The Use of Hands-On Table-Top Laboratories in Undergraduate Thermal-Fluid Science Courses

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ABSTRACT

The laboratory components of two upper level mechanical engineering thermal-fluid science courses at Union College were re-designed to use "table-top" experiments. The table-top lab setups allow the students to work simultaneously in groups of 2 or 3. The advantage of this approach is that the students participate actively in each lab (as opposed to "watch" the labs), they get hands-on experience with the phenomena under study, they control and use the data acquisition system, and the group interaction (between the 4-5 groups) appears to help motivate the students. As part of this redesign we designed and built a set of table-top wind tunnel systems each equipped with instrumentation for measuring flow velocity, pressure and temperature. The purpose of this paper is to describe these systems, to describe three lab exercises that use these systems, and to present some typical results.

INTRODUCTION

The engineering programs at Union College have recently been redesigned under a major grant from the GE Foundation. A college wide task force was formed, and after extensive work, a common core in engineering was developed. Concurrent to this effort, the Mechanical Engineering Department undertook a substantial review of the mechanical engineering program. The new mechanical engineering curriculum, which follows the common core in engineering and computer science through the first year and then branches into a mechanical engineering specific curriculum, contains both restructured and new courses. The philosophy of the program, which has been ABET 2000 accredited, is to build a strong foundation, emphasizing the fundamentals in both the mechanics and thermal-fluid science sides of the discipline reinforced by significant laboratory and design experiences for the students. The new mechanical engineering curriculum employs a model of experiential learning across the curriculum emphasizing hands-on design and lab work in most courses. More than 50% of the engineering courses have a laboratory component. It is generally felt that there is a high pedagogical value in hands-on experiences for students.

In the area of facilities, we also developed a new studio classroom for teaching core mechanical engineering courses. The new studio classroom consists of 12 two-person work stations (networked computer, lab set-up area, table, chairs) with an instructor’s unit and a large video display screen located at the front of the room. The computers are equipped with general purpose data acquisition boards which can be used to measure temperature and voltage.

Two of the thermal-fluid science courses, fluid mechanics and heat transfer, have been redesigned to take advantage of these electronic resources and to implement hands-on lab exercises. Both courses are taught to third year mechanical engineering students and each consists of 40 classroom lecture hours plus weekly 3-hour labs[1]. In the past, these courses used "canned" lab exercises with "store bought, off-the-shelf" equipment. Data was generally acquired as a group because we were limited to a single rather expensive set up for each lab. These labs operated in a demonstration mode rather than an inquiry-driven laboratory mode. To remedy this situation we developed a set of relatively inexpensive table top lab setups to be interfaced to the studio classroom data acquisition systems. The "table top" lab setups allow for more team-based learning by the students. They work simultaneously in groups of 2 or 3 (by simultaneously we mean that 4-5 groups of 2-3 students work on the labs at the same time). The advantage of this approach is that each student participates more actively in the lab (as opposed to having each student "watch" the lab). They get hands on experience with the phenomena under study and with data acquisition techniques, and the group interaction (between the 4-5 groups) appears to help motivate the students.

The "table-top" fluid mechanics experiments include an introduction to fluid property measurements, hydrostatics, transducer calibration and the study of a cylinder in cross flow. The heat transfer "table-top" experiments include an introduction to temperature measurement techniques, an introduction to computer modeling, transient and steady state conduction experiments, free and forced convection experiments and an electronics packaging design project. All of these experiments have multiple set ups and are interfaced to the data acquisition systems in the studio classroom. Several of these lab exercises make use of a table top wind tunnel system that was designed and built at Union College. The intent was to build multiple, inexpensive wind tunnels. We have traditionally used a single large wind tunnel, however it was used in a demonstration mode, or by groups of students working in isolation.

In the following sections we will describe the table top wind tunnel systems and discuss two fluid mechanics laboratory exercises (pressure transducer calibration and wake traverse of a cylinder in cross flow), and a heat transfer design exercise (electronics packaging).

THE TABLE TOP WIND TUNNEL SYSTEM

Figures 1 and 2 show a schematic and photograph of the table top wind tunnel system. The system consists of three parts: (1) the tunnel (with air supply and flow conditioning), (2) the probe traverse and measurement system and (3) the data acquisition system. Each is described in detail below.

The wind tunnel is constructed of 3/8" thick Plexiglas. It has a 4.7" by 4.7" square cross section. The length of the tunnel is 47". The test section is located 21.5" from the leading edge and consists of 4" removable side walls to which we can mount different fixtures for study. Access ports are placed along the top side of the tunnel (every 2 - 4") upstream and downstream of the test section. The air flow is supplied by an NMB 4715KL 12V DC fan (118 cfm at zero pressure drop) connected to a DC power supply. We use 2 inch long honeycomb at the inlet to the tunnel

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[1] Union College is on a ten week term system. Each course typically has 8 labs.

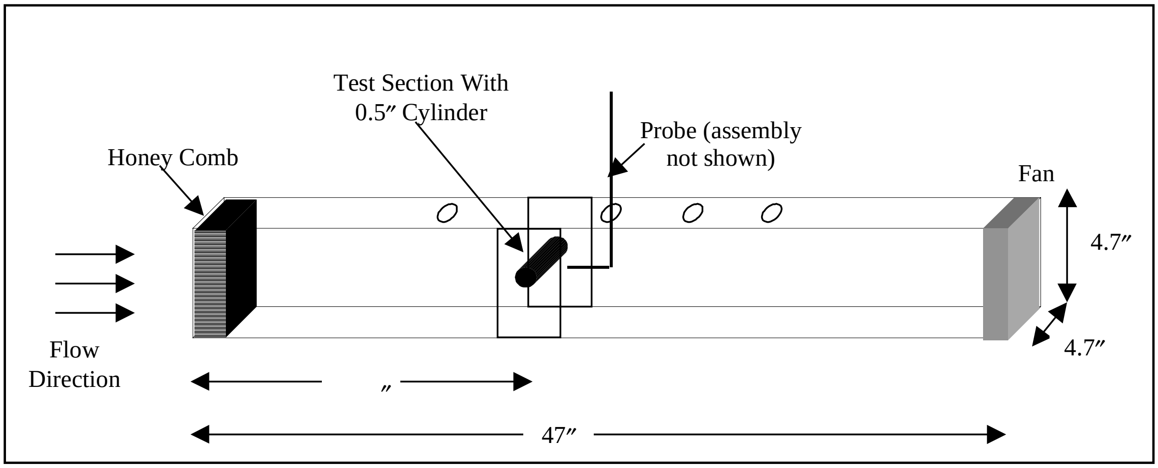


Figure 1. Schematic of table top wind tunnel.

to straighten the flow. Although the fan is a nominal 12 V fan, we use a DC power supply and vary fan voltage to get tunnel velocities in the range of 1 – 7 m/s.

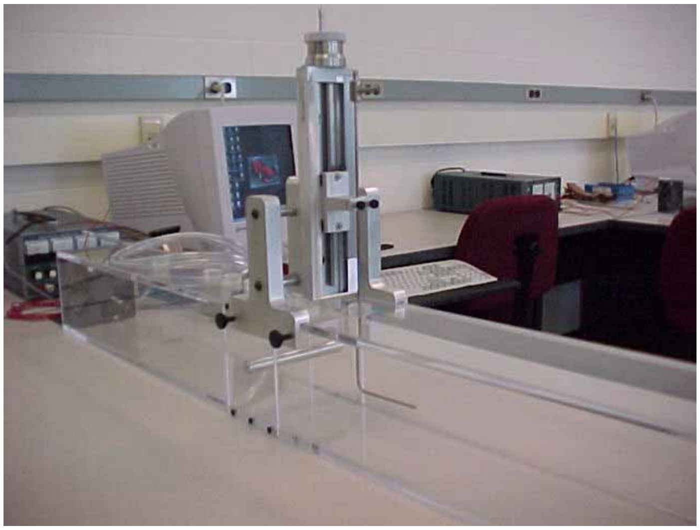


Figure 2. Picture of table top wind tunnel and probe assembly showing the test cylinder mounted on the test plate.

The probe traverse system consists of a Unislide manual translation unit, a custom built probe holder, a pitot probe and an Omega PX277-01D5V differential pressure transducer. The system can be seen in Figure 2. The Unislide translation unit attaches to the probe holder which is designed to sit on top of the tunnel. It can be easily positioned over any of the access ports. A pitot probe is clamped to the translation unit and easily traversed across the tunnel cross section. Thermocouple probes can also be attached to the translation unit.

The data acquisition system consists of a Pentium PC and a Keithly DASTC/B data acquisition board which reads both temperature and voltage levels. The output of the pressure transducer is connected to the board, as are any other required measurements (i.e thermocouples, or power supply voltage measurements).

The estimated cost of each of the table top wind tunnel systems is about $750. This includes the Unislide Assembly ($400), the pressure transducer ($250), the pitot probe ($35), the fan ($15) and the Plexiglas and construction supplies ($50). The Keithly data acquisition boards cost an additional $800 each. This estimate does not include a power source for the fans.

FLUID MECHANICS LABORATORY EXERCISES

We have developed two fluid mechanics laboratory exercises that use the table top wind tunnel system. The first exercise is a pressure transducer calibration and second is a wake traverse experiment that uses the calibrated transducers. Each of these is described below.

FLUIDS Lab 1: Calibrating a Pressure Transducer

The purpose of this experiment is to learn how to calibrate and use a pressure transducer, how to use a micro-manometer and how to use a computer data acquisition system. In addition, the calibrated pressure transducers are used to perform the wake traverse study of a cylinder in cross flow. The required equipment is: a micro-manometer, a pressure transducer and a pressure syringe system (syringe, tygon tubing, tee valves).

First the students set up the pressure transducer, micro-manometer and syringe system. A schematic of the system is shown in Figure 3. One side of the Tygon tube tee is connected to the high side of the micro-manometer and the other side to the high side of the pressure transducer. The syringe is then attached to the input side of the Tygon tube tee. Next, the low side of the micro-manometer is connected to the low side of the pressure transducer using a piece of Tygon tubing. The pressure transducer output is connected to the data acquisition system.

Next the students make a series of measurements for pressure differentials of 0 to 1 inch of water. The syringe system is used to supply a small but constant ΔP across both the transducer and the micro-manometer. The students read the micro-manometer to get ΔP and the voltage output of the transducer (E) is recorded by the computer. They then plot ΔP versus E and compare

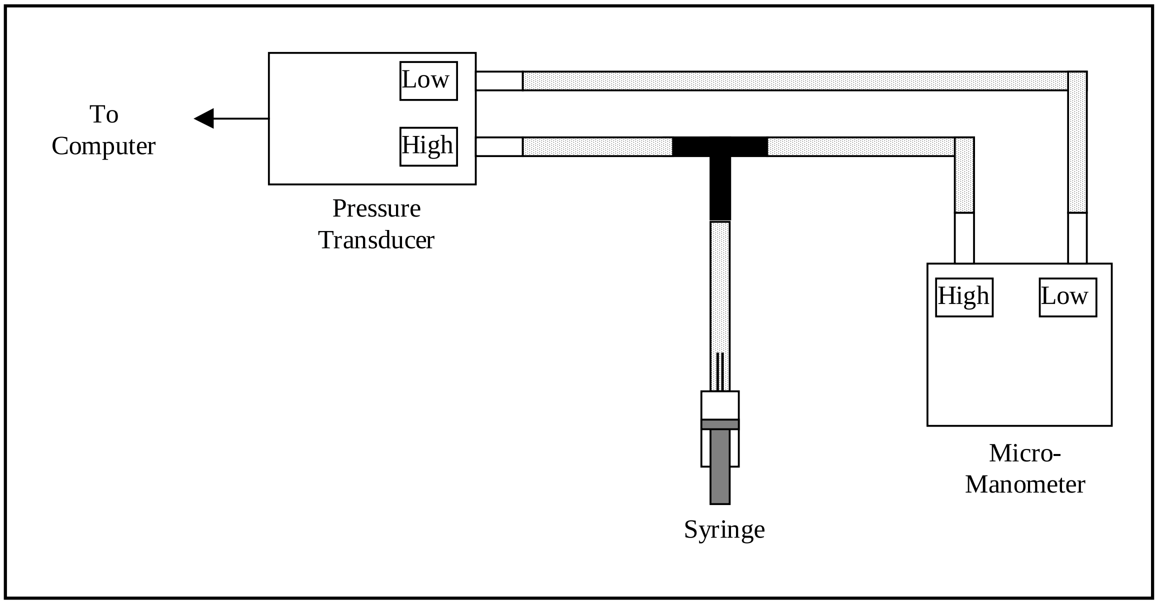


Figure 3. Schematic of pressure syringe system used to calibrate the transducer.

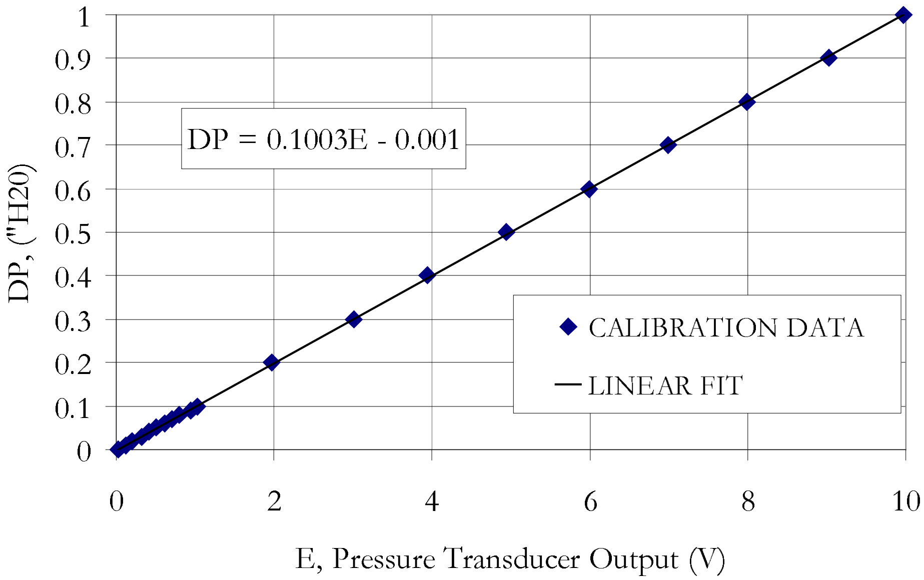


Figure 4. **Typical Pressure Transducer Calibration Curve showing agreement of data with manufacturers fit.**

it to the manufacturers calibration curve (which is ΔP = 0.1*E where ΔP is in inches of water and E is in volts). A typical calibration curve is shown in Figure 4. They are required to calculate a line fitting sample variance for the manufacturers calibration and determine if their results meet the accuracy specification. Next they fit a line to their data and calculate a line fitting sample variance which they also compare to the manufacturers calibration curve. The final step is to perform another linear regression in the differential pressure data range that corresponds to a pitot probe velocity of 2- 9 m/s and calculate a line fitting sample variance for the fit. They combine this with the resolution uncertainty of the micro-manometer and calculate the resultant uncertainty in velocity measurements in the range 2 to 9 m/s. Uncertainty results for the pitot probe velocities measured with this set up are from 8.5% (for the low velocity) to 0.5% (for the high velocity).

This lab exercise utilizes the table top setups and allows students to work simultaneously to calibrate the transducers. The group to group interaction allows students to compare results as the lab progresses as well as provide additional motivation. The set up as described works well. The only problems encountered were from leaks in the system which can be avoided with careful setup.

FLUIDS Lab 2: Measuring The Drag Coefficient on a Cylinder in Cross-Flow

The purpose of this experiment is to use a pitot probe and pressure transducer to measure the drag coefficient on a cylinder in cross flow. There are three major experimental methods for determining the drag of a body in a fluid stream: (a) by a direct method using a "drag balance"; (b) by an indirect method measuring the pressure distribution over the surface of the body, calculating the streamwise component of this force, and adding a very small calculated friction force due to viscosity; and (c) by another indirect method, measuring the rate of change of momentum of the fluid affected by the immersed body and applying Newton’s laws to obtain the force on the body. This lab demonstrates the third method to measure the drag force on a circular cylinder.

The basis of this method is to measure the change of momentum caused by the presence of a body in an airflow. The mean velocity of the air downstream of the body should be the same as that upstream due to conservation of mass. However, the velocity is lower immediately to the rear of the body, and higher on either side of it. This change in the velocity pattern together with the eddying from separation of the flow causes a momentum deficiency which can be calculated and related to the drag of the body.

In this lab a cylinder is placed in the table top wind tunnel and the velocity profile is measured upstream and downstream of the cylinder. Conservation of momentum is applied and the momentum deficit profile is numerically integrated to determine the drag on the cylinder. The required equipment includes the table top wind tunnel system and a 1/2" cylinder.

The first step is to mount the cylinder in the wind tunnel and set up the pressure transducer and pitot probe assembly. Next the students configure and start the data acquisition system and then measure the velocity upstream and downstream of the cylinder. The students also record all data necessary to do an uncertainty calculation.

The students then construct a plot of flow velocity, V versus vertical distance, y, for both upstream and downstream positions and calculate the mean velocity in the tunnel. Figure 5 shows a typical velocity profile taken at several port locations. Port 0 is located 5 inches upstream of the cylinder, Ports 5, 6, and 7 are located 1, 2 and 10 inches downstream of the cylinder .

The drag force is calculated by applying conservation of momentum to a control volume around the cylinder. The control volume extends into the free stream which is unaffected by the presence of the cylinder. The drag force is:

$$F_D = w \int_A U_\infty (U_\infty - u) dy \qquad (1)$$

In this equation, F_D is the drag force, w is the tunnel width, U_∞ is the upstream (free stream velocity) and u is the downstream velocity (a function of y). The students plot and numerically integrate the momentum deficit profile to calculate drag force. For the profile shown in Figure 5 the calculated drag coefficient is 1.12 at a Reynolds number of about 3000. The uncertainty range on the drag coefficient is about 10%. These results agree well with published data for flow past a cylinder. The table top wind tunnels are not large enough to remove all wall boundary layer effects, nor is there enough flow conditioning to provide perfectly uniform flow (as indicated by the asymmetry at the upstream port location in Figure 5). However, the wind tunnels work quite well as a teaching tool. The results generally agree with published data. Students appear to enjoy the hands on activity which motivates them to learn more. In fact, on one occasion a group of students stayed late and used the setup to measure and "see" a velocity boundary layer.

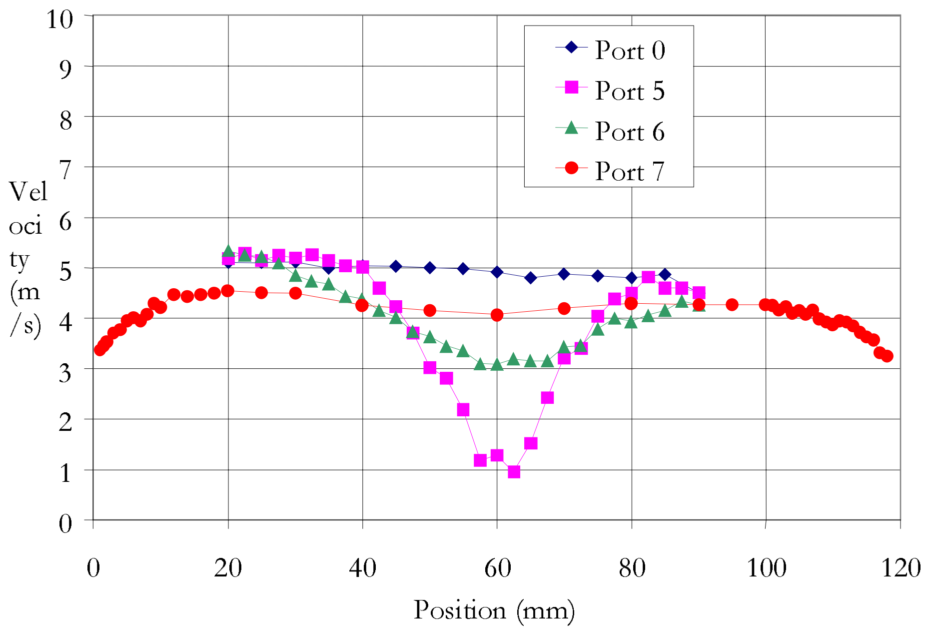


Figure 5. **Typical wake traverse results showing the velocity versus position in the tunnel at both upstream and downstream ports.**

HEAT TRANSFER LABORATORY EXERCISE

We have developed an electronics packaging design exercise in which students are asked to design a cooling system for a CPU chip. They use the table top wind tunnel systems to measure the heat transfer from a CPU chip under various conditions.

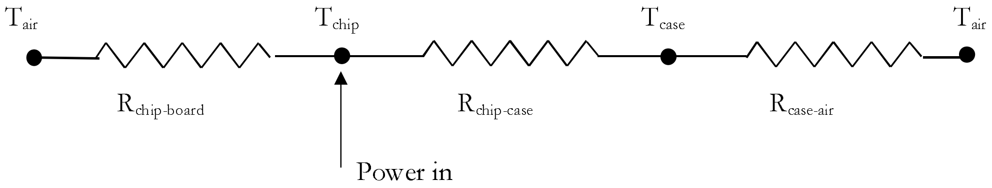
The students are specifically asked to perform tests to determine the chip case to ambient air thermal resistance and then predict resulting chip temperatures for four possible cooling schemes (forced, free convection, with or without a heat sink). In addition we ask them to perform a liquid crystal temperature visualization study to assess the heating effect of upstream modules and recommend a module to module spacing. They are told that the logic designers predict a power dissipation rate in the range 5-30 W per chip (depending on clock rate and internal structure), that the chip temperature must not exceed 85 ^{o}C, and that the conduction analysis group predicts the chip to board conduction resistance ($R_{chip-board}$) at 10 ^{o}C/W and the chip to case resistance ($R_{chip-case}$) at 1 ^{o}C/W.

The lab exercise lasts two weeks. We use a 2.1 x 1.9 x 3/8" aluminum block to model the CPU module. The blocks are instrumented with a thermocouple in the center and a film heater on the bottom. They are mounted on the Plexiglas test plate and inserted in the tunnel. In addition we use a thermocouple mounted on the back of the test plate to measure backside temperature (for a heat loss calculation), a thermocouple mounted in the air-stream for ambient air temperature measurement and a pitot probe to measure the air velocity.

During the first week we perform the forced convection studies. Each lab group performs a baseline test (no heat sink) at the nominal fan speed (12V) and then each group performs a test (no heat sink) at one of the following fan voltage values: 2, 4, 6, 8, 10, 14 V. These fan voltages result in an air speed range of about 1 - 6 m/s. Next each group performs a baseline test (large heat sink) at the nominal fan speed (12V) and then they perform a test (large heat sink) at one of the following fan voltage values: 2, 4, 6, 8, 10 , 14 V. Each lab group turns in a data sheet for each test at the end of the lab period and the results are posted so that the students can share the results and formulate a correlation for the heat transfer as a function of air velocity.

During the second week we perform the free convection tests. Each lab group performs a baseline test (no heat sink) at P = 1W and then they perform a test (no heat sink) at one of the following module power levels: 0.5, .75, 1.25, 1.5, 2.0, 2.5 W. Next each group performs a test (large heat sink) at one of the following module power levels: 1.25, 1.5, 2.0, 2.5, 3.0, 3.5W. These power levels are lower than predicted operating range but are required to maintain safe temperature levels in the lab. Each lab group turns in a data sheet for each test at the end of the lab period and the results are posted so that the students can share the results and formulate a correlation for the heat transfer as a function of input power.

To calculate the case to air thermal resistance the students conduct a steady state analysis of the module as shown in Figure 6. Power is dissipated in the chip and can travel from the chip to the case ($R_{chip\text{-}case}$) and then to the ambient ($R_{case\text{-}air}$) or it can conduct through the ceramic substrate and pins, to the PC board and out the back ($R_{chip\text{-}board}$). A simplified model of this process is:



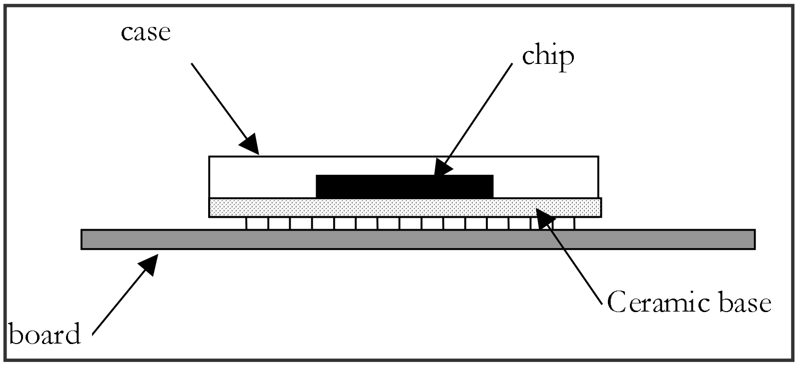


Figure 6. **Schematic of typical CPU module for heat transfer analysis.**

To estimate the case to air thermal resistance the students perform a control volume energy analysis on the module and estimate the amount of power that is convected away from the module, Q_{conv}:

$$Q_{conv} = P_{in} - Q_{loss} \tag{2}$$

In this equation, P_{in} is the power input to the heater which the students measure. The heat losses, Q_{loss} are due to conduction through the wood and along the leadwires, and radiation to the surroundings. The radiation losses are assumed to be negligible for the range of temperatures used in this experiment and a 1-D model is used to estimate Q_{loss} as conduction through the plywood base:

$$Q_{loss} = C_1 k_{plex} A_{\mathrm{mod}} \frac{(T_{\mathrm{mod}} - T_{plex})}{\Delta x_{plex}} \tag{3}$$

In this equation, $C_1 = ½$ is used to account for the spreading resistance, k_{plex} is the conductivity of plexiglas, A_{mod} is the foot print area of the module, T_{mod} is the measured temperature of the module, T_{plex} is the back side temperature of the plexiglas, and Δx_{plex} is the thickness of the plexiglas test plate. The case to air thermal resistance is calculated as:

$$R_{case-air} = \frac{(T_{\mathrm{mod}} - T_{amb})}{Q_{conv}} \tag{4}$$

The students calculate the case to air thermal resistance for all cases. Figure 7 plots the measured $R_{case\text{-}air}$ versus the power input to the module for the free convection studies. Both the no-heat sink and heat sink cases are shown on the plot as well as a power law fit to the data. Figure 8 shows a plot of the measured $R_{case\text{-}air}$ versus the approach velocity for the forced convection studies. Both the no-heat sink and heat sink cases are shown on the plot as well as a power law fit to the data.

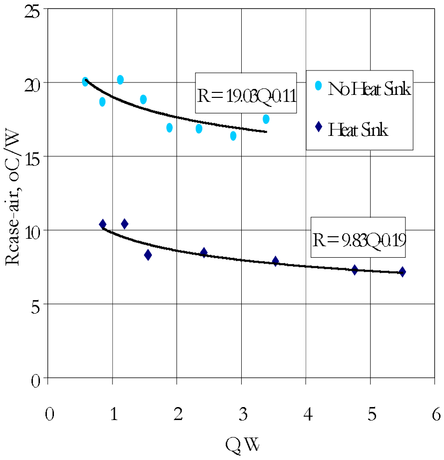


Figure 7. Free convection $R_{case\text{-}air}$ results for a range of power levels with and without a heat sink on the CPU.

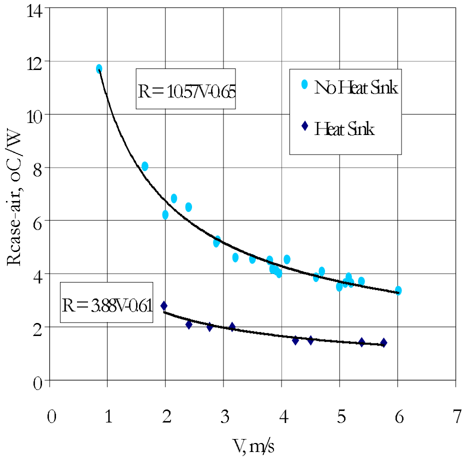


Figure 8. Forced Convection $R_{case\text{-}air}$ results for a range of velocities with and without a

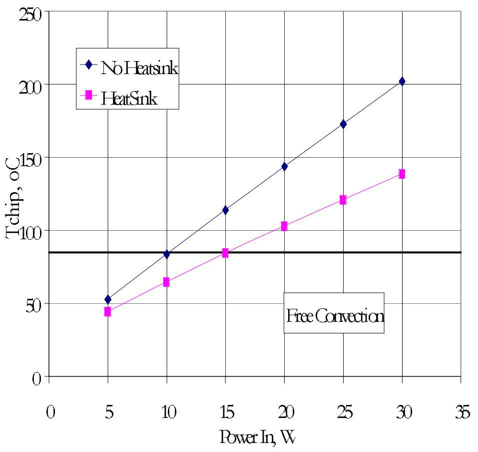


Figure 9. Predicted chip temperature versus input power for free convection conditions, with and without a heat sink.

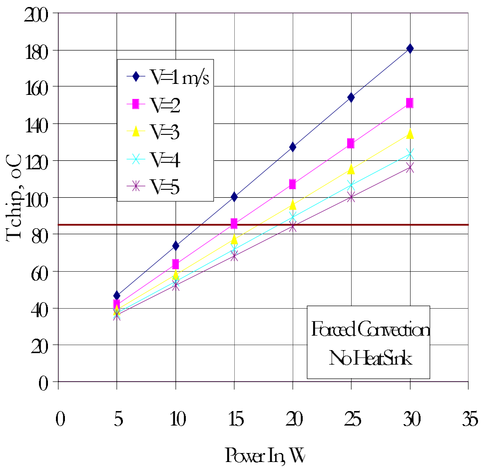


Figure 10. Predicted chip temperature versus input power for forced convection, w/o a heat sink, parametric in velocity.

The students use this data and the information provided about $R_{chip\text{-}case}$ and $R_{chip\text{-}board}$ to calculate the chip temperature for a range of conditions. Typical temperatures results are shown in Figures 9 and 10 which provide a parametric analysis of the predicted chip junction temperature and allow the students to choose a cooling scheme.The students are also asked to make some recommendations as to how close one could place the modules in a forced convection environment. To assess this we place a sheet of liquid crystals on the bottom surface of the tunnel and use a liquid crystal image processing system to measure wake temperatures downstream of the heated module. An image of the liquid crystals is shown in Figure 11 and the corresponding temperature field is shown in Figure 12. The students use this data to make a recommendation as to where to place the downstream module. Although we use the imaging system to get quantitative temperature measurements, it is also possible to effectively use the liquid crystals as a qualitative thermal visualization tool.

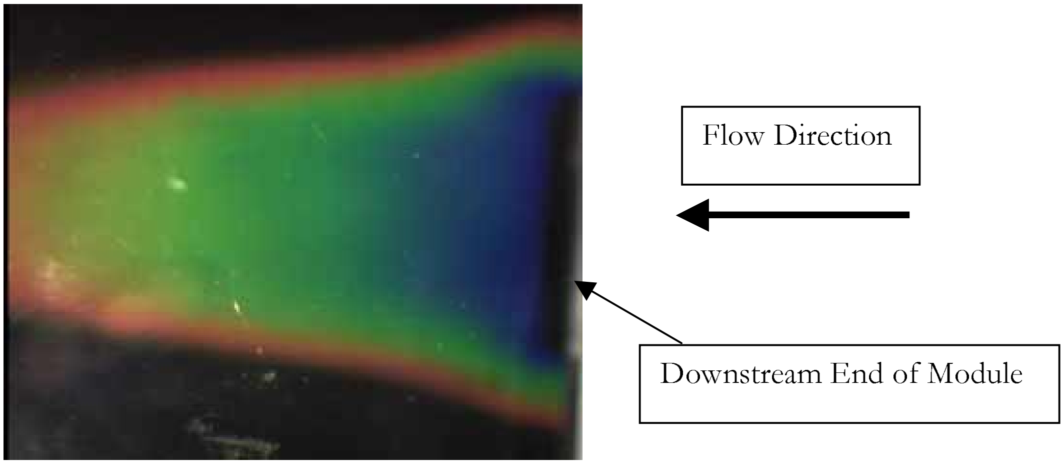


Figure 11. Photograph of liquid crystal sheet placed behind the heated modules.

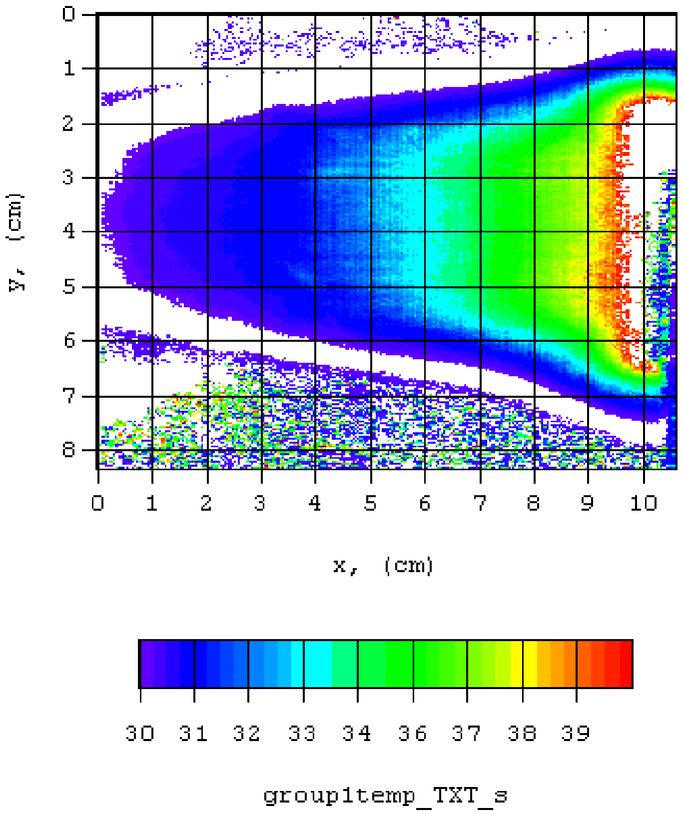


Figure 12. **Corresponding temperature results for the liquid crystals shown in Figure 11.**

Traditionally, our forced and free convection heat transfer laboratory exercises have used a single store bought convection setup. We either took data as a group or students groups signed up to take data at separate times. Overall it was not an effective way to run the labs because students were unable to actively participate in the experiment. The table top set-ups work extremely well to remedy this situation. By having each student group run tests for different operating conditions (i.e. speed or power level) we are able to combine the data and students have an opportunity to see how heat transfer correlations are formed. Due to the nature of heat transfer there can be a fair amount of time spent waiting for the systems to come to steady state (20-30 minutes for forced convection tests, 60 –90 for free convection) so we have tried to structure the labs appropriately.

CONCLUSION

Table top wind tunnel systems were designed, built, and incorporated into upper lever mechanical engineering courses in fluid mechanics and heat transfer. The use of multiple small-scale experimental systems by small teams of students allows for the students to become more actively engaged in the process of conducting experiments. It also allows for much of the laboratory component of these courses to be conducted within a studio environment, thereby allowing for the integration of the lecture and experimental parts of the course.

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