DEVELOPMENT OF A SIMPLE HOT BOX TO DETERMINE THE THERMAL CHARACTERISTICS OF A THREE-DIMENSIONAL PRINTED BRICKS

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ABSTRACT: With the rapid advancement in the application of innovative computational tools, in particular, parametric design, algorithmically-driven built forms have shown promise in the building industry as evidenced by the exponential growth of three-dimensional printing of building components over the past several years. With the promise to simplify construction, lower cost, increase speed and responsible use of natural resources, encourage recycled material use, and increase design flexibility, parametrized 3D printing represents a credible alternative to current construction practices. To date, the focus of research has been on printing techniques, materials, and structural performance, but many of the promised benefits and opportunities have remained largely unrealized. One of the topics that have received little attention is the study of the thermal performance of the 3D printed walls and envelope components. This paper describes the design and application of a small Hot Box Apparatus developed specifically to test the thermal performance of small and highly detailed samples produced in our labs. Based on several initial experiments, authors discuss in detail the testing procedures, the instrumentation, and the conditions of the tests. The discussion includes errors encountered and elaborates on their sources and how we addressed them in the two experiments that are the basis of this paper. The results revealed that the obtained values from the hotbox were within the acceptable margin of error found in similar laboratory tests. Data collected from testing a rigid polystyrene board of known thermal characteristics were used to estimate parameters used in the determination of the thermal resistivity (R-value) of the ceramic wall. Initial results the R-value of ceramic assembly were promising because of the ability to embed different shapes and sizes of air pockets in the wall. Recommendations include improving the performance of the Hot Box and instrumentation to increase the accuracy of the measurements.

KEYWORDS: Hot Box, Conduction, 3D Printing, Thermal Performance, Ceramic wall

INTRODUCTION

Driven by an explosive advancement in the application of innovative computational tools, in particular, parametric design, algorithmically-driven built forms have shown promise in the building industry. This is evidenced by the exponential growth of three-dimensional printing of building components over the past several years (Berman 2012; D'Aveni 2013; Docksai 2014). With the potential to simplify construction, lower cost, increase speed and responsible use of natural resources, encourage recycled material use, and increase design flexibility, parametrized 3D printing represents a credible alternative to current construction practices. To date, the focus of research has been on printing techniques, materials, and structural performance, but many of the promised benefits and opportunities have remained largely unrealized (Wu et al. 2016). One of the topics that have received little attention is the study of the thermal performance of the 3D printed walls and envelope components. Therefore, the primary objective of this study is to develop a small Hotbox to assess the thermal performance of 3D printed ceramic wall with an embedded semi-enclosed air spaces.

With the advancement of mechanical refrigeration in the early twentieth century, concern for thermal insulation quickly followed. Many of ASTM standards were developed by the National Institute of Standards and Technology (NIST) formerly known as the National Bureau of Standards. The first hot plate Hot Box Apparatus built by NIST in 1912. However, only after 1916 Dickenson and Van Dueson defined the standard terms, types of experiments, and provided accurate estimates of heat flow coefficients for air spaces and many insulation materials (Zarr 2001). Today the majority of tests are conducted on one of two Hot Box designs. The first configuration is the self-masking with a controlled guard chamber surrounding the metering box or the chamber (Figure 1). The second configuration uses ambient conditions as a surrounding guard. The metering room of this design uses highly resistive materials to heat flow. Figure 2 shows a calibrated Hot Box design with the specimen inserted in the middle separating the metering (hot) chamber from the climate (cold) chamber. This design is simpler but suffers from the potential for significant errors in the calculations due to the heat flow to the outside and though flanking.

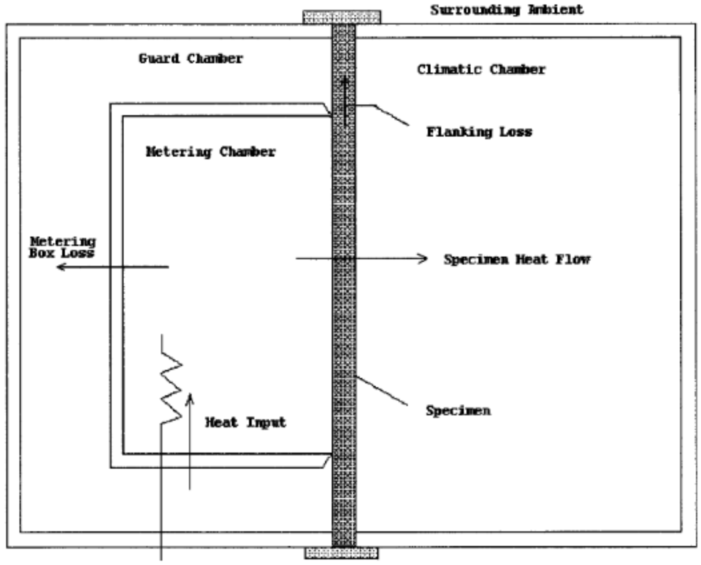


Figure 1: Guarded Hot Box. Source: (American Society for Testing Materials 2011)

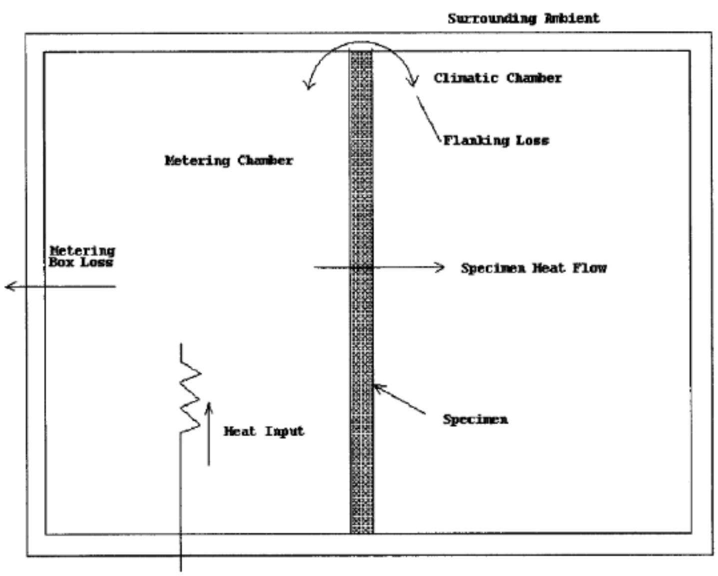


Figure 2: Calibrated Hot Box Apparatus. Source: (American Society for Testing Materials 2011)

Talk about Hotboxes, their designs, uses, and standards.

1.0 THE 3D PRINTED BRICK

In 2012, a 3D printed ceramic brick was developed to test the printing technology use at the scale of architecture and within the limitation of the printer dimensions (Figure 3). Each unit was made of stacked layers of 1/16 inch thick liquid ceramic slip cast recipe (Peters 2013). These units could be stacked and joined together to form a composite wall with air gaps and an interwoven perimeter (Figure 4). This design has attracted the attention of the design community and was awarded for its innovation and creativity. However, the brick as designed has potentially favorable thermal characteristics that could be studied and further enhanced. These are 1) ceramics have high thermal resistance, 2) each unit contains several enclosed air chambers, 3) the brick lining is thin and long, reducing the potential for thermal bridging. The objective of this research is to measure the thermal characteristics of the 3D printed wall and compare it with current construction assemblies.

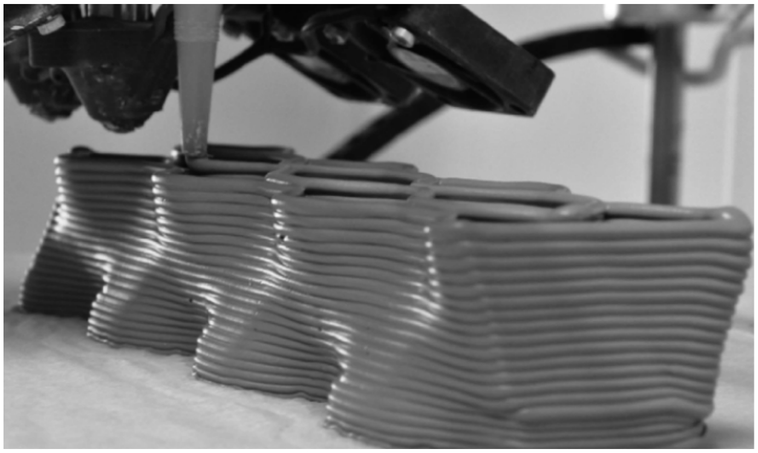


Figure 3: Printing the bricks on a desktop printer. Source (authors)

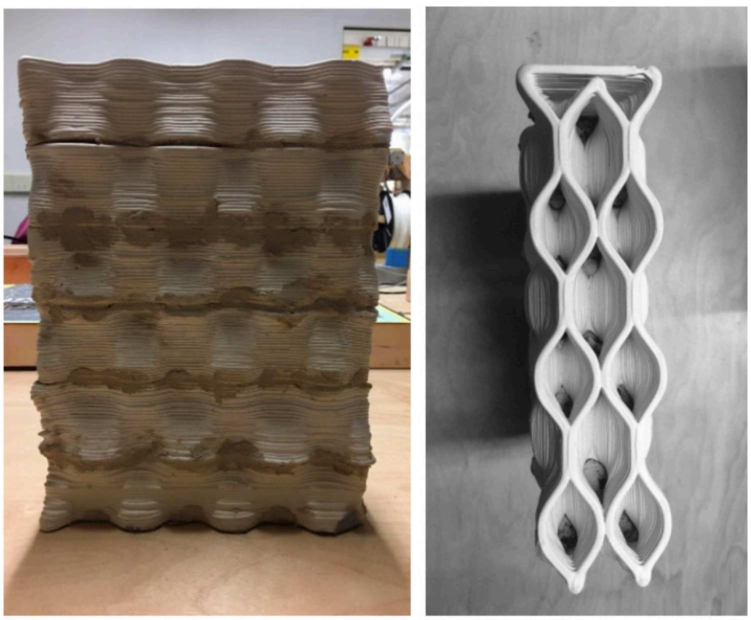


Figure 4: Tested wall (Source: Authors)

1.0 HOTBOX

The apparatus used to empirically determine the overall heat transmission of the ceramic wall assembly uses a calibrated design. The two-chamber are insulated with the specimen to be studied inserted in between. One of the chambers is heated, and the energy flow is metered while the second chamber is kept at a lower temperature. According to the American Society for Testing Materials, the apparatus is used to establish the minimum requirements to help the determination of steady state heat flow when exposed to controlled laboratory conditions (ASTM 2014; American Society for Testing Materials 2013). The apparatus is usually large and expensive (Seitz & Macdougall 2015; Schumacher et al. 2013). As a result, they are only located in national laboratories and large commercial testing facilities. The intent of this paper is to describe the development of a small, portable and inexpensive hot box for use in small laboratories commonly found in architecture and construction programs.

1.1. The Small Hotbox

The research team built an insulated plywood box measuring 20.5 x 8.0 x 11.25 in (Figure 5). The inner walls of the box are insulated with 2” thick expanded polystyrene. A second internal layer of plywood is attached to the inner wall. The metered chamber which we refer to as the hot chamber’s inner walls is covered with aluminum foil. When locked, the two chambers are completely isolated from the outside wall. Only a few sealed holes connect the temperature sensors and the heating element power source and controller (Figure 6). The tip of the heating element is covered with aluminum foil on the wall side to avoid heating the wall through radiation.

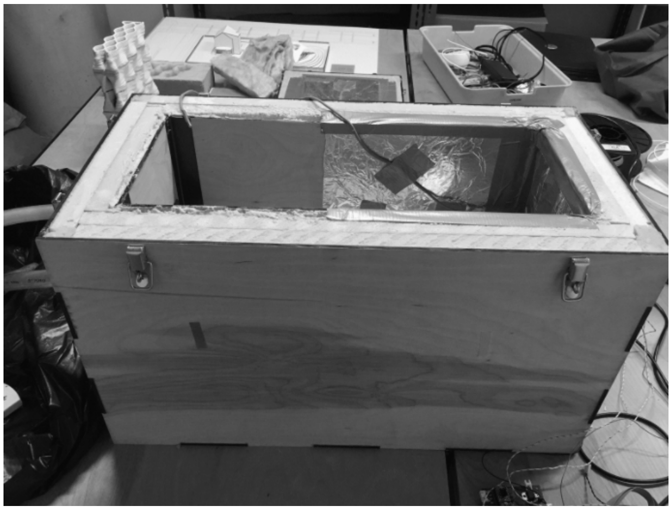
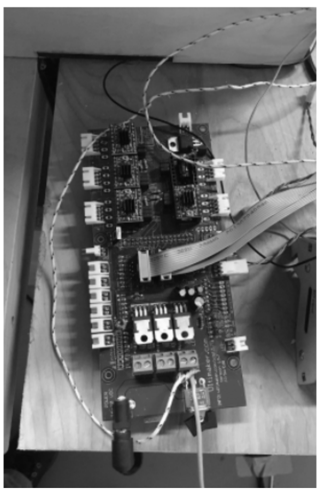


Figure 5: Hotbox assembly (Source: Authors)



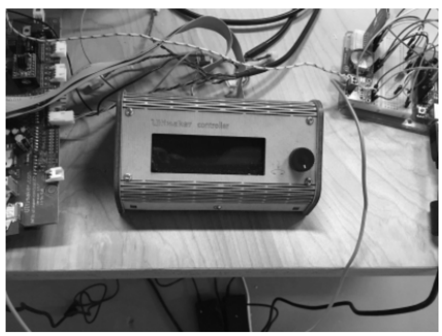


Figure 6: Heating Element Power (right) distribution and Power Controller (left)

The climatic chamber which will be referred to in this paper as the cold chamber is chilled with ice water that is pumped directly from a container outside the box (Figure 7). The water is continuously pumped from the ice and water filled container into the foils inside the cold chamber throughout the experiment.

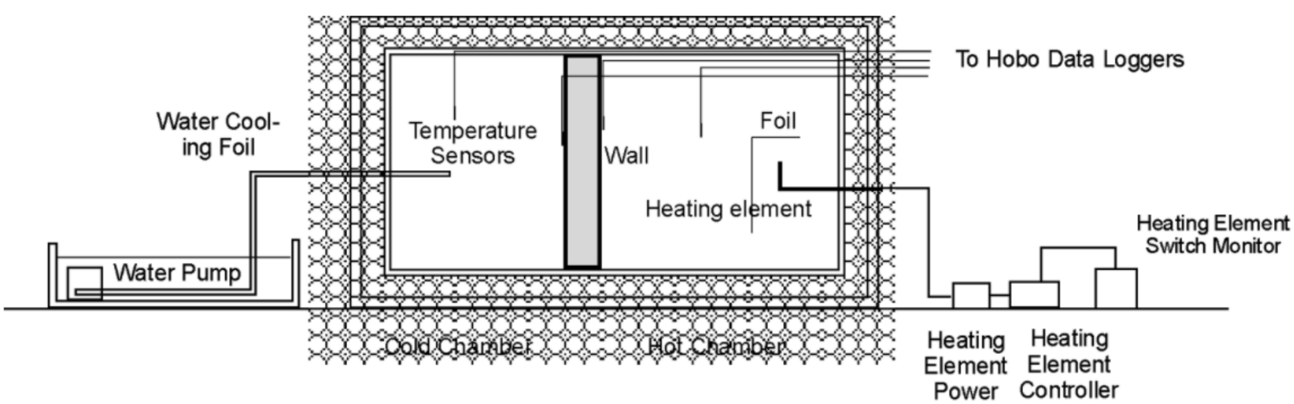


Figure 7: Experimental Design

1.2. Instrumentation

Temperature data were obtained using Hobo data loggers (Figure 8 & Figure 9) connected to external probes. The Hobo data loggers were calibrated before the initial laboratory tests. They were used to measure the instrumented wall hot and cold surface, as well as the air temperatures of the hot and cold chambers. The sensor probes were attached directly to the wall surface and covered with aluminum foil to protect the probe from reflected radiation from any potential heat source. The data loggers were setup to measure the temperature at the four locations inside the box, as well as the ambient temperature in the testing room. Temperature data was collected and recorded every minute for the duration of the experiment.

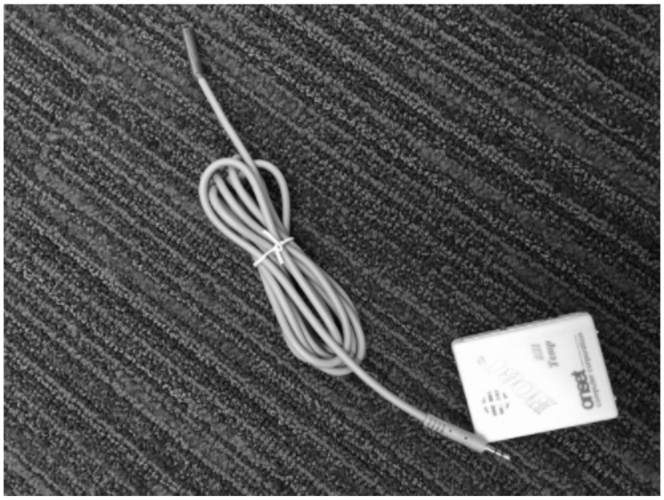


Figure 8: Hobo data loggers and temperature probe

The heating element was built from parts originally designed for a 12v, 40 W Power Resistor heating element for a 3D printer (Figure 6). Setting the controller at a particular temperature causes the heating element to operate until the sensor reaches the designated level. The controller then switches on and off to provide only the heat needed to maintain that desired temperature. The heat input equals the power transmitted while the switch is in the on position. The team assembled an Arduino data logger configured to monitor the switching periodicity by measuring the power in milliamps (mA) with a timestamp and record it to MicroSD card.

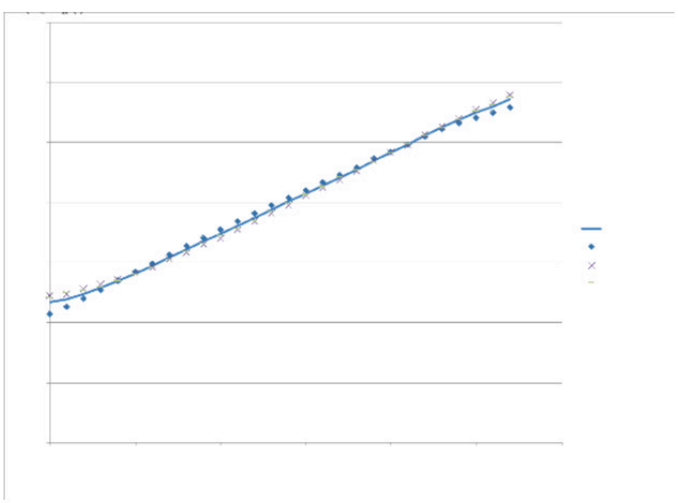


Figure 9: Calibration of the Hobo Sensors before testing

1.3. Wall assembly

A wall was constructed from modular ceramic bricks, each measuring 2.0 x 8.0 x 1.9 inches. Each of these walls is comprised of five blocks stacked vertically to form a 2.0 x 8.0 x 9.5-inch wall with vertically discontinuous oblong-shaped voids 2.3 x 1.0 x 9.5 inches. A second identical wall was built to test the more complex two-wythe wall configuration with a 2” air gap in between.

The wall was located in the middle of the hot box, and foam insulation was applied to seal the gaps between the assembly and the box's internal surfaces (Figure 7).

2.0 THE EXPERIMENT

Several initial experiments were conducted to test the hotbox, sensors and their locations, and to calibrate the testing protocols.

2.1 Experimental Protocol

- Each test took five hours.
- Each Hobo measured the temperature and recorded it every minute.
- Sensors were attached to the wall surfaces and kept in the middle of the hot and cold chambers without touching any surfaces.
- The heating element was shielded.
- The temperature in the hot chamber was set to 140 F.
- The ambient temperature was monitored every minute.
- The heating element switching monitor was connected, and light that switches on and off signified the switching periodicity of the controller. The measurements frequency was 1 Hz.
- The water pump chilled the cold chamber.
- A person was present during the tests at all times to monitor any sudden changes and notices an anomalous reading due to an error.
- Two experiments were conducted; The first one used a 2" rigid insulation board of a known R-value. The second experiment, we tested the ceramic wall (Single Wythe configuration)

2.2 Determine Steady State Condition

After completing the tests, data was collected and analyzed using a python script developed by the team. One of the objectives of data analysis to determine the steady state condition. This was achieved by calculating the temperature difference between the hot and cold surfaces and plotting over the duration of the experiment (Figure 10).

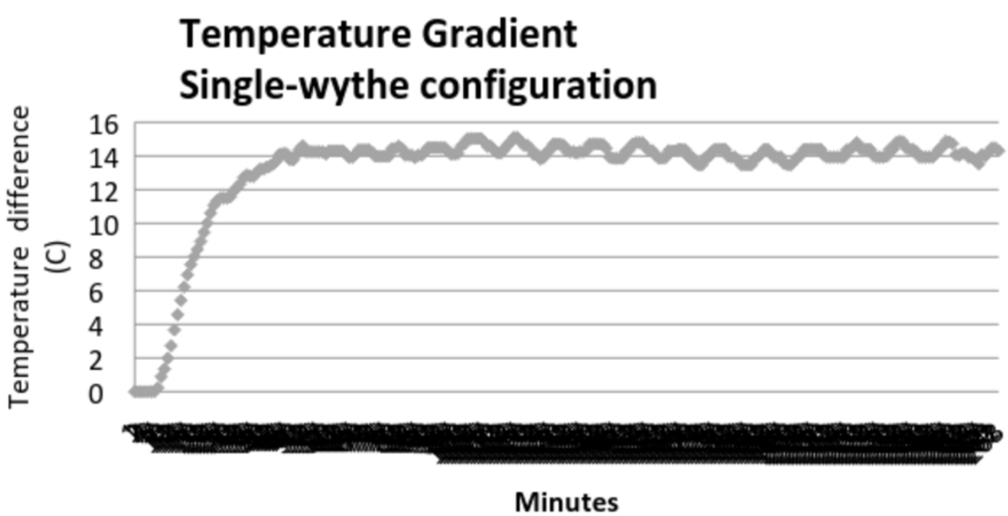


Figure 10: Temperature difference between the hot and cold surface in the single-wythe wall configuration

Temperature difference data was analyzed using a curve fitting algorithm. As a result, an exponential association (growth model) function was derived from fitting the data. The equation was used to determine the approximate temperature difference at which heat flow through the assembly reached steady state condition (Figure 11).

The best fitting curve for all experiments including the initial test was:

$$y=a(b-e^{-cx})$$

By solving for the first derivative $\partial y/\partial x \approx 0$, the solution of the derivation determines the approximate time it takes the temperature difference to reach the steady state condition (Figure 11).

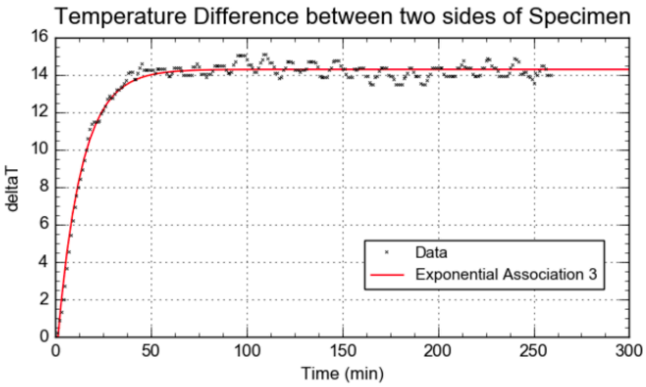


Figure 11: Determining the time it takes for the temperature difference reaches Steady State condition

2.4 Determining rate of Heat flow (Q)

Determining the heat input was accomplished in two steps; the first was to determine the times it takes the assembly to reach steady state conditions. An Arduino-based sensor was developed and deployed to count the number of times the heating element controller switched on and off. The time was recorded every time the event was counted (Figure 12). Periodicity data was added, and hourly power usage was estimated.

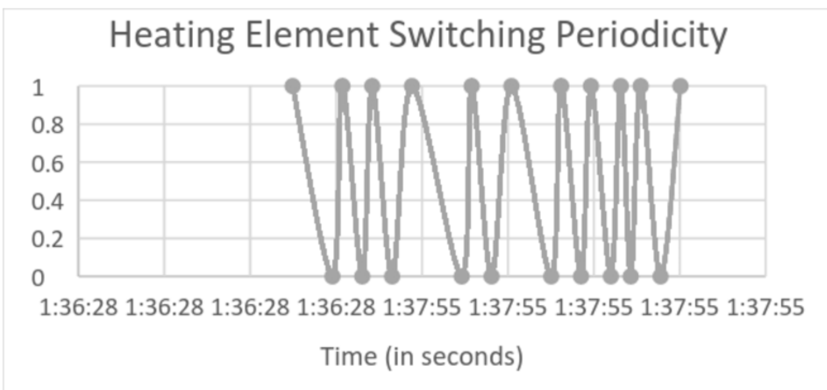


Figure 12: Data collected from heating element switching data logger

The time it took the temperature difference between the hot and cold surface of the wall to reach steady state condition ($\partial y/\partial x \approx 0$) was about 90 minutes for the single-wythe experiment. The hourly rate of heat input after 90 minutes of the experiment 35.4 Btu/hr (sensor was on 26% of the time). On the other hand, the heating element was switched on for about 25% of the time while testing the 2” rigid insulation allowing for about 34.2 Btu/hr to be input in the hot chamber. Data of this phase of the analysis was used to determine the total heat input to the hot (metered) chamber or Qheater input (Figure 13)

3.0 DETERMINATION OF THE R-VALUE

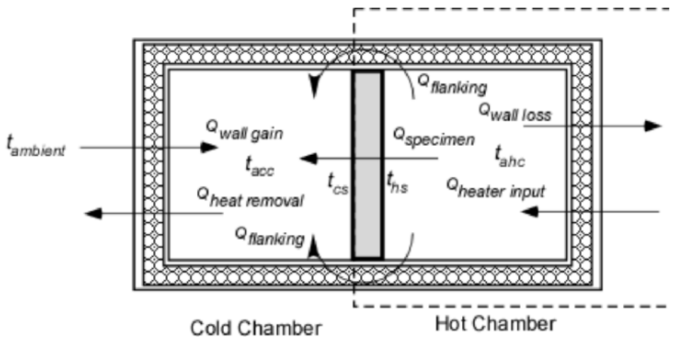


Figure 13: Establishing the thermodynamic solution system for the Hot Chamber

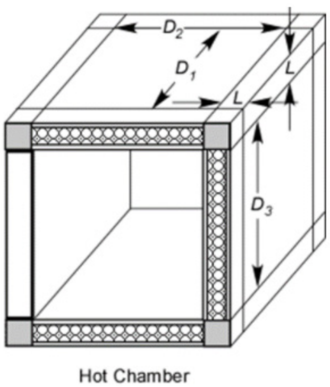


Figure 14: Estimating the Conductance Shape Factors of corners and edges

After reaching steady state condition, the following relationship should persist:

$-Q_{heater\ input}+Q_{wall\ loss}+2.Q_{flanking\ loss}+Q_{specimen\ loss}=0$ *or:*
$Q_{specimen\ loss}=Q_{heater\ inpu}t-Q_{wall\ loss}-2.Q_{flanking}$ (1)

Where:

$Q_{heater\ input}$ = *Time weighted power of heating element in volt-ampere* (VA)
$Q_{specimen}$ = *Conductive heat flow through the specimen in BTU/hr.*
$Q_{wall\ loss}$ = *Conductive heat loss through Hotbox surfaces of the hot chamber in BTU/hr.*
=

$$[8.Q_{cornbers}.U_{HB}+4.Q_{edge1}.U_{HB}+4.Q_{edge2}.U_{HB}+4.Q_{edge3}.U_{HB}+.U_{HB}(2.\frac{D_1D_2}{L}+2.\frac{D_1D_3}{L}+\frac{D_2D_3}{L})].(t_{hc}-t_{ambient})$$

Using the specimen of known thermal characteristics (2" Rigid Rigid insulation), we were able to estimate $Q_{flanking}$. However, because of the temperature at the hot chamber did not change between the rigid insulation and the ceramic wall experiments, we applied a function proposed by Yuan (Yuan 2001) to estimate the change in flanking due to change in specimen thickness (eq. 2):

$\Delta Q_{flanking}=0.0005.(L_{specimen1}-L_{specimen2})^2-0.1114.(L_{specimen1}-L_{specimen2})+6.0332$ (2)

The estimate of $Q_{flanking}$ of the ceramic wall was used to estimate $Q_{specimen}$ in equation (1).

The R-value or the overall Thermal Resistance ($R_{specimen}$) was calculated using;

$$R_{specimen}=\frac{A_{specimen}.(t_{hs}-t_{cs})}{Q_{specimen}}$$ (3)

Where:

$R_{specimen}$ = *Total Thermal Resistence*, $\frac{hr}{BTU} ft^2 .$°F

$A_{specimen}$=*Surface area of the wall*, ft^2

t_{hs}=*Wall surface Temperature in hot chamber °F*

t_{cs}=*Wall surface Temperature in cold chamber °F*

$Q_{specimen}$= *Net Heat Transfer, BTU/hr*

The resulting $R_{specimen}$ of the ceramic wall was 2.13 hr.ft².˚F/BTU.

4.0 DISCUSSIONS OF THE RESULTS

The discussion on the results of this study is focused on the lessons learned from the various experiments that took place and the experience with resolving the different issues that faced the team.

4.1. The Hotbox

Although the results are preliminary, the lessons learned from the exercise were invaluable to the team. A general comparison between preliminary laboratory measurements and the expected outcomes showed a margin of error within limits presented by other similar studies (Desogus et al. 2011). While some of the error sources in the determination of the R-value can partially be attributed to the heat loss beyond those estimated through the Heat Box walls and flanking, other uncertainties were inherent in the equations used (Asdrubali & Baldinelli 2011). Additional sources of errors are the mechanism used to determine the heat input through counting the periodicity of the controller switching. The small size of the hot box introduced additional levels of uncertainty caused by the relatively large heat loss through corners and edges.

The use of a small hot box, however, showed promise because of our potential ability to deploy it to test new configurations proved invaluable. The box was easy to set and test and inexpensive to operate. With larger wall sections, we will build a larger hot box on wheels to facilitate its movement from one space to another especially in an education setting where locating the apparatus in a permanent space may not be possible.

4.2. Limitations of the study

The most significant limitation facing the team is the lack of the relatively expensive heat flux meter. Without it, the uncertainty caused by the elaborate calculations based on estimates of box wall performance was larger than predicted. In addition, the team had to estimate the flanking based on the use of specimen materials of known R-values. However, with the variation in the temperature difference between the hot and cold surfaces, flanking estimation was impossible.

4.3. Planned future work

- Design and calibrate a larger hotbox
- Purchase and use a Heat Flux Meter

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