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Laboratory Fixture for Heat Transfer Using a Hair Drier

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Laboratory Fixture for Heat Transfer Using a Hair Dryer

Abstract

This paper describes a simple test fixture for conducting tests in heat transfer in an undergraduate engineering lab. The fixture consists of a common hair dryer that blows hot or cold air over a few relatively easy-to-construct fixtures and sensors. The experiments that can be performed with this equipment are: 1. Energy balance on the hair dryer using a wattmeter and temperature sensors to calculate the air flow rate, 2. Forced convection from a heated disc to show the effects of Reynolds number and free stream turbulence, 3. Free convection over a heated disc, 4. Transient heating and cooling of steel and nylon spheres (to illustrate the Biot number effect), and 5. Velocity and temperature distribution in a free jet. We show the fixtures, how the results compare with standard correlations, as well as experiment instructions and related worksheets to give to the students.

1. Introduction

We seek primarily to describe the test fixture in sufficient detail for others to construct. Secondly, we will also describe a few of the experiments that one can conduct with the fixture. Finally, we will illustrate some of the difficulties that students have conducting these experiments.

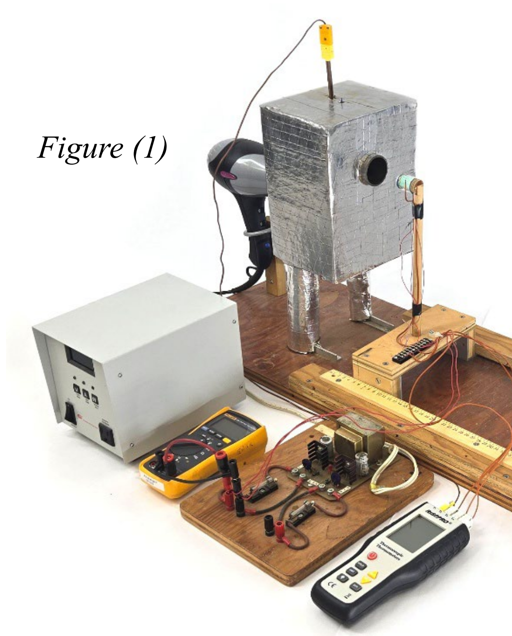
The value of this simple apparatus is that we can build many and thus have students work in groups of 3 to 4. Typically, we will have 4 groups in a lab period with an instructor and student assistant(s) (who did these experiments the previous year). The need for smaller groups of students to work in direct contact with the equipment has been recognized for many years. For example, see Bailey[1].

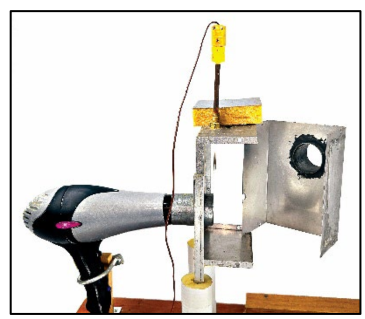
1.1 Apparatus Description

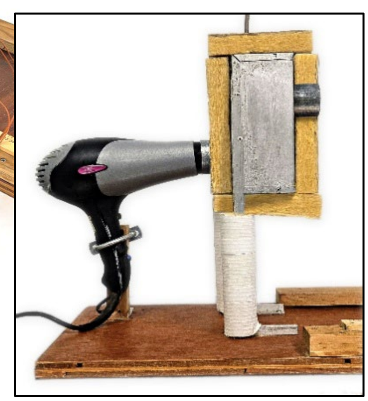
Figure (1) gives an overview of the basic unit. The hair dryer has ambient and heated air available at two levels. The maximum power is 1300 Watts which produces a temperature of up to 90°C and air velocity up to 15 m/s. The velocity over any objects placed downstream will be less based on the distance from the outlet. Thus, we can run experiments with forced convection over a range of velocities and temperatures.

Figure (2) shows typical air centerline temperature and velocity vs. distance from the outlet.

Figure (1)



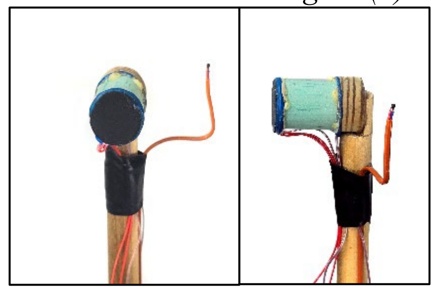




The aluminum box downstream of the hair dryer provides a collection of hot air for accurate measurement of its temperature. The offset ensures that the glowing heater in the hair dryer cannot be seen by any temperature probe downstream.

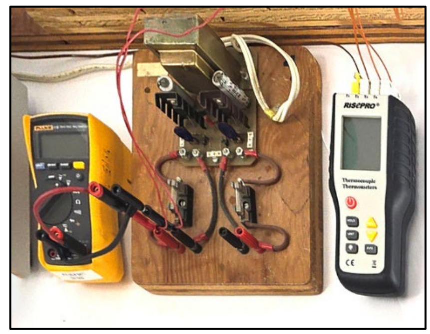
The air temperature can be monitored with a plain or shielded probe and the air velocity can be measured with a pitot tube or hot wire probe.

Figure (2)



The 19mm aluminum heated disc fixture is constructed as illustrated in Figure (2). The disc is heated from the back with a thin film heater with a resistance of 69 Ω. This is used for the forced and free convection tests. Power is provided by the Jameco model 29225 power supply shown Figure (3) with up to 12 Volts, 1 Amp). The Styrofoam backing and thermocouples are secured with glue suited for this application. We limit the power used so that the Styrofoam does not melt (which some student teams manage to do!)

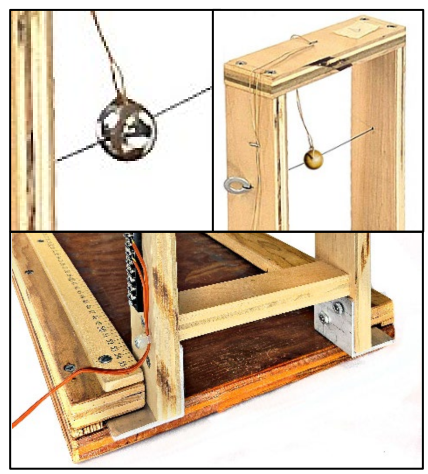
Figure (3)



The face of the disc is painted flat black so that the radiation loss can be determined with some accuracy. The disc conductivity is high enough that the surface temperature and heater temperature are the same. We have students verify this with an infrared temperature sensor.

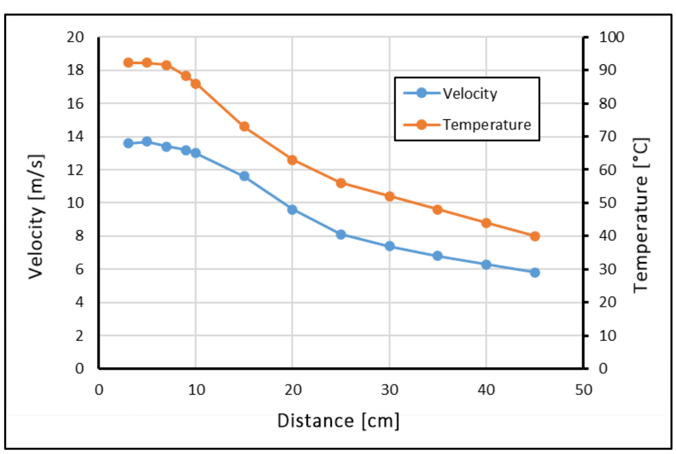
The spheres are of nylon and steel. These are used for transient heating and cooling tests. Small holes are drilled in which the surface and center temperatures are measured with inserted small wire-type K thermocouples. A through hole is used for the nylon line that supports the sphere.

Figure (4)



The fixtures for the heated disc and the spheres are simple frames with feet that slide along the slots shown in Figure (4). The air velocity vs. location can be measured by the students or simply provided, Figure (5).

Figure (5)



2. Experiments That Can Be Conducted

The following are typical experiments that we conduct with this equipment:

1. The energy balance on the hair dryer to determine the air mass flow rate, with proof that one can ignore the KE change in the air.
2. Forced convection heat transfer coefficient from the front and rear of a heated disc in the air stream
3. Free convection heat transfer coefficient from the vertical disc
4. Transient heat transfer from a steel and nylon sphere in free and forced convection, which illustrates the Biot number significance
5. Decay of temperature and velocity on the jet centerline (not described)
6. Velocity and temperature profile of the air jet (not described)

2.1 Experiment 1: Hair Dryer Airflow Rate

This is one of the simplest experiments one can conduct with this apparatus. The airflow rate through the hair dryer is easily determined if we equate the air temperature change to the energy input to the device, that is:

$$\dot{W} = \dot{m}c_p[T_o - T_i]$$

To do so, we must neglect the changes in kinetic and potential energy of the airflow and any heat loss from the hair dryer casing to the surroundings. The students do not know that these items are small enough to ignore. As a result, we can simply tell them that these assumptions are reasonable or use separate experiments to illustrate.

In this basic experiment, the wattmeter gives the power input. With the mass flow rate determined, the outlet air velocity is determined from the area of the outlet and the hot air density. Students can determine the outlet air density from the temperature. The kinetic energy can then be calculated to verify that it is relatively small. Here is the report sheet that students fill out (with the answers).

2.1.1 Sample Student Report

- Turn on the wattmeter to read Watts.
- Turn on the hair dryer at max fan and max heat
- Allow about 2 minutes for the temperatures to become constant

Record the data:

1. T_{in} (ºC) = 22 T_{out}(ºC) = 73 Watts = 1340 .
2. [4] Calculate the air mass flow rate = 0.026 kg/s

   (Specific heat of air is c_p = 1006 J/kg-K)

If the hair dryer outlet tube diameter is 44 mm, calculate what the air velocity would be here. For this, you will need the density at the higher temperature. Figure out how to determine this using the ideal gas equation. You should be able to do this without knowing the ideal gas constant for air. Assume that the inlet air density is 1.2 kg/m^3 at 20ºC (293K).

3. Outlet tube area A (m^2) = 0.00152 .
4. [4] Outlet air density = 1.016 kg/m^3 = $\frac{1.2[20+273]}{[73+273]} = 1.016$
5. [2] Outlet air velocity (m/s) = 16.8 = m/[ρA] = $\frac{0.026}{[0.00152 \times 1.016]} = 16.8$
6. [4] Determine the <u>kinetic energy per unit mass</u> associated with the outlet air velocity.

   KE = $16.8^2/2$ = 141 . What are the units? N-m/kg .

   (Note: Must be energy units, not m^2/s^2)
7. [2]The total kinetic energy is the mass flow rate times the KE per unit mass you just determined. Calculate what this is in Watts.

   Total KE = 3.7 W
8. [4] Using this, determine whether ignoring the KE change in the energy equation was a reasonable assumption. Explain why or why not.

   We can ignore the KE because it is much less than the total input Watts

---

This simple experiment can take students several hours. Thus, we tend to avoid imposing other issues such as measuring the heat loss from the insulated box and hair dryer casing to verify that it is small enough to ignore. The time required is longer because the instructor and student assistants work closely with each group to ask probing questions. In addition, as we will expand upon in a later section, student life experiences with physical devices have become so limited that they may not execute even simple testing without considerable guidance.

2.1.2 Complementary Studies with the Hair Dryer 1

It is interesting to put three different watt meters in series as illustrated in Figure (6). In this arrangement, we illustrate the evolution of the instruments and encourage a discussion of why they all will indicate a slightly different value. Students can speculate on whether the instruments themselves consume some power and switch the instruments around to confirm.

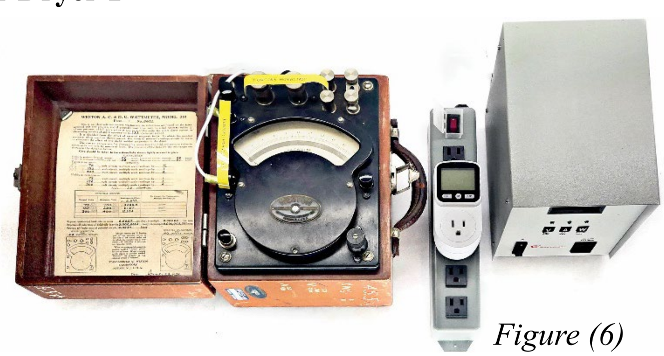


Figure (6)

The precision of the 1880 instrument is comparable to the much less expensive 2020 version. We also illustrate the internals of the old Weston instrument because the beauty and complexity this far in the past is not often appreciated.

2.1.3 Complementary Studies with the Hair Dryer 2

Calculate the heat loss through the insulation on the collection box. Here it is reasonable to take the surface temperatures on the inside and outside to be those of the air since the thermal resistance of the insulation is very large. The idea that this simple model using conduction through a plane wall gives us the maximum possible heat loss from the box and is sufficient to determine that this loss is negligible compared to the input power. The determination of the actual convection coefficients on the inside and outside of the box is difficult and, because of the objective of the exercise, this simplification is what the experienced engineer would use. Such skill is not obvious to the students. We have surface thermocouples on a separate unit to verify the assumption

2.1.4 Complementary Studies with the Hair Dryer 3

Verify that the heat loss from the hair dryer body to the ambient is small enough to ignore. For this, a separate setup with the hair dryer wired such that we can energize the heating coil without air flow is used. The power to the heating coil is set so that the temperature of the hair dryer tube is the same as when it is operating.

In this last example, it is important to have the student coach or the instructor discuss how the experienced engineer would estimate the heat loss from the hair dryer surface.

a. The temperature of the casing has to be low enough that the user does not get burned. The pain limit of human skin is on the order of 45°C so a temperature difference between the casing and the ambient will be about 25°C.

b. The surface area of the dryer is probably 0.1 m^2

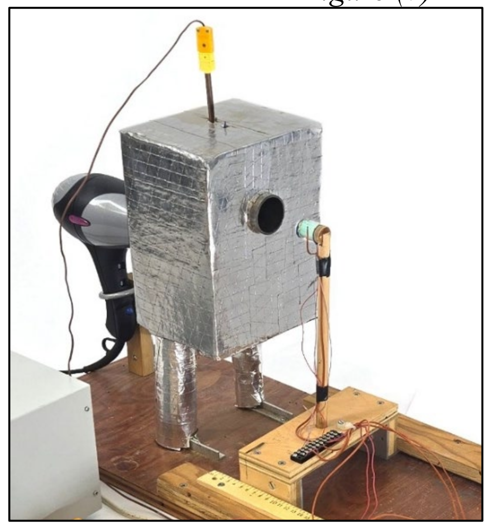
c. A typical convection coefficient would be 15 W/m^2-K.

d. Thus, the convection heat loss would be (15)(0.1)(25) = 37.5 Watts.
The hair dryer uses about 1200 Watts, so convective heat loss is 5% or less

It is best not to include these additional items as part of the first experiment because students have difficulty in recognizing the most important messages from the activity. Determining the air flow rate illustrates how one can apply conservation of energy to determine something that one cannot measure directly. That there is uncertainty in the measured parameters is a second important issue, which is better addressed in a separate experiment,

2.2 Experiment 2: Forced Convection from the Disc

Figure (7)



In this experiment, cold air is blown over the heated disc, Figure (7). The air velocity over the disc is varied by placing it at different locations downstream and using the hair dryer on "low" and "high" settings. We tell the students what voltage to apply to the disc heater for each condition since melting the Styrofoam backing is to be avoided. The resistance of the heater is used along with the supplied voltage to calculate the input power.

We subtract the radiation loss and graph the Nusselt vs. Reynolds number results. For comparison, we show the traditional textbook relations, as well as, the effects of free-stream turbulence.

Turbulence in the jet is Tu = 0.1 to 0.2 and has a significant effect (not accounted for in textbook correlations). The need to consider this in practical applications has been pointed out by Scott [2], based on many previous works such as [6] [7]. Based on a number of published papers, we use the following relations for air:

For disc facing the airflow:

$$Nu = \frac{\hbar D}{K} = 1.2 + 0.79\left[1 + \sqrt{Tu\sqrt{Re}}\right]\sqrt{Re} \qquad (1)$$

Separated flow behind the disc:

$$\mathrm{Nu} = \frac{\hbar \mathrm{D}}{\mathrm{K}} = 1.2 + 0.2\left[1 + 6300\left\{\frac{\mathrm{Tu}}{\mathrm{Re}}\right\}^{\frac{3}{4}}\right]\mathrm{Re}^{\frac{2}{3}} \qquad (2)$$

If we conduct the forced and free convection tests in one session, then the spreadsheet for data reduction is provided. If we run the two cases in two separate 3-hour sessions, then we can have the students set up the spreadsheet. Figure (8) shows typical results for the forced convection test.

Figure (8)

Disc Direction		Face Backwards
Disc Dia	[cm]	1.9
Insulation Thickness	[cm]	1.27
Insulation	[W/m-K]	0.032
Heater	[Ω]	68.6

Run		1	2	3	4	5	6
Blower Setting		Hi	Hi	Low	Low	Low	Low
x	[cm]	10	15	10	20	30	40
Air Velocity [m/s]	[m/s]	7.3	6.4	5.8	4.5	3.6	2.9
Recommended Volts	[V]	10	9	7	7	7	7
Volts	[V]	10.02	8.78	6.884	6.937	6.939	6.943
$T_1=T_{inf}$	[°C]	24.8	24	21.4	20.9	20.5	20.3
T_2	[°C]	55.9	49.2	40.2	40.9	42	43.5
T_3	[°C]	25.5	25.2	24.9	23.9	23.1	22.8
Watts	[W]	1.4636	1.1237	0.6908	0.7015	0.7019	0.7027
Radition Loss	[W]	0.0604	0.0472	0.0333	0.0354	0.0382	0.0415
Conduction Loss	[W]	0.0217	0.0171	0.0109	0.0121	0.0135	0.0148
Convection Net	[W]	1.3814	1.0594	0.6466	0.6539	0.6502	0.6464
h	[W/m^2-K]	156.7	148.3	121.3	115.3	106.7	98.3
$T_{Average\ Air}$	[K]	313.35	309.6	303.8	303.9	304.25	304.9
ρ_{AIR}	[kg/m^3]	1.13	1.14	1.16	1.16	1.16	1.16
k	[W/m-K]	0.0272	0.0269	0.0265	0.0265	0.0265	0.0266
μ	[kg/m-s]	1.92E-05	1.90E-05	1.88E-05	1.88E-05	1.88E-05	1.88E-05
Reynolds Number		5439	4870	4563	3538	2825	2267
Nusselt Number		109.3	104.6	87	82.7	76.4	70.3

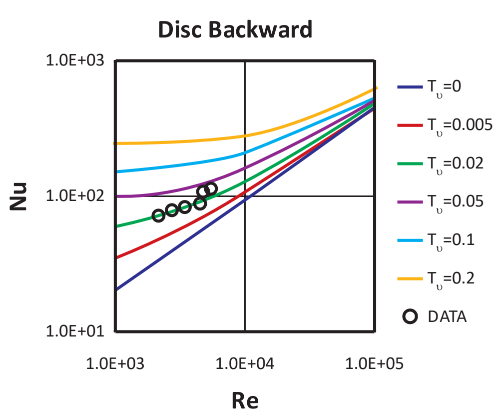
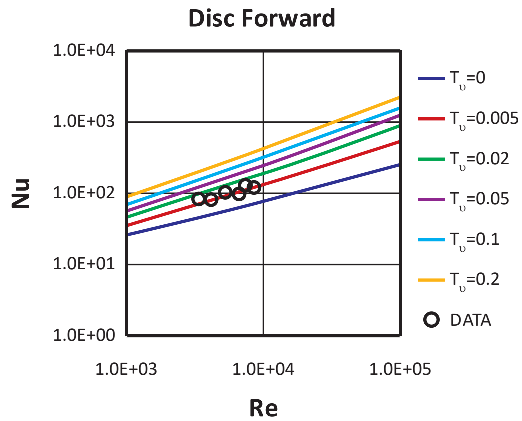


Figure (8) cont.

Disc Direction		Face Forward
Disc Dia	[cm]	1.9
Insulation Thickness	[cm]	1.27
Insulation	[W/m-K]	0.032
Heater	[Ω]	68.6

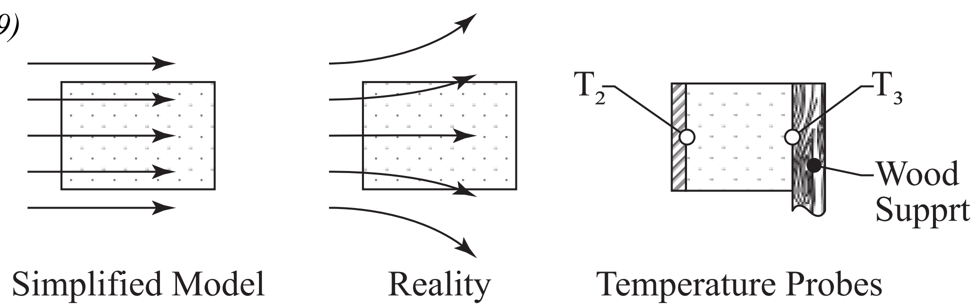
Run		1	2	3	4	5	6
Blower Setting		Hi	Hi	Low	Low	Low	Low
x	[cm]	10	15	10	20	30	40
Air Velocity [m/s]	[m/s]	7.3	6.4	5.8	4.5	3.6	2.9
DATA ENTRY							
Recommended Volts	[V]	9	9	7	7	7	7
Volts	[V]	8.7	8.8	6.995	6.981	6.972	6.948
$T_1=T_{inf}$	[°C]	22	23.7	22.5	21	20.5	20
T_2	[°C]	44.5	45.8	38.6	39	40.8	40.7
T_3	[°C]	25.4	25.4	25.2	23.9	23.5	23
CALCULATIONS							
Watts	[W]	1.1034	1.1289	0.7133	0.7104	0.7086	0.7087
Radition Loss	[W]	0.0408	0.0406	0.0284	0.0316	0.0359	0.0365
Conduction Loss	[W]	0.0139	0.0153	0.0096	0.0108	0.0124	0.0126
Convection Net	[W]	1.0486	1.0729	0.6753	0.668	0.6604	0.6546
h	[W/m^2-K]	164.4	171.2	147.9	130.9	114.7	111.5
$T_{Average\ Air}$	[K]	306.25	307.75	303.55	303	303.65	303.35
ρ_{AIR}	[kg/m^3]	1.15	1.15	1.16	1.17	1.16	1.16
k_{AIR}	[W/m-K]	0.0267	0.0268	0.0265	0.0264	0.0265	0.0265
μ_{AIR}	[kg/m-s]	1.89E-05	1.89E-05	1.87E-05	1.87E-05	1.87E-05	1.87E-05
Reynolds Number		8471	7363	6837	5321	4241	3422
Nusselt Number		117.1	121.4	106.2	94.1	82.3	80.1



2.3 Experiment 3: Free Convection from the Disc

For free convection from the disc, we place it in still air and provide heat electrically. In this situation, the conduction loss through the Styrofoam is significant and needs to be accounted for. The lab manual illustrates the heat flow paths as illustrated in Figure (9)

Figure (9)



Treating the Styrofoam cylinder as a plane wall does not reflect the real situation. However, the conduction heat loss will be a linear function of any reasonably selected temperature difference. Thus, we choose to model the loss as:

$$\dot{Q} = C[T_2 - T_3] \tag{3}$$

Where the value of "C" is determined by blocking heat loss from the front of the disc. There are two ways to do this as illustrated in Figure (10)—Method (A), and Figure (11)—Method (B) used by students.

Figure (10)—Method(A)

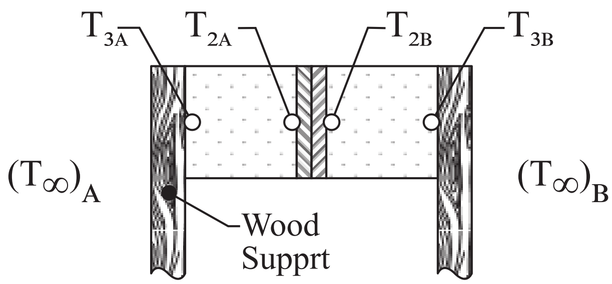
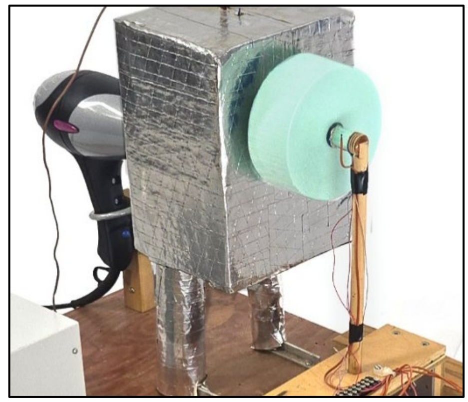
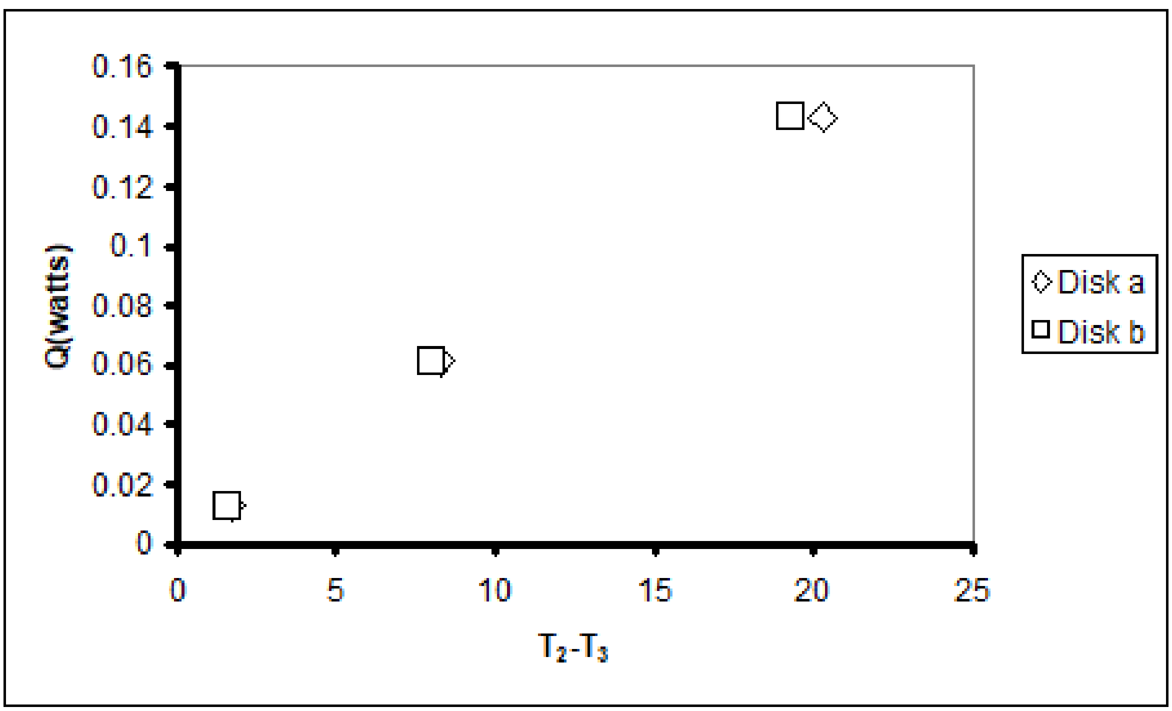


Figure (11)—Method (B)



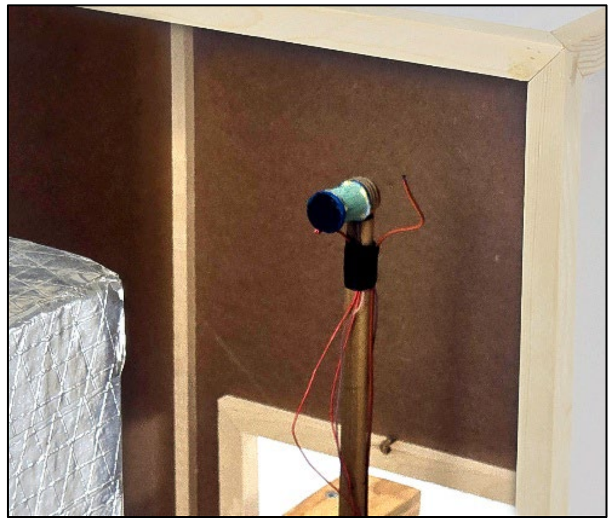
The value of "C" determined for several power inputs comes out essentially the same for both methods. We have the students use Method (B). Results of heat loss vs. temperature difference are essentially the same for both methods as Figure (12) shows.

Figure (12)



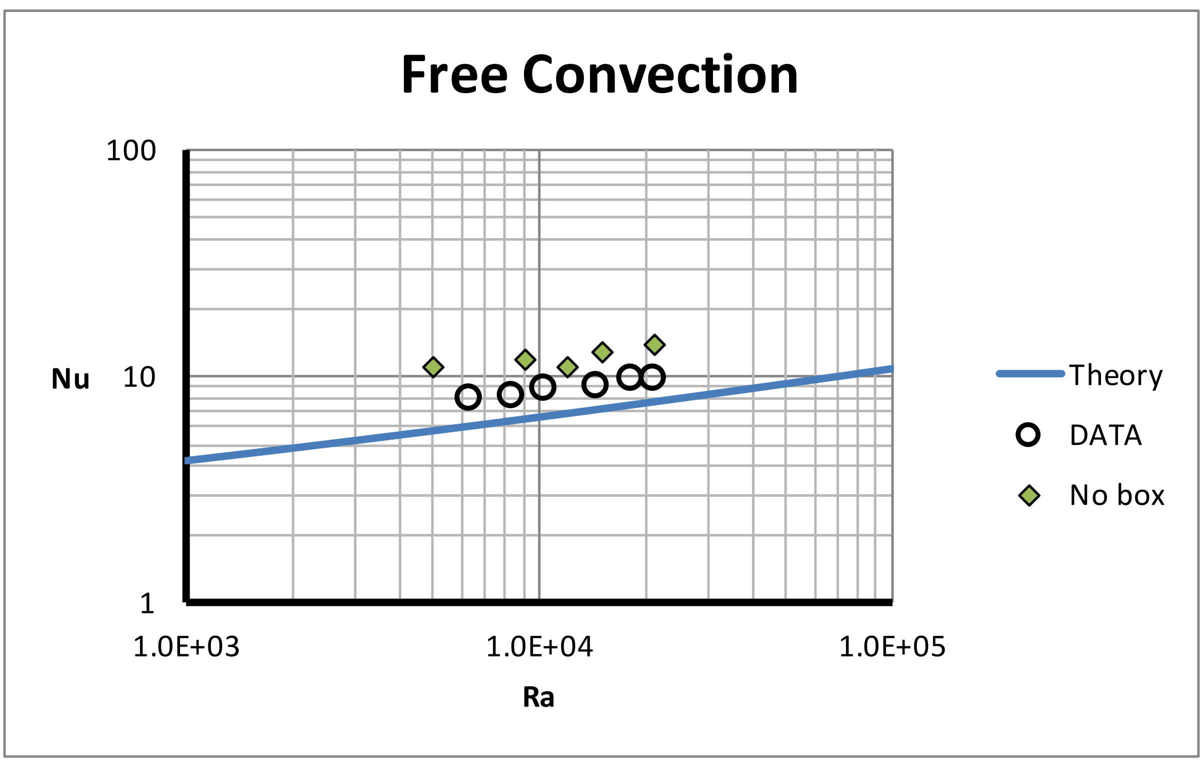
The textbook Nusselt vs. Rayleigh number relation for free convection on the vertical disc always gives a lower Nu than students measure. The lesson they learn is that there are no absolutely still air situations, especially inside a building. We employ a box enclosure as shown in Figure (13)

Figure (13)



Typical student results are shown below in Figure (14)

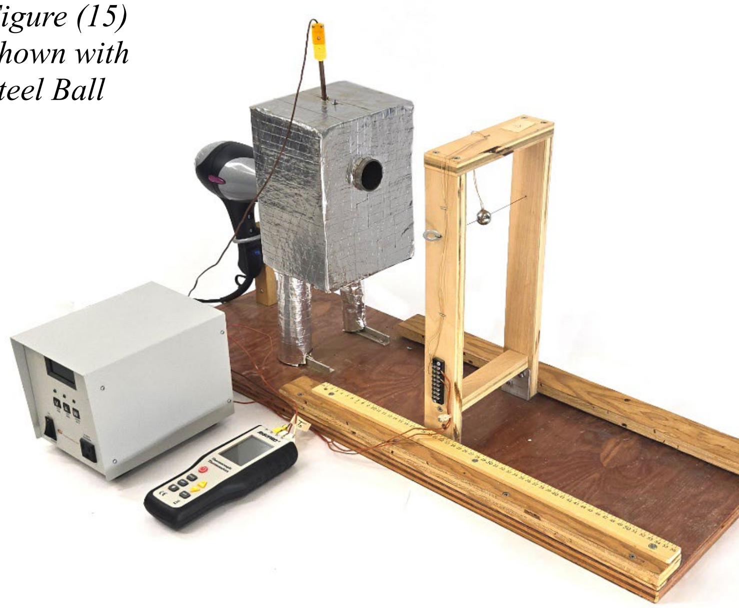
Figure (14)



2.4 Experiment 4: Transient Heating and Cooling of a Sphere

In these tests we subject the steel and nylon spheres to hot air from the hair dryer, Figure (15). We monitor the temperature increase of the surface and center of the sphere. Then we turn off the hair dryer and let the spheres cool down by free convection.

Figure (15)
Shown with
Steel Ball



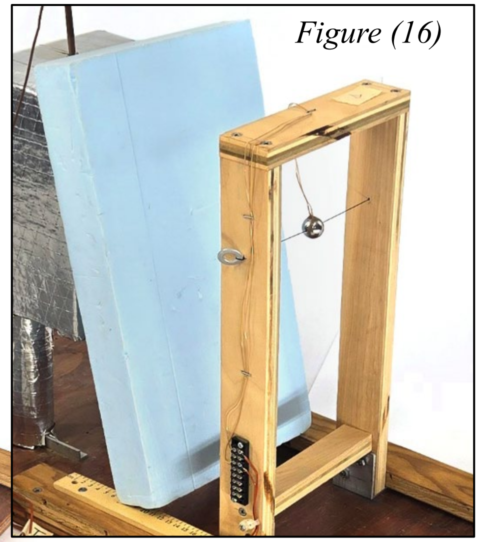
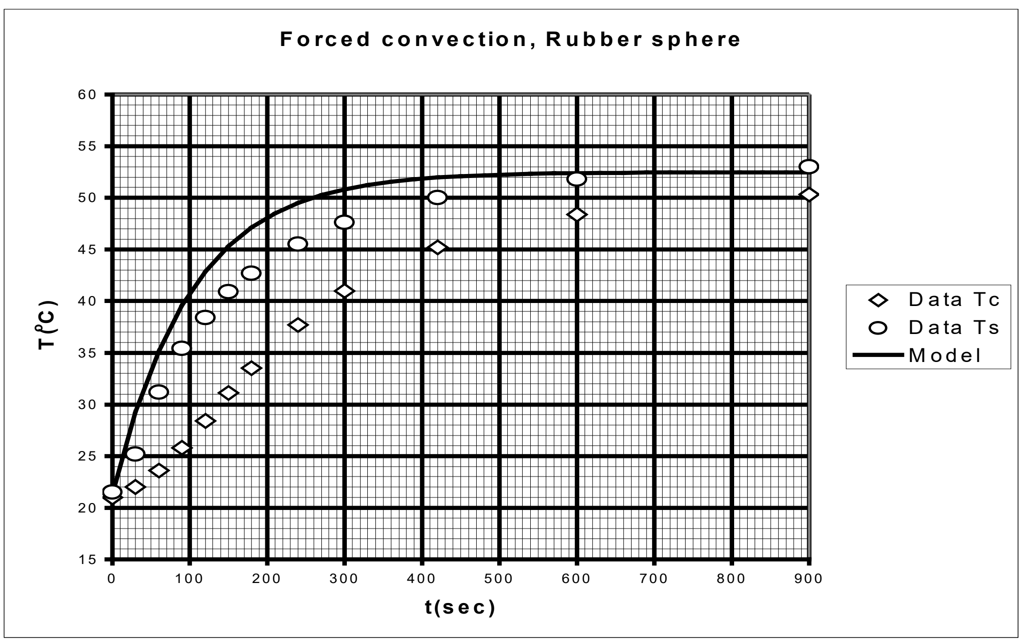


Figure (16)

When the experiment starts, we cover the air outlet for 2 minutes to allow the hair dryer outlet temperature to stabilize. Then the Styrofoam block, Figure (16), is removed and timing starts. Typical student data taken during the nylon sphere warmup is shown in Figure (17).

Figure (17)



The hair dryer is now turned off and the sphere is cooled by free convection. In this case, even the steel sphere shows some difference between the surface and center temperatures.

We do not use any data acquisition system for these experiments. Student must use their iPhone timer and manually write down the temperatures at the times on the data sheet. The datasheet for transient heating and cooling of the nylon sphere is illustrated in Figure (18)

Figure (18)

DATA SHEET 2: Nylon sphere		Enter data into excel spreadsheet as time between data points gets large	
Forced convection warmup test		Ambient T_a(°C)=	
Time (t)	T_c(°C)	T_s(°C)	Air chamber T_o (°C)
0			
30 sec			
1 min (60s)			
1.5 min (90s)			
2 min (120s)			
2.5 min (150s)			
3 min (180s)			
4 min (240s)			
5 min (300s)			
7 min (420s)			
10 min (600s)			
15 min (900s)			
Free convection cooldown test		Ambient T_a(°C)=	
Time (t)	T_c(°C)	T_s(°C)	
0			
30 seconds			
1 min (60s)			
1.5 min (90s)			
2 min (120s)			
3 min (180s)			
5 min (300s)			
10 min (600s)			
15 min (900s)			
20 min (1200s)			

This requires the students to stay engaged with the experiment. During this time, the instructor and/or student assistant can ask questions and create dialog with the student group.

Equally important is the critique of the data as the experiment progresses. Students are prone to complete the test and then make a graph or do calculations. If there is something wrong with the procedure or equipment, they do not discover it until the test is over. The idea of "watching the data as the test takes place" needs to be demonstrated and enforced as a standard procedure in testing.

We also find that students cannot always detect problems with the data during the test. This is because, even with a "model" curve to compare with, what reasonable data "should" look like is not obvious. This is why we have them write down the data by hand, then watch the data accumulate on the graph, and have the instructor present to guide their work.

3. Learning Methods

3.1 Typical Questions Asked in the Lab Report

In addition to providing the results from the tests, each lab report asks questions such as illustrated here:

3.1.1 Scenario A

> [20] Bob plans to test discs for free convection that are 4 times larger in diameter than used in lab. He wants to estimate how much heater power will be required to bring the big disc to the same temperature as our rig in lab.
>
> Bob notes that the small test rig we used consumed about 0.5 Watts total with 0.15 Watts lost in free convection, 0.1 lost in radiation, and 0.25 lost by conduction through the back of the disc. He uses this logic instead of calculations. You fill in the results:
>
> a. Radiation loss is proportional to the area of the disc. If the disc diameter is 4 times the small disc, the radiation heat loss should be ______Watts.
>
> b. The conduction loss through the Styrofoam back should be proportional to the area of the disc also—the conduction heat loss should be: _____Watts.
>
> For the free convection loss from the disc, Bob thinks that he should increase the ratio by the area of the disc. Judy says it is not the case because the convection coefficient will not be the same with the bigger disc even though the temperature difference between the disc and the air will be the same. Radish agrees with Judy and says that we should be able to figure out how much more the convection loss will be. Elaine agrees with Judy, but says that we cannot estimate the convection loss knowing only the diameter.
>
> Who is right? ☐ Bob ☐ Judy ☐ Radish ☐ Elaine
>
> If you agree with Radish, what would the free convection loss be: __________

3.1.2 Scenario B

> [10]"The conduction loss in free convection is too large," says Masuma, "We should make the Blue Styrofoam cylinder behind the disc twice as thick. That would make the conduction loss half as much".
>
> Amin replies, "That is completely wrong! The thicker cylinder will have twice the surface area for heat loss to the ambient and thus draw MORE heat away."
>
> "Masuma is sort of right," says Grace, "The conduction loss will be less but not half as much."
>
> Who is right? ☐ Masuma ☐ Amin ☐ Grace

3.2 Student Learning Issues

When this author took laboratory courses in the 1960s at a large university, we were in lab groups of several dozen students. Typically, there would be one or two large test rigs, such as a wind tunnel, operated by a laboratory technician. A graduate student would lead us in observing the test and writing down the raw data. Then we would be required to calculate items such as the Reynolds number, compare our results with textbook correlations, and write a formal report. The test fixtures were such that the technicians did not want us to "touch" them ourselves, and the graduate student was not much more familiar with the situation than we were. The purpose or "objective" of the exercise was primarily to demonstrate that the textbook relations were reasonable and for us to practice writing a formal technical report.

Based on the author's experience, items such as experimental uncertainty and experimental methods have become equally important while formal report writing is less common in general engineering practice. But "hands on" experiences are more important than ever as current students have fewer of these. For these to occur, students have to be able to conduct the tests themselves and instructor have to be proactive to detect and address areas of thinking not well developed in student minds yet

The value of using smaller, easy to construct equipment such as described here, allows us to have many identical units which students may operate themselves in groups of 3-5 students.

Student difficulties in learning from these lab experiences are mostly due to their lack of observation of the world around them (see the book on extinction of experience).

This test rig has been in use for the past 35 years. As such, we have been able to see the difficulties students have with figuring out the simple activities required to conduct the tests. Without supervision, current students are not very good at this. And they tend to get frustrated if not given significant help. Thus, the value of having many of these simple rigs so that student groups of 3-4 students can have their own apparatus. We also have student assistants that have run these labs the year before as well as the instructor. These mentors are two for every 4 student teams (about) and are continuously circulating to assist in running the equipment as well as asking questions. First, they have to help students execute the instructions. Then they provide help in answering the questions provided (examples of these questions are given below)

In addition to the above difficulties, simple figuring out how to conduct the test does not come easily for some groups. If, for example, we avoid this by giving them step-by-step instructions such as:

1. Turn on the thermocouple readout device
2. Make sure the readout is displaying reasonable numbers
3. Turn on the hair dryer to max air flow and max heat etc.,

We often encounter situations like this:

"Professor, the outlet air temperature is not changing".

"Is there air coming out of the hair dryer?"

"Oh, no. Is there supposed to be?"

"Did you plug in the hair dryer?"

"Oh."

This example situation demonstrates how students are simply checking off actions in the instructions and not looking at the test rig at all. In reference to Bloom's Taxonomy of knowledge, comprehension, application, analysis, synthesis, and evaluation; students are apt to memorize the material (knowledge) to use it in the lab (application) and report the results (analysis) [9]. What is missing is comprehension. Students struggle when asked questions that do not require following a formula [10],[11] (See: *Typical Questions Asked in the Lab Report)*. As a professional, they will be required to recognize situations as to when to apply the principles, especially when the problem does not fit a textbook scenario [8].

Over the years, we have had to add more specific steps that students must check off as they progress. Much of this has been to prevent them from melting the Styrofoam or other damaging mistakes. In the above example, we could add a step "Check to make sure there is air coming out of the hair dryer". However, this does not solve the problem of students not thinking! This is one of many reasons why having sufficient instructor or student assistant interaction is critical [11].

Well-polished, purchase equipment with whistles and bells can get in the way of seeing basic principles that can be lived out with simple and common items (e.g. a Hairdryer). This helps the students to see that they are surrounded by engineering principles in the everyday and mundane. The technique exemplifies Vygotsky's zone of proximal development where you teach a student just outside of their range of knowledge [11]. In a high-tech laboratory, there is the potential for students assume that these principles only exist in such a setting and are beyond them—that cellphone development is only for tech companies, yet one day that could be them.

The current literature reinforces our observation of student deficiencies. Student difficulties in learning from these lab experiences are partly due to their lack of observation of the world around them through free play (see Rosen [3]) Combined with the rise of the impacts of mobile technology on attention, memory, and delay of gratification, we see these issues becoming more significant in the lab.[4],[5].

4. Nomenclature

c_p = Specific heat (J/kg-K)

D = Diameter (m)

$\hbar$ = Convection coefficient (W/m^2-K)

K = Thermal conductivity (W/m-K)

$\dot{m}$= Mass flow rate (kg/s)

Nu = Nusselt number, $\hbar$D/K

$\dot{Q}$= Heat flow (W)

Re = Reynolds number, $\rho D\forall/\mu$

T = Temperature (^{o}C)

Tu = Degree of turbulence, $\forall'/\forall$

$\forall$ = Velocity (m/s)

$\forall'$ = Velocity fluctuation (m/s)

ρ = Density (kg/m^3)

μ = Viscosity (kg/m-s)

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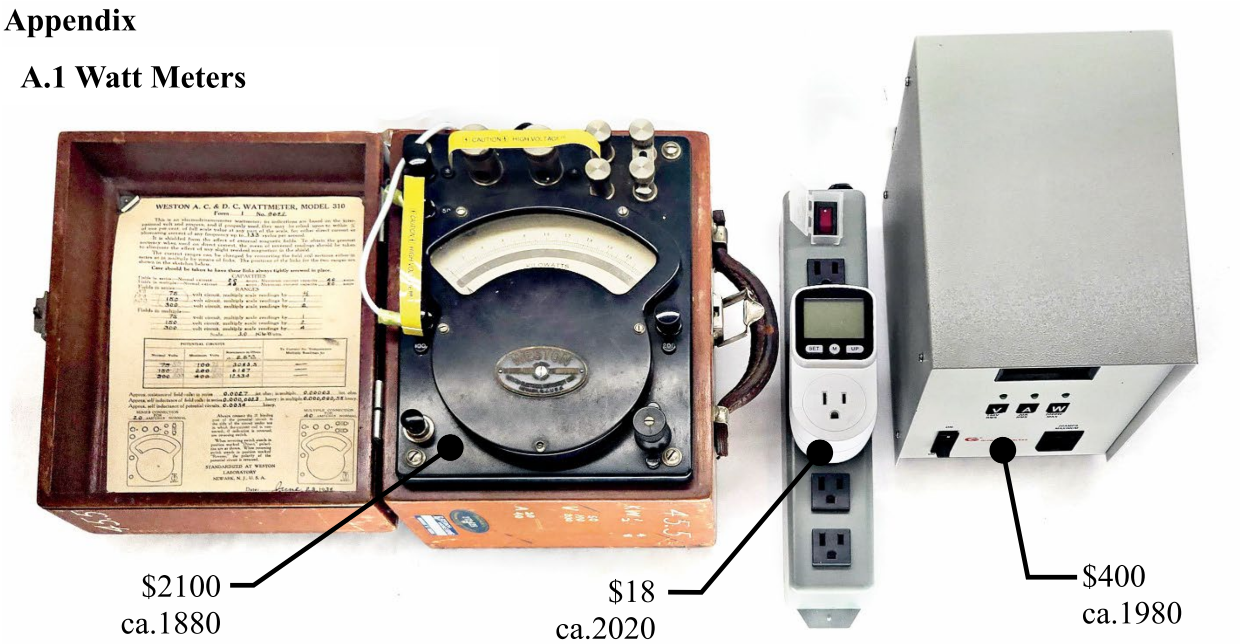
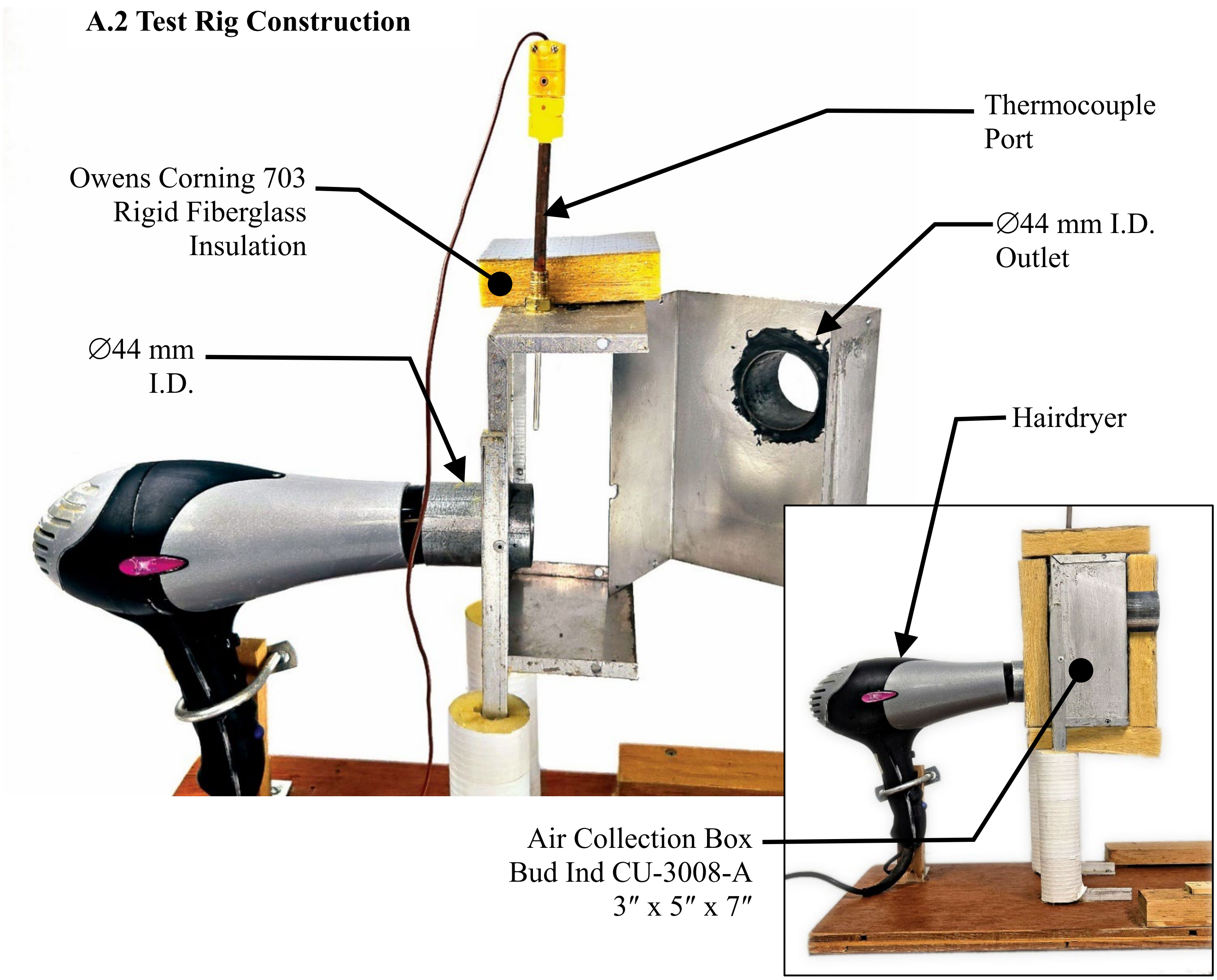
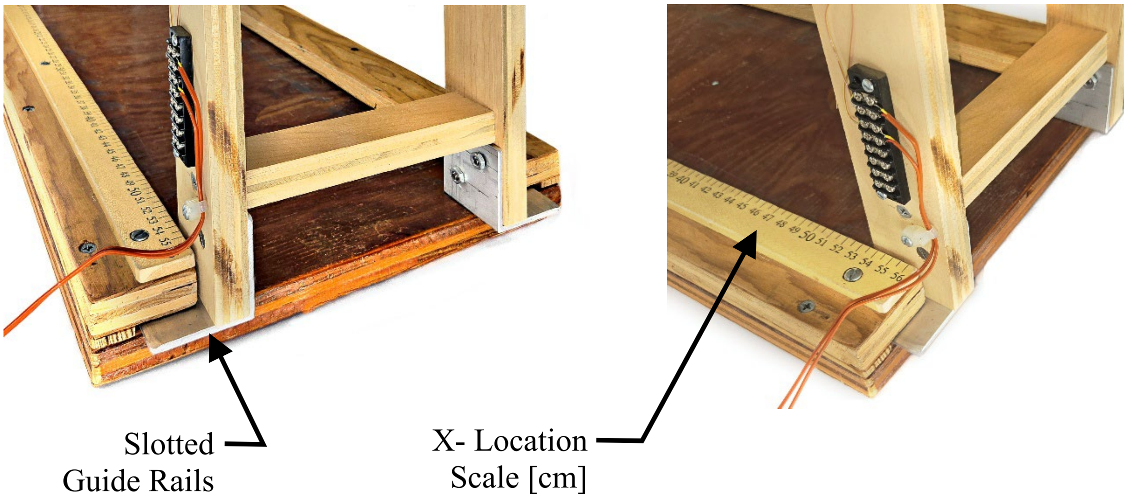
Appendix

A.1 Watt Meters

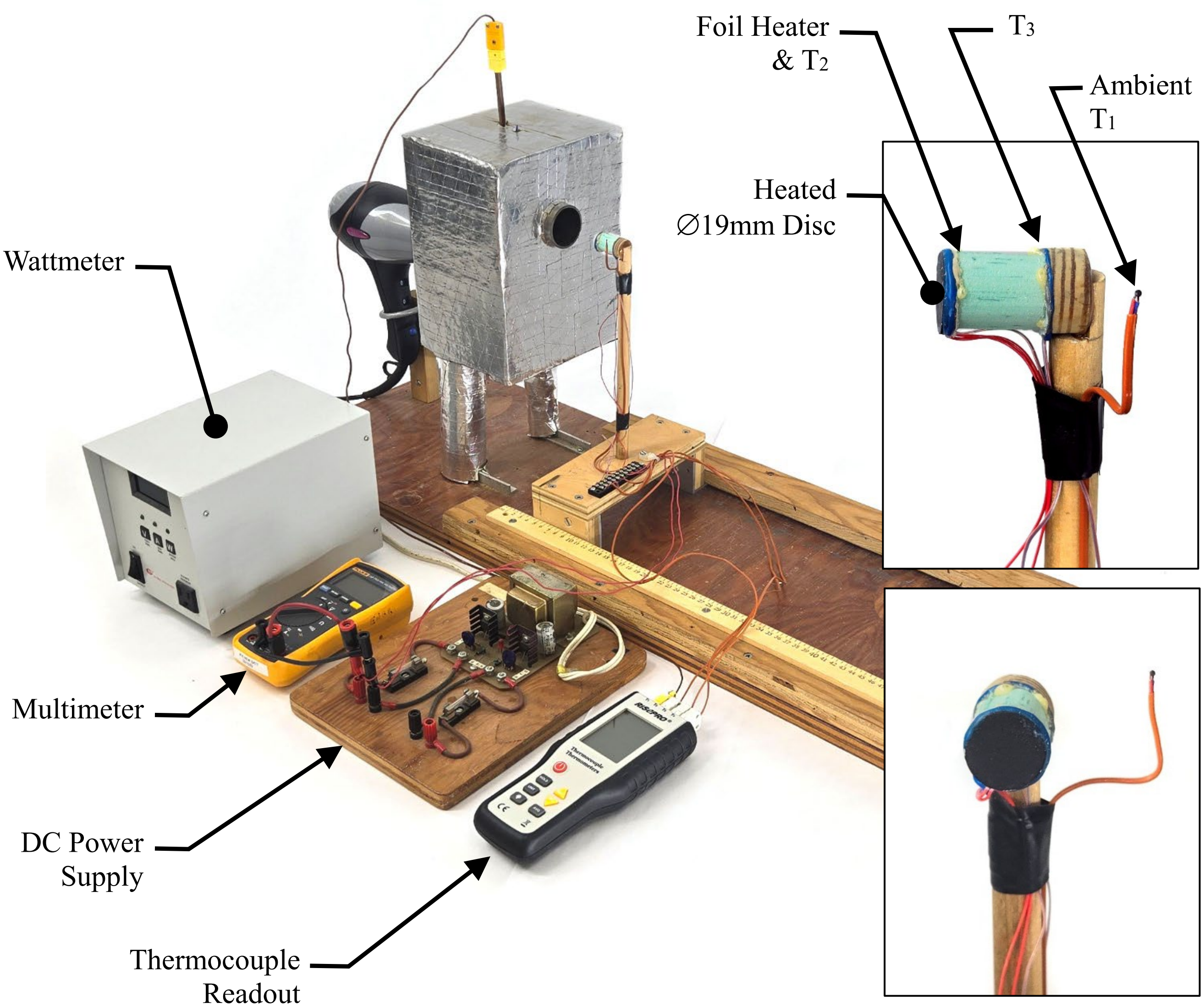


A.2 Test Rig Construction



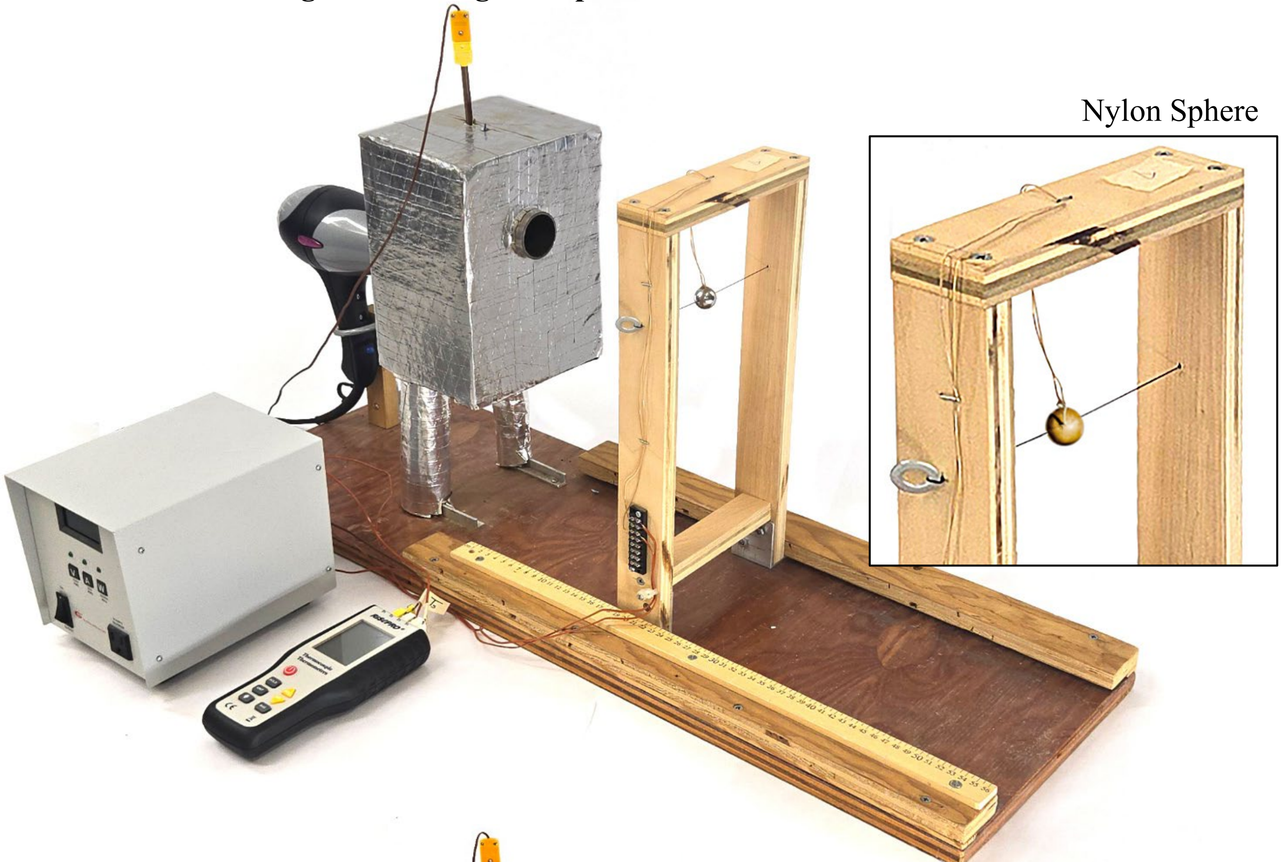


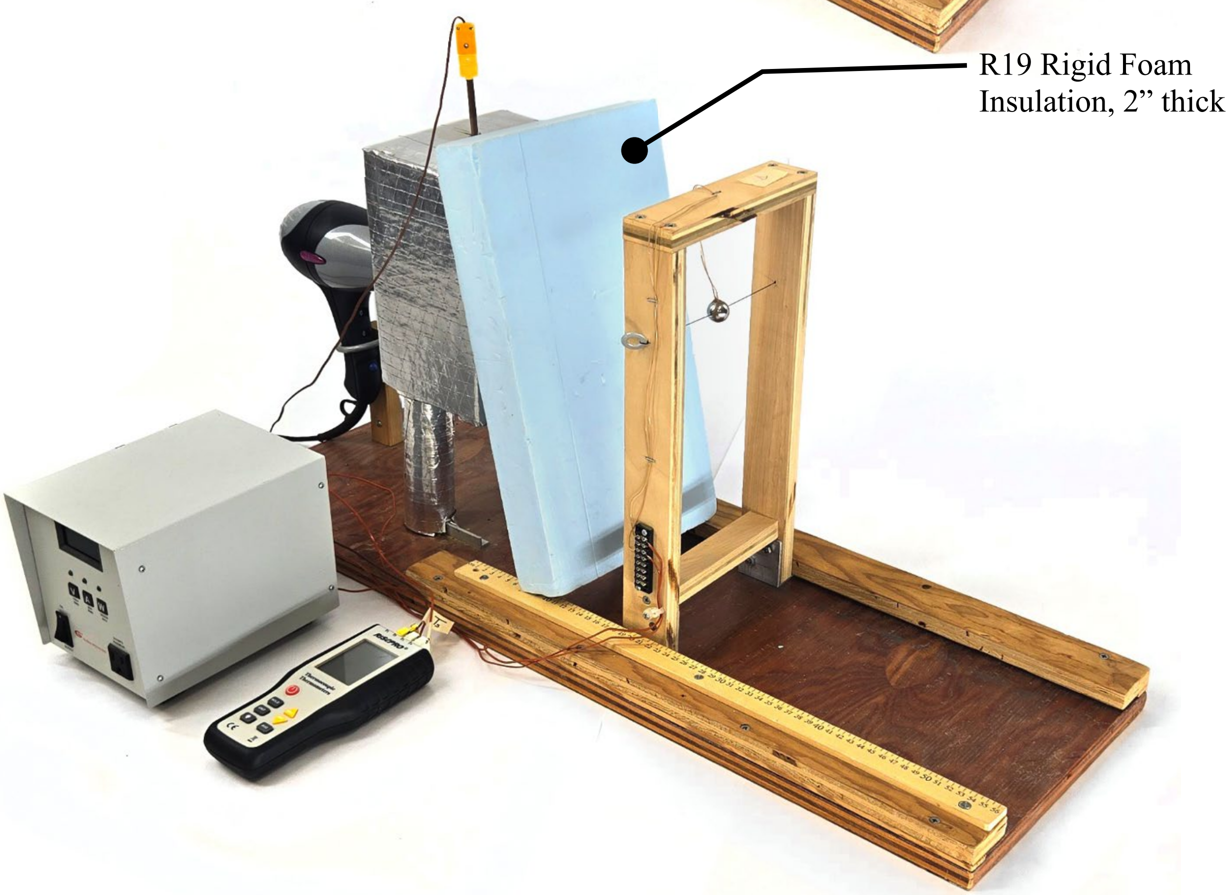
A.3 Free Convection Disk




R18 Rigid
Foam Board
∅5″ x 2″ Thick
Outlet Vent
Isolation Box
Used for Free
Convection Test

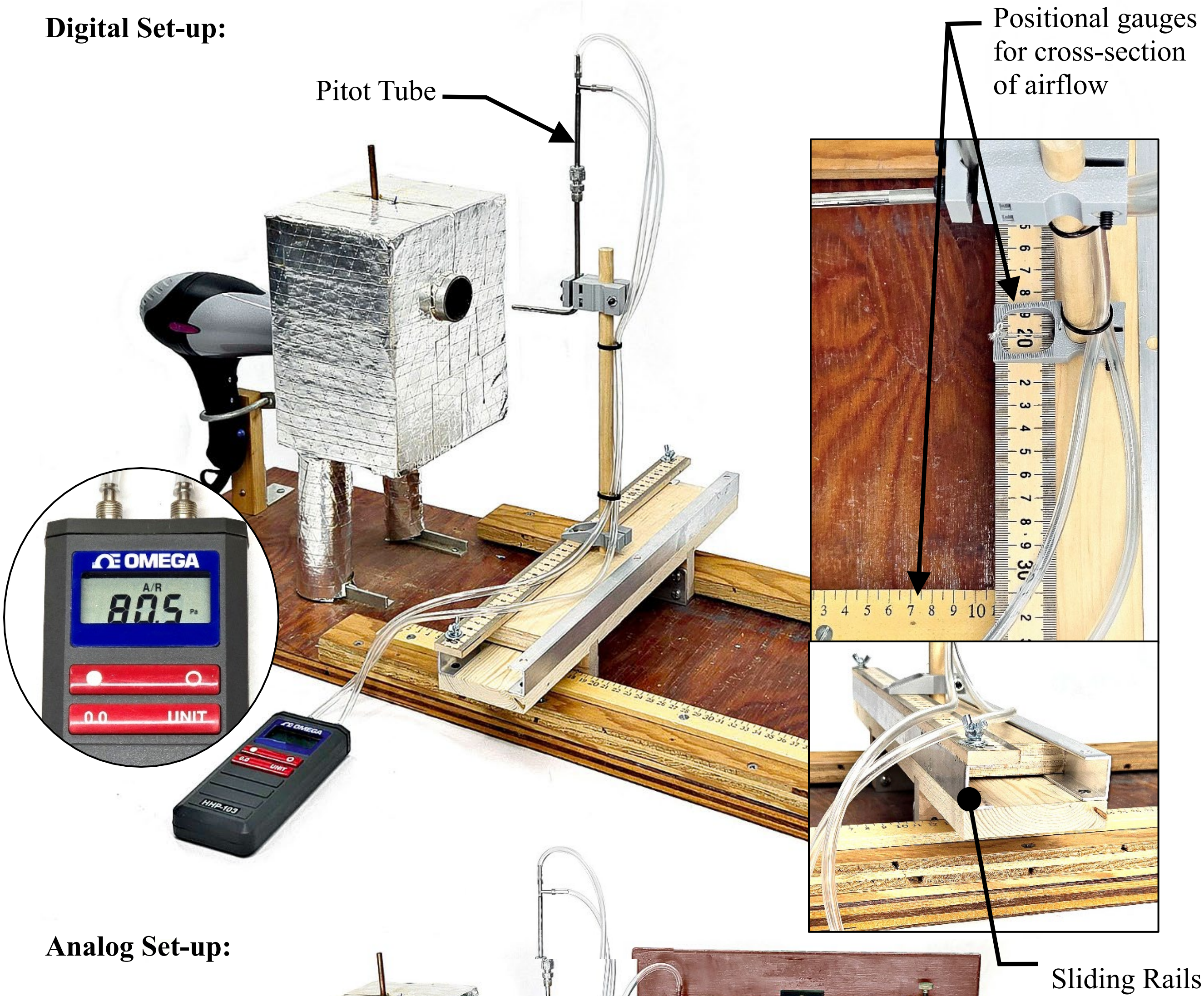
A.4 Transient Heating and Cooling of a Sphere





A.5 Velocity Profile of Air Stream

Digital Set-up:



Analog Set-up: