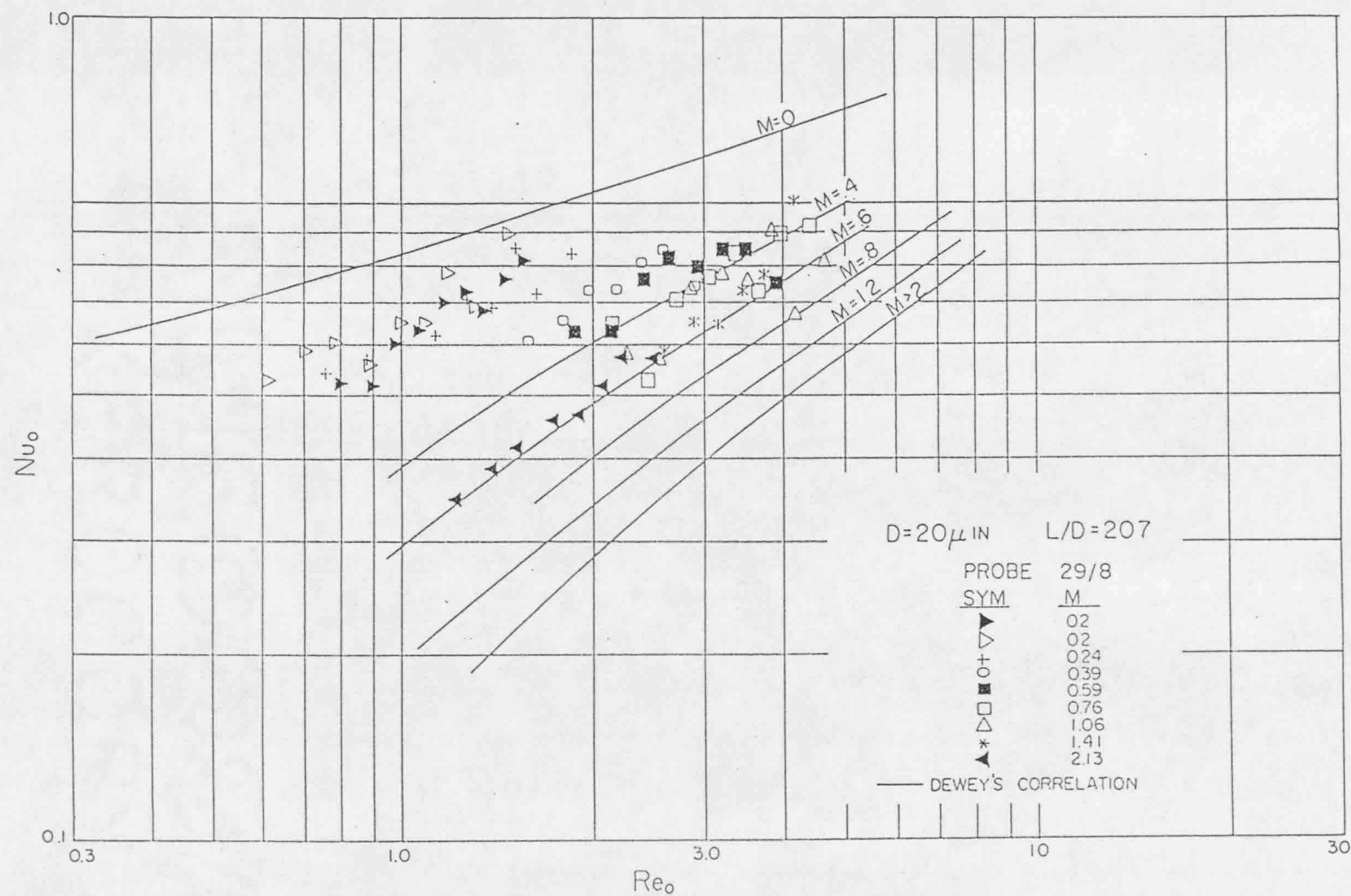


Figure 26. End loss corrected heat transfer data; probe 29/8.

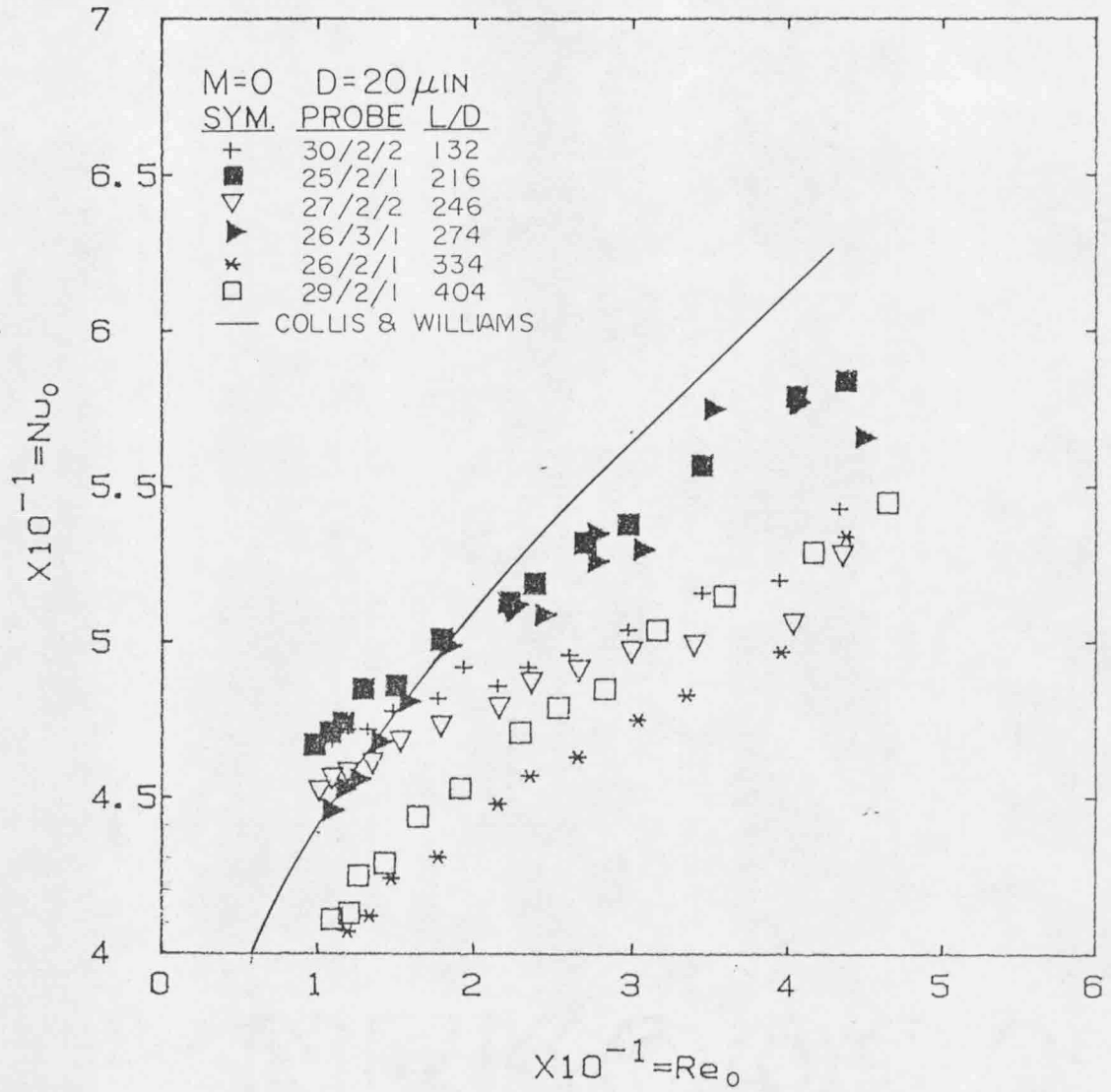


Figure 27. End loss corrected heat transfer data; $M=0$, $d=20 \mu\text{in}$.

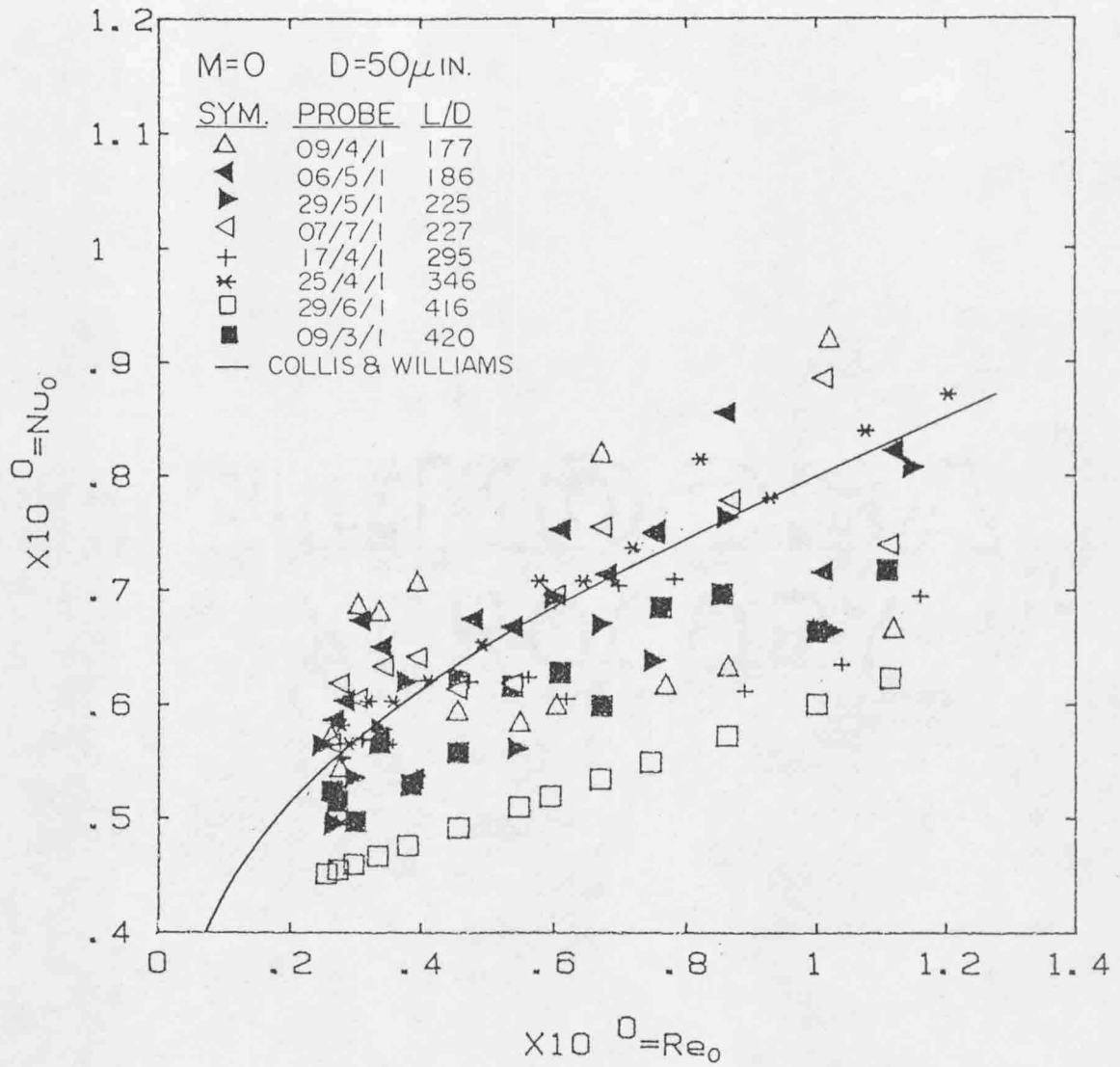


Figure 28. End loss corrected heat transfer data; $M=0$, $d=50\mu\text{in.}$

relatively well behaved data of figure 27, the scatter in the 50 μ in. data are attributed to some external source (i.e. electronics).

Figure 29 summarizes the data presented above. Data for hot-wires of aspect ratio less than 185 for 50 μ in wires and less than 280 for 20 μ in. wires are not included in the figure because of a definite support proximity dependence for hot wires of ℓ/d less than these values. The data of figure 25 was used for the compressible range of $M < 2$. and the scattered 50 μ in. low velocity data was not included.

End Loss Corrections

The variation of $\psi_N(S)_{i=0}$ (eqn. (2)) is shown in figure 30. For shorter wires where the support proximity affects the flow over the wire, the correction equation is of little value since the actual flow conditions in the vicinity of the hot-wire are not known. The magnitude of typical measured correction factors with Reynolds number is shown in figures 31-34. A correlation of ψ_N with ℓ/d was not attempted because, as shown in the Nusselt number data, Nu_m may vary considerably for hot-wires of nearly equal aspect ratio.

Recovery Temperature

Recovery temperature data are presented in figures 35-38. The recovery factors for 20 μ in. hot-wires used in this experiment are compared in figure 35 with data of similar flow conditions obtained by Demetriades [29]. No dependence on aspect ratio is evident in either the present data or the data of Demetriades. Attempts to correlate $\eta_{aw}(Kn)$ were not made considering the large variation of η_{aw} in figures 35 and 36. A surprising note is that these recovery temperature data

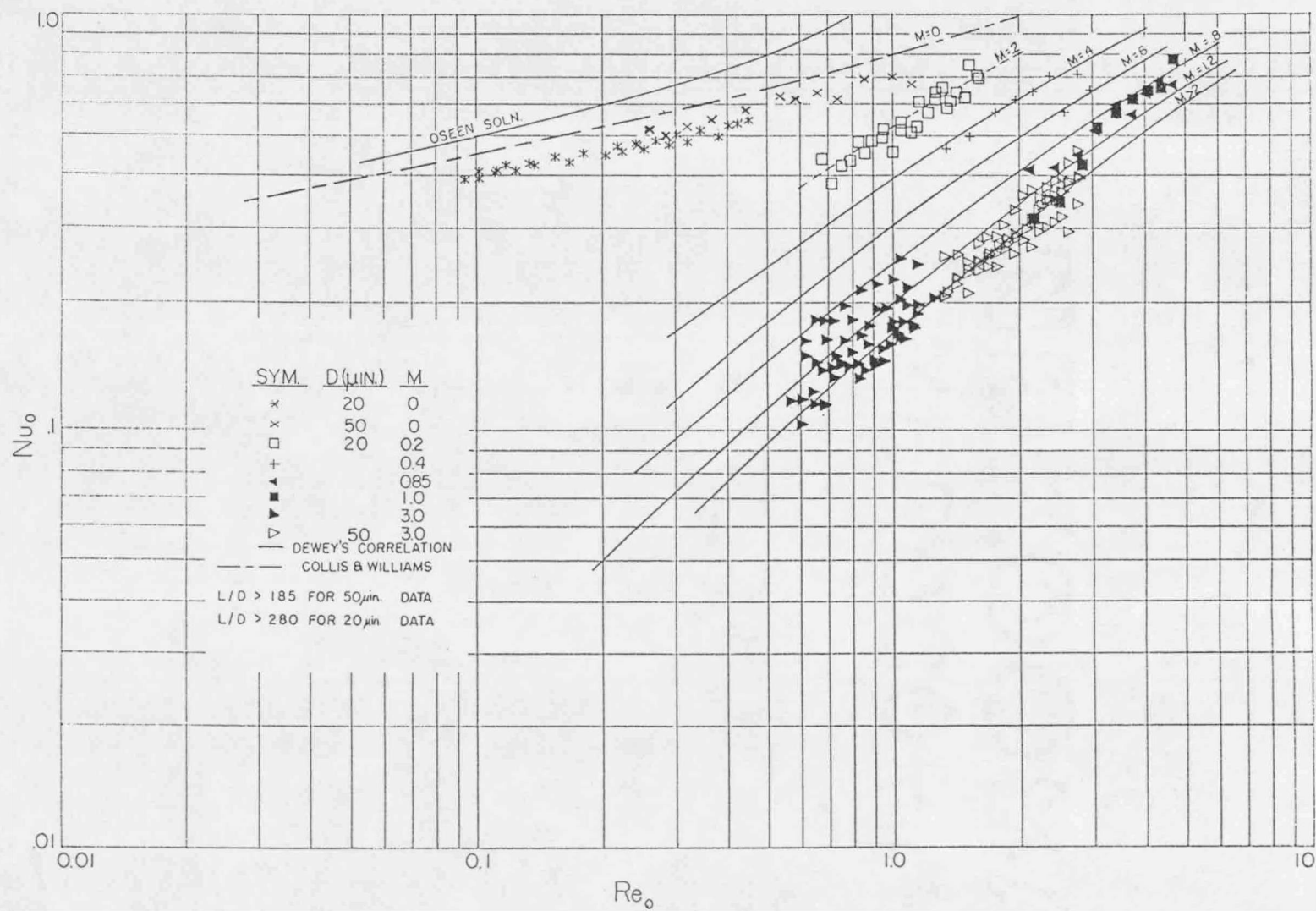


Figure 29. Summary of heat transfer data.

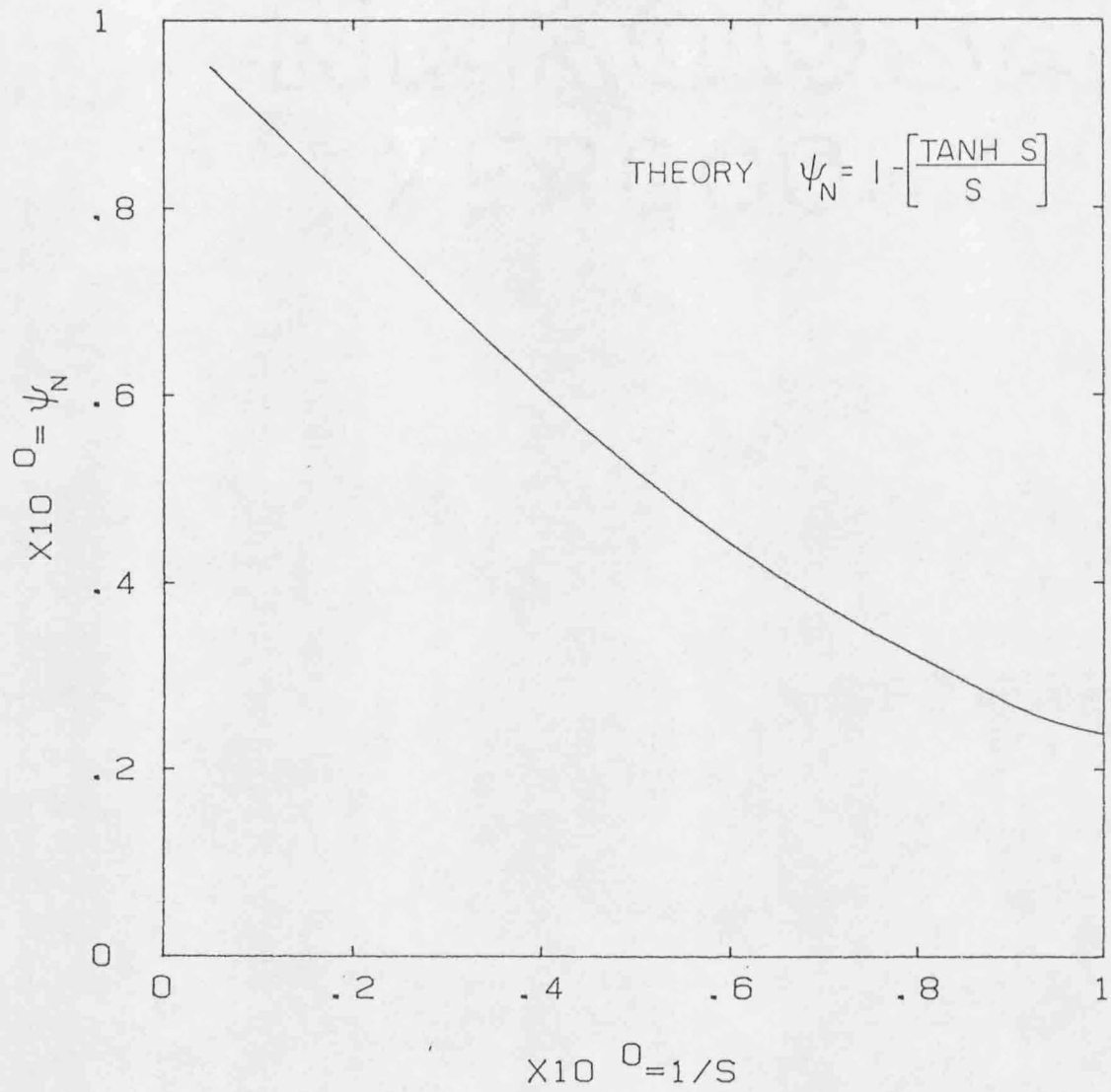


Figure 30. Theoretical end loss correction function.

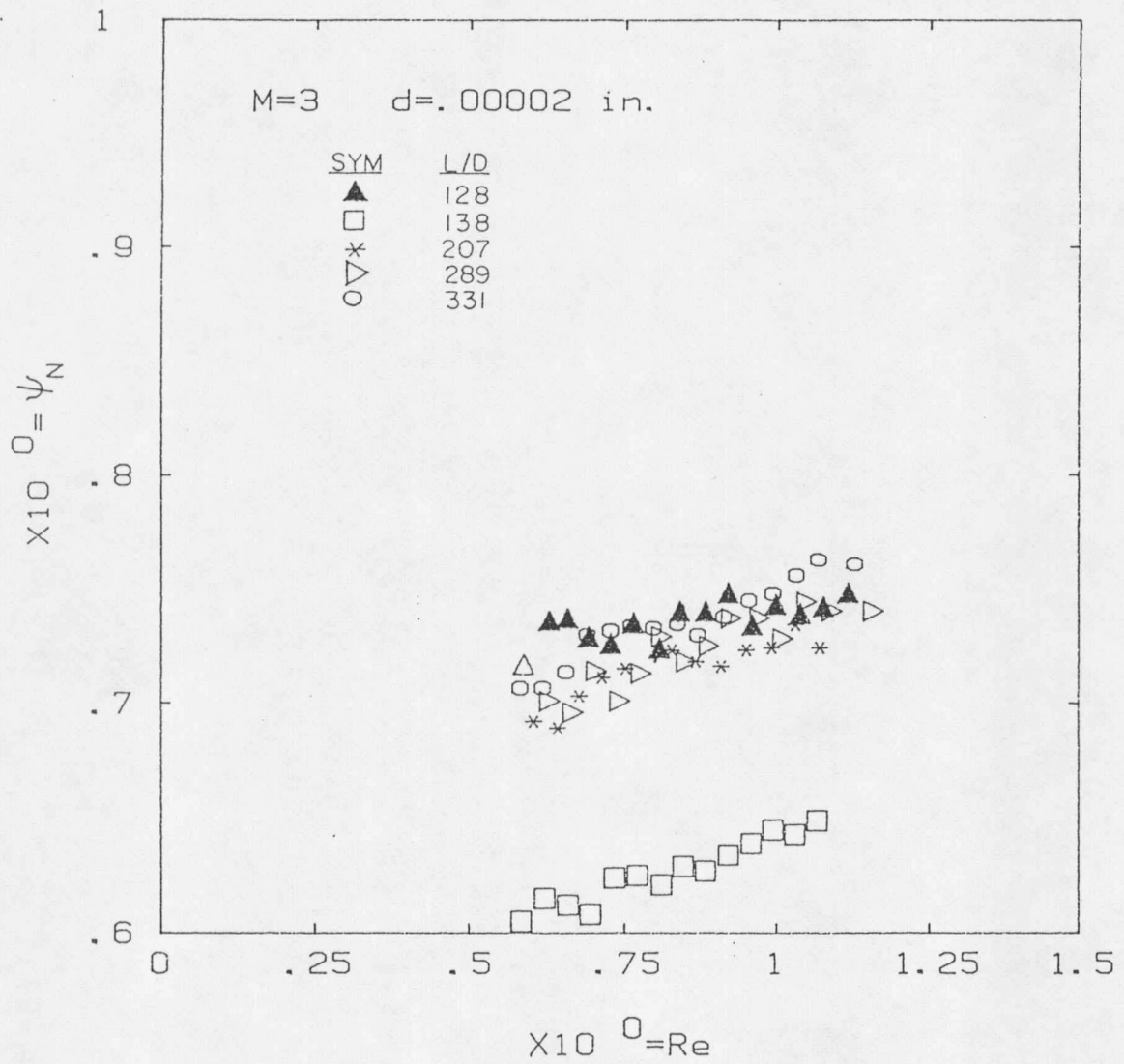


Figure 31. Typical end loss correction data; $M=3$, $d=20$ μ in.

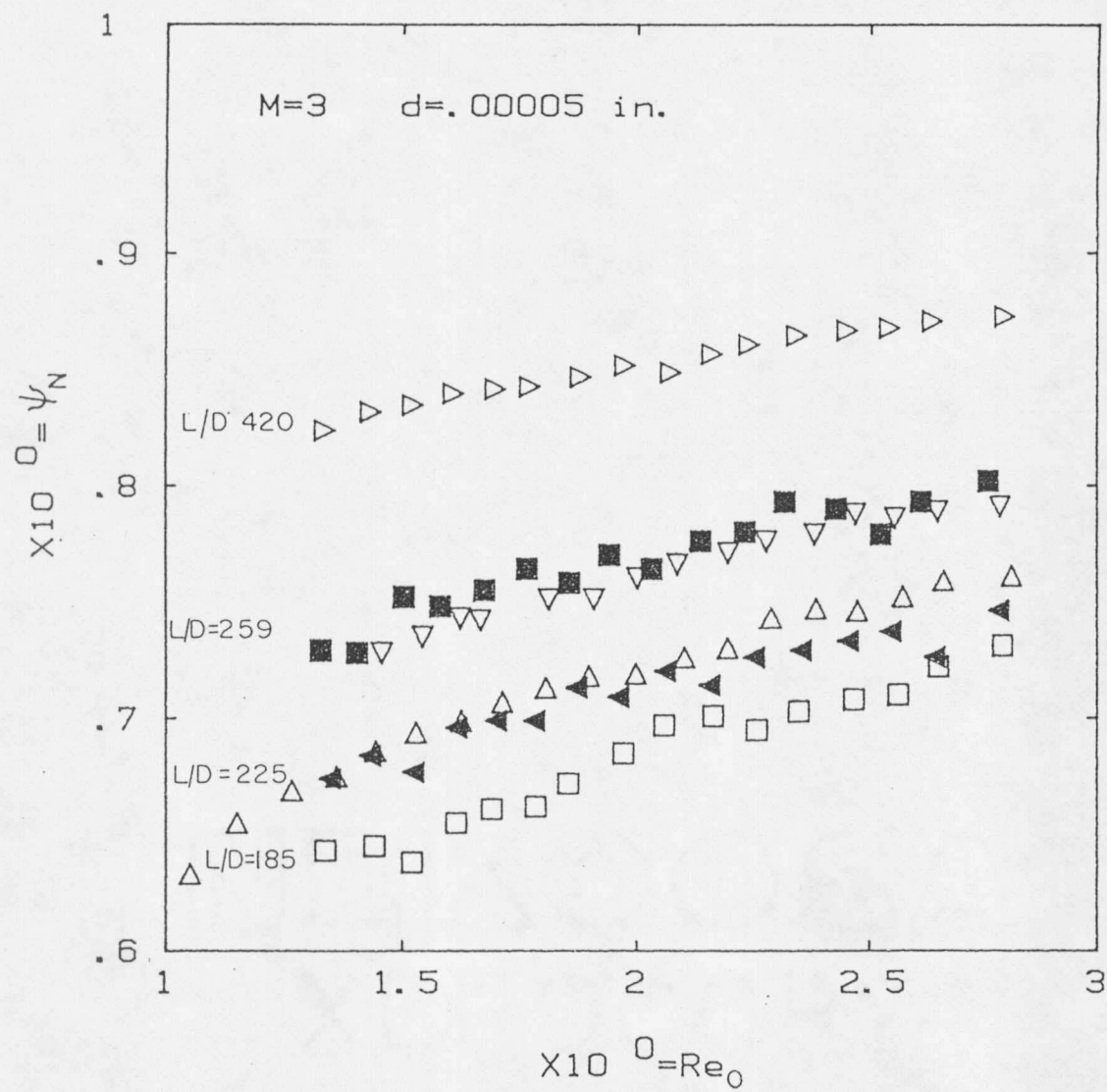


Figure 32. Typical end loss correction data; $M=3$, $d=50 \mu\text{in.}$

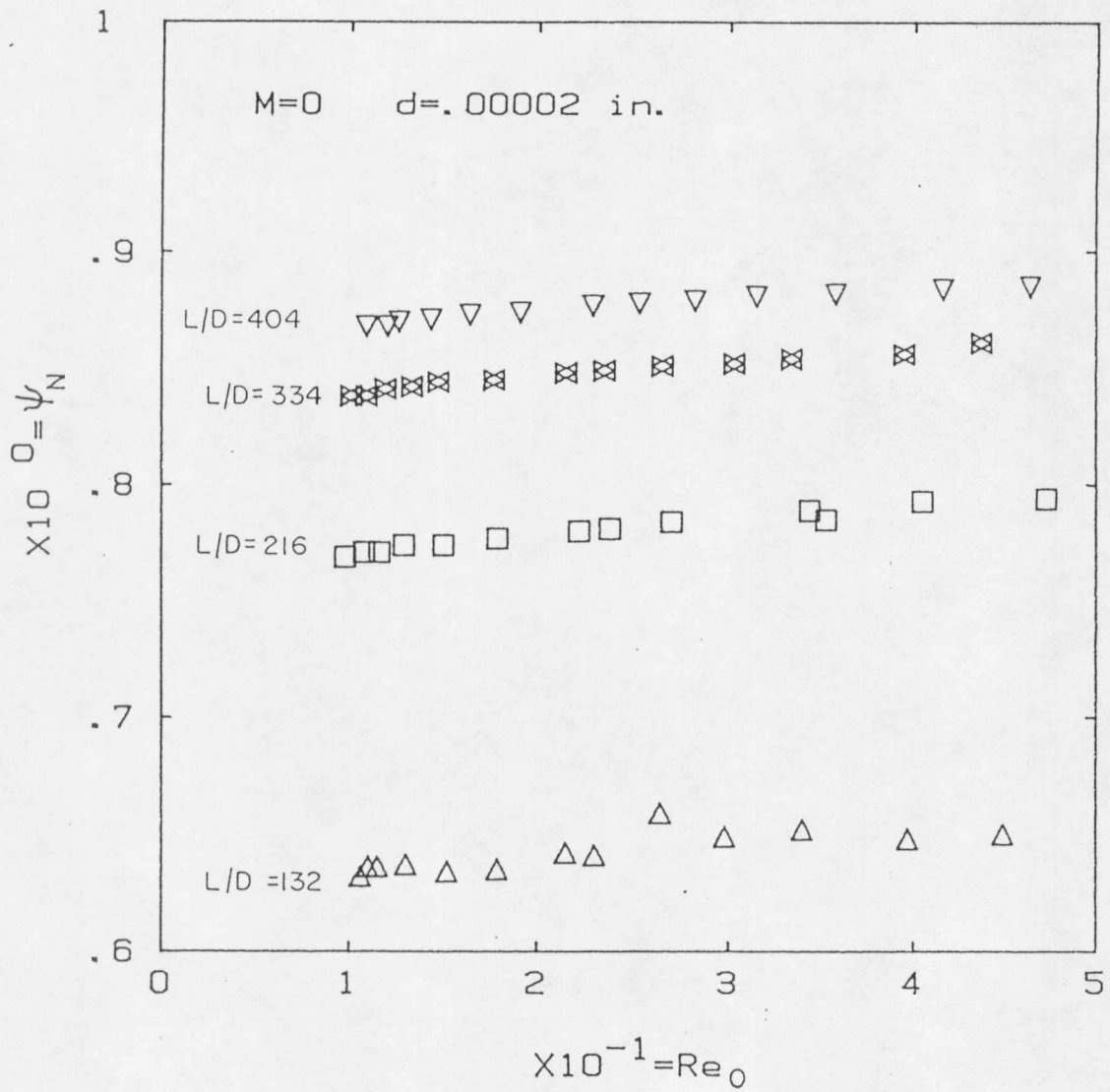


Figure 33. Typical end loss correction data; $M=0$, $d=20$ μ in.

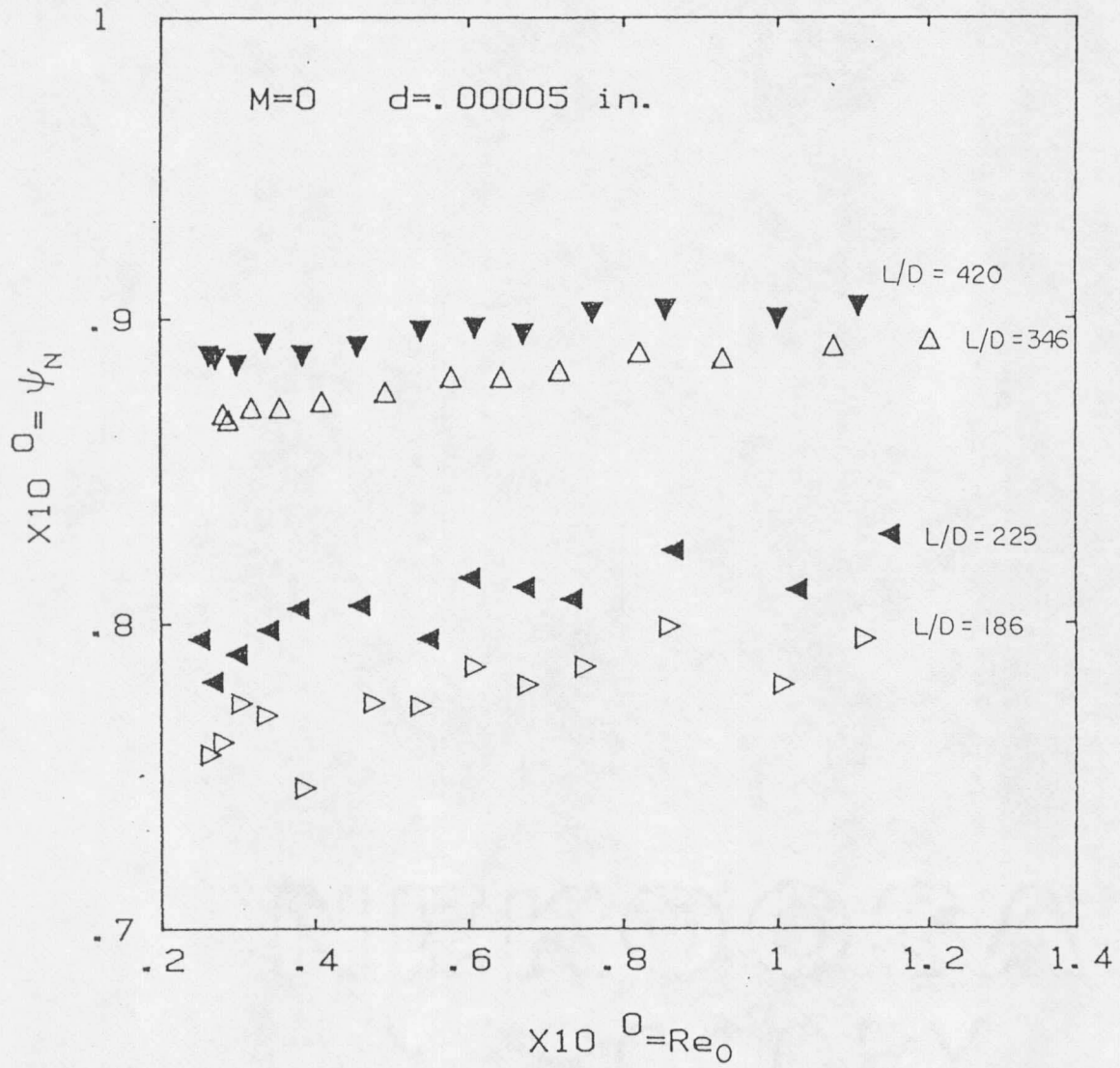


Figure 34. Typical end loss correction data; $M=0$, $d=50 \text{ } \mu\text{in.}$

indicate continuum or slip flow when recovery temperature data of Stalder et. al. at similar values of Kn ($0.6 < Kn < 2.5$) and molecular speed ratio ($s_1 = 2.5$) showed recovery factors consistently greater than unity indicating free-molecular flow.

The recovery factors for the $M=0$ data are shown in figures 37 and 38. For the continuum flow conditions of these tests ($.06 < Kn < .12$), the actual recovery temperature will not exceed the stagnation temperature. Recovery temperatures for 20 μ in. hot-wires in the low velocity tests were consistent at a value of $\eta_{aw} = 1.00 \pm .015$, with the exception of probe number 30/2/2 (figure 37). The scatter of the 50 μ in. Nusselt number data is also evident in the recovery temperature data of figure 38. The recovery factors of the well-behaved probe (29/6/1) also indicates the total temperature with $\eta_{aw} = 1.0 \pm .025$.

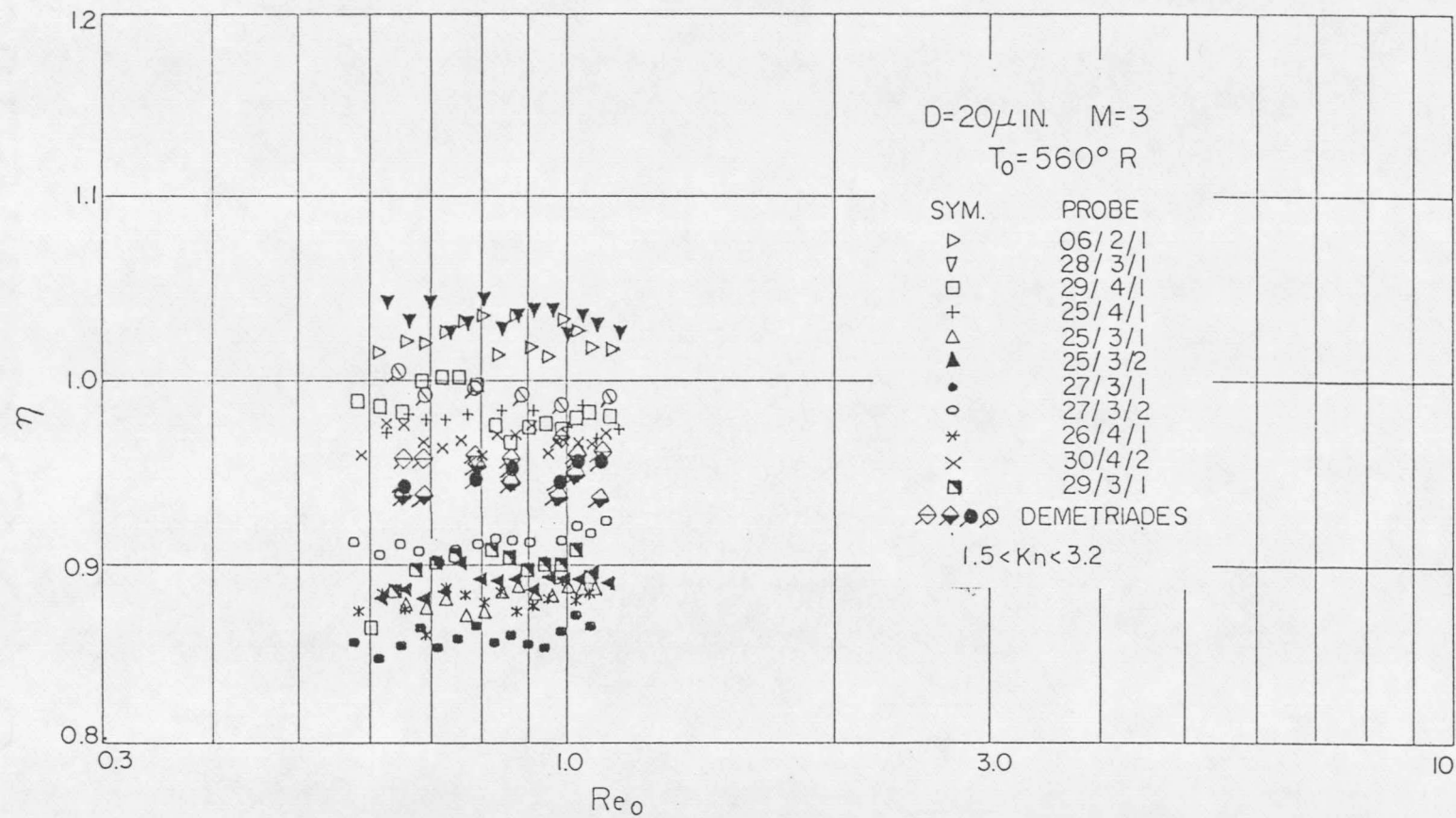


Figure 35. Recovery temperature data; $M=3$, $d=20\mu\text{in.}$

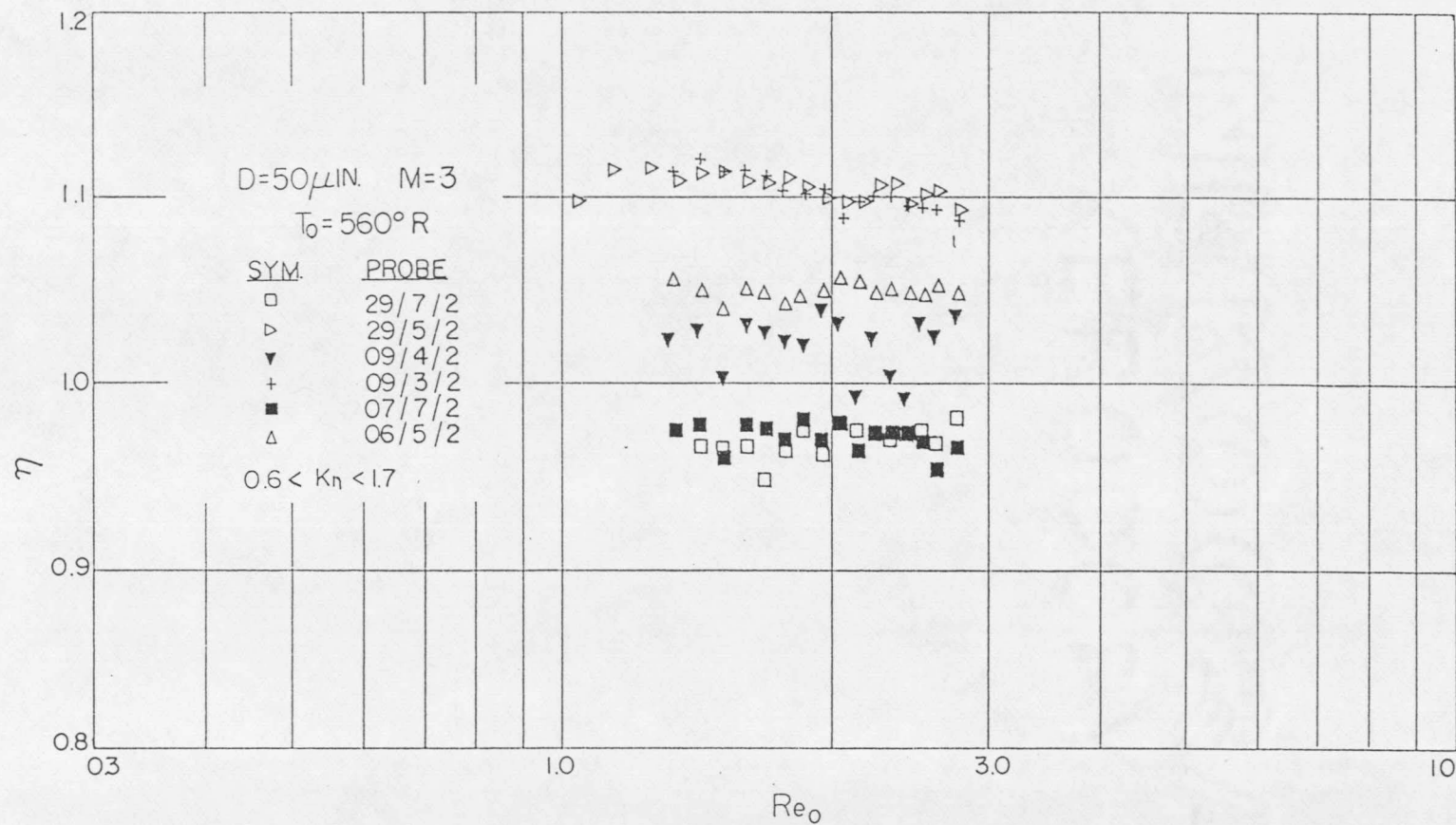


Figure 36. Recovery temperature data; $M=3$, $d=50\mu\text{in.}$

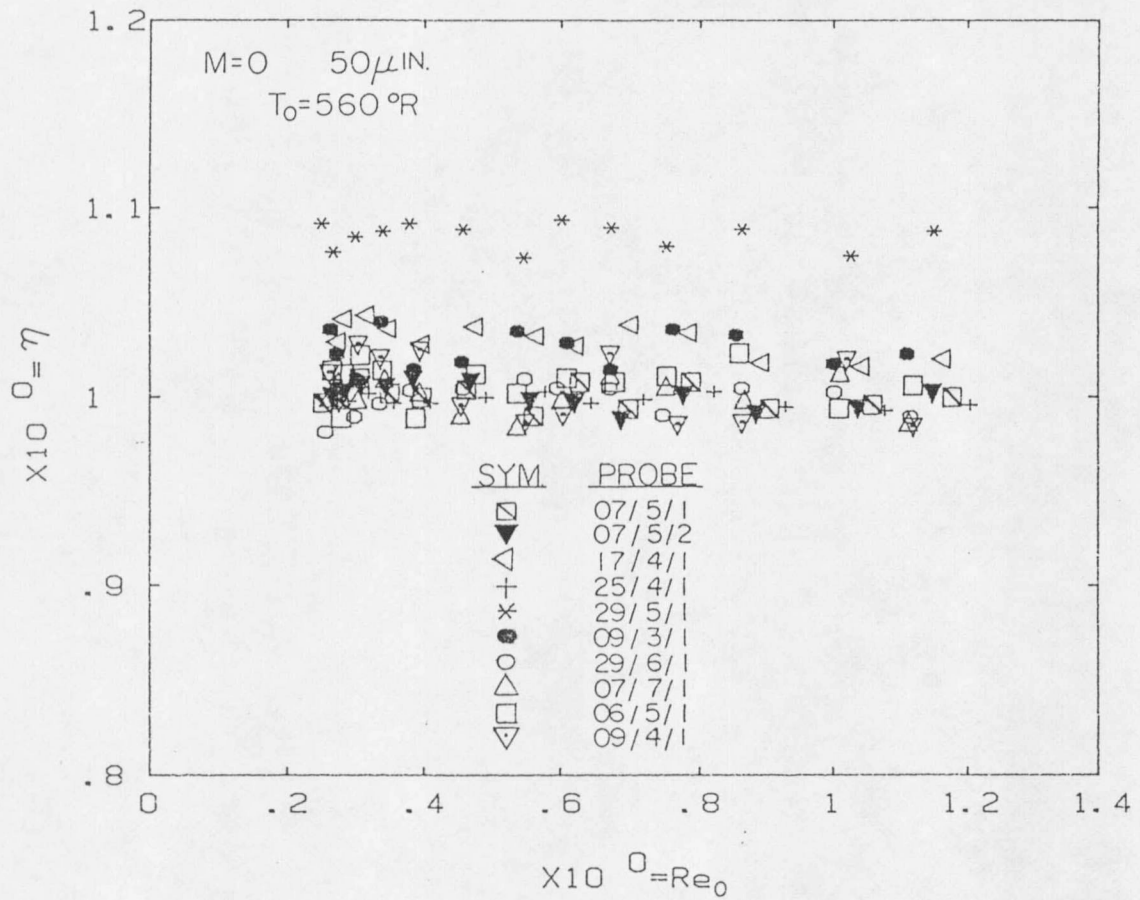


Figure 37. Recovery temperature data; $M=0$, $d=50\mu\text{in.}$

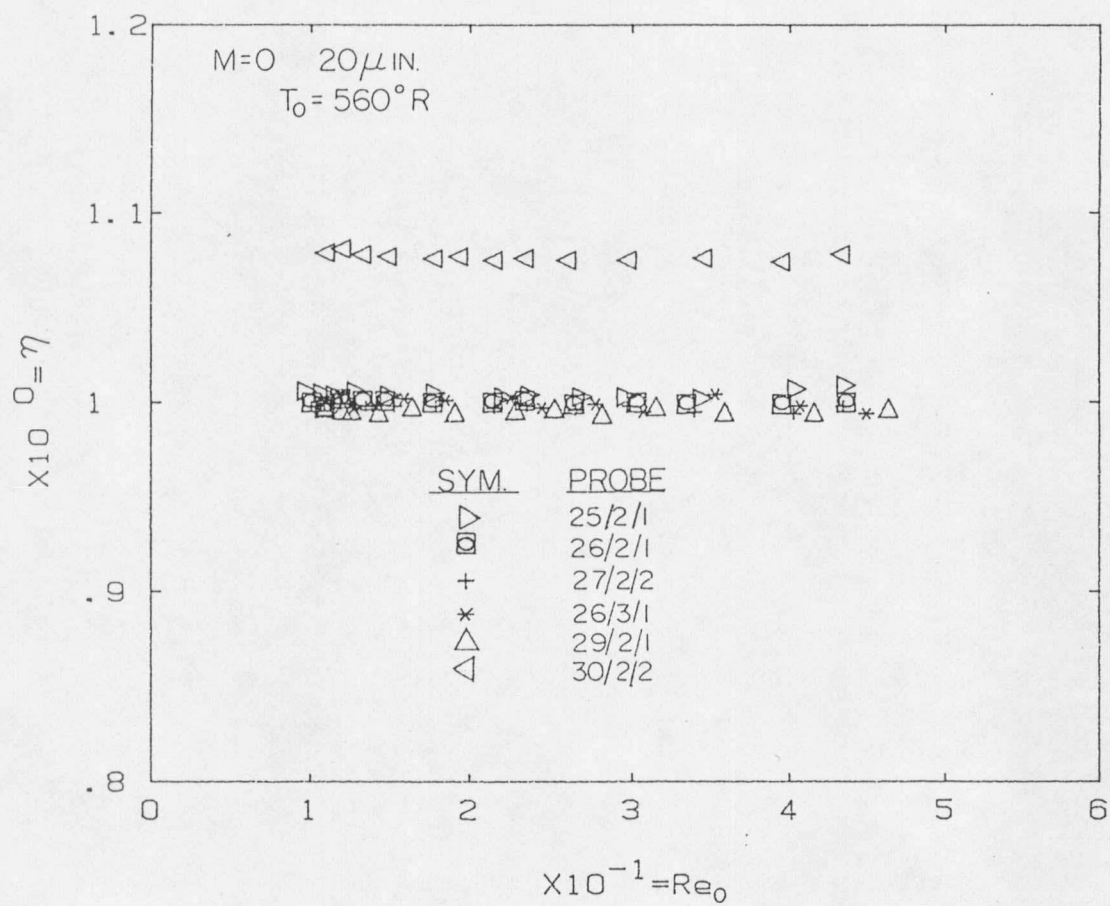


Figure 38. Recovery temperature data; $M=0$, $d=20\mu\text{in.}$

CHAPTER 5

CONCLUSION

The preceding results show that the heat loss characteristics for a finite hot-wire with configurations of the type used in this investigation may not be accurately predicted, and that individual flow calibration is required for each hot-wire used in quantitative flow study. Specific behavior patterns for these probes are summarized in the following discussion.

1. The heat loss from the hot-wires used in this investigation is clearly affected by the proximity of the support prongs. The result is an increase in the indicated Nusselt number with decreasing aspect ratio. An increase in heat transfer indicates either a decrease in the local M or an increase in the local Re . The effect is evident in the compressible flow data for 50 μ in. hot-wires with ℓ/d less than approximately 200 and 20 μ in. wires with $\ell/d < 300$. The theory assumes a uniform heat transfer coefficient over the length of the wire (i.e. uniform flow distribution) which may be a poor assumption considering the actual geometry of the hot-wire.
2. The compressible flow Nusselt number data of longer wires show general agreement with Dewey's correlation. The Mach number dependence indicated by previous investigations extends to the smaller hot-wires indicating a Mach number independence of Nu_0 for $M > 2$.

3. Incompressible heat loss data also appear to be affected by aspect ratio. The general trend is similar to the effect at higher velocity although a clear limit on ℓ/d is not visible in the data. The data for higher aspect ratio wires indicate values of Nu_0 smaller than values predicted by the correlation of Collis and Williams (by 5% - 20%).
4. As with the Nusselt number data, the recovery temperature of supersonic flow may not be accurately predicted and individual hot-wire calibration is necessary for quantitative recovery temperature measurements. Recovery temperatures in the range $.85 < \eta_{aw} < 1.12$ were measured in Mach 3 flow at 560 °R. Demetriades measured recovery factors in the range $.94 < \eta_{aw} < 1.01$ using similar probes subjected to similar flow conditions. No aspect ratio dependence is visible in either the data presented here or the data of Demetriades. Data obtained by Stalder et. al. for hot-wires in a rarefied supersonic flow with Knudsen numbers and molecular speed ratios equal to those of this experiment consistently indicate a recovery factor greater than unity. Possible causes for the discrepancy in the recovery factors between the two experiments is (1) the flow in the vicinity of the probe is affected by the support prongs so that the actual Reynolds number and Knudsen number are lower than for ideal conditions, and (2) the R vs. W polynomial fit of the flow calibration data using the method suggested by Demetriades incorrectly predicts the intercept $R(W=0)$ which determines the recovery temperature.

APPENDICES

APPENDIX A

OVEN CALIBRATION DATA REDUCTION CODE

```

10 REM OVENCALS
20 REM
30 REM This oven-calibration program uses quadratic fit of resistance vs
40 REM current squared or current-squared-times-resistance to find the
50 REM zero-current resistance at each temperature.
60 REM .....Assumption: wire diameter=0.00002 inch.....
70 REM Line 180 was added to correct wrong data file info during runs of
80 REM 1/26/83. If line resistance is correctly written in future data file
  s,
90 REM line 180 can be removed.
95 REM ..... UPDATED MAY 6, 1984 .....
100 DIM T(15),C1(181),V1(181),C(181),V(181),R(181),C2(181),B(181),B1(181)
120 DIM B2(181),B3(181)
130 DIM R2(16)
140 DIM R3(16)
150 DIM G9(16)
160 DIM R6(16)
170 DIM C3(181)
180 DIM D(20),D1(20),D2(20),D0(20),A0(20),A1(20),A2(20)
190 DIM VOLT(1081,2)
191 DIM N2(7)
200 INPUT "INPUT OVEN CALIBRATION DATA FILE:";F1$
210 OPEN "I",#1,F1$
220 PRINT
230 PRINT "THIS IS A QUADRATIC RESISTANCE-CURRENT FIT WITH OPTIONS:"
240 PRINT "      TYPE '1' TO FIT R-I2 (R=A+BI2+CI4)"
250 PRINT
260 PRINT "      TYPE '2' TO FIT R-RI2 (R=A+BRI2 +CR2I4)"
270 PRINT
280 PRINT "WHICH OPTION DO YOU WANT";
290 INPUT Z
300 INPUT "INPUT THE NUMBER OF WIRES IN THIS OVEN CALIBRATION ";N1
310 INPUT "INPUT THE NUMBER OF CURRENTS PER WIRE PER TEMPERATURE ";A3
320 INPUT "INPUT THE NUMBER OF TEMPERATURES USED ";T1
330 FOR I=1 TO T1
340 PRINT "INPUT TEMPERATURE NUMBER ";I
350 INPUT T(I)
360 NEXT I
370 PRINT
380 PRINT "      i(ma) = D1 + D2*(DIGITAL COUNTS)"
390 PRINT "      v(mv) = D3 + D4*(DIGITAL COUNTS)"
400 PRINT "      LINE RESISTANCE = D5 + D6*(TEMP. C)"
410 INPUT "INPUT D1";D1
420 INPUT "INPUT D2";D2
430 INPUT "INPUT D3";D3
440 INPUT "INPUT D4";D4
450 INPUT "INPUT D5";R1
460 INPUT "INPUT D6";S1
470 FOR I=1 TO N1
480 PRINT "INPUT THE INSTRUMENT NUMBER FOR POSITION NUMBER ";I
490 INPUT N2(I)
500 NEXT I
510 INPUT "INPUT STANDARD WIRE RESISTANCE (OHMS/FT) (CR=277970)";R6
520 IF R6=0 THEN R6=277970!
530 FOR I=1 TO A3*N1*T1
540 INPUT #1,VOLT(I,1),VOLT(I,2)
550 NEXT I
551 K=1
560 PRINT
570 X2=1

```

```

580 FOR I=1 TO T1
590 I2=I-1
600 C10 = I2*N1*A3 + (K-1)*A3 +1
610 FOR J=C10 TO (C10+A3-1)
620 V1(X2) = VOLT(J,1)
630 C1(X2) = VOLT(J,2)
640 X2 = X2 + 1
641 NEXT J
642 NEXT I
650 PRINT
660 PRINT
670 PRINT "THIS IS 'OVENCAL2' PROGRAM. ZERO-CURRENT RESISTANCES COMPUTED"
680 IF Z=2 GOTO 710
690 PRINT "BY QUADRATIC FIT OF R VS I2"
700 GOTO 720
710 PRINT "BY QUADRATIC FIT OF R VS I2R"
720 PRINT "-----"
730 PRINT
740 PRINT
790 FOR J=1 TO T1
800 LET G1=0
810 LET G2=0
820 LET G3=0
830 LET G4=0
840 LET G5=0
850 LET G6=0
860 LET G8=0
870 LET G7=0
880 PRINT
890 PRINT
900 PRINT "R-I2R DATA FOR T(DEG C)='";T(J)
910 PRINT "-----"
920 PRINT "I(MA)","V(MV)","I2(MA2)","I2R(MA2OHM)","R(OHM)"
930 PRINT
940 FOR N=(J-1)*A3+1 TO J*A3
950 LET C(N)=D1+D2*C1(N)
960 LET V(N)=D3+D4*V1(N)
970 LET R(N)=V(N)/C(N) - (R1 + S1 * T(J))
980 LET C2(N)=(C(N)^2)*R(N)
990 IF Z=1 GOTO 1020
1000 LET C3(N)=C2(N)
1010 GOTO 1030
1020 LET C3(N)=C(N)^2
1030 PRINT C(N),V(N),C(N)^2,R(N)*(C(N)^2),R(N)
1040 LET G1=G1+C3(N)
1050 LET G2=G2+C3(N)^2
1060 LET G3=G3+C3(N)^3
1070 LET G4=G4+C3(N)^4
1080 LET G5=G5+R(N)
1090 LET G6=G6+R(N)*C3(N)
1100 LET G7=G7+(C3(N)^2)*R(N)
1110 NEXT N
1120 LET D(J)=A3*G2*G4+2*G1*G2*G3-G2^3-A3*(G3^2)-(G1^2)*G4
1130 LET D0(J)=G5*G2*G4+G2*G3*G6+G1*G3*G7-(G2^2)*G7-(G3^2)*G5-G1*G4*G6
1140 LET D1(J)=A3*G4*G6+G1*G2*G7+G2*G3*G5-(G2^2)*G6-A3*G3*G7-G1*G4*G5
1150 LET D2(J)=A3*G2*G7+G1*G3*G5+G1*G2*G6-(G2^2)*G5-A3*G3*G6-(G1^2)*G7
1160 LET A0(J)=D0(J)/D(J)
1170 LET A1(J)=D1(J)/D(J)
1180 LET A2(J)=D2(J)/D(J)
1190 FOR N=(J-1)*A3+1 TO J*A3
1200 LET G8=G8+(R(N)-A0(J)-A1(J)*C3(N)-A2(J)*(C3(N)^2))^2

```

```

1210 NEXT N
1220 LET G9(J)=SQR(G8)/A3
1230 PRINT
1240 IF Z=1 GOTO 1270
1250 PRINT "CURVE-FIT OF R VS I2R GIVES R(I=0)=";A0(J)
1260 GOTO 1280
1270 PRINT "CURVE FIT OF R VS I2 GIVES R(I=0)=";A0(J)
1280 PRINT "RMS DEVIATION OF R FROM CURVE-FIT AT THIS TEMP. (OHMS)=";G9(J)
1290 PRINT
1300 PRINT
1310 NEXT J
1320 PRINT "SUMMARY: ZERO-CURRENT RESISTANCE VS. TEMPERATURE"
1330 PRINT "-----"
1340 PRINT
1350 PRINT "T(DEG C)", "R(OHMS)"
1360 PRINT
1370 PRINT
1371 F=0
1372 F1=0
1373 F2=0
1374 F3=0
1375 F4=0
1376 F5=0
1380 FOR J=1 TO T1
1390 PRINT T(J),A0(J)
1400 LET F=F+T(J)
1410 LET F1=F1+A0(J)
1420 LET F2=F2+T(J)*A0(J)
1430 LET F3=F3+T(J)^2
1440 NEXT J
1450 LET R4=(F*F1-T1*F2)/(F^2-T1*F3)
1460 LET R5=(F1-R4*F)/T1
1470 FOR J=1 TO T1
1480 LET F4=F4+(A0(J)-R5-R4*T(J))^2
1490 LET F5=F5+G9(J)
1500 NEXT J
1510 LET R7=(SQR(F4))/T1
1520 LET R8=F5/T1
1530 PRINT
1540 PRINT "DATA FILE FOR THIS CALIBRATION IS ";F1$
1550 PRINT "INSTRUMENT NUMBER IS ";N2(K)
1560 PRINT
1570 PRINT "CURVE-FIT OF R(I=0) VS T GIVES:"
1580 PRINT "AVERAGE RESISTANCE-CURRENT DEVIATION FOR ALL TEMPS (OHMS)=";R8
1590 PRINT "R0(OHMS, AT 0 DEG C)=";R5
1600 PRINT "ARO (OHMS/DEG C)=";R4
1610 PRINT "OVERALL RMS DEVIATION OF R FROM R-T CURVE (OHMS)=";R7
1620 PRINT "ALPHA (REFERRED TO R0 AS ABOVE, PER DEG C)=";R4/R5
1630 PRINT "L(cm)=";(12*(R5+20*R4)/R6)*2.54
1640 PRINT "L/D=";12*(R5+20*R4)/(.00002*R6)
1650 PRINT
1660 PRINT "HIT CR TO CONTINUE WITH NEXT WIRE";
1670 INPUT Z10
1675 IF K=N1 THEN GOTO 1700
1677 K=K+1
1690 GOTO 560
1700 CLOSE #1
1710 END

```

OK

APPENDIX B

FLOW CALIBRATION DATA REDUCTION CODE: INCOMPRESSIBLE FLOW

```

10 REM LOFLOW02
11 REM THIS PROGRAM USES DATA FROM THE LOW SPEED CALIBRATION TO DETERMINE
12 REM THE HOT-WIRE CHARACTERISTICS. CORRECTIONS FOR END LOSSES ARE MADE
13 REM USING DEWEY'S ITERATION PROCEDURE.
14 REM *****
20 DIM V(250),V1(250),C(250),C1(250),R(250),C2(250),C3(250)
30 DIM F1(250),F2(250),N(250),J(20),B12(20),M(20)
40 DIM D(20),D0(20),D1(20),D2(20),A0(20),A1(20),A2(20)
50 DIM B17(20),T1(20),N0(20),T2(250),T3(250),N1(250),N1(20)
60 DIM M4(20),R2(20),P3(20)
70 DIM U(20)
80 DIM T4(20),M5(20),R3(20),M6(20),R4(20),K1(20),N2(20),R5(20)
90 INPUT "INPUT FLOW CALIBRATION DATA FILE:";F14
100 OPEN F14 FOR INPUT AS FILE #1
110 INPUT #1,A11,A12,A13,A3,D1,D2,D3,D4,R1,P,A,S,T,L,D,P11
115 LET T=5/9*(T+460)
120 FOR N=1 TO A3*P
130 INPUT #1,V1(N),C1(N)
140 NEXT N
150 PRINT "INPUT VELOCITY PRESSURE INFORMATION (P0-P),(PA-P)"
160 FOR J=1 TO P
170 INPUT DP,DPA
180 DP=DP*1.87038
190 DPA=DPA*1.87038
200 PS=P11-DPA
210 RHO=PS*.0013594/(2925.6*T)
220 U(J)=(DP*1.32992*2/RHO)*.5
230 NEXT J
240 PRINT
250 PRINT
260 PRINT "THIS IS THE 'LOFLOW01' PROGRAM WHICH COMPUTES RESISTANCES AND"
270 PRINT "SLOPES BY QUADRATIC R-R12 FITS (I.E. R=A + B12R +C(I2R)2)"
280 PRINT "-----"
290 PRINT
300 PRINT
310 PRINT "PROBE HOLDER NO.:";A11
320 PRINT "WIRE NO.:";A12
330 PRINT "FLOW CALIBRATION NO.:";A13
340 PRINT "ALL DATA SHOWN ARE FOR TEMPERATURE (IN DEG K) OF:";T
350 PRINT "AND BAROMETRIC PRESSURE (IN MM HG) OF:";P11
360 PRINT "THE SUPPORT TEMPERATURE LOADING (TS-TE)/TO IS";
370 INPUT TS
380 PRINT
390 PRINT
400 FOR J=1 TO P
410 LET E=0
420 LET B1=0
430 LET B2=0
440 LET B3=0
450 LET B4=0
460 LET B5=0
470 LET B6=0
480 LET B7=0
490 LET B8=0
500 LET B9=0
510 LET B10=0
520 PRINT "OVERHEAT TRAVERSES FOR FLOW SPEED (IN CM/SEC) OF:";U(J)
530 PRINT
540 PRINT "I(MA)","I2(MA2)","I2R","R(OHMS)","TW(DEG K)"
550 PRINT

```

```

560 FOR N=(J-1)*A3+1 TO A3*J
570 LET V(N)=D1+D2*V1(N)
580 LET C(N)=D3+D4*C1(N)
590 LET R(N)=(V(N)/C(N))-R1
600 LET C2(N)=C(N)^2
610 LET C3(N)=(C(N)^2)*R(N)
620 LET T2(N)=273.15+R(N)/S-1/A
630 PRINT C(N),C2(N),C3(N),R(N),T2(N)
640 LET B1=B1+C3(N)
650 LET B2=B2+C3(N)^2
660 LET B3=B3+C3(N)^3
670 LET B4=B4+C3(N)^4
680 LET B5=B5+R(N)
690 LET B6=B6+R(N)*C3(N)
700 LET B7=B7+(C3(N)^2)*R(N)
710 NEXT N
720 LET D(J)=A3*B2*B4+2*D1*B2*B3-B2^3-A3*(B3^2)-(B1^2)*B4
730 LET D0(J)=B5*B2*B4+B2*B3*B6+B1*B3*B7-(B2^2)*B7-(B3^2)*B5-B1*B4*B6
740 LET D1(J)=A3*B4*B6+B1*B2*B7+B2*B3*B5-(B2^2)*B6-A3*B3*B7-B1*B4*B5
750 LET D2(J)=A3*B2*B7+B1*B3*B5+B1*B2*B6-(B2^2)*B5-A3*B3*B6-(B1^2)*B7
760 LET A0(J)=D0(J)/D(J)
770 LET A1(J)=D1(J)/D(J)
780 LET A2(J)=D2(J)/D(J)
790 FOR N=(J-1)*A3+1 TO J*A3
800 LET B8=B8+(R(N)-A0(J)-A1(J)*C3(N)-A2(J)*(C3(N)^2))^2
810 NEXT N
820 LET B17(J)=SQR(B8)/A3
830 PRINT
840 PRINT "RESULTS OF THE ABOVE R(W)=R(I2R) 2ND DEGREE FIT:"
850 PRINT "A0=";A0(J),"A1=";A1(J),"A2=";A2(J),"RMS DEVIATION=";B17(J)
860 PRINT "AND:"
870 LET T1(J)=A0(J)/S-(1/A)+273.15
890 PRINT "RE(OHMS)=",A0(J),"TE(DEGK)=";T1(J),"REC.FACTOR=";T1(J)/T
900 PRINT "KE(CGS)=";60+8.583*T1(J),"BURNOUT I AT I=0(MA)=";1/SQR(A1(J))
910 LET NO(J)=10*S/(3.1416*L*(446.5 +7.238*T1(J))*A1(J))
920 REM ZERO CURRENT CORRECTED NUSSELT NUMBER CALCULATION
930 NOC=NO(J)
940 K0=4.465+.07238*T
950 PRINT "Note: k is assumed const. like in this convention."
960 KW=30230*(1+.000107*(T1(J)-273))
970 S1=L/D*(NOC*K0/KW)^.5
980 TANHS=(EXP(S1)-EXP(-S1))/(EXP(S1)+EXP(-S1))
990 NI(J)=NO(J)*(1-1/S1*TANHS)
1000 DIFF=NI(J)-NOC
1010 IF ABS(DIFF)<.001 GOTO 1050
1020 IF DIFF<0 THEN NOC=(NI(J)+NOC)/2
1030 IF DIFF>.001 THEN NOC=NOC-DIFF/2
1040 GOTO 970
1050 PRINT "ZERO-CURRENT NU0 (CORRECTED)=";NI(J);"EXT. CL=";-A2(J)/A1(J)
1060 PRINT "CORRECTION FACTOR PSIN=";NI(J)/NO(J)
1070 PRINT
1080 PRINT
1090 PRINT "OVERHEAT DEPENDENCE OF NUSSELT NO. AT U(CM/S)=";U(J)
1100 PRINT
1110 PRINT "I(MA)    NM    NC    PSIN    NC/NE    TW/TE    (TW-TE)/T    PSIR"
1120 PRINT
1130 FOR N=(J-1)*A3+1 TO J*A3
1140 LET NI(N)=EXP((-A2(J)/A1(J))*C3(N))
1150 NM=NI(N)*NO(J)
1160 LET EPS=0

```



```

1170 LET NC=NM
1180 KW=30230*(1+.000107*(T2(N)-273))
1190 TW=(T2(N)-T1(J))/T
1200 IF T2(N)<T1(J) GOTO 1470
1210 ETAM=T2(N)/T
1220 ETAS=TS+T1(J)/T
1230 TI=TW
1240 S2=A*T/(1+A*(T1(J)-273))
1250 RV=4*A0(J)/(3.1416*D^2)
1260 PSIC=0
1270 REM CALCULATE THE CORRECTION PARAMETERS
1280 LAMBDA=L/D*(NC*(KC/KW))^*.5
1290 NU=(LAMBDA^2-C(N)^2*RV*L^2*S2/(4*KW*T))^*.5
1300 XI=NI(J)*(TI-EPS)/(TW*NM)
1310 NUT=NU*(1+S2*TW)^.5*XI
1320 OMEGA=(EXP(NU)-EXP(-NU))/(EXP(NU)+EXP(-NU))
1330 OMEGAT=(EXP(NUT)-EXP(-NUT))/(EXP(NUT)+EXP(-NUT))
1340 G1=OMEGAT/NUT
1350 G2=OMEGA/NU
1360 EPS=-TS*(G1/(1-G1))
1370 TI=(TW-TS*G2)/(1-G2)
1380 TC=TW/(TI-EPS)
1390 PSIN=TC*(1+S2*TI)/(1+S2*TW)
1400 PSIR=(1-ETAS/ETAM*G1)/(1-G1)
1410 IF ABS(PSIN-PSIC)<.001 GOTO 1460
1420 REM CALCULATE THE NEW PARAMETERS
1430 NC=PSIN*NM
1440 PSIC=PSIN
1450 GOTO 1290
1460 PRINT USING "#.### #.### #.### #.### #.### #.### #.### #.###"
&
(N),NM,NC,PSIN,NC/NI(J),T2(N)/T1(J),(T2(N)-T1(J))/T,PSIR
1470 NEXT N
1480 PRINT
1490 PRINT
1500 PRINT "- - - - -"
1510 PRINT
1520 NEXT J
1530 PRINT
1540 PRINT
1550 PRINT "SUMMARY: NUSSELT NO. AND RECOVERY FACTORS"
1560 PRINT "Nusselt nos. shown below are for the limit of zero current."
1570 PRINT "-----"
1580 PRINT
1590 PRINT "REYNOLDS & NUSSELT NOS. & REC. FACTOR BASED ON STAG. CONDITIONS"
1600 PRINT
1610 PRINT "U(CM/SEC)      RE      NU      PSIN      ETA"
1620 PRINT
1625 T=9/5*T-460
1630 FOR J=1 TO P
1640 LET R2=(1337*P11)/(2.882E+06*(T+460)*(5/9))
1650 LET M2=.0000109*((460+T)^1.5)/(T+659)
1660 LET R3(J)=D*R2*U(J)/M2
1670 PRINT USING "####.## #.### #.### #.### #.###", U(J),R3(
NI(J),NI(J)/NO(J),T1(J)/(5*(460+T)/9)
1680 NEXT J
1684 CLOSE #1
1690 END

```

APPENDIX C

FLOW CALIBRATION DATA REDUCTION CODE: COMPRESSIBLE FLOWS

```

10 REM HIFLOW02
12 REM THIS PROGRAM USES THE FLOW DATA FILE TO DETERMINE THE CORRECTED
14 REM HOT-WIRE CHARACTERISTICS USING DEWEY'S CORRECTION FACTOR ITERATION
16 REM PROCEDURE.
18 REM *****
20 DIM V(300),V1(300),C(300),C1(300),R(300),C2(300),C3(300)
30 DIM P1(300),P2(300),N(300),B12(20),M(20),J(20)
40 DIM D(20),D0(20),D1(20),D2(20),A0(20),A1(20),A2(20)
50 DIM B17(20),T1(20),N0(20),T2(300),T3(300),N1(300),N1(20)
60 DIM M4(20),R2(20),P3(20),KR(20)
70 DIM T4(20),M5(20),R3(20),M6(20),R4(20),K1(20),N2(20),R5(20)
80 INPUT "INPUT FLOW CALIBRATION DATA FILE: ";F1$
90 OPEN F1$ FOR INPUT AS FILE #1
100 INPUT #1, A11,A12,A13,A3,D1,D2,D3,D4,D5,D6,D7,D8,R1,P,A,S,T,L,D
110 FOR N=1 TO A3*P
120 INPUT #1,V1(N),P1(N),P2(N),C1(N)
130 NEXT N
131 LET T=5/9*(T+460)
140 PRINT
150 PRINT
160 PRINT "THIS IS THE 'HIFLOW01' PROGRAM WHICH COMPUTES RESISTANCES AND"
170 PRINT "SLOPES BY QUADRATIC R-RI2 FITS (I.E. R=A + B12R + C(I2R)2)"
180 PRINT "-----"
190 PRINT
200 PRINT
210 PRINT "PROBE HOLDER NO.:";A11
220 PRINT "WIRE NO.:";A12
230 PRINT "FLOW CALIBRATION NO.:";A13
240 PRINT "ALL DATA SHOWN ARE FOR STAG. TEMPERATURE (DEG K) OF:";T
245 PRINT "THE SUPPORT TEMPERATURE LOADING (TS-TE)/T0 IS";
246 INPUT TS
247 PRINT "INPUT PRESSURE MEASURED FOR DETERMINATION OF M (1-STATIC, CR-PITOT)"
248 INPUT PR
250 PRINT
260 PRINT
270 FOR J=1 TO P
280 LET B=0
290 LET B1=0
300 LET B2=0
310 LET B3=0
320 LET B4=0
330 LET B5=0
340 LET B6=0
350 LET B7=0
360 LET B8=0
370 LET B9=0
380 LET B10=0
390 FOR N=(J-1)*A3+1 TO J*A3
400 LET B9=B9+P1(N)
410 LET B10=B10+P2(N)
420 NEXT N
430 LET B11=B9/A3
440 LET B12(J)=D5+D6*B11
450 LET B13=B10/A3
460 LET B14=D7+D8*B13
470 LET B15=B14/B12(J)
472 IF PR=1 GOTO 544
480 LET M=1+SGR(-5*LOG(B15))
490 LET B16=((1+1.1667*(M^2-1))^(2.5))*((2.4*(M^2))/(.4*(M^2)+2))^(3.5)
500 IF (B15-B16)/B15 <= .001 GOTO 540

```

```

510 LET M1=M*(1-(E15-E16)/(4*B15))
520 LET M=M1
530 GOTO 490
540 LET M(J)=M
542 GOTO 550
544 M(J)=(((1/B15)^(.285714-1)*5)^(.5
550 PRINT "OVERHEAT TRAVERSES FOR P0(MM HG)=";B12(J)
560 PRINT "LOCAL M=";M(J)
570 PRINT
580 PRINT "I(MA)", "I2(MA2)", "I2R", "R(OHMS)", "TW(DEG K)"
590 PRINT
600 FOR N=(J-1)*A3+1 TO A3*J
610 LET V(N)=D1+D2*V1(N)
620 LET C(N)=D3+D4*C1(N)
630 LET R(N)=(V(N)/C(N))-R1
640 LET C2(N)=C(N)^2
650 LET C3(N)=(C(N)^2)*R(N)
660 LET T2(N)=273.15+R(N)/S-1/A
670 PRINT C(N), C2(N), C3(N), R(N), T2(N)
680 LET B1=D1+C3(N)
690 LET B2=B2+C3(N)^2
700 LET B3=B3+C3(N)^3
710 LET B4=B4+C3(N)^4
720 LET B5=D5+R(N)
730 LET B6=B6+R(N)*C3(N)
740 LET B7=B7+(C3(N)^2)*R(N)
750 NEXT N
760 LET D(J)=A3*B2*B4+2*B1*B2*B3-B2^3-A3*(B3^2)-(B1^2)*B4
770 LET D0(J)=B5*B2*B4+B2*B3*B6+B1*B3*B7-(B2^2)*B7-(B3^2)*B5-B1*B4*B6
780 LET D1(J)=A3*B4*B6+B1*B2*B7+B2*B3*B5-(B2^2)*B6-A3*B3*B7-D1*B4*B5
790 LET D2(J)=A3*B2*B7+B1*B3*B5+B1*B2*B6-(B2^2)*B5-A3*B3*B6-(B1^2)*B7
800 LET A0(J)=D0(J)/D(J)
810 LET A1(J)=D1(J)/D(J)
820 LET A2(J)=D2(J)/D(J)
830 FOR N=(J-1)*A3+1 TO J*A3
840 LET B8=B8+(R(N)-A0(J)-A1(J)*C3(N)-A2(J)*(C3(N)^2))^2
850 NEXT N
860 LET B17(J)=SQR(B8)/A3
870 PRINT
880 PRINT "RESULTS OF THE ABOVE R(W)=R(I2R) 2ND DEGREE FIT:"
890 PRINT "A0=";A0(J), "A1=";A1(J), "A2=";A2(J), "RMS DEVIATION=";B17(J)
900 PRINT "AND:"
910 LET T1(J)=A0(J)/S-(1/A)+273.15
920 PRINT "RE(OHMS)=";A0(J), "TE(DEG K)=";T1(J), "REC. FACTOR=";T1(J)/T
930 PRINT "KE(CGS)=";60+8.583*T1(J), "BURNOUT I AT I=0(MA)=";1/SQR(A1(J))
940 LET N0(J)=10*S/(3.1416*L*(446.5+7.238*T1(J))*A1(J))
950 REM ZERO CURRENT CORRECTED NUSSLELT NUMBER CALCULATION
960 N0C=N0(J)
970 K0=4.465+.07238*T
975 KW=30230*(1+.000107*(T1(J)-273))
976 ETAM0=TS+T1(J)/T
977 KR(J)=K0/KW
980 S1=L/D*(N0C*K0/KW)^(.5
990 TANHS=(EXP(S1)-EXP(-S1))/(EXP(S1)+EXP(-S1))
1000 NI(J)=N0(J)*(1-1/S1*TANHS)
1010 DIFF=NI(J)-N0C
1020 IF ABS(DIFF) < .001 GOTO 1040
1030 IF DIFF < 0 THEN N0C=(NI(J)+N0C)/2
1040 IF DIFF > .001 THEN N0C=N0C-DIFF/2
1050 GOTO 980

```

```

1060 PRINT "ZERO-CURRENT NU0 (CORRECTED)=";NI(J);"EXP. C=";-A2(J)/A1(J)
1065 PRINT "CORRECTION FACTOR PSIN=";NI(J)/NO(J)
1070 PRINT
1080 PRINT
1090 PRINT "OVERHEAT DEPENDENCE OF NUSSELT NO. AT P0(MM HG)=";B12(J)
1110 PRINT
1120 PRINT "I(MA)      NM      NC      PSIN      NC/NE      TW/TE      (TW-TE)/T      PSIR"
1130 PRINT
1140 FOR N=(J-1)*A3+1 TO J*A3
1160 LET NI(N)=EXP((-A2(J)/A1(J))*C3(N))
1180 NM=NI(N)*NO(J)
1190 LET EPS=0
1194 LET NC=NM
1220 KW=30230*(1+.000107*(T2(N)-273))
1230 TW=(T2(N)-T1(J))/T
1235 IF T2(N)<T1(J) GOTO 1490
1240 ETAM=T2(N)/T
1241 ETAS=TS+T1(J)/T
1245 TI=TW
1250 S2=A*T/(1+A*(T1(J)-273))
1260 RV=4*A0(J)/(3.1416*D^2)
1270 PSIC=0
1280 REM CALCULATE THE CORRECTION PARAMETERS
1290 LAMBDA=L/D*(NC*(K0/KW))^-.5
1300 NU=(LAMBDA^2-C(N)^2*RV*L^2*S2/(4*KW*T))^-.5
1305 XI=NI(J)*(TI-EPS)/(TW*NM)
1310 NUT=NU*(1+S2*TW)^.5*XI
1320 OMEGA=(EXP(NU)-EXP(-NU))/(EXP(NU)+EXP(-NU))
1330 OMEGAT=(EXP(NUT)-EXP(-NUT))/(EXP(NUT)+EXP(-NUT))
1340 G1=OMEGAT/NUT
1350 G2=OMEGA/NU
1360 EPS=-TS*(G1/(1-G1))
1380 TI=(TW-TS*G2)/(1-G2)
1385 TC=TW/(TI-EPS)
1390 PSIN=TC*(1+S2*TI)/(1+S2*TW)
1400 PSIR=(1-ETAS/ETAM*G1)/(1-G1)
1410 IF ABS(PSIN-PSIC)<.001 GOTO 1480
1420 REM CALCULATE THE NEW PARAMETERS
1460 NC=PSIN*NM
1465 PSIC=PSIN
1470 GOTO 1290
1480 PRINT USING "#.### #.### #.### #.### #.### #.### #.### #.###"
C(N),NM,NC,PSIN,NC/NI(J),T2(N)/T1(J),(T2(N)-T1(J))/T,PSIR
1490 NEXT N
1500 PRINT "- - - - -"
1510 PRINT
1520 NEXT J
1530 PRINT
1540 PRINT
1550 PRINT "SUMMARY: NUSSELT NO. AND RECOVERY FACTORS"
1560 PRINT "-----"
1570 PRINT
1580 PRINT "REQ & CORRECTED NUSSELT NOS. & REC. FACTOR BASED ON STAG. COND."
1590 PRINT
1600 PRINT "PO(MM)      M      RE      NU      PSIN      ETA      PSIR      KN"
1610 PRINT
1615 T=7/5*T-460
1620 FOR J=1 TO P
1630 LET P3(J)=1337*B12(J)
1640 LET M2=.0000107*((460+T)^1.5)/(T+659)

```



```

1650 LET M3=.000696/SQR((5/9)*(T+460))
1660 LET M4(J)=(1+.2*(M(J)^2))
1670 LET R2(J)=P3(J)*M(J)*(1/M2)*M3*(M4(J)^(-1.5))*(((1/M4(J))+(198.6/(460+T))^6
)/((1+198.6/(460+T))))
1680 LET T4(J)=(5/9)*(T+460)/M4(J)
1690 LET M5(J)=.0000109*((9/5)*T4(J)^1.5)/((9/5)*T4(J)+198.6)
1700 LET R3(J)=R2(J)*M5(J)/M2
1710 LET M6(J)=.0000109*((9/5)*T1(J)^1.5)/((9/5)*T1(J)+198.6)
1720 LET R4(J)=R2(J)*M5(J)/M6(J)
1730 LET K1(J)=60!+8.583*T1(J)
1740 LET K2=60+8.583*(5/9)*(460+T)
1750 LET N2(J)=N0(J)*K1(J)/K2
1760 LET R5(J)=SQR(D*R3(J))
1762 ETAM0=T1(J)/T
1764 ETAS0=TS+T1(J)/T
1770 NU0=L/D*(NI(J)*KR(J))^1.5
1780 OMEGA0=(EXP(NU0)-EXP(-NU0))/(EXP(NU0)+EXP(-NU0))
1790 PSIR0=(1-ETAS0/ETAM0*OMEGA0/NU0)/(1-OMEGA0/NU0)
1800 KN=1.48294*M(J)/(R2(J)*D)
1810 PRINT USING "###.##   #.###   #.###   #.###   #.###   #.###   #.###   #.###"
"&
E12(J),M(J),D*R3(J),NI(J),NI(J)/N0(J),T1(J)/(5*(460+T)/9),PSIR0,KN
1820 NEXT J
1830 PRINT
1840 PRINT
1845 CLOSE #1
1850 END

```

APPENDIX D

HOT-WIRE RESISTANCE-TEMPERATURE COEFFICIENTS

20 μ in. Wires

<u>PROBE</u>	<u>ℓ/d</u>	<u>$R_r (\Omega @ 0^\circ \text{C})$</u>	<u>$\alpha_r \times 10^3 (1/^\circ \text{C})$</u>
30/4/1	128	57.45	1.773
30/2/2	132	59.4	1.579
30/3/1	134	60.37	1.559
26/4/1	138	61.99	1.581
25/3/1	166	74.41	1.549
27/3/1	187	84.22	1.566
29/8/1	206	92.78	1.574
29/8/2	211	94.68	1.530
29/3/1	207	92.9	1.546
25/2/1	216	96.97	1.632
25/2/2	216	96.94	1.571
06/6/1	224	100.56	1.572
06/6/2	231	103.97	1.511
29/1/1	235	103.7	1.594
29/1/2	235	105.17	1.600
29/1/3	235	105.6	1.583
27/2/2	246	110.4	1.587
27/2/3	245	110.09	1.587
26/3/1	274	122.65	1.705
17/5/1	281	126.56	1.547
17/5/2	282	126.56	1.567
28/3/1	289	129.78	1.613
06/2/1	292	131.2	1.568
06/2/2	293	131.6	1.565
25/4/1	307	137.95	1.573
29/4/1	331	148.81	1.568
29/2/1	405	181.9	1.567

50 uin. Wires

<u>PROBE</u>	<u>ℓ/d</u>	<u>$R_T (\Omega @ 0^\circ\text{C})$</u>	<u>$\alpha_T \times 10^3 (1/^\circ\text{C})$</u>
29/7/1	94	16.96	1.419
29/7/2	94	16.74	1.624
09/4/1	176	31.7	1.602
06/5/1	186	33.23	1.674
29/5/1	225	40.34	1.591
07/7/1	227	40.59	1.657
26/5/1	259	46.52	1.562
07/4/1	293	52.56	1.606
17/4/1	295	52.86	1.634
06/4/1	413	74.14	1.626
29/6/1	416	74.65	1.590
09/3/1	419	75.15	1.679
07/6/1	448	80.39	1.575

APPENDIX E

FLOW CALIBRATION RESULTS

M=3; d=20 μ in.

FLOW CALIBRATION RESULTS: PROBE # :30/4/2

M	RE	NUM	NUC	PSIN	ETA	KN	1/S
3.051	1.116	1.427	1.067	0.748	0.971	1.611	.253
3.051	1.076	1.378	1.023	0.742	0.965	1.672	.258
3.052	1.038	1.353	1.000	0.739	0.966	1.733	.261
3.055	0.998	1.381	1.026	0.743	0.967	1.801	.258
3.059	0.959	1.309	0.961	0.734	0.960	1.874	.266
3.062	0.919	1.430	1.069	0.748	0.975	1.955	.252
3.066	0.881	1.360	1.007	0.740	0.970	2.037	.260
3.067	0.839	1.362	1.008	0.740	0.970	2.141	.260
3.069	0.806	1.227	0.888	0.724	0.959	2.228	.277
3.070	0.764	1.313	0.965	0.735	0.967	2.350	.266
3.069	0.728	1.243	0.902	0.726	0.963	2.464	.275
3.064	0.693	1.267	0.923	0.729	0.966	2.591	.272
3.064	0.659	1.332	0.982	0.737	0.975	2.725	.263
3.059	0.630	1.327	0.977	0.736	0.976	2.852	.264
3.060	0.589	1.184	0.849	0.717	0.959	3.051	.283

FLOW CALIBRATION RESULTS: PROBE # :26/4/1

M	RE	NUM	NUC	PSIN	ETA	KN	1/S
3.040	1.067	0.722	0.469	0.649	0.883	1.690	.353
3.040	1.030	0.703	0.452	0.643	0.879	1.751	.360
3.040	0.994	0.708	0.456	0.645	0.890	1.814	.358
3.040	0.958	0.689	0.440	0.639	0.880	1.883	.364
3.040	0.920	0.675	0.427	0.634	0.876	1.960	.370
3.040	0.882	0.656	0.411	0.627	0.873	2.044	.377
3.040	0.845	0.662	0.416	0.629	0.884	2.133	.375
3.040	0.810	0.640	0.398	0.621	0.878	2.225	.383
3.040	0.771	0.652	0.408	0.625	0.882	2.337	.378
3.040	0.734	0.648	0.404	0.624	0.886	2.454	.380
3.040	0.696	0.608	0.369	0.608	0.860	2.591	.398
3.040	0.660	0.619	0.379	0.612	0.874	2.732	.393
3.040	0.622	0.626	0.385	0.615	0.883	2.897	.390
3.040	0.585	0.601	0.364	0.605	0.873	3.082	.401

FLOW CALIBRATION RESULTS: PROBE # :25/3/1

M	RE	NUM	NUC	PSIN	ETA	KN	1/S
3.031	1.083	0.426	0.259	0.609	0.886	1.664	.396
3.031	1.047	0.419	0.254	0.605	0.886	1.722	.400
3.033	1.009	0.409	0.245	0.599	0.887	1.786	.407
3.035	0.968	0.400	0.237	0.593	0.882	1.861	.414
3.040	0.927	0.394	0.232	0.588	0.882	1.943	.419
3.043	0.885	0.390	0.228	0.585	0.887	2.034	.422
3.044	0.849	0.397	0.235	0.591	0.884	2.120	.416
3.044	0.810	0.376	0.216	0.570	0.873	2.222	.433
3.047	0.773	0.371	0.212	0.571	0.871	2.329	.430
3.045	0.733	0.370	0.211	0.571	0.860	2.457	.438
3.044	0.697	0.361	0.204	0.563	0.875	2.583	.447
3.042	0.661	0.361	0.203	0.563	0.877	2.724	.447

FLOW CALIBRATION RESULTS: PROBE # :25/3/2

M	RE	NUM	NUC	PSIN	ETA	KN	1/S
3.054	1.118	0.453	0.283	0.624	0.889	1.608	.380
3.053	1.075	0.450	0.280	0.622	0.895	1.671	.382
3.055	1.037	0.438	0.270	0.616	0.891	1.733	.389
3.058	0.997	0.431	0.263	0.611	0.891	1.801	.394
3.062	0.959	0.424	0.257	0.607	0.892	1.873	.398
3.065	0.919	0.404	0.241	0.595	0.885	1.953	.412
3.071	0.877	0.410	0.246	0.599	0.891	2.047	.407
3.076	0.837	0.405	0.241	0.595	0.890	2.143	.411
3.076	0.801	0.395	0.233	0.588	0.891	2.237	.419
3.073	0.760	0.401	0.237	0.592	0.900	2.361	.415
3.075	0.729	0.376	0.216	0.574	0.884	2.461	.434
3.072	0.691	0.367	0.208	0.567	0.880	2.595	.443
3.070	0.659	0.364	0.205	0.564	0.885	2.723	.448
3.061	0.619	0.349	0.193	0.552	0.880	2.899	.460

FLOW CALIBRATION RESULTS: PROBE # :27/3/1

M	RE	NUM	NUC	PSIN	ETA	KN	1/S
3.039	1.069	0.445	0.302	0.678	0.865	1.886	.324
3.043	1.029	0.449	0.305	0.679	0.871	1.952	.322
3.045	0.990	0.426	0.285	0.668	0.862	1.821	.333
3.049	0.948	0.410	0.271	0.661	0.853	1.901	.341
3.055	0.908	0.405	0.266	0.658	0.855	1.982	.345
3.059	0.868	0.405	0.267	0.658	0.860	2.073	.344
3.062	0.831	0.393	0.255	0.651	0.856	2.165	.352
3.063	0.793	0.394	0.257	0.652	0.865	2.269	.351
3.061	0.756	0.385	0.249	0.646	0.858	2.379	.356
3.061	0.716	0.375	0.240	0.640	0.853	2.505	.363
3.057	0.686	0.380	0.245	0.643	0.864	2.625	.359
3.056	0.653	0.356	0.224	0.628	0.854	2.756	.376
3.056	0.616	0.338	0.208	0.615	0.847	2.921	.390
3.055	0.578	0.345	0.214	0.621	0.856	3.116	.384

FLOW CALIBRATION RESULTS: PROBE # :27/3/2

M	RE	NUM	NUC	PSIN	ETA	KN	1/S
3.044	1.113	0.452	0.307	0.680	0.923	1.617	.322
3.046	1.070	0.422	0.280	0.665	0.916	1.682	.336
3.048	1.032	0.431	0.289	0.670	0.920	1.744	.332
3.051	0.991	0.406	0.269	0.658	0.912	1.815	.344
3.055	0.952	0.406	0.269	0.658	0.920	1.886	.344
3.059	0.912	0.387	0.250	0.647	0.911	1.970	.356
3.064	0.871	0.386	0.249	0.646	0.912	2.063	.357
3.065	0.834	0.375	0.240	0.639	0.913	2.154	.364
3.066	0.796	0.367	0.233	0.634	0.910	2.258	.369
3.062	0.752	0.353	0.221	0.625	0.907	2.390	.379
3.065	0.720	0.341	0.210	0.616	0.900	2.495	.388
3.066	0.683	0.344	0.213	0.618	0.906	2.630	.386
3.061	0.651	0.339	0.206	0.615	0.910	2.762	.390
3.063	0.617	0.323	0.194	0.601	0.904	2.914	.404
3.060	0.577	0.326	0.197	0.604	0.911	3.118	.401

FLOW CALIBRATION RESULTS: PROBE # :29/3/1

M	RE	NUM	NUC	PSIN	ETA	KN	1/S
3.042	1.070	0.472	0.342	0.724	0.892	1.683	.276
3.046	1.030	0.502	0.369	0.734	0.907	1.749	.266
3.048	0.991	0.471	0.341	0.724	0.899	1.817	.276
3.054	0.949	0.468	0.338	0.723	0.899	1.895	.278
3.059	0.907	0.450	0.322	0.716	0.896	1.983	.284
3.064	0.865	0.455	0.327	0.718	0.903	2.078	.282
3.067	0.826	0.469	0.339	0.723	0.907	2.176	.277
3.071	0.751	0.447	0.320	0.715	0.904	2.390	.286
3.070	0.714	0.438	0.311	0.711	0.900	2.515	.289
3.069	0.678	0.419	0.294	0.703	0.896	2.650	.297
3.068	0.643	0.387	0.267	0.689	0.884	2.793	.312
3.069	0.604	0.395	0.273	0.692	0.864	2.973	.308

FLOW CALIBRATION RESULTS: PROBE # :28/3/1

M	RE	NUM	NUC	PSIN	ETA	KN	1/S
3.020	1.157	0.268	0.198	0.740	1.025	1.559	.260
3.026	1.090	0.267	0.197	0.740	1.029	1.653	.261
3.028	1.049	0.274	0.204	0.744	1.034	1.718	.257
3.032	1.009	0.247	0.180	0.728	1.024	1.786	.273
3.033	0.971	0.263	0.194	0.737	1.037	1.855	.263
3.039	0.924	0.262	0.193	0.737	1.037	1.949	.263
3.043	0.887	0.243	0.176	0.725	1.034	2.030	.276
3.044	0.850	0.233	0.167	0.718	1.027	2.117	.283
3.046	0.810	0.249	0.182	0.729	1.043	2.220	.272
3.045	0.777	0.227	0.162	0.713	1.030	2.316	.288
3.045	0.743	0.213	0.149	0.701	1.025	2.420	.299
3.042	0.705	0.228	0.163	0.714	1.041	2.553	.287
3.041	0.668	0.206	0.144	0.696	1.031	2.693	.305
3.040	0.631	0.212	0.149	0.701	1.041	2.852	.300

FLOW CALIBRATION RESULTS: PROBE # :06/2/1

M	RE	NUM	NUC	PSIN	ETA	KN	1/S
3.035	1.134	0.239	0.174	0.726	1.017	1.589	.275
3.039	1.076	0.228	0.164	0.718	1.017	1.674	.283
3.041	1.037	0.234	0.169	0.722	1.026	1.736	.277
3.042	1.000	0.240	0.174	0.726	1.032	1.801	.274
3.046	0.960	0.207	0.145	0.700	1.013	1.876	.301
3.049	0.917	0.204	0.142	0.698	1.017	1.963	.303
3.052	0.881	0.223	0.159	0.713	1.034	2.041	.287
3.054	0.842	0.193	0.132	0.687	1.013	2.136	.315
3.056	0.809	0.215	0.152	0.707	1.034	2.224	.294
3.053	0.771	0.205	0.143	0.698	1.031	2.334	.302
3.052	0.735	0.193	0.133	0.687	1.025	2.447	.314
3.049	0.697	0.172	0.114	0.664	1.019	2.583	.338
3.048	0.664	0.173	0.115	0.665	1.020	2.711	.337
3.042	0.618	0.160	0.103	0.647	1.015	2.914	.355

FLOW CALIBRATION RESULTS: PROBE # :25/4/1

M	RE	NUM	NUC	PSIN	ETA	KN	1/S
3.022	1.153	0.317	0.247	0.781	0.973	1.564	.219
3.025	1.089	0.284	0.216	0.767	0.968	1.656	.233
3.028	1.049	0.326	0.255	0.784	0.986	1.718	.216
3.029	1.008	0.294	0.227	0.771	0.974	1.787	.229
3.038	0.923	0.288	0.221	0.768	0.983	1.950	.232
3.043	0.849	0.280	0.214	0.765	0.983	2.121	.235
3.042	0.777	0.260	0.196	0.754	0.981	2.317	.246
3.038	0.733	0.243	0.181	0.744	0.978	2.458	.256
3.037	0.698	0.243	0.181	0.744	0.978	2.578	.256
3.037	0.667	0.245	0.182	0.745	0.981	2.700	.255
3.037	0.630	0.221	0.162	0.729	0.971	2.859	.271

FLOW CALIBRATION RESULTS: PROBE # :29/4/1

M	RE	NUM	NUC	PSIN	ETA	KN	1/S
3.046	1.126	0.232	0.177	0.760	0.980	1.599	.240
3.047	1.068	0.236	0.180	0.762	0.982	1.685	.238
3.048	1.031	0.224	0.169	0.755	0.979	1.746	.245
3.050	0.993	0.213	0.159	0.747	0.973	1.812	.253
3.053	0.953	0.208	0.155	0.744	0.976	1.887	.256
3.060	0.911	0.198	0.146	0.737	0.974	1.973	.264
3.064	0.868	0.189	0.138	0.729	0.966	2.071	.271
3.064	0.835	0.195	0.143	0.734	0.975	2.151	.266
3.068	0.796	0.193	0.141	0.732	0.997	2.255	.268
3.067	0.760	0.194	0.142	0.733	1.001	2.364	.267
3.066	0.727	0.192	0.140	0.731	1.001	2.472	.269
3.057	0.690	0.189	0.138	0.729	0.999	2.607	.271
3.054	0.656	0.172	0.123	0.713	0.982	2.743	.288
3.053	0.619	0.166	0.118	0.706	0.985	2.907	.294
3.053	0.583	0.166	0.117	0.706	0.988	3.034	.295

M=3; d=50 μ in.

FLOW CALIBRATION RESULTS: PROBE # :29/7/2

M	RE	NUM	NUC	PSIN	ETA	KN	1/S
3.059	2.778	1.371	0.841	0.614	0.980	0.647	.391
3.063	2.632	1.209	0.701	0.580	0.966	0.683	.428
3.065	2.537	1.286	0.767	0.597	0.973	0.708	.409
3.068	2.435	1.238	0.726	0.587	0.971	0.737	.421
3.071	2.337	1.204	0.696	0.579	0.968	0.768	.429
3.074	2.246	1.178	0.675	0.572	0.971	0.799	.436
3.078	2.145	1.167	0.665	0.570	0.973	0.836	.440
3.082	2.052	1.212	0.703	0.580	0.977	0.874	.427
3.083	1.966	1.080	0.590	0.546	0.960	0.912	.467
3.083	1.870	1.141	0.642	0.563	0.973	0.956	.447
3.083	1.787	1.139	0.641	0.562	0.962	1.003	.448
3.082	1.692	0.986	0.509	0.516	0.946	1.060	.502
3.080	1.618	1.088	0.596	0.548	0.964	1.108	.464
3.078	1.519	1.062	0.574	0.541	0.963	1.181	.473
3.078	1.437	1.062	0.574	0.541	0.964	1.248	.473
3.076	1.351	0.932	0.463	0.497	0.939	1.328	.526

FLOW CALIBRATION RESULTS: PROBE # :09/4/2

M	RE	NUM	NUC	PSIN	ETA	KN	1/S
3.061	2.767	0.744	0.555	0.746	1.035	0.650	.254
3.064	2.619	0.638	0.460	0.721	1.024	0.686	.279
3.066	2.520	0.667	0.486	0.729	1.031	0.713	.272
3.069	2.425	0.476	0.316	0.666	0.990	0.740	.336
3.073	2.337	0.500	0.338	0.676	1.002	0.766	.326
3.077	2.227	0.569	0.399	0.701	1.023	0.806	.300
3.079	2.139	0.457	0.300	0.637	0.991	0.839	.345
3.084	2.044	0.556	0.387	0.697	1.031	0.877	.304
3.085	1.957	0.575	0.404	0.703	1.038	0.916	.298
3.086	1.870	0.504	0.342	0.678	1.019	0.959	.324
3.087	1.782	0.488	0.328	0.671	1.021	1.006	.331
3.084	1.692	0.488	0.328	0.671	1.026	1.060	.331
3.083	1.615	0.497	0.335	0.674	1.030	1.111	.327
3.082	1.519	0.409	0.258	0.631	1.001	1.181	.373
3.080	1.423	0.445	0.289	0.651	1.027	1.260	.352
3.077	1.320	0.423	0.270	0.639	1.022	1.359	.364

FLOW CALIBRATION RESULTS: PROBE # 106/5/2

M	RE	NUM	NUC	PSIN	ETA	KN	1/S
3.056	2.791	0.627	0.460	0.734	1.048	0.644	.267
3.058	2.649	0.593	0.430	0.725	1.052	0.678	.276
3.060	2.562	0.554	0.395	0.713	1.047	0.701	.288
3.061	2.466	0.549	0.390	0.711	1.048	0.728	.289
3.070	2.347	0.533	0.376	0.706	1.050	0.764	.295
3.073	2.258	0.510	0.356	0.692	1.048	0.794	.303
3.076	2.164	0.528	0.371	0.704	1.054	0.828	.297
3.081	2.059	0.514	0.360	0.699	1.056	0.870	.301
3.082	1.972	0.484	0.333	0.688	1.049	0.909	.313
3.083	1.855	0.455	0.307	0.675	1.046	0.966	.326
3.082	1.786	0.433	0.288	0.665	1.042	1.003	.337
3.082	1.691	0.432	0.287	0.665	1.048	1.060	.337
3.078	1.615	0.420	0.277	0.659	1.050	1.110	.343
3.075	1.521	0.389	0.250	0.642	1.039	1.179	.361
3.078	1.442	0.402	0.261	0.649	1.049	1.243	.353
3.073	1.339	0.399	0.258	0.647	1.055	1.339	.355

FLOW CALIBRATION RESULTS: PROBE # 107/7/2

M	RE	NUM	NUC	PSIN	ETA	KN	1/S
3.059	2.783	0.460	0.344	0.748	0.964	0.645	.252
3.061	2.641	0.406	0.296	0.729	0.952	0.680	.271
3.064	2.546	0.434	0.321	0.739	0.967	0.705	.261
3.066	2.453	0.424	0.312	0.736	0.972	0.732	.265
3.069	2.352	0.414	0.303	0.732	0.972	0.763	.268
3.073	2.252	0.406	0.296	0.729	0.972	0.797	.272
3.076	2.156	0.379	0.272	0.717	0.962	0.832	.283
3.080	2.061	0.391	0.282	0.722	0.977	0.869	.278
3.083	1.961	0.368	0.262	0.712	0.968	0.914	.289
3.083	1.872	0.377	0.270	0.716	0.979	0.957	.284
3.081	1.783	0.348	0.244	0.702	0.968	1.005	.299
3.081	1.701	0.347	0.244	0.702	0.974	1.053	.299
3.078	1.616	0.342	0.239	0.699	0.976	1.109	.302
3.077	1.524	0.310	0.211	0.680	0.958	1.176	.321
3.076	1.433	0.321	0.221	0.687	0.976	1.251	.314
3.076	1.348	0.306	0.207	0.677	0.973	1.330	.324

FLOW CALIBRATION RESULTS: PROBE # :29/5/2

M	RE	NUM	NUC	PSIN	ETA	KN	1/S
3.055	2.811	0.518	0.395	0.763	1.093	0.639	.238
3.058	2.660	0.512	0.389	0.761	1.103	0.675	.239
3.058	2.572	0.487	0.367	0.754	1.101	0.698	.246
3.059	2.473	0.469	0.351	0.748	1.096	0.726	.252
3.059	2.384	0.471	0.333	0.749	1.107	0.733	.251
3.061	2.288	0.469	0.342	0.745	1.106	0.785	.255
3.062	2.195	0.425	0.311	0.733	1.097	0.818	.268
3.066	2.102	0.412	0.300	0.728	1.097	0.853	.272
3.073	1.998	0.397	0.286	0.721	1.099	0.897	.279
3.075	1.898	0.394	0.284	0.720	1.105	0.944	.280
3.075	1.807	0.383	0.274	0.715	1.110	0.992	.285
3.076	1.714	0.370	0.262	0.709	1.107	1.046	.291
3.074	1.626	0.355	0.230	0.702	1.108	1.102	.299
3.072	1.529	0.345	0.241	0.697	1.113	1.172	.304
3.072	1.444	0.332	0.229	0.689	1.112	1.242	.312
3.072	1.362	0.313	0.212	0.678	1.108	1.316	.324
3.069	1.267	0.305	0.205	0.672	1.115	1.415	.329
3.070	1.151	0.285	0.188	0.658	1.114	1.537	.344
3.065	1.051	0.260	0.165	0.637	1.097	1.707	.366

FLOW CALIBRATION RESULTS: PROBE # :09/3/2

M	RE	NUM	NUC	PSIN	ETA	KN	1/S
3.057	2.796	0.458	0.400	0.874	1.087	0.643	.126
3.059	2.636	0.442	0.385	0.871	1.093	0.682	.129
3.061	2.543	0.423	0.367	0.868	1.094	0.707	.132
3.062	2.451	0.416	0.360	0.867	1.095	0.733	.133
3.064	2.343	0.407	0.352	0.865	1.100	0.767	.135
3.066	2.241	0.388	0.334	0.862	1.100	0.801	.138
3.068	2.161	0.368	0.316	0.858	1.097	0.831	.142
3.074	2.073	0.333	0.283	0.850	1.088	0.866	.150
3.078	1.975	0.342	0.291	0.852	1.104	0.908	.148
3.081	1.881	0.325	0.276	0.848	1.101	0.953	.152
3.079	1.773	0.310	0.262	0.844	1.103	1.012	.156
3.078	1.699	0.306	0.258	0.843	1.111	1.056	.157
3.078	1.609	0.300	0.252	0.841	1.114	1.115	.159
3.078	1.523	0.281	0.235	0.835	1.113	1.178	.163
3.078	1.434	0.274	0.228	0.833	1.120	1.251	.167
3.077	1.337	0.251	0.207	0.825	1.113	1.342	.175

.2<M<2.2; d=20 μ in.

FLOW CALIBRATION RESULTS: PROBE # :17/5/1 L/D=232

M	RE	NUM	NUC	PSIN	ETA	KN	1/S
0.202	1.610	0.809	0.693	0.857	1.011	0.185	.148
0.201	1.494	0.732	0.622	0.849	1.000	0.198	.151
0.197	1.352	0.690	0.583	0.844	1.001	0.215	.156
0.199	1.266	0.723	0.613	0.848	1.009	0.232	.152
0.199	1.146	0.628	0.525	0.836	0.996	0.256	.164
0.199	1.050	0.642	0.538	0.838	1.007	0.280	.162
0.202	0.953	0.620	0.518	0.835	1.010	0.313	.165
0.207	0.863	0.551	0.454	0.824	1.000	0.354	.178
0.212	0.783	0.519	0.424	0.818	1.004	0.410	.182

FLOW CALIBRATION RESULTS: PROBE # :17/5/2 L/D=282

M	RE	NUM	NUC	PSIN	ETA	KN	1/S
1.076	4.689	0.895	0.774	0.865	0.999	0.289	.135
1.075	4.389	0.769	0.656	0.853	0.994	0.309	.147
1.075	4.080	0.758	0.646	0.852	0.999	0.332	.148
1.075	3.751	0.724	0.615	0.849	1.003	0.361	.151
1.075	3.426	0.674	0.568	0.842	1.002	0.396	.158
1.074	3.083	0.625	0.523	0.836	1.005	0.440	.164
1.074	2.838	0.521	0.426	0.818	0.994	0.477	.182
1.073	2.507	0.436	0.348	0.799	0.985	0.540	.201
1.075	2.178	0.402	0.318	0.790	0.996	0.622	.211

FLOW CALIBRATION RESULTS: PROBE # :07/8/1 L/D=331

M	RE	NUM	NUC	PSIN	ETA	KN	1/S
0.198	1.591	0.847	0.748	0.883	0.991	0.184	.117
0.199	1.487	0.730	0.638	0.874	0.985	0.197	.126
0.198	1.368	0.750	0.657	0.875	0.996	0.213	.125
0.199	1.276	0.656	0.568	0.866	0.991	0.231	.134
0.202	1.178	0.593	0.509	0.859	0.985	0.253	.141
0.204	1.073	0.537	0.457	0.851	0.982	0.281	.149
0.210	0.983	0.568	0.486	0.855	0.991	0.315	.145
0.216	0.904	0.514	0.435	0.847	0.993	0.353	.153
0.225	0.804	0.519	0.440	0.848	0.998	0.412	.182

FLOW CALIBRATION RESULTS: PROBE # :07/8/2.

M	RE	NUM	NUC	PSIN	ETA	KN	1/S
0.851	4.644	0.763	0.669	0.877	0.977	0.245	.123
0.851	4.327	0.782	0.686	0.878	0.986	0.263	.122
0.851	4.017	0.726	0.634	0.873	0.984	0.283	.127
0.852	3.710	0.649	0.562	0.865	0.980	0.307	.135
0.852	3.414	0.685	0.595	0.869	0.987	0.333	.131
0.853	3.037	0.598	0.514	0.859	0.986	0.375	.141
0.854	2.766	0.528	0.449	0.849	0.981	0.412	.151
0.856	2.430	0.496	0.419	0.844	0.986	0.470	.156
0.858	2.122	0.491	0.414	0.843	0.994	0.539	.157

FLOW CALIBRATION RESULTS: PROBE # :07/8/3

M	RE	NUM	NUC	PSIN	ETA	KN	1/S
1.609	3.754	0.801	0.705	0.880	0.997	0.455	.120
1.564	3.611	0.709	0.618	0.872	0.996	0.467	.128
1.511	3.448	0.698	0.608	0.871	0.998	0.481	.129
1.457	3.282	0.731	0.639	0.874	1.002	0.497	.126
1.392	3.093	0.695	0.605	0.870	1.001	0.515	.130
1.321	2.891	0.599	0.515	0.859	0.997	0.535	.141
1.246	2.685	0.578	0.495	0.857	0.999	0.556	.143
1.149	2.430	0.566	0.483	0.855	1.003	0.584	.145
1.033	2.138	0.458	0.384	0.837	0.991	0.616	.163

FLOW CALIBRATION RESULTS: PROBE # :07/8/4

M	RE	NUM	NUC	PSIN	ETA	KN	1/S
0.400	2.964	0.741	0.648	0.875	0.983	0.195	.125
0.400	2.765	0.808	0.711	0.880	0.995	0.210	.120
0.400	2.571	0.659	0.571	0.867	0.985	0.225	.133
0.400	2.372	0.799	0.703	0.880	0.997	0.244	.120
0.400	2.163	0.733	0.641	0.874	0.998	0.268	.126
0.400	1.967	0.704	0.613	0.871	0.999	0.294	.129
0.400	1.761	0.656	0.569	0.866	0.995	0.329	.134
0.400	1.531	0.580	0.497	0.857	0.994	0.378	.143
0.400	1.348	0.546	0.465	0.852	0.997	0.430	.146

FLOW CALIBRATION RESULTS: PROBE # :29/8/1 L/D=207

M	RE	NUM	NUC	PSIN	ETA	KN	1/S
0.200	1.586	0.991	0.813	0.820	1.020	0.186	.180
0.200	1.483	0.935	0.761	0.814	1.021	0.199	.186
0.200	1.370	0.844	0.678	0.803	1.009	0.215	.197
0.203	1.286	0.899	0.728	0.810	1.022	0.233	.190
0.207	1.192	0.868	0.700	0.806	1.023	0.255	.194
0.210	1.086	0.793	0.632	0.796	1.018	0.285	.204
0.215	0.997	0.761	0.602	0.791	1.018	0.318	.209
0.223	0.917	0.665	0.515	0.774	1.005	0.358	.226
0.233	0.815	0.670	0.520	0.776	1.021	0.420	.225

FLOW CALIBRATION RESULTS: PROBE # :29/8/2

M	RE	NUM	NUC	PSIN	ETA	KN	1/S
1.061	4.689	1.138	0.949	0.834	1.010	0.286	.166
1.061	4.384	1.044	0.862	0.826	1.019	0.306	.174
1.060	4.069	1.031	0.850	0.824	1.023	0.330	.176
1.061	3.737	0.903	0.732	0.811	1.018	0.359	.189
1.061	3.438	0.867	0.699	0.806	1.020	0.391	.194
1.063	3.082	0.809	0.646	0.799	1.022	0.436	.201
1.064	2.776	0.761	0.620	0.794	1.028	0.485	.206
1.066	2.442	0.696	0.544	0.780	1.020	0.552	.220
1.068	2.092	0.624	0.478	0.766	1.023	0.645	.234

FLOW CALIBRATION RESULTS: PROBE # :29/8/3

M	RE	NUM	NUC	PSIN	ETA	KN	1/S
0.168	1.502	1.079	0.894	0.829	1.034	0.185	.171
0.166	1.331	0.856	0.689	0.805	1.030	0.206	.195
0.182	1.205	0.954	0.779	0.816	1.036	0.223	.184
0.183	1.111	0.812	0.649	0.799	1.029	0.242	.201
0.184	1.018	0.813	0.650	0.799	1.032	0.266	.201
0.182	0.908	0.710	0.556	0.783	1.026	0.296	.217
0.183	0.800	0.763	0.604	0.792	1.033	0.337	.208
0.187	0.717	0.742	0.585	0.788	1.035	0.385	.212
0.189	0.624	0.676	0.525	0.776	1.034	0.448	.224

FLOW CALIBRATION RESULTS: PROBE # :29/8/4

M	RE	NUM	NUC	PSIN	ETA	KN	1/S
0.239	1.683	1.013	0.833	0.823	1.030	0.187	.177
0.235	1.659	0.892	0.722	0.809	1.029	0.208	.191
0.234	1.537	1.030	0.849	0.824	1.035	0.224	.176
0.235	1.410	0.853	0.686	0.804	1.030	0.245	.196
0.235	1.289	0.876	0.708	0.808	1.024	0.268	.193
0.233	1.150	0.780	0.620	0.794	1.029	0.299	.206
0.233	1.013	0.766	0.607	0.792	1.026	0.338	.208
0.235	0.896	0.722	0.567	0.785	1.030	0.386	.215
0.237	0.770	0.691	0.539	0.779	1.031	0.453	.221

FLOW CALIBRATION RESULTS: PROBE # :29/8/5

M	RE	NUM	NUC	PSIN	ETA	KN	1/S
0.395	2.945	0.915	0.743	0.812	1.018	0.194	.188
0.394	2.624	1.026	0.845	0.824	1.028	0.217	.176
0.393	2.426	0.984	0.807	0.820	1.028	0.235	.180
0.393	2.214	0.907	0.735	0.811	1.027	0.257	.189
0.392	2.003	0.902	0.732	0.811	1.027	0.284	.189
0.392	1.823	0.819	0.656	0.800	1.024	0.312	.200
0.392	1.607	0.769	0.609	0.793	1.022	0.353	.207
0.392	1.385	0.690	0.537	0.779	1.019	0.411	.221

FLOW CALIBRATION RESULTS: PROBE # :29/8/6

M	RE	NUM	NUC	PSIN	ETA	KN	1/S
0.591	3.946	0.925	0.752	0.813	1.012	0.211	.187
0.591	3.535	1.027	0.846	0.824	1.020	0.235	.176
0.590	3.257	1.026	0.846	0.824	1.021	0.255	.176
0.589	2.974	0.971	0.795	0.818	1.021	0.279	.182
0.589	2.680	1.000	0.821	0.821	1.025	0.310	.179
0.588	2.447	0.935	0.761	0.814	1.025	0.339	.186
0.588	2.171	0.793	0.631	0.796	1.019	0.382	.204
0.589	1.902	0.791	0.629	0.796	1.023	0.436	.204

FLOW CALIBRATION RESULTS: PROBE # :29/8/7

M	RE	NUM	NUC	PSIN	ETA	KN	1/S
0.766	4.462	1.103	0.916	0.831	1.016	0.234	.169
0.764	4.017	1.079	0.894	0.829	1.016	0.259	.171
0.764	3.705	0.901	0.730	0.811	1.009	0.281	.189
0.763	3.411	1.013	0.834	0.823	1.018	0.305	.177
0.763	3.096	0.941	0.767	0.815	1.021	0.336	.185
0.762	2.755	0.876	0.707	0.807	1.017	0.377	.193
0.761	2.481	0.677	0.526	0.777	1.005	0.416	.223
0.762	2.180	0.811	0.648	0.799	1.021	0.478	.201

FLOW CALIBRATION RESULTS: PROBE # :29/8/8

M	RE	NUM	NUC	PSIN	ETA	KN	1/S
1.057	4.698	0.993	0.815	0.821	1.002	0.285	.179
1.056	4.229	0.840	0.675	0.803	0.999	0.317	.197
1.055	3.886	1.094	0.908	0.830	1.011	0.344	.170
1.055	3.563	0.937	0.783	0.815	1.014	0.375	.185
1.055	3.253	0.955	0.760	0.817	1.017	0.411	.183
1.054	2.902	0.911	0.740	0.812	1.021	0.461	.168
1.053	2.592	0.727	0.571	0.786	1.011	0.516	.214
1.054	2.297	0.740	0.583	0.788	1.019	0.562	.212

FLOW CALIBRATION RESULTS: PROBE # :29/8/9

M	RE	NUM	NUC	PSIN	ETA	KN	1/S
1.409	4.214	1.198	1.004	0.838	1.017	0.380	.162
1.409	3.781	0.949	0.774	0.816	1.015	0.424	.184
1.408	3.496	0.901	0.731	0.811	1.022	0.438	.189
1.408	3.205	0.810	0.647	0.799	1.017	0.500	.201
1.408	2.936	0.816	0.653	0.800	1.022	0.546	.200
1.407	2.635	0.744	0.587	0.789	1.023	0.608	.211
1.406	2.345	0.634	0.487	0.768	1.017	0.683	.232
1.406	2.022	0.628	0.481	0.767	1.023	0.792	.233

FLOW CALIBRATION RESULTS: PROBE # :29/8/10

M	RE	NUM	NUC	PSIN	ETA	KN	1/S
2.125	2.515	0.727	0.571	0.786	1.030	0.735	.214
2.126	2.243	0.729	0.573	0.786	1.035	0.825	.214
2.126	2.091	0.666	0.516	0.775	1.033	0.834	.226
2.125	1.920	0.609	0.465	0.763	1.032	0.963	.238
2.126	1.748	0.600	0.456	0.760	1.034	1.058	.240
2.127	1.532	0.553	0.414	0.749	1.035	1.203	.252
2.124	1.399	0.521	0.385	0.740	1.037	1.322	.261
2.122	1.227	0.477	0.346	0.725	1.036	1.507	.275

M=0; d=20 μ m.

FLOW CALIBRATION RESULTS: PROBE # 30/2/2 L/D=132

U(CM/SEC)	RE	NUM	NUC	PSIN	ETA	1/S
1638.83	0.433	0.830	0.543	0.634	1.078	.348
1490.93	0.394	0.804	0.520	0.647	1.074	.355
1301.82	0.344	0.799	0.516	0.646	1.076	.357
1122.25	0.297	0.785	0.504	0.642	1.075	.361
982.04	0.260	0.776	0.496	0.639	1.075	.364
884.92	0.234	0.772	0.472	0.638	1.076	.365
814.10	0.215	0.765	0.486	0.636	1.075	.368
728.87	0.193	0.771	0.472	0.638	1.077	.366
668.27	0.177	0.760	0.482	0.634	1.076	.369
558.21	0.148	0.755	0.478	0.633	1.077	.371
501.00	0.132	0.749	0.472	0.630	1.078	.373
448.68	0.119	0.749	0.472	0.630	1.081	.373
411.02	0.109	0.744	0.468	0.629	1.079	.375

FLOW CALIBRATION RESULTS: PROBE # 25/2/1 L/D=216

U(CM/SEC)	RE	NUM	NUC	PSIN	ETA	1/S
1642.69	0.437	0.735	0.584	0.795	1.009	.205
1521.98	0.405	0.730	0.579	0.794	1.007	.206
1291.66	0.344	0.706	0.557	0.790	1.002	.210
1115.45	0.297	0.685	0.538	0.786	1.003	.214
1013.00	0.270	0.678	0.532	0.785	1.003	.215
892.77	0.238	0.663	0.519	0.782	1.004	.218
832.57	0.222	0.657	0.513	0.781	1.003	.219
673.77	0.179	0.644	0.501	0.778	1.005	.222
561.87	0.150	0.627	0.486	0.775	1.004	.225
486.02	0.129	0.626	0.485	0.775	1.006	.225
436.54	0.116	0.614	0.474	0.772	1.004	.228
404.27	0.108	0.611	0.471	0.772	1.005	.229
369.20	0.098	0.606	0.467	0.771	1.006	.230

FLOW CALIBRATION RESULTS: PROBE # 27/2/2 L/D=146

U(CM/SEC)	RE	NUM	NUC	PSIN	ETA	1/S
1644.71	0.435	0.652	0.528	0.811	0.998	.189
1522.80	0.403	0.628	0.506	0.807	0.994	.193
1280.69	0.339	0.620	0.499	0.805	0.995	.195
1129.82	0.299	0.618	0.497	0.805	0.998	.195
1005.31	0.266	0.611	0.491	0.804	0.996	.197
892.50	0.236	0.607	0.487	0.803	0.998	.197
816.27	0.216	0.598	0.479	0.801	0.997	.199
678.51	0.179	0.591	0.473	0.800	0.998	.200
571.26	0.151	0.586	0.468	0.799	0.998	.201
502.28	0.133	0.578	0.461	0.797	0.998	.203
449.03	0.119	0.575	0.458	0.797	0.999	.203
405.92	0.107	0.572	0.456	0.796	0.999	.204
383.17	0.101	0.569	0.452	0.795	0.998	.205

FLOW CALIBRATION RESULTS: PROBE # 26/3/1 L/D=274

U(CM/SEC)	RE	NUM	NUC	FSIN	ETA	1/S
1641.52	0.400	0.678	0.564	0.834	0.994	.164
1484.56	0.407	0.690	0.577	0.836	0.993	.164
1283.06	0.362	0.688	0.575	0.836	1.004	.164
1121.28	0.367	0.648	0.530	0.829	0.995	.171
1013.20	0.278	0.605	0.526	0.818	0.999	.172
892.37	0.245	0.617	0.507	0.825	0.997	.175
825.25	0.226	0.620	0.512	0.826	1.002	.174
674.54	0.185	0.608	0.499	0.824	1.001	.176
580.24	0.159	0.537	0.481	0.820	1.002	.180
514.90	0.141	0.573	0.468	0.818	0.998	.180
464.61	0.127	0.559	0.456	0.815	0.997	.181
429.52	0.113	0.556	0.453	0.815	1.004	.185
402.37	0.110	0.543	0.446	0.813	1.001	.187

FLOW CALIBRATION RESULTS: PROBE # 26/2/1 L/D=334

U(CM/SEC)	RE	NUM	NUC	FSIN	ETA	1/S
1645.16	0.437	0.620	0.534	0.861	1.000	.139
1487.87	0.395	0.581	0.497	0.856	0.999	.144
1257.08	0.334	0.566	0.483	0.854	0.999	.146
1138.92	0.303	0.557	0.475	0.853	1.000	.147
997.33	0.265	0.544	0.463	0.851	0.999	.149
885.17	0.235	0.527	0.457	0.850	1.001	.150
810.27	0.215	0.529	0.448	0.849	1.000	.151
667.23	0.177	0.510	0.431	0.846	1.000	.154
533.31	0.147	0.502	0.424	0.844	1.001	.156
501.81	0.133	0.490	0.412	0.842	1.001	.156
448.33	0.119	0.484	0.407	0.841	1.002	.159
410.76	0.109	0.470	0.394	0.838	0.998	.162
381.74	0.101	0.467	0.392	0.838	1.000	.162

FLOW CALIBRATION RESULTS: PROBE # 29/2/1 L/D=404

U(CM/SEC)	RE	NUM	NUC	FSIN	ETA	1/S
1686.85	0.464	0.615	0.545	0.886	0.997	.114
1511.97	0.416	0.598	0.529	0.884	0.995	.116
1303.68	0.358	0.584	0.515	0.883	0.995	.117
1144.45	0.315	0.571	0.504	0.881	0.998	.119
1024.25	0.282	0.552	0.485	0.879	0.994	.121
918.87	0.253	0.546	0.479	0.878	0.997	.122
832.98	0.229	0.537	0.471	0.877	0.996	.123
675.41	0.191	0.513	0.453	0.875	0.995	.125
596.99	0.164	0.508	0.444	0.873	0.998	.127
519.27	0.143	0.493	0.429	0.871	0.995	.129
459.07	0.126	0.488	0.425	0.871	0.996	.129
434.91	0.120	0.475	0.413	0.869	0.996	.131
395.71	0.109	0.473	0.411	0.868	0.997	.132

M=0; d=50 μ m.

FLOW CALIBRATION RESULTS: PROBE #09/4/1 L/D=177

U(CM/SEC)	RE	NUM	NUC	PSIN	ETA	1/S
1633.49	1.117	0.873	0.667	0.764	0.984	.236
1489.48	1.019	1.154	0.921	0.799	1.019	.201
1261.93	0.863	0.836	0.634	0.758	0.986	.243
1122.26	0.768	0.819	0.618	0.755	0.985	.246
980.82	0.671	1.043	0.821	0.787	1.022	.213
883.49	0.604	0.799	0.600	0.751	0.990	.249
802.81	0.549	0.782	0.585	0.748	0.986	.252
665.60	0.455	0.794	0.595	0.750	0.995	.250
576.39	0.394	0.919	0.708	0.770	1.024	.230
491.54	0.336	0.891	0.682	0.766	1.020	.234
443.05	0.303	0.897	0.688	0.767	1.027	.233
401.32	0.275	0.737	0.545	0.739	0.997	.262
382.04	0.261	0.769	0.573	0.745	1.012	.255

FLOW CALIBRATION RESULTS: PROBE #06/5/1 L/D=186

U(CM/SEC)	RE	NUM	NUC	PSIN	ETA	1/S
1637.45	1.117	1.032	0.823	0.797	1.006	.203
1476.66	1.008	0.915	0.716	0.783	0.994	.217
1258.63	0.959	1.069	0.856	0.801	1.023	.199
1103.46	0.755	0.756	0.753	0.750	1.011	.212
994.11	0.678	0.912	0.714	0.782	1.008	.218
892.43	0.609	0.956	0.753	0.788	1.010	.212
787.39	0.537	0.861	0.668	0.775	1.002	.225
699.18	0.477	0.869	0.675	0.776	1.012	.224
567.90	0.388	0.714	0.535	0.749	0.989	.251
496.90	0.339	0.843	0.651	0.772	1.014	.228
448.94	0.306	0.868	0.674	0.776	1.022	.224
413.89	0.282	0.791	0.604	0.763	1.012	.237
388.78	0.265	0.772	0.587	0.760	1.014	.240

FLOW CALIBRATION RESULTS: PROBE # 29/5/1 L/D=225

U(CM/SEC)	RE	NUM	NUC	PSIN	ETA	1/S
1634.09	1.149	0.972	0.808	0.830	1.087	.170
1457.57	1.025	0.817	0.665	0.813	1.074	.187
1226.67	0.863	0.926	0.764	0.826	1.088	.174
1068.90	0.752	0.789	0.639	0.809	1.079	.191
956.78	0.673	0.823	0.670	0.814	1.089	.186
855.96	0.602	0.849	0.694	0.817	1.093	.183
777.03	0.547	0.706	0.562	0.797	1.073	.203
651.77	0.458	0.776	0.627	0.808	1.088	.192
538.65	0.379	0.769	0.621	0.807	1.091	.193
482.99	0.340	0.724	0.579	0.800	1.087	.200
424.39	0.299	0.677	0.536	0.792	1.084	.208
378.86	0.267	0.631	0.495	0.784	1.076	.216
355.86	0.250	0.708	0.565	0.797	1.091	.203

FLOW CALIBRATION RESULTS: PROBE #07/7/1 L/D=227

U(CM/SEC)	RE	NUM	NUC	PSIN	ETA	1/S
1626.76	1.110	0.897	0.740	0.825	0.987	.175
1478.49	1.009	1.055	0.886	0.840	1.013	.160
1268.70	0.866	0.939	0.779	0.829	0.999	.171
1100.26	0.751	0.908	0.750	0.826	1.006	.174
983.99	0.671	0.913	0.755	0.827	1.012	.173
881.18	0.601	0.849	0.696	0.820	0.999	.180
787.46	0.537	0.765	0.619	0.809	0.985	.191
666.01	0.454	0.760	0.614	0.808	0.991	.192
576.75	0.393	0.791	0.642	0.812	1.003	.188
501.98	0.342	0.782	0.634	0.811	1.010	.187
443.33	0.302	0.751	0.606	0.807	0.999	.193
401.57	0.274	0.766	0.619	0.809	1.008	.191
382.28	0.261	0.707	0.566	0.800	1.000	.200

FLOW CALIBRATION RESULTS: PROBE #17/4/1 L/D=295

U(CM/SEC)	RE	NUM	NUC	PSIN	ETA	1/S
1646.26	1.159	0.807	0.695	0.821	1.020	.139
1474.44	1.038	0.740	0.635	0.815	1.016	.145
1262.58	0.889	0.718	0.612	0.852	1.018	.148
1109.40	0.781	0.824	0.710	0.853	1.034	.137
990.18	0.697	0.816	0.704	0.862	1.038	.138
880.01	0.619	0.711	0.605	0.851	1.027	.149
798.19	0.562	0.731	0.624	0.853	1.032	.147
671.62	0.473	0.727	0.620	0.853	1.037	.147
559.97	0.394	0.639	0.538	0.842	1.028	.158
469.76	0.365	0.668	0.565	0.846	1.036	.154
442.67	0.312	0.674	0.571	0.847	1.043	.153
395.93	0.279	0.659	0.553	0.844	1.041	.156
383.35	0.270	0.576	0.495	0.836	1.029	.164

FLOW CALIBRATION RESULTS: PROBE # 25/4/1 L/D=346

U(CM/SEC)	RE	NUM	NUC	PSIN	ETA	1/S
1669.68	1.203	0.976	0.872	0.893	0.996	.107
1492.32	1.075	0.942	0.840	0.891	0.993	.109
1283.53	0.928	0.880	0.781	0.897	0.995	.113
1139.76	0.801	0.916	0.815	0.890	1.003	.110
998.23	0.719	0.833	0.737	0.884	0.999	.116
894.47	0.644	0.803	0.708	0.882	0.997	.118
801.84	0.578	0.803	0.708	0.882	1.003	.118
682.96	0.492	0.744	0.652	0.877	1.000	.123
569.46	0.410	0.711	0.621	0.874	0.997	.126
494.09	0.356	0.691	0.603	0.872	0.997	.128
442.88	0.319	0.692	0.603	0.872	1.002	.128
400.78	0.289	0.652	0.566	0.868	0.998	.132
385.33	0.278	0.669	0.582	0.870	1.006	.130

FLOW CALIBRATION RESULTS: PROBE #29/6/1 L/D=416

U(CM/SEC)	RE	NUM	NUC	PSIN	ETA	1/S
1636.98	1.113	0.744	0.670	0.900	0.989	.100
1469.65	1.000	0.775	0.699	0.902	1.002	.098
1267.00	0.862	0.762	0.687	0.901	1.004	.099
1096.51	0.746	0.686	0.615	0.896	0.990	.104
985.25	0.670	0.709	0.637	0.898	1.004	.102
874.28	0.555	0.685	0.613	0.896	1.004	.104
805.37	0.548	0.697	0.625	0.897	1.009	.103
672.65	0.457	0.644	0.575	0.892	1.004	.108
558.26	0.380	0.615	0.547	0.889	1.003	.111
491.19	0.334	0.593	0.526	0.887	0.996	.113
437.03	0.297	0.565	0.500	0.884	0.989	.116
401.04	0.273	0.583	0.517	0.886	1.004	.114
375.13	0.255	0.536	0.472	0.881	0.981	.119

FLOW CALIBRATION RESULTS: PROBE #09/3/1 L/D=420

U(CM/SEC)	RE	NUM	NUC	PSIN	ETA	1/S
1633.86	1.108	0.794	0.718	0.904	1.022	.096
1474.47	1.000	0.737	0.664	0.901	1.017	.099
1260.22	0.854	0.772	0.697	0.903	1.032	.097
1122.51	0.761	0.760	0.685	0.902	1.035	.098
991.27	0.672	0.669	0.599	0.895	1.014	.105
897.83	0.609	0.700	0.628	0.898	1.028	.102
793.52	0.538	0.687	0.616	0.897	1.034	.103
673.27	0.456	0.626	0.558	0.892	1.018	.108
567.72	0.385	0.596	0.530	0.889	1.014	.111
496.74	0.337	0.636	0.567	0.892	1.039	.108
443.15	0.300	0.561	0.497	0.895	1.009	.115
401.41	0.272	0.581	0.515	0.887	1.022	.113
368.66	0.263	0.590	0.524	0.888	1.035	.112

REFERENCES CITED

REFERENCES CITED

1. Betchov, R. Proc. Koninkl.Ned Akad. Wefenschap., 51, 721, 1948.
2. Kovasznay, L.S.G., and Tormark, S.I.A., "Heat Loss of Hot-Wires in Supersonic Flow", Bumblebee Rep. No. 127, Dept. of Aero, John Hopkins University, 1950.
3. Dewey, C.F. Jr., "Measurements in Highly Dissipative Regions of Hypersonic Flows- Part I. Hot-Wire Measurements in Low Reynolds Number Hypersonic Flows", Ph.D. thesis, California Institute of Technology, Pasadena, CA., 1963.
4. Behrens, W., "Hot-Wires of Finite Length for Compressible Flow Fluctuation Measurements", unpublished rough draft, California Institute of Technology, Pasadena, CA., 1972.
5. Laufer, J. and McClellan, R., "Measurements of Heat Transfer from Fine Wires in Supersonic Flows", J. Fluid Mech., Vol. 1, No. 3, pp. 276-289, 1956.
6. Cybulski, R.J. and Baldwin, L.V., "Heat Transfer from Cylinders in Transition from Slip Flow to Free-Molecule Flow", NASA Memo. 4-27-59E, 1959.
7. Vrebalovich, T. "Heat Loss from Hot-Wires in Transonic Flow", Summary Report No. 36-14, Jet Propulsion Lab., Pasadena, CA., May, 1964.
8. Stalder, J.R., Goodwin, G. and Creager, M.O., "Comparison of Theory and Experiment for High Speed Free-Molecule Flow", NACA Rep. No. 1032, 1951.
9. Cole, J.D. and Roshko, A., "Heat Transfer from Wires at Reynolds Numbers in the Oseen Range", Proc. 1954 Heat Trans. and Fluid Mech Inst., Stanford University Press, Stanford, CA., 1954, pp.13-24.
10. Demetriades, A., "Catalog of Hot-Wire Characteristics", unpublished, Dept. of Mech. Engr., Montana State University, Bozeman, MT., 1983.
11. McAdams, W.H., Heat Transmission, 3rd ed., McGraw-Hill Book Co. Inc., New York, 1954, p. 259.
12. King, L.V., "On the Convection of Heat from Small Cylinders in a Stream of Fluid : Determination of the Convection Constants of Small Platinum Wires with Applications to Hot-Wire Anemometry.", Phil. Trans., A 214, p. 373, 1914.

13. Hilpert, R., "Forschung auf dem Gebiete des Ingenieurwesens", Bd. 4, pp. 215-222, 1933.
14. Collis, D.C. and Williams, M.J., "Two-Dimensional Convection from Heated Wires at Low Reynolds Numbers", J. Fluid Mech., Vol. 6, pp 357-384, 1959.
15. Baldwin, L.V., Sandborn, V.A., and Laurence, J.C., "Heat Transfer from Transverse and Yawed Cylinders in Continuum, Slip, and Free-Molecule Flows", J. Heat Trans., pp. 77-86, May, 1960.
16. Kovasznay, L.S.G., "The Hot-Wire Anemometer in Supersonic Flow", J. Aero. Sci., pp. 565-584, Sept. 1950.
17. Spangenberg, W.G., "Heat Loss Characteristics of Hot-Wire Anemometers at Various Densities in Transonic and Supersonic Flow", NACA TN 3381, 1955.
18. Winovich, W. and Stine, H.A., "Measurements of the Non-Linear Variation with Temperature with Heat Transfer Rate from Hot-Wires in Transonic and Supersonic Flow", NACA TN 3965, 1957.
19. Lowell, H.H. "Design and Application of Hot-Wire Anemometers for Steady-State Measurements at Transonic and Supersonic Air Speeds", NACA TN 2117, 1950.
20. Sandborn V.A. and Domitz, S., Unpublished research at Lewis Research Center, NASA, 1956.
21. Weltmann, R.N. and Kuhns, P.W., "Heat Transfer to Cylinders in Crossflow in Hypersonic Rarefied Gas Streams", NASA TN D-267, 1960.
22. Wong, H., "Design and Development of a Free-Molecule Heat Transfer Probe", Project Report HE-100-143, University of Calif.(Berkeley), 1956.
23. Baldwin, L.V., "Slip Flow Heat Transfer from Cylinders in Subsonic Airstreams", NACA TN 4369, 1958.
24. Demetriades, A., "Nusselt Number and Recovery Factor Measurement with the Hot-Wire Anemometer", Personal Communication, Dept. of Mech. Engr., Montana State University, Bozeman, MT. Feb., 1983.
25. Drummond, D., Rogers, B. and Demetriades, A., "Design and Operating Characteristics of the Supersonic Wind Tunnel", MSU/SWT Rep. TR-81-01, Dept. of Mech. Engr., Montana State University, Bozeman, MT, Jan. 1981.

26. Demetriades, A. and Fishbaugher, M., "Instructions for Fabricating and Calibrating Hot-Wire Probes", Unpublished Rep., Dept. of Mech. Engr., Montana State University, Bozeman, MT.
27. Fishbaugher, M., "Analysis of Hot-Wire Structures", Personal Communication, Dept. of Mech. Engr., Montana State University, Bozeman, MT, Oct. 1983.
28. Schlichting, H., Boundary Layer Theory, McGraw-Hill Book Co., 7th ed., New York, p. 17, 1979.
29. Demetriades, A., "Final Report: Advanced Penetration Problems Program", SAMSO publication no. TR-71-78, April, 1971.

MONTANA STATE UNIVERSITY LIBRARY

MATIN

H442 Hertel, P. S.

cop.2 Heat transfer characteristics of small configuration.

[illegible]

MAIN
N378
H442
cop.2