Experimental Investigations of a Full-Scale Wall Element in a Large Guarded Hot Box Setup

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Experimental Investigations of a Full-Scale Wall Element in a Large Guarded Hot Box Setup: Methodology Description

Martin Veit
Hicham Johra
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Foreword

The aim of this technical report is to describe the *Large Guarded Hot Box* setup of Aalborg University, Department of the Built Environment (https://www.en.build.aau.dk/), that used to test the effective U-value of a full-scale wall element. These experimental tests were carried out from September 2021 to December 2022.
Summary

In this technical report, a brief introduction is given on internal convection in insulation materials, which can decrease the thermal performance of building elements. This phenomenon is characterized by air movements inside insulation porous materials caused by thermal buoyancy (natural convection).

To then determine these phenomena, an experimental setup is described in detail, such that the construction of the wall element, material properties and characteristics is given, both with principle drawings, dimensions and pictures of the real wall element.

To perform the experiments, a description of the large guarded hot box that has been used is given, with relevant dimensions and blueprints. In addition, a brief description of the control system is given.

A detailed description of the calibration procedures and used equipment is given. This includes Pt100 temperature sensors, type-K thermocouples, humidity sensors and air velocity sensors.

Examples of calibration curves are shown for each calibration method of the sensors. The placement of the sensors is also given, which is based on relevant standards for the specific measurements carried out in this investigation. The placement includes both the number of sensors, along with the location inside the hot box.

Finally, the methodology for performing the actual measurement campaign is described, which is both for steady-state experiments and dynamic experiments.

These methodology descriptions should enable the replication of the measurement campaign performed for this study.
1 Introduction and motivations

Buildings account for 40% of the total energy use in the world, therefore, there is an incentive to reduce it [23]. When the buildings account for such a significant amount of the total energy demand, and thereby CO₂ emissions, buildings are a focus area for the Paris agreement aiming at keeping the average global temperature rise below 1.5 °C. To accomplish this, CO₂ emissions will have to reach net zero by 2050 [7][9]. At the same time, the building floor space around the world has increased by 65% since the year 2000. To keep the energy use as low as possible, new buildings need to be energy efficient. Therefore, all countries need to make mandatory building codes adapted to their respective climate to improve energy performance significantly [9].

In Denmark, where it is a rather cold climate compared with the rest of the world, one way to reduce energy demand is by reducing the need for space heating by means of renovation of the insulation of buildings’ envelopes. In 1961, the building regulation introduced the first requirements for thermal insulation and tightened it up regularly to comply with the stricter energy requirements [3]. The determination of a building’s energy requirements relies on a theoretical calculation of the energy balance. The procedure is simplified: it is a summation of the gains and losses a building has, which is converted into the value of energy demand. The method may be inaccurate since the outdoor conditions are monthly average and does not include aspects such as wind exposure and solar irradiance on the construction elements. Furthermore, the control strategy of the building installations is simplified, the material properties are constant and not a function of temperature and humidity. The method is an adequate standardized way of comparing buildings but may not reflect their actual energy performance.

Another detail in the analysis that is not included, is the effect of internal convection. Internal convection in insulation porous material is air movement caused by thermal buoyancy induced by the thermal gradient in the insulation layer and in between the “cold” and “warm” sides of the latter (see Figure 1). The effective U-value is a corrected U-value, which takes the effect of dynamic conditions into account. This is measured in

Figure 1. Illustration of the principle of internal natural convection.
a full-scale wall element, where the U-value is assessed in steady-state or in dynamic conditions to get a more representative U-value for practical purposes.

When calculating the U-value of a wall element, the standard recommends to include the effect of internal convection if there is a risk of internal convection onset. As internal convection is not a heavily studied phenomenon (especially not in vertical insulation layers), not much literature exists on full-scale experimental setups. This makes it difficult to establish a verified method of determining if an insulation material is prone to internal convection, and if so, the effect thereof.

This technical report thus aims to contribute to the current body of literature regarding full-scale experiments on wall elements, with a focus on how to assess the phenomenon of internal convection and the effective U-value with steady-state and dynamic boundary conditions.

This report contains descriptions of the different elements, the calibration procedure needed to obtain reliable results, the placements of the sensors, how to correctly ground the setup and finally the methodology needed to measure internal convection and the effective U-value, so the results are replicable for future studies.

2 Description of the tested wall element

The wall element is 4.8 x 4.8 m in total, to fit the hot box (external: 4.8m x 4.8 m, internal: 3.6 x 3.6 m). The wall is constructed with outer wall sections that cover the areas that the sides of the hot box touch, and inner wall sections that are unobstructed in the metering area of the hot box. This is shown in Figure 2 where the grey area indicates the area where the sides of the hot box are in contact with the wall element.

The wall element is constructed with wooden battens, with a center-to-center distance of 600 mm for most wall sections. For practical purposes, due to the geometrical construction of the hot box, the outermost sections are 550 mm instead. The wooden battens are construction wood with material properties given in Table 1. The dimensions of the inner wall section are 600 mm in width and 3700 mm in height, which is then filled with the insulation material of choice. In this project, the insulation material investigated was loose-fill wood fiber insulation.

To contain the insulation material, the frame is covered in OSB plates with a thickness of 12 mm on the side facing the hot side, and 22 mm on the side facing the cold side.

A principle sketch of the wall element is shown in Figure 2 and a picture of the actual wall element is shown in Figure 3.
Figure 2. The framework for the wall element used for the experimental setup. The grey area denotes the boundary area, where the edges of the hot box are situated. All measurements are in millimeters.
A section view (A-A) of the wall element is shown in Figure 4. Here the wooden battens, OSB plates and insulation material are shown. The material properties of the materials are shown in Table 1.
Table 1. Material properties for each material in the wall construction. *Density for OSB plate of hot and cold side, respectively.

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal conductivity [W/m K]</th>
<th>Density [kg/m$^3$]</th>
<th>Specific heat capacity [J/kg K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood fiber insulation</td>
<td>0.0382</td>
<td>43</td>
<td>1950</td>
</tr>
<tr>
<td>Construction wood</td>
<td>0.12</td>
<td>536</td>
<td>1200</td>
</tr>
<tr>
<td>OSB wooden plate</td>
<td>0.13</td>
<td>610/590*</td>
<td>1200</td>
</tr>
</tbody>
</table>

When measuring the U-value, the construction details have to be known. For homogenous wall elements, which is not common because of practical issues, the procedure to measure the U-value is straightforward, as the heat flow is purely one-dimensional.

The wall element consists of insulation and wooden separators, so it is not entirely homogeneous. According to [11], a wall can be classified as non-homogeneous or in-homogenous if the local differences in the surface temperature are below are above 20%, respectively. From the point onward, homogenous will describe wall elements that fulfill the requirement, and heterogenous for wall elements that do not fulfill the requirement. As the U-value cannot be reliably determined for heterogeneous specimens, and the methods used depend on the classification of the wall element, the heterogeneity of the wall element is determined. The wall classification (surface temperature homogeneity) is determined with the modelling software COMSOL Multiphysics. Table 1 shows the material properties used for the simulation.

The boundary conditions for the simulation are an indoor temperature of 20 °C with a surface thermal resistance of 0.13 m$^2$ K/W and an outdoor temperature of -12 °C with a surface thermal resistance of 0.04 m$^2$ K/W. For all surfaces where the specimen is in contact with either the hot box or the laboratory air environment, the boundary conditions is a temperature of 20 °C and a surface thermal resistance of 0.13 m$^2$ K/W.

Based on these assumptions and the material properties, the COMSOL simulation gives a temperature profile for the wall element. Figure 5 shows the temperature distribution for the hot side, cold side, and the entire wall element.
The temperature differences caused by the heterogeneities have a maximum deviation of 2.5% when not considering the effects from the boundaries 0.5 m into the construction. Therefore, the wall element is, by definition, homogenous, and the experiment follows the methods proposed in [11].

3 Description of the Large Guarded Hot Box

The methodology to perform experiments using a Large Guarded Hot box is described in [11].

The experimental tests are performed in a Large Guarded Hot Box (see Figure 6). It consists of a hot and a cold side. The hot side is fully guarded by a ventilated cavity with a controlled temperature that follows that of inside the hot test zone, meaning that no unwanted heat transfer occurs from the surrounding surfaces of the test zone, making the adiabatic assumption valid.

The hot box setup makes it possible to measure and identify the heat transfer through the specimen and, in that way, estimate the U-value. The cold side of the Large Guarded Hot Box represents the outdoor climate (heat sink). The temperature and solar radiation of the cold side are controlled to emulate a specific weather scenario for the specimen.
Figure 6. The Large Guarded Hot Box used for the experiment with the hot and cold sides represented in red and blue, respectively. The tested specimen is in between the hot and cold zones.

The guarded hot box has an internal height and width of 3.6 m (see Figure 7). These dimensions make it ideal for testing full-scale construction elements.

Figure 7. A section view of the hot part of the Large Guarded Hot Box along with the inner dimensions. The ventilated cavity is highlighted with a green color.
3.1 Description of the Hot Box control system

In this section, the temperature control system for the guarded zone of the hot box is described. The principle of the feedback loop is shown in Figure 8 where two feedback loops are run in parallel. The main idea is to control the temperature inside the guarded hot zone of the Large Guarded Hot Box, and then control the guarded zone of the Large Guarded Hot Box to minimize the temperature difference between the hot zone and the guarded zone.

![Figure 8. Schematic of the control strategy for the guarded hot zone of the hot box.](image)

The top control loop regulates the temperature in the hot zone, and the bottom loop regulates the temperature in the guarded zone. A setpoint is chosen for the temperature in the hot zone. The temperature in the hot zone is then used as a setpoint for the controller regulating the guarded zone. The actuator in the top loop is a small ventilator placed in the hot box, which both ensures the mixing of air in the hot box, and heat load, as it is assumed that all the power sent to the ventilator is transferred as heat in the hot box environment.

The bottom loop uses a PI-controller to actuate a heating coil close to the ventilation unit that distributes air into the guarded zone.

This setup has shown to be very useful and efficient, as the temperature difference between the hot box and guarded zone (linked to the minimal heat loss to the guarded zone) was approximately 0.02 °C during the testing of the control strategy.
4 Calibration of sensors

This section describes the calibration procedure for the equipment: Pt100 sensors, thermocouples, anemometers and humidity sensors.

4.1 Calibration of Resistance Temperature Detectors (RTD) Pt100

4.1.1 Calibration equipment

In the following, a list shows the equipment used, and Figure 9 shows the setup.

1. Pt 100 temperature probes
2. F200 Precision Thermometer
3. Isocal-6 Venus dry isothermal block
4. NI 9216 module
5. PC with LabVIEW

Item 1 is the Pt 100 temperature probe, which is an RTD temperature probe and the subject of this calibration. The Pt 100 sensors are the sensors used to measure the temperature in the (cold junction) compensation box for the Helios data logger and thermocouples. The measuring range is -200 to 850 °C with a precision of 0.15 °C [17].

Item 2 is the F200 Precision Thermometer from ASL and used as the true value (reference) of the temperature for the calibration of the Pt100 sensors. The measuring range is -200 to 850 °C with an accuracy of 0.01 °C and a resolution of 0.001 °C [2].

Item 3 is the Isocal-6, which is a temperature well used to construct measurement points for calibration of the Pt 100s and the type-K thermocouples. It has a range of -55 to 140 °C and stability of 0.03 °C [14].

Item 4 is a NI 9216 module (National Instruments), which is the data logger for the Pt100 temperature probes, which measure the temperature in the (cold junction) compensation box of the Helios datalogger for type-K thermocouple temperature measurement. The measuring range is -200 to 850 °C, and the accuracy is 0.15 °C in the range -200 to 150 °C [19].
4.1.2 Calibration procedure

The Isocal-6 maintains a temperature that is then measured precisely with the F200 Precision Thermometer and the Pt100 sensors. The response of the Pt100 sensor is very linear, therefore, four different calibration points are deemed sufficient. The calibration temperature points on the Isocal-6 were 18 °C, 20 °C, 22 °C and 24 °C, which ranges way above and below what the (cold junction) compensation box experiences during the measurement campaign in the controlled environment of the laboratories. The measured temperature is an average of 120 seconds of data for each temperature. The reference temperature from the F200 Precision Thermometer is a 1-minute average of the readings when the latter are stable. All the used Pt100s undergo this procedure, and the calibration curves are determined from linear regression using the Least Squares method. During the calibration of the Pt100 sensors, the software uses a pre-calibration of type PT3851. The type PT3851 should therefore be used for the operation of the Helios datalogger for type-K thermocouples connected to the (cold junction) compensation box monitored by the mentioned Pt100 sensors.

4.1.3 Results

This section shows an example of a calibration curve for a single Pt100. In Figure 10, the measured points for a Pt100 are shown, along with the fitted first-order polynomial and the function of the fitted polynomial.
The calibration function for the Pt100 shown in Figure 10 is $y = 0.99x - 0.18$ with a $R^2$-value of 1.00. This procedure should be performed for all Pt100 sensors. To validate the precision of the Pt100s after calibration, the procedure should be performed again with the calibrated sensors. The error should be less than $\pm 0.01 \, ^\circ\text{C}$ for all the Pt100 sensors used.
4.2 Calibration of thermocouples

4.2.1 Thermocouples

This part of the appendix will go through the calibration of the thermocouples. An illustration of the setup is shown in Figure 11.

![Figure 11. Principle sketch of the experimental setup for the calibration of the thermocouples.](image)

4.2.2 Calibration equipment

In the following, the equipment used for this calibration is listed and described.

1. Type-K thermocouples
2. Helios datalogger
3. Compensation box
4. Pt 100 temperature probes
5. Copper cables
6. F200 Precision Thermometer
7. Isocal-6 Venus dry isothermal block
8. NI 9216 module

Item 1 is the type-K thermocouples, meaning that they are formed by two different nickel alloys named Chromel and Alumel. These are the temperature sensors connected to the Helios datalogger and are the subject of this calibration. They have a sensitivity of approximately $41 \mu V/K$ and a range of -200 to 1260 °C.

Item 2 is the Fluke Helios Plus 2287A datalogger, a modular data acquisition system where each module contains up to 20 thermocouples. The resolution for this system is 0.488 $\mu V$, which corresponds to 0.012K for type K thermocouples. The datalogger has a logging interval of 8 seconds for all sensors during the calibration.
Item 3 is the (cold junction) compensation box, which connects the thermocouples that measure the temperature with the copper cables connected to the Helios datalogger. The compensation box uses terminal blocks in a metal casing to shield the wires from radiation, which could influence the measurement. Furthermore, the compensation box is covered in expanded polystyrene to obtain stable temperature inside the compensation box.

Item 4 is the Pt100s used in the compensation box. The thermocouple temperature measurements depend on the temperature difference between the cold junction and the measurement tip. The Pt100s have a measuring range of -200 to 850 °C.

Item 5 is copper-wire cables connected from the cold junction compensation box to the Helios datalogger.

Item 6, 7 and 8 are described previously.

The setup used is shown in Figure 12, except for item 8 (the NI 9216 module).

![Figure 12. Experimental setup for the calibration of the thermocouples.](image)

4.2.3 Mitigation of electrical noise

As the thermocouples are sensitive to electrical noise, preventive measures reduce this and make the measurements more reliable and stable. No power cables and electrical equipment should be in the vicinity of the thermocouples, and at the same time, the equipment is grounded to mitigate electrical noise. During calibration, the power cable from the Isocal-6 leads in the opposite direction of the thermocouples direction.
The grounding will remove residual current that can impact the measurements and is performed by grounding the equipment in series or parallel without creating ground loops. Figure 13 shows the principle of the grounding for the calibration of the thermocouples.

4.2.4 Calibration procedure

The thermocouples are bundled together in pairs of five for each hole in the Isocal-6 wells to ensure that the thermocouples’ measured temperature corresponds with the true temperature from the F200 Precision Thermometer. All of the thermocouples can be inserted down in the temperature well. So the same conditions are exerted on all thermocouples. Furthermore, each measuring point of the thermocouples is covered with tape to ensure that the measurement is not affected by the conductive metal in the temperature well or other thermocouples (avoid short-circuiting thermocouples and avoid contact with well metal block that might hold static charges.

One insulates the compensation box further to avoid air movements into the rectangular holes in the compensation box. The insulation consists of paper towels such that a minimal amount of air can enter the compensation box and change the temperature locally at the junctions. The placement of the F200 Precision thermometer is in the outer ring of the metal sheathing such that it will experience the same conditions as
the thermocouples. Before initiating the calibration, one insulates the top of the Isocal-6. Figure 14 shows the placement of the thermocouples and the F200 Precision Thermometer.

The design temperature points on the Isocal-6 were between -10 to 50 °C for the thermocouples that are placed inside the wall element and on the hot side of the hot box. For the cold box, thermocouples are calibrated in the range -20 to 10 °C, as this is the expected range of the temperature on the cold side of the hot box. The measured temperature is an average of 120 seconds of data for each temperature point. The reference temperature from the F200 Precision Thermometer is a 1-minute average of the readings when the latter are stable. This procedure is done for all of the thermocouples, such that each thermocouple has a corresponding calibration curve.

![Figure 14. Isocal-6 metal insert with thermocouples and F200 Precision Thermometer.](image)

4.2.5 Results

In this section, an example shows a calibration curve for a single thermocouple. The polynomial is of the third order, as the thermo-electric effect between the two alloys is temperature-dependent. In Figure 15, the measured voltage for a thermocouple is shown along with the corresponding temperature difference between the junction and measuring point.
The function of the calibration curve for the thermocouple shown in Figure 15 is
\[ y = -10.01 \cdot 10^7 x^3 - 4.22 \cdot 10^5 x^2 + 2.52 \cdot 10^4 x - 0.15 \]

with an \( R^2 \)-value of 1.00.

To validate the precision of the thermocouples after calibration, the procedure should be performed again with the calibrated sensors. It is possible to obtain an error of less than \( \pm 0.15 \) °C.

4.3 Calibration of Anemometers

This appendix explains the procedure for the calibration of anemometers, including the explanation of the equipment, the measurement procedure, the measurements, how to determine the calibration curves, and the calibration results to ensure correct air velocity measurements. The calibration compares the voltage response from the anemometers to a specific air velocity measured using a reference measurement.

4.3.1 Calibration equipment

The equipment needed to calibrate the anemometers is listed below.

1. Dantec 54R102 thermal comfort probes (hot-sphere anemometer)
2. Jet wind tunnel
3. Dantec Comfort Sense 8-port
4. Orifice plates
5. Micromanometer with tubes
6. Digital pressure gauge
7. NI 9216 module with a calibrated Pt100
Item 1 is the hot-sphere anemometer from Dantec, of the type 54R102, and it is the subject for this calibration. The anemometers are used to measure the air velocity, with a measuring range of 0.05 to 5.0 m/s with a precision of 2% in the range 0.05 to 1 m/s and a precision of 5% in the range 1.0 to 5.0 m/s [16].

Item 2 is a jet wind tunnel with a dedicated ventilator connected to it. It generates airflows where the air velocity can be determined using orifice plates and corresponding calibration curves.

Item 3 is the Dantec Comfort Sense 8-port datalogger, which logs the data from the anemometers. It has eight input ports.

Item 4 is the orifice plates used to generate a pressure drop through the orifice, where a corresponding air velocity can be determined using corresponding calibration curves for each orifice plate. The orifice plates have orifice diameters of 10 mm, 23 mm and 46 mm.

Item 5 is the micromanometer of the type Min2P from Debro. The measuring range is 20 mbar with an uncertainty of 0.02 mmH2O [5].

Item 6 is a barometer that corrects the air velocity. It is a digital pressure gauge from Mensor of the type 2104 with a compensated temperature range between 15 to 45 °C and a warm-up time of 15 minutes. The precision in the compensated temperature range is 0.01 % of the reading [18].

Item 7 is a datalogger for Pt100 temperature probes, which measures the air temperature in the room where the anemometers’ calibration took place.

Figure 16 shows the setup for calibration of the anemometers.
4.3.2 Calculation of the reference air velocity in the wind tunnel

Using orifice plates with corresponding calibration curves makes it possible to determine the reference air velocity. The calibration curves are different for each orifice plate. Table 2 shows the given calibration curves and ranges for each orifice plate. The pressure difference is given in mbar and the air velocity is calculated in m/s.

Table 2. Information regarding the different orifice plates.

<table>
<thead>
<tr>
<th>Diameter</th>
<th>Range</th>
<th>Criterion</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 mm</td>
<td>0 – 11 cm/s</td>
<td>Δp &lt; 0.5 mbar</td>
<td>v = 14.663 Δp^{0.3378}</td>
</tr>
<tr>
<td>10 mm</td>
<td>0.11 – 0.42 m/s</td>
<td>Δp &gt; 0.5 mbar</td>
<td>v = 0.157 Δp^{0.485}</td>
</tr>
<tr>
<td>23 mm</td>
<td>0.25 – 1.1 m/s</td>
<td>–</td>
<td>v = 0.744 Δp^{0.4516}</td>
</tr>
<tr>
<td>46 mm</td>
<td>1 – 5 m/s</td>
<td>–</td>
<td>v = 2.886 Δp^{0.49}</td>
</tr>
</tbody>
</table>

Information about the air temperature and barometric pressure is needed to perform a velocity correction before it is possible to calibrate the anemometers. The calibration curves for the orifice plates describe the velocity at a certain air temperature, with an air density of air = 1.2 kg/m³. Therefore, a correction of the
velocities is necessary. Using the Ideal Gas Law, it is possible to calculate the air density from the room temperature. The equation below shows the calculation of the air density at a specific temperature.

\[
\rho_{\text{air,corr}} = \frac{M P_{\text{bar}}}{RT}
\]

- \(\rho_{\text{air,corr}}\): Density of the air \([\text{kg/m}^3]\)
- \(M\): Molar mass of air \([\text{kg/mol}]\)
- \(P_{\text{bar}}\): Barometric pressure \([\text{Pa}]\)
- \(R\): Gas constant \([\text{J/(mol K)}]\)
- \(T\): Air temperature \([\text{K}]\)

The molar mass of atmospheric air is 28.97 g/mol, and the gas constant is 8.1315 J/(mol K). The barometric pressure is determined using the Digital Pressure Gauge, and the temperature is measured using a Pt100. To calculate the velocity correction, the equation below is used.

\[
v_{\text{corr}} = v_{\text{meas}} \sqrt{\frac{1.2 \text{ kg/m}^3}{\rho_{\text{air,corr}}}}
\]

- \(v_{\text{corr}}\): Velocity after density correction \([\text{m/s}]\)
- \(v_{\text{meas}}\): Measured air velocity \([\text{m/s}]\)

The measured velocity should be corrected using the earlier procedure to take the actual air density into account for each velocity measurement.

### 4.3.3 Grounding

It is essential to ground the measuring equipment, computer, and monitor without creating ground loops to reduce electrical noise on the equipment. When the equipment is grounded, it minimizes the risk of large offsets or fluctuations in the measurement. Only a single piece of equipment for measurement is grounded, while the rest of the equipment connects from the grounded equipment in either series or parallel without making grounding loops. Figure 17 shows the grounding of the equipment. The cables to each anemometer have a ground, so they are automatically grounded when connected to the Dantec 8-port.
4.3.4 Calibration procedure

The barometric pressure and room temperature must be known for the velocity correction before it is possible to calibrate the anemometers. Therefore, the barometric pressure and room temperature are performed as point measurements at the beginning of each new calibration for the anemometers.

Each anemometer is placed in the jet wind tunnel perpendicular to the flow direction when generating each measurement point with the different orifice plates. The jet wind tunnel must be vertical, with a downward air stream since this is the expected airflow direction inside the hot box.

The calibration of the anemometers depends upon their usage. Therefore, the calibration of the anemometers on either side of the Large Guarded Hot Box is different. The range for the anemometers in the hot box is 0.05 – 0.25 m/s with a total of 6 points. The range for the anemometers in the cold box is 1 – 5.0 m/s with a total of 5 points. Each measurement point from the anemometers is an average of 120 seconds at each velocity.

The Debro Micromanometer determines the pressure difference across the orifice plates, which is performed as a point measurement after the ventilator has reached steady-state. When the range of each orifice plate is exceeded, a new orifice plate with a larger orifice diameter is inserted into the jet wind tunnel.
4.3.5 Results

This section presents the results. It shows only a single calibration curve which is the result for each anemometer. The calibration file for each anemometer does not appear since the calibration does not yield a calibration function. Instead, it is a calibration file loaded into a program for each anemometer. A linear interpolation is performed by the anemometer program to transform the measured signal into valid air velocity measurements. The voltage signal from the anemometer will be converted to the corresponding air velocity, as shown in Figure 18, based on a calibration file.

![Figure 18. Example of a calibration curve for a single anemometer.](image)

To validate the precision of the anemometers after calibration, the procedure should be performed again with the calibrated sensors.

4.4 Calibration of humidity sensors

This section explains the procedure for the calibration of the humidity sensors to ensure correct measurements of the humidity inside the insulation material and on the cold side and hot side of the hot box. The calibration procedure compares the humidity from the Dewmaster 3000 to the reference measurement from the HygroDat 100. Furthermore, the Dewmaster 3000 is also calibrated according to temperature since the relative humidity depends on the temperature.
4.4.1 Calibration of HygroDat 100

4.4.2 Calibration equipment

The equipment needed for calibration of the HygroDat 100 is listed below.

1. F200 Precision Thermometer
2. Novasina calibration salts
3. HygroDat 100

Item 1 is the F200 Precision Thermometer from ASL, which measures the air temperature in the room. The measuring range is -200 to 850 °C with an accuracy of 0.01 °C and a resolution of 0.001°C [2].

Item 2 is calibrations salts that follow the international standard SAL-SC. The calibration salts consist of five different salts, which cover the relative humidity interval from approximately 11 to 90 % depending on the temperature during the calibration since the calibrations salts’ relative humidity depends upon the temperature [20].

Item 3 is the HygroDat 100, a precision humidity sensor and the subject of this calibration. It has a measuring range between 0 to 100% relative humidity, a resolution of 0.1% and a precision of 0.5% relative humidity [21].

Figure 19 shows the setup for calibration of the HygroDat 100.

![Figure 19. Experimental setup for calibration of the HygroDat 100.](image-url)
4.4.3 Measurement

The calibration of the HygroDat 100 needs calibration salts. Table 3 shows the used calibration salts.

Table 3. Summary of the calibration salts used. *The stated relative humidity is at a temperature of 20 °C.

<table>
<thead>
<tr>
<th>Chemical name</th>
<th>Salt standard</th>
<th>Measurement point* [%RH]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithium chloride</td>
<td>SC-11</td>
<td>11.3</td>
</tr>
<tr>
<td>Magnesium chloride</td>
<td>SC-33</td>
<td>33.1</td>
</tr>
<tr>
<td>Magnesium nitrate</td>
<td>SC-53</td>
<td>54.4</td>
</tr>
<tr>
<td>Natrium chloride</td>
<td>SC-75</td>
<td>75.5</td>
</tr>
<tr>
<td>Barium chloride</td>
<td>SC-90</td>
<td>90.5</td>
</tr>
</tbody>
</table>

Demineralized water is added to the calibration salts to ensure that each container with salt has water that can evaporate to reach the specified humidity of each salt. Afterward, one inserts the HygroDat 100 sensor into each container with calibration salts. As the relative humidity is dependent on the temperature of the salt, the air temperature is measured using the F200 Precision Thermometer.

Each calibration salt has a calibration curve that is temperature-dependent. In the calibration curve, it is possible to interpolate between different temperature points of the salts. Figure 20 shows an example of a calibration curve for a calibration salt. These calibration datapoints can be found directly on the containers of the calibration salts.

![Figure 20. Calibration curve for calibration salt SC-53.](image-url)
Each measurement of a calibration salt has to reach a steady state, which takes approximately 30 minutes. After that, the value is saved by the HygroDat 100. After each calibration salt procedure is over, a calibration curve appears for the HygroDat 100.

To validate the precision of the Hygrodat 100, the procedure should be performed again after calibration. It is possible to obtain an error less than ±0.4%.

4.5 Calibration of Dewmaster 3000 - Temperature

4.5.1 Calibration equipment

The equipment needed for calibration of the temperature sensors of the Dewmaster 3000 is listed below.

1. Dewmaster 3000
2. Isocal-6
3. F200 Precision Thermometer

Item 1 is the Dewmaster 3000, a piece of equipment that can measure the temperature and relative humidity. It is an Arduino that has 10 Sensirion sensors of the type SHT75. It has a temperature range between -40 to 123.8 °C, an accuracy between 0.3 to 1.5 °C depending on the environmental temperature. It has a relative humidity range between 0 to 100%, an accuracy of 1.8% between 10 to 90%, and a resolution of 0.05% [1].

Item 2 is the Isocal-6, which is a temperature well used to construct measurement points used to calibrate the temperature sensors in the Dewmaster 3000. It has a range of -55 to 140 °C and a stability of 0.03 °C [14].

Item 3 is the F200 Precision thermometer, which is previously described.

Figure 21 shows the setup for calibration of the temperature sensors in the Dewmaster 3000.
4.5.2 Calibration procedure

The temperature well maintains different temperature points, so it is possible to compare the measured temperature of the sensors with the reference temperature from the F200 Precision Thermometer. The Dewmaster 3000 has to be inserted into the bottom of the temperature well. Then each sensor is exposed to the same environment as the rest. After insertion of the sensors, one insulates the top of the Isocal-6 to avoid heat loss and air from entering the temperature well.

The temperature well generates four temperature points as the RTD sensors are experiencing a linear relationship with the measured temperature at different temperatures. The expected temperature range for the experiment is between -10 and 50 °C, so the design temperature setpoints are -10, 10, 30, and 50 °C. The measured temperature is an average of 120 seconds of data for each temperature point. The reference temperature from the F200 Precision Thermometer is a 1-minute average of the readings when the latter are stable. All the sensors undergo this procedure, and the calibration curves appear from linear regression using the Least Squares method.

4.5.3 Results

This section shows an example of a calibration curve for a single sensor. Figure 22 shows the measured points for a sensor.
The trend line shown in Figure 22 has the function $1.01x + 0.11$ with an $R^2$-value of 1.00.

To validate the precision of the sensors after calibration, the procedure should be performed again with the calibrated sensors. It is possible to obtain an error of less than $\pm 0.15 \, ^\circ C$.

### 4.6 Calibration of Dewmaster 3000 - Relative humidity

#### 4.6.1 Calibration equipment

The equipment needed for calibration of the Dewmaster 3000 is listed below.

1. HygroDat 100
2. Dewmaster 3000
3. Vötsch VCL 7010 Environmental Chamber
4. F200 Precision Thermometer

Item 1 is the HygroDat 100, which is a precision relative humidity sensor. It has a measuring range between 0-100 % relative humidity and has a resolution of 0.1%.

Item 2 is the Dewmaster 3000, which can measure both temperature and relative humidity.

Item 3 is the environmental chamber of the type VCL 7010, used to create a controlled environment regarding temperature and relative humidity. It has a temperature range between 10 to 98 °C for climatic tests, with a
temperature deviation in the center of the chamber of 0.3 to 0.5 °C. The humidity range is between 10 to 98% for climatic tests, with a relative humidity deviation in the center of the chamber of 1 to 3% [10].

Item 4 is the F200 Precision thermometer.

The setup for calibration of the Dewmaster 3000 with respect to humidity is shown in Figure 23.

4.6.2 Calibration procedure

The VCL710 environmental chamber generates measurement points for temperature and relative humidity. The environmental chamber generates ten measuring points: two different temperatures and five different points for relative humidity for each temperature. The entire measurement program is shown in Figure 24. The grey area in Figure 24 is the operating range of the environmental chamber.

The environmental chamber has to reach a steady-state for each measurement point. Each measurement point is stabilized for three hours to ensure a steady-state condition. The Dewmaster 3000 sensors are placed inside the environmental chamber in a bundle in the vicinity of the F200 Precision Thermometer and
HygroDat 100 to ensure similar conditions for the precision instruments as the sensors. This is shown in Figure 25.

Figure 24. Measurement program for the environmental chamber. The grey area denotes the range of the environmental chamber.

Figure 25. Dewmaster 3000 sensors inside the environmental chamber, close to the F200 Precision Thermometer and HygroDat 100.
The measured humidity is an average of 120 seconds of data for each temperature point where the two Dewmaster 3000s have a logging frequency of 30 seconds. The readings from the HygroDat 100 and F200 Precision Thermometer are point measurements.

Another setup is made to accommodate measurement points outside the VCL 7010 Environmental Chamber range. The principle of the setup is to generate a measurement point with 0% relative humidity using air from a pressure air gun. The sensors are placed in a container with pressurized air to create an overpressure. Another tube leads from the container to the outside to let the air out. By doing this, the clean air with 0% relative humidity will enter, and the remaining air with humidity is drained out of the chamber. Figure 26 shows the setup.

![Figure 26. Setup for obtaining a relative humidity point with 0% relative humidity.](image)

The sensors from each channel measure the temperature, which is calibrated according to the earlier described calibration, and then the relative humidity can be determined using multivariate linear regression. The equation for this is shown below.

\[
v_{corr} = \beta_0 + \sum_{i=1}^{n} \beta_i x_i
\]

- \( \gamma \) Output
- \( \beta_0 \) Constant regression coefficient
- \( \beta_i \) \( i^{th} \) regression coefficient
- \( x_i \) \( i^{th} \) input parameter

The goal is to obtain an expression with the regression coefficients such that the model can be used to make new predictions that take the temperature into account. The regression coefficients can be determined using
the method of Least Squares. So, in the end, one selects the final expression for each relative humidity channel of the Dewmaster 3000. An example of a calibration expression is shown below

\[ y = 1.11 \, x_{RH} + 0.07 \, x_T - 11.70 \]

Where \( x_{RH} \) is the measured relative humidity of the sensor, and \( x_T \) is the measured temperature of the sensor. \( x_T \) is corrected according to the calibration using the F200 Precision Thermometer.
5 Placement of sensors in the test setup

There are two different objectives of the measurement campaign: to measure if internal convection is occurring inside the insulation layer and to determine the effective U-value of the entire wall element. The description of the placement of the sensors is split into two parts. The first part is about the sensors for internal convection, and the second part is for determining the effective U-value of the wall element.

5.1 Investigations of the internal convection

As internal convection is a phenomenon that happens inside the porous insulation material, sensors should be placed in the insulation layer. Due to the lack of literature on how to measure this internal convection, it is unclear which resolution of sensors should be used. In this specific setup, a total of 5 internal temperature sensors were used, spaced evenly throughout the thickness of the insulation layer.

In the preliminary investigations of the experimental setup, it was concluded that welded thermocouples should be used. In hindsight, it would likely not make a significant difference to use thermocouples with twisted ends, and since these are less fragile and easier to produce, the latter is recommended.

Furthermore, different options for mounting the thermocouples were investigated, where it was found that thermocouples glued to a nylon string with shrinking tape were sufficiently stable and did not allow for a significant loss in precision of the placement. This is shown in Figure 27.

![Figure 27. The chosen solution for mounting the thermocouples inside the insulation layer.](image)

Besides sensors in the width of the construction elements, different heights should also be investigated, as the temperature profiles obtained by the sensors has been shown to differ as a function of height.

An example of this is shown in Figure 28. It should be noted that a single wall section could be investigated. Since they are exposed to the same conditions, the system is assumed to be symmetrical. However, boundary effects could have an effect.
5.2 Investigations of the effective U-value

To measure the effective U-value, different sensors have to be used to fulfil the requirements of [11]. The placement of these sensors is according to that standard and explained in the following section.

5.2.1 Surface temperature measurements

According to [11], the surface temperature measurements has to be evenly distributed over the specimen area and located opposite each other on the hot and cold side of the hot box. The experiment requires at least two sensors per square meter as a minimum amount of sensors unless further information is available.

If the wall element is non-homogenous, additional sensors should be placed in the regions of the inhomogeneities. However, there is no requirement for the number of sensors for these regions.
Due to the number of sensors required to measure the surface temperature, a symmetry assumption can be applied. An example of a wall configuration is shown in Figure 29 where sensors are placed in points mirrored from the middle, which can be used to verify the symmetry assumption.

![Figure 29: Placement of thermocouples on the wall element using symmetry and zones of equal area. The black crosses are the placements of the sensors. The circles indicate the placement of the supplementary sensors. All dimensions are indicated in millimeters.](image)

To make sure that the sensors are in thermal contact with the surface, a thermal paste should be applied at the measurement tip of the temperature sensors (type-K thermocouples). Furthermore, tape close to the measurement tip can be applied to hold the sensor on the wall surface. [11] also requires the thermocouple to be placed on an isotherm, meaning a region with the same temperature. This is done by taping the thermocouple to the wall without overlapping with any inhomogeneous regions. These requirements are shown in Figure 30.
Besides the surface temperature of the specimen, the surface temperature of the remaining surfaces in the hot box needs to be measured. Every wall requires two per surface except for two. The increased amount of thermocouples is due to the large surface areas and higher amount of openings and insulated perforations. Figure 31 illustrates the placement of the thermocouples.

![Figure 30. Left) Shows thermocouples mounted on the specimen with thermal paste. Right) Shows how the thermocouple are mounted using tape along the isotherm.](image)

<table>
<thead>
<tr>
<th>Cold side</th>
<th>Hot side</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1/2</td>
</tr>
<tr>
<td>2</td>
<td>2/2</td>
</tr>
<tr>
<td>3</td>
<td>3/2</td>
</tr>
<tr>
<td>4</td>
<td>4/2</td>
</tr>
<tr>
<td>5</td>
<td>5/2</td>
</tr>
<tr>
<td>6</td>
<td>6/2</td>
</tr>
<tr>
<td>7</td>
<td>7/2</td>
</tr>
<tr>
<td>8</td>
<td>8/2</td>
</tr>
<tr>
<td>9</td>
<td>9/2</td>
</tr>
<tr>
<td>10</td>
<td>10/2</td>
</tr>
<tr>
<td>11</td>
<td>11/2</td>
</tr>
<tr>
<td>12</td>
<td>12/2</td>
</tr>
</tbody>
</table>

![Figure 31. Placement of thermocouples to measure the surface temperature of the hot box, illustrated as an exploded cuboid.](image)

The temperature sensors take place on the surface, similar to the temperature sensors on the specimen. Thermal paste is used with tape along the surface.
5.2.2 Air temperature measurements

As with the surface temperature, the air temperature measurements must be distributed evenly. The same requirements for the number of temperature sensors are present, meaning two thermocouples per square meter. However, the same assumption with symmetry and the temperature distribution of the wall is applicable, and the air temperature measurements take place in the same grid as the surface measurements, not including the additional thermocouples. The placement of the sensors is shown in Figure 32.

The dynamic experiment uses the artificial sun. Therefore, the thermocouples in the cold side of the hot box are preemptively radiation-shielded using a silver casing, according to the requirement stated in [11]. The temperature sensors’ distance to the wall depends on whether or not forced or free convection is present. As the cold side of the hot box uses a ventilation unit to adjust the temperature, it provides a large amount of air close to the specimen. Therefore, the cold side will experience forced convection, and the thermocouples have to probe the bulk air temperature. The sensors will be placed 10 cm from the wall to accommodate this requirement. In the hot side of the hot box, only natural convection is present, and the thermocouples are therefore required to be outside the boundary layer of the specimen. The thermocouples
are placed 10 cm from the wall to accommodate this requirement. Figure 33 illustrates the placement of the thermocouples in a vertical cut lengthwise of the hot box.

*Figure 32. Placement of thermocouples to measure air temperature using symmetry and zones of equal area. The black crosses are the placements of the sensors. All measurements are in millimeters.*
In total, 38 thermocouples measure the air temperature in the hot and cold side of the hot box. The sensors are mounted using a nylon string, shrinking tape and glue to avoid displacements in the vertical position of the sensors.

5.2.3 Air velocity measurements

The air speed has to be measured to determine the convective coefficient of the surface resistance. For this purpose, anemometers are used near the interior and external wall in the guarded zone, placed 3 cm from the wall. 16 anemometers are used for this, evenly distributed between the external and internal surfaces. The anemometer’s placement is shown in Figure 34. The crosses represent the placement of the anemometer relative to the wall element.
Figure 34. Placement of anemometers for both interior and external side of the wall element. All measurements are in millimeters.

It is possible to determine the convective coefficient of the surface resistance on both the interior and exterior sides of the wall by using anemometers. [13] prescribes that it is only needed to determine the air speed adjacent to the exterior side of the external wall. However, for experimental purposes, it is used to measure the air speed near the interior side as well. The anemometers are placed on metal stands in the hot and cold sides of the hot box. The anemometers in the hot side are close to the specimen orthogonally. The anemometers in the cold side are placed close and parallel to the specimen. They are parallel to the specimen, as the metal stand cannot be placed at a sufficient distance for the anemometers to be placed orthogonally to the specimen. The placement of the anemometers themselves is deemed adequate to not influence the measurements. A close-up of an anemometer is shown in Figure 35.
5.3 Grounding

This section will purely focus on what is done to ground the setup in its entirety. The following equipment is used for the data acquisition:

1. Helios 2287A Datalogger
2. Dewmaster 3000 (DM3000)
3. Dantec 8-port anemometer datalogger

The measurement equipment is grounded in series when adequate. The setup is grounded as shown in the schematic in Figure 36.

![Figure 36. Schematic of the grounding for the entire data acquisition setup.](image)

The NUC (mini-computer) and computer screen and the Dantec 8-port are grounded separately. The DM3000s are grounded through the USB cable connected to the computers, and the Helios systems are grounded in series to a power plug. The setup in its entirety is shown in Figure 37.

![Image of a hot-sphere anemometer placed in the hot side of the hot box.](image)
6 Test methodology

This section describes the measurement procedure for both steady-state and dynamic experiments. The experiments aim to determine the U-value of the full-scale wall element experimentally and compare it with a steady-state calculation based on DS 418 standard [4].

6.1 Steady-state measurements

The procedure for the steady-state measurement of the U-value is described in ISO 8990 [11]. The measured U-value is estimated based on the equation below.

\[
U = \frac{\Phi}{A (T_{ni} - T_{ne})}
\]

<table>
<thead>
<tr>
<th>U</th>
<th>Heat transfer coefficient</th>
<th>[W/(m² K)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Phi)</td>
<td>Heat flow through specimen</td>
<td>[W]</td>
</tr>
<tr>
<td>A</td>
<td>Area perpendicular to heat flow</td>
<td>[m²]</td>
</tr>
<tr>
<td>(T_{ni})</td>
<td>Interior environmental temperature</td>
<td>[°C]</td>
</tr>
<tr>
<td>(T_{ne})</td>
<td>Exterior environmental temperature</td>
<td>[°C]</td>
</tr>
</tbody>
</table>

In the equation, the heat flow is equal to the amount of heat supplied to the guarded zone of the hot box. The equation determines the interior and exterior environmental temperatures.
The given equations in this section imply that the surface temperature of the hot and cold parts of the hot box is measured, the surface temperature of the specimen, the velocity adjacent to the specimen, and the power added to the guarded zone of the hot box (hot zone). Each measurement must consist of average values from 3 hours of data, and two successive measurements should agree within 1% to be accepted as stable. The stability criteria involve the U-value measurements, the added power, and the temperature measurements.

Alternatively, it is possible to use surface temperature measurements instead of environmental temperatures. During the measurement campaign in the project, these two methods gave very similar results. However, the method with environmental temperatures was used in this study.

6.2 Dynamic measurements

The procedure for the dynamic measurement of the U-value is based on the standard ISO 9869-1 [12]. The measured U-value is calculated from the equation below. The environmental temperatures are calculated in the same way as described previously. The dynamic experiment should last for at least 72 hours and the U-value must not deviate by more than 5% from the value obtained 24 hours before.
\[
U = \frac{\sum_{j=1}^{n} Q_j}{A \sum_{j=1}^{n} (T_{nij} - T_{nej})}
\]

- \( \sum_{j=1}^{n} Q_j \): Number of measurements
- \( [\cdot] \): Sum of added power
- \( \sum_{j=1}^{n} (T_{nij} - T_{nej}) \): Sum of environmental temperature difference
- \( [\cdot] \): Area of specimen

6.3 Cases

In the following, suggestions for cases for the experiment are provided.

Both steady-state experiments and dynamic experiments have been tested in the laboratory. For the steady-state cases, a fixed temperature is given for both the hot and cold sides of the hot box. It is possible to deviate from these cases to test for more extreme scenarios, but the cases are already quite extreme.

The dynamic cases use a sinusoidal temperature profile instead of an actual day profile of Denmark, since this allows for a larger temperature difference for a single day. The sinusoidal signal has a mean temperature of -10 °C with different amplitudes, and a time period of 24 hours.

For steady-state cases, refer to Table 4 and for dynamic cases, refer to Table 5. The dynamic cases are visualized in Figure 38.

**Table 4. Steady-state experimental cases.**

<table>
<thead>
<tr>
<th>Case #</th>
<th>Indoor temperature [°C]</th>
<th>Outdoor temperature [°C]</th>
<th>( \Delta T ) [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
<td>-20</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>-20</td>
<td>40</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>-10</td>
<td>30</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>5</td>
<td>20</td>
<td>20</td>
<td>0</td>
</tr>
</tbody>
</table>

**Table 5. Dynamic experimental cases.**

<table>
<thead>
<tr>
<th>Case #</th>
<th>Indoor temperature [°C]</th>
<th>Outdoor conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean [°C]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Amplitude [°C]</td>
</tr>
<tr>
<td>1</td>
<td>20</td>
<td>-10</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>-10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
</tr>
</tbody>
</table>
Figure 38. Illustration of dynamic day profiles.
7 References


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