Insulation and Zero Plus Energy Buildings – Development of a Small Scale Undergraduate Lab to Investigate the Effect of Insulation on Energy Transfer Using Thermal Imaging Cameras

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Abstract

Recently the Center for Energy, Transportation and the Environment (CETE) at the University of Tennessee at Chattanooga completed the renovation of a Zero Plus Energy Building by adding a highly efficient geothermal heat pump, a 16 kW solar array in addition to the 8 kW already in place, and improving the insulation used within the 10,000 square foot facility. Several senior capstone design teams have been tasked with designing and building small scale experiments, to be used in academic laboratories, which will demonstrate some of the building's features. The work presented in this paper details an apparatus that was created to quantitatively evaluate the heat flux through a surface, in order to estimate the losses associated with poor insulation. A small enclosed container was built, along with an interior heating element, to simulate a room within the facility. Two thermal imaging cameras were used to map the temperature profile on the interior and exterior side of one of the container's faces. Two sets of experiments were run in which the entire box was heated from room temperature to an approximate steady state condition. For the first set of tests the entire box was left un-insulated and for the second set the box was completely insulated except the surface being examined by the thermal imaging cameras. An algorithm was developed using Matlab software to calculate the heat rate through the front surface based on the digital images provided by the thermal imaging cameras and Fourier's Law of Conduction. It was found that at approximate steady state conditions the heat rate increased through the front face during the insulated test by 125%, over the uninsulated test, for a 60W heating element and 134% for a 100W heating element. Future work will expand on this project by using this apparatus to conduct multiple heat transfer and thermodynamic experiments.

Keywords

Insulation, Energy Transfer, Thermal Imaging, Zero Energy Building, Sustainability

Introduction

During the 1980's the Tennessee Valley Authority (TVA) began the process of developing electric buses for commuters in the downtown area of Chattanooga Tennessee. A laboratory, along with a one-mile test track, was built on the banks of the Tennessee River to provide an area for testing and refinement. While work on the buses has continued over the years, the building has recently been provided to the University of Tennessee at Chattanooga for research in sustainability. As part of a senior design project a group was tasked with determining the possibility of converting the building into a Zero Plus Energy facility (more energy is produced than consumed). After confirming the feasibility of this project, a research grant was procured to add a highly efficient geothermal heat pump, an additional 16 kW solar array (8 kW already existed), and an improvement to the facilities insulation.

While a great deal of public attention has been given to highly efficient devices such as the geothermal heat pump, and to alternative energy producing devices such as the solar array, less attention has been given to improving the quality of insulation. The goal of this work was to provide a small-scale experiment, applicable for mechanical, chemical and aerospace engineering undergraduate labs, to show students the effect of insulation on developing zero plus buildings.

Apparatus

The apparatus created for this project was designed to be portable so that it could easily be used as a laboratory experiment or a classroom demonstration. For this reason the box needed to be relatively small and light. The dimensions of the box were also driven by the focal length of the two Flir I5 thermal imaging cameras used to take pictures of both sides of the front face of the box. Figures 1 and 2 show the apparatus that was created. The final apparatus is 2’-10” long and has an interior cross sectional area of 8” x 6”.

The main camera was placed on the top of the box looking through a pre-cut hole so that it could capture a thermal map of the inside front face. 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 view. The front face used for testing was a $^3/_8$” thick piece of oriented strand board (OSB), which was chosen for its low thermal conductivity of only 0.13 W/mK. This would allow the box to have a large temperature difference across the front face providing more accurate heat flux calculations. The rest of the box was constructed out of ¾” thick white pine wood whose conductivity is similar to OSB at 0.12 W/mK. Silicon caulk was used to seal all of the edges on the inside of the box to 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 attach the front face, which allow the user to easily interchange the front face material for future studies.

An incandescent light bulb was chosen as the heating element due to the large amount of heat produced relative to its size. Two light bulbs, whose power ratings would be familiar to all students, were used for this project: a 60W and a 100W bulb. Each bulb was painted with black grill paint so that radiation effects would be minimized when measuring air temperature using type K thermocouples.

The two Flir I5 cameras selected, measure the intensity of radiation in the infrared part of the electromagnetic spectrum and then 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. The cameras chosen are capable of recording images that are 100 pixels by 100 pixels providing a total of 10,000 temperature readings that are then used to determine the heat flux and heat rate accurately over an entire surface. In order to accommodate both cameras, a second camera stand was built to replicate how the camera is held on the main apparatus. During testing this second camera stand was placed so that both cameras were equidistance from the front face of the box providing an identical field of view.

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 B1284 insulation with an R-value of 13 was used to wrap the box completely in order to direct as much energy as possible through the front face of the box, which is a main focus of this work.

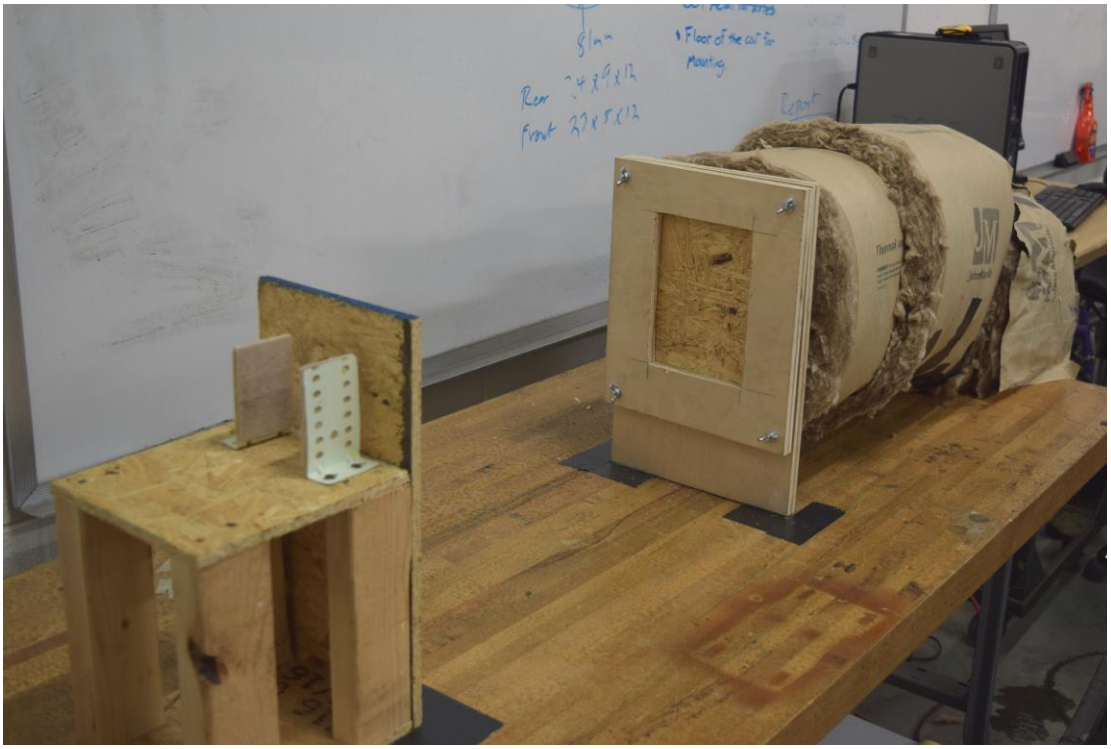

Figure 1 Completed Apparatus With Insulation

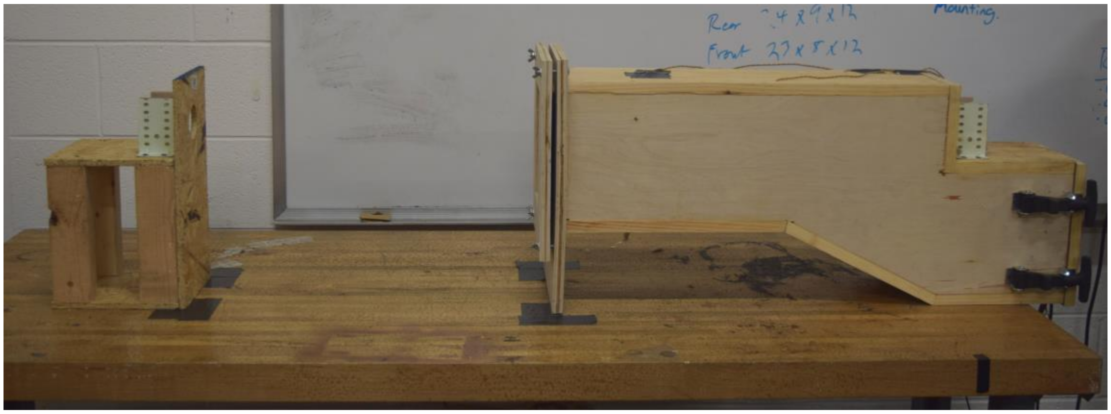

Figure 2 Completed Apparatus Without Insulation

Digital Processing Algorithm

Fourier's Law for one-Dimensional Conduction was assumed for all calculations performed during this project. 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 examining the following four variables: temperature difference (ΔT), material length (Δx), material cross-sectional area (A), and thermal conductivity (k). The general expression for *Fourier's Law* is given below in Equation 1.[1]

$$q'_x = -kA\frac{dT}{dx} \qquad (1)^1$$

The minus sign in the above equation is a consequence of the fact that heat is transferred in the direction of decreasing temperature.[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.[1] Heat flux is calculated by dividing the heat rate q'_x by the cross-sectional area A.[1] Heat flux in the x-direction is given below in Equation 2.

$$q''_x = -k\frac{dT}{dx} \qquad (2)^1$$

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. 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 3 shown below.

$$q''_x = -\frac{k}{L}\left(T_{s,2} - T_{s,1}\right) = \frac{k}{L}\left(T_{s,1} - T_{s,2}\right) \qquad (3)^1$$

The temperatures $T_{s,1}$ and $T_{s,2}$ used in Equation 3 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. Equation 3 was used to both analyze the data and to drive the project design. The original design used aluminum for the front face material instead of OSB. However, the high thermal conductivity of aluminum caused the temperature difference between $T_{s,1}$ and $T_{s,2}$ to be so small that it was difficult to get any meaningful results with the thermal imaging cameras. By using OSB, which has a relatively low thermal conductivity compared to aluminum, a measurable temperature difference across the face was observed.

Emissivity, a thermal property of a substance, plays an important role in how much infrared radiation is emitted from an object. Because the thermal imaging cameras do not detect emissivity a constant emissivity factor must be set on the cameras in order to calculate the correct temperature. Flir Systems state "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."[5] Emissivity values typically range between 0.1 and 0.95.[5] The Flir I5 has built in emissivity values that can be chosen based on the material type being imaged (0.85 was used for this work).

As mentioned previously the Flir I5 cameras chosen for this project output images containing 10,000 pixels of information. This data is analogous to using 10,000 thermocouples, thus providing a major benefit over more conventional temperature measurement devices. Typical thermograms produced by the camera for the inner and outer front face of the box can be seen below in Figure 3.

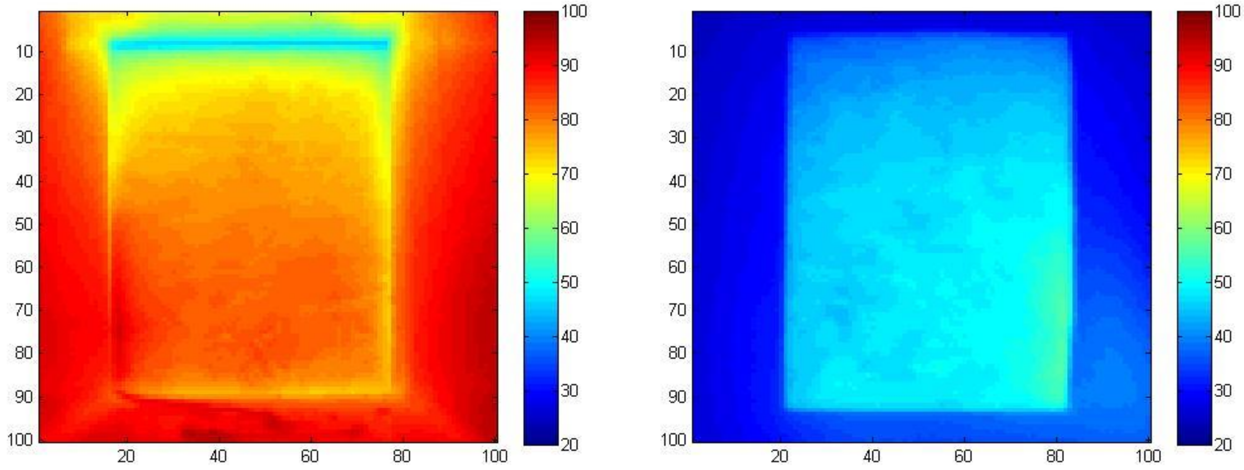

Figure 3 Typical Thermograms For Inner and Outer Front Face Surfaces (Scale represents temperature in Degrees Celsius)

Matlab software was used to analyze the thermograms and to calculate the heat flux through the front face. The program used comma separated variable (csv) files, generated from the thermograms, to create a 100 by 100 array of temperature data. This information was then cropped by deleting the rows and columns specified at the beginning of the code by the user. The cropping was necessary as the apparatus was designed to take an image that captured an area slightly larger than the front face. This excess area needed to be deleted in order to get an accurate representation of the temperatures across the front face alone. 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 held the values of the difference in temperature (dt) through the face at each pixel location. This array of temperature differences corresponds to the variable dt seen in Equations 1 and 2 above. The 2D array was then placed into a 3D array (with time as the third dimension) and the loop was repeated until all 2-picture sets had been subtracted and placed within the 3D array. The Matlab algorithm then used *Fourier's Law* to calculate the heat rate at each pixel location at each time interval that the images were taken. Temperature values between images were averaged in order to find the heat flux in between picture sets. A numerical integration technique was then employed 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 passing through the portion of the face represented by that pixel area during that time interval. The code then loops and finds the total amount of energy through the entire 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. For this work a focus is also placed on the final heat rate data, assumed to be at or near steady state for each test, for comparative purposes.

Results

As stated previously four tests were conducted for this project: 60W bulb without insulation, 60W bulb with insulation, 100W bulb without insulation, and 100W bulb with insulation. Figure 4 below show the temperature versus time data for all four tests.

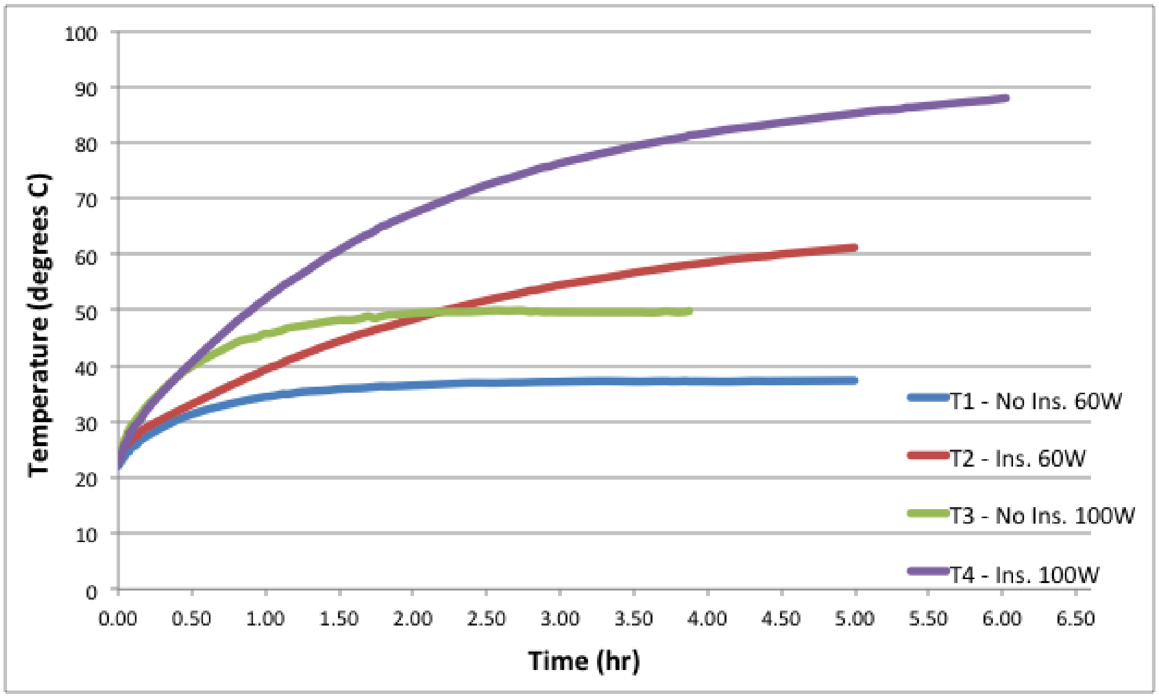

Figure 4 – Average Temperature Inside the Apparatus for each Test

For the first test, the apparatus was left completely un-insulated, 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. A summary of the results for the first test can be seen below in Table 1.

Table 1 Test #1 – 60W Bulb – No Insulation

Total Energy From Light Bulb (kJ)	1028.1
Total Energy Out the Front Face (kJ)	53.1
Front Face Area as % of Total Surface Area	4.5%
% Energy Going Out Front Face	5.2%
Avg Heat Rate Through Front Face (W) at Steady State	4.7

The results show that the percent of heat going out the front face is larger than the percent of surface area the front face makes up. The front face only accounts for 4.5% of the total heated surface area; yet, 5.2% of the total energy went through that face. This occurs because the front face is half as thick as the rest of the wood providing a smaller resistance for heat transfer. It is also worth noting that the bulb is at its furthest distance away from the front face. If the bulb were placed closer to the front face, the amount energy going through would be expected to significantly increase. Finally, at steady state conditions the average heat rate through the front face is 4.7W.

The second test used the same 60W light bulb as the first test, but for this test the entire box was insulated except on the front face. Again pictures of both sides of the front face were taken every 20 minutes for 5 hours. A summary of the results for the second test can be seen below in Table 2.

Table 2 Test #2 – 60W Bulb – Fully Insulated Except Front Face

Energy From Light Bulb (kJ)	1028.1
Energy Out the Front Face (kJ)	94.1
Front Face Area as % of Total Surface Area	4.5%
% Energy Going Out Front Face	9.2%
Avg Heat Rate Through Front Face (W) at Steady State	10.6

The results again show that the percent of heat going out the front face is larger than the percent of surface area the front face makes up. As previously stated the front face only accounts for 4.5% of the total heated surface area; yet, 9.2% of the total energy went through this face. This occurs because the front face was left un-insulated while the remainder of the box was insulated. The heat rate at approximately steady state was found to be 10.6W, which is 125% greater than for case 1.

The third test used a 100W bulb without insulation and lasted for 4 hours. 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. Similar to the 60W test without insulation, the 100W test without insulation also had 5.2% of the energy transfer through the front face and at steady state the heat rate was 7.9W. A summary of the results for the third test can be seen below in Table 3.

Table 3 Test #3 – 100W Bulb – No Insulation

Energy From Light Bulb (kJ)	1425.5
Energy Out the Front Face (kJ)	74.6
Front Face Area as % of Total Surface Area	4.5%
% Energy Going Out Front Face	5.2%
Avg Heat Rate Through Front Face (W) at Steady State	7.9

The fourth and final test was 6 hours long and also used a 100W light bulb. For this test the insulation was reinstalled to match the conditions of test number two. The fourth test lasted longer than the un-insulated case because the insulation made it more difficult to reach an approximate steady-state. Like the second test, the fourth test had a much larger amount of heat transfer through the front face compared to the two tests without insulation. 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 flux values for the 100W tests nearly double the 60W tests for both the insulated and un-insulated cases. Also at steady state the heat rate increased from 7.9W for the uninsulated case to 18.5W for the insulated case, a 134% increase. A summary of the results for the fourth test can be seen below in Table 4.

Table 4 Test #4 – 100W Bulb – Fully Insulated Except Front Face

Energy From Light Bulb (kJ)	2138.2
Energy Out the Front Face (kJ)	219.6
Front Face Area as % of Total Surface Area	4.5%
% Energy Going Out Front Face	10.3%
Avg Heat Rate Through Front Face (W) at Steady State	18.5

In order to compare the results from each test, all of the results were compiled in to Table 5 below.

Table 5 Summary of Results for All Four Tests

Test #	1	2	3	4
Date	1/17/15	1/22/15	1/24/15	1/29/15
Bulb (W)	60	60	100	100
Insulation	Yes	No	No	Yes
Front Face as % of Total Surface Area	4.5%	4.5%	4.5%	4.5%
% Energy Through the Front Face	9.2%	5.2%	5.2%	10.3%
Avg Heat Rate Through Front Face (W) at Steady State	4.7	10.6	7.9	18.5

The results shown above verified what was expected. All tests show that more energy was transferred through the front face than what would be expected based on area considerations alone. This is due to the fact that although the thermal conductivity for all walls is similar, the front face was half as thick as the rest of the box. For the two tests that were insulated, the percent of energy traveling through the front face almost doubled the un-insulated cases. For a final comparison between the insulated tests and the un-insulated tests see Table 6 below.

Table 6 Comparison Between Insulation and No Insulation for Both Bulbs

Bulb	60 W Bulb	100 W Bulb
% Increase in Heat Rate Through Front Face at Steady State Due to Insulation	125%	134%

Conclusion

The final results for this work show that for the 60W bulb by adding insulation the average heat rate through the front face increased by 125% at steady state. Similarly for the 100W bulb the average heat rate increased by about 134% after insulation was added. These results provide quantitative evidence to engineering students of the effect of poor insulation on heat loss and the need to improve insulation when creating a zero energy plus building.

Recommendations and Future Work

Based on the success of this work and the flexibility of the apparatus, several new experiments are being considered such as examining the effect of heat transfer rates using insulations with different R-values. It would also be desirable to add a convection component to this lab by adding a small fan located on the outside front face of the box. Using the same data collection as discussed in this paper, convection coefficients could be calculated quickly and easily. A second experiment would focus on a comprehensive energy tracking experiment. This was attempted during our reported experiments but there was a large discrepancy between the energy into the box and the energy out. This can be directly related to the lack of thermocouples placed around the interior of the box, which would be needed to gain an accurate understanding of the temperature distribution throughout. We have currently purchased sixteen additional thermocouples and have begun the process of developing an accurate energy tracking experiment. We also plan on conducting an FEA analysis allowing students to compare computational and experimental results.

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