VERSATILE, LOW COST CONVECTIVE HEAT TRANSFER LAB

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Abstract

Illustrations of external convection generally require wind tunnels or expensive purchased modules. This paper describes a versatile, bench top rig for external free and forced convection which may be constructed for less than $200. The low cost allows enough units to be built so that students may work in small groups. The rig uses a common hair drier as the air source with a simple box to create a hot or cold jet. Various objects placed at different distances from the air source provide for Reynolds number variations. Experiments and test objects are described for transient heating and cooling of spheres and free and forced convection from a heated disc. The effects of free stream turbulence on forced convection can also be demonstrated. A web site is given from which the manuals and details of the rig may be obtained.

Introduction

Experiments to illustrate the phenomena of forced and free convection are a very important part of engineering heat transfer courses. The need for such laboratory work is increasingly important as more of our students arrive with little or no practical experience.

Several commercial equipment rigs may be purchased for external free and forced convection demonstrations. While these are smaller and more portable than most older experiments based on fixed wind tunnels, they are quite expensive. This means that most institutions will have only one of each. In large classes, this limits the amount of interaction that any individual student may have with the equipment.

A number of institutions have created some effective low-cost rigs for various heat transfer studies. For example, Cloette [1] used the temperature distribution in a copper rod acting as a fin to measure the forced convection to air from a fan. Erens [2] blew air over vertical hollow tubes of various cross sectional shapes with steam condensing on the inside. Mullisen [3] describes projects in which students instrument heated cylinders and attached them to bicycles, moving cars, immersed in flowing streams, etc. to determine forced convection. Campo [4] heated stainless steel spheres in an oven and then exposed them to still air.

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All of these examples illustrate that simple equipment is quite effective in illustrating basic heat transfer principles to students.

In the Mechanical and Aerospace Engineering Department at the University of Virginia, we decided to create a similar learning tool unit that would serve several purposes and be of low enough cost to allow us to construct several. We also decided to use some geometries for convection other than the standard flat plate, cylinder, etc. to show students that something that was not in their textbooks still adhered to the general principles. In the process, we were also able to illustrate some clever experimental methods.

Basic Test Rig

The device created consists of a common hair drier as a source of hot air and several different objects that are mounted on a board downstream of the air jet. For objects, we chose 2.5cm diameter steel and nylon spheres and a 1.9cm diameter heated vertical disk for illustrating transient conduction and forced and free convection.

The basic system as set up for the sphere tests is shown in Figure (1). The elements of the system are described in more detail in Figure (2).

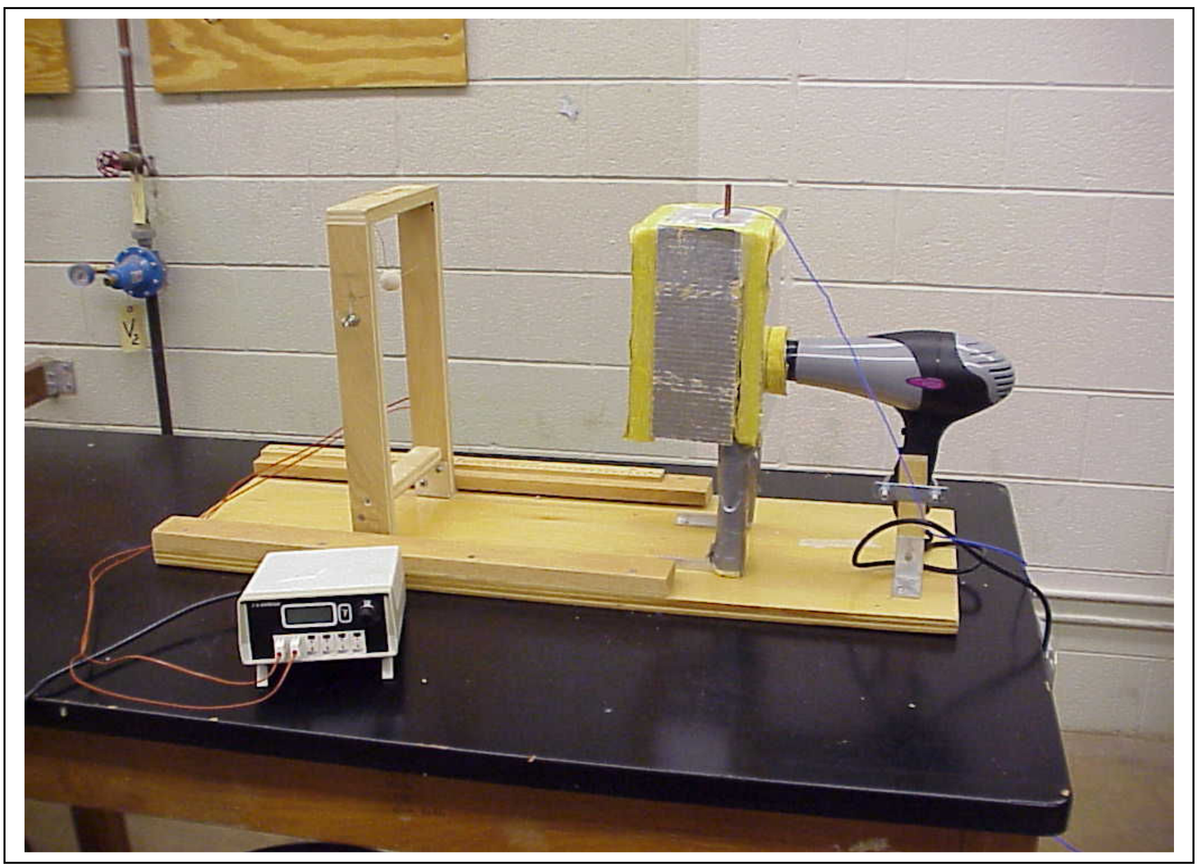

FIG. 1: <u>Test Rig Setup for the Sphere</u>

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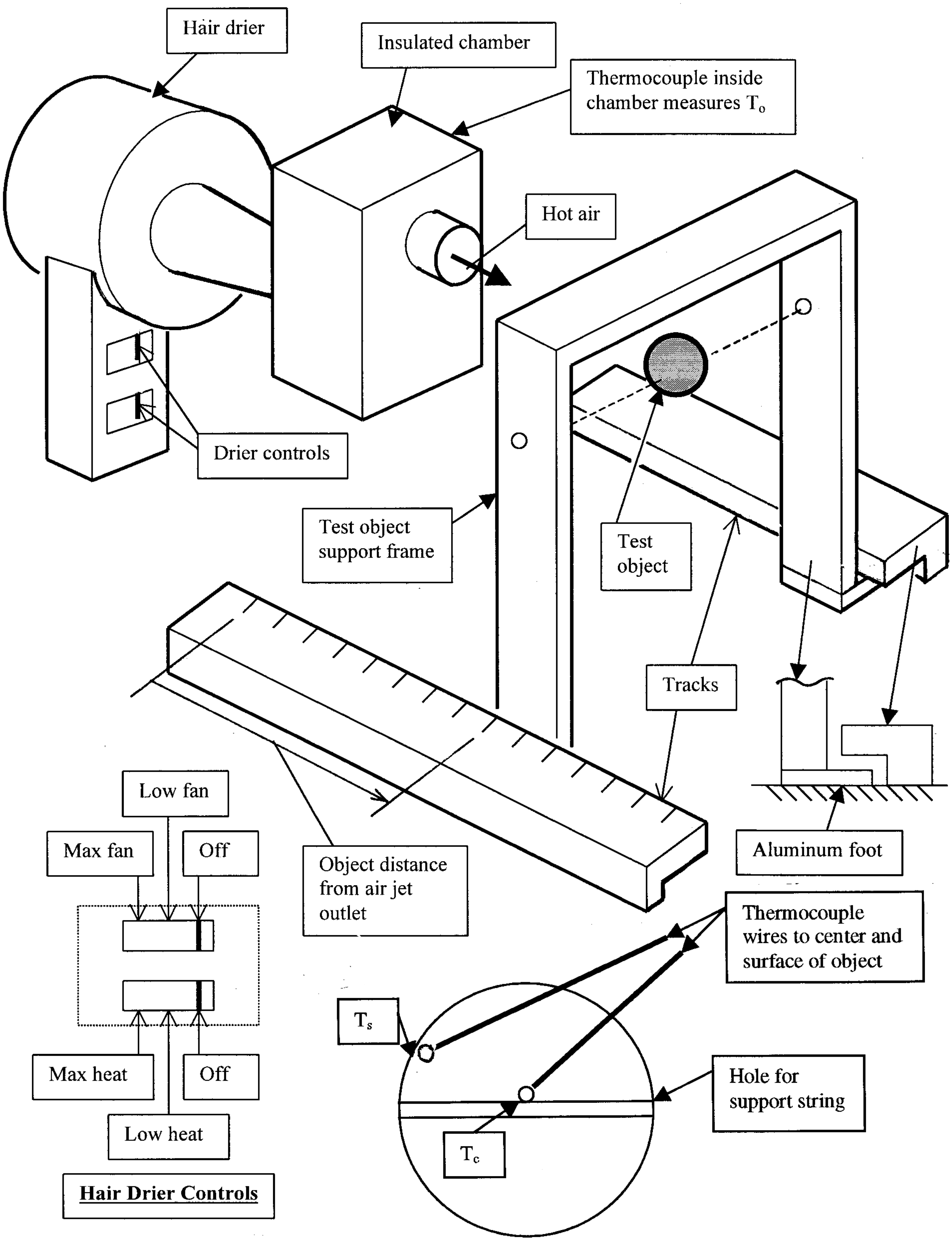

FIG. 2: Sketch of Apparatus for the Sphere as Provided in the Experiment Manual

The insulated box is a standard electronic "BUD" box CU-2108-B that is 7x5x3 inches. The two tubes attached to the box for the hair drier input and hot air outlet are 1.5 inch automobile exhaust pipe. These were flared by the local muffler shop and are secured as illustrated in Figure (3). The box is then covered with rigid fiberglass insulation.

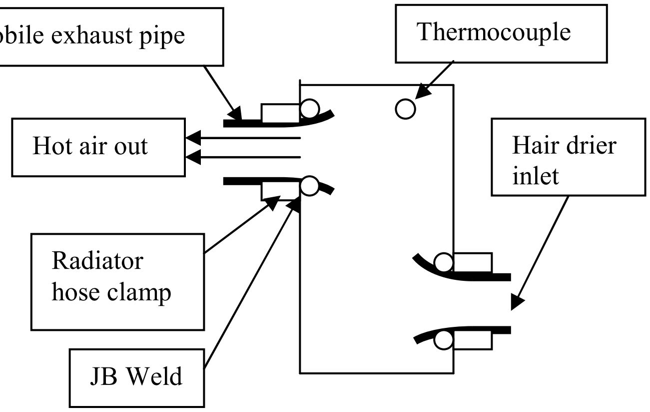

FIG. 3: Details of Box Construction

The hair drier exhausts into the insulated chamber where a thermocouple measures the air temperature. In this way, we may measure the watts into the hair drier and then use conservation of energy to determine the air flow rate. From this we may determine the exit velocity of the jet. Calibration with a pitot probe then provides a profile of the jet velocity and temperature downstream of the jet source. This information allows the student to determine the temperature and velocity of air striking the sphere. The study of the jet temperature and velocity profile is another experiment.

The insulated chamber has an offset so that no radiation from the hair drier heating coils can leave through the air outlet hole or affect the measured outlet air temperature. This radiation is a significant factor if one uses the hair drier directly.

The wood frame supporting the sphere slides along tracks that allow one to position it at different distances from the air outlet. The sphere is suspended on nylon fishing line that is kept taut by wrapping it around an eye bolt that can be turned and secured. Small holes are drilled in the sphere to accommodate the line and the two Chr-Al thermocouples of 30 gauge wire.

The construction of the disc test fixture is illustrated in Figure (4). The disc is 1.9 cm diameter aluminum about 1mm thick. The Minco foil heater and thin film thermocouple are glued to the back and this is then glued to a 2 cm thick Styrofoam insulation disc and this to the wood support block on the stand. The disc is heated using a simple DC power supply (Jameco 29225) to the foil heater. The temperature difference across the Styrofoam insulation is measured with thermocouples and used to estimate the loss from the back of the disc. The exposed disc surface temperature is measured with an infrared sensor (Omega OS643E-LS).

Figure (5) shows the disc fixture in place. In this arrangement, one may determine the forced air convection coefficient on the rear of a short cylinder or on the surface of a vertical disc is free convection. Turning the disc around allows one to measure the forced convection coefficient on the front of a disc.

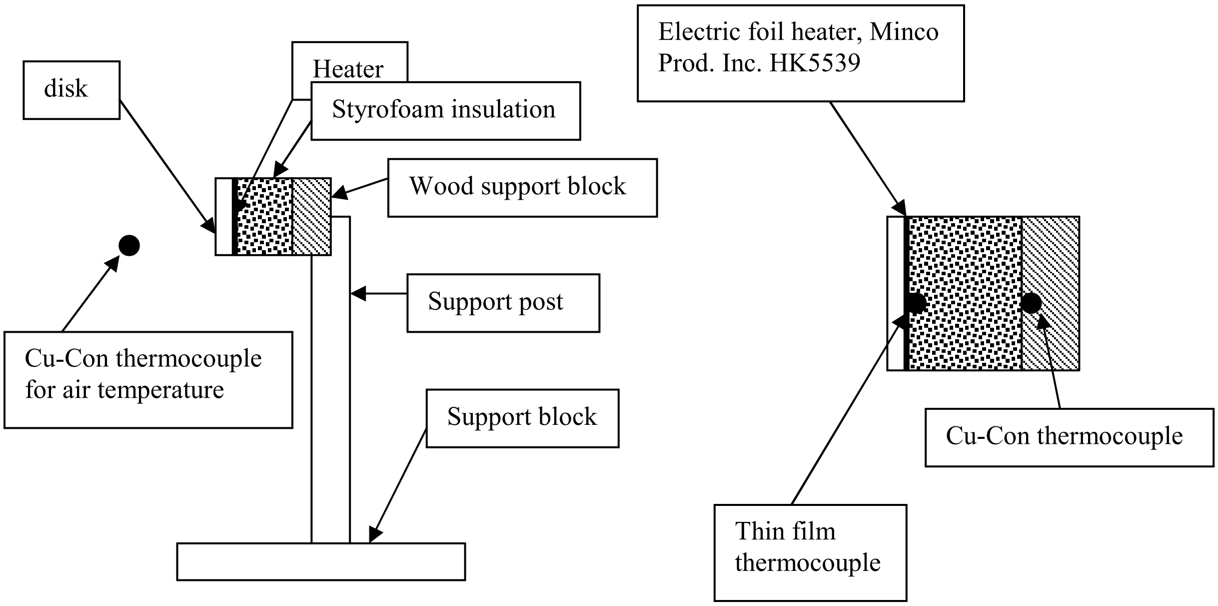

FIG. 4: Details of the Disc Fixture

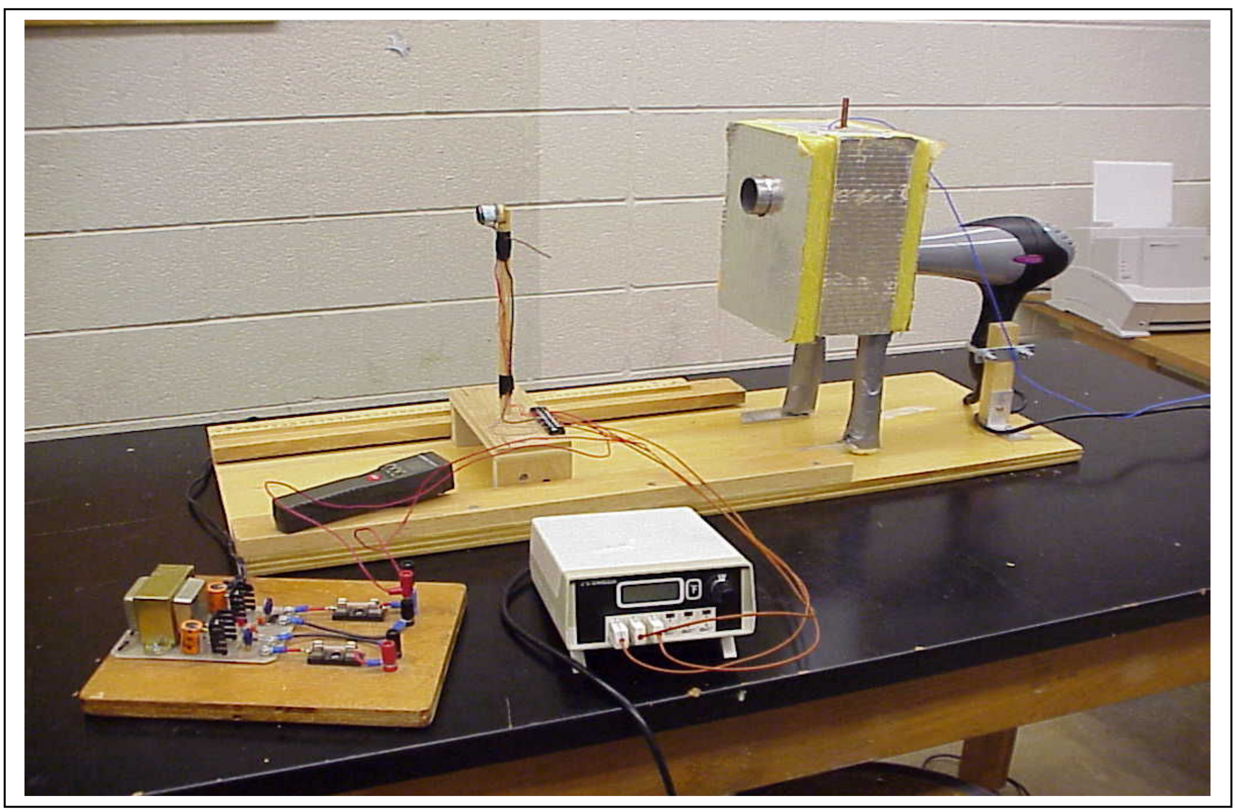

FIG. 5: Test Rig Setup for the Disc

Experiments With Spheres

We use the spheres in forced convection to illustrate the lumped thermal capacitance and one-dimensional transient conduction models. Here is how a typical the test proceeds:

1. The sphere is located at a set distance from the hot air outlet at which we know the average air velocity from previous calibration.
2. A thick block of Styrofoam insulation is placed in front of the sphere and the hair drier is turned on. The insulation keeps the hot air from striking the sphere during the several minutes required to bring the insulated box up to a steady temperature
3. The insulation block is taken away and students record the air temperature, surface and center temperature of the sphere over a 15 minute period.
4. The data is later put into a spreadsheet and compared with the analytical models.

Figure (6) shows the student data for the sphere compared with that predicted using the lumped capacitance model for the known air velocity and several levels of free stream turbulence.

Hot air T_a(°C)=		22.5
t(sec)	T_{center}(°C)	$T_{surface}$(°C)
0	22.5	22.5
10	24.3	24.7
20	26.6	27.1
30	28.7	29.0
40	30.1	30.2
60	33.4	33.5
90	38.2	38.5
120	40.9	41.0
150	43.6	43.7
180	45.8	45.9
240	48.9	49.0
360	52	52
600	54	54
900	55	55

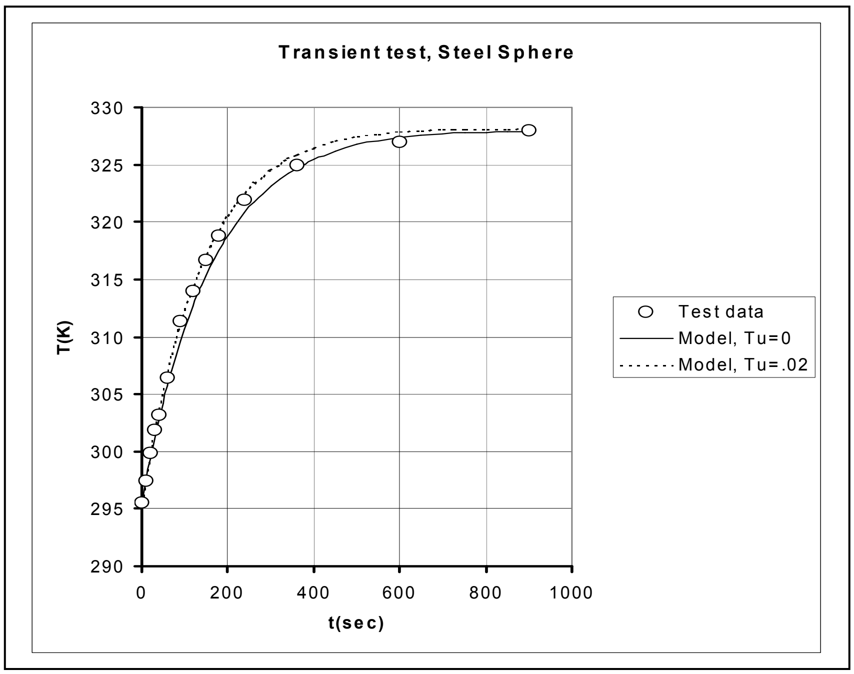

FIG. 6: Typical Student Data for Transient Heating of the Steel Sphere by Forced Convection

The "model" curve is calculated using a correlation for the forced convection that includes the effects of free stream turbulence since the air from the insulated box has very high free stream turbulence. A number of references point out the significance of this [5,6,7].

After the sphere has reached a steady temperature, the hot air is turned off and the sphere allowed to cool by free convection and radiation. Students then use the measured slope of the temperature vs. time curve to determine the free convection coefficient from the sphere. The calculations are done on a spreadsheet. Students are required to vary the emissivity of the surface to see how it affects their calculated free convection coefficient.

Forced Convection Experiments with The Heated Disc

We chose the disc geometry because information about free and forced convection from discs is not available in undergraduate heat transfer texts. This gives us the opportunity to show students that heat transfer theory and dimensional analysis really work outside the textbook. We are also able to show the effects of free stream turbulence which are not discussed in textbooks.

In the forced convection experiments, students use a simple plane wall conduction model to account for heat loss from the back of the disc through the Styrofoam. Then an energy balance gives the heat loss from the disc and the convection heat transfer coefficient. Students plot their data and compare it with several models from the literature and with instructor data taken on a set of similar discs of other sizes up to 15cm diameter.

Figure (7) illustrates typical student results for the disc facing the air stream. Similar success occurs when the disc is turned around for convection from the rear of a short cylinder.

Students discover that the difference between the instructor tests on larger discs (up to 15cm diameter) and their tests is due to the higher free stream turbulence in the air from the hair drier. The instructor tests are run in a wind tunnel.

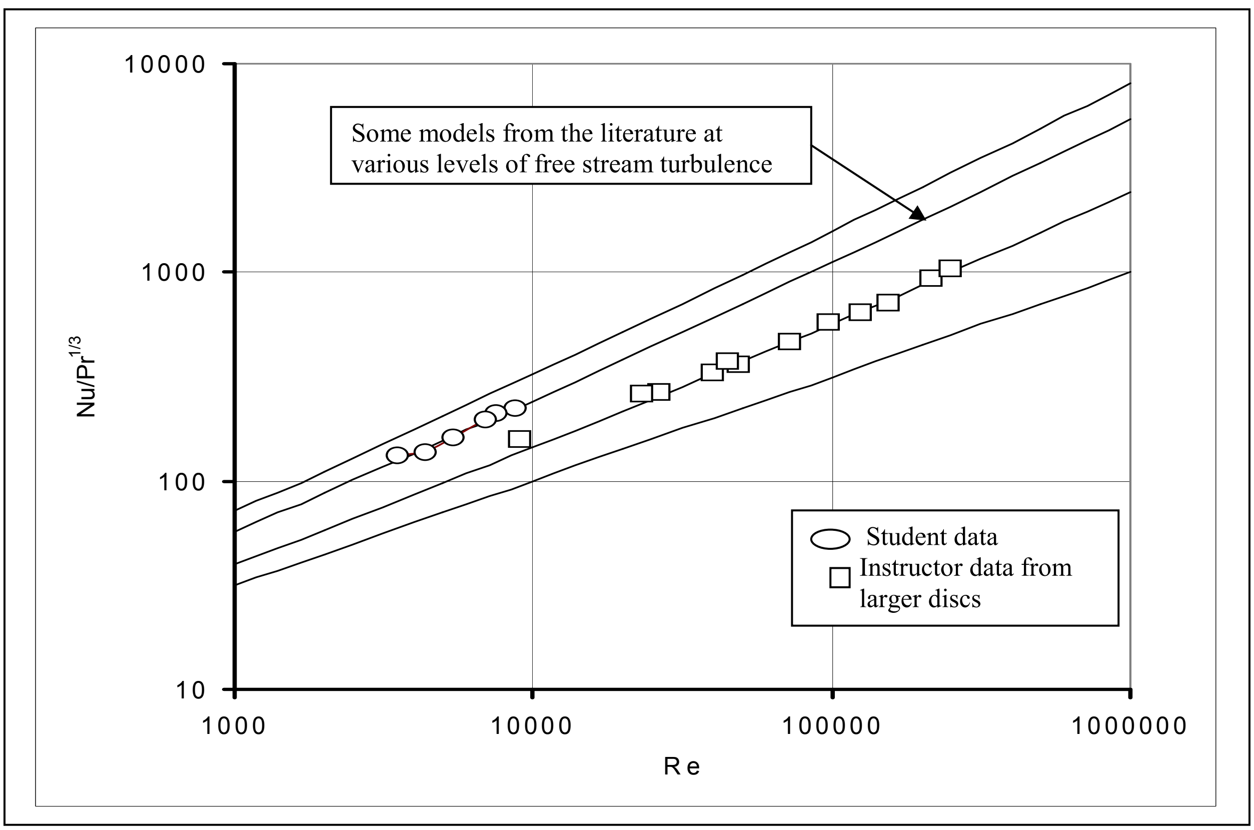

FIG. 7: Typical Results for Forced Convection On the Front of the Disc

When the students run tests for forced convection with the disc facing away from the air flow, they are required to read two of the few references on this configuration [8,9] and compare their results. We find that most students have very little exposure to what is available outside their textbooks and this exercise is enlightening.

Free Convection Experiments with the Heated Disc

In these experiments, the disc is heated while sitting in the still air of the lab room.

The first issue that we discuss is the difference between constant heat flux and constant surface temperature conditions. With the infrared temperature sensor, students are able to detect a noticeable difference in temperature across the surface of the disc in forced convection but very little in the free convection test. With the heater generating a constant heat flux, they are asked to discuss why there is no temperature variation across the disc. The reason is that the aluminum plate is able to conduct heat radially and this evens out the temperature.

With a higher convection coefficient in the forced convection case, this conduction is not able to even out the temperature. Students require considerable guidance to come to this realization.

The second issue is the determination of the heat loss from the back of the disc through the insulation. In the forced convection case, this loss is only a few percent of the total heater power. Thus a simple plane wall conduction model, while not truly correct, is adequate. In the free convection case, the heat loss through the back insulation is a large part of the energy balance. How to determine this?

We encourage the students to think about options such as a two or three dimensional conduction model. Since there is no information about the free convection loss from the short cylinder that constitutes the insulation and the wood support disc, and since the surface temperature is not constant, we bring them to realize that a full finite element model would be required to account for this loss analytically.

The solution is to place two discs face-to-face as shown in Figure (8). Because the faces of the two disks are clamped together, there is no heat loss from them by free convection or radiation. All of the electric power put into the heaters must escape through the back of the disks. This heat loss will be a linear function of the temperature difference across the insulation. Students run this test and obtain verification as shown in Figure (8). Then the slope of this line is used to calculate the loss from the back of the discs in the free convection test. To date, we have found no student groups able to come up with this solution on their own.

The final issue involves the results. The free convection coefficient for the discs in the lab is about twice as large as theory predicts. The reason is that the air currents in the lab room due to the building ventilation system are sufficient to make this a mixed convection problem. This is an interesting point that most students do not realize.

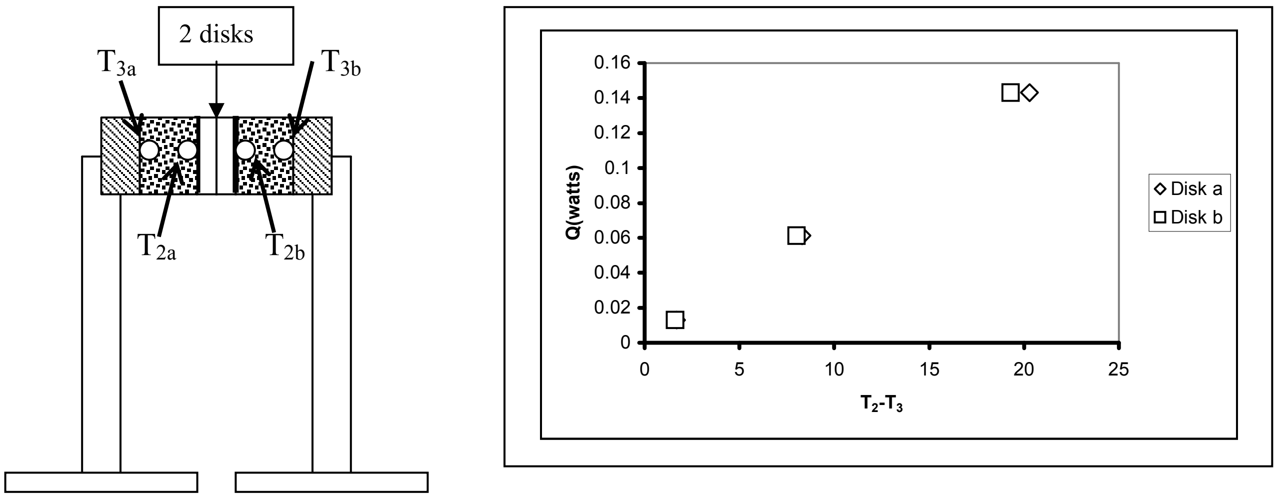

FIG. 8: Method of Determining Heat Loss from the Back of the Disc in Free Convection

Conclusions

We have described the construction and use of a simple, low cost rig for free and forced convection experiments. Because of the low cost, enough of these rigs may be constructed to provide direct hands-on experiences for many small groups of students.

We have found that students are eager to accept textbook formulas for convection without question and without much thought about their application. In real world situations, objects are not all nice shapes like spheres and plates, surface conditions are not constant temperature or constant heat flux, etc. With this test rig, we are able to promote discussions of these and other issues that cause students to think. The rig also helps us expose students to topics like free stream turbulence effects, the fact the few real situations involve pure free convection, and the vast amount of information in the technical literature.

Further information and manuals for some of the experiments may be found on the toolkit.virginia.edu website under the MAE 384 course.

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