A Lab Experiment Involving Free Convection Heat Transfer from a Flat Horizontal Plate

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Abstract

A number of simple modifications were made to an experiment involving free convection heat transfer from a flat horizontal plate to make it safer and more convenient for use in a standard undergraduate laboratory. The experiment was made safer by employing a thinner (1.3 cm, or ½ in) aluminum plate that weighs about 6.5 kg and was made more convenient by using a laboratory oven for preheating, an insulated cooling stand to allow for free convection from only the exposed surface and the use of MATLAB® in place of TKSolver® for data analysis. A typical experiment with the apparatus will require less than 1 ½ hours, which will fit nicely into the time available for laboratory at most universities. The major cost in the experiment is the plate itself, which can be purchased for about $100. Reasonable free convection heat transfer coefficients of 6-8 $\frac{W}{m^2K}$ were obtained experimentally, which compare favorably with coefficients of 5-7 $\frac{W}{m^2K}$ from the Churchill/Chu relationship.

Keywords

laboratory, heat transfer, free convection, experimentation, modeling

Introduction

Laboratory is an essential part of the undergraduate curriculum in every field of engineering [1]. Although the number and types of laboratories can vary from discipline to discipline and school to school, undergraduate laboratories are very important because they introduce students to important engineering equipment and illustrate many of the principles and correlations that are presented in the classroom. Laboratories also give students a chance to work with their hands and develop important teamwork and leadership skills. Written and oral communication skills are strengthened in the preparation of written reports and oral presentations. Indeed, ABET Course Instructional Outcomes 3 (an ability to communicate effectively with a range of audiences), 5 (an ability to function effectively on a team . . .) and 6 (an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions) are most easily satisfied through laboratory and capstone design activities.

In teaching undergraduate laboratory, the development of a “stable” of good quality lab experiments is essential. The experiments can be either virtual or physical (hands-on with the equipment), although there have been many discussions on the pros and cons of using each of these types of undergraduate labs. Korestky *et al*. [2] offered an opinion that virtual labs are better for experimental design, critical thinking and dealing with ambiguity, while physical labs are better for understanding lab protocols and specific content. Wiesner and Lan [3] state that physical experiments need to remain in the curriculum but note that virtual labs can also be used without compromising student learning. Regardless of the type of lab, several labs or lab variations are necessary so that the instructor can "mix it up" each semester and hopefully not see student lab report submittals from previous semesters.

Penney and Clausen [4] developed a number of fluids and heat transfer experiments that could be used either as laboratory experiments or as demonstrations in the classroom. Almost all of the experiments were constructed from scrap materials or materials that were readily available in most engineering machine shops. One of these experiments investigated the heat transfer from an upward facing horizontal flat plate by free convection [5]. The experiment gave reasonable results ($h_{EXP} = 8 \frac{W}{m^2K}$ vs. $h_{CORR} = 5.6\frac{W}{m^2K}$) but the aluminum plate utilized in the experimental work was a bit heavy and cumbersome in size (45.7 cm x 30.5 cm x 3.8 cm, weighing 14.4 kg), while the heat-up time in an insulated box using a hair dryer was too long (nearly an hour) and the cool down time was also a bit too long (over an hour) to easily accomplish the experiment in a standard lab period.

As an Honors project, Alexa Moreno was charged with modifying this free convection experiment as needed to fit into a standard laboratory period and also modify the experiment so that it can be carried out more safely. In addition, she was to modify the numerical solution of the resulting differential equation to use Matlab® instead of TKSolver®. With these changes, the overall objectives of this experiment were to:

1. Determine the experimental free convection heat transfer coefficient for the top surface of a horizontal hot plate exposed to air
2. Compare the results with results generated from the appropriate correlation of Churchill and Chu [6].

Experimental

Apparatus

The following equipment were used in carrying out this experiment:

- A used Fisher Econotemp 30G laboratory oven with inside dimensions of 48 cm x 46 cm x 38 cm (19 in x 18 in x 15 in) was used in heating the plate
- A 61 cm x 30 cm x 1.3 cm (24 in x 12 in x ½ in) aluminum plate, with a black painted finish, 6.51 kg in weight, was the primary plate for use in the experiment. In addition, a second 61 cm x 30 cm x 2.5 cm (24 in x 12 in x 1 in) aluminum plate, with a black painted finish, 13 kg in weight, was also used in the development of the best operating conditions for the experiment.
    - A 10 cm (4 in) deep, 6.4 mm (¼ in) diameter hole was drilled in the center of the long side of each plate to accommodate the thermocouple, which was fully inserted into the hole.
- A 66 cm x 36 cm x 5 cm (26 in x 14 in x 2 in), inside dimensions, PVC box was used in forming the cooling stand
- THERMAX sheathing insulation, 1.3 cm (½ in) thick, 3.3 R factor, was used to insulate the plate when inside the PVC box. During cooling, the plate rested on three layers of

insulation inside the box and insulation was additionally placed along the perimeter of the box between the plate and the PVC.
- An Omega HH12 thermocouple reader
- Thermocouple wire: Teflon insulated, 24 gauge, type K—thermocouples were used to monitor the oven temperature and the temperature at the center of the plate
- Stopwatch
- Rubber stopper
- Pry bar, small, to more easily pick up the heavy plate

The experimental apparatus is shown in the photographs of Figures 1 and 2.

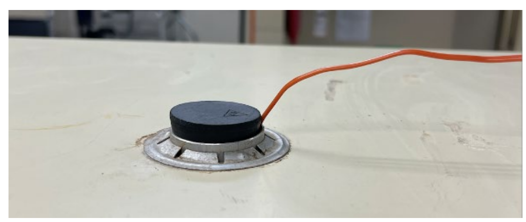

Figure 1. Heating the Plate (left) and Sealing the Oven with a Rubber Stopper (right)

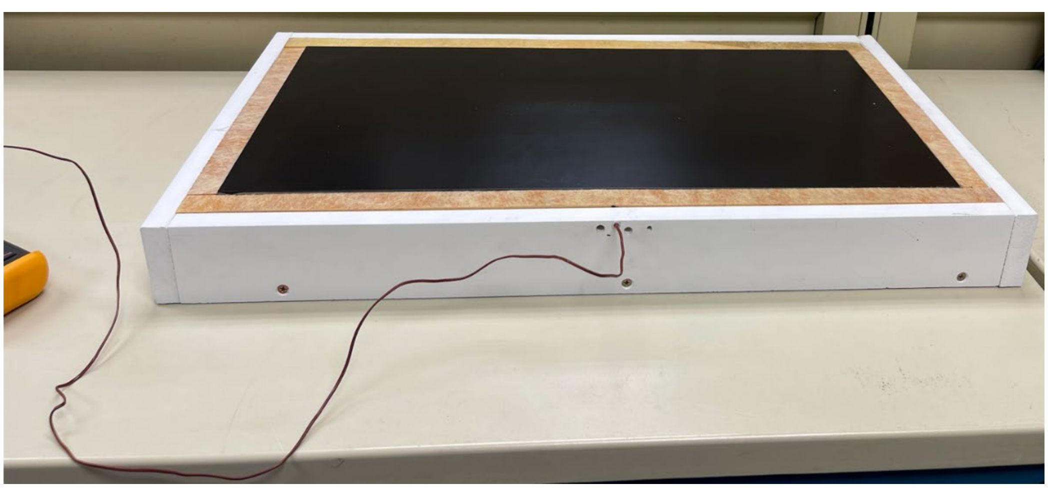

Figure 2. Monitoring the Cooling of the Insulated Plate as it Rests in the PVC Stand

Procedure

Setup

1. Determine the weight of the aluminum plate and the surface area of the face of the plate.
2. After placing the aluminum plate inside the pre-heated oven, as shown in Figure 1, close the oven door and heat the plate to an internal temperature of 60-135°C, with 85°C found as a good target temperature for use in the lab experiment.
3. Using insulated gloves and other protective equipment, move the plate to the PVC cooling stand, black side facing up, surrounded by thermal insulation on the bottom of the plate and the sides of the plate as shown in Figure 2. Insert the thermocouple into the side of the stand through the drilled in hole in line with the drilled hole in the aluminum plate to monitor the temperature changes with time.

Testing

1. Start the stopwatch as soon as the temperature is no longer climbing and record the initial temperature.
2. Record the time at each successive 1°C change in temperature until the temperature drops at least 20°C. In using an initial temperature of 85°C, a final temperature of 45°C works well.
3. Repeat the experiment as necessary.

Safety Concerns

1. Wear safety glasses at all times.
2. Be very careful when handling the aluminum plate, both hot and cold, because dropping it can potentially break bones.
3. Always wear protective clothing (heat resistant lab coat, sleeves and gloves that are protective to temperatures as high as 150°C) when handling the hot aluminum plate.

Experimental Data

As was noted in the Experimental section, two plates were purchased for use in the experiment:

- A 61 cm x 30 cm x 1.3 cm (24 in x 12 in x ½ in) aluminum plate, with a black painted finish, weight: 6.51 kg
- A second 61 cm x 30 cm x 2.5 cm (24 in x 12 in x 1 in) aluminum plate, with a black painted finish, weight: 13 kg

Experiments performed with the 2.5 cm (1 in) plate required more than three hours to heat the plate and then reduce the temperature by 20°C by free convection. In addition, the weight of the plate (13 kg) made it impractical for use in the undergraduate lab. The 2.5 cm (1 in) plate was thus eliminated for lab use and all future experiments were carried out with the 1.3 cm (½ in) plate.

Table 1 summarizes a number of heating experiments performed with the 1.3 cm (½ in) plate. The time required for heating depends on the oven setting, how long the oven was preheated prior to inserting the plate for heating and the desired final temperature. Having said all of this, preheating can be expected to require 30-50 min, which is acceptable for a standard laboratory period.

Table 1. Summary of Heating Experiments Performed with the 1.3 cm (½ in) Plate

Run	Initial Temperature, °C	Final Temperature, °C	Heating Time, min
1	21	103.5	30
2	21	85.3	40
3	21	132.3	30
4	21	115.9	30
5	21	64.0	30
6	21	69.9	30
7	21	105.5	50
8	21	100.3	40
9	21	85.0	50

Figure 3 presents typical results from the cooling of the 1.3 cm (½ in) plate, with temperature plotted on the y-axis and time plotted on the x-axis. The experimental results are shown as small circles on the figure. In this experiment, the initial temperature of the pre-heated plate was 357 K (84°C) and the final temperature after 2,000 s (33.3 min) was 318 K (45°C). Thus, the whole experiment could be carried out in 1 ½ hr, excluding the time to preheat the oven.

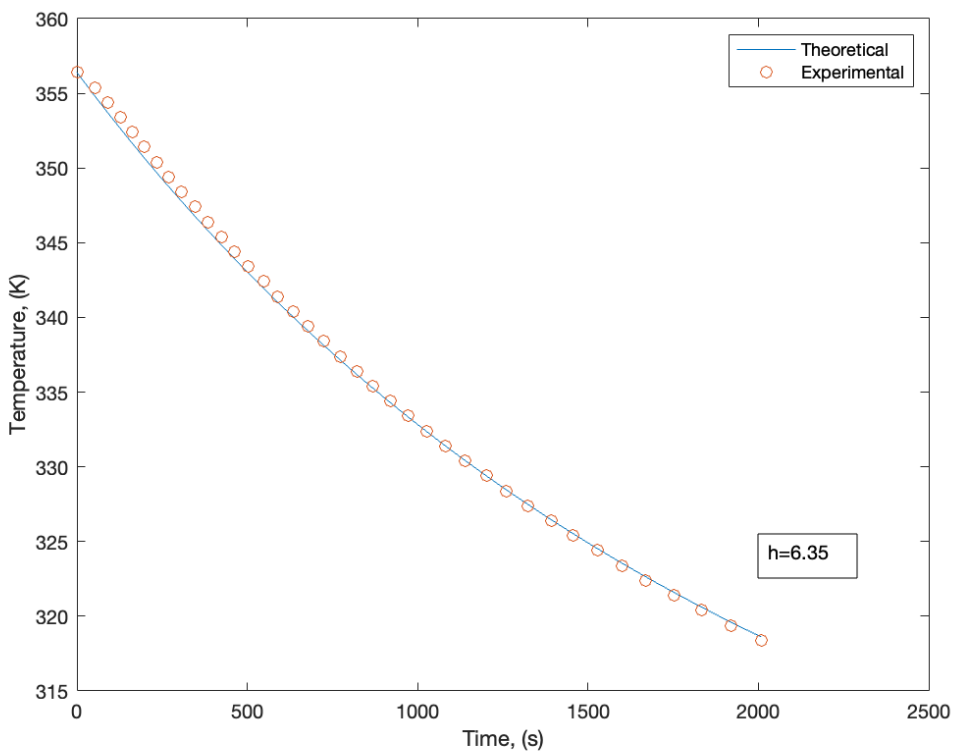

Figure 3. Typical Results from the Cooling of the Flat Plate by Free Convection

Data Reduction

The development of equations for the modeling of the experiment was previously presented by Clausen and Penney [5] and is only shown here for the convenience of the reader.

A heat balance on the center plate, with no heat generation, yields:

$$-q_{Out} = q_{Acc} \tag{1}$$

The plate is cooled by free convection and radiation:

$$q_{Out} = q_{Conv} + q_{Rad} = hA_s(T_s - T_a) + \varepsilon\sigma A_s(T_s^4 - T_a^4) \tag{2}$$

The plate accumulates heat with an inverse relationship to time as it cools back to room-temperature:

$$q_{ACC} = -M\left(C_p\right)\frac{dT}{dt} = -\rho V\left(C_p\right)\frac{dT}{dt} \tag{3}$$

Thus, the heat balance of Equation 1 yields Equation 4:

$$\left(hA_s(T_s - T_a) + \varepsilon\sigma A_s(T_s^4 - T_a^4)\right) = -\rho V\left(C_P\right)\frac{dT}{dt} \tag{4}$$

Experimental data of temperature vs. time were used to determine the "best fit" experimental heat transfer coefficient by integrating Equation 4 numerically using the MATLAB® ode-45 function. Other integration techniques may be used.

The heat transfer coefficient from the literature was determined using the correlation for free convection from a horizontal heated, upward-facing plate [6], shown in Equations 5a and 5b:

$$Nu = 0.54Ra^{\frac{1}{4}} \qquad 10^4 < Ra < 10^7 \tag{5a}$$

$$Nu = 0.15Ra^{\frac{1}{4}} \qquad 10^7 < Ra < 10^{11} \tag{5b}$$

where the Rayleigh number is calculated as in Equation 6:

$$Ra = \frac{g\beta(T_S - T_\infty)L^3}{\vartheta^2}\ Pr \tag{6}$$

In Equation 6, the length of the plate is the characteristic length in free convection and, for a horizontal flat plate, $L = \frac{A_S}{P}$. Assuming that the surrounding air is an ideal gas, the volumetric expansion coefficient may be calculated in Equation 7:

$$\beta = \frac{1}{T} \qquad (7)$$

Finally, h_{CORR} may be calculated from the Nusselt number:

$$h_{CORR} = \frac{kNu}{L} \qquad (8)$$

Reduced Results and Discussion

Along with the experimental data, Figure 3 also presents a curve showing the numerical integration of Equation 4 using the "best fit" experimental heat transfer coefficient. In this and all of the experiments, the experimental data and correlated data agreed very closely at all points on the curves. The emissivity (ε) of the black painted surface was assumed to be 0.98. The experimental heat transfer coefficient (h_{EXP}) was 6.35 $\frac{W}{m^2K}$ at a surface temperature of 356 K (83.4°C), while the coefficient based on the Churchill/Chu relationship (h_{CORR}), as calculated in Equations 5-8 was 6.39 $\frac{W}{m^2K}$.

Table 2 presents a summary of nine experiments in cooling the heated plate by natural convection. Shown for each run are the initial temperature of the plate, the final temperature of the plate and the time required to cool the plate. Initial temperatures ranging from 63-98°C were used, requiring cooling times of 18-33 min. Although it doesn't seem to matter very much, a good target starting temperature for future experimentation is 85°C. Also shown are the experimental heat transfer coefficients from Equation 4, the "best fit" coefficients calculated from the Churchill/Chu relationship and the errors assuming the correlation is correct. The average experimental coefficient was 7.1 $\frac{W}{m^2K}$ and the average coefficient from the correlation was 6.4 $\frac{W}{m^2K}$. The errors in the coefficients ranged from -0.3-32.6% with an average error of 11.4%. Experimental coefficients that are a bit higher than the Churchill/Chu relationship are expected due to unavoidable air currents that are present in the laboratory. It is also interesting to note that the experiments that were performed a bit earlier in the semester had less error than the experiments performed nearer the end of the semester.

Table 2. Summary of the Experimental Results and Heat Transfer Coefficients for the Cooling of a Flat Plate by Natural Convection

Run	Temperature, °C		Cooling time, min	h, $\frac{W}{m^2K}$		
	Initial	Final		h_{EXP}	h_{CORR}	% error
1	76	45	25.8	6.2	6.22	-0.3
2	84	45	25.8	6.35	6.39	-0.6
3	93	63	23.0	6.5	6.57	-1.1
4	98	58	30.3	7.0	7.36	-4.9
5	63	39	30.2	7.0	5.87	19.2
6	70	41	24.8	6.75	6.05	11.6
7	82	52	18.3	7.25	6.36	14.0
8	75	45	33.3	8.25	6.22	32.6
9	76	45	29.7	8.25	6.22	32.6

Conclusions and Future Work

Simple modifications were made to a laboratory experiment on the cooling of a plate by free convection which will make it easier and better to use in the undergraduate laboratory. The experiment was made safer by employing a thinner aluminum plate that weighs about 6.5 kg and was made more convenient by using a laboratory oven for preheating, an insulated cooling stand to allow for free convection from only the exposed surface and the use of MATLAB® in place of TKSolver® for data analysis. A typical experiment with the apparatus will require less than 1 ½ hr, which will fit nicely into the time available for laboratory at most universities. The major cost in the experiment is the plate itself, which can be purchased for about $100. Reasonable free convection heat transfer coefficients of 6-8 $\frac{W}{m^2K}$ were obtained experimentally, which compare favorably with coefficients of 5-7 $\frac{W}{m^2K}$ from the Churchill/Chu relationship.

The experiment with the horizontal flat plate could easily be modified to give a vertical orientation so that other heat transfer correlations could be tested. In addition, forced convection could be added to either experiment by employing fans to blow over the plates and once again test other heat transfer correlations.

Nomenclature

A_S	area for convection, m^2
C_p	specific heat of the aluminum plate or cylinder, J/kg K
g	gravitational constant, m/s^2
h	convection heat transfer coefficient, W/m^2 K
h_{CORR}	correlated heat transfer coefficient, W/m^2 K
h_{EXP}	experimental heat transfer coefficient, W/m^2 K
k	fluid thermal conductivity, W/mK
L	length of the plate or cylinder, m
m	mass of the plate or cylinder, kg
Nu	Nusselt number
P	Perimeter of rectangular plate, m
Pr	Prandtl number of the fluid
q_{OUT}	heat transfer out of the system, W
q_{ACC}	heat accumulated in the system, W
q_{CONV}	heat transfer by convection, W
q_{RAD}	heat transfer by radiation, W
Ra	Rayleigh number of the fluid
T_{ATM}	temperature of the surroundings (atmospheric), K
T_{PLATE}	temperature at the center of the plate, K
V	volume of the plate or cylinder, m^3
β	volumetric expansion coefficient, K^{-1}
ε	emissivity of the surface
μ	dynamic viscosity of air, Ns/m^2
ν	kinematic viscosity of air, m^2/s
ρ	density of the aluminum plate or cylinder, kg/m^3

σ Stefan-Boltzmann constant, W/m^2K^4

Acknowledgment

The authors acknowledge the skills of Mr. Dearl Peachee in purchasing and constructing the lab equipment.

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