Aspirating Probes for Measurement of Mean Concentration and Fluctuating Quantities in Supersonic Air/Helium Shear Layers

by

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(ABSTRACT)

Two aspirating hot-film probes are developed to make measurements in supersonic air/helium shear layers. The first probe is designed to measure local mean gas composition and is referred to as the mean concentration probe. This probe consists of a constant temperature hot-film sensor operating in a channel with a choked exit. The flow over the hot-film is influenced only by total temperature, total pressure, and gas composition. The mean probe is easily calibrated and shows acceptable sensitivity to flow angularity. The second probe is based on an improved design of the mean concentration probe. In addition to measuring mean composition, this second probe also measures turbulence intensities of Reynolds number and thermal conductivity using a multiple overheat method. This probe is referred to as the turbulent probe. Both probes are used in the study of supersonic air/helium mixing layers in the VPI&SU 23 cmx23 cm Supersonic Wind Tunnel. Profiles of mean and turbulent quantities are presented.

Acknowledgements

I would like to thank the members of my advisory committee; Dr. Wing Ng, Dr. Larry Roe, and Dr. Joseph Schetz. I could not have succeeded without their help and understanding. I would especially like to thank Dr. Ng for his patience and willingness to work with me.

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List of Illustrations

Nomenclature

a,b	-	calibration constants for the hot-film probe
A	-	Area
d	-	hot-film diameter
d_{eq}	-	equivalent diameter of tear drop injector
h	-	injector slot height
i_F	-	hot-film current
k	-	thermal conductivity of the fluid a the total temperature
l	-	hot-film length
M	-	Mach number
Nu	-	Nusselt number
P	-	Pressure
q_F	-	hot-film heat transfer rate
Re_d	-	Reynolds number based on hot-film diameter
R_S	-	resistance of bridge arm in series with the hot-film probe
R_F	-	resistance of hot-film probe
T	-	Temperature
V_F	-	hot-film voltage

V^2	-	mean squared voltage
x	-	axial distance from injector
y	-	vertical distance form tunnel floor
$\mathfrak{R}$	-	universal gas constant
γ	-	ratio of specific heats
θ	-	turbulent probe constant
μ	-	viscosity of the fluid at the total temperature
χ	-	mole fraction of helium
ρu	-	mass flux

Subscripts

c	-	conditions at the hot-film plane
h	-	helium
m	-	air/helium mixture
s	-	static
T	-	total temperature

Superscripts

*	-	conditions at choked orifice
( )′	-	fluctuating component
$\overline{( )}$	-	mean component

1.0 Introduction

Recent interest in supersonic and hypersonic atmospheric vehicles has revealed a need for additional research in turbulent mixing of high speed flows. This thesis describes the development of the two aspirating probes to fulfill this need. The first probe is designed for mean gas composition measurements. The second probe is an improvement over the first probe, where in addition to mean concentration, fluctuating Reynolds number and thermal conductivity can also be measured. This research was performed in a supersonic wind tunnel where a stream of helium is injected into a Mach 3 air freestream. From the mean concentration measurement, the local gas constant and ratio of specific heats are known and with the help of other conventional steady state measurements, mean flow quantities such as velocity, density, and Mach number can be determined [1]. The motivation for measuring fluctuating quantities in an air/helium shear flow is that it will help explain the turbulence effects on mixing and also provide data for computation and turbulent modeling in the future.

Several researchers have developed aspirating probes to measure gas species concentration. Blackshear and Fingerson adopted a probe geometry consisting of a single hot-film sensor behind a choked orifice in order to measure either temperature or species concentration in a constant pressure flow [2]. Brown and Rebollo constructed a smaller probe of similar arrangement to measure gas

composition at constant gas temperature [3]. Jones and Wilson used a constant temperature film sensor upstream of a choked orifice for gas composition measurement and an auxiliary constant current film to compensate for slow changes in free-stream gas temperature [4]. Ahmed and So used a hot-wire aspirating concentration probe to measure gas composition in a swirling flow environment in a model cylindrical combustor [5]. Adler constructed a gas sampler analyzer and used a hot-wire to determine concentration fields of binary gaseous mixtures [6]. Way and Lilly used a two-sensor hot-wire probe to determine both velocity and concentration, which required elaborate calibration and data processing to separate the concentration information [7,8]. All of the above experiments were in subsonic flows. Devillers and Diep used a single-element, bare hot-wire probe to determine gas mixture concentrations in a supersonic flow, but knowledge of pressures and heat transfer conditions around the hot-wire had to be known. As a result, the data reduction is complicated and time consuming [9]. The mean concentration probe presented in this thesis provides a quick and simple means to determine the concentration in supersonic flows.

There is no data in the existing literature on measuring fluctuating Reynolds number and thermal conductivity in a supersonic binary-gas shear layer. The method used in the turbulent probe is similar in principle to the single sensor, multiple overheat method used to measuring fluctuating mass flux and total temperature in a supersonic flows [10,11]. The advantage of using the turbulent aspirating probe as opposed to a bare hot-film sensor is than mean concentration

can also be retrieved from the data.

The object of this thesis is to describe two different hot-film aspirating probes used to make measurements in supersonic air/helium shear layers. In this thesis the mean concentration probe will be presented first, followed by the turbulent probe and ending with the conclusions and recommendations.

2.0 Mean Concentration Probe

The mean concentration probe is a custom built aspirating-type probe. The design of the probe is based on an aspirating probe by Ng and Epstein [12] and a sampling probe by Thomas and Schetz [13]. It is designed to measure the mean concentration of an air/helium mixture in a supersonic blowdown tunnel. The probe uses a hot-film sensor and once calibrated, can determine concentration on-site without the use of a gas sampler and analyzer. The mean concentration profile when coupled with other conventional steady-state measurements are used to calculate mean flow quantities such as velocity, density, and Mach number. In this chapter, the probe design and principle of operation will be described. This will be followed by a description of the calibration, experimental

facilities, and data reduction. Next, results are presented for the mean concentration profile measured in a helium/air shear layer.

2.1 Probe Design

The configuration of the concentration probe is presented in Fig. 1. The probe stem consists of two sections of stainless steel tubing that are welded together. The tip of the probe is inclined at a 5 degree angle which enables it to make measurements near the tunnel floor. A hot-film sensor is housed in the probe tip. Suction to pull the air-helium mixture is provided by a vacuum line connected to the nylon insert at the base of the probe.

Figure 2 shows the design of the probe tip. The probe has a removable cap so that a broken sensor can easily be replaced. The hot-film sensor is soldered onto brass supports which are electrically insulated with epoxy. The inlet hole at the tip of the probe has a diameter of 0.028-cm (0.011-in), and the choked orifice inside the probe has a diameter of 0.056-cm (0.022-in). These diameters are chosen so that the standoff shock at the probe tip can be swallowed into the probe. Flow visualization from spark schlieren during the experiment in a Mach 3 flow verifies this design intention. The internal probe diameter diverges from 0.028-cm (0.011-in) at the inlet to 0.121-cm (0.0475-in) at the sensor plane, causing a normal shock to occur inside the probe in the diverging channel. In this fashion, a stream tube equal in area to the probe capture area enters the probe undisturbed.

Schematic of the
Mean Concentration Probe

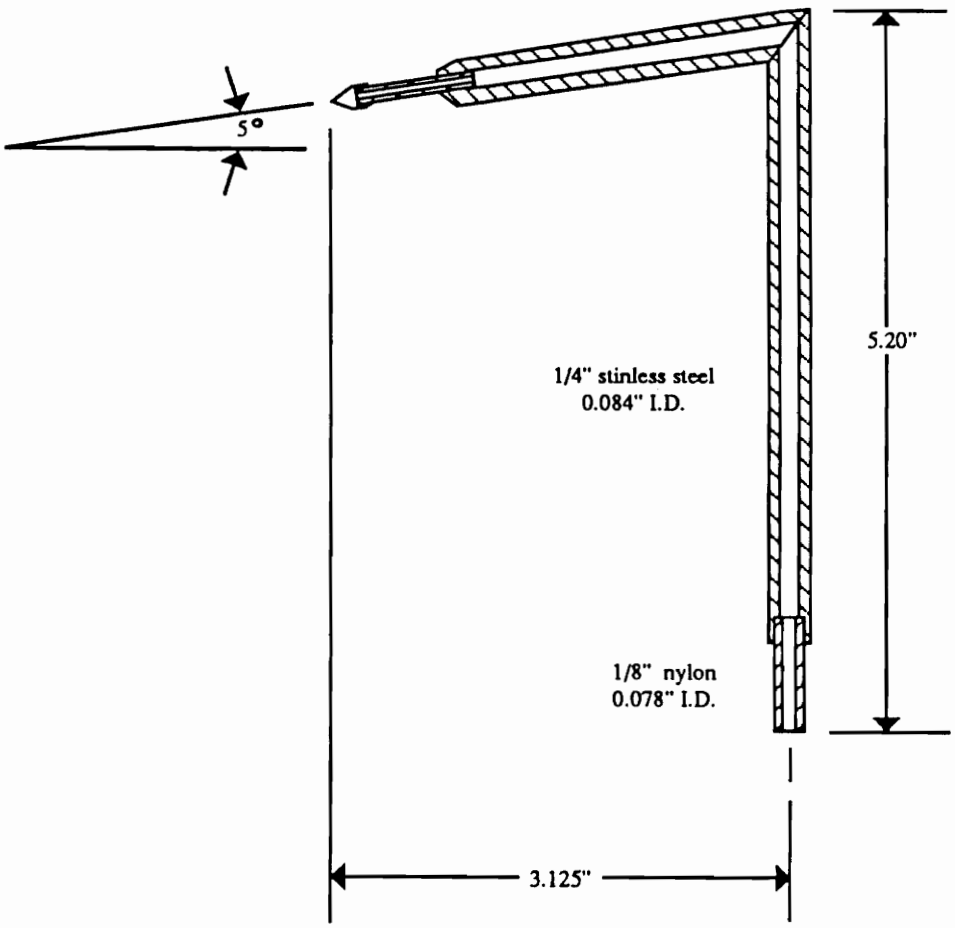


Figure 1. Schematic of Mean Concentration Probe

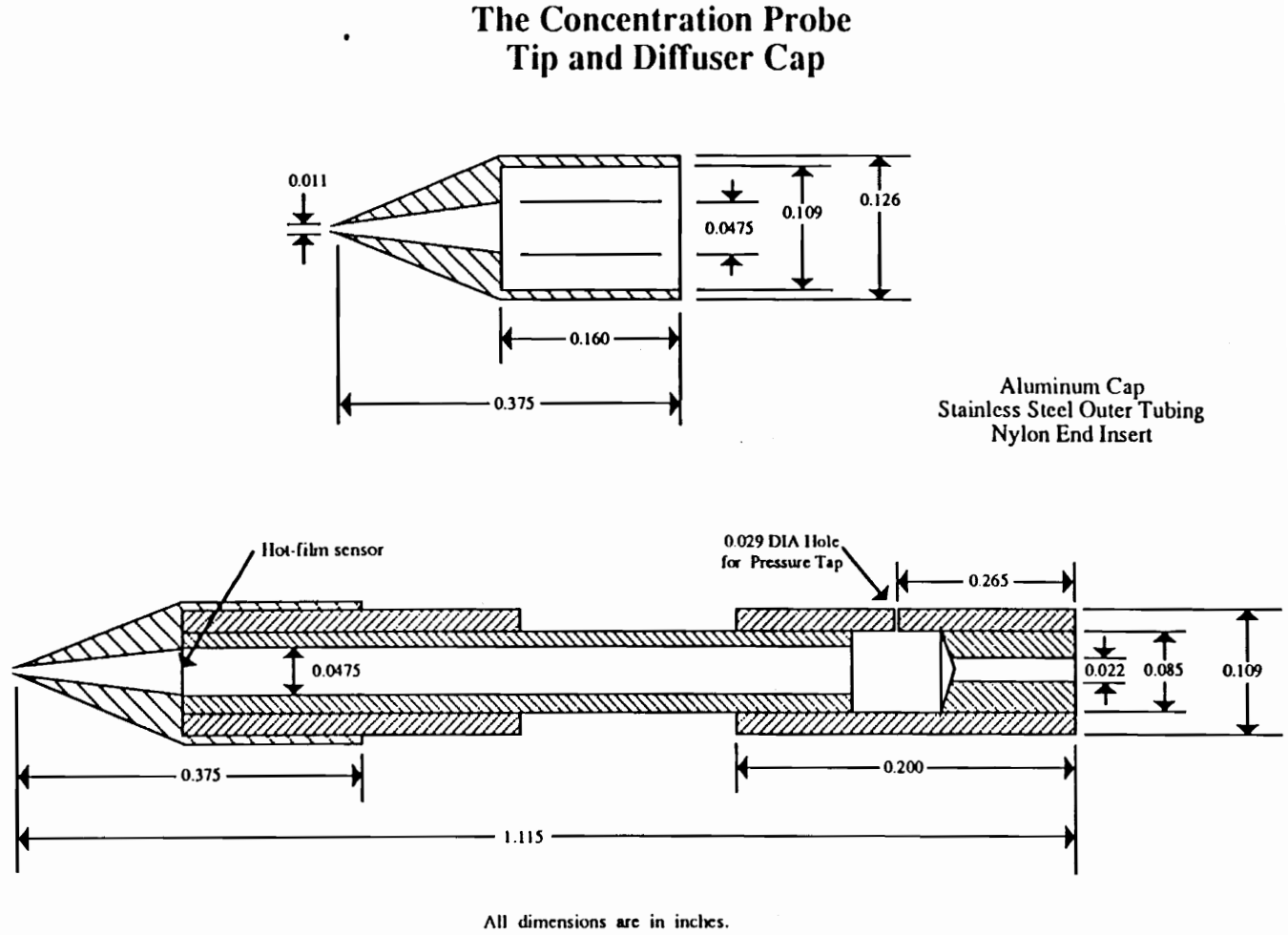


Figure 2. Mean Concentration Probe Tip and Diffuser Cap

A pressure tap near the hot-film sensor measures the pressure before the choked orifice. This pressure is referred to as P1. The back pressure behind the orifice is also measured and is denoted as P2. The ratio of these pressures confirms the choked condition at the 0.022 in. orifice. In addition, using one-dimensional gas-dynamic equations, the strength and location of the shock wave in the diverging channel of the probe can be estimated based on the measurements of P1. These calculations also confirm that the shock wave always occurs in the diverging channel of the probe. As will be shown in the next section, P1 is also required in the data reduction to determine concentration.

2.2 Principle of Operation

The hot-film in the concentration probe is connected to a Dantec constant temperature anemometer. The principle of the anemometer is to measure the convective heat transfer of the film to the surrounding fluid. Mass flux (ρu) influences the heat transfer at the hot-film plane. For channel flow, the one dimensional continuity equation can be written as

$$\rho U = \left(\frac{P_T}{\sqrt{T_T}}\right)\sqrt{\frac{\gamma}{\Re}}\, M\left(1+\frac{\gamma-1}{2}M\right)^{-(\gamma+1)\,/\,2(\gamma-1)} \tag{2.1}$$

with sonic flow ($M=1$) at the channel orifice Eqn. 2.1 reduces to

(2.2) $$(\rho u)^* = \left(\frac{P_T}{\sqrt{T_T}}\right) \sqrt{\frac{\gamma}{\mathfrak{R}}} \left(\frac{2}{\gamma+1}\right)^{\gamma+1 \,/\, 2(\gamma-1)}$$

where * denotes the sonic conditions at the throat.

Equating continuity at the wire plane with the choked orifice in the probe, the mass flux at the wire plane becomes

(2.3) $$(\rho u) = \left(\frac{P_T}{\sqrt{T_T}}\right) \frac{A^*}{A_c} \sqrt{\frac{\gamma}{\mathfrak{R}}} \left(\frac{2}{\gamma+1}\right)^{\gamma+1 \,/\, 2(\gamma-1)}$$

Thus the mass flux at the wire plane is a function of total pressure and total temperature in the probe, ratio of orifice to wire plane area, and local properties of the gas.

As shown in Fig. 3 the anemometer is basically a Wheatstone bridge with the hot-film serving as one of the arms. Electric current passes through the circuit so that the hot-film is maintained at a constant temperature, and therefore constant resistance.

The rate of heat transfer from the hot-film is given as

(2.4) $$q_F = i_F^2 R_F$$

where the current to the film is

Sketch of Anemometer Bridge

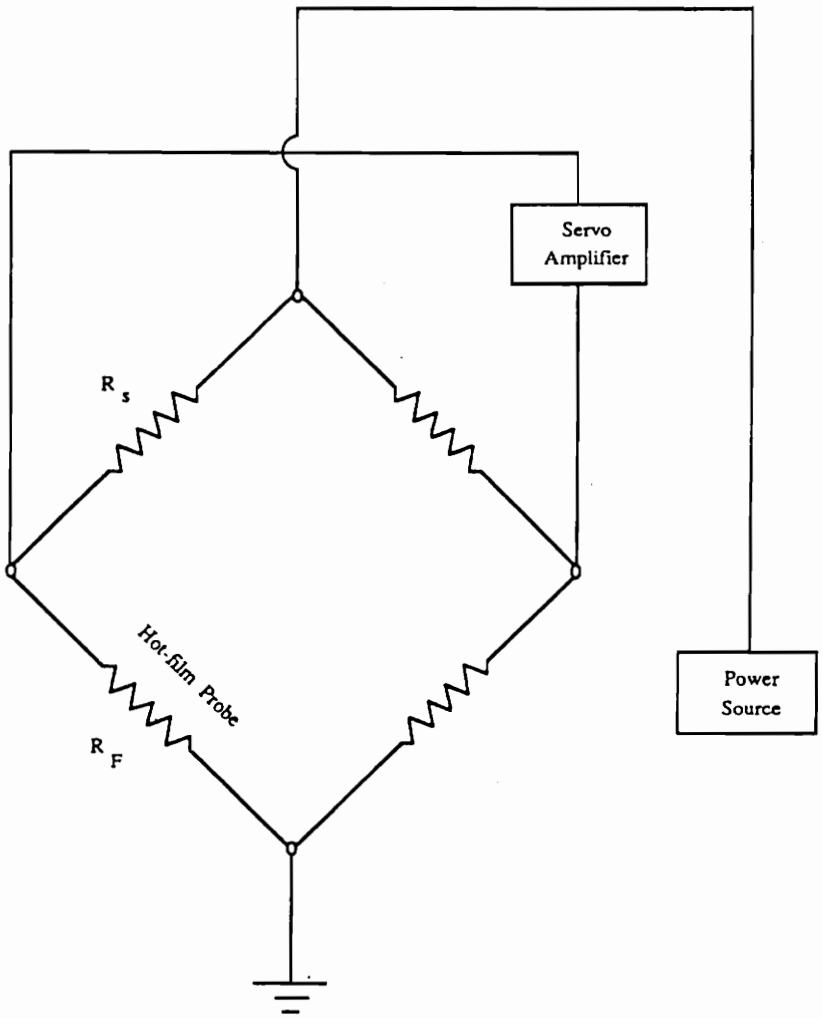


Figure 3. Sketch of Anemometer Bridge

(2.5) $$i_F = \frac{V_F}{R_F + R_S}$$

For a hot-film the Nusselt number is defined as

(2.6) $$Nu \equiv \frac{q_F}{\pi k l (T_F - T_T)}$$

Combining Eqns. 2.4, 2.5 and 2.6, the Nusselt number becomes a function of the hot-film voltage

(2.7) $$Nu = \frac{V^2 R_F}{(R_F + R_S)} \frac{1}{\pi k l (T_F - T_T)}$$

Nusselt number can also be related to the mass flux through the Reynolds number

(2.8) $$Nu = a_i \sqrt{(\rho u \times \frac{d}{\mu})} + b_i$$

where a_i and b_i are calibration constants and i denotes different helium concentration levels.

Next, Eqns. 2.7 and 2.8 are set equal and the mass flux is replaced with Eqn. 2.3. Hence, the hot-film voltage is related to the flow conditions inside the probe channel

$$V^2 = \frac{(R_S+R_F)^2}{R_F}\,\pi l k\left[\, a_i\left\{\frac{d}{\mu}\left(\frac{P_T}{\sqrt{T_T}}\right)\frac{A^*}{A_c}\sqrt{\frac{\gamma}{\Re}}\left(\frac{2}{\gamma+1}\right)^{\gamma+1\,/\,2(\gamma-1)}\right\}^{1/2} + b_i\right](T_F-T_T)$$

(2.9)

where k, μ, γ, and $\Re$ are function of the gas composition.

This is the equation used to reduce the data. For a given probe geometry and a given hot-film sensor, the above equation can be expressed as:

$$V^2 = \textit{function}\ (\textit{gas composition},\ T_T,\ P_T).$$

Thus, to retrieve the mean concentration; the hot-film voltage, the stagnation pressure and temperature in the probe must be known.

The measurement of stagnation pressure in the probe is approximated by measuring the wall static pressure inside the probe (P1). This is justified since the Mach number in the constant area channel, which is located downstream of the shock inside the probe, is 0.05, giving a ratio of static to total pressure of 0.99. The calibration of the hot-film sensor in the concentration probe, as well as the data reduction, are all in terms of this pressure P1.

The compact nature of the probe precludes the measurement of total temperature simultaneously with pressure and hot-film voltage. Instead, a separate diffuser thermocouple probe is used to determine the distribution of stagnation temperature during a separate run. As mentioned previously, a shock wave exists inside the concentration probe at a location upstream of the sensor plane.

However, since there is no change in stagnation temperature across a shock, the stagnation temperature at the sensor plane is the same as that in the freestream outside the tip of the probe. Hence it is possible to use the temperature data from a separate thermocouple probe in the data reduction.

2.3 Calibration

The time required to setup and calibrate the concentration probe is approximately three hours. The results of the calibration are used to calculate constants for five different concentration levels. These constants are used to generate calibration curves that are inputs to the data reduction program.

2.3.1 Calibration Setup

Figure 4 shows the concentration probe calibration set up. The pressure vessel has a volume of 11500-cm^3 (700-in^3) and is connected to the air-helium supply. The pressure vessel is evacuated by a vacuum pump. A type k (Chromel-Alumel) thermocouple connected to an Omega HH81 digital thermometer measures total temperature in the calibration vessel. The total pressure in the chamber along with P1 and P2 from the probe are measured by mercury manometers. The ratio of P2/P1 is monitored to ensure that the probe is choked during the calibration.

2.3.2 Calibration Procedure

The calibration vessel is first evacuated to remove any air or helium. The chamber is then pressurized to 2 atm with a known helium/air mixture. With the

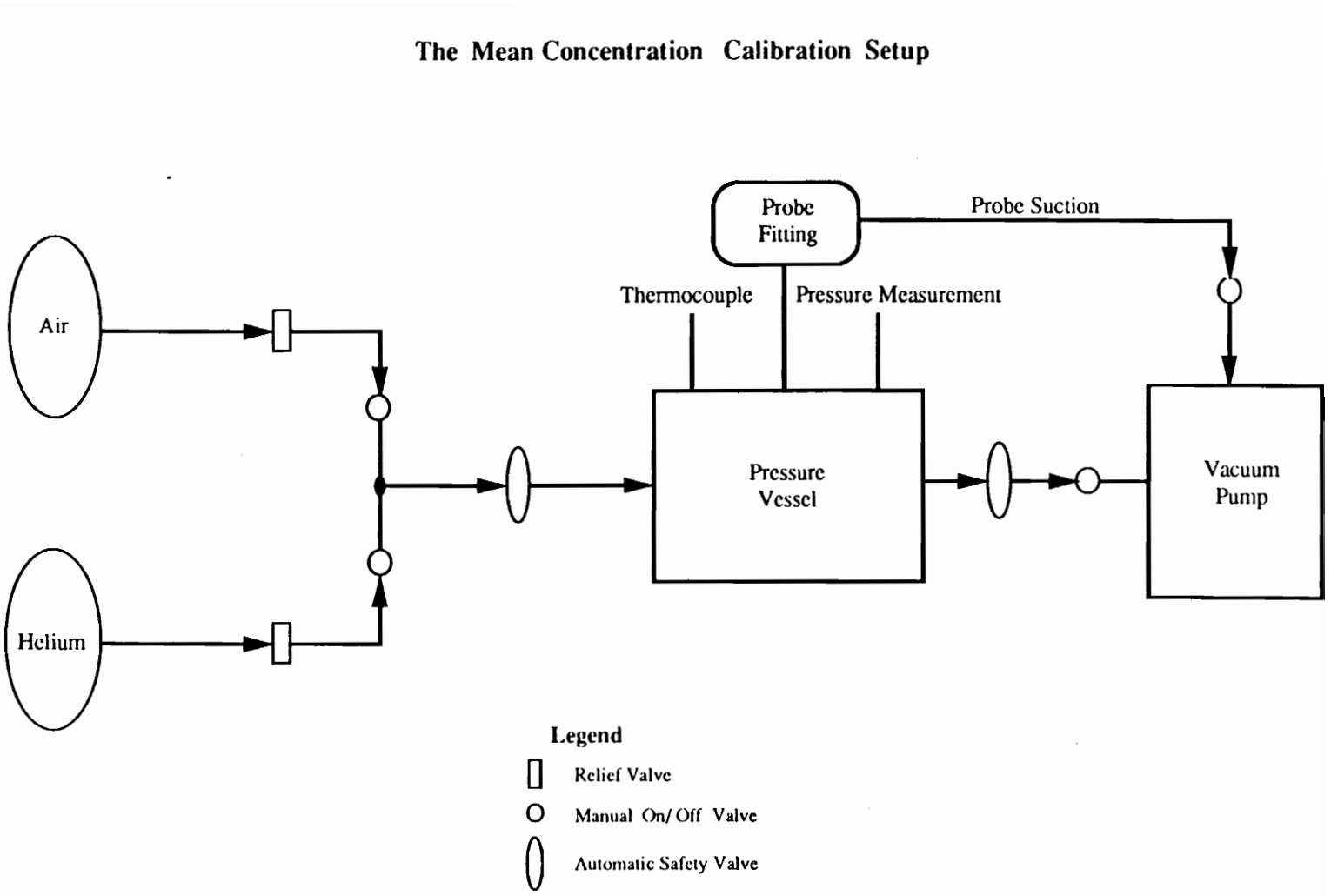


Figure 4. Mean Concentration Calibration Setup

probe aspirating, the pressure is lowered to the first calibration point. Voltage from the hot-film, P1, P2, and the temperature reading from the digital thermometer are recorded. The pressure in the calibration vessel is then lowered to the next calibration pressure. A total of six different pressures are used to calibrate for one specific air-helium mixture. The five molar helium concentration levels used in this experiment are 0, 25, 50, 75, and 100%. Different and more concentration levels can be used in the calibration. For example in supersonic mixing of air and helium, the interest is in low levels of helium (stoichiometric proportions). Therefore the calibration should include more low molar helium concentration levels.

The mole fraction of helium is determined by the partial pressures in the calibration vessel

$$\chi_h = \frac{\textit{Moles of helium}}{\textit{Moles of mixture}} = \frac{P_h}{P_m} \tag{2.10}$$

where h is the helium and m refers to the mixture properties. For example, to get a 50% molar concentration, the chamber is pressurized with the helium to half of the desired total pressure. Next, air is introduced into the chamber until the final total pressure is reached.

2.3.3 Calibration Curves

The calibration constants a and b for each of the five concentration levels are determined by a least squares method on Eqn. 2.8 with Eqn. 2.7 substituted for the Nusselt number and Eqn. 2.2 for the mass flux. A listing of the computer

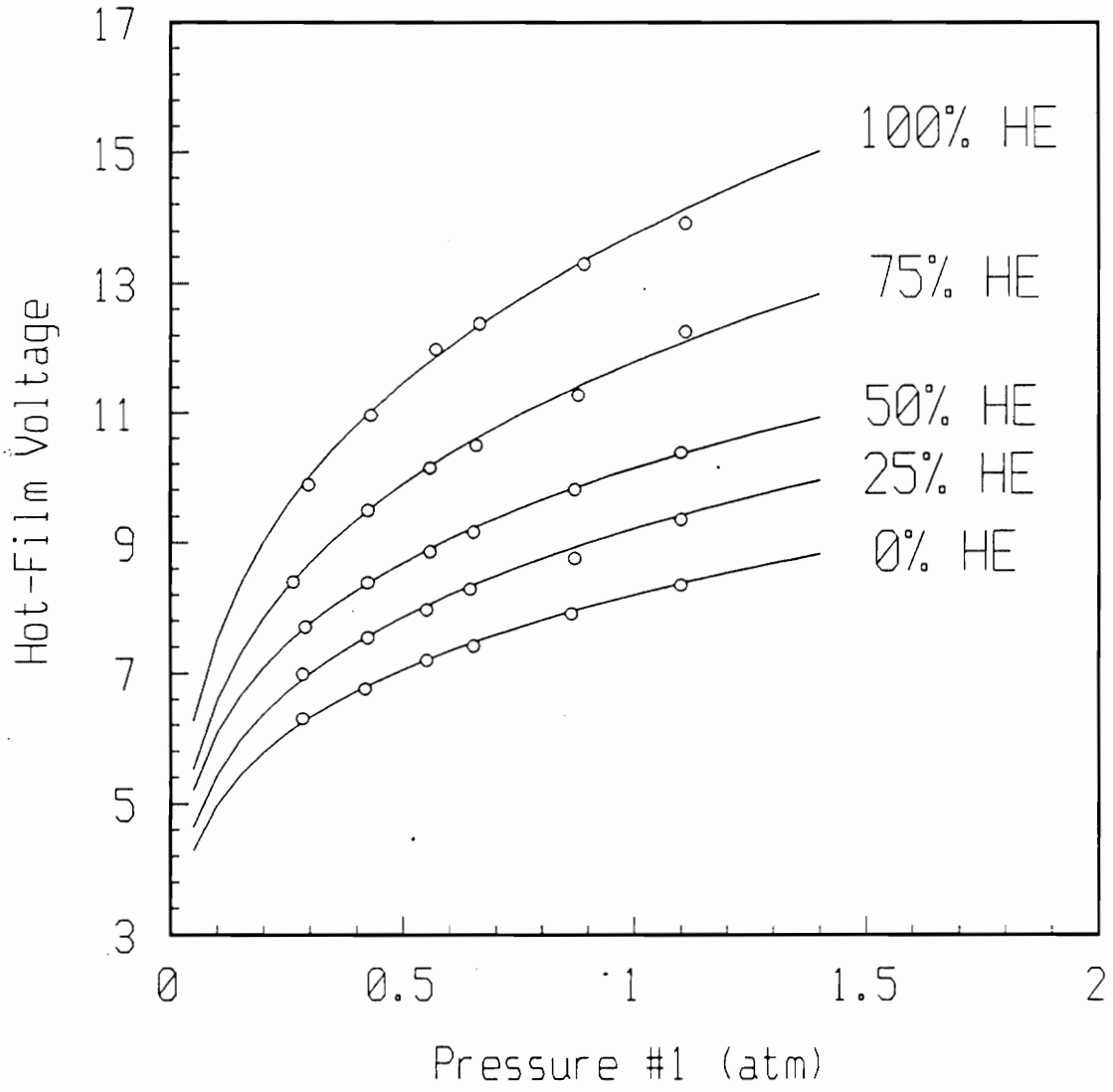


Figure 5. Mean Calibration Curve

program Curve.FOR used to calculate the calibration constants may be found in Appendix A.

The constants are used to generate calibration curves; an example at one specific temperature is shown in Fig. 5. The maximum error in a typical curve fit is less than 2% molar fraction of helium.

2.4 Experimental Setup

2.4.1 Facility

The experiment is performed in the VPI&SU 23-cm X 23-cm blowdown supersonic wind tunnel. The model, shown in Fig. 6, consists of a tangential supersonic 2-D slot injection of helium into a supersonic air stream. The injector was a rearward facing step slot designed to provide a slot freestream Mach number of 1.78 at a total pressure of 11 psia. The freestream Mach number of the mainstream is approximately 3.0, with a total pressure of 95 psia. The slot height, H, is 1.21 cm. Data are taken at an axial location, x/H, of 4.1.

2.4.2 The probe traversing mechanism

In the wind tunnel, the hot-film probe is attached to the traversing mechanism which is secured underneath the floor of the test section. The traverse contains a Computer Devices Corporation Model 34D-92091 stepping motor. A pinion is connected to the shaft of the motor and drives a rack. The

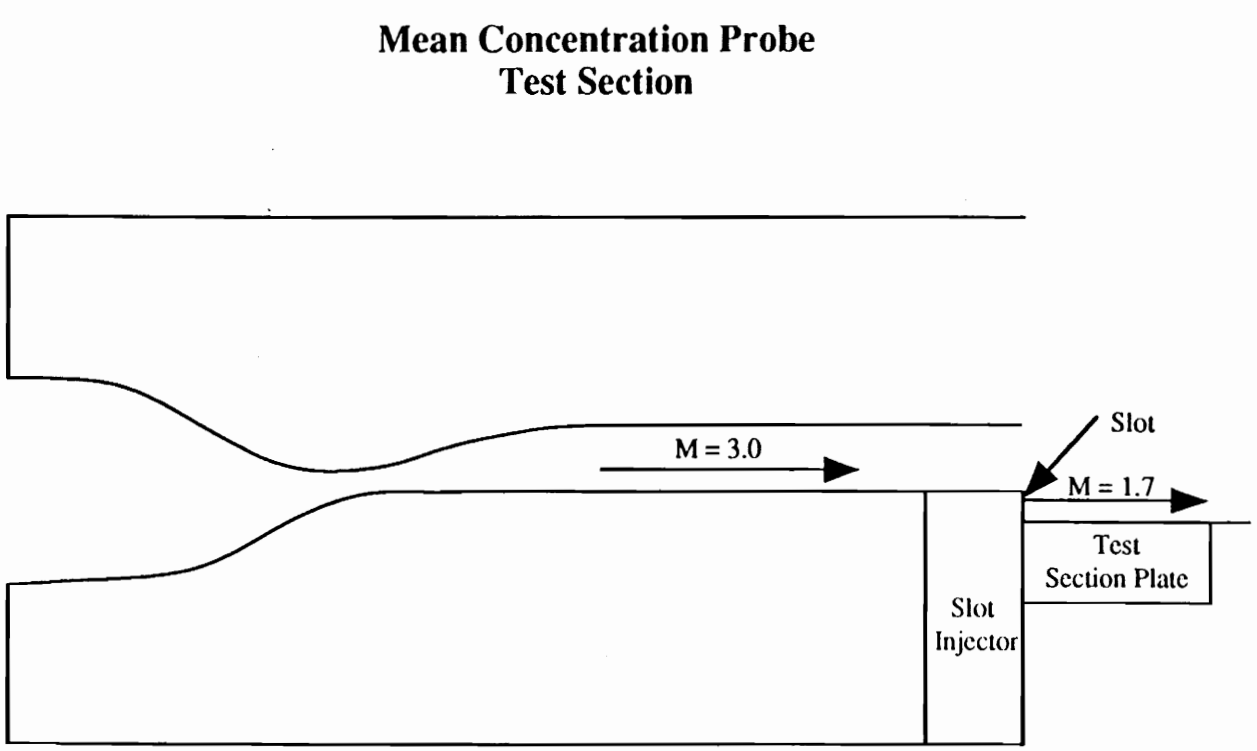


Figure 6. Mean Concentration Probe Test Section Configuration

probe base is clamped to a mounting bracket which is attached to the top of the rack.

An IBM pc controls the stepping motor which determines the probe's vertical direction, height, and speed in the wind tunnel. In this experiment the probe traverses approximately 38-mm (1.5-in) at a speed of 7.6-mm/s (0.3-in/s). This allows time for the probe to cross through the mixing layer and into the freestream and return to the tunnel floor before the wind tunnel is shut off.

The position of the probe is determined using a Trans-tek 245 Linear Voltage Displacement Transducer (LVDT). The LVDT consists of a core which induces a voltage in the interior windings as a linear function of the displacement from the electrical center. The LVDT housing is clamped to the traverse frame and the core attaches to the rack.

2.4.3 Data Acquisition

The wind tunnel operation and data acquisition are controlled by an IBM pc. These operations include starting and stopping of the tunnel, regulating the settling chamber pressure, and controlling the vertical position of the probe. The pc is equipped with a Metrabyte model Dash-16f Analog/Digital I/O board. The A/D board converts signals from 0-10 volts to 0-4095 digital counts and stores it on a floppy disk. Data from the hot-film voltage, P1, and P2 of the concentration probe along with the probe position are taken. Also the settling chamber pressure and temperature,and helium injection pressure and temperature data are recorded. The total temperature of the flow field is taken with a diffuser type thermocouple

probe during a different run. Data are sampled at 150 Hz. A schematic of the data acquisition instrumentation is presented in Fig. 7.

The P1 pressure is measured with a Statham 0-50 psig transducer, and the P2 pressure is measured with a MB Electronics 0-10 psig transducer. The millivolt signals from these transducers are amplified with Ectron amplifiers and then passed through a 4-pole Bessel filter with a cut-off frequency of 340 Hz.

The hot-film voltage from the Dantec anemometer goes into a TSI Intelligent Flow Analyzer model 100 (IFA-100) which filters the input at 300 Hz and offsets the dc level of the signal so that it can be digitized. The LVDT signal is also connected to the IFA-100 and is filtered at 50 Hz with a gain of 2.

The thermocouple probe consists of an Omega type-k (chromel-Alumel) butt-welded wire housed in a ceramic tip. The wire leads plug into an Omega Omni IIb amplifier that has an electronic ice-point reference junction. The signal is augmented with an Ectron amplifier.

The tunnel is also instrumented to measure the total pressure and total temperature in the settling chamber (upstream of the nozzle block) and plenum chamber of the injector. The pressure measurements are taken with pitot probes. The temperature readings are measured using a butt-welded type k thermocouple wire. These signals are amplified and low pass filtered before being sampled.

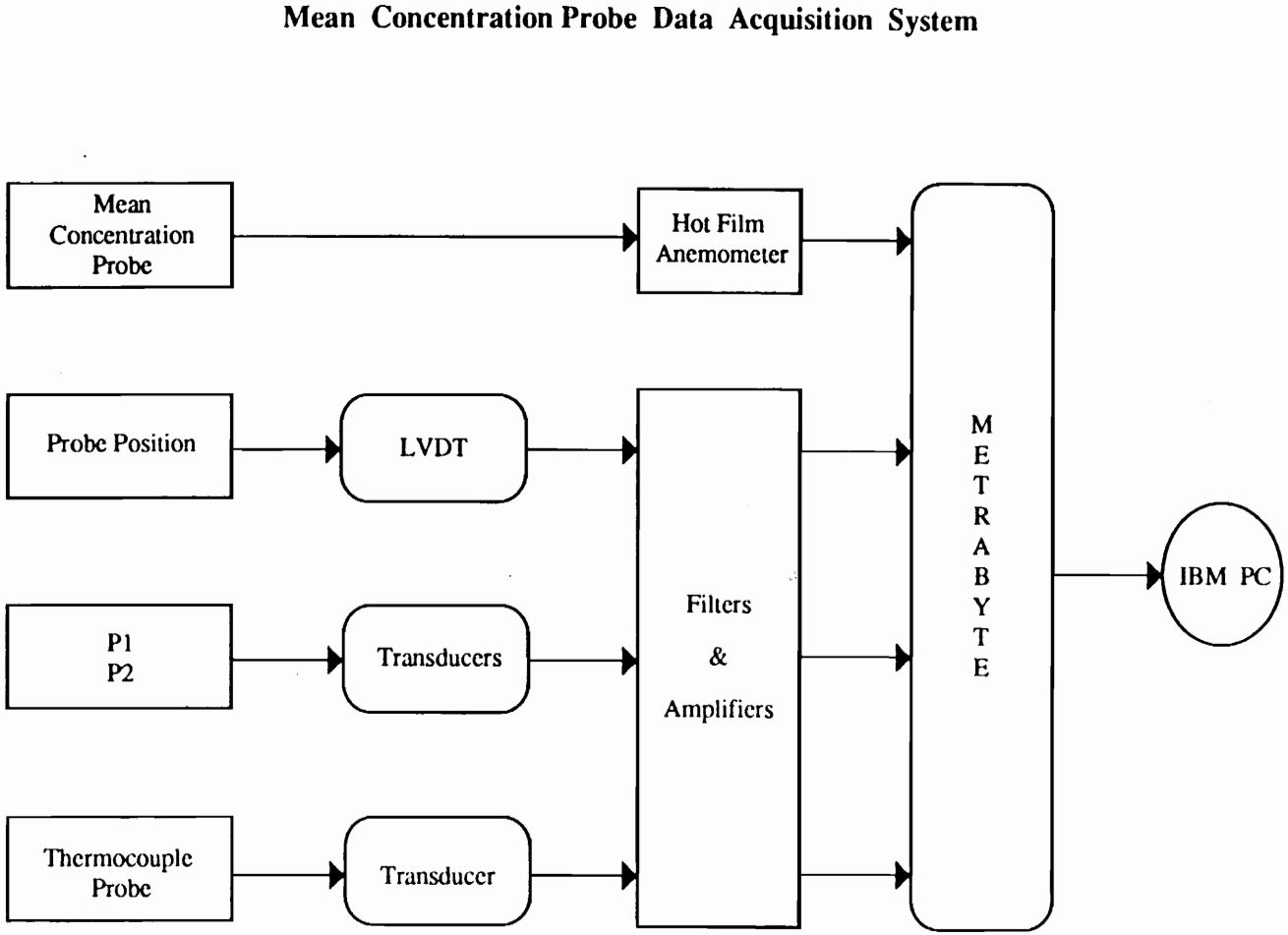


Figure 7. Mean Concentration Probe Data Acquisition System

2.5 Data Reduction

The procedure to determine the helium concentration is conceptually very simple. For a specific total temperature, a known hot-film voltage and P1 locates a point on the calibration curve. By interpolating between lines of constant concentration, the level of helium can be determined (see Fig. 5). A listing of the computer program Conc.FOR used to reduce the data is in Appendix A. The reduction of the raw data requires iteration. However, convergence is achieved in about four iterations for each data point and the concentration profile is obtained in a matter of minutes.

2.6 Results

Figure 8 shows the raw data from the concentration probe in terms of hot-film voltage and P1. Also provided is the total temperature profile, as measured with the thermocouple probe in a different run. The variation in total temperature across the shear layer is less than 12° Kelvin. The traverse distance, y, is nondimensionalized by the slot height H. The probe traverses far enough into the air freestream where the signals are essentially constant.

The results of the reduced data are shown in Fig 9. The trend shows that very little mixing occurs at an axial station of $x/H = 4.1$. The potential core due to the slot injection of helium is clearly identified. Pure helium is found from the tunnel floor up to y/H of 0.6. Beyond y/H of 0.6, the concentration of helium gradually

Raw Data Profiles

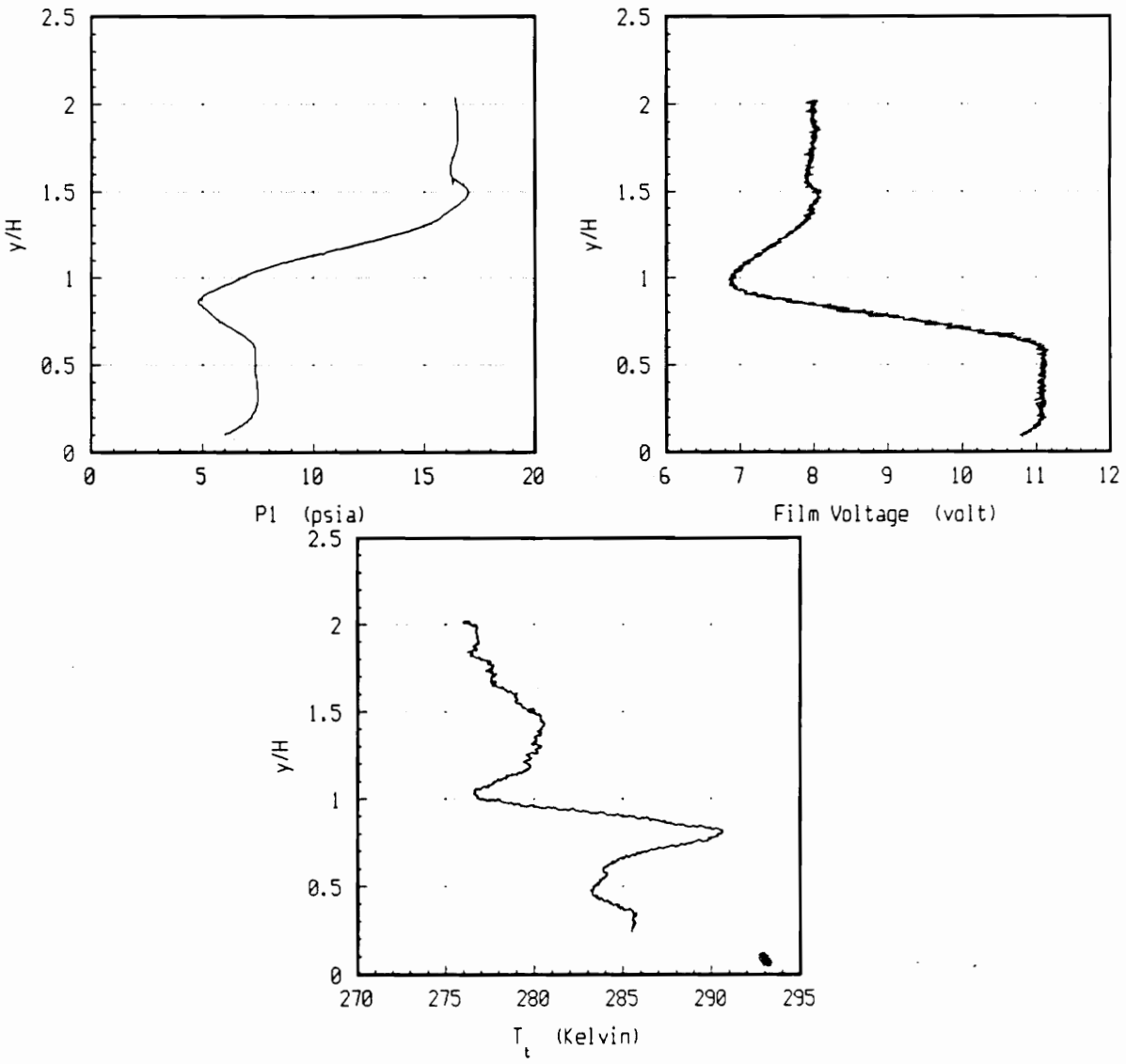


Figure 8. Raw Data Profiles

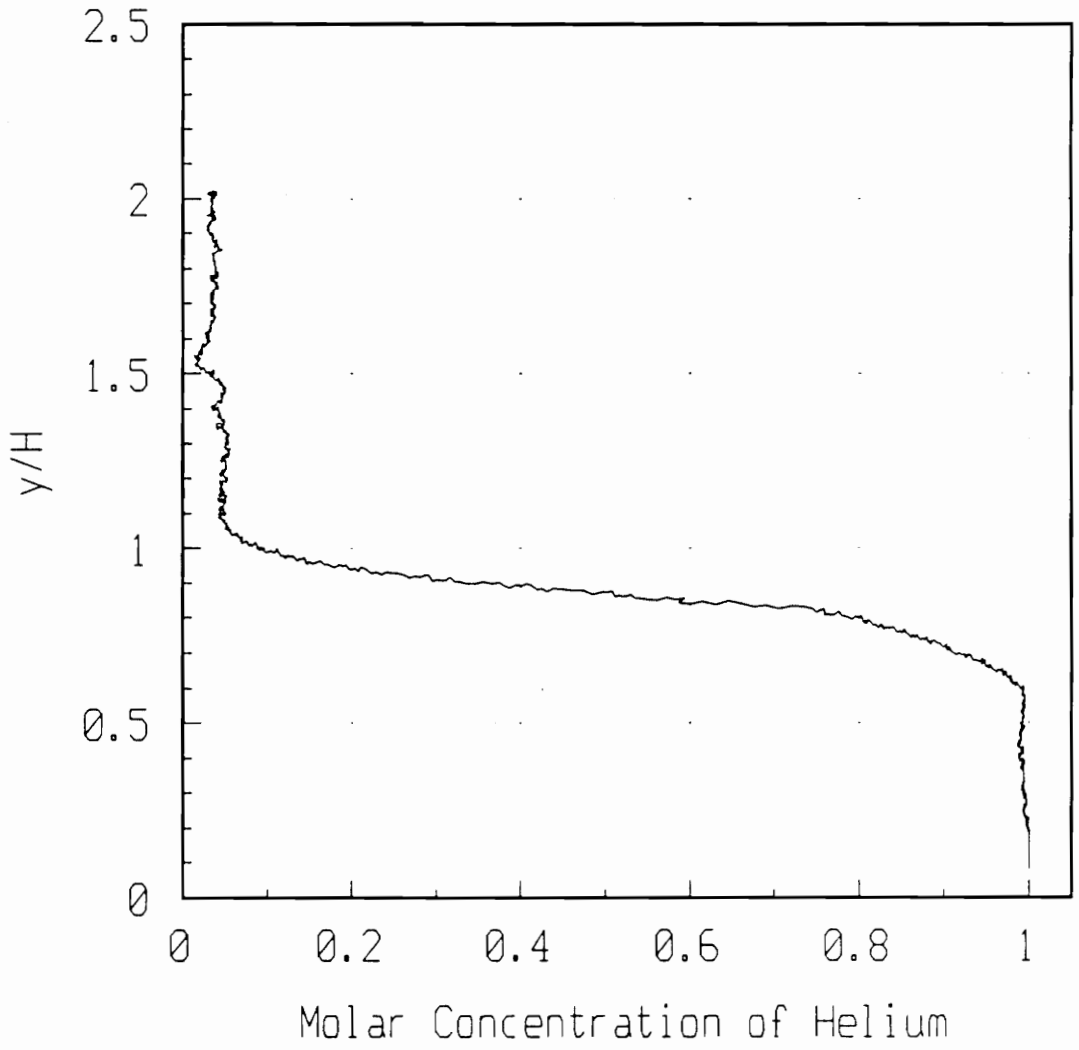


Figure 9. Mean Concentration Profile at x/h = 4.1

decreases to about 0% at y/H of 1.0, and remains at 0% above y/H of 1.0, as expected.

Figure 8 shows that the hot-film voltage has a minimum at y/H of 1.00, and P1 indicates a minimum at y/H of 0.85. However, the reduced concentration data do not exhibit any local minima at all. Instead, a smooth and gradually decreasing profile of concentration is obtained from the raw data. This is an important observation and it adds confidence to the performance of the concentration probe.

2.7 Discussion

Once the mean concentration profile is known, the gas constant and the ratio of specific heats can be determined. This information is then used in the Rayleigh Pitot equation and the cone-flow equation in order to determine Mach number and the static pressure from the measurements of the Pitot and cone-static probes. Together with the measurements from the total temperature probe, all the mean flow quantities such as velocity, density, mass flux, etc., can be calculated.

The sensitivity of the concentration probe to flow angularity is determined in a small supersonic tunnel. The data from the probe are taken at various angles with a known helium concentration. The angular sensitivity of the probe within 15° is less than 2.5% in molar concentration of helium.

An analysis was performed using Eqn. 2.9 to see how much error will be introduced in the concentration measurement if the stagnation temperature is assumed to be constant across the shear layer. Typically, there is a 12° Kelvin

variation in stagnation temperature. As seen in Fig 10, the error when assuming a constant temperature profile is less than 2% mole fraction of helium. Thus the concentration probe is relatively insensitive to the change in stagnation temperature.

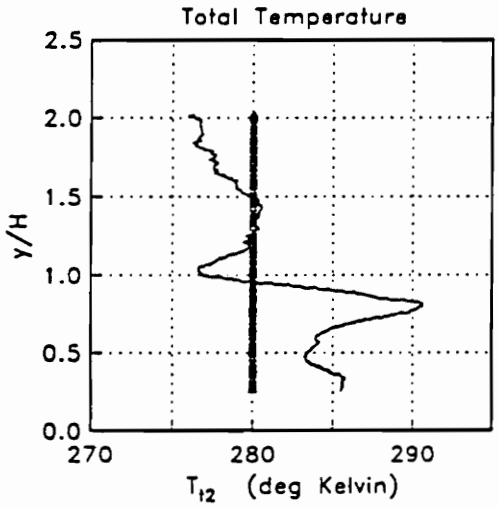
The accuracy for the measurement of P1 is no better than 0.2 psia (1%). For a given hot-film, the day-to-day variations in the dc level due to aging, instrument drift, etc. is 1% in hot-film voltage. Based on these numbers, an error analysis of Eqn. 2.9 shows that the absolute accuracy of the probe is about 1% in mole fraction of helium. During the experiment, the probe is always traversed high enough to the freestream of the airflow, where the concentration of helium is zero percent. This information is used as an on-site calibration of the probe to account for the day-to-day variations in the dc drift of the hot-film sensor. In the data reduction, the hot-film voltage can be shifted so that the zero percent helium concentration is matched with the air freestream.

The present design of the probe can only allow measurements of mean concentration. The frequency response of the probe is limited by the measurements of P1. The response P1 is estimated to be about 0.1 second, which is similar to the response of a typical cone-static probe. Even though the response of the hot-film sensor is above 20 kHz, the overall frequency response is only 10 Hz. However, this is adequate for mean flow measurements.

Another limiting factor for the frequency response is the "flush-out" time of the probe, which is the time required for a fluid particle to travel from the sensor

Temperature Sensitivity

Temperature profile = solid lines
Temperature constant = △



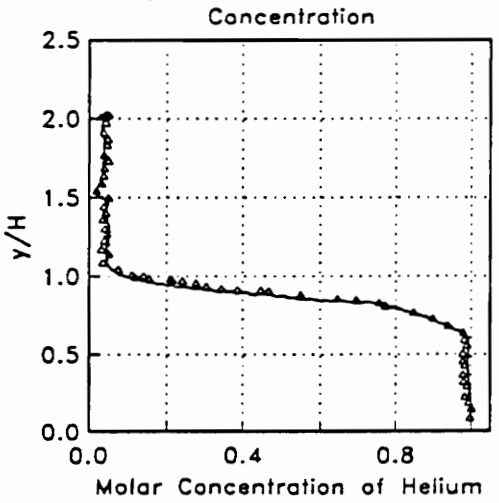


Figure 10. Temperature Sensitivity

plane to the choked orifice. This time constant is important since the mass flow rate inside the probe is governed by the flow at the choked orifice and the assumption is that the hot-film at the sensor plane sees essentially the same mass flow rate. Based on the dimension of the probe and a typical Mach number inside the probe, this time constant is estimated to be 0.5 msec, which is much less than the time constant for the measurement of P1.

Since the normal shock in the diverging channel of the concentration probe is upstream of the hot-film sensor, any change in the location of this shock due to unsteadiness can affect the shock strength and thus the total pressure at the sensor plane. This will, of course, change the output of the hot-film sensor. The background noise level of the hot film in the concentration probe is found to be 0.2V peak-to-peak, which is significantly higher than the noise level of a bare hot-film sensor in quiescent air (typically 2mV peak-to peak). The inherent high background noise level in the aspirating probe is believed to be caused by the unsteady shock motion. An analysis based on one-dimensional gas dynamics shows that a shock displacement distance as little as 0.13 mm (0.005-in) is enough to account for the observed noise level in the concentration probe.

In summary, the mean concentration probe has successfully been used for the measurement of helium concentration in a supersonic air-helium shear layer. However if turbulent concentration measurement is desired, the mean concentration probe is unable to do this. Based on Eqn. 2.9, fluctuations in hot-film voltage and stagnation pressure (P1) from the concentration probe are

needed to make turbulent concentration measurements. The hot-film background noise level and the response of P1 prevent direct measurements of fluctuating concentration. As will be seen in the next chapter, a new approach will be presented where fluctuations of a property of the gas mixture will be measured. The fluctuations in concentration cannot be measured directly; rather fluctuating the Reynolds number and thermal conductivity are measured instead.

3.0 Turbulent Probe

As seen in the last chapter, the mean concentration probe was successfully used to measure gas composition in a Mach 3 supersonic air/helium shear layer. However, the hot-film background noise level and the response of P1 limit the use of the mean concentration probe from making turbulent measurements. As a first attempt to measure the fluctuations in a property of a gas mixture, a new probe was built based on an improved design of the mean concentration probe. In this thesis, this probe is referred to as the turbulent probe, to be distinguished from the mean concentration probe describe in the previous chapter. This turbulent probe does not measure fluctuating concentration directly. Instead, it is designed to measure time averaged fluctuations in Reynolds number and thermal conductivity using a multiple overheat method. The turbulent probe also measures mean concentration in the same way as the mean concentration probe. This information is used in the calibration and reduction of the turbulent data. This chapter begins with a description of the turbulent probe; followed by the principle of operation,

experimental setup and data reduction. Results of the turbulent measurement will then be presented and discussed.

3.1 Turbulent Probe Design

Figure 11 shows the geometry of the tip of the turbulent probe. Similar to the mean concentration probe, the turbulent probe contains an orifice that chokes the flow inside the probe. It is also designed to swallow the standoff shock at the probe tip. The turbulent probe also has a pressure tap (P1) located in the constant area channel. The difference between the two probes is the location of the hot-film sensor. For the turbulent probe, the hot-film is soldered to the tip of the probe as opposed to being inside the probe. It should be pointed out that with the sensor mounted at the probe's tip, the hot-film response for the turbulent probe is not different than that of a bare hot-film sensor mounted on needle prongs. However, as will be shown later, the present arrangement of the turbulent probe also allows for the retrieval of mean concentration profile from the raw data. This is an important advantage over a conventional bare hot-film sensor. In the next section, it will be described how the turbulent probe measures time averaged fluctuations in Reynolds number and thermal conductivity.

3.2 Principle of Operation

The turbulent probe measures mean concentration as well as fluctuations in Reynolds number and thermal conductivity. However, the principle of operation

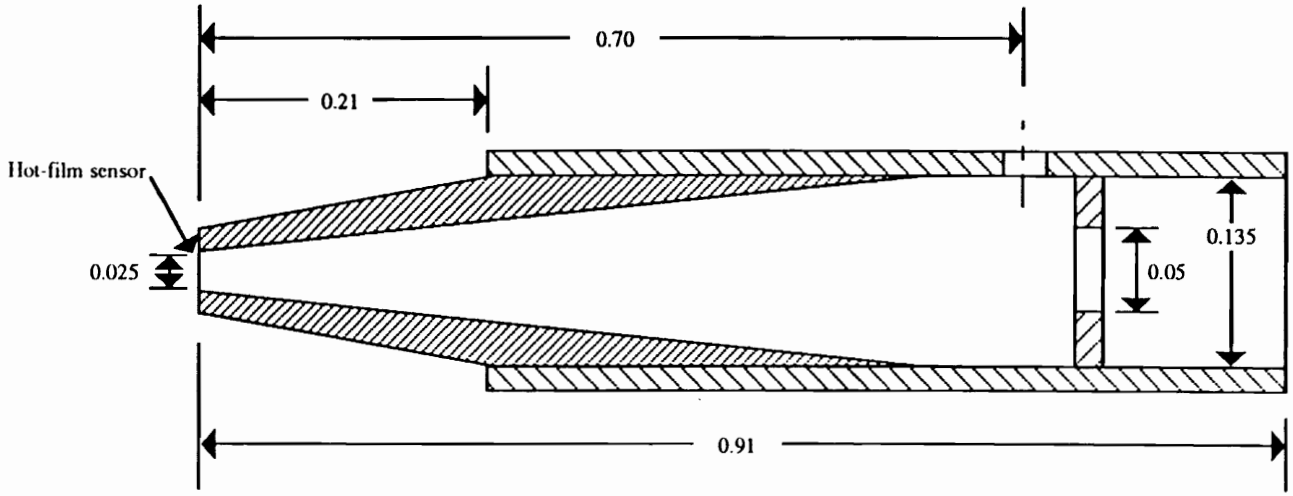


Figure 11. Turbulent Probe Tip

for these measurements is quite different. The mean concentration is determined with a single overheat ratio while the turbulent measurements require a multiple overheat method.

3.2.1 Mean Concentration

Mean concentration is determined in the same way as discussed in section 2.2 where Eqn 2.9 used in the data reduction is

$$V^2 = \frac{(R_S+R_F)^2}{R_F}\,\pi lk\left[a_l\left\{\frac{d}{\mu}\left(\frac{P_T}{\sqrt{T_T}}\right)\frac{A^*}{A_c}\sqrt{\frac{\gamma}{\Re}}\left(\frac{2}{\gamma+1}\right)^{\gamma+1\,/\,2(\gamma-1)}\right\}^{1/2}+b_l\right](T_F-T_T)$$

Hot-film voltage is a function of mean gas composition, total temperature and total pressure in the probe. As will be shown later, measuring the mean quantities is important as it is used in the calibration and data reduction of the turbulent measurements.

3.2.2 Turbulent Measurement

For the turbulent measurement, the relationship used between Nusselt number and Reynolds number is

(3.1) $$Nu = a\sqrt{Re_d} + b$$

As seen in Eqn. 2.7, the Nusselt number is a function of the probe's hot-film voltage

$$Nu = \frac{V^2 R_F}{(R_F + R_S)} \frac{1}{\pi k_T l (T_F - T_T)}$$

Combining Eqn 2.7 with Eqn. 3.1

(3.2)
$$V^2 = \frac{(R_S + R_F)^2}{R_F} \pi l k \left[a_l \{Re_d\}^{1/2} + b_l \right] (T_F - T_T)$$

This equation is in a similar form as Eqn. 2.9. Rewriting Eqn. 3.2

(3.3)
$$V^2 = \theta \, (a\sqrt{Re_d} + b) \, k$$

where θ is a constant and given by

(3.4)
$$\theta = \frac{(R_F + R_L)^2}{R_F} \pi l (T_F - T_T)$$

Replacing V by $\overline{V} + v'$, Re_d by $\overline{Re}_d + Re_d'$, and k by $\overline{k} + k'$, and retaining only the first order terms, eqn. 3.2 can be written as

(3.5) $$\overline{V^2} + 2\bar{V}v' = \theta\bar{k}(a\sqrt{\overline{Re_d}}+b) + \theta k'(a\sqrt{\overline{Re_d}}+b) + \theta\bar{k}\frac{a}{2}\sqrt{\overline{Re_d}}\frac{Re'_d}{\overline{Re_d}}$$

Solving Eqn. 3.4 for $\frac{v'}{\bar{V}}$ and noting that

(3.6) $$\overline{V^2} = \theta\bar{k}(a\sqrt{\overline{Re_d}} + b)$$

the relationship becomes

(3.7) $$\frac{v'}{\bar{V}} = F\frac{k'}{\bar{k}} + G\frac{Re'_d}{\overline{Re_d}}$$

where

(3.8) $$F = \frac{1}{2}$$

and

(3.9) $$G = \frac{1}{4}\left(1 + \frac{b}{a\sqrt{\overline{Re_d}}}\right)$$

Taking the mean-square value of Eqn 3.7

(3.10)
$$\overline{\left(\frac{v'}{\bar{V}}\right)^2} = F^2\overline{\left(\frac{k'}{\bar{k}}\right)^2} + 2FG\overline{\left(\frac{k'}{\bar{k}}\frac{Re_d'}{\overline{Re_d}}\right)} + G^2\overline{\left(\frac{Re_d'}{\overline{Re_d}}\right)^2}$$

where G is a function of the overheat ratio.

As can be seen Eqn. 3.10 has three RMS (Root Mean Squared) fluctuating unknowns; Reynolds number, the thermal conductivity, and their cross-correlation. Three overheats are needed to solve this system of three equations with three unknowns. Presenting Eqn. 3.10 in matrix form

$$\begin{vmatrix} \left(\frac{k'}{\bar{k}}\right)^2 \\ \left(\frac{k'}{\bar{k}}\frac{Re'_d}{\overline{Re_d}}\right) \\ \left(\frac{Re'_d}{\overline{Re_d}}\right)^2 \end{vmatrix} = \begin{vmatrix} \left(\frac{1}{2}\right)^2 & \frac{1}{4}\left(1+\frac{b_1}{a_1\sqrt{\overline{Re_d}}}\right)^{-1} & \left(\frac{1}{4}(1+\frac{b_1}{a_1\sqrt{\overline{Re_d}}})^{-1}\right)^2 \\ \left(\frac{1}{2}\right)^2 & \frac{1}{4}\left(1+\frac{b_2}{a_2\sqrt{\overline{Re_d}}}\right)^{-1} & \left(\frac{1}{4}(1+\frac{b_2}{a_2\sqrt{\overline{Re_d}}})^{-1}\right)^2 \\ \left(\frac{1}{2}\right)^2 & \frac{1}{4}\left(1+\frac{b_3}{a_3\sqrt{\overline{Re_d}}}\right)^{-1} & \left(\frac{1}{4}(1+\frac{b_3}{a_3\sqrt{\overline{Re_d}}})^{-1}\right)^2 \end{vmatrix}^{-1} \begin{vmatrix} \left(\frac{v'}{\bar{V}}\right)^2_1 \\ \left(\frac{v'}{\bar{V}}\right)^2_2 \\ \left(\frac{v'}{\bar{V}}\right)^2_3 \end{vmatrix}$$

(3.11)

where a_1, a_2, a_3 and b_1, b_2, b_3 are the calibration constants at different overheat ratios. These calibration constants are determined by a linear least squares fit using Eqn 3.1 where the local $\overline{Nu}$ and $\overline{Re_d}$ values are calculated from the mean

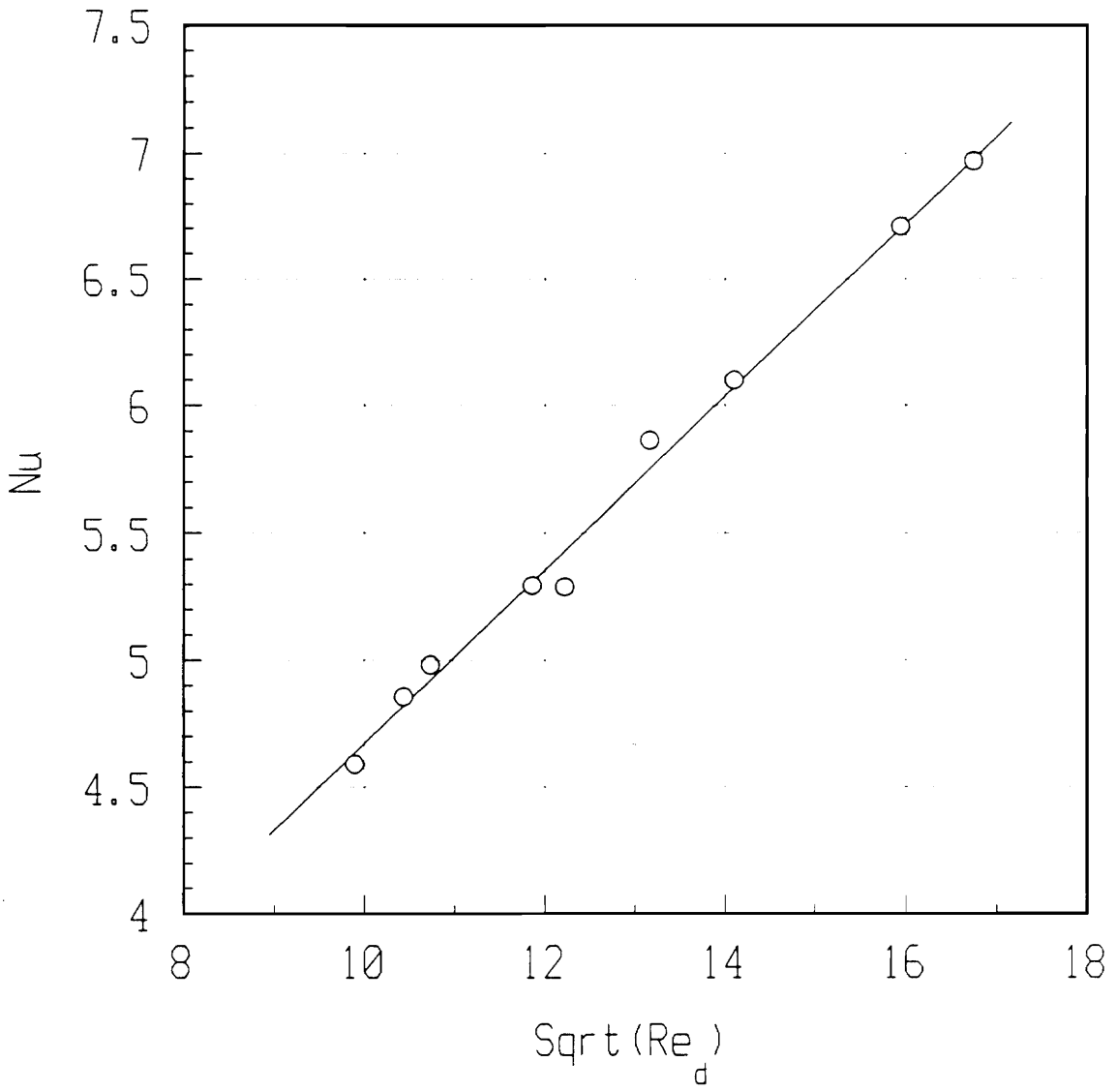


Figure 12. Turbulent Calibration Curve

concentration as obtained from the same probe using the method described in section 3.2.1. Program Cal.FOR listed in appendix B is used to compute the calibration constants. Figure 12 shows the results of a typical calibration where the largest error is approximately 3%.

3.3 Experimental Setup

3.3.1 Facility

The experiment for the turbulent probe is performed in the same Mach 3 blowdown tunnel as the mean concentration probe; however, the injection geometry is different. For this experiment the model consists of a flat plate with a single sonic transverse injector. The injector has a hydraulic diameter, d_{eq}, of 0.42-cm (0.164-in.). The operation of the wind tunnel is the same as described in chapter 2. Data are taken on the centerline of the injector at an axial location, x/d_{eq}, of 11.8.

3.3.2 Data Acquisition

The set up for the data acquisition is the same as in section 2.4 except that the hot-film voltage and LVDT signal are also connected to a Lecroy Analog/Digital system. This system provides the data acquisition for the turbulent measurements. and is controlled by another IBM pc. The data are sampled continuously at 20 kHz with a low pass filter of 9 kHz. A schematic of the data acquisition system is presented in Fig 13.

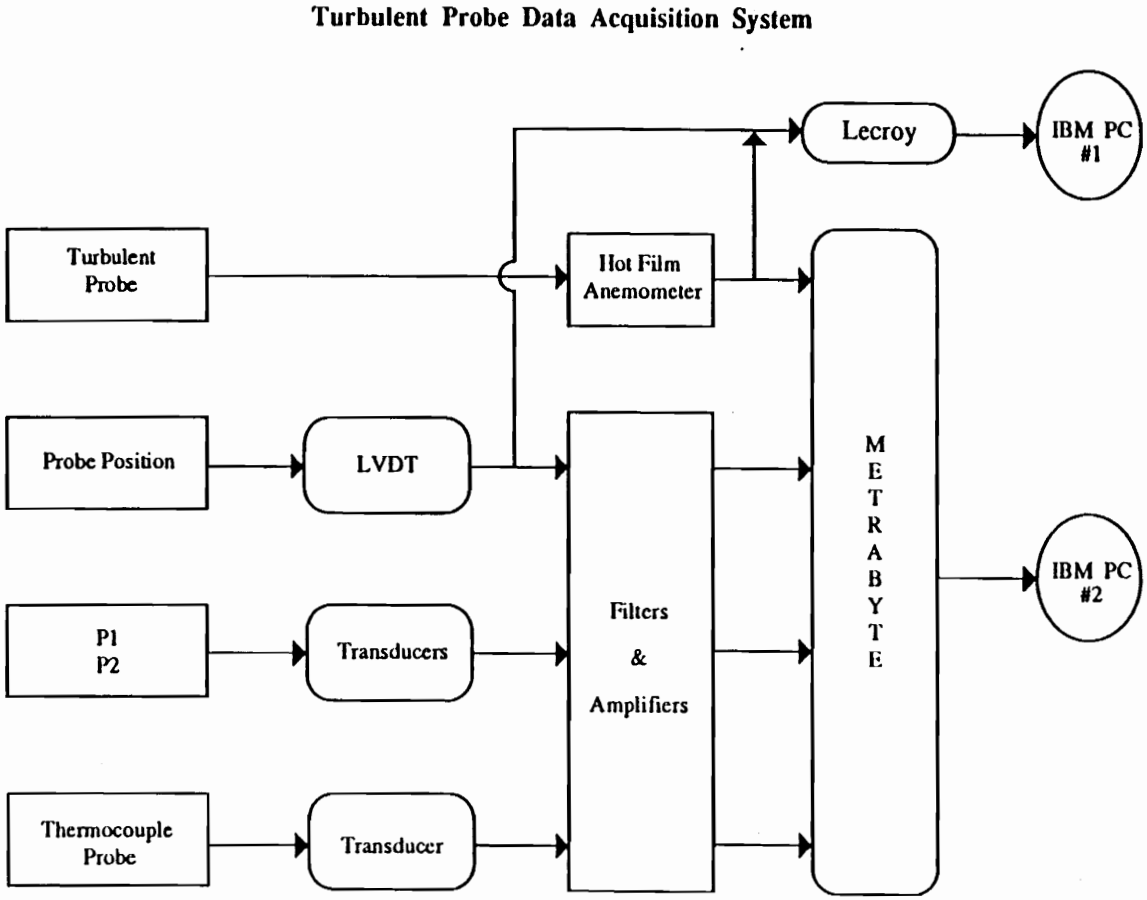


Figure 13. Turbulent Probe Data Acquisition System

3.4 Data Reduction

In order to reduce the turbulent raw data, the mean concentration profile must be known. The profile is used in both calibrating the turbulent probe and as an input in the data reduction program. The reduction procedure for the mean concentration is the same as discussed in section 2.5.

3.4.1 Turbulent data reduction

The three overheat ratios used in this experiment are 2.0, 1.65, and 1.5. The data were taken in three different runs. It is important to note that the tunnel conditions should be matched as closely as possible. The reduction was performed on a pc using two FORTRAN programs listed in Appendix B. The program Avg.FOR calculates the RMS hot-film voltage averages for every 100 data points or 5 msec. The program Solve.FOR solves the system of three equations for turbulent intensities of Reynolds number and thermal conductivity.

3.5 Results

Figure 14 shows the mean concentration profile as measured with the turbulent probe. The traverse distance is nondimensionalized by the equivalent diameter of the injector d_{eq}. As a consistency check, the concentration profile is compared to the results derived from the mean concentration probe in a separate run. The difference between the two is not greater than 2% molar helium concentration. This conclusion adds confidence to the performance of the

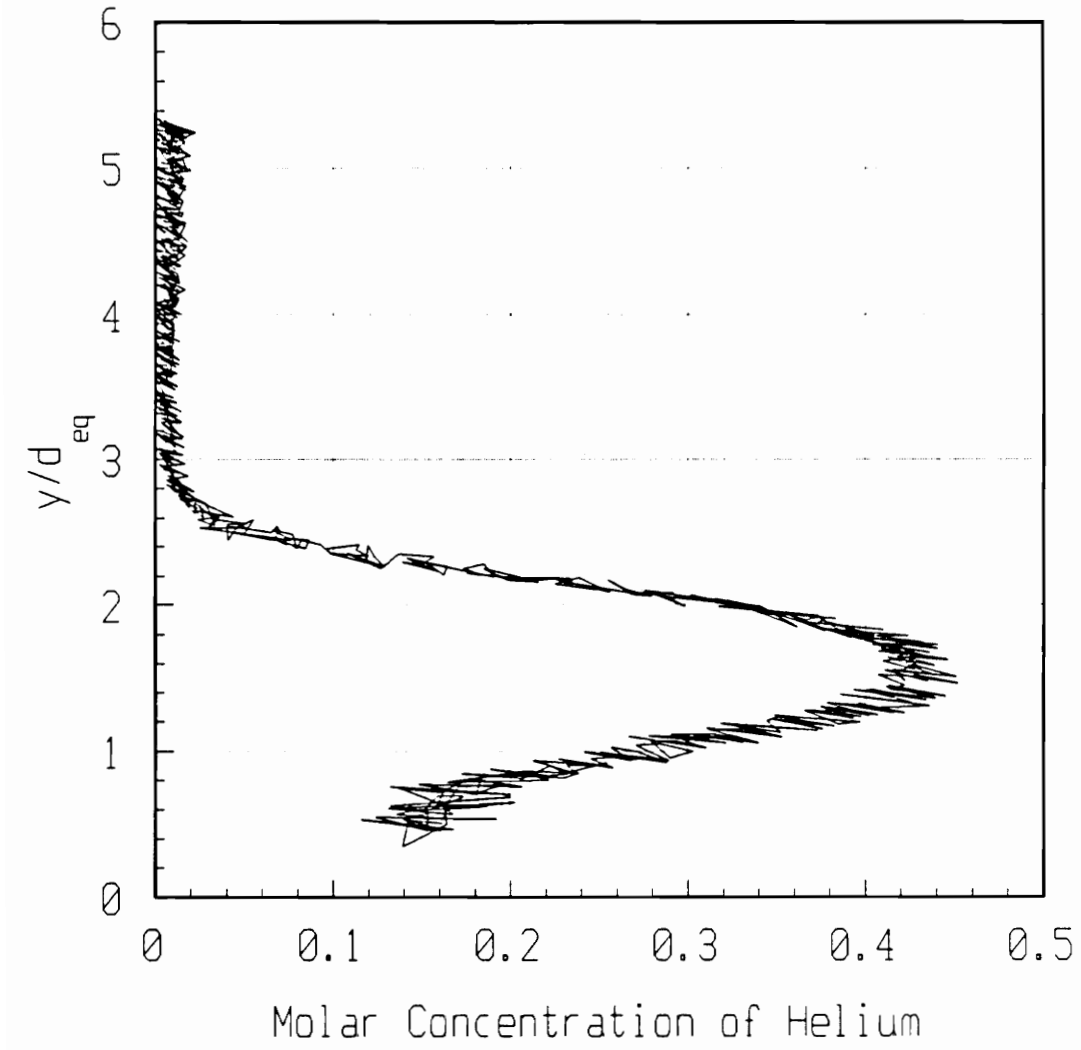


Figure 14. Mean Concentration from Turbulent Probe

turbulent probe. The maximum observed concentration is 42% and occurs at y/d_{eq} of 1.5. The helium concentration profile is smooth, continuous and, as to be expected, gradually decreases to around 0 % in the air freestream.

The results of the multiple overheat hot-film data are presented in Fig 15. The time averaged peak turbulence intensity for both Reynolds number and thermal conductivity occur at y/d_{eq} of 2.4. The maximum intensity for Reynolds number is approximately 1.0 and the maximum intensity for thermal conductivity is approximately 0.45.

An error analysis and sensitivity study on Eqn. 3.11 show that the matrix used to solve for the fluctuations in Reynolds number and thermal conductivity is ill-conditioned. The matrix is very sensitive to small changes. For example, a change of the mean Reynolds number by 5% between runs will cause the peak intensities to increase by 80%. It is noted that the maximum difference in Reynolds number between the three runs during the experiment is greater than 5%. In conclusion, the tunnel conditions are not able to be matched close enough from run to run to solve for the fluctuations in Reynolds number and thermal conductivity using a three-overheat method.

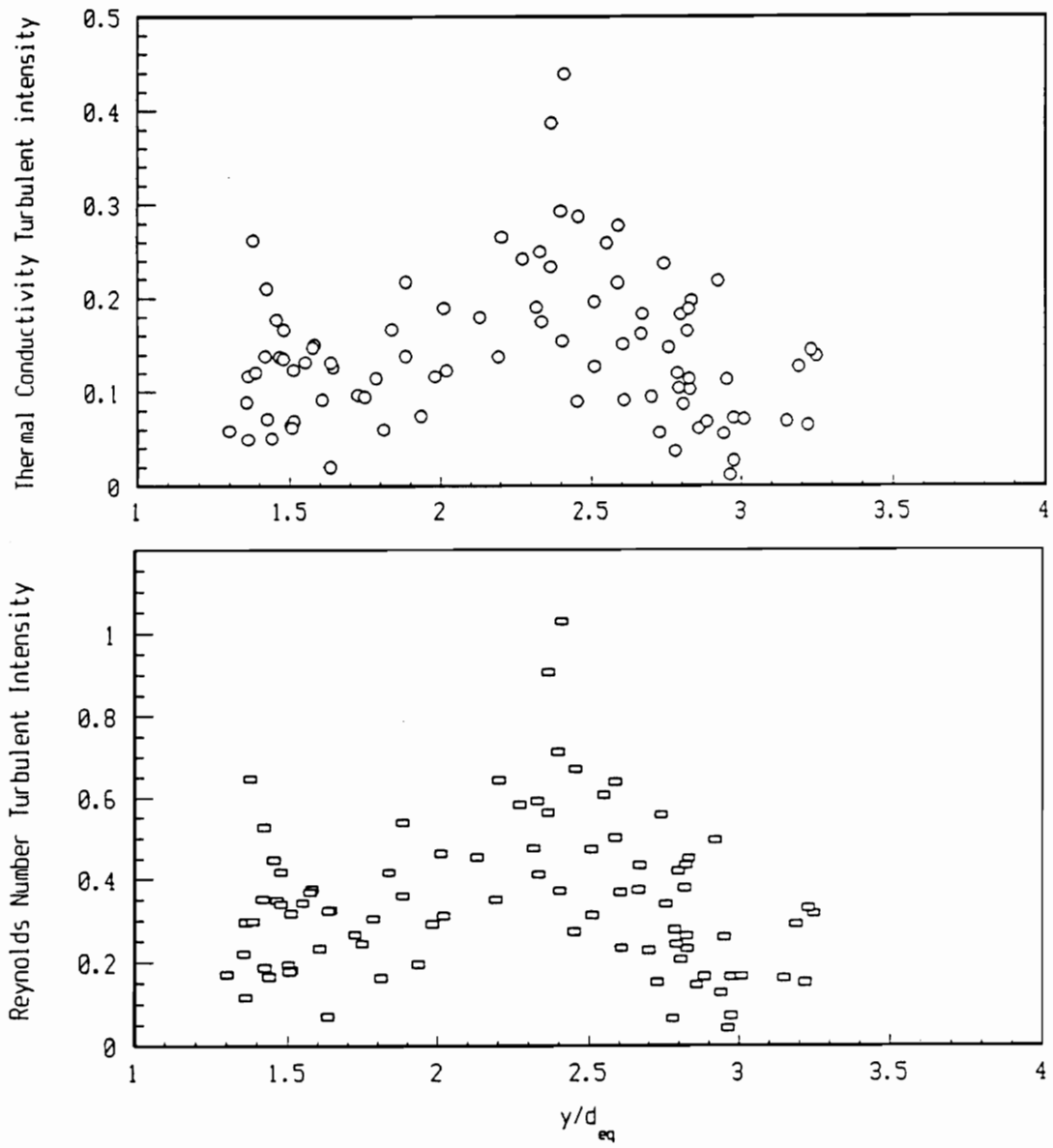


Figure 15. Turbulent Intensity Profiles

4.0 Conclusions and Recommendations

A concentration probe was designed for the measurement of mean gas composition in supersonic flows. The instrument is an aspirating-type hot-film probe with an internal choked orifice. The probe swallows the stand-off shock in front of the probe so that a streamtube equal in area to the capture area can enter the probe undisturbed. The probe is successfully used to survey the concentration profile in a Mach 3 supersonic air/helium shear layer. Coupled with other conventional steady-state measurements, mean flow quantities such as velocity, density, and mach number can be determined.

The inherent background voltage noise level due to unsteady shock and the slow response of the pressure measurement inside the probe prevented the use of the mean concentration probe from making turbulent measurement. As a result, a turbulent probe was designed to measure time averaged turbulent intensities of Reynolds number and thermal conductivity using a three-overheat method. The turbulence values at all locations were higher than expected. The reason for this is that the data reduction is very sensitive to the small variations in tunnel conditions from run to run.

It should be noted that the limitation of the turbulent probe is not in its design rather than in its implementation. Three overheat ratios is the minimum that is required to reduce the data. The number of overheat ratios should be increased

to minimize the sensitivity to the changes in tunnel conditions.

The following are recommendations for future design of aspirating probes and instrumentation:

a. addition of a thermocouple inside the aspirating probe.

b. addition of fast response pressure transducer inside the probe.

c. anemometer able to quickly change overheat ratios during a single run.

d. increase the number of overheat ratios to reduce the data.

Additionally, a method needs to be developed where fluctuations in concentration can be determined from the measured fluctuations in thermal conductivity. This would be an extension of the research done by Buddenberg and Wilke who developed equations between the physical properties of the mixture and it's concentration [14].

Appendix A

Program Curve.FOR

```
C*********************************************************************
C                        - Curve.Fortran -                            *
C                                                                     *
C                                                                     *
C      --this program generates the calibration constants from an     *
C        imput hot-film voltage, total pressure, total temperature,   *
C        and helium concentration.                                    *
C           HELIUM CONCENTRATION.                                     *
C      --a least squares fit is used to minimize the error.           *
C      --viscosity and conductivity are a function of temperature     *
C        and 1 atm pressure.                                          *
C                                                                     *
C                                                                     *
C                    JOEL C. ROSSON      BEGUN 2/19/85                *
C                    FEI T. KWOK      MODIFIED 10/20/88               *
C                    TODD NINNEMANN   MODIFIED  9/15/89               *
C*********************************************************************
C
      DIMENSION TT(20),PT(20),AP1(20),XHE(20)
      DIMENSION F1(20,2),FT1(2,20)
      DIMENSION FT1A1(2),FT1F1(2,2)
      DIMENSION A1(20),B1(20)
      DIMENSION VIS(16,2), CON(16,2)
      DIMENSION VISA(16,2),CONA(16,2),VISHE(16,2),CONHE(16,2)
C
C  VOLTAGE VS. TOTAL TEMPERATURE AND PRESSURE DATA
C          TT(K), PT(PSI),XHE(MOLE FRACTION)
C  L=NUMBER OF DATA VALUES FOR CALIBRATION
      WRITE(8,*)'        CC1              XN1          TRT'
      WRITE(8,*)'        RCAB             RRT          RSET1'
       do  99 kj=1,5
       NUM=NUM+1
       READ(NUM,*) NR,L,TRT,RCAB,RRT,RSET1
       DO 10 I=1,L
       READ(NUM,*) AP1(I),TT(I),PT(I),XHE(I)
   10  CONTINUE
C
C  VISCOSITY FOR AIR IN KG/M*S OR N*S/M**2
       DATA VISA/140.,150.,160.,180.,200.,220.,240.,260.,280.,
     1  290.,300.,310.,320.,330.,340.,350.,
     1    .96112E-5,1.0283E-5,1.08842E-5,1.20866E-5,1.3289E-5,
     1  1.43694E-5,1.54498E-5,1.64844E-5,1.74732E-5,1.79676E-5,
     1  1.8462E-5,1.89196E-5,1.93772E-5,1.9834E-5,2.02924E-5,
     1   2.075E-5/
C
C  THERMAL CONDUCTIVITY FOR AIR IN W/M*K
       DATA CONA/140.,150.,160.,180.,200.,220.,240.,260.,280.,
     1  290.,300.,310.,320.,330.,340.,350.,
     1  .0128372,.013735,.014606,.016348,.01809,.019762,
     1  .021434,.023064,.024652,.025446,.02624,.026998,
     1  .027756,.028514,.029272,.03003/
C
C VISCOSITY FOR HELIUM IN KG/M*S
      DATA VISHE/140.,150.,160.,180.,200.,220.,240.,260.,280.,
     1  290.,300.,310.,320.,330.,340.,350.,
     1  1.22E-5,1.288E-5,1.344E-5,1.455E-5,1.566E-5,
     1  1.657E-5,1.749E-5,1.839E-5,1.927E-5,1.971E-5,2.015E-5,
     1  2.059E-5,2.103E-5,2.147E-5,2.191E-5,2.235E-5/
C
C THERMAL CONDUCTIVITY FOR HELIUM IN W/M*K
```

```
      DATA CONHE/140.,150.,160.,180.,200.,220.,240.,260.,280.,
     1  290.,300.,310.,320.,330.,340.,350.,
     2  9.07E-2,9.5E-2,9.92E-2,1.072E-1,1.151E-1,
     3  1.228E-1,1.304E-1,1.374E-1,1.447E-1,1.484E-1,1.52E-1,
     4  1.555E-1,1.591E-1,1.626E-1,1.662E-1,1.697E-1/
C
      A = 0.
      R = 0.
C
C*************************************************************
C
C  RS=SERIES RESISTANCE (OHMS)
       RS= 50.0
C  RCAB=CABLE RESISTANCE(OHMS)
C  RSET1=ANEMOMETER RESISTANCE SETTING(OHMS)
C  RWIRE=HOT WIRE RESISTANCE AT THE OPERATING TEMP.
       RWIRE1=RSET1-RCAB
C  RRT=HOT WIRE RESISTANCE AT ROOM TEMPERATURE(OHMS)
C  TRT=STANDARD ROOM TEMP (K)
C  Y=THERMAL COEEFICIENT OF RESISTIVITY FOR PT COATED TG(K**-1)
       Y=0.0024
C  RWIRE=RRT(1+Y(TWIRE-TRT)
       TWIRE1=TRT+(RWIRE1/RRT-1.0)/Y
C  XL=WIRE LENGTH (INCHES CONVERTED TO METERS)
       XL=0.020*0.0254
C  XD=WIRE DIAMETER (INCHES CONVERTED TO METERS)
       XD=0.001*0.0254
C  B=RATIO OF THROAT AREA TO WIRE PLANE AREA
       B=0.214515
C  D=RATIO OF STATIC TO TOTAL TEMP FOR ISENTROPIC CHOKE
       D=1.00000
C  A=RATIO OF SPECIFIC HEATS
       PI=3.141593
C  R=GAS CONSTANT (KJ/KG*K) CONVERT TO J/KG*K
C*************************************************************
C
C  CALCULATE A1,B1,A2,B2 FOR EACH DATA SET
       DO 1000 I=1,L
       T=D*TT(I)
       PT(I)=PT(I)*6894.757
       XAH = XHE(I)
       DO 50 J=1,15
       IF((T.GE.VISA(J,1)).AND.(T.LE.VISA(J+1,1))) GO TO 55
   50  CONTINUE
   55  CONTINUE
C
      CALL MIXTURE(VIS,CON,VISA,CONA,VISHE,CONHE,A,R,J,XAH)
       G=(2.0/(A+1.0))**((A+1.0)/(2.0*(A-1.0)))
C
C
       VIS1=VIS(J,2)
       VIS2=VIS(J+1,2)
       CON1=CON(J,2)
       CON2=CON(J+1,2)
       TEMP1=VIS(J,1)
       TEMP2=VIS(J+1,1)
       V=VIS1+(VIS2-VIS1)*(T-TEMP1)/(TEMP2-TEMP1)
       C=CON1+(CON2-CON1)*(T-TEMP1)/(TEMP2-TEMP1)
       A1(I)=LOG((AP1(I)**2*RWIRE1)/((TWIRE1-D*TT(I))*(RS+RWIRE1+
     1 RCAB)**2*PI*XL*C))
```

```
      B1(I)=LOG(XD*PT(I)*B*G/V*(A/(R*TT(I)))**0.5)
 1000 CONTINUE
C  GENERATE THE F MATRIX
      DO 200 I=1,L
      F1(I,1)=1.0
      F1(I,2)=B1(I)
  200 CONTINUE
C  GENERATE THE F TRANSPOSE MATRIX
      DO 300 I=1,L
      FT1(1,I)=1.0
      FT1(2,I)=B1(I)
  300 CONTINUE
C  CALCULATE FT * F MATRIX
      DO 352 I=1,2
      DO 351 J=1,2
      FT1F1(I,J)=0.0
      DO 350 K=1,L
      FT1F1(I,J)=FT1F1(I,J)+FT1(I,K)*F1(K,J)
  350 CONTINUE
  351 CONTINUE
  352 CONTINUE
C  CACUALATE THE FT * A MATRIX
      DO 401 I=1,2
      FT1A1(I)=0.0
      DO 400 K=1,L
      FT1A1(I)=FT1A1(I)+FT1(I,K)*A1(K)
  400 CONTINUE
  401 CONTINUE
C  FT*F(I,J) * (CC,XN) = FTA1(I) SOLVE 2 EQUATIONS AND TWO UNKNOWNS
      DET1=FT1F1(1,1)*FT1F1(2,2)-FT1F1(1,2)*FT1F1(2,1)
C
      CC1=(FT1A1(1)*FT1F1(2,2)-FT1A1(2)*FT1F1(1,2))/DET1
      CC1=EXP(CC1)
      XN1=(FT1F1(1,1)*FT1A1(2)-FT1F1(2,1)*FT1A1(1))/DET1
C  PRINT RESULTS
      write(6,42)xhe(i)
      write(8,42)xhe(i)
      WRITE(6,500)CC1,XN1
   42 FORMAT(1X,'XHE = ',F4.2)
  500 FORMAT(1X,'CC1= ',F10.8,3X,'XN1= ',F10.8)
      WRITE(8,700)CC1,XN1,TRT
      WRITE(8,800)RCAB,RRT,RSET1
  700 FORMAT(1X,3F15.8)
  800 FORMAT(3(5X,F10.5))
      write(6,*)
      write(8,*)
C
C  PERCENT ERROR
        WRITE(7,42)XHE(I)
     DO 501 I = 1 , L
      T=D*TT(I)
      XAH = XHE(I)
      DO 503 J=1,15
      IF((T.GE.VISA(J,1)).AND.(T.LE.VISA(J+1,1))) GO TO 504
  503 CONTINUE
  504 CONTINUE
C
     CALL MIXTURE(VIS,CON,VISA,CONA,VISHE,CONHE,A,R,J,XAH)
      G=(2.0/(A+1.0))**((A+1.0)/(2.0*(A-1.0)))
C
```

```
C
       VIS1=VIS(J,2)
       VIS2=VIS(J+1,2)
       CON1=CON(J,2)
       CON2=CON(J+1,2)
       TEMP1=VIS(J,1)
       TEMP2=VIS(J+1,1)
       V=VIS1+(VIS2-VIS1)*(T-TEMP1)/(TEMP2-TEMP1)
       C=CON1+(CON2-CON1)*(T-TEMP1)/(TEMP2-TEMP1)
C
       APCALC = ((RS+RWIRE1+RCAB)**2/RWIRE1*PI*XL*C*CC1*
     1              (XD*PT(I)*B*(A/(R*TT(I)))**0.5*G/V)**XN1*
     2              (TWIRE1-D*TT(I)))**0.5
C
         ERRV = ABS(AP1(I)-APCALC)/AP1(I) * 100.
         WRITE(7,502) AP1(I) , APCALC , ERRV
  501 CONTINUE
  502  FORMAT(2X,'EXP V=',E15.7,2X,'CALC V=',E15.7,2X,'% ERROR=',E15.7)
C
      WRITE(7,*)
   99 continue
       STOP
       END
C
c**********************************************************************
      SUBROUTINE MIXTURE(VIS,CON,VISA,CONA,VISHE,CONHE,A,R,J,TT)
      DIMENSION VIS(16,2),CON(16,2),VISA(16,2),CONA(16,2),
     1          VISHE(16,2),CONHE(16,2)
      REAL MHE,MA,M,MUA,MUHE,KHE,KA
C
C  HELIUM PROPERTIES
      XHE = TT
      MHE = 4.00260
      RHE = 8317./MHE
      CPHE = 5200.
C
C  AIR PROPERTIES
      XA = 1. - XHE
      MA = 29.
      RA = 8317./MA
      CPA = 1005.7
C
C  MIXTURE PROPERTIES
      M = XHE * MHE + XA * MA
      CP =(MHE* XHE * CPHE + XA * CPA*MA)/M
      R = 8317./M
      CV = CP - R
      A = CP / CV
      WRITE(6,*)XHE,A,R
C
      IXHE = NINT(100. * XHE)
      WRITE(6,*)XHE,IXHE
      DO 10 I = J , J+1
            VIS(I,1) = VISHE(I,1)
            CON(I,1) = CONHE(I,1)
      IF(IXHE.EQ.100)THEN
         WRITE(6,*)' ENTERING ALL HELIUM ****'
         VIS(I,2) = VISHE(I,2)
         CON(I,2) = CONHE(I,2)
      ELSE IF(IXHE.EQ.0)THEN
```

```
      WRITE(6,*)' ENTERING ALL AIR ***'
      VIS(I,2) = VISA(I,2)
      CON(I,2) = CONA(I,2)
   ELSE
      WRITE(6,*)' ENTERING MIX ***'
         MUA = VISA(I,2)/(1+XHE/XA*(1+SQRT(VISA(I,2)/VISHE(I,2))
     1          *(MHE/MA)**.25)**2/(2.82843*SQRT(1+MA/MHE)))
         MUHE = VISHE(I,2)/(1+XA/XHE*(1+SQRT(VISHE(I,2)/
     1           VISA(I,2))*(MA/MHE)**.25)**2/(2.82843*
     2           SQRT(1+MHE/MA)))
         VIS(I,2) = MUA + MUHE
       KA = CONA(I,2)/(1+XHE/XA*(1+SQRT(CONA(I,2)/CONHE(I,2))
     1       *(MHE/MA)**.25)**2/(2.82843*SQRT(1+MA/MHE)))
       KHE = CONHE(I,2)/(1+XA/XHE*(1+SQRT(CONHE(I,2)/CONA(I,2)
     1        )*(MA/MHE)**.25)**2/(2.82843*SQRT(1+MHE/MA)))
       CON(I,2) = KA + KHE
   END IF
      WRITE(6,*)VIS(I,1),VIS(I,2),CON(I,1),CON(I,2)
10 CONTINUE
   RETURN
   END
```

Program Conc.FOR

```
C*********************************************************************
C                          - Conc.FOR -                               *
C                                                                     *
C       --this program reduces the hot-film voltage,total pressure,   *
C         and total temperature into molar helium concentration       *
C                                                                     *
C                                                                     *
C                  JOEL C. ROSSON      BEGUN 2/19/85                  *
C                 FEI T. KWOK      MODIFIED 10/20/88                  *
C                 TODD NINNEMANN   MODIFIED  9/15/89                  *
C*********************************************************************
C
      DIMENSION TT(1000),PT(1000),AP1(1000),XHE(1000),YLVDT(1000)
      DIMENSION VISA(16,2),CONA(16,2),VISHE(16,2),CONHE(16,2)
      DIMENSION CC1(10) , XN1(10)
C
C  VOLTAGE VS. TOTAL TEMPERATURE AND PRESSURE DATA
C    TT(K), PT(PSI),XHE(MOLE FRACTION)
C  L=NUMBER OF DATA VALUES FOR CALIBRATION
      OPEN(5,FILE='CALIB.IN',STATUS='OLD',FORM='FORMATTED')
      OPEN(6,FILE='RUN.IN',STATUS='OLD',FORM='FORMATTED')
      OPEN(7,FILE='RUN.OUT',STATUS='NEW',FORM='FORMATTED')
      OPEN(8,FILE='LIMIT',STATUS='NEW',FORM='FORMATTED')
      READ(5,*) NR,L,TRT,RCAB,RRT,RSET1,D,TOL,NCONST,DELX
      WRITE(*,*)NR,L,TRT,RCAB,RRT,RSET1,D,TOL,-TOL,NCONST,DELX
      WRITE(*,*)
C  *** INPUT  XHE = 0.0  TO  XHE = 1.0  ***
      DO 252 I = 1 , NCONST
        READ(5,*) CC1(I) , XN1(I)
         WRITE(*,*) CC1(I) , XN1(I)
  252  CONTINUE
      WRITE(*,*)' LOADING DATA VALUES . . .'
      DO 10 I=1,L
      READ(6,*) YLVDT(I),AP1(I),PT(I),TT(I)
   10  CONTINUE
C
C  VISCOSITY FOR AIR IN KG/M*S OR N*S/M**2
      DATA VISA/140.,150.,160.,180.,200.,220.,240.,260.,280.,
     1       290.,300.,310.,320.,330.,340.,350.,
     1   .96112E-5,1.0283E-5,1.08842E-5,1.20866E-5,1.3289E-5,
     1   1.43694E-5,1.54498E-5,1.64844E-5,1.74732E-5,1.79676E-5,
     1   1.8462E-5,1.89196E-5,1.93772E-5,1.9834E-5,2.02924E-5,
     1    2.075E-5/
C
C  THERMAL CONDUCTIVITY FOR AIR IN W/M*K
      DATA CONA/140.,150.,160.,180.,200.,220.,240.,260.,280.,
     1       290.,300.,310.,320.,330.,340.,350.,
     1   .0128372,.013735,.014606,.016348,.01809,.019762,
     1   .021434,.023064,.024652,.025446,.02624,.026998,
     1    .027756,.028514,.029272,.03003/
C
C VISCOSITY FOR HELIUM IN KG/M*S
      DATA VISHE/140.,150.,160.,180.,200.,220.,240.,260.,280.,
     1     290.,300.,310.,320.,330.,340.,350.,
     1     1.22E-5,1.288E-5,1.344E-5,1.455E-5,1.566E-5,
     1     1.657E-5,1.749E-5,1.839E-5,1.927E-5,1.971E-5,2.015E-5,
     1    2.059E-5,2.103E-5,2.147E-5,2.191E-5,2.235E-5/
C
C THERMAL CONDUCTIVITY FOR HELIUM IN W/M*K
      DATA CONHE/140.,150.,160.,180.,200.,220.,240.,260.,280.,
```

```
     1     290.,300.,310.,320.,330.,340.,350.,
     2     9.07E-2,9.5E-2,9.92E-2,1.072E-1,1.151E-1,
     3    1.228E-1,1.304E-1,1.374E-1,1.447E-1,1.484E-1,1.52E-1,
     4     1.555E-1,1.591E-1,1.626E-1,1.662E-1,1.697E-1/
C
      A = 0.
      R = 0.
C
C*************************************************************
C
C  RS=SERIES RESISTANCE (OHMS)
       RS= 50.0
C  RCAB=CABLE RESISTANCE(OHMS)
C  RSET1=ANEMOMETER RESISTANCE SETTING(OHMS)
C  RWIRE=HOT WIRE RESISTANCE AT THE OPERATING TEMP.
       RWIRE1=RSET1-RCAB
C  RRT=HOT WIRE RESISTANCE AT ROOM TEMPERATURE(OHMS)
C  TRT=STANDARD ROOM TEMP (K)
C  Y=THERMAL COEEFICIENT OF RESISTIVITY FOR PT COATED TG(K**-1)
       Y=0.0024
C  RWIRE=RRT(1+Y(TWIRE-TRT)
       TWIRE1=TRT+(RWIRE1/RRT-1.0)/Y
C  XL=WIRE LENGTH (INCHES CONVERTED TO METERS)
       XL=0.020*0.0254
C  XD=WIRE DIAMETER (INCHES CONVERTED TO METERS)
       XD=0.001*0.0254
C  B=RATIO OF THROAT AREA TO WIRE PLANE AREA
       B=0.214515
C  D=RATIO OF STATIC TO TOTAL TEMP FOR ISENTROPIC CHOKE
C      D=0.9725
C  A=RATIO OF SPECIFIC HEATS
       PI=3.141593
C  R=GAS CONSTANT (KJ/KG*K) CONVERT TO J/KG*K
C*************************************************************
C
      V = 0.0
      C = 0.0
      G = 0.0
C
C      WRITE(*,*)' INPUT VOLTAGE, PRESSURE, TEMP,CONC,CONST.'
C      READ(*,*) VOLT , PTT , T ,XAH , IA
C      PTT=PTT*6894.757
C      DO 90 J=1,15
C      IF((T.GE.VISA(J,1)).AND.(T.LE.VISA(J+1,1))) GO TO 95
C  90  CONTINUE
C  95  CONTINUE
C
C       CALL MIXTURE(VISA,CONA,VISHE,CONHE,A,R,J,XAH,T,V,C,G)
C
C       VAH =((RS+RWIRE1+RCAB)**2/RWIRE1*PI*XL*C*CC1(IA)*(TWIRE1-
C    1     T)*(XD/V*B*G*PTT*(A/(R*T))**0.5)**XN1(IA))**0.5
C
C       SH = VOLT - VAH
        WRITE(*,*)' INPUT SHIFT VALUE IN VOLTS (EXP-CALC)'
        READ(*,*) SH
        WRITE(8,*) SH
        WRITE(*,*) SH
C
      NCOUNT = 0
      NC0 = 0
```

```
      NC1 = 0
      DO 1000 I=1,L
       T=TT(I)
       PT(I)=PT(I)*6894.757
       DO 50 J=1,15
       IF((T.GE.VISA(J,1)).AND.(T.LE.VISA(J+1,1))) GO TO 55
   50  CONTINUE
   55  CONTINUE
C
       XLOW = 0.0
       XUP = DELX
       DO 253 ILIMS = 1 , NCONST-1
        CALL MIXTURE(VISA,CONA,VISHE,CONHE,A,R,J,XLOW,T,V,C,G)
C
        VLOW =((RS+RWIRE1+RCAB)**2/RWIRE1*PI*XL*C*CC1(ILIMS)*(TWIRE1-
     1     T)*(XD/V*B*G*PT(I)*(A/(R*TT(I)))**0.5)**XN1(ILIMS))**0.5
     2       + SH
C
C
        CALL MIXTURE(VISA,CONA,VISHE,CONHE,A,R,J,XUP,T,V,C,G)
C
       VUP=((RS+RWIRE1+RCAB)**2/RWIRE1*PI*XL*C*CC1(ILIMS+1)*(TWIRE1-
     1   T)*(XD/V*B*G*PT(I)*(A/(R*TT(I)))**0.5)**XN1(ILIMS+1))**0.5
     2       + SH
C
        IF(ILIMS.EQ.1.AND.AP1(I).LT.VLOW)THEN
           XHE(I) = 0.0
           NC0 = NC0 + 1
           WRITE(8,*) I,XHE(I),AP1(I)-VLOW
           GO TO 1600
         ELSE IF(ILIMS.EQ.NCONST-1.AND.AP1(I).GT.VUP)THEN
           XHE(I) = 1.0
           NC1 = NC1 + 1
           WRITE(8,*) I,XHE(I),AP1(I)-VUP
           GO TO 1600
         END IF
C
         IF(AP1(I).EQ.VLOW)THEN
            XHE(I) = XLOW
             GO TO 1600
         ELSE IF(AP1(I).EQ.VUP)THEN
            XHE(I) = XUP
            GO TO 1600
         ELSE IF(AP1(I).GT.VLOW.AND.AP1(I).LT.VUP) THEN
            XM = (XUP - XLOW) / (VUP - VLOW)
            XHE(I) = XM * (AP1(I) - VLOW) + XLOW
            GO TO 1600
         END IF
         XLOW = XUP
         XUP = XLOW + DELX
  253 CONTINUE
 1600  WRITE(7,*) YLVDT(I),XHE(I)
       NCOUNT = NCOUNT + 1
C
      WRITE(*,*)I
 1000 CONTINUE
      WRITE(*,*)' Number of pts used = ',NCOUNT,' out of ',L
      WRITE(*,*)
      WRITE(*,*)' Number of pts. forced to 1.0 = ',NC1
      WRITE(*,*)
```

```
      WRITE(*,*)' Number of pts. forced to 0.0 = ',NC0
      CLOSE(5)
      CLOSE(6)
      CLOSE(7)
      CLOSE(8)
       STOP
       END
C
      SUBROUTINE MIXTURE(VISA,CONA,VISHE,CONHE,A,R,J,TT,T,V,C,G)
      DIMENSION VIS(16,2),CON(16,2),VISA(16,2),CONA(16,2),
     1          VISHE(16,2),CONHE(16,2)
      REAL MHE,MA,M,MUA,MUHE,KHE,KA
C
C  HELIUM PROPERTIES
      XHE = TT
      MHE = 4.00260
      RHE = 8317./MHE
      CPHE = 5200.
C
C  AIR PROPERTIES
      XA = 1. - XHE
      MA = 29.
      RA = 8317./MA
      CPA = 1005.7
C
C  MIXTURE PROPERTIES
      M = XHE * MHE + XA * MA
      CP = ( XHE * CPHE * MHE + XA * CPA * MA ) / M
      R = 8317./M
      CV = CP - R
      A = CP / CV
C
      IXHE = NINT(100. * XHE)
      DO 10 I = J , J+1
            VIS(I,1) = VISHE(I,1)
            CON(I,1) = CONHE(I,1)
      IF(IXHE.EQ.100)THEN
         VIS(I,2) = VISHE(I,2)
         CON(I,2) = CONHE(I,2)
      ELSE IF(IXHE.EQ.0)THEN
         VIS(I,2) = VISA(I,2)
         CON(I,2) = CONA(I,2)
      ELSE
            MUA = VISA(I,2)/(1+XHE/XA*(1+SQRT(VISA(I,2)/VISHE(I,2))
     1            *(MHE/MA)**.25)**2/(2.82843*SQRT(1+MA/MHE)))
            MUHE = VISHE(I,2)/(1+XA/XHE*(1+SQRT(VISHE(I,2)/
     1             VISA(I,2))*(MA/MHE)**.25)**2/(2.82843*
     2             SQRT(1+MHE/MA)))
            VIS(I,2) = MUA + MUHE
          KA = CONA(I,2)/(1+XHE/XA*(1+SQRT(CONA(I,2)/CONHE(I,2))
     1         *(MHE/MA)**.25)**2/(2.82843*SQRT(1+MA/MHE)))
          KHE = CONHE(I,2)/(1+XA/XHE*(1+SQRT(CONHE(I,2)/CONA(I,2)
     1          )*(MA/MHE)**.25)**2/(2.82843*SQRT(1+MHE/MA)))
          CON(I,2) = KA + KHE
       END IF
   10 CONTINUE
C
         G=(2.0/(A+1.0))**((A+1.0)/(2.0*(A-1.0)))
C
         VIS1=VIS(J,2)
```

```
            VIS2=VIS(J+1,2)
            CON1=CON(J,2)
            CON2=CON(J+1,2)
            TEMP1=VIS(J,1)
            TEMP2=VIS(J+1,1)
            V=VIS1+(VIS2-VIS1)*(T-TEMP1)/(TEMP2-TEMP1)
            C=CON1+(CON2-CON1)*(T-TEMP1)/(TEMP2-TEMP1)
C
C       WRITE(*,*) V , C
C
        RETURN
        END
```

Appendix B

Program Avg.FOR

```
C*********************************************************************
C                                                                     *
C                          -  Avg.FOR -                               *
C                                                                     *
C          --this program makes an RMS squared average of             *
C            voltage flucuation over mean voltage.                    *
C                                                                     *
C                                                                     *
C                   RODNEY BOWERSOX      BEGUN 9/15/89                *
C                   TODD NINNEMANN    MODIFIED 2/20/90                *
C                                                                     *
C*********************************************************************
C
      DIMENSION V1(10001),V2(10001),V3(10001),ys(100),ysavg(100)
      DIMENSION VRMSS(3)
      REAL L,KT
C
      OPEN(1,FILE = 'HW6.DAT')
      OPEN(2,FILE = 'HW4.DAT')
      OPEN(3,FILE = 'HW3.DAT')
      open(4,file = 'ys.bar')
      DO 10 I=1,10000
        READ(1,*) V1(I)
   10 contINUE
      DO 11 I=1,10000
        READ(2,*) V2(I)
   11 CONTINUE
      DO 12 I=1,10000
        READ(3,*) V3(I)
   12 CONTINUE
      do 14 i=1,100
        read(4,*)ysavg(i)
   14 continue
      CLOSE(1)
      CLOSE(2)
      CLOSE(3)
      CLOSE(4)
      open(6,file = 'fg.6')
      open(4,file = 'fg.4')
      open(3,file = 'fg.3')
      I1 = 0
      DO 30 I=1,100
        I1 = I1 + 1
        SUM1 = 0.
        SUM12 = 0.
        SUM2 = 0.
        SUM22 = 0.
        SUM3 = 0.
        SUM32 = 0.
        j=0
        DO 40 J=1,100
          J1 = J1+1
          SUM1 = SUM1 + V1(J1)
          SUM12 = SUM12 + V1(J1)*V1(J1)
          SUM2 = SUM2 + V2(J1)
          SUM22 = SUM22 + V2(J1)*V2(J1)
          SUM3 = SUM3 + V3(J1)
          SUM32 = SUM32 + V3(J1)*V3(J1)
   40 continue
      XN = FLOAT(100)
```

```
      V1BAR = SUM1/XN
      V2BAR = SUM2/XN
      V3BAR = SUM3/XN
      V1SBAR = SUM12/XN
      V2SBAR = SUM22/XN
      V3SBAR = SUM32/XN
C
C   CALCULATE THE RMS VOLTAGES ---> (v'/vbar)rms squared  vector
C
      XNM1 = FLOAT(99)
      VRMSS(1)=(SUM12/XNM1-SUM1*SUM1/XN/XNM1)/V1BAR/V1BAR
      VRMSS(2)=(SUM22/XNM1-SUM2*SUM2/XN/XNM1)/V2BAR/V2BAR
      VRMSS(3)=(SUM32/XNM1-SUM3*SUM3/XN/XNM1)/V3BAR/V3BAR
      write(6,*)ysavg(i1),vrmss(1)
      write(4,*)ysavg(i1),vrmss(2)
      write(3,*)ysavg(I1),vrmss(3)
C
   30 CONTINUE
      STOP
      END
```

Program Solve.FOR

```
C*********************************************************************
C                          -  Solve.FOR -                             *
C                                                                     *
C                                                                     *
C       --This program solves a linear system of 3 equations for      *
C         fluctuations in thermal conductivity and Reynolds number    *
C                                                                     *
C              RODNEY BOWERSOX      BEGUN 9/15/89                     *
C              TODD NINNEMANN      MODIFIED 2/20/90                  *
C                                                                     *
C                                                                     *
C*********************************************************************
C
      real *8 V1(10001),V2(10001),V3(10001),TT1(100),HT(200)
      real *8 XY(3,3),Z(3),RETTBAR(3),FG(3,3),VRMSS(3),FLUX(3)
      real *8 HTR(200),HTC(200),CND(200),C(200),RED(200),RE(200)
      REAL *8 L,KT
C
      PI = 4.*ATAN(1.)
      NAVE = 100
      NUM = 160
      NPTS = 100
      OPEN(1,FILE = 'tot.6')
      OPEN(2,FILE = 'tot.4')
      OPEN(3,FILE = 'tot.3')
      DO 10 I=1,100
        READ(1,*)ht(i), V1(I)
   10 CONTINUE
      DO 11 I=1,100
        READ(2,*)ht(i), V2(I)
   11 CONTINUE
      DO 12 I=1,100
        READ(3,*)ht(i), V3(I)
   12 CONTINUE
      CLOSE(1)
      CLOSE(2)
      CLOSE(3)
      OPEN(1,FILE = 'WIRE6.M')
      READ(1,*) A1,B1,L,RW1,RS,TW1,RLEAD
      OPEN(2,FILE = 'WIRE4.M')
      READ(2,*) A2,B2,L,RW2,RS,TW2,RLEAD
      OPEN(3,FILE = 'WIRE3.M')
      READ(3,*) A3,B3,L,RW3,RS,TW3,RLEAD
      CLOSE(1)
      CLOSE(2)
      CLOSE(3)
C
      OPEN(1,FILE = 'RE.7')
      OPEN(2,FILE = 'K.DAT')

      DO 3 I = 1 , NUM
        READ(1,*) HTR(I),RED(I)
        READ(2,*) HTC(I),C(I)
    3 CONTINUE
      CLOSE(1)
      CLOSE(2)
      XLAST=HTR(NUM)
      IFLAG=0.0
      FIRST=HTR(1)
      DO 23 JK=1,NPTS
```

```
          IF(HT(JK).LT.FIRST) GO TO 55
          IF(HT(JK).GT.XLAST) GO TO 55
             IFLAG=IFLAG+1
             DO 6 I2 = 1 , NUM
                IF(HT(JK).GE.HTR(I2).AND.HT(JK).LE.HTR(I2+1)) THEN
                  XMR= (RED(I2+1)-RED(I2)) / (HTR(I2+1) -
     1                 HTR(I2))
                RE(IFLAG)= XMR * (HTR(I2)-HT(JK)) + RED(I2)
                  XMC= (C(I2+1)-C(I2)) / (HTC(I2+1) -
     1                 HTC(I2))
                CND(IFLAG)= XMC * (HTC(I2)-HT(JK)) + C(I2)
                END IF
      6      CONTINUE
     55 FED=1.0

     23 CONTINUE
        TT1BAR = 292.
        C1 = ((RS+RW1+RLEAD)**2*PI*L*(TW1-TT1BAR))/RW1
        C2 = ((RS+RW2+RLEAD)**2*PI*L*(TW2-TT1BAR))/RW2
        C3 = ((RS+RW3+RLEAD)**2*PI*L*(TW3-TT1BAR))/RW3
C
C    OPEN OUTPUT FILE
C
        OPEN(1,FILE = 'MOH.DAT')
        OPEN(2,FILE = 'TCON.RMS')
        OPEN(3,FILE = 'RE.RMS')
        open(4,file = 'fg.dat')
        open(5,file = 'flux2.dat')
        WRITE(1,100)
   100 FORMAT(3X,3Hy/S,7X,3HTt1,8X,6H Kbar ,6X,6HSRebar,4X,9H(k')rms/k,
      $       1X,11H(Re')rms/Re)
C
        I1 = 0
        DO 30 I=1,100
          I1 = I1 + 1
        VRMSS(1)=v1(i1)
        VRMSS(2)=v2(i1)
        VRMSS(3)=v3(i1)
C
C    FILL THE fg MATRIX
C
        KT=CND(I1)
        SQRE=SQRT(RE(I1))
        zqre=sqrt(1.05*re(i1))
        sqret=sqrt(0.95*re(i1))
        F1=0.5
        F2=0.5
        F3=0.5
        G1=0.25/(1.0+(b1/(a1*sqre)))
        G2=0.25/(1.0+(b2/(a2*sqret)))
        G3=0.25/(1.0+(b3/(a3*zqre)))
C
        FG(1,1)=(F1)**2
        FG(1,2)=2.*(F1)*(G1)
        FG(1,3)=(G1)**2
        FG(2,1)=(F2)**2
        FG(2,2)=2.*(F2)*(G2)
        FG(2,3)=(G2)**2
        FG(3,1)=(F3)**2
        FG(3,2)=2.*(F3)*(G3)
```

```
      FG(3,3)=(G3)**2
      write(4,500) fg(1,1),fg(1,2),fg(1,3),vrmss(1),
     &             fg(2,1),fg(2,2),fg(2,3),vrmss(2),
     &             fg(3,1),fg(3,2),fg(3,3),vrmss(3)
C
      CALL S3BY3(FG,VRMSS,FLUX)
C
      IF(FLUX(1).LT.0.0) GO TO 25
      IF(FLUX(3).LT.0.0) GO TO 25
C
      WRITE(1,200)HT(I1),TEMP,KT,SQRE,SQRT(FLUX(1)),SQRT(FLUX(3))
      WRITE(2,*)HT(I1),SQRT(FLUX(1))
      WRITE(3,250)HT(I1),SQRT(FLUX(3))
      write(5,250)HT(i1),flux(2)
c     write(5,*)I1,V1BAR,V1SBAR
   25 CONTINUE
   30 CONTINUE
  200 FORMAT(6(E11.4))
  250 FORMAT(2(2X,E11.4))
  500 format(3(2x,e11.4,2x,e11.4,2x,e11.4,4x,e11.4/)//)
      CLOSE(1)
      CLOSE(2)
      CLOSE(3)
      STOP
      END
C
C*************************************************************
C  SUBROUTINE: S3BY3
C
C
      SUBROUTINE S3BY3(A,B,X)
      real *8 A(3,3),B(3),X(3)
      DETA = A(1,1)*(A(2,2)*A(3,3)-A(3,2)*A(2,3))
     $     - A(2,1)*(A(1,2)*A(3,3)-A(3,2)*A(1,3))
     $     + A(3,1)*(A(1,2)*A(2,3)-A(2,2)*A(1,3))
      X(1) = B(1)*(A(2,2)*A(3,3)-A(3,2)*A(2,3))
     $     - B(2)*(A(1,2)*A(3,3)-A(3,2)*A(1,3))
     $     + B(3)*(A(1,2)*A(2,3)-A(2,2)*A(1,3))
      X(1) = X(1)/DETA
      X(2) = A(1,1)*(B(2)*A(3,3)-B(3)*A(2,3))
     $     - A(2,1)*(B(1)*A(3,3)-B(3)*A(1,3))
     $     + A(3,1)*(B(1)*A(2,3)-B(2)*A(1,3))
      X(2) = X(2)/DETA
      X(3) = A(1,1)*(B(3)*A(2,2)-B(2)*A(3,2))
     $     - A(2,1)*(B(3)*A(1,2)-B(1)*A(3,2))
     $     + A(3,1)*(B(2)*A(1,2)-B(1)*A(2,2))
      X(3) = X(3)/DETA
      write(9,*)deta
      RETURN
      END
```

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Vita

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