Design of an Affordable Hot Box Testing Apparatus

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Abstract. As sustainable construction has evolved in Canada, the need for technical information to enable building permitting and product certification has grown. Prefabricated straw bale panels continue to evolve, however there is still substantial variability in materials and construction from one region to the next. Typical thermal testing of multilayer wall systems is conducted using a hot box apparatus according to standards comparable to ASTM C1363. Individual tests conducted in accordance with the standard by an accredited laboratory can cost between $6,000 and $20,000 per sample. Many labs have wait lists of several months. This is a significant expense for a small business involved in construction of only a few residential buildings per year. The cost of conducting multiple tests to evaluate a range of production parameters has thus far been prohibitive for stakeholders involved in residential construction using natural materials.

This paper describes the design and construction of a small-scale, affordable hot box apparatus for testing of straw bale and other non-conventional building panels. The apparatus meets the minimum metering area and minimum number of temperature sensors per unit of wall area stipulated by ASTM C1363. Design details and costs of the apparatus are discussed, as are the characterization and operation of the apparatus. Some typical testing of straw bale panels and potential future improvements are also discussed.

Introduction

Sustainable building advocates have conducted several laboratory tests in varying jurisdictions to satisfy permit requirements for construction and as part of the broader effort to legitimize the use of materials not explicitly prescribed by building codes [1,2,3]. While the results of the tests have generally established these materials to be safe for use in residential construction, the range of construction practices and material sources present a complex set of variables for stakeholders who wish to develop a market for non-conventional materials in sustainable building.

Test results are required to acquire building permits and material certifications [2,4]. New companies require tests on a range of prototypes to optimize material selection and panel design. The cost of individual tests limits the number of iterations and variations that can be tested as new products are being developed, presenting a challenge for small enterprises attempting to bring a product to market.

The properties of non-conventional materials can create challenges when conducting thermal tests using apparatus designed for conventional materials. For example, past tests conducted on straw bale panels varied in reliability due to poor fit of stacked bales inside conventional testing frames [1,2]. Specimens required lengthy drying times, and required up to two weeks for heat flows to approach steady-state [1,2]. This significantly raises the cost of testing non-conventional materials when many commercial labs have wait times of 3 to 6 months [5].

One alternative to commercial testing is a smaller, university-based testing programme that can allow companies to investigate several prototypes or designs at relatively low cost. These results can be used to identify promising designs and refine prototypes for manufactured materials.

The objective of this paper is the design, construction, and characterization of a small-scale, affordable apparatus for thermal testing of non-conventional building panels. Given that straw bale construction is one of the most common non-conventional building methods in Canada [4], and has the potential to become more common through manufacturing of prefabricated panels, prefabricated plastered straw panels were the first wall assembly examined using the apparatus.

Design & Fabrication Methods

A hot box apparatus was designed to accommodate testing a variety of wall assemblies built using non-conventional materials. The budget was constrained to approximately $30,000 CAD. This compares to upwards of $1 million CAD for commercial hot-box testing apparatus [5].

ASTM Standard C1363-11 details the requirements for design and operation of a test apparatus for evaluating thermal performance of building materials and envelope assemblies by means of a hot box apparatus [6]. Employing parameters from the target test standard, efforts were undertaken to follow the requirements for minimum metering area and minimum number of temperature sensors per unit of area. The sensors measure the surface-to-surface heat transfer rather than the overall thermal resistance, and the initial performance is evaluated using simplified heat transfer calculations.

Specimen panels were designed to be large enough to provide a representative area of the wall system to be tested, but small enough to be constructed and moved on wheels, so that they can be fabricated and dried without causing extended delays in testing activities. The apparatus can be operated by one person, with parts that can fit through a typical door opening when disassembled.

The apparatus incorporated a hot box apparatus, with matching specimen frames sized to typical stacked bales. The metering box and cold box were built on wheels, to accommodate testing of wall specimens of varying thickness. Panels were built on insulated rolling frames, cured and dried in a heated environmental chamber, and then wheeled into place between the two sides of the hot box apparatus.

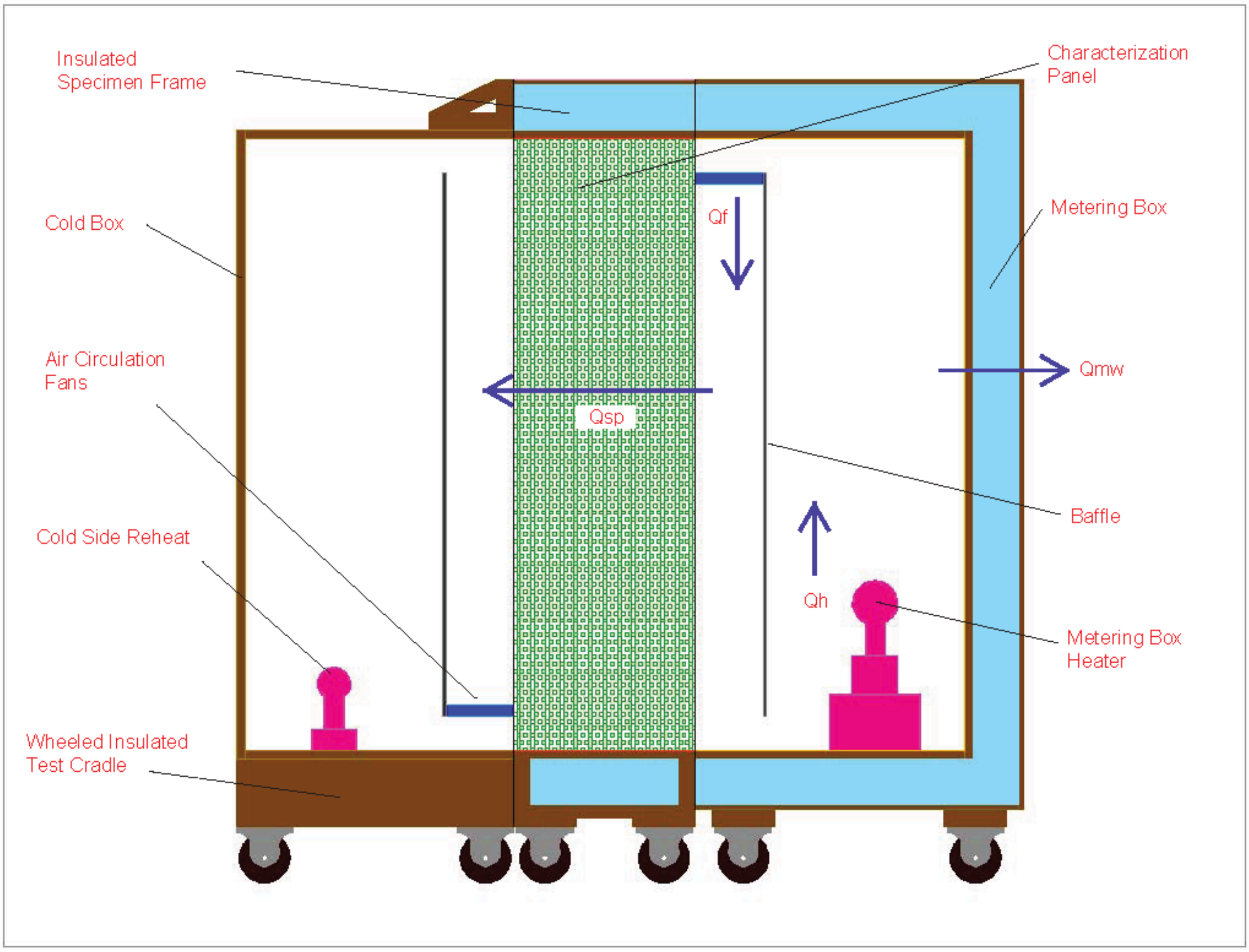

Fig. 1 - Schematic of Hot Box Apparatus

It was determined that a calibrated hot box assembly would be most appropriate for use in the existing environmental chambers. Relying on an existing environmental chamber in the Queen's Structural Engineering Laboratory to provide the cooling for the cold side of the specimen, the limiting factors in design and dimensioning of the apparatus were the size of the door opening for the cold room. Factoring in the thickness of EPS insulation and cladding for the hot box and surround panels installed around the specimen, the optimal specimen size was determined to be 1.18m by 1.37m, with a thickness of 0.41m to reflect the size of full bales inside a typical plastered straw bale wall (Figure 1).

The hot box, as shown in Figure 2, was constructed using a 19mm plywood box clad with two 38.1mm layers of EPS foam, one 25.4mm layer of EPS foam, and was sheathed with 12.7mm poplar plywood to protect the exterior of the apparatus. Layers of material were joined with Gorilla glue, and joints were staggered and sealed with caulking and tape to prevent air leakage.

Though cooling is provided by the environmental chamber, an uninsulated plywood box, shown in Figure 1, was constructed with dimensions identical to the inside of the hot box to provide controlled air circulation along the face of the specimen, with refined temperature control provided by a reheating assembly using a low-wattage lightbulb.

Inside both boxes, the interior space was designed with enough depth to house a 6mm fiberboard baffle installed 0.15m from the face of the specimen, as well as a heating and air circulation assembly consisting of four computer fans and a single lightbulb inside a canister (Figure 1).

As shown in Figure 2, each specimen prepared for testing is fitted with insulation plugs around its perimeter, identical to the layers insulating the hot box and the wheeled test cradle beneath it. To minimize heat lost around the perimeter of the specimen, the edges where the hot box and cold box meet the specimen are fitted with neoprene gasket and the assembly is closed tightly by means of threaded rod and bolts tightened on steel angle mounted to the hot and cold boxes on either side of the specimen. A similar design has been described by Straube [7]. A reinforcing bracket of the same steel angle is used to secure the foam plugs tightly around the perimeter of the specimen, with neoprene gasket used to create a thermal break between the specimen frame and the reinforcing bracket.

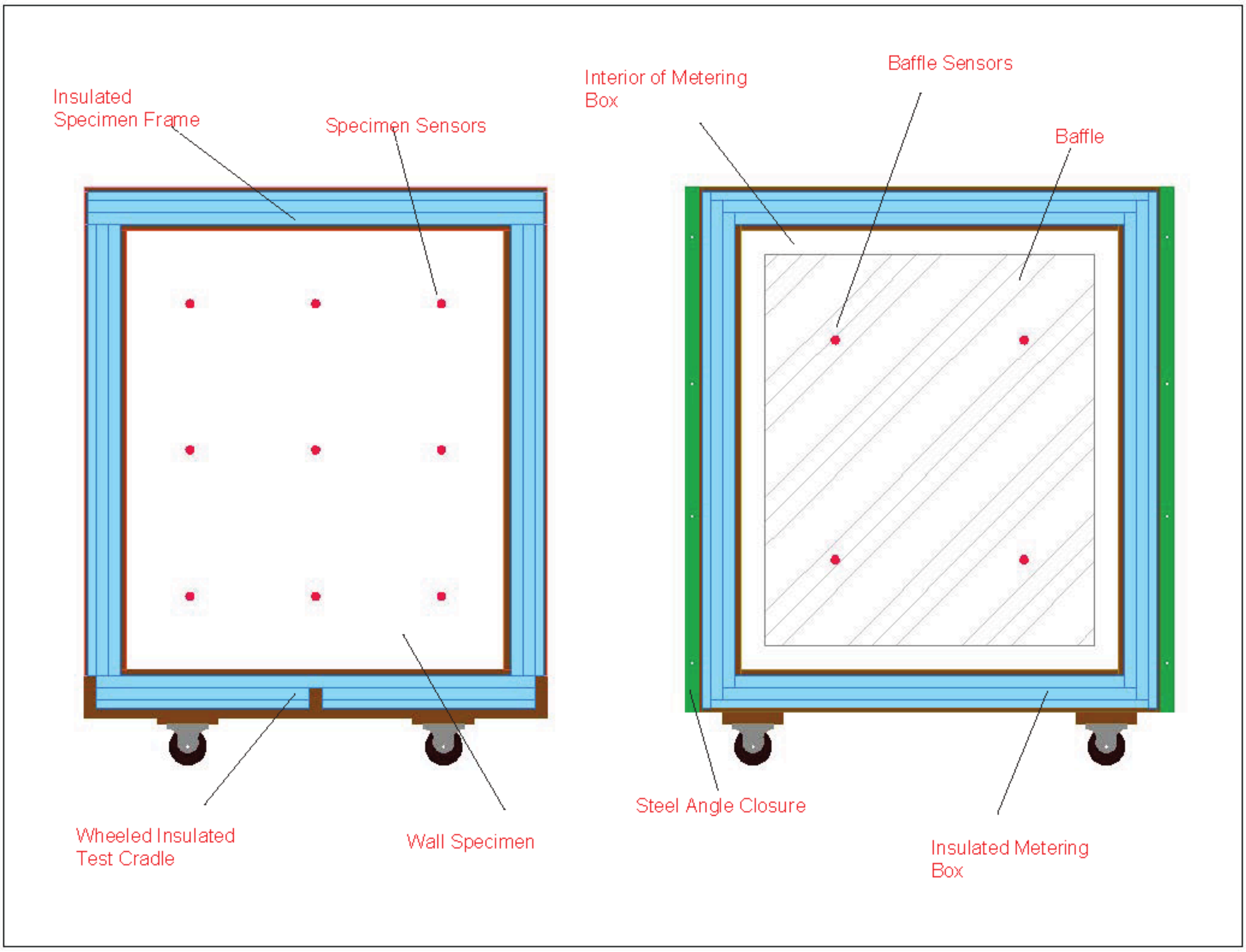

Fig. 2 - Specimen and Interior of Hot Box Apparatus

While ASTM C1363 specifies thermocouples made of 30AWG wire, these were too fine to solder and install effectively. Thermocouples fabricated from 4.75m lengths of Type T 24AWG wire were installed with foil tape to ensure that only the temperature of the surface is being measured, with Gorilla tape layered on top to maintain consistently high surface emissivity and ensure adhesion at all temperatures of operation. Temperature control is provided by feedback sensors inside the hot and cold boxes, each wired to an Omega 2110J controller set to maintain proportional temperature control by providing pulsed power to the lightbulb inside each box.

A customized data acquisition system was assembled from four 16-channel data acquisition cards (two MCCDAQ USB-2416 with AI-EXP32) connected to the 64 thermocouples, as well as a custom-fabricated Digital I/O counter for the purpose of measuring power consumption. Two sets of 32 channels are recorded. Readings are taken every 2 seconds, and data is averaged and recorded every 10 seconds.

This apparatus meets the requirements for the number of thermocouples per square meter on the calibrated hot box, baffles and specimen surfaces, and for the minimum specimen area. In addition, no thermocouples were installed in the air curtain between the baffles and specimen faces, due to limitations in the number of data acquisition channels.

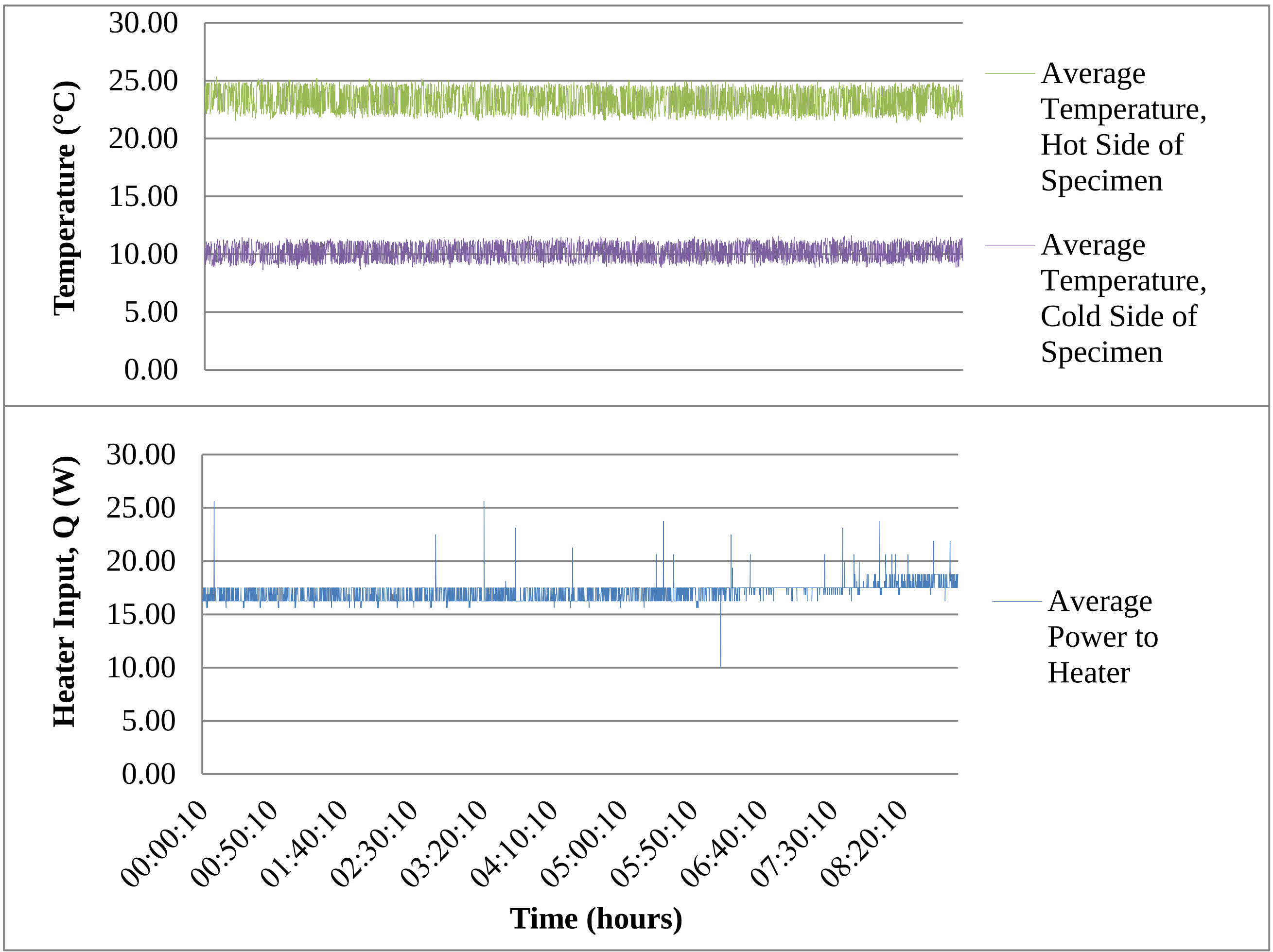

Fig. 3 – Specimen Temperature & Heater Input to Hot Box Apparatus - Characterization

ASTM C1363 requires tests to run for a period of six consecutive Time Constants with temperatures held at steady state [6]. The Time Constant is the time required for the system to return within 37% of equilibrium after a step change of 1°C [6]. The variability of the temperature in the environmental chamber prevented achieving this degree of sensitivity. The system was observed to respond to a 6-degree change in temperature within 12 hours, arriving within 37% of equilibrium within 8 hours. It was thus determined that the effective Time Constant could be estimated to be 90 minutes, and the duration of a full test accordingly is estimated to be 9 hours.

Figure 3 shows typical temperature and power measurements during characterization testing. The average of 9 thermocouples per side of the specimen is displayed, with average power input to the metering box heater and fans shown below. The temperature readings cycle within a range of values, with the overall average temperature remaining nearly constant.

ASTM C1363 recommends that temperatures should vary by no more than 1°C [6]. The results in Figure 3(a) indicate that average temperatures on the surface of the specimen and baffles varied by +/- 2°C. The power input to the metering box varied within +/- 2.5W.

Characterization & Estimation of Metering Box and Flanking Losses

The basis of hot box thermal testing is measurement of the heat flow through the specimen, Q_{sp}. The total heat input, Q_{aux}, can be measured, and the loss through the walls of the metering box, Q_{mw}, and at the edges of the specimen (flanking losses), Q_{fl}, are subtracted to determine the heat flow through the specimen, Q_{sp}. To estimate these losses at the range of test temperatures, a series of calculations are used to estimate metering box and flanking losses, and a characterization procedure is followed.

A characterization panel with a thickness of 0.41m was constructed with details and dimensions identical to the straw panels, using 12 layers of EPS foam. Table 1 presents the details of the characterization panel and metering box construction. The heat flow, Q, through the panel can be calculated as:

$$Q = \frac{A * (t_1 - t_2)}{R} \quad (1)$$

where A is the surface area of the panel, R is the thermal resistance of the characterization panel, and t_1 and t_2 are the temperatures on the hot side and cold side, respectively, of the panel. The heat flow into the metering box, Q_{aux} is:

$$Q_{aux} = Q_h + Q_f \quad (2)$$

where Q_h is the measured power consumption of the heater inside the metering box, and Q_f is the nominal power consumption of the fans.

The experimental metering wall and flanking losses are the difference between Q_{aux} and the calculated Q:

$$Q_{mw} + Q_{fl} = Q_{aux} - Q \quad (3)$$

Table 1 – Apparatus Dimensions & Material Properties

Properties:	**Metering Box:**	**Specimen:**
Dimensions (W x H x D, m)	1.18 x 1.37 x 0.6	1.18 x 1.37 x .41
A_{eff} (m)	4.7	1.62
Edge Length / Perimeter (m)	7.52	5.11
L (m)	0.13	0.41
R-Value (F ft^2 h/Btu)	16.51*	59.75**
RSI (K m^2/W)	2.91	10.53
λ_{eff} (W/m K)	0.0459	0.0386

* R-Values of materials retrieved from product labeling and published manufacturer data [8,9].
** R-values of materials retrieved from product labeling.

Losses were measured at four different external temperatures as indicated in Table 2. The metering box temperature was maintained at approximately 21 °C. The average actual dT is the difference between the hot and cold surface temperatures of the characterization panel. The Q_h is the average heater power measured during each test. The fan power, Q_f was not measured, but estimated to be 17.28 W based on manufacturer's specifications. The total experimental metering box wall and flanking losses are plotted in Figure 4. The experimental losses increase linearly with increasing temperature difference, as would be expected.

Table 2 – Experimental Characterization of Metering Box

Set Point Ext (°C)	**Set Point Int (°C)**	**Nominal dT (°C)**	**Avg Actual dT (°C)**	**Avg Q_h (W)**	**Q_{fan} (W)**	**Total Heat Input Q_{aux} (W)**	**Experimental Box Loss, Q_{mw+fl} (W)**
15	21	6	4.8	2.64	17.28	19.92	19.2
6	21	15	13.1	17.03	17.28	34.31	32.3
-9	21	30	28.8	54.64	17.28	71.92	67.5

-24	21	45	43.18	87.70	17.28	104.98	98.3

The theoretical metering box and flanking losses were also estimated. The metering box effective area normal to heat flow, A_{eff} is:

$$A_{eff} = A_{in} + 0.54 \cdot L \cdot \Sigma e_i + 0.60 \cdot L^2 \quad (4)$$

where A_{in} is the inside surface area of the metering box in m^2, L is the metering box wall thickness in m, and e_i is the sum of all eight metering chamber interior edge lengths formed where two walls meet, in m. The heat flow per unit time, q is

$$q = \frac{\lambda_{eff} \cdot A_{eff} \cdot (t_{in} - t_{out})}{L} \quad (5)$$

where λ_{eff} is the metering chamber effective wall thermal conductivity, and t_{in} and t_{out} are, respectively, the metering wall inside and outside surface temperatures.

The theoretical flanking loss, Q_{fl}, is:

$$Q_{fl} = \lambda_{eff} \cdot (A/L)_{eff} \cdot \Delta t_{a-a} \quad (6)$$

where λ_{eff} is the effective thermal conductivity of the box and specimen frame insulation and the skin material, $(A/L)_{eff}$ is the effective area/path length of entire specimen frame around its perimeter, and Δt_{a-a} is the air-to-air temperature difference.

Table 3 – Theoretical Heat Loss from Metering Box

Set Point Ext (°C)	**Set Point Int (°C)**	**Nominal dT (°C)**	**Estimated Metering Box Loss, Q_{mw} (W)**	**Estimated Flanking Loss, Q_{fl} (W)**	**Box & Flanking Losses, Q_{mw+fl} (W)**
15	21	6	11.1	1.2	12.3
6	21	15	27.7	3.0	30.7
-9	21	30	55.4	5.9	61.3
-24	21	45	83.2	8.9	92.1

Equations 4, 5, and 6, along with the input data in Table 1, were used to estimate the metering box and flanking losses. Typical values for metering wall and flanking losses are indicated in Table 3. Total non-specimen losses are plotted in Figure 4 for comparison with the experimental values. The experimental values are approximately 15% higher than the theoretical values at each temperature difference. The difference can be attributed to additional heat loss around wiring and fasteners, which is not accounted for in the theoretical calculations, and the approximations made for the flanking loss calculations.

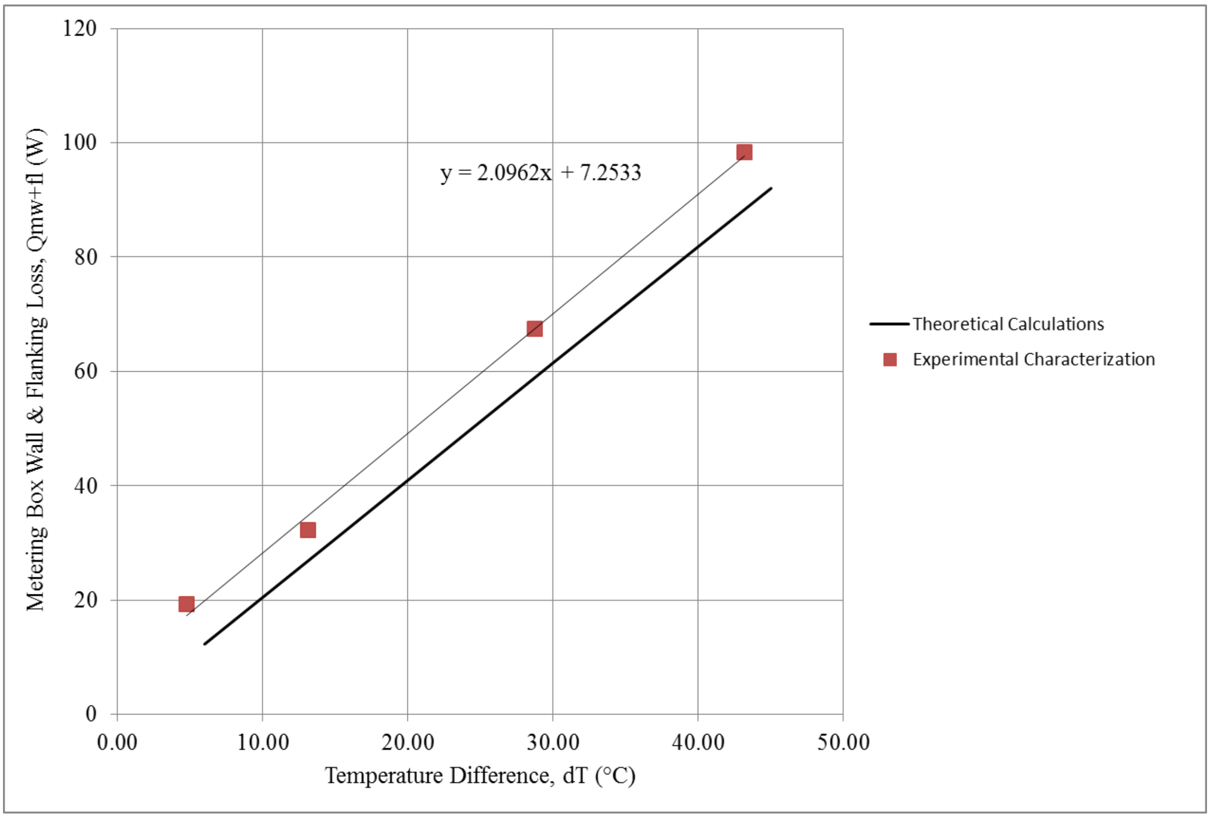

Fig 4 - Theoretical Calculations & Experimental Characterization of Hot Box Apparatus

The experimental characterization loss values will be used to calculate the metering box and flanking losses for the actual temperature differences observed in tests on prefabricated straw specimens, so that the heat loss through the specimen can be calculated to determine R-value. Note that these loss values are only valid for a wall with a thickness of 0.41 m, and recharacterization must be conducted for specimens of differing thickness.

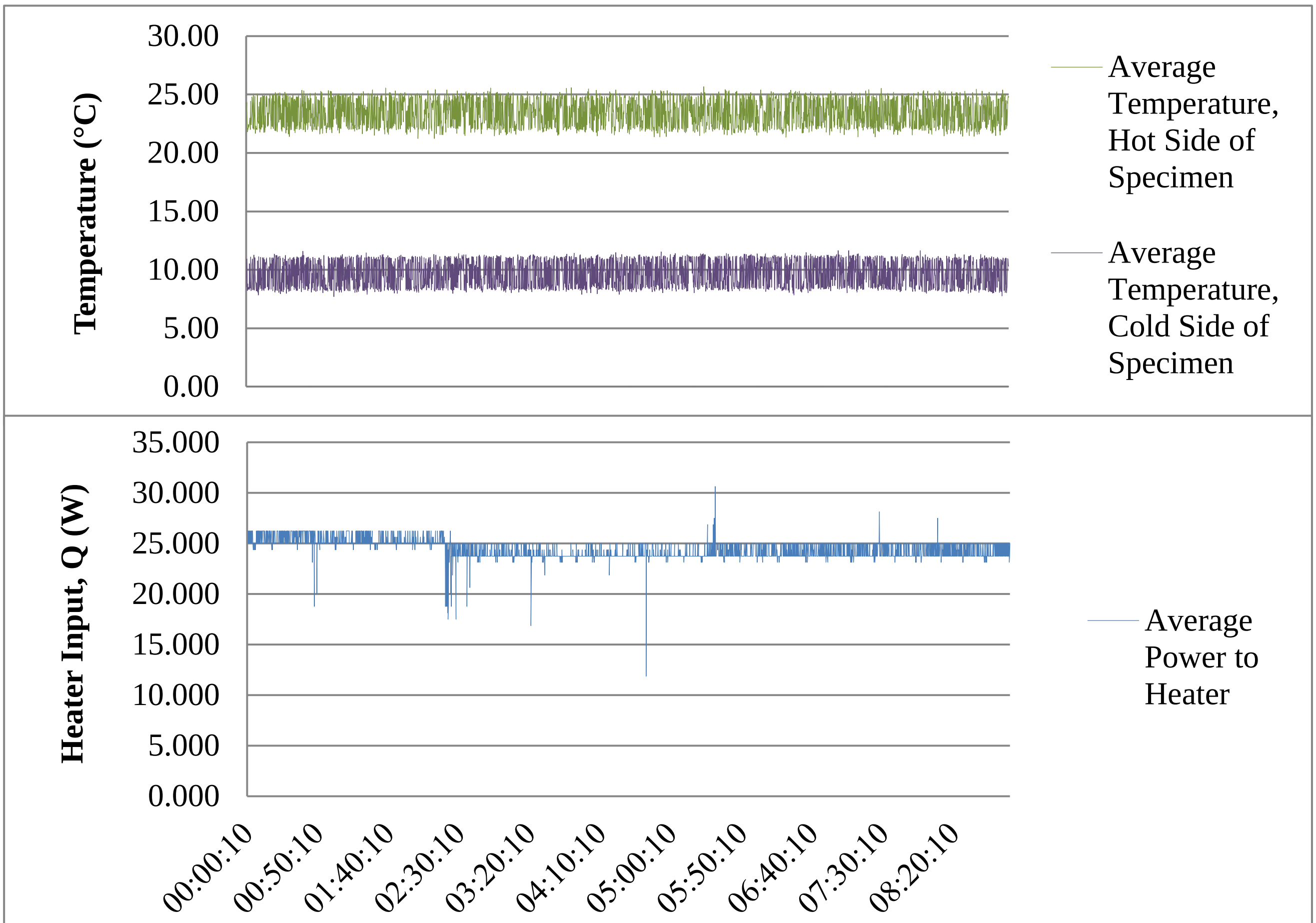

Fig. 5 - Specimen Temperature & Heater Input to Hot Box Apparatus – Straw Bale Panel

Figure 5 shows the temperatures and measured input heat for a prefabricated straw bale panel being tested using the hot box apparatus. While the variations in heater power and specimen surface temperature are greater than permitted by ASTM C1363, a steady state heat flow is achieved. With this information, the surface to surface thermal resistance, R, can be calculated.

Cost of Apparatus

Costs of construction of the metering box (Table 4) are similar to the cost of a single full scale test conducted in an accredited laboratory. These costs do not include the cost of environmental chambers and chiller equipment, as these are assumed to be more widely available in university laboratories than specialized thermal testing equipment. The costs of operating heating and cooling equipment for each test are also not included, as these vary with the type of chiller equipment, quality of insulation in environmental chambers, and the time to equilibrium for the specimen being tested.

Table 4 - Total Cost of Apparatus

Item	**Costs**
Building Materials	$2,025
Hardware	$1,420
Sensors, Controls & Electronics	$2,810
Data Acquisition & Equipment	$2,880
SUBTOTAL:	$9,135
Design, Fabrication & Commissioning:	$28,000
TOTAL:	**$37,135**

Discussion & Recommendations

While the average temperature on the baffles and specimen surfaces and power input to the metering box remain steady, the temperature readings fluctuate +/- 2°C with air circulation inside the hot and cold boxes, and +/- 3°C with the on and off cycles of the chillers in the environmental chamber. While the temperatures read by matching pairs of thermocouples on the interior and exterior of the metering box rise and fall together by as much as 10°C as cold air flows over the outside of the metering box, the power input to the box remains nearly constant. Despite this, over the long test period required for straw specimens, power consumption was observed to vary by only +/- 2.5W and the change in power consumption was found to be less than 1%.

The control of temperature and accuracy of readings can be refined with improvements to the physical design of the hot box apparatus. Following initial commissioning of the apparatus, and prior to characterization, foam baffles were installed to shield the exterior of the hot box from the direct gusts of chilled air cooling the environmental chamber. With these changes made, the variation in temperature across the face of the specimen was brought to less than 3°C – still exceeding the requirement stipulated by ASTM C1363-11, but within a range sufficient to demonstrate steady power consumption at a given temperature set point.

The heat loss could be further controlled by cladding or constructing a guard chamber over the exterior of the hot box with vacuum insulated panels (VIPs), to limit the non-specimen heat loss and protect the sensors on the exterior of the metering box from irregular cold air gusts from the chiller.

Future iterations of the apparatus design could substitute three layers of VIPs for the EPS insulation in the metering box and specimen frame, however, the manufactured dimensions of the VIPs would limit the flexibility of the design. Due to the fragility of VIPs, inside and outside surfaces would need to be clad with 6mm wood paneling, with tape and caulking applied at every joint. This would produce a more accurate result because a metering box with a thermal resistance of R-90, or RSI 15.85 K m^2/W, would reduce the metering box loss to a small share of total heat input, thus reducing uncertainty of calculated thermal resistance values.

Heat loss due to flanking may be further limited by replacing the neoprene gaskets with closed cell foam, to ensure even compression and air sealing at all temperatures seen in testing. It is also possible that greater flanking loss is caused by out of plane distortions where the specimen frame meets the perimeter of the prefabricated panels. These gaps could be reduced by installing foam gaskets where the specimen frame meets the perimeter of the panel, and by adding screw clamps to the steel angle surrounding the specimen frame to ensure that it is in continuous contact with the perimeter of the specimen.

Condensation was observed on the exterior of the cold box and on the cold side of the specimen due to the moisture accompanying airflow from the chiller. This could be monitored with installation of the relative humidity sensors. In addition to effects of condensation, it is possible that there is heat loss due to air seepage through plastered wall specimens. Different results may be obtained if the specimens are re-tested with plastic sheeting applied over each face, over top of the thermocouples.

Questions regarding moisture and climate conditions inside the metering box and cold box could be further addressed through installation of the airflow sensors, air pressure sensors, and relative humidity sensors required for compliance with ASTM C1363-11.

It is not known whether the power consumed by the fans varies with temperature. This could be measured by adding a second Digital I/O meter to measure the power input to the fans inside the metering box.

To calculate the overall thermal resistance, R_u, and thermal transmittance, U, the determination of environmental temperature would need to be completed. This would require calculation of the surface-to-air heat transfer coefficients, and would also require installation of thermocouples in line with the baffle thermocouples in the centre of the air curtain (76mm from either surface, in the airflow). Given that the average temperatures on the baffle and the face of the specimen differ from each other by only 0.5°C to 1°C, and given that these and the power input remain in near equilibrium over a long test period, the surface to surface thermal resistance is likely to represent a value that very nearly approximates overall thermal resistance.

Summary

While the design and performance of the hot box apparatus does not meet the requirements of ASTM C1363 exactly, its affordable design and portability enables testing of material variations and prototypes of wall assemblies, providing accuracy within 15% of theoretical. Having a construction cost of approximately $37,000 makes initial testing accessible to small enterprises that have limited access to funds for testing more than one specimen, and require multiple tests to refine early prototypes.

While the lesser size and limitations of sensors and temperature fluctuations provide a result that is less precise than that provided by full scale tests, this apparatus has the advantage of being operable by one person. It also has the advantage of being demountable, so that it can be removed and stored when not in use, or operated in environmental chambers of varying control and capacity. It also allows for multiple specimen types to be fabricated on customized frames, so that specimens can be exchanged nondestructively and can be re-tested with modifications at a later date.

It is expected that minor refinements to the construction of the apparatus and sensor assemblies could provide additional gains in test accuracy, and that these could be achieved with minimal additional cost.

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