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The Design, Construction and Commissioning of a Small Scale Dynamic Calibrated Hot Box (CHB)

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ABSTRACT
Sustainable construction and in particular the sustainability of materials is a global issue with legislation on material properties and product performance at the forefront. In traditional constructed buildings however, it can be extremely challenging to get accurate data on performance. The variability of building materials design, manufacture and construction from different eras is substantial, even within local areas due to the vernacular nature of construction from these periods. Material properties testing can be expensive and is not always readily available when required and is therefore often ignored, particularly in the retrofitting of historic buildings. This can have major adverse effects on the building fabric and for its inhabitant's health if the appropriate material interventions are not chosen. An inexpensive environmental chamber for testing such materials has been designed and built at the Dublin Institute of Technology, (DIT) Ireland, adopting comparable standards from EN ISO 8990 and ASTM C1363. This paper describes the design requirements for the construction of an affordable and mobile calibrated hot box (CHB) for the testing of historic materials. A characterisation panel has been used to carry out early calibration testing and the results of this are discussed. Improvements and tweaking of the first test are also discussed.

KEYWORDS
Calibrated hot box, Historic materials, Characterisation panel, Data acquisition.

INTRODUCTION
Buildings' energy consumption accounts for approximately 40% of total energy use in developed countries. The legislation on energy efficiency in buildings, such as the EU Directive 2010/31 has tried to raise minimum energy efficiency standards, for both the single components and the entire building. The building fabric plays a fundamental role in its energy balance, particularly the thermal properties when exposed to moisture and often generic values are used in ideal situations when modelling. In solid walled structures these values are, expensive and difficult to accurately ascertain due to the inconsistency of materials.
To establish accurate and reliable data on structures with different materials used in the one homogenous unit requires different approaches such as numerical simulation, but this is only as accurate as the accuracy of the inputs which often tend not to be validated. Hot boxes have been used to establish accurate properties with guarded hot boxes used mainly for commercial use and calibrated hot boxes used in laboratory work, where often it is necessary for greater levels of refinement and accuracy be achieved. The design of the hot box produced at the DIT was motivated by the need for such testing of small building elements from historic buildings primarily. These material dimensions influenced the design and construction of the whole apparatus and in particular the dimensions of the panel which hosts the sample.
Hot boxes require two closed rooms kept at constant, individual temperatures: a metering chamber, which is warm and the environmental chamber that is cold. A test wall typically containing the specimen under test, divides the two chambers. The overall thermal resistance

is evaluated from the heat flux between the two chambers including that of the internal and external air resistances. This research paper looks at the design, build and calibration of a calibrated hot box (CHB) constructed in the Dublin Institute of Technology, incorporating guidelines from EN ISO 8990 and ASTM C1363-05 with the primary aim of designing and constructing an affordable dynamic environmental test chamber. The construction of the facility was carried out in the Dublin Institute of Technology (DIT) workshops and Labs.

Objectives

a) Design and construct a dynamic environmental hot box to meet the input requirements for a later hygrothermal simulation, establishing thermodynamic properties b) Calibrate a small-scale, affordable apparatus for thermal testing of non-conventional materials using a characterisation panel of known thermal conductivity and c) Analyse and compare measured versus theoretical data to establish % error.

Literature review

Typical thermal testing of multilayer wall systems is conducted using a hot box apparatus according to standards comparable to ASTM C1363 [2] and EN ISO 8990 [4]. 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 historic brick varied in reliability due to poor fit inside conventional testing frames (Baker, 2011). EN ISO 6990 & 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. The sensors measure the surface-to-surface heat transfer rather than the overall thermal resistance, and the initial performance is evaluated using heat transfer calculations.

Ulgen (2002) measured the time lag and decrement factor using wall compositions of opaque materials in a hot box simulation. Sala et al., (2008) conducted dynamic testing of insulated brick walls using a calibrated guarded hot box. The two types commonly used are the: Guarded hot box : In the guarded hot box, the metering box is surrounded by a guard box in which the environment is controlled to minimize lateral heat flow in the specimen. The total heat flow through the specimen will then be equal to the heat input to the metering box. In practice, there will be a limit in detecting imbalance in each test. (EN ISO 8990) [4]

Calibrated hot box : The calibrated hot box is surrounded by a temperature-controlled space not necessarily at the same air temperature as inside the metering box. The heat losses through the box walls are kept low by using a construction of high thermal resistance. The power input shall be corrected for the wall and flanking losses. The correction for chamber and flanking losses are determined by tests on specimens of known thermal resistance. For flanking loss calibration, the calibration specimens should cover the same thickness and conductivity range as the specimens to be measured and the temperature range of intended use. (EN ISO 8990) Schumacher, et,. al,.(2013) constructed a hot box and concluded that the thermal performance of wall assemblies is complex and heavily influenced by factors such as insulation level, air leakage, thermal bridging, operating conditions, moisture content and installation defects and argue that simple R value calculation is not sufficient to address the above factors. They contend that more sophisticated testing is required before a new metric for testing is established. They used finite element programme analysis for the flanking losses.

International Standards lays down the principles for the design of the apparatus and minimum requirement that shall be met. It does not, however, specify a particular design since requirements vary, particularly in terms of size, and also to a lesser extent in terms of operating conditions. This International Standard describes also the apparatus, measurement technique and necessary data reporting.

The air exchange rate (AER) is not often measured in hot box construction and three methods using tracer gases exist for its determination. These are the concentration decay method, the constant injection method, and the constant concentration method (Laussman e t.. a l . 2011). The primary function being to establish additional heat losses at junction interfaces.

METHODOLOGY

All thermal bridge calculations were carried out according to EN ISO 10211. Numerical simulations were performed using the 2D and 3D finite element program Psi Therm. The U-value of the metering chamber was calculated according to EN ISO 6946:2007

Design for construction

Concept: It was determined that a calibrated hot box would be the most suitable for the testing requirements within the DIT. The limiting factors in design and dimensioning of the apparatus were the size of the door openings in different buildings as it was constructed in the Bolton street campus, 4-5 Km away. Transportation also determined the overall weight and mobility of the unit and had to be factored into the design and construction. The maximum specimen area achieved was 715mm (L) by 715 mm (H) by 200mm (T). 200mm was chosen as being capable of testing a panel of representative material to achieve accurate results. Bricks from a historic building have been prepared to a test standard size of 180 x 80 x 55mm for testing in the chamber. The following items were addressed: Identification of experiments to be carried out, Comply with standards, Capable of testing historic elements, Self-contained unit, Logging capabilities/ dynamic, Humidifier capacity and location, Highly insulated, Thermal bridge free or as low as practicably possible, Constructible in DIT and mobile, Good compactness ratio, Robust but adaptable specimen holder panel, Cost effective, Compliance and Practical implications re; budget, size, mobility.

Construction of CHB

The hot box, shown in Figure 1 was constructed using a 45 mm medium density fibreboard (mdf) outer structural layer, with one layer of 200mm EPS insulation glued to the inside surfaces with PVA glue. Air leakage was prevented by using a brush-on waterproof tanking layer, this also ensuring that the insulation and mdf thermal properties do not change due to moisture uptake from within. A 100mm wide mdf strip was glued on internally to provide fixings for the heaters/fans thus ensuring no fixings penetrated the eps. Heating is produced by a single 60W resistance heater located as far as is practicably possible away from the specimen. Cooling is provided by the environmental chamber on the other half of the apparatus, -a insulated box identical in size and construction to the metering box. The cooling is provided by a chiller unit placed on top of the unit with the evaporator connected internally. The identical dimensioning of the hot box ensures that air circulation and velocity across the sample face should be almost identical as they are placed in the same position in both boxes. Both boxes were designed to accommodate a 6mm mdf baffle painted matt black, installed 200mm from the face of the test specimen. Air circulation is provided by 2 computer fans per box placed behind the baffles in identical positions. Each specimen prepared for testing, is fitted with insulation plugs around its perimeter, identical to the layers insulating the hot box.

Four castors per box allow for easy opening and closing of the units. External threaded bars are used to tighten the two chambers together during testing, minimising air leakage. A humidifier has been fixed to the outside of the chamber and each chamber is equipped with a humidity probe and 8 thermocouples. All data is acquired and managed by the use of a single National Instruments cRio datalogger using Labview programming.

Calibration: The accuracy of each individual apparatus shall be estimated with reference to homogeneous specimens of thermal conductance extending over a range of temperatures, close to what the final testing conditions are likely to be. The metering chamber was set up to keep steady-state conditions: the set point was 30 °C, with an air flow rate of 3.8 m/s measured and RH that ranges in average between 30% - 47% with the environmental (cold) chamber value 'set point' changing at 5 ^{0}C intervals from 25, 20, 15, 10, and 0 ^{0}C, until steady state environment was reached at each.

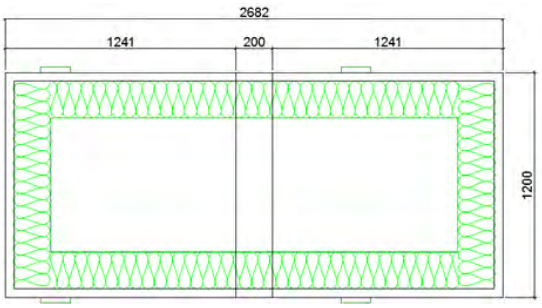

Figure 1.Horizontal section through apparatus.

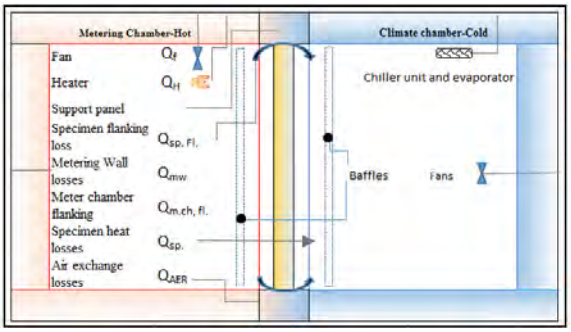

Figure 2. Components and Heat Pathways

Air Exchange Rate (AER)

The air change rate (ACR) through the box as a whole was determined through standard tracer gas measurement. After CO_2 was released into the chamber, its concentration decays exponentially, if no further CO_2 supply occurs and if the driving forces for air exchange remain constant. After introduction of the CO_2 into the sealed enclosure, the concentration of the gas decreased as air entered and exited. Plotting the natural logarithm of this exponential decay curve against time normally result in a straight line, the slope of which is the (AER) air changes per unit time The mass balance equation is used to describe the relationship between the concentrations of gas in a space as a function of time. The general form of the equation for calculating air exchange per unit time is given as follows:

$$N = [\ln(C_{int}\ t\ 0 - C_{ext}) - \ln(C_{int}\ t\ 1 - C_{ext})]/(t1 - t0) \quad (1)$$

where N= number of air changes, C_{int} t 0 = internal concentration of tracer gas in enclosure at start, C_{ext} = external concentration of tracer gas in room, C_{int} t 1 = internal concentration of tracer gas in enclosure at end, t 0 =time at start (days), t 1 = time at end (days) and ln = natural logarithm.

CHARACTERISATION AND ESTIMATION OF LOSSES

A characterization panel of known thermal resistance (wood fibre board λ 0.04 W/mK) is used in a number of tests, over the expected operating temperature range. Each test determines the difference between the measured heat input to the metering chamber and the heat transfer through the characterization specimen, calculated from the measured temperature drop across it and its known resistance.

Calculations: A significant difference in temperature across the specimen is suggested. The air velocity on both sides was held constant and the heat flow across the sample was measured.

EN ISO 8990 and ASTM C1363-05 requires the following heat balance equation be verified. A schematic showing the heat transfer pathways is given in Figure 2.

$Q_{Source} = Q_{Heater} + Q_{Fans}$, Specimen = $U_{Specimen}$ x $A_{Specimen}$ x ΔT and
$Q_{metering\ chamber\ losses} = U_{Chamber}$ x $A_{Chamber}$ x $\Delta T + \dot{V}c\rho\rho\Delta T + Q_{flanking}(W)$ (2)

Where: $A_{Specimen}$ = Sample area (m^2), $Q_{Heaters}$ = Heat input from heaters (W), Q_{Fans} = Heat input from fans (W), $Q_{m\ ch}$= Heat transfer rate through metering walls, floor and ceiling (W), $Q_{flanking}$ = Heat transfer rate at junction of specimen to frame (W), $U_{chamber}$ = Thermal conductivity of the chamber (W/m^2.K), $A_{chamber}$ = Area of chamber walls where losses occur (m^2), $\dot{V}$ = Air exfiltration rate m^3/s, c_p = A Specific Heat Capacity of 1007 J/kg.K at 30 ^{0}C is used, ρ = Air density between 1.16 – 1.27 kg/m^3 used, ΔT_{air}=Inside to outside temperature difference (^{0}C), $\Delta T_{surfaces}$= Temperature difference between hot and cold surfaces (^{0}C), $U_{Specimen}$ = Thermal conductivity of the sample (W/m^2.K)

RESULTS

The results of the CO_2 analysis are shown in Figure 3, where the air exchange rate equals the slope of the line at 0.087 ach and this is multiplied by the chamber volume to get a volume per second time of 1.313E-05 to be used in the heat balance equation. The test was conducted at ambient temperature only and accounted for less than 2% of the overall energy input, however further tests at different temperatures should further verify this figure.

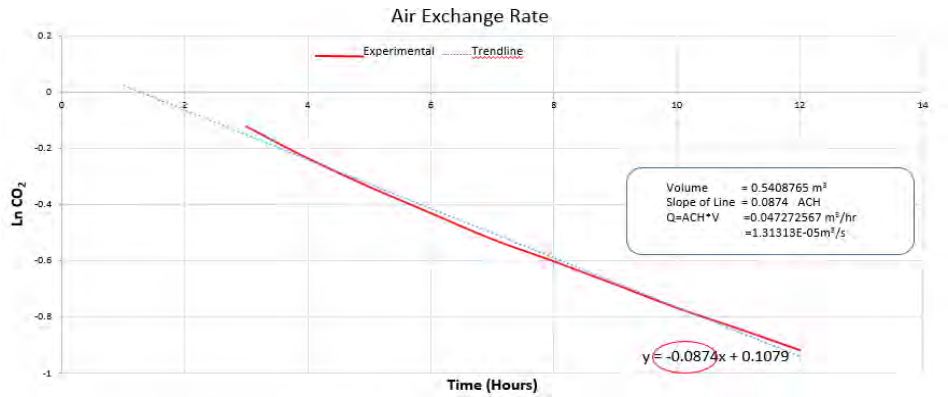

Figure 3. CO_2 results for air leakage of the chambers.

Table 1. Measured and calculated results over delta T of 5, 10, 15, 20 &25 ^{0}C

Delta T	30_25	30_20	30_15	30_10	30_05	30_00
Q_{fl}	1.28	1.21	1.22	0.93	0.86	1.14
$U_{ch}*A_{ch}*dT_{surf}$	3.85	3.70	3.71	3.23	3.01	3.45
V*Cp*p*dTair	0.13	0.12	0.12	0.10	0.09	0.11
Q_{fl} sample	0.18	0.40	0.62	0.85	1.08	1.14
$U*A*dT_{specimen}$	0.99	2.21	3.47	4.73	6.06	6.35
Q_{H+F}	6.76	7.94	9.04	10.26	11.39	12.55
Balance equation	*0.33*	*0.29*	*-0.10*	*0.42*	*0.29*	*0.37*
$Q_{AER}+Q_{fl}+Q_{fl}+Q_{mw}$	6.43	7.64	9.14	9.83	11.10	12.18
% Error	4.83	3.69	-1.09	4.14	2.55	2.94

Characterisation results

Table 1 shows the inputs for the heat balance equation measured over five delta T's during the testing of an 80mm woodfibre board. The stated manufacturer's lambda value for this panel is 0.04 W/mK and is used in the U value component (Table 1) of the U*A*dTspecimen. As the balance equation should read 0, the percentage error shown in the last row is just under 5%.
The theoretical and experimental results are plotted in Figure 3 and can be seen to have good correlation with the distance between the lines representing the gap to be identified.

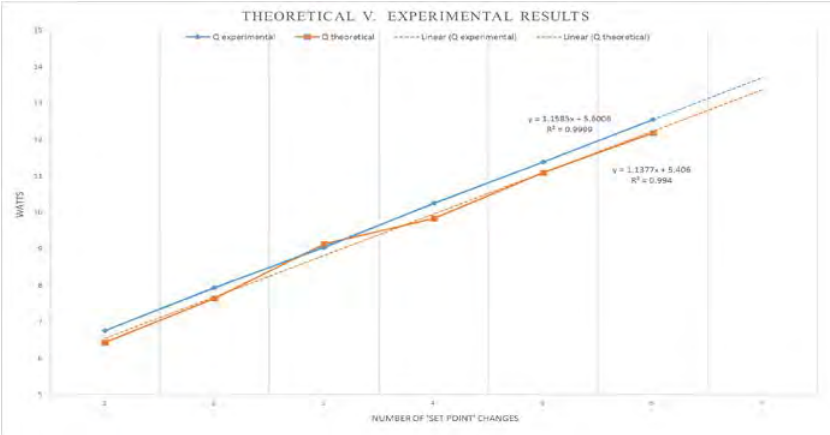

Figure 3. Theoretical versus Experimental losses of wood fibre board over 5 ΔT's

ANALYSIS AND DISCUSSION

The limitations of this CHB are its relatively small size and also the fine levels of accuracy of some of the equipment but these have been counteracted by the extra care taken in the construction and calibration process. The maximum size of 715mm by 715mm sample area size requires that the thermal bridge calculation needs to be extremely accurately identified.

The advantages of reduced dimensions over more traditional hot box systems however, provides a reduced mass and, thus, reduced thermal inertia of the overall system. First tests on a wood fibre board of an accepted conductivity (0.04 W/mK) shows very close relationship between theoretical and experimental data. The percentages of error varies by approximately 5%. The average temperatures in both chambers were steady throughout the testing period. Investigation is required to establish the cause of the slight non-linearity at delta T, of 15 ^{0}C.

Finally the CHB built in the DIT set out to design and build an affordable testing chamber for establishing the material properties of historic building materials with the first step of calibrating a panel thickness of 80mm of known thermal conductivity. This was satisfactorily achieved and the percentages error of approximately 5% is acceptable for this apparatus The next steps of testing historic building materials from a case study building is currently underway, with the results being inputted to a hygrothermal simulation.

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