Data Acquisition System for an Undergraduate Fin Heat Exchanger Experiment

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I. Introduction

In an effort to meet ABET requirements for utilizing Data Acquisition Systems (DAS) in thermal science, the Department of Mechanical Engineering at Loyola Marymount University has developed and incorporated a new experiment into the required junior-level thermal science laboratory course in mechanical engineering. The purpose of the experiment is to teach students what modern data acquisition systems are, and how a personal computer-based data acquisition system can be used to acquire, process and analyze data. The system under consideration consists of a 12"x12", 1620W (120V, 13.5A) Mirak[TM] hot plate, made by the Barnstead-Thermolyne Corporation, to which four different fins (one cylindrical, one conical, one rectangular, and one pyramidal) are attached in an upright position. Each fin is eight inches long, and a thermocouple is attached to the base of each fin, where the fin is mounted to the hot plate, as well as at one-inch intervals along the vertical axis of each fin. The thermocouples are connected to an input board that serves as an interface between the thermocouples and the data acquisition system.

The data acquisition system to be used is designed for the Windows PC, in conjunction with data acquisition hardware. The DAS uses the LabVIEW[1] graphical programming language to create Virtual Instruments (VIs). The software and the DAS hardware are produced by National Instruments.

In the study of heat transfer from extended surfaces, students can investigate the characteristics of heat exchangers, including heat balance, heat transfer coefficients, and Nusselt-Reynolds correlation. The temperature profiles of the various fins will be plotted and their efficiencies calculated and compared. It is hoped that the information presented will be useful to those interested in developing similar data acquisition and control experiments.

II. Objectives:

The main objectives of this experiment are as follows:
1. To use the DAS to record the temperature of each thermocouple along the length of each fin.
2. To plot the temperature against the distance X (measured from the base of the thermocouple) on a single graph.
3. To make a least-square fit to the data.
4. To determine the convection heat transfer coefficient of each fin.
5. To determine the effectiveness of each fin.

III. Theoretical Background

The overall theory involved in this experiment can be divided into two topics: principles of data acquisition systems, including an overview of the LabVIEW Virtual Instrument (VI), and the principles of heat transfer from extended surfaces. Each of these will be discussed in this section.

A. Principles of Data Acquisition Systems

The Data Acquisition System (DAS) can be defined as an electronic instrument or group of interconnected electronic hardware items, dedicated to the measurement and quantization of analog signals for digital analysis or processing. In this regard, the DAS is the analog interface to the digital world. A graphic picture of where the data acquisition system fits is given in Figure 1.
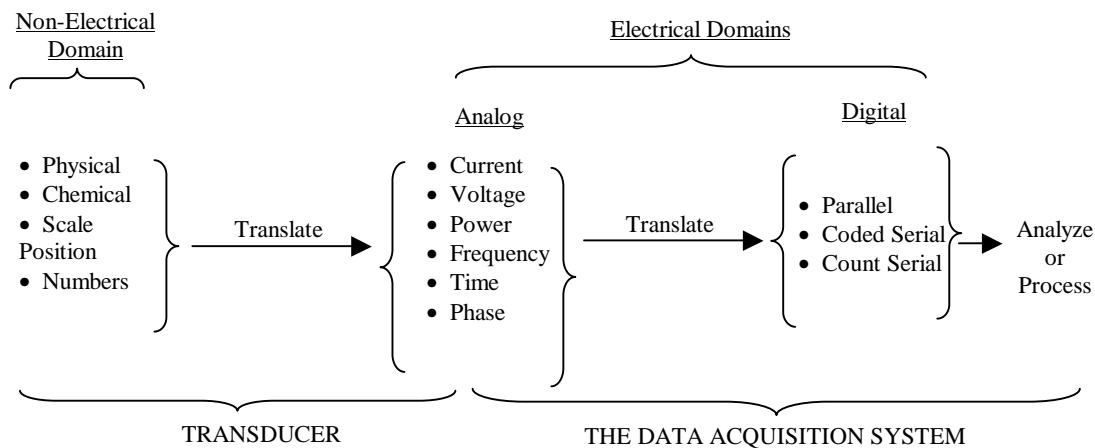

Figure 1: Where the Data Acquisition System Fits

Once the parameters to be measured are translated into the analog electrical domain, the DAS performs the translation to the digital-electrical domain. In some cases, the DAS simply records or stores the digital data while more advanced systems may do the analysis or further processing. For instance, a DAS may be as simple as a digital voltmeter (DVM) or it may be complex enough to contain a computer as part of its hardware. A block diagram of the microcomputer

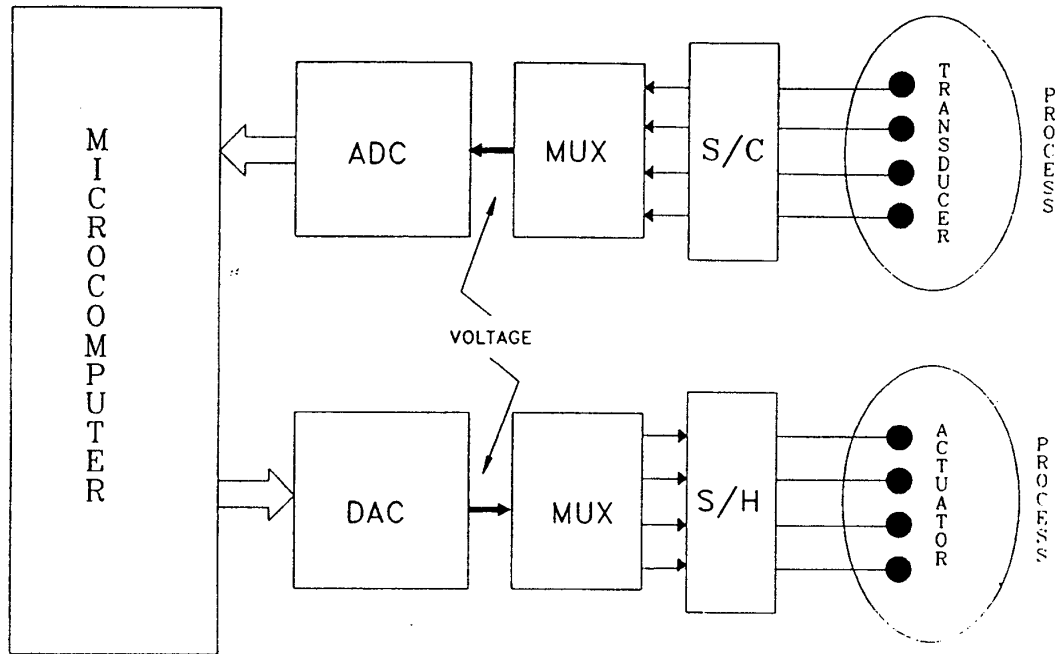based DAS and its functions can be seen in Figure 2. Figure 3 illustrates the DAS used in this experiment.

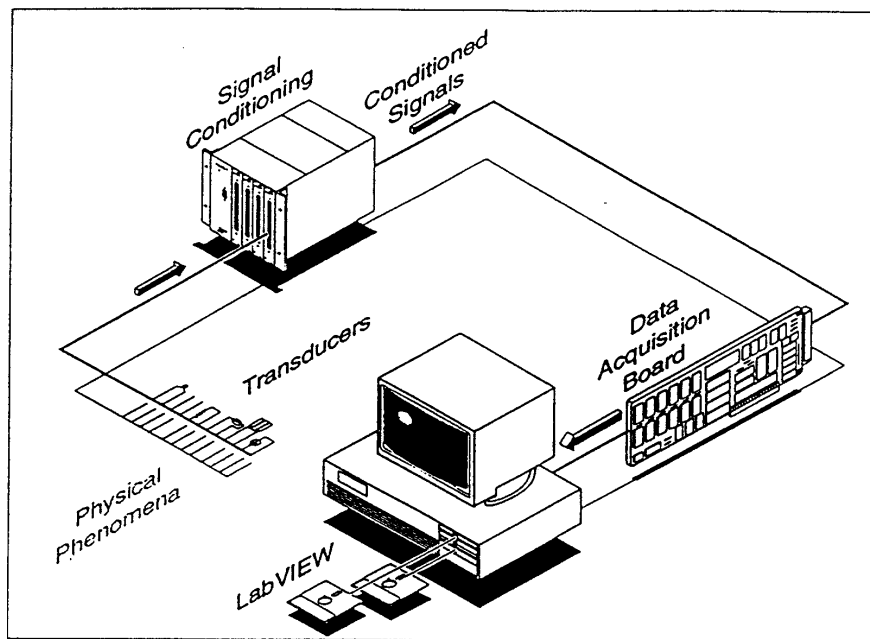Figure 2: Elements of a Microcomputer Control System

Figure 3: Data Acquisition System Components[1]

B. Introduction to LabVIEW VI[1]

Within the DAS, it is the LabVIEW Virtual Instrument (VI) that simplifies data acquisition. This powerful software program allows for the development of virtual instruments to read, interpret, and display the data read by the Data Acquisition System in a useful format such as a table or a graph.

The VI has two parts—the front panel and the diagram (Figures 4 and 5). The front panel displays the graphs and charts and includes buttons for controlling the DAS. The VI diagram is the mechanism that processes the sampled data and formats it so that it can be displayed by the front panel. By graphically editing these two parts of the VI, the user can modify both the function and the look of the VI.
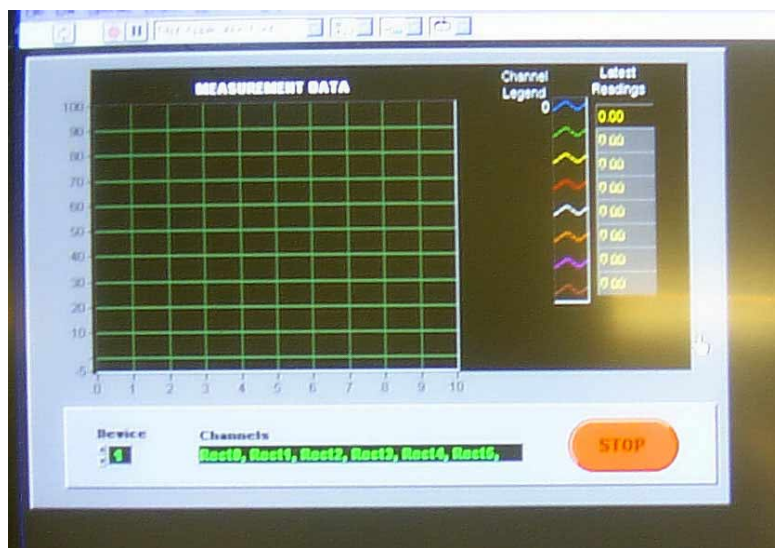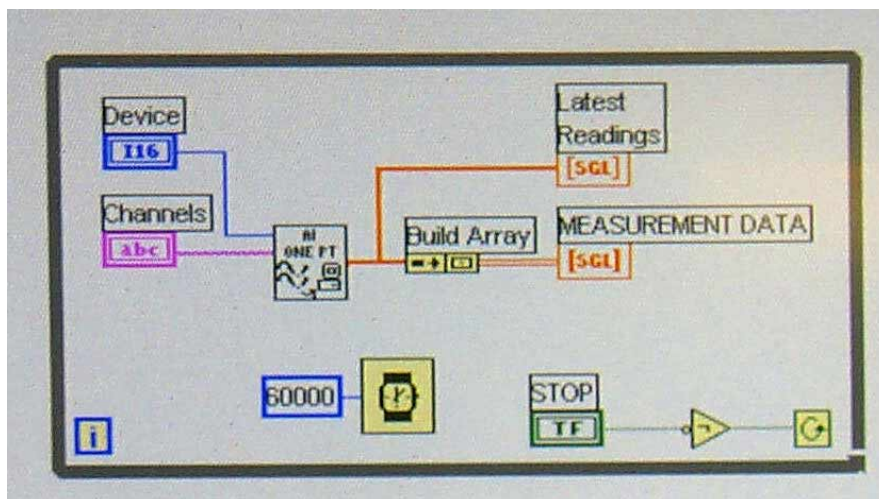

Figure 4: VI Front Panel

Figure 5: VI Diagram

C. Principles of Heat Transfer[2]

Extended surfaces (fins) are used to enhance the heat transfer rate between a solid and a surrounding fluid. This is accomplished by increasing the surface area available for convective heat transfer. The analysis of a fin can be simplified with the assumptions of one-dimensional steady state conduction, constant thermal conductivity, negligible surface radiation, and no heat generation.
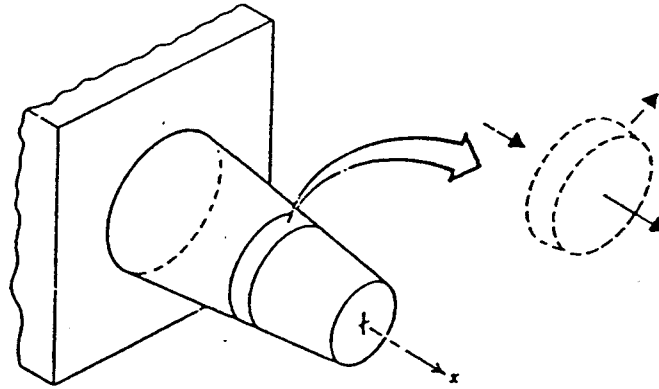

Figure 7: General extended surface

Figure 7 shows a fin extending from a flat plate along with an incremental control volume. Energy conservation requires that the difference in conduction heat transfer rates between the inlet and outlet of the control volume equal the convective heat transfer rate from the surface of the control volume to the surrounding fluid. That is,

$$q_I - q_L = q_{CONV} \tag{1}$$

where q_I = conduction heat flux at inlet to control volume, BTU/(hr-ft^2)
q_L = conduction heat flux at outlet to control volume, BTU/(hr-ft^2)
q_{CONV} = convection heat flux from surface of control volume, BTU/(hr-ft^2)

Using Fourier's law for one-dimensional conduction and Newton's law of convective cooling results in

$$h = \frac{\left[-k \cdot A_I \cdot \dfrac{dT}{dX_I} \right] - \left[-k \cdot A_L \cdot \dfrac{dT}{dX_L} \right]}{A_S (T_S - T_\infty)} \tag{2}$$

where h = convection heat transfer coefficient at fin surface, BTU/(hr-ft^2-°F)
k = thermal conductivity of fin material, BTU/(hr-ft^2-°F)
A_I = inlet cross sectional area, ft^2

dT/dX_I = temperature gradient at inlet, °F/ft
A_L = outlet cross sectional area, ft^2
dT/dX_L = temperature gradient at outlet, °F/ft
A_S = surface area of incremental control volume, ft.^{2}
T_S = surface temperature of element, °F
T_∞ = ambient fluid temperature, °F

Since flow conditions vary along the fin surface due to changes in the hydrodynamic and thermal boundary layers, equation (2) must be applied to each incremental control volume along the fin. The average convection coefficient about an entire fin is

$$h_F = \frac{1}{A_F} \sum (h \cdot A_S)$$ (3)

where h_F = average fin convection heat transfer coefficient, BTU/(hr-ft^2-°F)
       A_F = surface area of entire fin, ft^2

Fin effectiveness is defined as the ratio of the heat transfer rate from a fin mounted on a surface to the heat transfer rate that would exist from a base plate with surface area equal to the fin base cross sectional area. If it is assumed that the heat transfer coefficient for the base plate is equal to the average fin convection heat transfer coefficient given by equation (3), the fin effectiveness is

$$EFF = \frac{\sum A_S (T_S - T_\infty)}{A_B (T_B - T_\infty)}$$ (4)

where EFF = fin effectiveness
       A_B = hot plate surface area covered by fin, ft^2
       T_B = base plate temperature, °F

Fin effectiveness should be as large as possible and greater than two in order to be economically justifiable.

IV. Experimental Setup[3]

The experimental setup can be divided into two parts—the DAS setup and the VI setup. Each is described below.

A. DAS Setup

Four fins are to be analyzed in this experiment. They are fitted with thermocouples at one-inch intervals along their length so they can be partitioned into eight control volumes. Temperature gradients across the inlet area and across the outlet area for each control volume can be determined using recorded thermocouple measurements. The surrounding fluid is room temperature air.

As seen in Figure 8, the setup consists of a 1600W (120V, 13.3A) type 2200 Hot Plate (made by Thermoline Corp.) to which four fins have been attached. A rheostatic device controls the electrical power input to the plate. The arrangement can be operated in either horizontal or vertical orientation. The material, profile, and dimensions of the fins are as follows.

1. Cylindrical fin, brass, 0.75" diameter, 8" long.
2. Conical Fin, brass, 0.75" base diameter, 8" long.
3. Rectangular fin, stainless steel, 0.75" square base, 8" long.
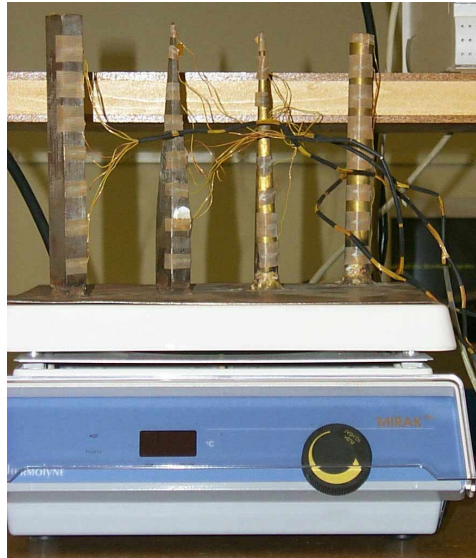4. Pyramidal fin, stainless steel, 0.75" square base, 8" long.

Figure 8: Hot Plate and Fin Setup

Each fin is fitted with nine copper-constantine thermocouples (Type K), one at the base, and the rest at one inch spacing along the length. The reference junction for all thermocouples is embedded in a steel block sitting on the table. The thermocouples are connected to a National Instruments Data Acquisition Board to permit automatic scanning and recording of temperatures.
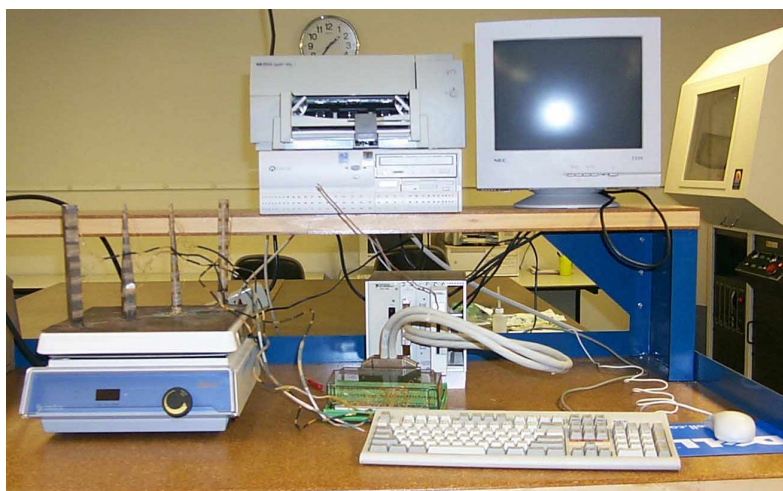

Figure 9: Complete Experiment Setup

Figure 9 shows a photograph of the complete experimental setup. The Data Acquisition Board used for this experiment is the National Instruments NBM1016 for the PC. This board is connected to a National Instruments SCXI 1000 chassis. This chassis allows for the use of several different signal-conditioning boards. Plugged into the SCXI 1000 is the SCXI 1100 module. This module can simultaneously sample signals from 32 differential thermocouples. The data acquired by this equipment is sent to the PC and is processed by the LabVIEW software produced by National Instruments.

B. VI Setup[1]

Before creating a VI, the DAS devices must be configured using NI-DAQ Configuration Tool, and the thermocouple channels need to be created and configured using the DAQ Channel Wizard (Figure 4). It's also a good idea to use the Channel Wizard to test each channel before proceeding[1]. Once these things have been done, the VI can be created as follows.
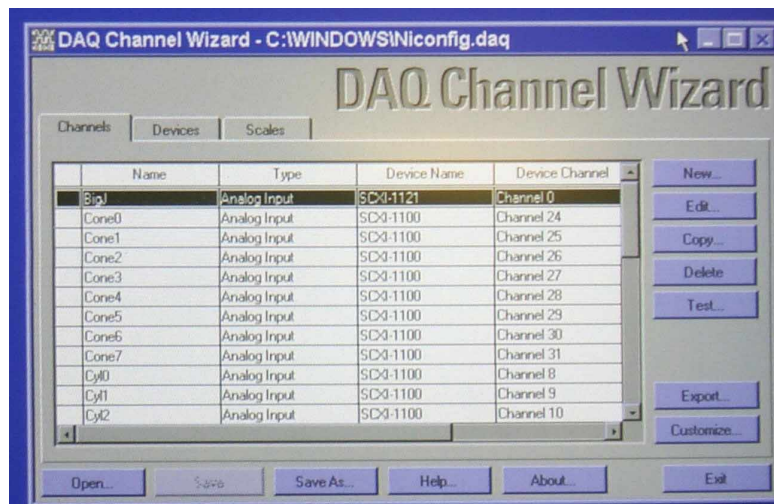

Figure 6: National Instruments DAQ Channel Wizard

1. Run LabVIEW to create a new VI.
2. Run the Solutions Wizard.
3. Select the DAQ Solutions Wizard.
4. Now, check the channels using the DAQ Channel Wizard. Then click "Next."
5. Using the Solutions Gallery select "Transducer Measurements" and Continuous thermocouple Measurement." Click Next.
6. Select a SCXI module (SCXI 1100, 1102, etc.) that is attached to the thermocouples.
7. Select the channels to be scanned (hold the Shift key to select multiple channels). You may wish to select the channels for just one Fin. Later, you can easily select channels for another fin and click "Open Solution" to create another VI for that fin.
8. Click "Open Solution."
9. Now that the VI is open choose "Show Diagram" form the "Windows" Menu. The diagram will open, and you can edit the timing interval (in milliseconds) by clicking on the value in the blue box to the left of the stopwatch icon (Note: To edit the diagram, the VI must not be running).

10. Close the diagram. The front panel will appear again.
11. Select "run" from the "Operate" menu to start collecting data.
12. The vertical and horizontal scales of the graph can be changed by simply clicking on an axis value and typing a new value. This can be done while the VI is running.

V. Procedure

The procedure for performing the experiment is as follows:
1. The hot plate is first powered-on using a specified power setting (DO NOT GO BEYOND 200°C), and the system is allowed to come to equilibrium.
2. Open LabVIEW and create the VI as described above.
4. The VI's block diagram is programmed to include a variable sampling rate. The sampling rate is set to five minutes to allow time to record the temperature readings before the next set of samples is taken.
5. The DAS is used to record the temperatures of thermocouples at several points in time so that an average measurement can be calculated for each thermocouple.
6. The temperature data are then analyzed for results.

VI. Results

Three sets of data were taken for each fin using LabVIEW. Then, using Excel, each set was averaged and fitted with a least-squares second order polynomial. Figure 10 compares the temperature at intervals along the length of each fin. Figures 11 through 14 show the temperature profile for each fin.
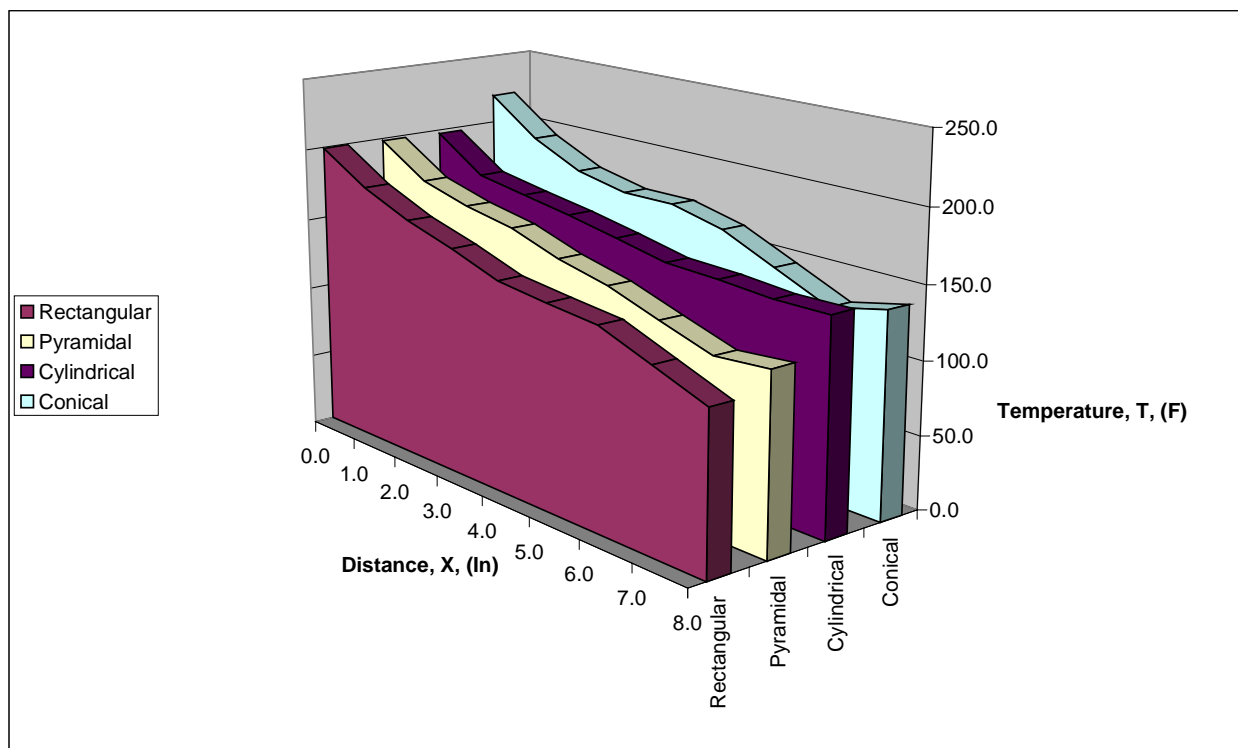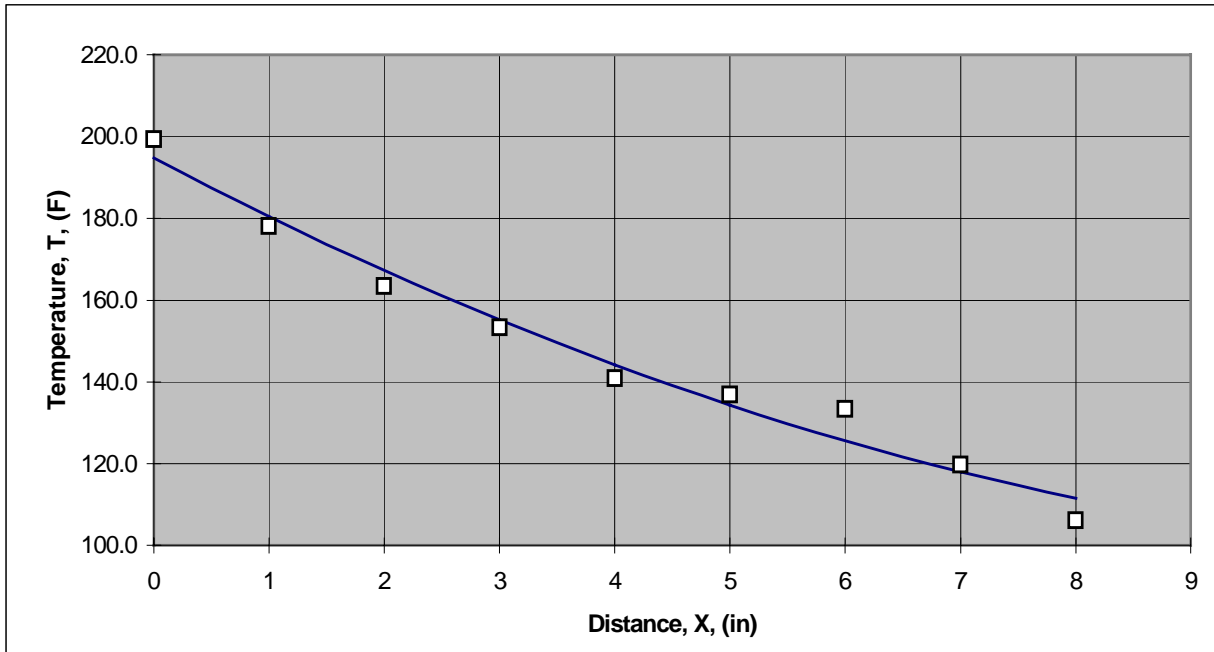

Figure 10: Average Temperature vs. X
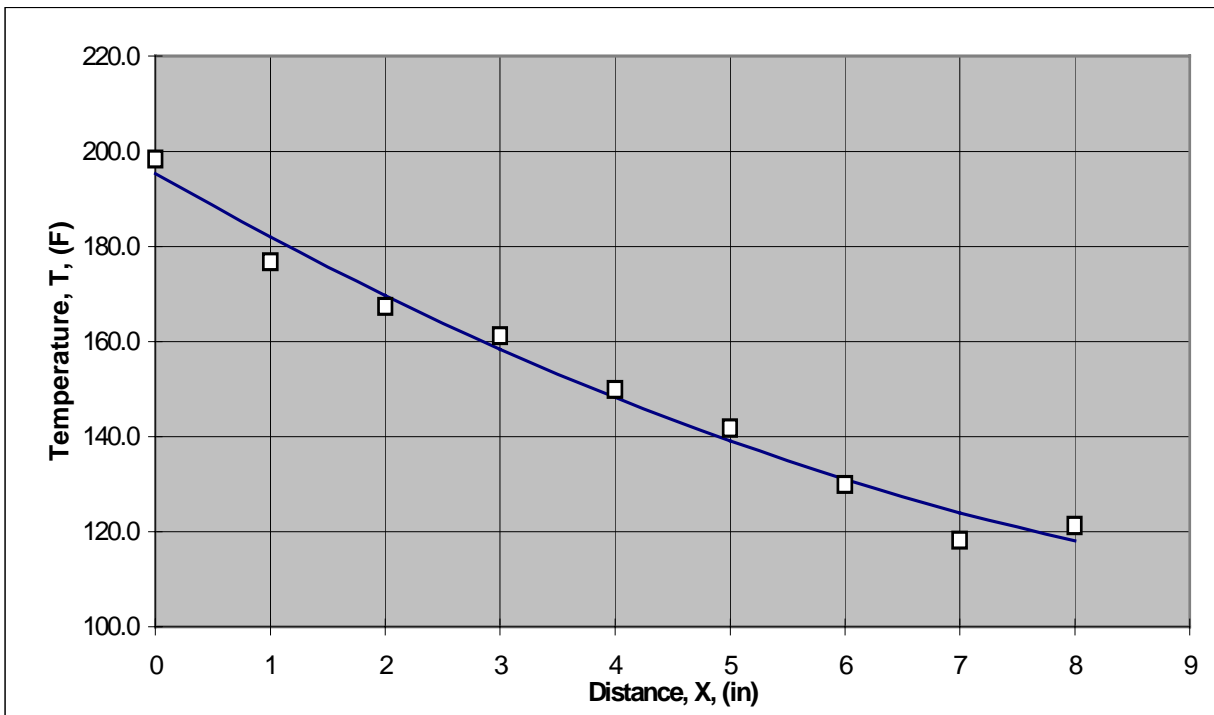
Figure 11: Rectangular Fin, Average

Figure 12: Pyramidal Fin, Average

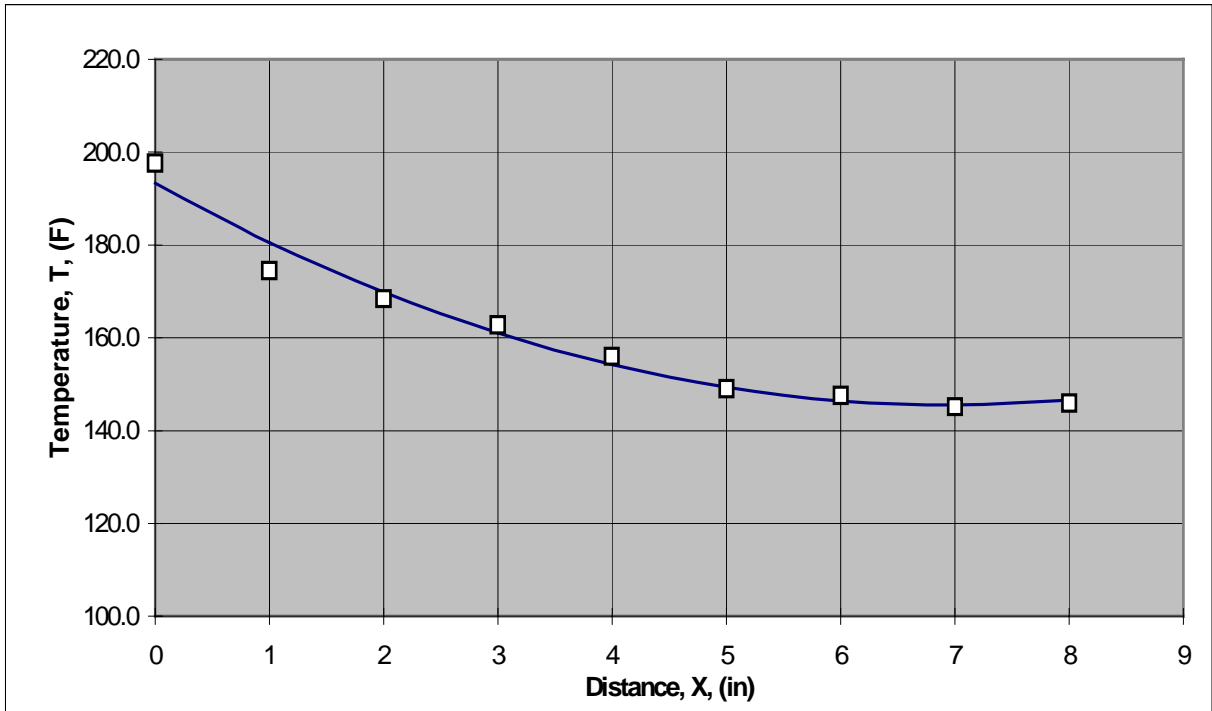Figure 13: Conical Fin, Average

Figure 14: Cylindrical Fin, Average

The results for average heat transfer coefficient and effectiveness are shown in Table 1. Using Excel, these results were calculated from the data in the figures, the equations and dimensions in the text, and the following parameter values:

k(stainless steel) = 8.29 BTU/hr-ft-°F
k(brass) = 64.1 BTU/hr-ft-°F

TABLE 1: Fin Parameters from Measured Data

Fin Shape	Heat Transfer Coefficient	Fin Effectiveness
Rectangular	0.26	22.1
Pyramidal	0.81	13.2
Conical	5.50	15.6
Cylindrical	3.35	25.1

The base plate temperature was 220.1 °F. With good thermal contact it would be reasonable to assume that the bases of the fins were at the same temperature as the base plate. Inspection of the data and experimental setup indicated that this was true only for the conical fin. Therefore the base temperatures of the other fins have been estimated to be approximately the average between the base and first thermocouple temperature.

Inspection of Figures 11 through 14 shows that the data are not entirely consistent. A higher-order polynomial would have made a better fit, but would have introduced physically unreasonable fluctuations in the curves. The disparity in the values of the heat transfer coefficients is due largely to the difference in thermal conductivity of the two materials. The large values for fin effectiveness are a result of the large surface area to base area ratio in equation (8).

VII. Discussion and Conclusions

The main purpose of the experiment was to get acquainted with the Data Acquisition System and how to make automatic temperature measurements of extended surfaces. From the measured data, the heat transfer coefficients and effectiveness of various fins were calculated. Several factors impaired the accuracy of the data. Some of the thermocouples were not firmly attached to the fins. Better shielding of radiation and convection from the base plate is needed. Random error in the electronics, material variation in the thermocouple and the geometry of the fins might have also contributed to the inconsistency of data.

VIII. References

1. *LabVIEW and Data Acquisition*. National Instruments. January 1994 Edition. Part No. 320628-01. Austin, Texas.

2. F.P. Incropera and D.P. Dewitt. *Introduction to Heat Transfer*, 2nd Edition. New York: Wiley.
3. Gonzaga University. *Mechanical Engineering Laboratory Manual*. 1989. Spokane, WA: Gonzaga University.

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As an electrical engineer, Rudolf Marloth worked for many years in the defense industry, primarily at Hughes Aircraft. He recently received an M.S. in Mechanical Engineering from LMU and is pleased to continue his association with students and faculty by working on projects like this.

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