N94- 36407

MEASUREMENT OF SURFACE HEAT FLUX AND TEMPERATURE

R. M. Davis

G. J. Antoine

T. E. Diller

and

A. L. Wicks

Department of Mechanical Engineering
Virginia Polytechnic Institute & State University
Blacksburg, Virginia 24061-0238

Telephone 703-231-7198

Measurement of Surface Heat Flux and Temperature

R. M. Davis, G. J. Antoine, T. E. Diller, and A. L. Wicks
Department of Mechanical Engineering
Virginia Tech
Blacksburg, VA 24060-0238

PREREQUISITE KNOWLEDGE

Students should have an undergraduate course in heat transfer to understand the fundamentals of conduction, convection, and radiation heat transfer. An understanding of transient conduction is important and a background including semi-infinite conduction solutions is helpful. An introduction to elementary experimental statistics is necessary.

OBJECTIVES

The experiment demonstrates a new sensor technology. The students use the sensor to observe details of a combustion flame and allows them to experience the application of modern research. The data processing clearly demonstrates the different effects of integrating versus differentiating data.

EQUIPMENT AND SUPPLIES

1. Heat Flux Microsensor and associated amplifier
2. Self-igniting propane torch
3. TEGAM thermocouple read out
4. DC power supply
5. Elenco Precision Bread board
6. Texas Instruments 741 OP-AMP
7. Voltmeter
8. Macintosh Quadra 700 computer
9. LabVIEW software
10. Leather gloves

INTRODUCTION

The Heat Flux Microsensor is a new sensor which was recently patented [1] by Virginia Tech and is just starting to be marketed by Vatell Corp. The sensor is made using thin-film microfabrication techniques directly on the material that is to be measured. It consists of several

thin-film layers forming a differential thermopile across a thermal resistance layer. As illustrated in Fig. 1, the measured heat flux q is proportional to the temperature difference across the resistance layer [2]

$$q = \frac{k_g}{\delta_g}(T_1 - T_2)$$ (1)

where k_g is the thermal conductivity and δ_g is the thickness of the thermal resistance layer. Because the gages are sputter coated directly onto the surface, their total thickness is less than 2 μm, which is two orders of magnitude thinner than previous gages. The resulting temperature difference across the thermal resistance layer ($\delta < 1$ μm) is very small even at high heat fluxes. To generate a measurable signal many thermocouple pairs are put in series to form a differential thermopile [2], as illustrated in Fig. 2.

The combination of series thermocouple junctions and thin-film design creates a gage with very attractive characteristics. It is not only physically non-intrusive to the flow, but also causes minimal disruption of the surface temperature. Because it is so thin, the response time is less than 20 μsec [3]. Consequently, the frequency response is flat from 0 to over 50 kHz. Moreover, the signal of the Heat Flux Microsensor is directly proportional to the heat flux. Therefore, it can easily be used in both steady and transient flows, and it measures both the steady and unsteady components of the surface heat flux.

A version of the Heat Flux Microsensor has been developed to meet the harsh demands of combustion environments. These gages use platinum and platinum-10% rhodium as the thermoelectric materials. The thermal resistance layer is silicon monoxide and a protective coating of Al_2O_3 is deposited on top of the sensor. The thin-film pattern of all six layers is superimposed in Fig. 3. The large pads are for connection with pins used to bring the signal out the back of the ceramic. In addition to the heat flux measurement, the surface temperature is measured with a platinum resistance layer (RTS). The resistance of this layer increases with increasing temperature. Therefore, these gages simultaneously measure the surface temperature and heat flux. The demonstrated applications include rocket nozzles, SCRAM jet engines, gas turbine engines, boiling heat transfer, flame experiments, basic fluid heat transfer, hypersonic flight, and shock tube testing. The laboratory involves using one of these sensors in a small combustion flame. The sensor is made on a 2.5 cm diameter piece of aluminum nitride ceramic.

Heat Transfer

The fast time response of the temperature and heat flux sensors allows the comparison of time-resolved measurements. The temperature rise of the ceramic substrate is caused by the heat transfer from the flame to the surface. Modeling of the heat transfer allows prediction of the temperature rise for the measured heat flux. Alternatively, the temperature measurement can provide an independent measure of the surface heat flux. If the ceramic piece is considered to be a one-dimensional semi-infinite solid as sketched in Fig. 4, the temperature history is

$$T_s - T_i = \frac{2q\sqrt{t}}{\sqrt{\pi}\sqrt{k\rho C}}$$ (2)

for a constant surface heat flux starting at time $t=0$. The values of the thermal conductivity (k), the density (ρ), and the specific heat (C) of the ceramic substrate are listed below.

$$k = 165 \text{ W/m} \cdot \text{K}$$
$$\rho = 3290 \text{ kg/m}^3$$
$$C = 713 \text{ J/kg} \cdot \text{K}$$
$$\alpha = 7.03 \times 10^{-5} \text{ m}^2/\text{s}$$

The surface temperature predicted by the semi-infinite solution is correct to within 1.0% for times less than [4]

$$t = 0.3 \frac{L^2}{\alpha} \tag{3}$$

where α is the thermal diffusivity and L the thickness of the substrate, which is 6.35 mm for the given substrate. For times longer than given by eq. (3) the analytical solution loses accuracy. Experimentally the temperature will rise faster than the semi-infinite solution predicts. For the present case the effect should be small for times less than 1 second. A good additional assumption is that the presence of the gage itself does not affect the substrate response of eq. (2).

The sensitivity of the Heat Flux Microsensor, S, is used to convert the voltage signal, E, to heat flux.

$$q = \frac{E}{S} \tag{4}$$

Calibrations give a gage sensitivity of $S=23.2 \text{ mV/(W/cm}^2)$ for the signal from the amplifier box (at 1000X amplification). The equation to convert the RTS signal (at the 500X setting of the amplifier box) to temperature is

$$T_s = (132.33 \frac{^\circ C}{V}) E - 286.06 ^\circ C \tag{5}$$

Data Processing

Equation (2) relates the temperature change of the surface of a material to a single step change of the surface heat flux. Manipulation of this type of equation gives the temperature response to a varying heat flux signal as a series solution [5]. This can be in the form of a series of impulse functions as shown in Fig. 5. The solution for the temperature response to a varying heat flux input is

$$T_s(t_n) - T_i = \frac{2}{\sqrt{\pi} \sqrt{k\rho C}} \sum_{j=0}^{n-1} q_j \left[\sqrt{t_n - t_j} - \sqrt{t_n - t_{j+1}} \right] \tag{6}$$

Note that this is similar to integrating the heat flux measurements.

In similar fashion the solution for determining the heat flux from a given set of surface temperatures is [4]

$$q(t_n) = \frac{2\sqrt{k\rho C}}{\sqrt{\pi}} \sum_{j=1}^{n} \frac{T_j - T_{j-1}}{\sqrt{t_n - t_j} + \sqrt{t_n - t_{j-1}}} \qquad (7)$$

Note that this is similar to differentiating the surface temperature measurements.

Both of these expressions are in the form needed for digital signal processing. They have been programmed on a computer disc for subsequent processing of the data. A listing of the FORTRAN code is attached. By calculating the corresponding surface temperature response to the measured heat flux and comparing with the experimental temperatures, additional confidence in the measurements can be established. The data processing task is to do this and to quantify the results.

As an additional check of the program for data processing, a manual comparison can be performed using eq. (2). Simply input an average heat flux over the time of the heated portion of the test and compare the surface temperature rise with that calculated with the program. It should be reasonably close.

Data Acquisition

The LabVIEW software (a product of National Instruments) allows the student to formulate an instrument in software. This instrument, referred to as a virtual instrument, incorporates the data acquisition with drivers to support high speed A/D boards, preprocessing algorithms, such as digital filters, and post processing capability. The post processing for this experiment may include the differentiation, or integration of the digital data. This software also provides data formats for storage. Although the LabVIEW software is not required to perform this experiment, the iconified format and the flexibility permit numerous variations in the experiment without extensive software revision. This software is used extensively throughout the laboratory experience to promote the concept of integrated data acquisition, signal conditioning, post-processing and graphical displays.

PROCEDURE

The flame is provided by a propane torch which is aimed directly at the heat flux gage, as illustrated in Fig. 6. The torch has a self igniter which is activated by a button on the front. To ignite the torch the gas is turned fully on by the knob on the back and then the button is pressed. After the flame is adjusted to the desired level the test is started by opening the shutter to allow the flame to impinge on the heat flux gage. A chromel/alumel thermocouple is provided to measure the flame temperature. An amplifier box is provided with the gage to boost the heat flux signal and convert the resistance of the surface RTS to a voltage.

Safety Considerations

Because the students are dealing with a high temperature flame test (1200°C), they need to be reminded of a few safety factors.

1.   Do not touch the upper part of the apparatus. When opening and closing the gate, leather gloves may be worn as added protection.

2.   Do not leave the flame on for longer than necessary. Always turn it off between tests. Because it does not have active cooling, the entire apparatus will become excessively hot with only a few minutes continuous operation.

3.   Do not run the flame on the gage for over a few seconds at a time. Leave the shutter closed at all times except when actually taking data. This should keep the temperatures well below 100°C.

Zeroing the Amplifier

After the amplifier is turned on and allowed to stabilize, both channels need to be zeroed. Set the switch on the amplifier to the zero position. Connect the output from heat flux channel to a voltmeter. Adjust the appropriate pot so that the output reads 0.0 V. Connect the output from the RTS channel (surface temperature) to the voltmeter. Adjust the appropriate pot so that the output reads 0.0 V. When the switch is flipped from zero to test, the output of the heat flux channel should be 0.0 V, but there will be a DC offset of 2 or more volts on the temperature channel. This reflects the resistance of the RTS at room temperature. Because the change in resistance is only millivolts, this offset must be removed from the RTS output before being processed by the computer to maximize the resolution of the A/D conversion. Therefore, a differential amplifier should be used to remove 2 volts from the signal.

Building a Differential Amplifier

Construct the amplifier on the breadboard as illustrated in Fig. 7. An accurate reading of V_{in1} (~ 2 V) should be taken by the voltmeter and recorded to be re-inserted into the computer.

Experimental Tests

Connect the heat flux and differential amplifier outputs directly into the interface box (A/D board). Start the VI on the computer. Adjust the gain and offset for each channel (Hint: Remember the 2 V that was measured and subtracted previously). Adjust Time Base, Interval and Samples/channel accordingly. Record the values for Interval and Samples/channel for each test for use in the FORTRAN code for data processing.

When ready to acquire data, light the propane torch. Immediately after pressing the Acquire Data button open the gate. Each test should last no more than 2 seconds. Save the data and repeat the test until you have acquired at least five sets of data. Try to use varying flame heights and conditions for each test. Observe the flame and make notes to explain the observed heat flux response.

Statistical Treatment of Data

For each test use the FORTRAN code to calculate the surface temperature and heat flux values to compare with the corresponding measured values. Compute the residuals of the measured and calculated data for both the heat flux and temperature responses. Plot the residuals and perform a visual analysis. Discuss whether the data looks random or if there appears to be some bias error present.

Compute the mean and the standard deviation of the residuals. Perform a 95% confidence interval for the mean. Discuss results. Are the values different when computed for the first 1 second of the flame test than for the entire sampling period?

Given that the estimated uncertainty for heat flux is 0.05 W/cm^2 and for temperature is 0.2°C, are the methods presented in this lab acceptable? Use the uncertainty to discuss your error, and discuss which assumptions made in the calculations most likely lead to this error. Provide a plot of the residuals and a tabulated summary of the statistical data.

From the calculated values of the heat flux and surface temperature determine which is a better approximation of the measured data. Discuss the advantages and disadvantages of each method.

Sample Results

Each student should plot comparisons of their measured and calculated data versus time for both temperature and heat flux and the resulting residuals from these comparisons. Sample results are illustrated in Figures 8-11. Students are expected to complete a statistical analysis of their data and present it in tabulated form as shown in Table 1 for the results in the figures.

Table 1 Statistical Results of Temperature and Heat Flux Residuals

	Total Test	Total Test	First Second of Flame	First Second of Flame
	T_s (°C)	q (W/cm^2)	T_s (°C)	q (W/cm^2)
Mean	1.41	-2.69	0.25	-1.86
Standard Deviation	1.80	4.15	0.57	3.62
95% Confidence Interval	±0.25	±0.59	±0.16	±1.0

INSTRUCTOR NOTES

1. Care should be exercised once the test has been run several times because the Heat Flux Microsensor housing becomes hot. Leather gloves can be worn as a precaution when opening and closing the gate.

2. Due to 60 Hz noise from surrounding equipment, a high sampling frequency should be used on the LabVIEW software or an anti-aliasing filter should be used.

3. Results of the sample test are typical. The means of the residuals are close to zero (based on the 95% confidence intervals) only for the first second of the flame. The semi-infinite assumption of the model breaks down for the four seconds of the test time. This is also evident in the large increase of standard deviation of the temperature residuals going from the one second to the four second time interval. Because of the small change in standard deviation of the heat flux residuals, it can be concluded that the data set is ergodic and the residuals are obtained from the sample population throughout the test period. This is not true for the temperature residuals.

4. The students should be able to identify that the calculation from the measured heat flux to the surface temperature (an integration type process) is preferable to the temperature to heat flux calculation (a differentiation type process).

REFERENCES

1. Diller, T. E., and Onishi, S.,"Heat Flux Gage," U.S. Patent No. 4,779,994, Issued 25 October 1988.

2. Hager, J. M., Onishi, S., Langley, L. W., and Diller, T. E., "High Temperature Heat Flux Measurements," **AIAA Journal of Thermophysics and Heat Transfer**, Vol. 7, 1993, pp. 531-534.

3. Hager, J. M., Simmons, S., Smith, D., Onishi, S., Langley, L. W., and Diller, T. E., "Experimental Performance of a Heat Flux Microsensor," **ASME Journal of Turbomachinery**, Vol. 113, 1991, pp. 246-250.

4. Diller, T. E., "Advances in Heat Flux Measurement," **Advances in Heat Transfer**, Vol. 23, 1993, pp. 279-368.

5. Baker, K. I. and Diller, T. E., "Unsteady Surface Heat Flux and Temperature Measurements," ASME Paper No. 93-HT-33, 1993.

SOURCES OF SUPPLIES

1. Heat Flux Microsensor - $1500, Vatell Corp., Blacksburg, VA 24060, (703) 961-3576
2. Heat Flux Amplifier Box - $1500, Vatell Corp., Blacksburg, VA 24060
3. Thermocouple read out - $100, TEGAM, Madison, OH 44057, (216) 428-7505
4. BernzOmatic 2-piece Propane Torch Kit, Model TS 2000K - $18, WalMart
5. LabVIEW - $500 (Educational discount), National Instruments
6. Elenco bread board - $35, Radio Shack
7. Macintosh Quadra 700 computer - $4,000, Apple Computer
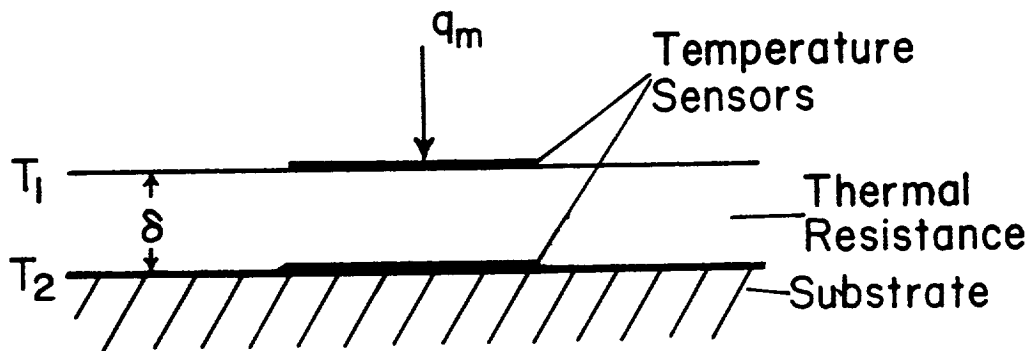8. Texas Instruments 741 OP-AMP - $1, Radio Shack

Fig. 1 Measurement Concept of Heat Flux Microsensor
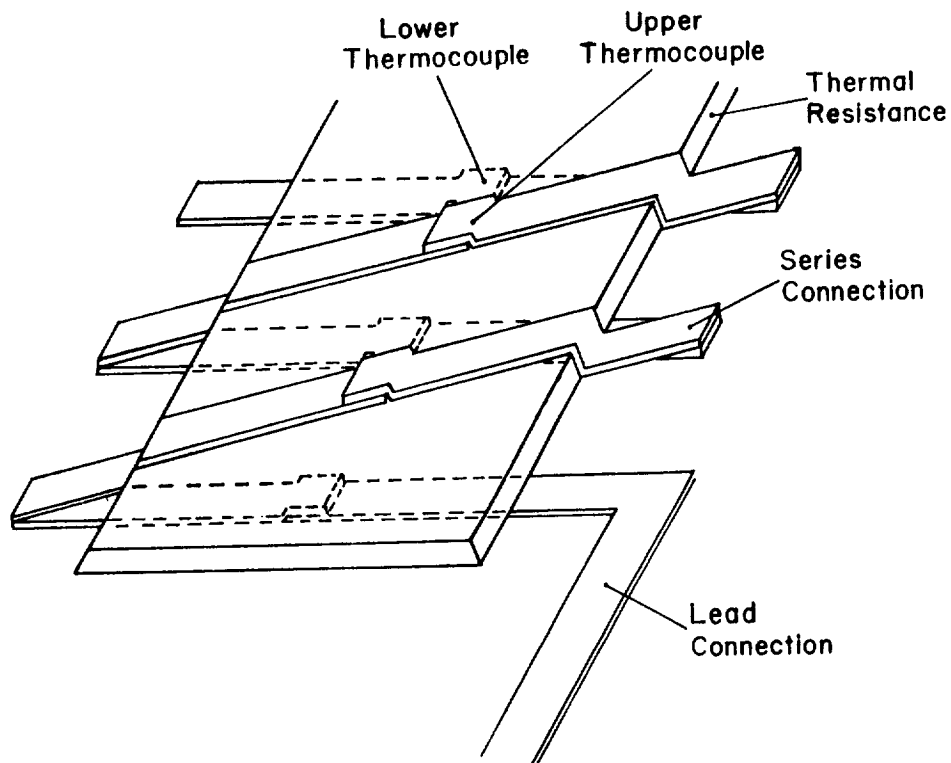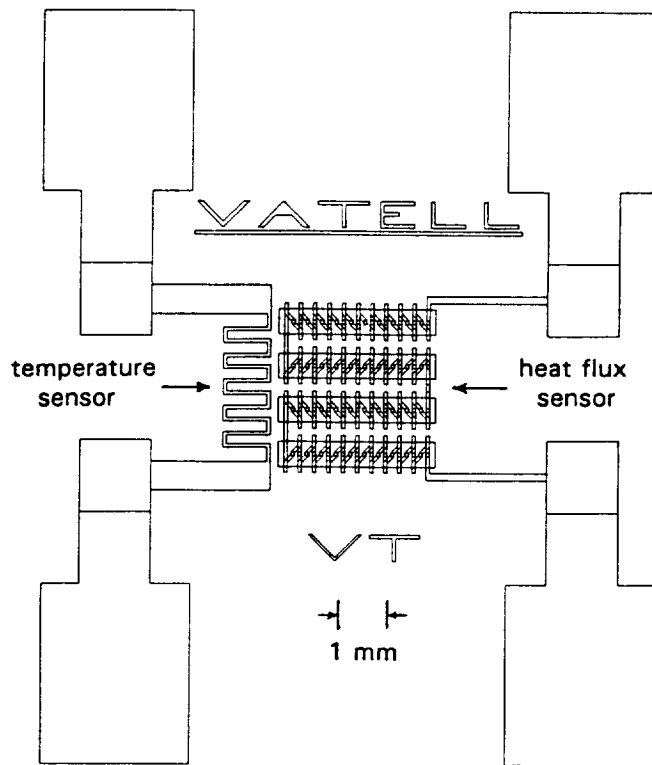

Fig. 2 Differential Thermopile

Fig. 3 Overlay Pattern of Heat Flux Microsensor
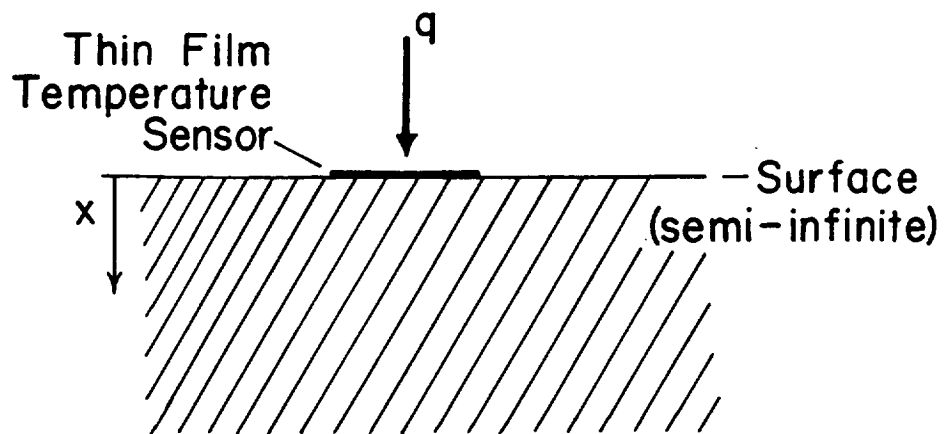

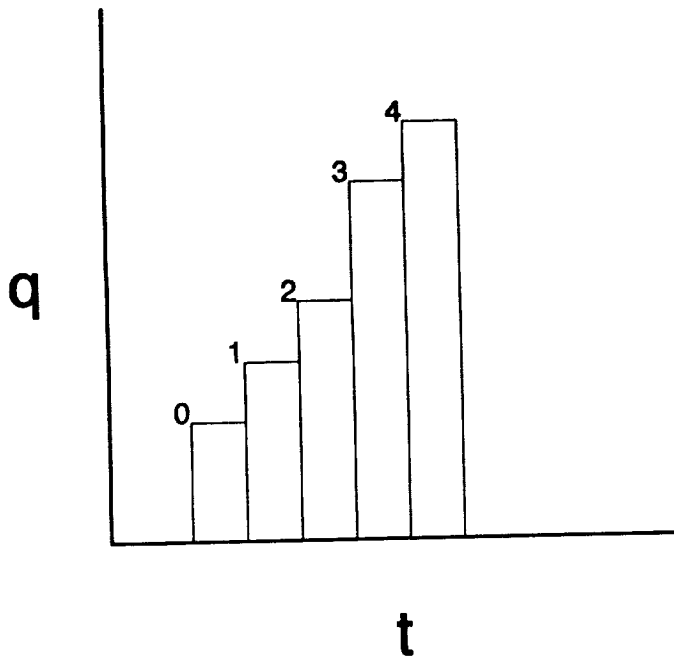Fig. 4 Semi-Infinite Conduction Geometry

Fig. 5 Impulse Representation of Heat Flux
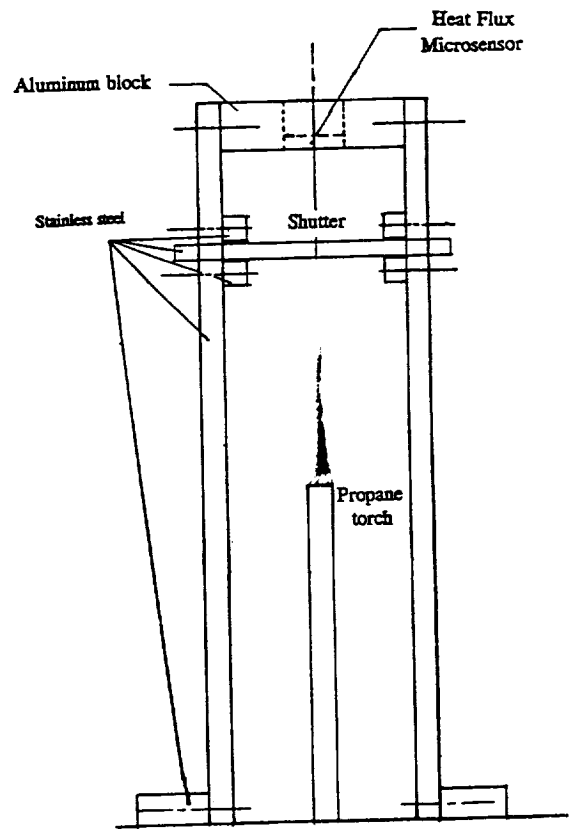

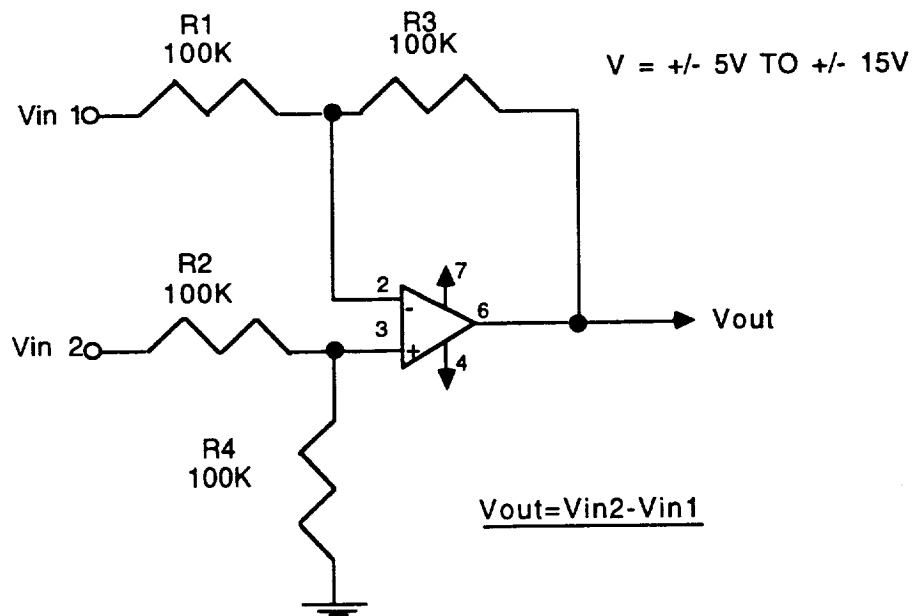Fig. 6 Experimental Flame Apparatus
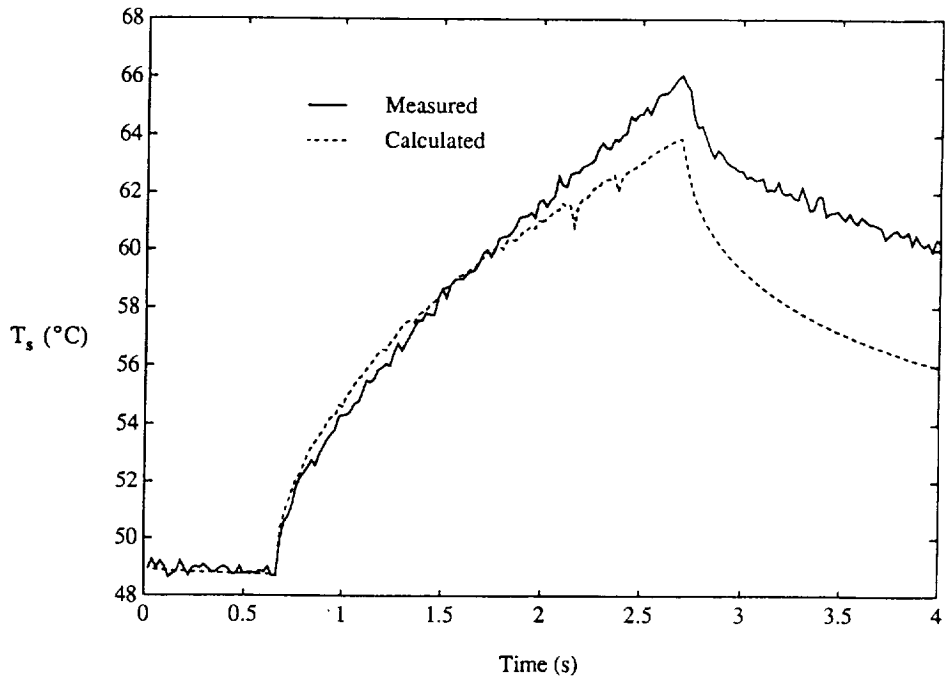

Fig. 7 Differential Amplifier

Fig. 8 Measured and Calculated Temperature
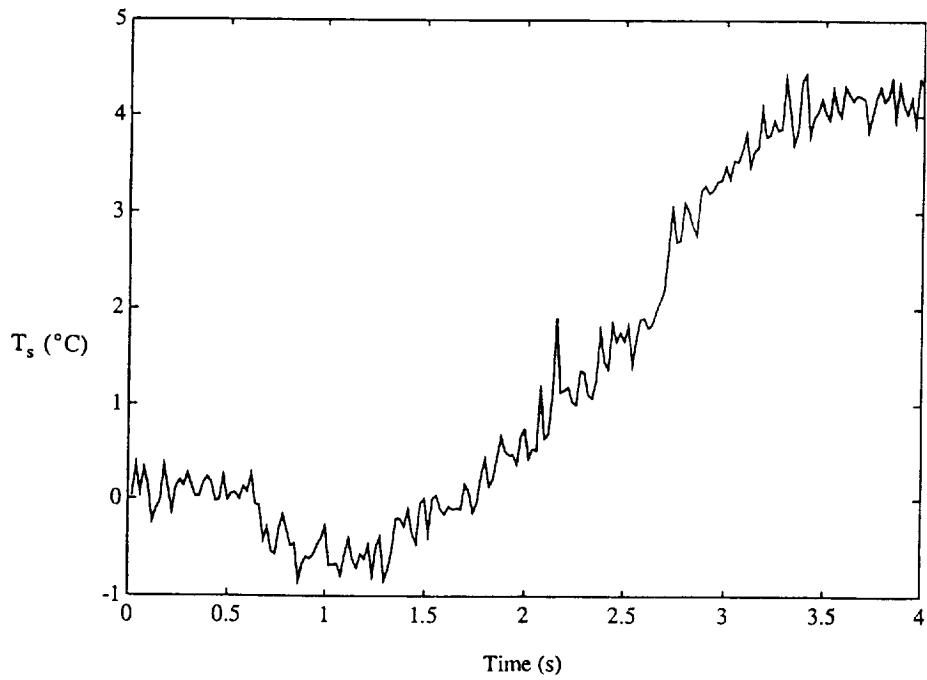

Fig. 9 Temperature Residuals (Meas.-Calc.)

Fig. 10   Measured and Calculated Heat Flux
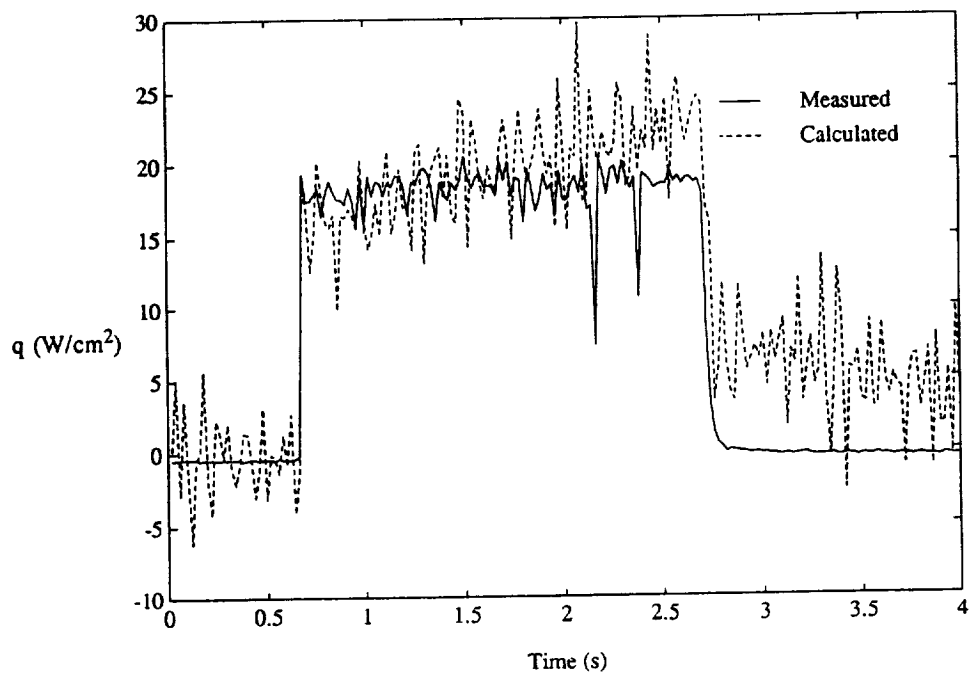

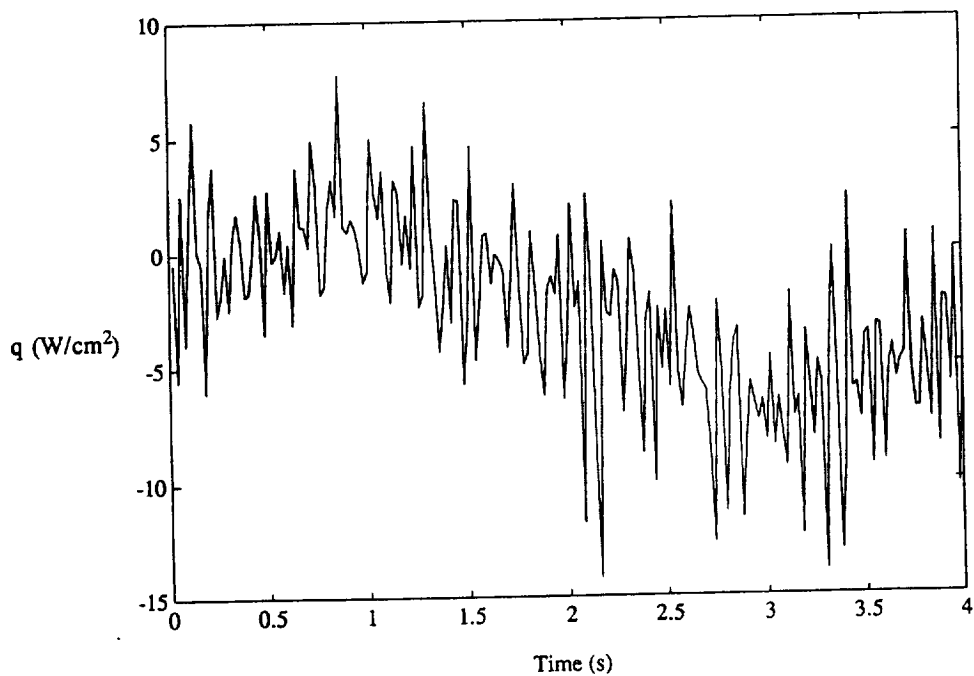Fig. 11   Heat Flux Residuals (Meas.-Calc.)

```
***********************************************************************
*     This program converts the voltages obtained from the heat flux         *
*     sensor to their corresponding heat flux and temperature                 *
*     responses. It also utilizes the Cook and Felderman method to            *
*     differentiate temperature with respect to time to obtain the            *
*     corresponding heat flux and Green's function to integrate the           *
*     heat flux with respect to time to yield temperature.  Variables         *
*     used are:                                                               *
*     K...thermal conductivity of resistance layer (W/cmK)                    *
*     RHO...density of resistance layer (kg/cm^3)                             *
*     CP...specific heat of resistance layer (J/kgK)                         *
*     S...sensitivity of sensor (mV/W/cm^2)                                   *
*     ALPHA...thermal property of resistance layer                           *
*     TIME()...time interval                                                  *
*     QVOLT()...voltage corresponding to measured heat flux                   *
*     TVOLT()...voltage corresponding to measured temperature                 *
*     QEXP()...heat flux calculated from experimental voltage                 *
*     TEXP()...temperature calculated from experimental voltage               *
*     QCALC()...heat flux calculated from temperature                         *
*     TCALC()...temperature calculated from heat flux                         *
*     TIMEF...number of data points taken                                     *
***********************************************************************


      REAL K, RHO, CP, S, ALPHA, TIME (201), QVOLT(201), TVOLT(201),
     +QEXP(201), TEXP(201), QCALC(201), TCALC(201)
      INTEGER TIMEF
      PARAMETER (PI=3.141592654)


***********************************************************************
*     The ASCII data file is opened and an output file is created             *
***********************************************************************


      OPEN (9, FILE = 'RUN3.DAT')
      OPEN (6, FILE = 'RUN3.OUT')


***********************************************************************
*     Definition of thermal properties of resistive layer                     *
***********************************************************************


      K=1.65
      RHO=3.29E-3
      CP=713
      S=23.1765
      ALPHA=K/RHO/CP
      TIMEF = 200


***********************************************************************
*     Do loop to read ASCII file and convert voltages to corresponding        *
*     heat flux and temperature values                                        *
***********************************************************************


      DO 1 I = 1, TIMEF
        READ (9, *) TIME(I), QVOLT(I), TVOLT(I)
        QEXP(I) = QVOLT(I)*1000/S
```

```
      TEXP(I) = 132.33*TVOLT(I)-286.06
1     CONTINUE


***********************************************************
*    Do loop to perform numerical expression developed by Cook and        *
*    Felderman to calculate heat flux from surface temperature            *
***********************************************************

      DO 2 M = 1, TIMEF
       QCALC(M) = 0
      DO 3 L = 2, M
       QCALC(M) = QCALC(M) + (TEXP(L) - TEXP(L-1))/(SQRT((M -L)*.02)
     + +SQRT((M-L+1)*.02))
3     CONTINUE
       QCALC(M) = 2.*SQRT(K*RHO*CP)/SQRT(PI)*QCALC(M)
2     CONTINUE


***********************************************************
*    Do loop to perform method of Green's function to calculate           *
*    temperature from heat flux and write all previously calculated       *
*    values to the output file created above                              *
***********************************************************

      DO 4 N = 1, TIMEF
       TCALC(N) = TEXP(1)
      DO 5 J = N, 1, -1
       IF (J.EQ.1) THEN
         TCALC(N) = TCALC(N) - 2.*SQRT(ALPHA)/K/SQRT(PI)*QEXP(J)
     +   *(SQRT(((N-.5)-(J-.5))*.02)-SQRT((N-.5)*.02))
       ELSE
         TCALC(N) = TCALC(N) -2.*SQRT(ALPHA)/K/SQRT(PI)*QEXP(J)
     +   *(SQRT(((N-.5)-(J-.5))*.02)-SQRT(((N-.5)-(J-1.5))*.02))
       ENDIF
5     CONTINUE
20    FORMAT (1X, F16.5, 2X, F16.5, 2X, F16.5, 2X, F12.8)
      WRITE (6, 20) QEXP(N), TEXP(N), QCALC(N), TCALC(N)
4     CONTINUE

      STOP
      END
```