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Integration of the Design-Build-Test concept in an undergraduate heat transfer laboratory

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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 in order to increase the heat loss from a surface. In the testing phase, 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 serves to enhance the understanding of the transfer of thermal energy by undergraduate mechanical engineering students, while also facilitating to expose them to several important concepts involved in heat transfer.

INTRODUCTION

Heat transfer is a very important subject and has long been an essential part of mechanical engineering curricula all over the world. Heat transfer is encountered in a wide variety of engineering applications where heating and cooling is required. Heat transfer plays an important role in the design of many devices, such as spacecrafts, radiators, heating and air conditioning systems, refrigerators, power plants, as well as many other applications.

The Design-Build-Test (DBT) concept has, recently, been used in undergraduate engineering laboratories [1][2]. It has also been utilised in capstone senior design projects in which students design, develop, build and test [3]. Traditional undergraduate heat transfer laboratories in mechanical engineering expose 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 require that graduates of engineering programs possess *an ability to design and conduct experiments, as well as to analyse and interpret data* … [and] … *an ability to design a system, component or process to meet desired needs* [4]. To meet the requirements of these ABET accreditation criteria, the faculty of the Mechanical Engineering programme at Indiana University-Purdue University Fort Wayne, Fort Wayne, USA, has begun the development of DBT experiments in all required laboratories of the Mechanical Engineering programme. 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; this is presented in the article. A prototype of this experimental apparatus is shown in Figure 1.

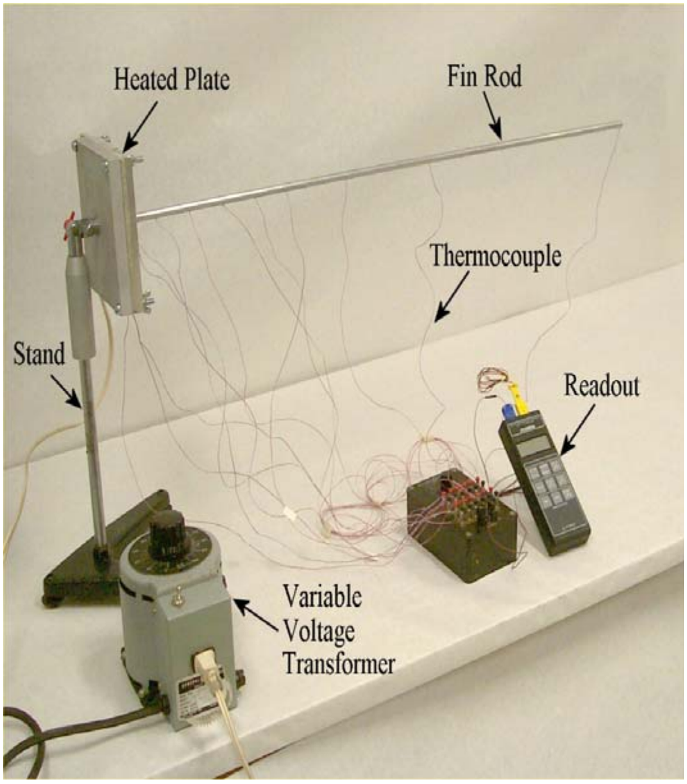

Figure 1: Fin attachment experimental apparatus.

EQUIPMENT AND INSTRUMENTS

The equipment and instruments utilised were as follows:

- Constant-temperature heated surface: this heated surface was made of four composite layers that were held together by screws. The upper layer was an aluminium plate, while the second layer consisted of a heating pad that could be controlled for electrical energy input. The third layer was a Transite insulating material, while the bottom layer of the heated plate was another aluminium plate that served as backing and support for the heated plate structure.

- Circular rods of different materials (aluminium, 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 delivered to the heating pads.
- Thermocouples and a readout.

PROBLEM STATEMENT

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

- The fin rod must have been just long enough for the temperature of the tip of the fin to be the same as the temperature of the adjacent air.
- The fin rod material was composed of aluminium, copper or steel.
- The fin rod had to 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°C).
- The fin rod had to be instrumented with thermocouples to allow for comparison with the theory learned in the lecture class.

Student teams were 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 was assigned a different set of these values. Student teams are not to repeat the same experiment carried out by a previous team. This is an indication of the flexibility of the experiment.

Once the experiment was assembled, student teams were required to test it by performing out the experiment and comparing the measured data with the theory (analytical and numerical solutions). Their results then had to be presented in a written report.

DESIGN PROCESS

The team had to decide on the fin rod material (ie thermal conductivity, k, is now known) and determine the proper value for the convective heat transfer coefficient, h.

Once k and h are known, students could calculate, using equation 1, the diameter of the fin rod that would be able to dissipate the assigned value of heat, Q_f, from the heated surface, in order 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) is valid when the tip of the fin is at the same temperature as the adjacent fluid (ie the infinitely long). According to Mills this condition is achieved when mL is larger than about 4 [5].

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

One important parameter that is involved in the design of such fin attachment is the heat transfer coefficient. However, values for the heat transfer coefficient associated with this kind of engineering application (ie fin attachment) are not readily available in the literature. This is because the relations for heat transfer coefficient associated with circular rods that can be found in the literature are based on either a uniform surface temperature or a uniform surface heat flux. The fins, by nature, exhibit a decaying *exponential* temperature distribution (not uniform).

In addition, the heat transfer coefficient relations available in the literature are applicable only for the case of pure natural convection in *still air*. The fin attachment is designed for real life applications where the *still air* condition does not exist. Moreover, the heat transfer coefficient relations in the literature are for convection only. Also, the heat dissipated by the fin is through both convection and radiation.

Because of the lack of heat transfer coefficient correlations for this kind of application (ie the design of fin attachment) the author has experimentally developed the following correlation equation for the average heat transfer coefficient associated with horizontally oriented circular fin rods that account for the effects of both modes of heat transfer (convection and radiation):

$$h = 17.1 - 0.664D \qquad (2)$$

where D is the fin diameter in mm and h is the average heat transfer coefficient in $W/m^2.^oC$.

The fin rod diameter range used in establishing the correlation equation (2) is $3.18\ mm \le D \le 12.7\ mm$. The empirical correlation equation (2) predicts the measured average heat transfer coefficient to within 10%.

BUILDING AND TESTING PROCESS

Once a design is approved by the laboratory instructor, the student team then assembled the experimental apparatus and made the necessary connections.

The experimental procedure was designed to be very simple, quick, and straightforward to carry out. First, the energy source had to be turned on and the electrical energy input was adjusted to the desired heating level by using the variable voltage transformer. Second, when the system reached steady-state conditions, the axial temperature distribution, T(x), of the rod was measured. In addition, the surrounding air temperature, T_∞, was determined by utilising the portable thermocouple.

After performing the experiment, the measured data is compared with the results obtained 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] or Özisik [7], is given by:

$$T(x) - T_\infty = (T_o - T_\infty)\exp(-mx) \tag{3}$$

The numerical scheme that students were asked to use was the finite-difference method. The finite-difference numerical scheme is described elsewhere by Fox, Dusinberre, and Forsythe and Wasow [8-10]. In this method, the partial differential equation of heat conduction can be approximated by applying 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 (ie obtain the finite-difference representation of the partial differential equation). This can be carried out 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 the node temperature denoted by T_n, n = 0, 1, 2, …, N, as shown in Figure 2. The resulting general form of the finite-difference equation for the internal nodes (ie n = 1, 2, …, N-1) is as follows:

$$\frac{kA_c}{\Delta x}(T_{n-1} - T_n) + \frac{kA_c}{\Delta x}(T_{n+1} - T_n) + hP\Delta x(T_\infty - T_n) = 0 \tag{4}$$

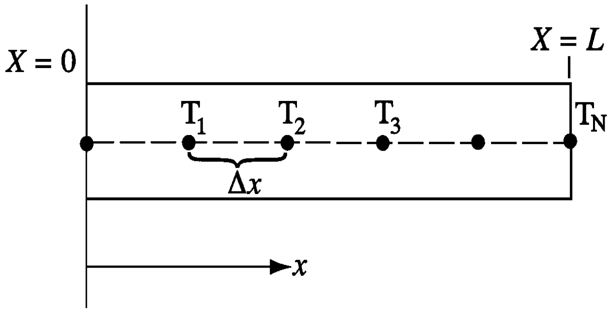

Figure 2: Nomenclature for finite-difference nodes.

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

IMPLEMENTATION

This design of the experiment was scheduled to be integrated into the junior level heat transfer laboratory in spring 2003. Each student team was given a handout that described the nature of the experiment, their design objective (see Problem Statement section above), as well as the safety considerations.

The student team was 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 timetable for the student teams to complete this project satisfactorily was the following: Each student team had two laboratory periods to complete the experiment. The first period was spent on designing the system, while the second incorporated building and testing their design. Then, they were asked to submit their results in a written report after one week.

CONCLUSION

A design of experiment for the undergraduate heat transfer laboratory was developed for the students in the Mechanical Engineering programme 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 set-up is relatively simple and the needed equipments are relatively inexpensive and they are available in almost all undergraduate heat transfer laboratories.

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