Integration a Design of Experiment in the Heat Transfer Laboratory

Hosni I. Abu-Mulaweh
Department of Engineering
Indiana University-Purdue University at Fort Wayne
Fort Wayne, IN 46805, USA

Abstract

The Design-Build-Test approach was used in developing an experiment for a junior-level heat transfer laboratory. In this experiment, student teams design, build, and test a fin attachment to increase the heat loss from a surface. In the testing phase, the students get the opportunity to compare the measured temperature profiles in the fin to both analytical and numerical (finite difference) solutions. This kind of experience enhances the understanding of the transfer of thermal energy by undergraduate mechanical engineering students and exposes them to several important concepts in heat transfer.

I. Introduction

The Design-Build-Test (DBT) concept has, recently, been used in undergraduate engineering laboratories [1, 2] and also in capstone senior design projects in which students design, develop, build, and test [3]. Traditional undergraduate heat transfer laboratories in mechanical engineering expose the students to heat transfer concepts presented in lecture classes, but do not provide them with design experiences similar to what they might face as thermal engineers in industrial positions. In addition, the Accreditation Board for Engineering and Technology (ABET) accreditation criteria requires that graduates of engineering programs possess “an ability to design and conduct experiments, as well as to analyze and interpret data” [4] and “an ability to design a system, component or process to meet desired needs” [4]. To meet the requirements of this ABET accreditation criteria, the faculty of the mechanical engineering program at Indiana University-Purdue University Fort Wayne has begun the development of DBT experiments in all required laboratories of the mechanical engineering program. The faculty believes that this approach would enhance and add another dimension to the teaching/learning experience in a laboratory course. One of the first DBT experiments to be developed was a fin attachment design experiment is presented in this paper. A prototype of this experimental apparatus is shown in Figure 1.

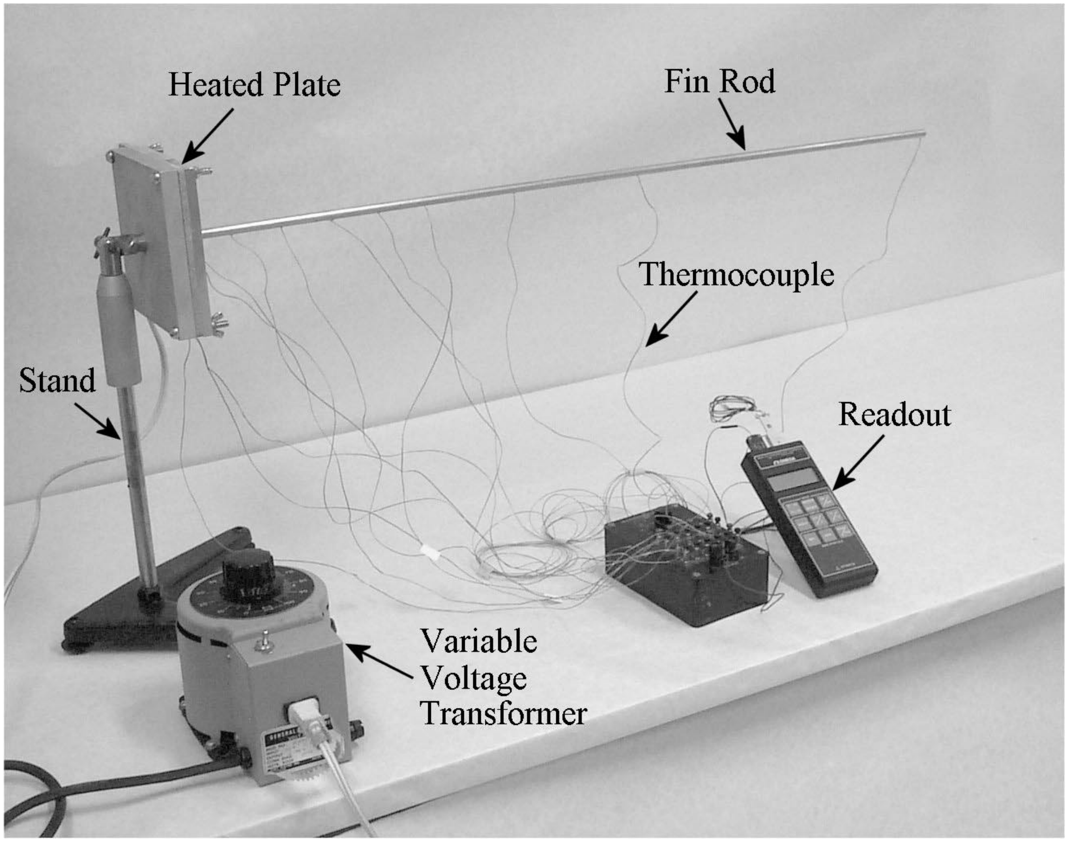

Figure 1: Fin Attachment Experimental Apparatus

II. Equipment and Instruments

- Constant-temperature heated surface. This heated surface is made of four composite layers that are held together by screws. The upper layer is an aluminum plate. The second layer consists of a heating pad that can be controlled for electrical energy input. The third layer is a Transite insulating material. The bottom layer of the heated plate is another aluminum plate to serve as backing and support for the heated plate structure.

- Circular rods of different materials (aluminum, copper, and steel) and different diameters.

- A short stand for mounting the fin attachment.

- A variable voltage transformer to adjust and control the level of electrical energy to the heating pads.

- Thermocouples and readout.

III. Problem Statement

- Student teams are instructed to design, develop, and construct a portable fin experimental apparatus for the undergraduate heat transfer laboratory that meets the following requirements and specifications:

1. The fin rod must be just long enough for the temperature of the tip of the fin to be the same as the temperature of the adjacent air.
2. The fin rod material is either, aluminum, copper, or steel.
3. The fin rod must be able to dissipate a given amount of heat (say, for example, 5 Watts) from a surface maintained at a known constant temperature (say, for example, 120^{o}C).
4. The fin rod is to be instrumented with thermocouples to allow for comparison with theory learned in lecture class.

- Student teams are given the following data: the amount of heat, Q_f, that need to be dissipated from the heated surface by the fin and the temperature, T_o, at which the surface is to be kept along with the ambient temperature, T_∞.

  It should be noted that every student team is assigned a different set of these values. Student teams do not repeat the same experiment that was done by a previous team. This is an indication of the flexibility of the experiment.

- Once the experiment is assembled, the student teams are required to test it by performing out the experiment and comparing the measured data with theory (analytical and numerical solutions) and present their results in a written report.

IV. Design Process

The team has to decide on the fin rod material (i.e., thermal conductivity, k, is now known) and determine, from literature, the proper value for the convective heat transfer coefficient, h. Once k and h are known, they can calculate, using equation 1, the diameter of the fin rod that will be able to dissipate the assigned value of heat, Q_f, from the heated surface to keep it at the assigned temperature value, T_o.

$$Q_f = \sqrt{hPkA_c}\,(T_o - T_\infty) \qquad (1)$$

Where, $A_c = \pi D^2/4$ is cross-sectional area, and $P = \pi D$ is the perimeter.

Equation 1 above is valid when the tip of the fin is at the same temperature as the adjacent fluid (i.e., the infinitely long). According to Mills [5] this condition is achieved when mL is larger than about 4.

Where $m = \sqrt{\frac{hP}{kA_c}}$ and L is the length of the fin rod. From this information they can determine the right length of the fin rod. It should be noted here that with mL > 4, the fin efficiency, $\eta_{longfin} = \frac{1}{mL}$, would be less than 25%.

V. Building and Testing Process

Once a design is approved by the laboratory instructor, the student team assembles the experimental apparatus and makes the necessary connections.

The experimental procedure is very simple, quick, and straight forward to carry out. First, turn on the energy source and adjust the electrical energy input to the desired heating level using the variable voltage transformer. Second, when the system reaches steady-state conditions, measure the axial temperature distribution, T(x), of the rod. In addition, measure the surrounding air temperature, T_∞, using the portable thermocouple.

After performing the experiment, the measured data is compared with results from theory. For the current fin case under consideration, the analytical temperature distribution, in any standard heat transfer textbook such as Incropera and DeWitt [6] and Özisik [7], is given by:

$$T(x) - T_\infty = (T_o - T_\infty)\exp(-mx) \qquad (2)$$

The numerical scheme that the students are asked to use is finite-difference method. The finite-difference numerical scheme is described by Fox [8], Dusinberre [9], and Forsythe and Wasow [10]. In this method, the partial differential equation of heat conduction is approximated by a set of algebraic equations for temperature at a number of nodal points. Therefore, the first step in the analysis is the transformation of the differential equation of heat conduction in the fin into a set of algebraic equations (i.e., obtain the finite-difference representation of the partial differential equation). This can be done considering an energy balance for a typical internal node of fin rod. It should be noted that the temperatures at the boundaries are prescribed; that is $T(0) = T_o$ and $T(L) = T_\infty$. The rod is divided into N subregions, each $\Delta x = L/N$, and denote the node temperature by T_n, n = 0, 1, 2, …, N, as shown in Fig. 2. The resulting general form of the finite-difference equation for the internal nodes (i.e., n = 1, 2, …, N-1) is

$$\frac{kA_c}{\Delta x}(T_{n-1} - T_n) + \frac{kA_c}{\Delta x}(T_{n+1} - T_n) + hP\Delta x(T_\infty - T_n) = 0 \qquad (3)$$

The simultaneous algebraic equations for temperatures at the nodal points can be solved by Gaussian elimination method, Gauss-Seidel Iteration, or by matrix inversion method. Computer programs for the solution of the simultaneous algebraic equations using these schemes are found in Özisik [7].

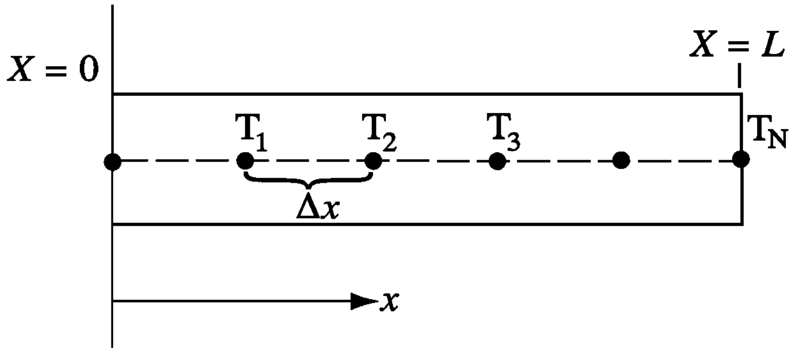

Figure 2: Nomenclature for finite-difference nodes.

VI. Implementation

This design of experiment is planned to be integrated into the junior level heat transfer laboratory in the spring of 2003. Each student team will be given a handout that describes the nature of the experiment, their design objective (see Problem Statement section above), and safety considerations. The student team will be asked to perform the design calculation first, to check with their laboratory instructor about their design and demonstrate to the instructor that their design met the objectives prior to beginning the actual assembly of components. The recommended time table for the student teams to complete this project satisfactorily is the following: Each student team will have two laboratory periods to complete the experiment. The first period will be spent designing the system and the second in building and testing their design. Then, they will be asked to submit their results in a written report after one week.

VII. Conclusion

A design of experiment for the undergraduate heat transfer laboratory was developed for the students in the Mechanical Engineering program at Indiana University-Purdue University Fort Wayne. In this experiment, student teams design, build, and test a fin attachment to increase the heat loss from a surface. This experiment is relatively an easy-to-implement experiment. In addition, the experimental setup is relatively simple and the needed equipments are relatively inexpensive and they are available in almost all undergraduate heat transfer laboratory.

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HOSNI I. ABU-MULAWEH

Hosni I. Abu-Mulaweh is an Associate Professor of Mechanical Engineering at Indiana University-Purdue University, Fort Wayne, Indiana. He earned his B.S., M.S., and Ph.D. in Mechanical Engineering from the University of Missouri-Rolla, Rolla, Missouri. His areas of interest are Heat Transfer, Thermodynamics, and Fluid Mechanics.