Examination of heat flux through a surface using digital image processing of infrared images

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Examination of Heat Flux Through a Surface Using Digital Image Processing of Infrared Images

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Departmental Thesis

The University of Tennessee at Chattanooga

Mechanical Engineering

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Examination Date: March 4, 2015

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Above all, I give the greatest thanks to my savior Jesus Christ, for blessing me beyond what I deserve, and giving me opportunities to study His creation; none of this would be possible without Him.
EXECUTIVE SUMMARY

The task for this project was to design and construct a system that could be used to examine heat transfer through a surface by analyzing images produced using thermal imaging cameras. A long rectangular box made of pinewood was constructed and a light bulb was inserted to provide a heating element. The front face of the box was made to be interchangeable so that various materials could be tested. Two Flir I5 thermal imaging cameras were used to take pictures of both sides of the front face at specific time intervals in order to determine the temperature distribution of the face. This temperature distribution was related to a heat flux using *Fourier’s Law* to calculate the heat flux, heat rate, and heat loss through the front face. An algorithm was developed using Matlab software specifically for this apparatus to analyze the data from the cameras. A data acquisition system and thermocouples were used to track the heat transfer through the air and other portions of the box. Insulation was used for various tests to show the effects of insulation and how it can direct heat flow.

The tests conducted for this project successfully showed how energy is transferred through different mediums and how it can be directed by using insulation. The final project deliverables for the complete system were the box, camera stand, two thermal imaging cameras, thermocouples, DAQ system, LabVIEW program, Excel workbook, and Matlab algorithm. There is plenty of room to expand and improve on the current system and create more opportunities to study different types of heat transfer. Dr. Margraves plans to use this system for future student engineering laboratory experiments, as well as demonstrations for summer youth programs.
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I. INTRODUCTION

The main goal of this project was to create a heat transfer apparatus that could be used in laboratory experiments or classroom demonstrations for students. Dr. Margraves plans to use this apparatus in engineering lab classes and in demonstrations for middle school students during summer youth programs. For these reasons, it was important that the apparatus be mobile and allow for multiple ways to show heat transfer phenomenon. Dr. Margraves wanted to use thermal imaging cameras and thermocouples to demonstrate how newer technology could more easily measure heat transfer. The apparatus also needed to have an interchangeable front face so that a variety of materials could be tested. The testing apparatus needed to be able to demonstrate how heat is transferred through different materials and how it is affected by insulation. In order to meet Dr. Margraves’ needs, primary goals of the project were developed as follows:

- Design and construct a well-insulated apparatus to be used in conjunction with thermal imaging cameras that demonstrates how heat is transferred through material.
- Design and construct an adaptable apparatus that can be used for various experiments in the future. This includes the development of an interchangeable front face, which will allow for testing of a wide variety of materials.
• Provide a DAQ system that compares thermocouple results to the results obtained from the cameras, in addition to measuring the heat transfer through other parts of the apparatus.

• Create an algorithm using Matlab software that will import data from the cameras and calculate heat rate, heat flux, and heat loss through the front surface of the apparatus.

In order to determine whether or not these goals were achieved, four tests were conducted with varying insulation and heat input. Analysis of these test results shows that the apparatus works as expected, and that the apparatus will demonstrate heat transfer well in future laboratory experiments.
II. THEORY

Heat Transfer concepts by One-Dimensional Conduction were used as the basis for the calculations and experiments performed during this project. According to Incropera, Dewitt, and Bergman “Heat transfer is thermal energy in transit due to a spatial temperature difference.”\(^1\) In other words, heat transfer occurs when there is a temperature difference in a medium or between media.\(^1\) Conduction is a type of heat transfer that occurs when a temperature gradient exists within a solid or fluid medium.\(^1\) The higher temperatures within the medium are associated with higher molecular energies, while lower temperatures are associated with lower molecular energies. As the molecules collide within the medium, energy is transferred from the more energetic molecules to the less energetic.\(^1\) For this reason Incropera et al. state that “Conduction may be viewed as the transfer of energy from the more energetic to the less energetic particles of a substance due to interactions between the particles.”\(^1\) Energy transfer by conduction must occur in the direction of decreasing temperature when a temperature gradient is present; this is because energy transfers from the more energetic (higher temperature) states to the less energetic (lower temperature) states as directed by the second law of thermodynamics.

*Fourier’s Law* is a rate equation that can be used to express heat transfer by conduction.\(^1\) This law was not derived by principles, but rather, it was developed from observed phenomena and experiments.\(^1\) *Fourier’s Law* is independent of time and is used to find the heat transfer rate \(q_x\) by using the following four variables: temperature difference \((\Delta T)\), material length \((\Delta x)\), material cross-sectional area \((A)\),
and thermal conductivity ($k$). The thermal conductivity is a constant that is specific to the material used as the medium, and varies between different materials. The general expression for *Fourier’s Law* is given below in Equation 1.

$$ q_x' = -kA \frac{dT}{dx} $$  \hspace{1cm} (1)\textsuperscript{1}

Evaluating Equation 1 for the limit as $\Delta x \to 0$, the heat rate equation, in units of energy per time, is obtained below.

$$ q_x'' = -kA \frac{dT}{dx} $$  \hspace{1cm} (2)\textsuperscript{1}

The minus sign in the above equations is a consequence of the fact that heat is transferred in the direction of decreasing temperature, as stated above.\textsuperscript{1} Heat flux $q_x''$ is a quantity defined as the heat transfer rate in the x direction per unit area perpendicular to the direction of transfer.\textsuperscript{1} Heat flux is calculated by dividing the heat rate $q_x'$ by the cross-sectional area $A$.\textsuperscript{1} Heat flux in the x-direction is given below in Equation 3.

$$ q_x'' = -k \frac{dT}{dx} $$  \hspace{1cm} (3)\textsuperscript{1}

It is important to note the difference between heat rate $q_x'$ and the heat flux $q_x''$ is that heat flux is the rate of heat transfer per unit area.\textsuperscript{1} Therefore, the heat rate by conduction $q_x'$ through a material with cross-sectional area $A$, is the product of the heat flux and area $A$. This is shown below in Equation 4.

$$ q_x' = q_x'' \cdot A $$  \hspace{1cm} (4)\textsuperscript{1}

Common units for heat rate $q_x'$ and heat flux $q_x''$ are *Watts* and *Watts/meters$^2$* respectively.\textsuperscript{1}
As seen above, Fourier’s Law is a directional quantity used to describe heat flux $q''_x$ that travels normal to the cross-sectional area A. Although heat regularly transfers across three-dimensional space, this project was primarily concerned with one-dimensional conduction in the x-direction and therefore has limited the equations appropriately. Specifically, one-dimensional steady state conduction was used to quantify the system under study. Incropera et al. state, “despite their inherent simplicity, one-dimensional, steady-state models may be used to accurately represent numerous engineering systems.”¹ For one-dimensional steady state conduction through a plane wall, Fourier’s Law can be simplified for heat flux, which is given in Equation 5 shown below.

$$q''_x = -\frac{k}{L}(T_{s,2} - T_{s,1}) = \frac{k}{L}(T_{s,1} - T_{s,2}) \quad (5)$$

The temperatures $T_{s,1}$ and $T_{s,2}$ used in Equation 5 represent the temperatures at the surface on either side of a wall that has a thickness L. The thermal conductivity for the specific wall material is represented by k. Similarly to heat flux, the heat rate equation can be simplified by multiplying Equation 5 by the cross sectional area A to obtain Equation 6.

$$q'_x = -\frac{kA}{L}(T_{s,1} - T_{s,2}) = \frac{kA}{L}(T_{s,1} - T_{s,2}) \quad (6)$$

Equations 5 and 6 are the two most important equations for this study and were used not only to analyze the data but also to drive project design. The variables in this equation were used to help choose materials, apparatus size, and heating methods. In order to find the total heat loss through a wall for a finite length of time, Equation 6 is multiplied by time t. Since the heat rate is typically given in units of Joule/sec, by
multiplying by the amount of time in seconds that the test was conducted, the total amount of heat travelling through the wall can be found in Joules. This is shown below in Equation 7.

\[ q_x = -\frac{kA}{L} (T_{s,1} - T_{s,2})t = \frac{kA}{L} (T_{s,1} - T_{s,2})t \quad (7) \]

The heating apparatus used in this project was modeled using one-dimensional conduction heating methods, and therefore Fourier’s Law was used as the foundation for this project and was the basis for both analysis and design.

In order to calculate how the heat transfers through the box, two different temperature-sensing methods were used. Four type K thermocouples were used to find the temperature changes over time: two were used to determine the energy stored in the air and two were used to determine the energy moving through the sides of the box. A thermocouple is created by a junction formed between two dissimilar metals. A temperature dependent voltage is created due to the temperature difference between the two dissimilar metals. This phenomenon that creates a voltage is known as the Seebeck Effect. The Seebeck Effect is characterized by a temperature difference between two dissimilar electrical conductors producing a voltage difference between the two substances. Data acquisition equipment was used to relate the voltage from the thermocouples to a temperature measurement.

For calculating the amount of heat transferred to the air from the light bulb, the temperature of the air was measured using two thermocouples. The amount of heat transferred to the air was found by using Equation 8 below.

\[ q = mC_v(T_2 - T_1) = \rho V C_v(T_2 - T_1) \quad (8) \]
The mass of the air, represented by \( m \), is found by multiplying the density of the air \( \rho \) and the volume \( V \) of the heated air inside the box. The specific heat at constant volume, represented by \( C_v \), is 0.718 kJ/kgK for air. The temperatures \( T_1 \) and \( T_2 \) are the temperatures of the air at the beginning and end of the test respectively.

The second method for obtaining temperature values in this project was thermal imaging. Thermal imaging cameras measure the intensity of radiation in the infrared part of the electromagnetic spectrum and convert it to a visible image called a thermogram.\(^4\) The thermograms show temperature distribution as a color variation based on the intensity of the infrared radiation in that area. Infrared radiation lies between the visible and microwave portions of the electromagnetic spectrum; Thermal radiation, or heat, is the primary source for infrared radiation.\(^4\) If an object has a temperature above absolute zero, it emits infrared radiation.\(^4\) Therefore practically all objects emit some amount of infrared radiation based on its temperature. The higher the object’s temperature, the more infrared radiation it will emit. Thermal imagining cameras measure the emitted infrared radiation from an object and relate it to the surface temperature of that object.\(^5\) Although temperature has a great effect on the amount of radiation emitted by an object, it is not the only contributing factor.\(^5\)

Emissivity, a thermal property of a substance, plays an important role in how much infrared radiation is emitted from an object. The thermal imaging cameras do not detect emissivity and therefore a constant emissivity factor must be set on the cameras in order to calculate the correct temperature. Flir Systems says “the most
important object parameter to set correctly is the emissivity which, in short, is a measure of how much radiation is emitted from the object, compared to that from a perfect black body of the same temperature. Emissivity values typically range between 0.1 and 0.95.

As mentioned above thermocouples relate a measured voltage to a temperature at a single specific location. Thermal imaging cameras use complex algorithms to translate the measured infrared radiation into a visible radiometric image containing temperature values at each pixel location. The Flir I5 cameras used in this project output images with 10,000 pixels. This means that each picture contains 10,000 temperatures, which is analogous to using 10,000 thermocouples and is one of the major benefits of using thermal imaging cameras. These temperature values of both measurement devices were used in conjunction with Fourier’s equations to find the heat flux, heat rate, and heat loss through an object.

In order to support the use of the thermal imaging cameras for this project, a comparative analysis between using the cameras and using a single thermocouple was conducted. For this comparison the cameras were used to capture the temperatures of the front face at two times, 30 minutes apart, as the box was heated. In order to simulate the use of a single thermocouple, the center data point of these pictures was taken and copied into the rest of the matrix, based on a constant temperature across the face. The Matlab algorithm was used to analyze both cases and the results are shown below in Table 1.
Table 1 Comparison Between Cameras and Single Thermocouple

<table>
<thead>
<tr>
<th>Type</th>
<th>Camera - 10,000 pts.</th>
<th>Thermocouple - 1 pt.</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Flux Through Front Face (W/m²)</td>
<td>396.6</td>
<td>435.1</td>
<td>9.71%</td>
</tr>
<tr>
<td>Heat Rate Through Front Face (W)</td>
<td>12.3</td>
<td>13.5</td>
<td>9.71%</td>
</tr>
<tr>
<td>Heat Loss Through Front Face (kJ)</td>
<td>22.1</td>
<td>24.3</td>
<td>9.71%</td>
</tr>
</tbody>
</table>

The results of this comparison show that the data from using only one thermocouple is off by nearly 10% compared to using a camera that outputs 10,000 data points. The benefit of using Flir I5 thermal imaging cameras is that they effectively equal using 10,000 thermocouples. The single thermocouple incorrectly showed that more heat went through the front face than what actually did. This is because the center point, which is the hottest part of the front face, was used as the basis for the temperature across the entire face. By using the thermal imaging cameras the lower temperatures around the edges of the face could be accounted for easily. The other major benefit of thermal imaging cameras is that they provide a non-intrusive means of measurement; thermocouples, on the other hand, alter the system they are measuring because they must be in contact with the system. Thermal imaging cameras can also be used to map the temperature distribution across an entire face, and output a 3D map of the temperatures. This yields a significant increase in the information collected than would be possible using only a few thermocouples.
III. EXPERIMENT

Apparatus

The apparatus was designed to be portable so that it could easily be used as a laboratory experiment or a class demonstration. For this reason the box needed to be relatively small and light. The dimensions of the box were not only driven by mobility, but also by the focal length of the camera. At 2 feet away, the Flir I5 thermal imaging camera takes a picture that is roughly 8 inches by 6 inches. In order to accommodate the camera’s focal length, the box was designed to have a long rectangular shape. The box shape also needed to hold a heating element and allow the camera to take a picture of the front face without being obstructed by the heating element. Figure 2 below shows the diagram for the box design.

Figure 1 Diagram for Thermal Imaging Box
Section B – B of the above diagram shows the front face of the box that the cameras imaged. The box was designed to have an interchangeable front face so that different materials could be tested. The main camera was placed upside down looking through a hole in the box so that it could take a picture of the inside front face. Two metal brackets with felt on the inside held the camera in place. The heating element was housed in the portion of the box directly under the camera so that it would not block the camera’s field of vision. This end of the box could be removed for easy access to the heating element and was held in place by Bugpack hood latches.

The front piece of wood shown in section B – B had a hole cut through it, with a counter-sunk rim that held the interchangeable front face. The front face used for testing was a $\frac{3}{8}''$ thick piece of oriented strand board (OSB). A $\frac{3}{8}''$ thick piece of aluminum was initially used but had such a high thermal conductivity that it caused problems with measuring the correct temperatures. Based on Equation 2, if 60W were going through the front face, the aluminum would only have a temperature difference of 0.07 °C. Due to the loss of energy through other parts of the system it would be impossible for all 60W from a 60W light bulb to exit through the front face. This means that the actual heat rate through the aluminum would be lower than 60W and the temperature difference would drop even more. This small temperature difference is driven by aluminum’s high thermal conductivity of 237 W/mK. The Flir I5 cameras were not sensitive enough to read these small temperature differences in the aluminum, and therefore OSB was used for the front face due to its thermal conductivity of only 0.13 W/mK.
In order to retain as much heat as possible, wood was chosen as the base material for the box due to its low thermal conductivity. The box was constructed out of ¾” thick white pine wood. Silicon caulk was used to seal all of the edges on the inside of the box to also help retain heat. All of the non-removable faces were put together using wood glue and screws. Four bolts with wing nuts were used to hold the front face on and allow the user to easily interchange the front face material. The final constructed box can be seen below in Figures 3 and 4.

Figure 2 Completed Box
The heating element chosen for this project was an incandescent light bulb. A light bulb is an inexpensive heating element that puts off a large amount of heat compared to its small size, and was therefore a perfect choice for this project. Two light bulbs were used for this project: a 60W and a 100W bulb. Each bulb was painted with black grill paint so that minimal light from the bulb would shine through and affect the camera’s image. In order to accommodate future projects, a small 3” computer fan was also mounted on the inside of the end face of the box to provide a variety of ways to demonstrate heat transfer.
Two identical Flir I5 thermal imaging cameras were used to capture images of both the inside and outside of the front face of the box. The Flir I5 takes pictures that are 100 pixels by 100 pixels and therefore outputs an image that has 10,000 pixels. At each pixel location, there is a temperature value that the camera calculates based on the amount of infrared radiation detected in that area. This means every image has 10,000 temperature readings, which can then be used to find the heat flux, heat rate, and heat loss accurately over an entire surface. Typical pictures of the inside and outside front faces can be seen in Figures 5 and 6 below.

![Figure 4 Typical Thermogram Inside Front Face](image-url)
In order to accommodate both cameras, a second camera stand was built to replicate how the camera is held inside the apparatus. During testing this second camera stand was placed so that both cameras were the same distance from the front face of the box. The second camera stand can be seen below in Figure 7.
Type K thermocouples were used in conjunction with a data acquisition system from National Instruments to capture the amount of heat being transferred into the air and the amount of heat being transferred into the rest of the wood. Four thermocouples were used: two hung through the top of the box that measured air temperature, and two were placed on the inner and outer surfaces of the top plate of the box. The two thermocouples on either side of the top piece of wood were used to calculate the heat flux, heat rate, and total heat loss through the portion of the box not captured by the thermal imaging cameras. The two thermocouples hung in the air were used to calculate the amount of heat transferred to the air. All of the
thermocouples placed inside the box were positioned so that they did not interfere with the images from the cameras.

Four experiments were conducted for this project: 60W bulb with insulation, 60W bulb without insulation, 100W bulb with insulation, and 100W bulb without insulation. Johns Manville insulation was used to wrap the box completely in order to force as much energy as possible through the front face of the box. One of the demonstrations this box will be used for is to show how energy can be directed by using insulation. Energy flows, like water, through the path of least resistance. By adding insulation to portions of the box, those areas become more resistant to energy flow and therefore can direct that energy elsewhere. Figures 8 and 9 below show the completed testing apparatus with insulation and without insulation respectively.

Figure 7 Completed Apparatus With Insulation
For a complete list of materials, temperature sensing equipment, and data acquisition equipment used in this project, see Appendix A.

**Procedure**

The procedure can be broken up into three main parts: set up, testing, and analysis. Factors such as bulb wattage, whether or not to use insulation, and how often images would be taken were decided before starting each test. Depending on the desired test parameters, the bulbs and insulation were changed. How often the images were taken during the test was also decided during the set up. Typically images were taken every 30 minutes. This was subject to change however, based on the total length of the time for the test. The initial set up involved measuring the distances between the front face to both cameras and adjusting the second camera stand so that these distances were equal. The main box and camera stand were placed on a single table that was long enough to fit the entire apparatus. Since multiple tests were going to be conducted, marks were made on the table around the edges of both the main box
and second camera stand in order to assure proper placement during each test. Before testing the cameras were charged and placed into their holders pointing towards the front face of the box. The cameras were adjusted by tilting the handle so that the outline of the front face was well defined within the camera’s view. The tests were all over 3 hours long and the camera chargers were kept nearby in case they were needed. The DAQ and computer were turned on and the LabVIEW program was opened in order to run a quick test and make sure that the thermocouples were reading ambient room temperature. Once the box, camera stand, and cameras were in place, and the DAQ and LabVIEW were reading correctly, the test was ready to begin.

The first step when testing was to take the initial pictures of the front face with each camera. The initial pictures were of the inner and outer surfaces of the front face at ambient conditions. After these pictures were taken, the light bulb was turned on and the LabVIEW program was started. A stopwatch was used as the timer to know when to take pictures with the cameras. Once started, the LabVIEW program was set to take temperature readings every 10 seconds with the thermocouples until the stop button was pressed. During testing, care was taken not to nudge or move the cameras in order to ensure that the cameras were taking images of the same location each time. These pictures were taken on both cameras simultaneously at every pre-determined interval until the temperatures began to reach steady state, or the total test time decided upon before the test had passed. Once the test time was reached, the stop button on the LabVIEW program was pressed, and the data was saved to an Excel
file. At this point the testing was complete; the light bulb was unplugged, and the cameras were put away.

After testing was complete, the USB cable for the cameras was used to extract the images from each camera and place them on to a computer. The files from each camera were placed in separate folders so that the order the images were taken, and the camera the images came from could be easily identified. Using the Flir tools software, available for free from Flir Systems, a comma separated values (csv) file was extracted from each picture and named using the following convention: 01Pic1, 01Pic2, 02Pic1, 02Pic2 etc. This naming convention specified the number in the sequence the image was taken, and whether the picture was of the inside of the box (Pic1) or of the outside of the box (Pic2). The naming convention was also important to ensure that the Matlab algorithm would read the files in the correct order. After the files had been renamed, they were placed in one folder that had the date of the test as the folder name. Before running the csv files through the Matlab code, the number of rows and columns to delete out of each file had to be determined. This step was necessary due to the fact that the pictures from the cameras were slightly larger than the area of the front face. The Matlab algorithm was designed to crop each 10,000-point matrix based on the rows and columns specified by the user. Conditional formatting in Excel was used to color each cell on a csv file. After zooming out, the outline of the front face could be easily seen and the rows and columns that should be removed were easily identified. The portion of the Matlab code that cropped the files would then be changed accordingly for each specific test. After the Matlab algorithm
had been updated with the correct rows and columns to be deleted, the time in between images, and the file path for the csv files, the program was ready to run.

The data analysis Excel workbook created for this project would then be used for all final data analysis. The temperatures exported from LabVIEW were copied on to the first sheet of the Excel workbook. Matlab output such as heat flux, heat rate, and heat loss through the front face were also inputted into the identified places on the first sheet of the Excel workbook. Due to some tests taking more time than others, the formulas on the other sheets used to find the heat transfer information from the thermocouples were often referring to incomplete data ranges. These formulas were checked for each test and changed to include all of the temperature information from the thermocouples. Once the ranges were properly identified and all input information had been entered on the first sheet, the Excel workbook then calculated and provided all results of the test on the last sheet of the workbook. For further details, a step-by-step procedure for the set up, testing, and analysis has been provided in Appendix B.

**Coding and Calculations**

As discussed above two programs and an Excel workbook were developed for the analysis of this project. LabVIEW was used to interface with the thermocouples and DAQ during testing. The LabVIEW program used waveform plots to record temperature values from the thermocouples every 10 seconds. After the program stopped and the test was complete, these waveform plots could be exported to an
Excel sheet that gave a table of temperature values and time values. A copy of the LabVIEW program can be seen in Appendix C.

Matlab was used to analyze the csv files from the cameras and calculate heat flux, heat rate, and total heat loss through the front face. The Matlab program pulled the csv files from a given directory and read them in as a 2D array. This 2D array was made up of 100 rows and 100 columns where each data point provided a temperature value. The program immediately cropped each array by deleting the rows and columns specified at the beginning of the code by the user. One portion of the program was designed to bring a 2-picture set of arrays into the program at the same time, one image from the inside camera, and one image from the outside camera. The program subtracted the outside array from the inside array which created a new 2D array that hold the values of the difference in temperature (dt) at each pixel location. This array of temperature differences corresponds to the variable dt seen in Equations 2 and 3 above. This 2D array was then placed into a 3D array and the loop was repeated until all 2-picture sets had been subtracted and placed within the 3D array. This 3D array, named dt, held the temperature difference at each pixel location at each time interval the pictures were taken. For example, if a test was run for four hours, and pictures were taken every 30 minutes, there would be 18 pictures and the 3D array would hold nine 2D arrays of temperature differences through the face (the first is the initial array measured at ambient temperature). The Matlab algorithm then used Fourier’s Law to calculate the heat rate at each pixel location at each time interval that images were taken. Temperature values between images were averaged
in order to find the heat flux, heat rate, and heat loss in between picture sets. A numerical integration technique was used to calculate the total heat loss through the face at each pixel location during the total test time. This technique takes an average heat rate between each time interval and then multiplies that heat rate by the time between picture sets. By doing this it solves for the amount of energy that went through the front face during that one time interval. The code then loops and finds the total amount of energy through the front face in between each time interval. It finishes the numerical integration by summing across the total test time and solving for the total energy through the front face at each pixel location. This total heat loss at each pixel was placed into a single 2D array. Lastly, the program used this 2D array to calculate the average heat flux, average heat rate, and total heat loss through the front face of the box. See Appendix D for a full copy of the Matlab code.

The Excel workbook was used to bring all of the calculations in to one place. After the Matlab algorithm calculated the average heat flux, average heat rate, and total heat loss through the front face, these values were inputted on the first sheet of the Excel workbook. The values from the thermocouples that LabVIEW output were also copied to the first sheet of the Excel workbook. Using the equations discussed above in the Theory section, the Excel workbook calculates energy from the light bulb, energy into the air, and energy through the box excluding the front face. The Excel workbook and the Matlab program work together to find how the heat is transferred for the four tests that were completed.
Results

Four tests were performed: 60W bulb with insulation, 60W bulb without insulation, 100W bulb with insulation, and 100W bulb without insulation. The first test, where the entire box was insulated except on the front face, used a 60W bulb and lasted for a total time of 5 hours. Pictures of both sides of the front face were taken every 20 minutes. The temperatures over the duration of the test, as recorded by the thermocouples, can be seen below in Figure 10.

![Figure 9 60W Bulb With Insulation Thermocouple Temperature Data](image)

The four thermocouples used to track temperature changes were placed in the box according to the legend above in Figure 10. T0 and T1 were used to measure the change in air temperature throughout the total test time. T2 and T3 were used to measure the temperature difference between the inside and outside of an insulated
wall so that the flux through these walls could be estimated. The total energy input into the box was 1028.1 kJ. The energy into the air was found to be 1 kJ, the energy through the front face was found to be 94.1 kJ, and the energy going through the other walls of the box was found to be 502.8 kJ. This means that 430.2 kJ, or 41.8% of the energy, was unaccounted for during the first test. This energy that is unaccounted for most likely occurs due to the spatial variation in temperature throughout the box. Spatial heating occurs because the light bulb is placed in the rear of the box, and therefore the box does not heat up evenly. Only two thermocouples were used to find the heat flux going through the insulated sides of the box, and that heat flux was assumed to be the same throughout the box. This assumption, although not accurate, was necessary due to the small amount of resources available for this project. Since there were only four thermocouples, two were used for the wood, and two were used for the air. The thermocouples used to find the heat flux through the wood were placed about 1.5 feet from the light bulb. This means that the wood where the thermocouples were placed had a lower temperature and lower heat flux than the wood nearest the bulb. The second reason the heat is likely unaccounted for could be due to small leaks between joints and insulation within the box. For the purposes of the calculations the box is treated as fully insulated, when in fact, there are likely leaks and heat being lost at various joints and holes (i.e. the interface between the box and camera). Table 2 shows a summary of the results for the first test.
Table 2 Test #1 – 60W Bulb – Fully Insulated Except Front Face

<table>
<thead>
<tr>
<th>Energy From Light Bulb (kJ)</th>
<th>1028.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Into the Air (kJ)</td>
<td>1.0</td>
</tr>
<tr>
<td>Energy Out the Front Face (kJ)</td>
<td>94.1</td>
</tr>
<tr>
<td>Energy Through Other Walls (kJ)</td>
<td>502.8</td>
</tr>
<tr>
<td>Energy Unaccounted For (kJ)</td>
<td>430.2</td>
</tr>
<tr>
<td>Front Face Area as % of Total Surface Area</td>
<td>4.5%</td>
</tr>
<tr>
<td>% Energy Going Into the Air</td>
<td>0.10%</td>
</tr>
<tr>
<td>% Energy Going Out Front Face</td>
<td>9.2%</td>
</tr>
<tr>
<td>% Energy Going Through Other Walls</td>
<td>48.9%</td>
</tr>
<tr>
<td>% Energy Unaccounted For</td>
<td>41.8%</td>
</tr>
<tr>
<td>Avg Heat Rate Through Front Face (W)</td>
<td>5.2</td>
</tr>
<tr>
<td>Avg Heat Rate Through Other Walls (W)</td>
<td>27.9</td>
</tr>
<tr>
<td>Avg Heat Flux Through Front Face (W/m²)</td>
<td>168.9</td>
</tr>
<tr>
<td>Avg Heat Flux Through Other Walls (W/m²)</td>
<td>42.2</td>
</tr>
</tbody>
</table>

One of the most important things that the results show is that the percent of heat going out the front face is larger than the percent of area the front face makes up. The front face only accounts for 4.5% of the total heated area; yet, 9.2% of the total energy went through that face. This occurs because the front face was left uninsulated and is half as thick as the rest of the wood. More energy goes out of the front face than would be expected based on the surface area that the front face makes up. This occurs despite the fact that the light is at its furthest distance away from the front face. If the light bulb was placed closer to the front face, the amount energy going through the front face would be expected to increase. The insulation surrounding the box drives the heat out the front and the smaller thickness of the wood allows heat to pass through easier.
The second test used the same 60W light bulb as the first test, but the insulation on the box was removed. In this test, only 32.5% of the energy was unaccounted for. This is likely due to less of an effect of spatial heating compared with the insulated test since there is no insulation around the box and the heat can travel easier. The temperature change through the box over time for this test can be seen below in Figure 11.

![Temperature Change Graph](image)

**Figure 10 60W Bulb No Insulation Thermocouple Temperature Data**

Although there was no insulation, the percentage of heat going out of the front face was still a little higher, at 5.2% of the energy, than the 4.5% of total area the front face makes up. This was expected because the front face still has a thickness that is half as thick as the rest of the box and therefore has a lower thermal resistance, Table 3 shows a summary of the results from the second test.
Table 3 Test #2 – 60W Bulb – No Insulation

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy From Light Bulb (kJ)</td>
<td>1028.1</td>
</tr>
<tr>
<td>Energy Into the Air (kJ)</td>
<td>0.5</td>
</tr>
<tr>
<td>Energy Out the Front Face (kJ)</td>
<td>53.1</td>
</tr>
<tr>
<td>Energy Through Other Walls (kJ)</td>
<td>640.3</td>
</tr>
<tr>
<td>Energy Unaccounted For (kJ)</td>
<td>334.1</td>
</tr>
<tr>
<td>Front Face Area as % of Total Surface Area</td>
<td>4.5%</td>
</tr>
<tr>
<td>% Energy Going Into the Air</td>
<td>0.05%</td>
</tr>
<tr>
<td>% Energy Going Out Front Face</td>
<td>5.2%</td>
</tr>
<tr>
<td>% Energy Going Through Other Walls</td>
<td>62.3%</td>
</tr>
<tr>
<td>% Energy Unaccounted For</td>
<td>32.5%</td>
</tr>
<tr>
<td>Avg Heat Rate Through Front Face (W)</td>
<td>3.0</td>
</tr>
<tr>
<td>Avg Heat Rate Through Other Walls (W)</td>
<td>35.5</td>
</tr>
<tr>
<td>Avg Heat Flux Through Front Face (W/m²)</td>
<td>95.3</td>
</tr>
<tr>
<td>Avg Heat Flux Through Other Walls (W/m²)</td>
<td>53.8</td>
</tr>
</tbody>
</table>

The third test used a 100W bulb and the insulation was not reinstalled until test four. As would be expected, the heat rate and heat flux for both the front face and rest of the wood increased with the 100W bulb compared to the 60W bulb. Only 32.6% of the heat was unaccounted for in the third test, which is comparable to the amount that was unaccounted for in the 60W test without insulation. This further supports the idea that the unaccounted for energy is missing largely due to spatial heating and not having enough thermocouples to accurately represent the temperature change throughout the wood. The temperature change over time during the third test can be seen below in Figure 12.
Similar to the 60W test without insulation, the 100W test without insulation also had 5.2% of the energy go through the front face. A summary of the results for the third test can be seen below in Table 4.
The fourth test also used a 100W light bulb and the insulation was reinstalled to match the conditions of test one. This test, similar to the 60W test with insulation, had a larger amount of unaccounted for energy compared to the two tests without insulation. The unaccounted for energy during the fourth test was 43.7% and is again likely due to the large effect of spatial heating. Also like the first test, the fourth test had a much larger amount of heat go through the front face compared to the two tests without insulation. The temperature change over time throughout the box for the fourth test can be seen below in Figure 13.
Figure 12 100W Bulb With Insulation Thermocouple Temperature Data

For the fourth test, 10.3% of the energy went through the front face as compared to only 5.2% for the un-insulated tests, and 9.2% for the 60W – insulated test. The heat rate and heat flux values for the 100W tests nearly double the 60W tests for both the insulated and un-insulated cases. This is expected due to the higher wattage bulb being used. A summary of the results for the fourth test can be seen below in Table 5.
### Table 5 Test #4 – 100W Bulb – Fully Insulated Except Front Face

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy From Light Bulb (kJ)</td>
<td>2138.2</td>
</tr>
<tr>
<td>Energy Into the Air (kJ)</td>
<td>1.7</td>
</tr>
<tr>
<td>Energy Out the Front Face (kJ)</td>
<td>219.6</td>
</tr>
<tr>
<td>Energy Through Other Walls (kJ)</td>
<td>982.9</td>
</tr>
<tr>
<td>Energy Unaccounted For (kJ)</td>
<td>934.0</td>
</tr>
<tr>
<td>Front Face Area as % of Total Surface Area</td>
<td>4.5%</td>
</tr>
<tr>
<td>% Energy Going Into the Air</td>
<td>0.08%</td>
</tr>
<tr>
<td>% Energy Going Out Front Face</td>
<td>10.3%</td>
</tr>
<tr>
<td>% Energy Going Through Other Walls</td>
<td>46.0%</td>
</tr>
<tr>
<td>% Energy Unaccounted For</td>
<td>43.7%</td>
</tr>
<tr>
<td>Avg Heat Rate Through Front Face (W)</td>
<td>10.2</td>
</tr>
<tr>
<td>Avg Heat Rate Through Other Walls (W)</td>
<td>45.3</td>
</tr>
<tr>
<td>Avg Heat Flux Through Front Face (W/m^2)</td>
<td>328.4</td>
</tr>
<tr>
<td>Avg Heat Flux Through Other Walls (W/m^2)</td>
<td>68.6</td>
</tr>
</tbody>
</table>

In order to compare the results from each test, all of the results were compiled into Table 6 below.
Table 6 Summary of Results for All Four Tests

<table>
<thead>
<tr>
<th>Test #</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>1/17/15</td>
<td>1/22/15</td>
<td>1/24/15</td>
<td>1/29/15</td>
</tr>
<tr>
<td>Bulb (W)</td>
<td>60</td>
<td>60</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Insulation</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Front Face as % of Total Surface Area</td>
<td>4.5%</td>
<td>4.5%</td>
<td>4.5%</td>
<td>4.5%</td>
</tr>
<tr>
<td>% Energy Into the Air Inside the Box</td>
<td>0.10%</td>
<td>0.05%</td>
<td>0.06%</td>
<td>0.08%</td>
</tr>
<tr>
<td>% Energy Through Other Walls</td>
<td>48.9%</td>
<td>62.3%</td>
<td>62.1%</td>
<td>46.0%</td>
</tr>
<tr>
<td>% Energy Through the Front Face</td>
<td>9.2%</td>
<td>5.2%</td>
<td>5.2%</td>
<td>10.3%</td>
</tr>
<tr>
<td>% Energy Unaccounted For</td>
<td>41.8%</td>
<td>32.5%</td>
<td>32.6%</td>
<td>43.7%</td>
</tr>
<tr>
<td>Avg Heat Flux Through Front Face (W/m²)</td>
<td>168.90</td>
<td>95.30</td>
<td>167.30</td>
<td>328.40</td>
</tr>
<tr>
<td>Avg Heat Flux Through Other Walls (W/m²)</td>
<td>42.20</td>
<td>53.80</td>
<td>92.60</td>
<td>68.60</td>
</tr>
<tr>
<td>Avg Heat Rate Through Front Face (W)</td>
<td>5.20</td>
<td>3.00</td>
<td>5.20</td>
<td>10.20</td>
</tr>
<tr>
<td>Avg Heat Rate Through Other Walls (W)</td>
<td>27.90</td>
<td>35.50</td>
<td>61.20</td>
<td>45.30</td>
</tr>
</tbody>
</table>

The results shown above were able to verify what was expected for these tests. All of the tests show that more energy went through the front face than what would be expected based on its area. This is due to the front face being half as thick as the rest of the walls and therefore, heat travels through the front face easier than the other walls. For the two tests that were insulated, the energy through the front face almost
doubled the un-insulated cases. For a comparison between the insulated tests and the un-insulated tests see Table 7 below.

**Table 7 Comparison Between Insulation and No Insulation for Both Bulbs**

<table>
<thead>
<tr>
<th></th>
<th>60 W Bulb</th>
<th>100 W Bulb</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Increase in Heat Loss Through Front Face Due to Insulation</td>
<td>76.9%</td>
<td>98.1%</td>
</tr>
<tr>
<td>% Increase in Heat Flux Through Front Face Due to Insulation</td>
<td>77.2%</td>
<td>96.3%</td>
</tr>
<tr>
<td>% Increase in Heat Rate Through Front Face Due to Insulation</td>
<td>73.3%</td>
<td>96.2%</td>
</tr>
<tr>
<td>% Decrease in Heat Loss Through Other Walls Due to Insulation</td>
<td>-21.5%</td>
<td>-25.9%</td>
</tr>
<tr>
<td>% Decrease in Heat Flux Through Other Walls Due to Insulation</td>
<td>-21.6%</td>
<td>-25.9%</td>
</tr>
<tr>
<td>% Decrease in Heat Rate Through Other Walls Due to Insulation</td>
<td>-21.4%</td>
<td>-26.0%</td>
</tr>
</tbody>
</table>

Table 7 shows that for the 60W bulb by adding insulation the total heat loss, average heat rate, and average heat flux through the front face all increased by 73% - 77%. Similarly for the 100W bulb the total heat loss, average heat rate, and average heat flux all increased by about 97% after insulation was added. It is also important to note that since a greater amount of energy went through the front face of the box, less
energy had to go through the other walls of the box. For the 60W bulb the total heat loss, average heat rate, and average heat flux through the other walls decreased by about 21.5% after adding insulation. The total heat loss, average heat rate, and average heat flux decreased by about 26% for the 100W bulb after adding insulation. These results show that heat can be directed by increasing the amount of material surrounding a heated area and/or by changing the material surrounding the area to one with a lower thermal conductivity.
III. CONCLUSIONS & RECOMMENDATIONS

The goals of this project were all met and the apparatus was proven to be a useful demonstration of how energy travels. The results found from the four tests showed that energy could be directed, and to some extent quantified, by using insulation and by varying the wattage of the heat source. This apparatus will prove to be a valuable experiment and demonstration for Dr. Margraves to use when teaching about heat transfer concepts.

The final box was well insulated and able to be used in conjunction with thermal imaging cameras that showed how energy is transferred through different materials. The box was also made adaptable and has allowed room for expansion of other projects related to the same apparatus. Some future projects may include testing with different materials, using more thermocouples, or blowing air from a fan across the front face to study heat transfer by convection. The front face of the box was made interchangeable and allows for a wide variety of materials to be tested. A data acquisition (DAQ) system was provided with a program that uses four thermocouples to measure temperature inside, on, and around the apparatus. An algorithm was completed using Matlab software to import files from the cameras and use the data to calculate the average heat rate, average heat flux, and total heat loss through a surface. The adaptability of the apparatus allows for both basic and in depth studies of heat transfer. The final thermal imaging apparatus provided to Dr. Margraves will be useful for demonstrations and laboratory experiments for both college and middle school students.
A list of recommendations has been put together in order to improve this project or other similar projects related to a thermal imaging apparatus.

- Purchase a larger DAQ and more thermocouples so that an accurate representation of the temperature change through the insulated walls could be measured.

- Add to the Matlab code so that it analyzes the data from the thermocouples as well as from the cameras. Ideally, this new program would perform all of the calculations related to the project and the Excel workbook could be discarded.

- Redesign the brackets that hold the cameras in place during testing. New brackets should be sturdy enough to hold the cameras in the exact same location during every test. If this was implemented, it would cut out the step of having to locate which rows and columns of the csv files needed to be removed for each test. The Matlab program could then be changed to always delete the same rows and columns, which would be a major help in streamlining the analysis.

- Change the front face material to ¾” White Pine Wood so that it matches the rest of the box. With no insulation, the energy would not be expected to go out the front face like it has in the earlier tests with a thinner front face. Due to the light bulb placement at the rear of the box, the energy going through the front face would be expected to be less than the 4.5% for a test without insulation.

- Find a way to batch convert the jpeg images to csv files. Currently each image has to be individually converted using the free version of Flir Tools.
• Design a remote controlled trigger mechanism that could automatically take pictures on the cameras at pre-determined intervals.

• Redesign the box to be smaller so that it does not take hours to reach steady state.
LIST OF REFERENCES


2http://www.facstaff.bucknell.edu/, “Temperature Sensor - the Thermocouple.”

3http://thermoelectrics.matsci.northwestern.edu/, “Thermoelectrics: The Seebeck Effect.”


APPENDICES
## Appendix A: Material List for Complete Apparatus

### Table 8 Material List for Complete Thermal Imaging Apparatus

<table>
<thead>
<tr>
<th>Material Description</th>
<th>QTY</th>
<th>Vendor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1X10 White Pinewood</td>
<td>6</td>
<td>Home Depot</td>
</tr>
<tr>
<td>2 X 4 OSB Wood Sheets</td>
<td>1</td>
<td>Home Depot</td>
</tr>
<tr>
<td>2 X 3 X 96” Wood Studs</td>
<td>1</td>
<td>Home Depot</td>
</tr>
<tr>
<td>Felt Pad</td>
<td>2</td>
<td>Home Depot</td>
</tr>
<tr>
<td>Silicon Caulk</td>
<td>2</td>
<td>Home Depot</td>
</tr>
<tr>
<td>1-1/4” Drywall Screws Pack</td>
<td>1</td>
<td>Home Depot</td>
</tr>
<tr>
<td>1” Drywall Screws Pack</td>
<td>1</td>
<td>Home Depot</td>
</tr>
<tr>
<td>Black Spray Paint</td>
<td>1</td>
<td>Home Depot</td>
</tr>
<tr>
<td>Extension Cord</td>
<td>2</td>
<td>Home Depot</td>
</tr>
<tr>
<td>Light Bulb Fixture Rated for 60W</td>
<td>1</td>
<td>Home Depot</td>
</tr>
<tr>
<td>Light Bulb Fixture Rated for 100W</td>
<td>1</td>
<td>Home Depot</td>
</tr>
<tr>
<td>60W Light Bulb</td>
<td>1</td>
<td>Home Depot</td>
</tr>
<tr>
<td>100W Light Bulb</td>
<td>1</td>
<td>Home Depot</td>
</tr>
<tr>
<td>Bolts</td>
<td>4</td>
<td>Home Depot</td>
</tr>
<tr>
<td>Wing Nuts</td>
<td>4</td>
<td>Home Depot</td>
</tr>
<tr>
<td>Washers</td>
<td>4</td>
<td>Home Depot</td>
</tr>
<tr>
<td>Tie Plates</td>
<td>4</td>
<td>Home Depot</td>
</tr>
<tr>
<td>Brackets</td>
<td>4</td>
<td>Home Depot</td>
</tr>
<tr>
<td>Elmer’s Wood Glue</td>
<td>1</td>
<td>Home Depot</td>
</tr>
<tr>
<td>Gorilla Glue</td>
<td>1</td>
<td>Home Depot</td>
</tr>
<tr>
<td>Johns Manville Insulation: B1284 , R -13</td>
<td>1</td>
<td>Home Depot</td>
</tr>
<tr>
<td>Fan: OD9225-SPOT</td>
<td>1</td>
<td>Mouser Electronics</td>
</tr>
<tr>
<td>Bugpack Hood Latches</td>
<td>4</td>
<td>Amazon</td>
</tr>
<tr>
<td>Aluminum 3003-H14 1/8&quot; X 12&quot; X 12”</td>
<td>1</td>
<td>Amazon</td>
</tr>
<tr>
<td>K-Type Thermocouple Wire, Fiberglass (32 °F to 900 °F) 1 m</td>
<td>4</td>
<td>Amazon</td>
</tr>
<tr>
<td>USB DATA ACQ SYS 8DE/16SE CH</td>
<td>1</td>
<td>Amazon</td>
</tr>
<tr>
<td>Flir I5 Thermal Imaging Camera</td>
<td>2</td>
<td>Amazon</td>
</tr>
</tbody>
</table>
Appendix B: Step by Step Testing Procedure

Set Up

1. Charge cameras before testing to be sure they will have plenty of battery life during the test.
2. Make sure the light bulb has been off for a long period of time and that the apparatus has had sufficient time to reach ambient room temperature.
3. Check the positions of the thermocouples to be sure they are in the desired locations and will not interfere with the cameras line of sight.
4. Decide test parameters:
   a. What wattage bulb should be used, 60W or 100W?
   b. Will insulation be used or not?
   c. How often will images be taken, and how long will the test last? An example would be to take pictures every 30 minutes.
   d. What material will be used for the front face?
5. Change the bulb if needed.
6. Re-install or un-install insulation if needed.
7. Change out the front face of the box if needed.
8. If there are not makers on the table where the apparatus is located, the position of the apparatus will have to be checked and/or repositioned.
   a. Measure the distance from the camera on the main box to the middle of the front face on the main box (this distance may vary slightly depending on the thickness of the front face material).
   b. Move the second camera stand so that the second camera is the exact same distance to the middle of the front face. Be sure the second camera stand is parallel to the main box.
   c. If there will be multiple tests to run, it is wise to mark the edges of both the main box and second camera stand on the table, using a pencil.
or tape. This way the apparatus can be set up in the exact same position for later tests.

9. Check both cameras for the memory cards and make sure the pictures are saving properly.

10. Set the emissivity values on the cameras to the correct value that corresponds to the front face material.

11. Set the color scheme on the camera to preference.

12. Once the cameras have been verified to be ready, place them into their holders on both the main box and second camera stand.
   a. If cameras are not fully charged, be sure there are outlets nearby the testing area so that the cameras can be plugged in while testing if needed.
   b. Get any extension cables if they may be needed to charge the cameras.

13. Look through the viewfinder on each camera and tilt the camera until the outline of the front face can be clearly seen.
   a. A trick that can help is to run your finger along the outline of the front face. This will leave a heat residue on the front face for just a few seconds, but long enough to position the camera so that the front face is in clear view.

14. Turn on the DAQ and open the LabVIEW program on the computer.
   a. Press the start button on the LabVIEW program, let it run for a minute and then press stop.
   b. Export the data to Excel and check the temperature values to make sure they are at ambient room temperature and that the thermocouples seem to be giving reasonable values.

15. The setup is now complete and the testing can begin.

*Note: When using the 100W light bulb, do not test for more than 3 hours as the heat from the high temperatures can cause damage to the camera.
Testing

1. Take an initial picture on each camera of the front face at ambient room temperature.
2. Have stopwatch or timer on hand to use for knowing when its time to take pictures with the cameras. A picture will need to be taken with each camera at each pre-determined interval. Currently, the pictures must be taken manually.
3. Plug in the light bulb, press start on the LabVIEW program, and press start on the stopwatch or timer.
4. Take pictures on both cameras simultaneously at every pre-determined interval that was decided during the set up.
   a. Be cautious and careful not to nudge the cameras while taking pictures. The cameras need to remain as stable as possible so that the pictures will be of the exact same location every time.
5. After the last picture has been taken, press stop on the LabVIEW program, unplug the light bulb, and remove the cameras from the apparatus.
6. Export the LabVIEW data to an Excel file and save to a flash drive or other location.
7. If the analysis will not begin immediately, take special care to store the cameras in their proper cases.
8. Shut down the DAQ and computer. Be sure all wires and cords are put away and the light bulb is not plugged in before leaving the apparatus.
9. The testing is now complete and the analysis can begin.
Analysis

1. Plug each camera into a computer using the provided USB cable with the camera. Extract the images from each camera and separate the pictures into individual folders for camera 1 and camera 2.

2. Use the Flir Tools software to open the folders that have the pictures in them. Click on an image to enlarge it; then right click and select the option to export the image as a comma separated value (csv) file.

3. Save the csv files for every picture using the following naming convention: 01Pic1, 01Pic2, 02Pic1, 02Pic2 etc. The first digit in the convention tells the where the image falls in the sequence. The number after “Pic” tells which camera that image comes from. Pic1 refers to the camera that captures the inside of the front face, and Pic2 refers to the camera that captures the outside of the face. For example, if pictures are taken every 30 minutes, 03Pic2 would be the outside image taken at time equals 1 hour.

4. Create a folder with the test date as the folder name and place all of the csv files from both cameras into this folder.

5. Open two pictures in Excel: one from the inside camera and one from the outside camera. Zoom out and resize all rows and columns so that the widths of the columns are the same size as the heights of the rows (each cell should be square shaped).

6. Use Excel’s conditional formatting to color each cell in the file.

7. The outline of the front face should now be easily seen. Make note of each row and column that needs to be deleted so that only the front face remains. This should be done for both the inner and outer faces, as the rows and columns that should be removed are likely different. Close Excel once this is finished.

8. Open the Matlab code and type the number of minutes between picture sets at the top of the code. Update the code to reflect the correct rows and columns that should be removed from both the inside and outside pictures.
the brackets [ ], for the corresponding variable, the number of each row and column that should be removed.

9. If the front face material has been changed, be sure to check the thermal conductivity constant and front face thickness that is used in the Matlab algorithm. These values may need to be changed depending on the type of material used for the front face.

10. Copy the file path where the csv files for both cameras are located and paste it into the 3 locations within the Matlab code that it is specified. The portion of the Matlab code with the file path is purple and should be easily recognizable.

11. Click run to start the Matlab program; after a few seconds the variables should show up in the workspace tab of Matlab. The variables that are of most concern are: Qout, qavg, and qxavg. These variables give the total heat loss, average heat rate, and average heat flux through the front face for the entire testing period.

12. Save the Matlab file and open the data analysis Excel workbook.

13. Paste the Qout, qavg, and qxavg values from Matlab into the first page of the Excel workbook.

14. Input the test time and the bulb wattage on the first page of the Excel workbook.

15. Open the Excel file with the data from the thermocouples that was exported from LabVIEW at the end of the test.

16. Copy the temperature values from the thermocouple Excel sheet and paste them on to the first page in the analysis Excel workbook. Depending on the length of the test the thermocouple data may be longer or shorter than a previous test already in the Excel workbook. The following formulas/cells need to be checked and corrected so that the match the correct range for the thermocouple data:

   a. The chart on the “corrected thermocouples” tab will need to have the data ranges for each curve corrected.
b. Columns F, G, and H on the “Q through Wood Calc” tab refer directly to the thermocouple data on the earlier tabs. There should be corresponding formula for each data point of the thermocouples. The formulas in columns F, G, and H may need to be extended or shortened.

c. On the “Energy Balance Calculation” tab the cells C11 and C13 used to calculate the heat transfer to the air need to be checked. These cells find the average air temperature and need to have their reference values updated.

17. All of the results of the test should now be displayed on the last two sheets of the Excel file.

18. The analysis of this test is now complete, be sure to save all programs, data, and files to an appropriate location.
Appendix C: LabVIEW Program Block Diagram and Front Panel

Figure 13 LabVIEW Program Block Diagram
Figure 14 LabVIEW Program Front Panel
Appendix D: Matlab Program Code

clearvars;
cle; 

%INPUT – Make sure this is correct for each test 
% NOTE: Make sure folder path is correct. 
deltaT = 30*60; % seconds between picture sets 
rows = 100-14; 
columns = 100-38; 

removerowspic1=[1 2 3 4 5 6 93 94 95 96 97 98 99 100]; 
removecolspic1=[1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100]; 
removerowspic2=[1 2 3 4 5 6 93 94 95 96 97 98 99 100]; 
removecolspic2=[1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100]; 

%Calculations Begin: 

% Pull all csv files, subtract 2 pictures to get dt. 
% Put all matrices of dt at each pixel into one large 3D matrix. 

Directory = dir(’E:\DHON\Tests\Testing 01-29-2014_100W_Ins\csv files\*.csv’); 
Seq = {Directory.name}; %this gets the name of files in directory 
ii=1; 
matrixnum = 1; 
pics = numel(Seq)/2; 
dt = zeros(rows,columns,pics);
while ii<numel(Seq);
    a = csvread(['E:\DHON\Tests\Testing 01-29-2014_100W_Ins\csv files\ Seq{ii}']);
    a(removerowspic1,:)=[ ];
    a(:,removecolspic1)=[ ];

    n = ii +1;
    b = csvread(['E:\DHON\Tests\Testing 01-29-2014_100W_Ins\csv files\ Seq{n}']);
    b(removerowspic2,:)=[];
    b(:,removecolspic2)=[ ];

    c = fliplr(b);
    dt(:,:,matrixnum) = a - c;
    matrixnum = matrixnum + 1;
    ii=ii+2;
end

% Heat Flux Calculation at every pixel

k = 0.13; % Thermal Conductivity  W/(m K)
dx = 3/8*0.0254; % Wall Thickness m
qx = -k * dt/dx; % Heat Flux per pixel W/(m^2)

% qx is a large 3D matrix of 2D matrices that contains heat flux at each
% pixel per 2 picture set.

% Heat Rate Calculation for every pixel

Apixel = 48/(rows*columns)*(0.0254^2); % Cross sectional area of a pixel(m^2)
q = qx * Apixel; % Heat Rate (W)
%Qloss = Total Heat Loss Through Each Pixel (2D Matrix in Joules)
Qloss = zeros(rows,columns);
iii=1;setnum1=1;setnum2=2;

while iii<pics;
    Qloss = Qloss + ((q(:,:,setnum1)+q(:,:,setnum2))/2)*deltaT;
    setnum1 = setnum1 +1;
    setnum2 = setnum2 +1;
    iii = iii + 1;
end

%Qout = Total heat loss through the face of the box in Joules
Qout = sum(sum(Qloss));

%qavg = Avg Heat rate out front of box in Watts
qavg = Qout/(deltaT*(pics-1));

%qxavg = Avg Heat Flux out front of box in W/m^2
qxavg = qavg/(48*0.0254^2);