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Heat Transfer from Plates

Leanza Trevino
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Heat Transfer from Plates

Leanza Treviño

A Thesis Presented to Committee on Undergraduate Studies
in the
College of Engineering, Ralph E. Martin Department of Chemical Engineering

in Partial Fulfillment of the Requirements
for the Degree with Honors
of Bachelor of Science in Chemical Engineering

University of Arkansas
Fayetteville, Arkansas

March 2023

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Summary

The purpose of this honors thesis is to create an experiment for the CHEG Lab I course. This is a continuation of work done by Alexa Moreno. She created an experiment to model free convection of a horizontal plate. In this report, free and forced convection of a vertical and horizontal plate, respectively are modeled. This report explains the motivation for creating this heat convection experiment, the results of performing the experiment, and provides recommendations for future work on this experiment.

Introduction

Undergraduate students pursuing a chemical engineering degree must successfully complete the chemical engineering Lab I and Lab II courses. The purpose of this honors thesis is to create an experiment for the Lab I course.

Previous work performed by Alexa Moreno modeled free convection of a horizontal plate. Over the course of nine experiments, she produced data with an average error of 13.05% as compared to a theoretical model. The same equipment was used for the experiments discussed here, with some additions for the forced convection experiment.

Students will be tasked to study free convective heat transfer by monitoring temperature changes over time for an aluminum plate that has been heated and allowed to cool in an insulated stand with the vertical face being exposed to atmospheric temperature and pressure. Forced convective heat transfer is studied by monitoring temperature changes over time for an aluminum plate that has been heated and allowed to cool in an insulated stand with the vertical face being exposed to forced convection via a set of fans blowing over the surface. The students will record experimental data and determine a best fit experimental heat transfer coefficient by using MATLAB to solve a differential equation for the heat balance. In addition, a theoretical heat transfer coefficient will be determined from empirical correlations (Cengel 2007, Table 9-1, p. 511). The experimental and theoretical heat transfer coefficients will be compared and discussed. Recommendations for further improvement include a more rigorous calculations approach that does not assume constant film properties.

Experimental Approach

The aluminum plate was painted black on the face that is to be exposed to air because the emissivity coefficient of black paint is known. The emissivity coefficient is used in the calculations for the experimental heat transfer coefficient. An insulated stand was built to prevent heat loss on all other sides of the plate aside from the face painted black. The stand was constructed with PVC material and built with enough room to have thermal insulation underneath the plate and around the sides of the plate. A hole was drilled in the stand, insulation, and plate large enough for a thermocouple wire to fit to monitor temperature changes over time. An oven, already owned by the chemical engineering department, was used to heat the aluminum plate as displayed in Figure 1.

Figure 1. Experimental Apparatus

A 0.5” plate was used for the experiment. The desired temperature range to monitor was 75°C to 45°C. Multiple runs were executed to ensure that the data extracted would prove beneficial for students to replicate and discuss. The total time for the experiment takes 50-60 minutes for one plate to heat and cool long enough to see the entire temperature range desired.

As Lab I is allotted a longer time slot, students may perform back-to-back experiments modeling both free and forced or free horizontal and vertical convection with the use of a second aluminum plate. This requires placing the second plate in the oven upon removal of the first. Running the series of two takes approximately 90 minutes.

Calculations Approach

Once sufficient data was collected, MATLAB's ode45 function was used to model the experiment. To determine the experimental heat transfer coefficient, the heat transfer coefficient was manually changed to determine the value at which the integrated differential equation best matched the experimental data plotted. This is a brute force method and most certainly not the most efficient way to find the coefficient. However, Lab I students have limited coding experience, so this method is a good approach for a beginner to try. In the future, more advanced, iteration-loop-based coding along with defining a metric to determine how well two lines match each other could be applied to find the exact number for the experimental heat transfer coefficient.

Results

A summary of the experiment time and errors for three free convection runs is displayed below in Table 1. Table 2 is a similar summary for forced convection results.

Table 1. Free Convection Experimental Data Summary

Run	Total Run Time (min)	Percent Error
1	53	17.1
2	60	23.3
3	46	17.1
Average	53	19.2

Table 2. Forced Convection Experimental Data Summary

Run	Total Run Time (min)	Percent Error
1	41	47.7
2	36	45.9
3	39	50.9
4*	50	49.9
Average	41.5	48.6

*Run 4 was left in oven too long, time to reach desired high temperature was approximately 10 minutes less than actual time left heating in oven.

Figures 2 and 3 show the experimental data from free and forced convection runs with low percentage errors.

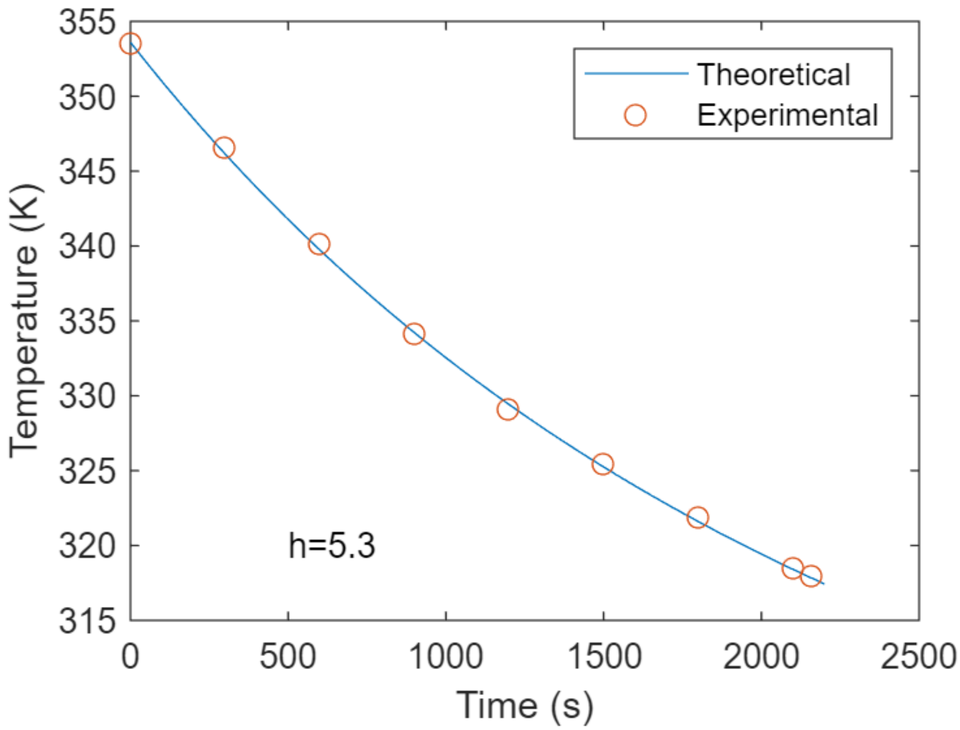


Figure 2. Run 1. Free Convection 4 Oct 2022

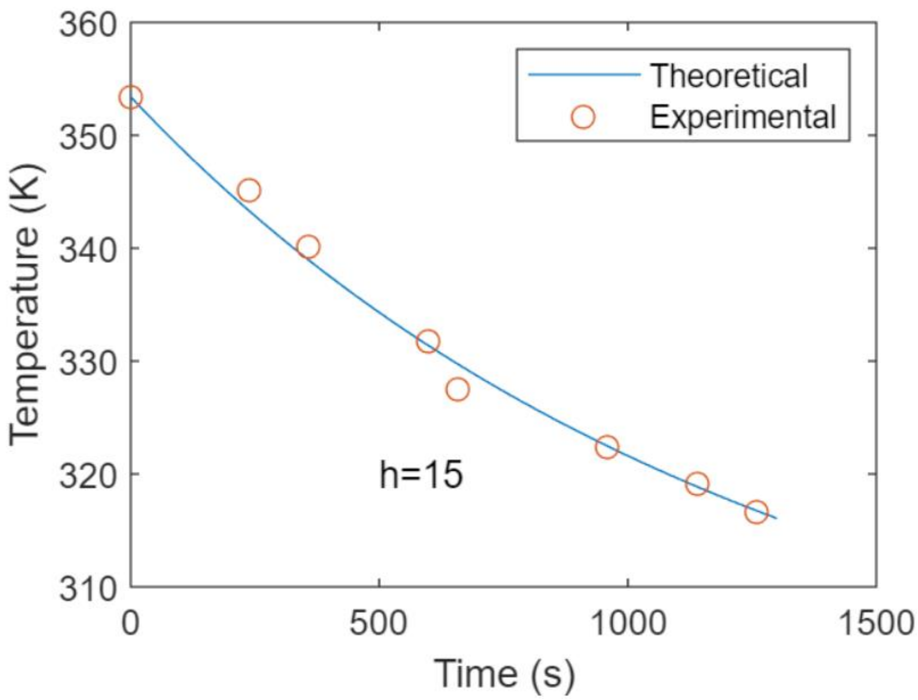


Figure 3. Run 1. Forced Convection 11 Oct 2022, 130 V

A summary of relevant data for these runs are displayed in Tables 3 and 4. These are used to determine the percent error and integrity of the experiment.

Table 3. Summary of Relevant Data for Run 1 Free

	Value	**Units**
h_{CORR}	6.39	
h_{EXP}	5.3	
Tplate	80.6	°C

Table 4. Summary of Relevant Data for Run 1 Forced

	Value	**Units**
h_{CORR}	7.85	
h_{EXP}	15	
Tplate	80.4	°C
V at 130V	2.54	m/s

Discussion

As previously determined in work by Alexa Moreno, MATLAB is an effective tool for analyzing the data. The experimental heat transfer coefficient for free convection was consistently less than the calculated theoretical heat transfer coefficient.

The experimental heat transfer coefficient for forced convection was consistently greater than theoretical. The significantly larger percent difference in this data could be a result of incorrect windspeeds. The stand made for the vertical experiment causes inconsistent wind flow across the surface. For the experimental value, the measurement was taken at the point above the thermocouple. However, minor differences in the location resulted in notable windspeed variances. The overall discrepancies for forced and free convection can also be accounted for by noting the use of constant parameter assumptions. This is not true for the actual situation as the film temperature is changing throughout, thus altering various other values.

Conclusion

Both a forced and free convection experiment can be performed in a Lab I session. Handouts for both cases were created and are available in the Appendix. Experimental and theoretical data correlated closely for free convection experiments. In forced convection experiments the experimental heat transfer coefficient was consistently higher than the theoretically calculated value, but this provides further discussion points for future students. For future improvement of the forced convection calculations, the changing film temperature could be accounted for.

Appendix

Data Reduction

A heat balance on the center plate, with no heat generation, yields Equation 1:

$$-q_{OUT} = q_{ACC} \tag{1}$$

The plate is cooled by free convection and radiation, as is shown in Equation 2:

$$q_{OUT} = q_{CONV} + q_{RAD} = hA_S(T_{PLATE} - T_{ATM}) + \varepsilon\sigma A_S(T_{PLATE}^4 - T_{ATM}^4) \tag{2}$$

The plate accumulates heat with an inverse relationship to time as it cools back to room-temperature, noted in Equation 3:

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

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

$$-\left(hA_S(T_{PLATE} - T_{ATM}) + \varepsilon\sigma A_S(T_{PLATE}^4 - T_{ATM}^4)\right) = \rho V\left(C_p\right)\frac{dT}{dt} \tag{4}$$

Experimental temperature data will be used to determine the "best fit" experimental heat transfer coefficient by integrating Equation 4 using MATLAB's ode45 function.

The heat transfer coefficient from the literature can be determined using the correlation for free convection from a horizontal heated, horizontal-facing plate (Cengel 2007, p. 511, Table 9-1), shown in Equations 5.

$$Nu = \left[0.825 + \frac{0.387Ra^{1/6}}{\left[1+\left(\frac{0.492}{Pr}\right)^{9/16}\right]^{8/27}}\right]^2 \tag{5}$$

where the Rayleigh number is calculated as in Equation 6:

$$Ra = \frac{g\beta(T_{PLATE}-T_{ATM})L^3}{\nu^2}\boldsymbol{Pr} \tag{6}$$

The heat transfer coefficient from the literature can be determined using the correlation for forced convection from a heated, horizontal-facing plate (Cengel 2007, p. 402), shown in Equations 5a and 5b:

$$Nu = 0.664Re^{0.5}Pr^{1/3} \qquad Re < 5 \times 10^5 \tag{7a}$$

$$Nu = 0.037Re^{0.5}Pr^{1/3} \qquad 5\times10^5 < Re < 10^7 \tag{7b}$$

where the Reynolds number is calculated as in Equation 7 (constants from Cengel 2007, Equation 6-13, p.366):

$$Re = \frac{\rho VL}{\mu} \tag{8}$$

In Equation 6, the depth of the plate is the characteristic length in free convection for a horizontal flat plate. Finally, h_{CORR} may be calculated from the Nusselt number as shown in Equation 7:

$$h_{CORR} = \frac{kNu}{L} \quad (9)$$

The experimental coefficient will be higher than the coefficient calculated from a literature correlation since it is impossible to remove all forced convection influences and achieve only free convection.

Sample Calculation

Free Convection

The theoretical heat transfer coefficient, h_{CORR}, is calculated using the equation below:

$$h_{CORR} = \frac{kNu}{L}$$

Nu is calculated by finding the Rayleigh number, where $\beta = \frac{1}{T}$, with T being the internal temperature of the plate at 356.4 K, g equal to 9.81 m/s^2, ν equal to 0.00002085 m^2/s, and Prandtl number of air equal to 0.7157.

$$Ra = \frac{g\beta(T_{PLATE} - T_{ATM})L^3}{\nu^2}\boldsymbol{Pr} = \frac{9.81\frac{m}{s^2} * \frac{1}{356.4K} * (356.4\ K - 294\ K) * 0.108m^3}{\left(0.00002085\frac{m^2}{s}\right)^2} * 0.7157 = 3.58 \times 10^6$$

Because the Rayleigh number is in magnitude of 10^6, equation 5a is used to calculate Nu.

$$Nu = \left[0.825 + \frac{0.387Ra^{1/6}}{[1 + \left(\frac{0.492}{Pr}\right)^{9/16}]^{8/27}}\right]^2 = \left[0.825 + \frac{0.387(3.58 \times 10^6)^{1/6}}{[1 + \left(\frac{0.492}{0.7157}\right)^{9/16}]^{8/27}}\right]^2 = 23.43$$

The fluid thermal conductivity of air, k, is 0.02945 W/mK. Therefore,

$$h_{CORR} = \frac{0.02945W/mK * 23.43}{0.108\,m} = 6.39\frac{W}{m^2K}$$

The experimental heat transfer coefficient, h_{EXP}, was found to be 6.35. The percent error can be calculated using the following equation:

$$\frac{(experimental\ value - theoretical\ value)}{theoretical\ value} \times 100\%$$

Applying this formula, the percent error for this experimental run would be:

$$\frac{(5.3 - 6.39)}{6.39} \times 100\% = 17\%$$

Forced Convection

The theoretical heat transfer coefficient, h_{CORR}, is calculated using the equation below:

$$h_{CORR} = \frac{kNu}{L}$$

Nu is calculated by finding the Reynolds number where the density and viscosity of air at room temperature are used. The characteristic length of the plate is 0.6096 m, and the velocity is 2.54 m/s.

$$Re = \frac{1.168(2.54)(0.6096)}{1.81 \times 10^{-5}} = 99918$$

Because the Reynolds number is less than the magnitude of 10^5, equation 5a is used to calculate Nu. The Prandtl number of air is 0.7157.

$$Nu = 0.664Re^{0.5}Pr^{1/3} = 0.664(99918)^{0.5}(0.7157)^{1/3} = 187.7$$

The fluid thermal conductivity of air, k, is 0.02945 W/mK. Therefore,

$$h_{CORR} = \frac{0.02945W/mK * 187.7}{0.6096\, m} = 7.85\frac{W}{m^2K}$$

The experimental heat transfer coefficient, h_{EXP}, was found to be 6.35. The percent error can be calculated using the following equation:

$$\frac{(experimental\ value - theoretical\ value)}{theoretical\ value} \times 100\%$$

Applying this formula, the percent error for this experimental run would be:

$$\frac{(15 - 7.85)}{7.85} \times 100\% = 47.7\%$$

Sample Code

Free Convection

The following code was used to find the theoretical values for the run shown in the sample calculation along with a figure. This code produces Figure 1 shown earlier.

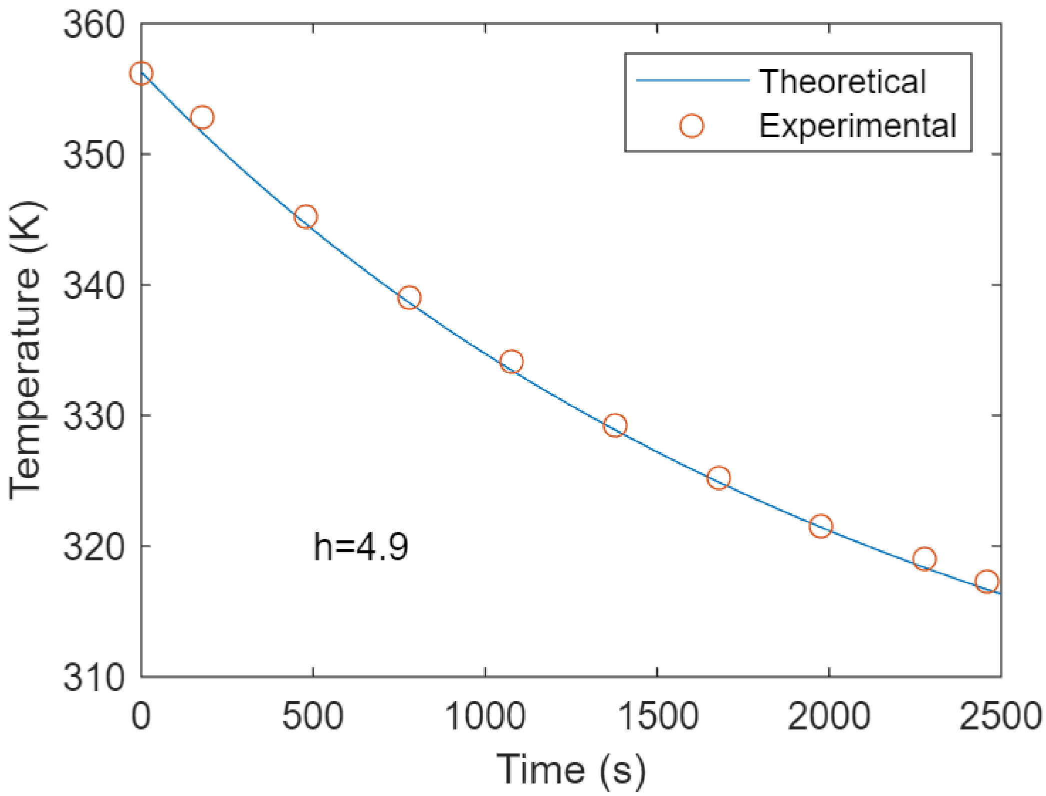
```
%Theoretical Data
%Constants
l=.6096;   %length of aluminum plate, m
w=.33528;  %width of plate, m
As=l*w;    %surface area of plate, m^2
Tatm=294;  %temp of room, K
e=.98;     %emissivity for black painted plate
o=5.67e-8; %Stefan-BOltzman constant
ht=.00635; %thickness of plate, m
V=As*ht;   %volume of plate, m^3
m=6.51;    %mass of plate, kg
p=m/V;     %density of plate, kg/m^3
Cp=900;    %specific heat capacity of aluminum, kJ/kg*K
h=5.3;     %heat transfer coefficient, W/m^2*K
%Calling Experimental from Excel
texp=xlsread("HonorsProjectLab1.xlsx",'free 2','E9:E17')
Texp=xlsread("HonorsProjectLab1.xlsx",'free 2','I9:I17')
Tplate=xlsread("HonorsProjectLab1.xlsx",'free 2','I9')
%tspan and function definition
tspan= [0,2200];
odefun= @(t,Tplate) (-(h*As*(Tplate-Tatm)+e*o*As*(Tplate^4-Tatm^4)))/(p*V*Cp);
%Using Ode45
[t,Tplate]=ode45(odefun,tspan,Tplate);
%plotting
plot(t,Tplate)
hold on
scatter(texp,Texp)
hold on
xlabel('Time (s)')
ylabel('Temperature (K)')
legend( 'Theoretical', 'Experimental')
txt='h=5.3'
text(500,320,txt)
hold off
```

Forced Convection

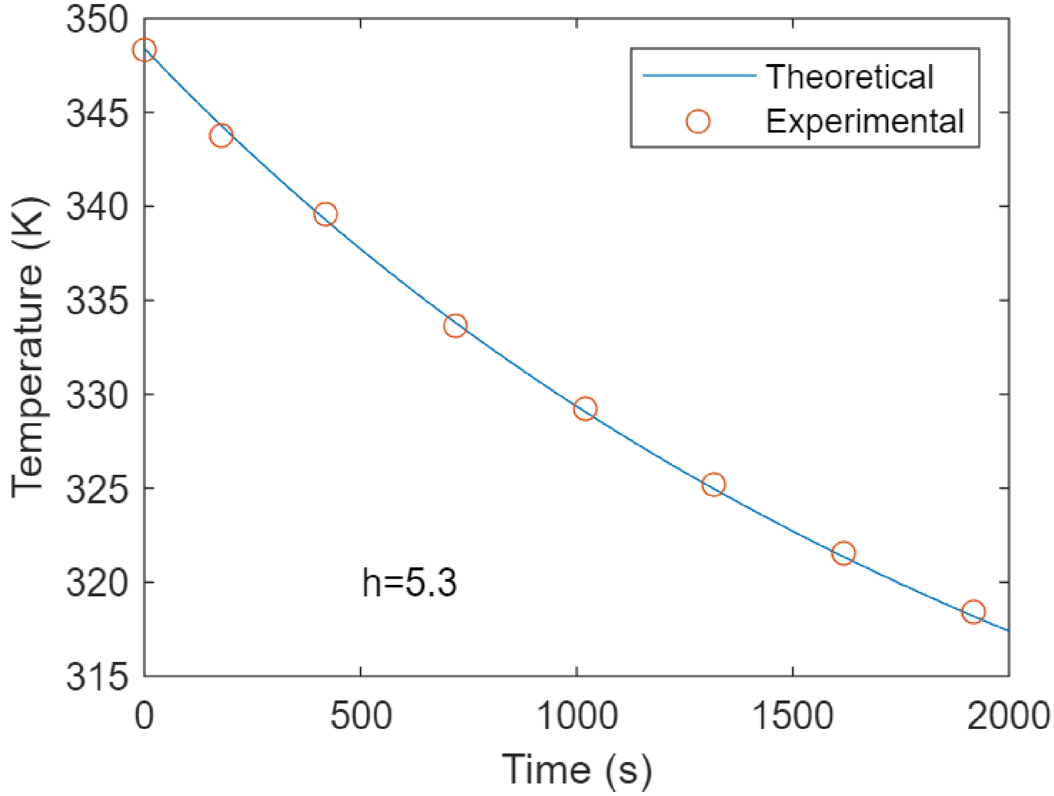
The following code was used to find the theoretical values for the run shown in the sample calculation along with a figure. This code produces Figure 1 shown earlier.

```
%Theoretical Data
%Constants
l=.6096;   %length of aluminum plate, m
w=.33528;  %width of plate, m
As=l*w;    %surface area of plate, m^2
Tatm=294;  %temp of room, K
e=.98;     %emissivity for black painted plate
o=5.67e-8; %Stefan-BOltzman constant
ht=.00635; %thickness of plate, m
V=As*ht;   %volume of plate, m^3
m=6.51;    %mass of plate, kg
p=m/V;     %density of plate, kg/m^3
Cp=900;    %specific heat capacity of aluminum, kJ/kg*K
h=14.7;   %heat transfer coefficient, W/m^2*K
%Calling Experimental from Excel
texp=xlsread("HonorsProjectLab1.xlsx",'forced 4','E10:E17')
Texp=xlsread("HonorsProjectLab1.xlsx",'forced 4','I10:I17')
Tplate=xlsread("HonorsProjectLab1.xlsx",'forced 4','I10')
%tspan and function definition
tspan= [0,1500];
odefun= @(t,Tplate) (-(h*As*(Tplate-Tatm)+e*o*As*(Tplate^4-Tatm^4)))/(p*V*Cp);
%Using Ode45
[t,Tplate]=ode45(odefun,tspan,Tplate); %final number should be starting temp in data
%plotting
plot(t,Tplate)
hold on
scatter(texp,Texp)
hold on
xlabel('Time (s)')
ylabel('Temperature (K)')
legend( 'Theoretical', 'Experimental')
txt='h=14.7'
text(500,330,txt)
hold off
```

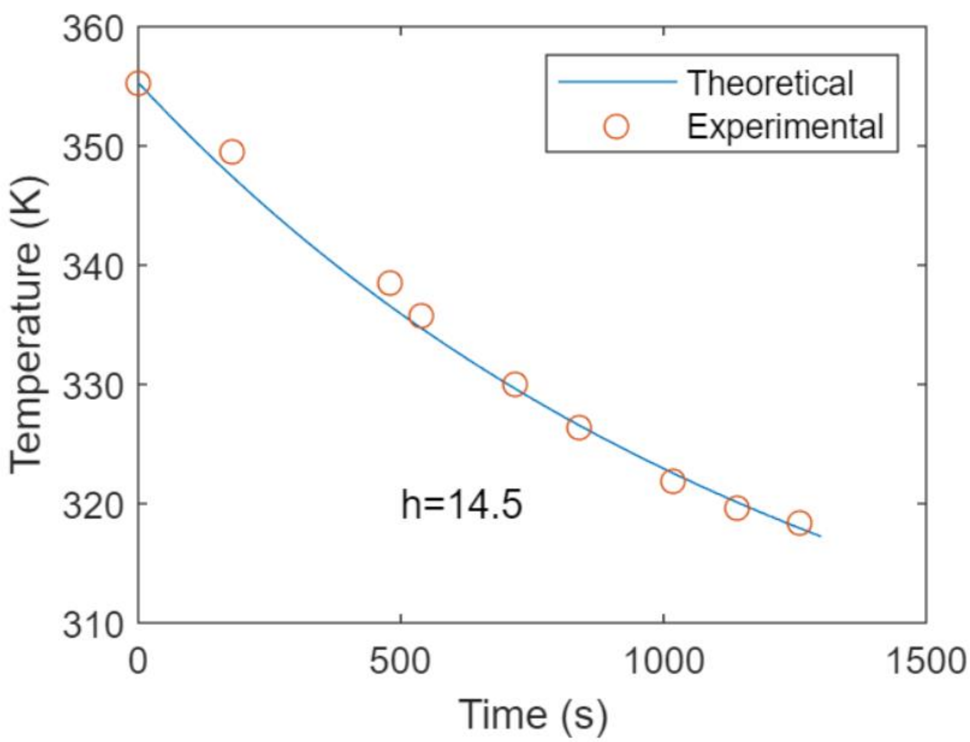
Figures



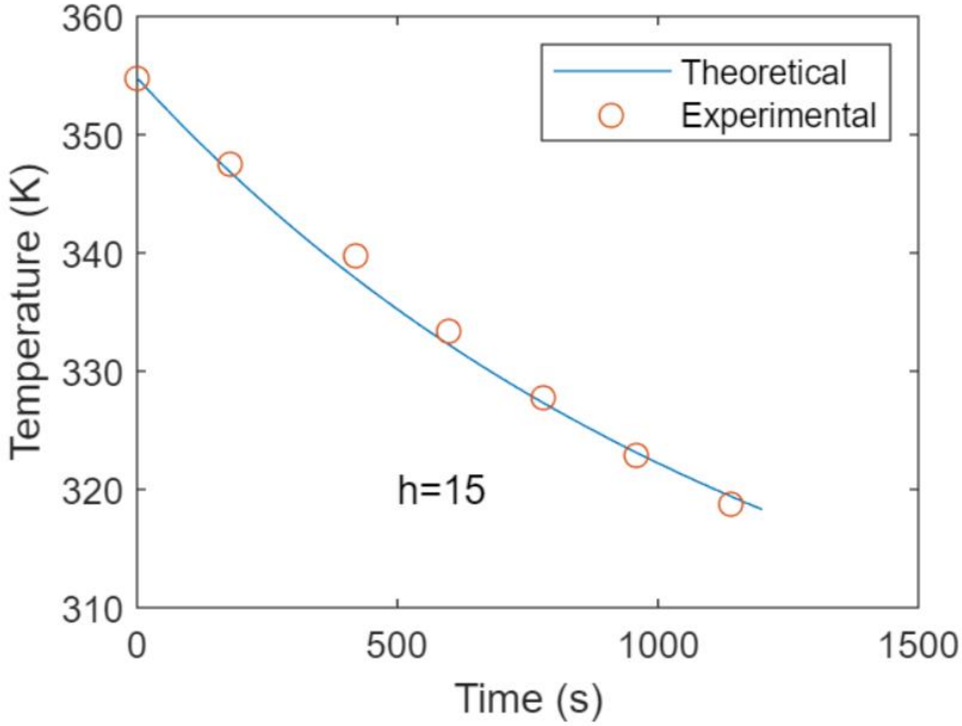
Run 2. Free Convection 4 Oct 2022



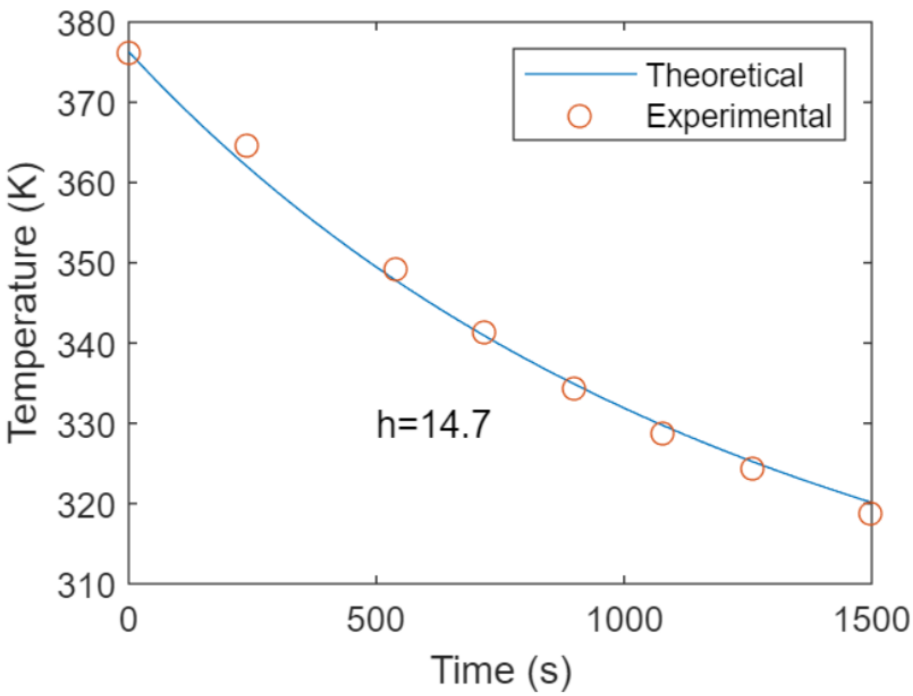
Run 3. Free Convection 4 Oct 2022



Run 2. Forced Convection 11 Oct 2022, 130 V



Run 3. Forced Convection 31 Oct 2022, 90 V



Run 4. Forced Convection 31 Oct 2022, 90 V

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CHEG 4332L
CHEMICAL ENGINEERING LABORATORY II

FREE CONVECTION HEAT TRANSFER FROM PLATES

Authors: Edgar C. Clausen (University of Arkansas), W. Roy Penney (University of Arkansas), Alexa Moreno (University of Arkansas), Leanza Trevino (University of Arkansas)

PURPOSE

The purpose of this experiment is to provide the students with experience modeling free convection heat transfer from an aluminum plate in the vertical position. Also, the students will apply heat transfer theory by determining experimental and theoretical heat transfer coefficients. The students will become familiar with MATLAB's ode45 function and scatter plot capabilities.

REPORT

1. Plot the experimental data using MATLAB's scatter plot function.
2. Generate model plot using MATLAB's ode45 function.
3. Using the model plot, determine the experimental free convection heat transfer coefficient for the surface of a vertical hot plate exposed to air.
4. Compare the results with results generated from the appropriate correlation of Churchill and Chu (Cengal 2007).

REFERENCES

1. Cengel, Y.A. 2007. *Heat and Mass Transfer: A Practical Approach, Chapter 9: Natural Convection.* Pages 503-560. 3rd edition. Boston: McGraw-Hill.
2. Omega Engineering. 2017. *Emissivity of Common Materials*. No date. Accessed August 14, 2017. https://www.omega.com/literature/transactions/volume1/emissivitya.html.

PROCEDURE

Equipment Description

The aluminum plate (24”x13”x0.5”, 6.51 kg) is heated to 85°C inside the Fisher Oven. To keep record of the plate temperature, a thermocouple is inserted in the center of the plate with the oven door closed, as shown in Figure 1. To ensure that heat does not escape the oven, a rubber stopper is used to seal the hole at the top of the oven, as shown in Figure 2. A thermocouple is also used to monitor the temperature of the inside of the oven, also pictured in Figure 2.

Figure 1. Experimental Apparatus inside Fisher Oven.

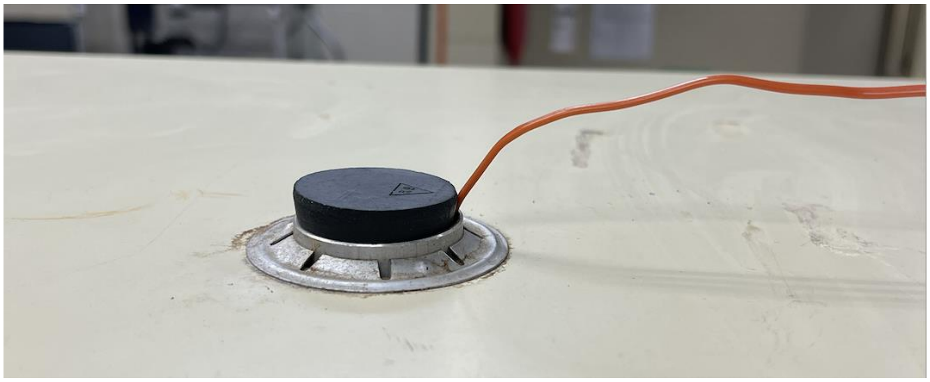

Figure 2. Rubber Stopper.

After the desired internal temperature is reached, the plate is moved to a 27.5” x 15.5” x 3” PVC stand, black side showing, surrounded by thermal insulation on the back of the plate and the sides of the plate. The thermocouple is inserted in 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 over time as shown in Figure 3.

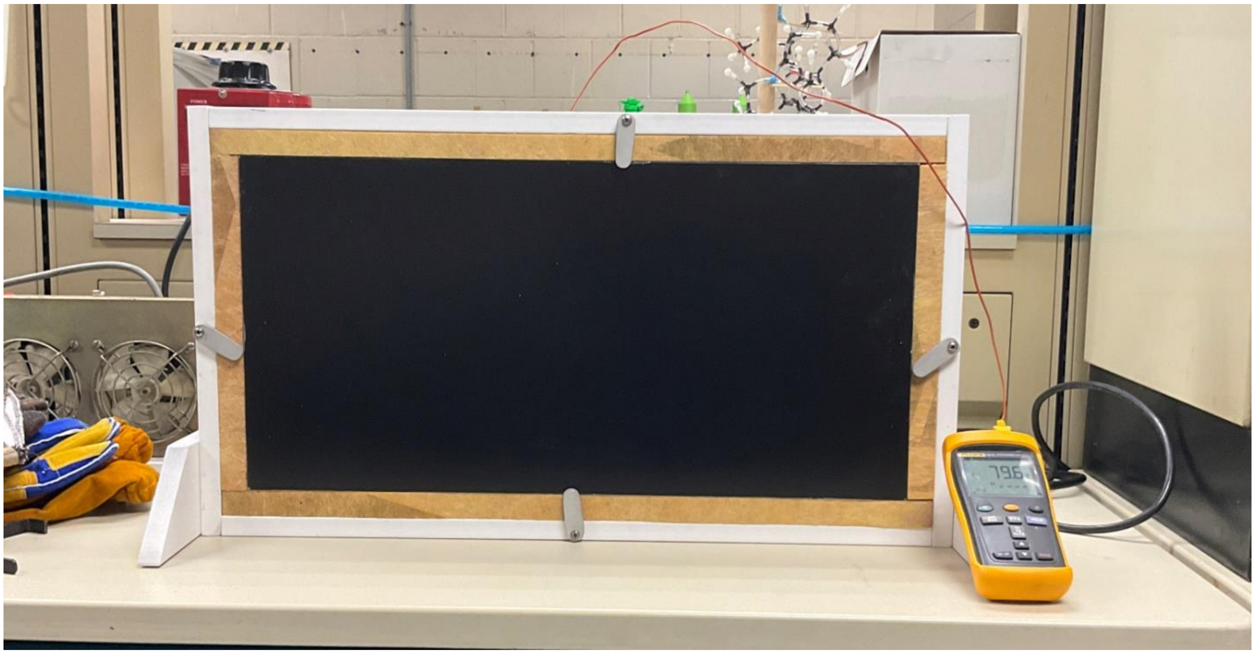

Figure 3. Experimental Apparatus for Cooling

Materials and Equipment Needed

The following equipment are used in carrying out this experiment:

- Oven
- Aluminum Plate, painted black on one face with a hold drilled from one side to the center
- Insulation (THERMAX Sheathing, 3.3 R factor per ½" of board)
- PVC Stand
- Stopwatch
- Thermocouple Reader
- Two Thermocouple Wires
- Rubber Stopper
- Pry Bar

Procedure

1. Safety precautions that must be followed during the experiment include:
    a. Wear proper PPE, including safety goggles, long sleeve shirt, long pants, closed toed shoes.
    b. Wear fire-safe lab coat, thermal arm sleeves, and high heat-resistant gloves when opening the oven and transferring the heated plate.
    c. Use pry bar when lifting the aluminum plate out of insulation and transferring to oven.
    d. Be sure to have group members steer clear of path when transferring the aluminum plate.
2. The oven will be pre-heated by the TA. Ensure all PPE is worn before opening the oven door. Lift the aluminum plate with the pry bar and transfer to the inside of the oven as seen in Figure 1.
3. Insert the shorter thermocouple wire into the hole at the top of the oven, avoiding touching the plate, to monitor the temperature inside the oven (make sure the oven is never losing temperature). Hold the wire in place with rubber stopper, shown in Figure 2.
4. Slide the longer thermocouple wire through the hole in the side of the aluminum plate and shut the oven door.
5. Wait for the aluminum plate to reach an internal temperature of 85°C.
6. Once the desired temperature is reached, remove the rubber stopper and remove the thermocouple wire from inside the oven.
7. Be sure all PPE is worn, open the oven door, pull thermocouple wire out of the hole, transfer plate to insulated stand and insulate the last side of the aluminum plate.
8. Insert the longer thermocouple wire into the side of the insulation stand to the center of the plate, as shown in Figure 3.
9. Start the stopwatch as soon as the temperature is no longer climbing and record the initial temperature.
10. Record the temperature every 3 minutes until the temperature reaches 45°C.
11. Stop the stopwatch. Remove the thermocouple wire from the side of the plate. Shut off the thermocouple reader and clean the area, putting away all PPE.

APPENDIX

1. *Data Reduction*

A heat balance on the center plate, with no heat generation, yields Equation 1:

$$-q_{OUT} = q_{ACC} \tag{1}$$

The plate is cooled by free convection and radiation, as is shown in Equation 2:

$$q_{OUT} = q_{CONV} + q_{RAD} = hA_S(T_{PLATE} - T_{ATM}) + \varepsilon\sigma A_S(T_{PLATE}^4 - T_{ATM}^4) \tag{2}$$

The plate accumulates heat with an inverse relationship to time as it cools back to room-temperature, noted in Equation 3:

$$q_{ACC} = m(C_p)\frac{dT}{dt} = \rho V(C_p)\frac{dT}{dt} \tag{3}$$

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

$$-\left(hA_S(T_{PLATE} - T_{ATM}) + \varepsilon\sigma A_S(T_{PLATE}^4 - T_{ATM}^4)\right) = \rho V\left(C_p\right)\frac{dT}{dt} \tag{4}$$

Experimental temperature data will be used to determine the “best fit” experimental heat transfer coefficient by integrating Equation 4 using MATLAB’s ode45 function.

The heat transfer coefficient from the literature can be determined using the correlation for free convection from a heated, vertical-facing plate (Cengal 2007, p. 402), shown in Equations 5.

$$Nu = \left[0.825 + \frac{0.387Ra^{1/6}}{\left[1+\left(\frac{0.492}{Pr}\right)^{9/16}\right]^{8/27}}\right]^2 \tag{5}$$

where the Rayleigh number is calculated as in Equation 6:

$$Ra = \frac{g\beta(T_{PLATE} - T_{ATM})L^3}{\nu^2}\boldsymbol{Pr} \tag{6}$$

In Equation 6, the depth of the plate is the characteristic length in free convection for a horizontal flat plate. Finally, h_{CORR} may be calculated from the Nusselt number as shown in Equation 8:

$$h_{CORR} = \frac{kNu}{L} \tag{8}$$

The experimental coefficient will be higher than the coefficient calculated from a literature correlation since it is impossible to remove all forced convection influences and achieve only free convection.

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CHEG 4332L
CHEMICAL ENGINEERING LABORATORY II

FORCED CONVECTION HEAT TRANSFER FROM PLATES

Authors: Edgar C. Clausen (University of Arkansas), W. Roy Penney (University of Arkansas), Alexa Moreno (University of Arkansas), Leanza Trevino (University of Arkansas)

PURPOSE

The purpose of this experiment is to provide the students with experience modeling forced convection heat transfer from an aluminum plate in the vertical position. Also, the students will apply heat transfer theory by determining experimental and theoretical heat transfer coefficients. The students will become familiar with MATLAB's ode45 function and scatter plot capabilities.

REPORT

1. Plot the experimental data using MATLAB's scatter plot function.
2. Generate model plot using MATLAB's ode45 function.
3. Using the model plot, determine the experimental forced convection heat transfer coefficient for the top surface of a vertical hot plate with forced convection.
4. Compare the results with results generated from the appropriate correlation of Churchill and Chu (Cengal 2007).

REFERENCES

1. Cengel, Y.A. 2007. *Heat and Mass Transfer: A Practical Approach, Chapter 9: Natural Convection.* Pages 503-560. 3rd edition. Boston: McGraw-Hill.
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The aluminum plate (24”x13”x0.5”, 6.51 kg) is heated to 85°C inside the Fisher Oven. To keep record of the plate temperature, a thermocouple is inserted in the center of the plate with the oven door closed, as shown in Figure 1. To ensure that heat does not escape the oven, a rubber stopper is used to seal the hole at the top of the oven, as shown in Figure 2. A thermocouple is also used to monitor the temperature of the inside of the oven, also pictured in Figure 2.

Figure 1. Experimental Apparatus inside Fisher Oven.

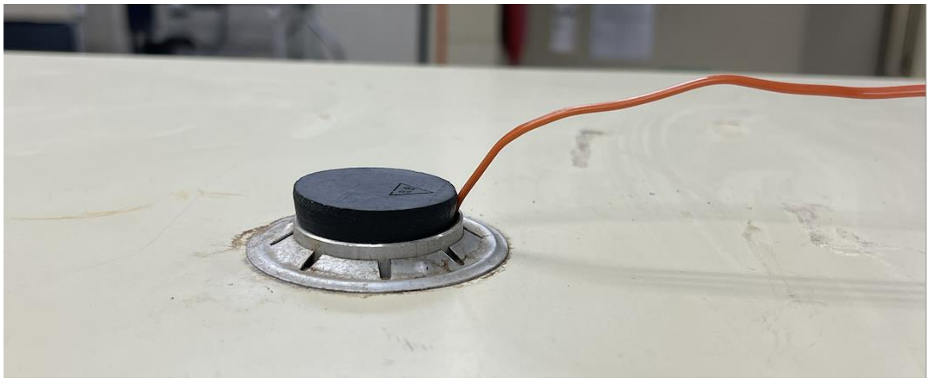

Figure 2. Rubber Stopper.

After the desired internal temperature is reached, the plate is moved to a 27.5” x 15.5” x 3” PVC stand, black side showing, surrounded by thermal insulation on the back of the plate and the sides of the plate. The thermocouple is inserted in 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 over time. A series of fans are aimed at the plate as shown in Figure 3.

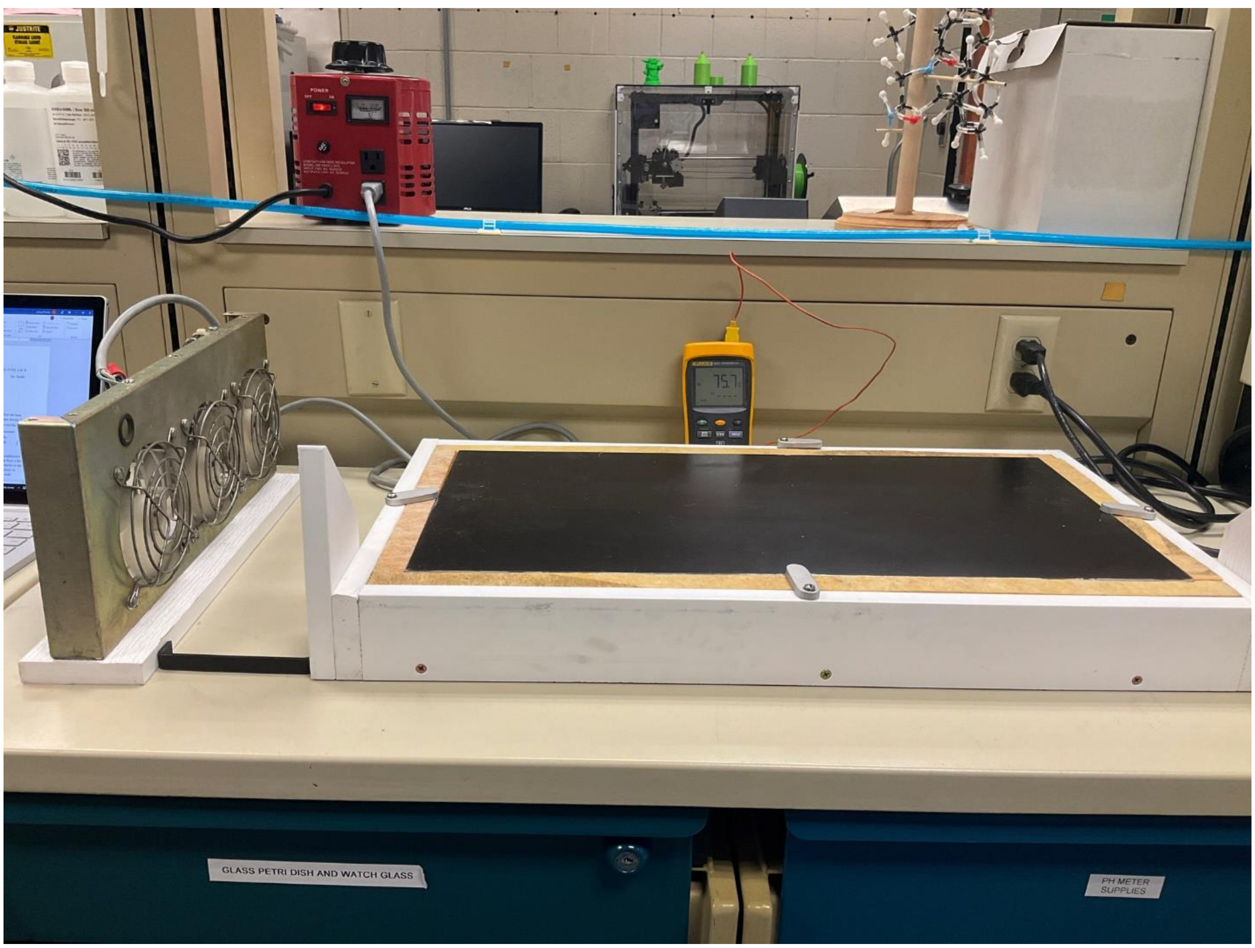

Figure 3. Equipment Setup.

Materials and Equipment Needed

The following equipment are used in carrying out this experiment:

- Oven
- Aluminum Plate, painted black on one face with a hold drilled from one side to the center
- Insulation (THERMAX Sheathing, 3.3 R factor per ½” of board)
- PVC Stand
- Stopwatch
- Thermocouple Reader
- Two Thermocouple Wires
- Rubber Stopper
- Pry Bar

Procedure

12. Safety precautions that must be followed during the experiment include:
    a. Wear proper PPE, including safety goggles, long sleeve shirt, long pants, closed toed shoes.
    b. Wear fire-safe lab coat, thermal arm sleeves, and high heat-resistant gloves when opening the oven and transferring the heated plate.
    c. Use pry bar when lifting the aluminum plate out of insulation and transferring to oven.
    d. Be sure to have group members steer clear of path when transferring the aluminum plate.
13. The oven will be pre-heated by the TA. Ensure all PPE is worn before opening the oven door. Lift the aluminum plate with the pry bar and transfer to the inside of the oven as seen in Figure 1.
14. Insert the shorter thermocouple wire into the hole at the top of the oven, avoiding touching the plate, to monitor the temperature inside the oven (make sure the oven is never losing temperature). Hold the wire in place with rubber stopper, shown in Figure 2.
15. Slide the longer thermocouple wire through the hole in the side of the aluminum plate and shut the oven door.
16. Wait for the aluminum plate to reach an internal temperature of 85°C.
17. Once the desired temperature is reached, remove the rubber stopper and remove the thermocouple wire from inside the oven.
18. Be sure all PPE is worn, open the oven door, pull thermocouple wire out of the hole, transfer plate to insulated stand and insulate the last side of the aluminum plate.
19. Insert the longer thermocouple wire into the side of the insulation stand to the center of the plate, as shown in Figure 3.
20. Turn on the fans and record windspeed at the point above the thermocouple’s internal position in the plate.
21. Start the stopwatch as soon as the temperature is no longer climbing and record the initial temperature.
22. Record the temperature every 3 minutes until the temperature reaches 45°C.
23. Stop the stopwatch. Remove the thermocouple wire from the side of the plate. Shut off the thermocouple reader and clean the area, putting away all PPE.

APPENDIX

3. Data Reduction

A heat balance on the center plate, with no heat generation, yields Equation 1:

$$-q_{OUT} = q_{ACC} \tag{1}$$

The plate is cooled by free convection and radiation, as is shown in Equation 2:

$$q_{OUT} = q_{CONV} + q_{RAD} = hA_S(T_{PLATE} - T_{ATM}) + \varepsilon\sigma A_S(T_{PLATE}^4 - T_{ATM}^4) \tag{2}$$

The plate accumulates heat with an inverse relationship to time as it cools back to room-temperature, noted in Equation 3:

$$q_{ACC} = m(C_p)\frac{dT}{dt} = \rho V(C_p)\frac{dT}{dt} \tag{3}$$

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

$$-\left(hA_S(T_{PLATE} - T_{ATM}) + \varepsilon\sigma A_S(T_{PLATE}^4 - T_{ATM}^4)\right) = \rho V\left(C_p\right)\frac{dT}{dt} \tag{4}$$

Experimental temperature data will be used to determine the “best fit” experimental heat transfer coefficient by integrating Equation 4 using MATLAB’s ode45 function.

The heat transfer coefficient from the literature can be determined using the correlation for free convection from a horizontal heated, horizontal-facing plate (Cengal 2007, p. 402), shown in Equations 5a and 5b:

$$Nu = 0.664Re^{0.5}Pr^{1/3} \qquad Re < 5 \times 10^5 \tag{5a}$$
$$Nu = 0.037Re^{0.5}Pr^{1/3} \qquad 5\times10^5 < Re < 10^7 \tag{5b}$$

where the Reynolds number is calculated as in Equation 6 (constants from Cengal 2007, Equation 6-13, p.366):

$$Re = \frac{\rho VL}{\mu} \tag{6}$$

In Equation 6, the depth of the plate is the characteristic length in free convection for a horizontal flat plate. Finally, h_{CORR} may be calculated from the Nusselt number as shown in Equation 7:

$$h_{CORR} = \frac{kNu}{L} \tag{7}$$

The experimental coefficient will be higher than the coefficient calculated from a literature correlation since it is impossible to remove all forced convection influences and achieve only free convection.

4. 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	characteristic 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
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

References

Cengel, Yunus A. 2007. *Heat and Mass Transfer: A Practical Approach, Chapters7 & 9: Forced Convective Heat Transfer & Natural Convection.* 3rd edition. Boston: McGraw-Hill.

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