HÖGSKOLAN DALARNA

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Heat transfer tests on EPS material and massive timber wall component

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Author:
Youcef Boussaa and Luqman Alkhado

Supervisor(s):
Tomas Persson

Examiner:
Amir Sattari

Course Code: EG3020

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Dalarna University
Energy Engineering

Abstract

Timber walls are known to be an energy efficient component in the building envelope. These building elements are essential in the passive design and have been pointed out to their ability to regulate the indoor climate and reduce energy demand. Heat transfer measurements of thermal transmittance value of Iso-timber wall component have been performed with the climate chamber at three temperature differences. The influence of temperature variations on the thermal conduction of the wall were investigated. The temperature on the warm side was kept at room temperature 20 °C while the cold side temperature was decreased from 0 C to -20 C during the tests. As the temperature difference is increased, the thermal transmittance value of the timber wall component decreased slightly due to decrease in the thermal conductivity value. The effect of density and porosity on the thermal conductivity may be related to the presence of air voids and cell boundaries inside the timber wall. Results have showed that the U-value of the timber wall component decreases at higher temperature differences which indicates the higher degree of insulation of the timber wall component.

Contents

Abbreviations

Abbreviation	Description
CLT	Cross Laminated Timber
CHB	Calibrated Hot Box
EPS	Expanded Polystyrene
GHB	Guard Hot Box

Nomenclature

Symbol	Description	Unit
U	Thermal transmittance	$W/(m^2·K)$
ΔT	Temperature Difference	K
RH	Relative humidity	%
T_a	Air temperature	°C
T_s	Surface temperature	°C
P	Power	W
R	Thermal resistance	$(m^2·K) /W$
λ	Conductivity	$W/(m·K)$

1 Introduction

Global warming has a significant impact on communities, human health and the climate. In Sweden, the average recorded temperatures in July during the period 1961-1990 was 17 °C [1]. However, in summer 2018 the temperatures recorded in the Scandinavian country for July month have an average of 23 °C. On the other hand, temperatures are expected to drop during the winter seasons and colder months are expected.

The most promising solution to relieve the climate change is to improve the energy efficiency and reduce the energy demand [2]. In Sweden, 36 % of the total energy is used by the sector of residential buildings and service organizations [3]. The Swedish parliament (June 2006) has decided to lower the total energy demand in residential buildings by 20 % per heated unit area in 2020 [3]. To achieve this goal, the country focused on reducing the heating demand by the construction of passive houses and renovating the existing buildings to improve their insulation. The passive house is a concept of energy efficient buildings which is based on minimizing heat demand by improving the airtightness and reducing the U-values of the building frame.

An increase in the integration of wooden material as structural elements has become now a global appreciation [2]. The natural and high-tech material has unique characteristics which made it a subject of several research papers. In Sweden, wooden buildings account for 90 % of the total market share for single-family houses [4]. The availability of timber material has made it an important alternative in the design of floor and wall components. This material has concurred the Swedish construction market in recent years due to its economic value and service life, along with the short production time which results in a lower impact on the environment.

Wood material enhances the efficiency of buildings by creating comfortable living atmosphere and lowering the heating demand at the same time. Material with high moisture buffering capacity could be used to passively control the indoor moisture condition and consequently improve the indoor environmental quality and reduce the latent heat load of buildings. Also, the wood material provides the building envelope with the required thermal inertia to store the energy in times of abundance, the heat stored in the internal and external building component is then emitted back when a decrease in the indoor temperature occurs [5]. This shall contribute to the efficiency of buildings by reducing the heating load while maintaining the thermal comfort. Moreover, the ability of the wooden material to regulate the indoor humidity levels due to its moisture buffering property shall enhance the indoor air quality. Also, the reduction of the indoor humidity levels will lower the ventilation rate and thus energy demand for the building.

Walls are responsible for a considerable portion of the heat lost from building envelopes due to their large surface area. As a result, designing wall components that have good thermal insulation properties is essential to reduce the transmission heat losses from buildings. Achieving low thermal transmittance value in walls (U-value < 0.2 W/(m^2·K)) has become a common regulatory in Swedish buildings [5]. Wood material contains crystalline structure of cellulose chains which may be amended due to temperature variations, this shall result in major changes in physical and thermal properties of the wood which may affect its ability to conduct heat [6]. Manufacturers are continuously developing technologies to maintain the theoretical U-value of walls by proper modification of insulation material, wall layers, moisture content and type of heat exchange of the structure.

The total U-value of buildings located in low-temperature regions such as Sweden varies [7]. Total U-value is the sum of thermal transmittance values for building elements. This variation in the total U-value of the building is due to change in thermal properties of the building elements such as, walls, windows, floors…etc. Since heat loss through walls accounts for the largest portion of the total heat losses through the building envelope, providing wall component with appropriate thermal transmittance properties shall have a positive impact on the thermal performance of buildings and thus reduce the energy demand. The timber wall component has relatively low U-value compared to other material such as, concrete which helps to maintain the heat indoor in cold climates. However, the adaptivity of the U-value for the timber when subjected to different temperature differences shall be evaluated. An increase in the U-value when a higher temperature difference occurs implements higher heat losses through the wall component. On the other hand, a reduction or tolerant increase in the U-value of the wall when subjected to extreme outdoor temperatures implements good insulation properties of the wall component.

Moreover, the temperatures in the Scandinavian region can vary significantly during a short period of time. It may drop rapidly at night when the solar radiation is absent and increase vice versa during the day. Hence, it is important to analyze the behavior of the wall component under sudden temperature changes by measuring the average U-value during the test and calculating the deviation from the accepted reference value. The accepted reference value is the U-value provided by the manufacturer data. Also, analyzing the thermal inertia of the wall component by measuring the surface temperatures and the time it takes to reach close value with air temperatures. The dynamic testing is not following any standard and is developed from the basic knowledge about heat transfer concept.

The project started by performing measurements on specimens with known thermal properties to determine the reliability of the enclosure. The purpose of this experimental work is to analyze the heat transfer mechanism in timber wall component. Measuring the U-value of the wall at different temperatures and performing dynamic variation tests. This shall result in clear insight on the adaptability and ability of the wall component to withstand extreme temperatures variations. An method to calculate the U-value of the specimen based on Fourier law (equation 4.3) of heat conduction is followed, determination of the power dissipated through each test component and reverse the calculation to obtain the U-value for the wall component. Along the test experiments which took period of one month, moisture content in wood and relative humidity were recorded in the warm chamber with variation in time.

1.1 Aims & Objectives

The main aim of this experimental work is to investigate the potential to use the existing climate chamber at Dalarna University to evaluate heat transfer coefficients of real walls with thickness up to 300 mm with respect to uncertainties and repeatability related to this type of testing. In addition, the aim is to determine how the effective heat transfer coefficient (U-value) of a timber wall component (300 mm), the influence of the outdoor temperature level and if the outdoor temperature varies in cycles.

These following objectives are set to fulfill the aim of this project:

- Reviewing the national and international standards that define the method to determine the thermal properties of the specimens.
- Daily laboratory work and frequent meetings with the supervisor due to continuous developments in the scope of work and emerging issues.
- Preparation of calibration panels with thicknesses equal to the thickness of the intended test wall specimen, 200 mm and 300 mm respectively.
- Perform software calculations on the temperature data to evaluate the uncertainties of the results.
- Background research on the subject of heat and moisture transfer in wooden walls.
- Prepare the climate chamber to withstand the 300 mm massive wood wall testing.
- Perform heat transfer tests on the massive timber wall components and determine the heat transfer coefficient.

2 Literature Review

2.1 Heat transfer in walls

Heat transfer through walls is a complicated mechanism that consists of combined processes of conduction, convection and radiation. According to the international standard (ISO 8990) [8], the measurement account for the total heat transferred from one side of the specimen to the other side provided the difference in the temperatures between both sides, regardless of the separate processes of heat transfer. Hence, when certain property is to be further analyzed, test results will help analyze the effect of using specific insulant on that property.

The factors that affect the thermal transmission properties are [8]:

- Wall specimen type and dimensions
- Boundary conditions
- Direction of heat transfer
- Temperature, and temperature differences
- Air velocity and relative humidity

The temperature difference between the wall surface and the surrounding air causes convective air currents to occur which results in heat transfer from air to the wall surface, or vice versa. When the air hits the surface of the wall the air velocity is reduced; the air motion becomes streamline, heat is transferred by conduction from the streamlines to the solid surface of the wall in a laminar motion. Heat is also transferred to the surface by radiation. The magnitude of the transferred heat in each process depends on the absolute temperature, the temperature difference, and the character of the surfaces and surroundings. For instance, the present of reflecting surfaces such as, clean-bright metal, shall reduce the amount of transferred hear by radiation means at ordinary temperatures.

In this experimental work, the one-dimensional steady heat conduction is considered, the heat transfer due to convection and radiation were not considered. During winter heat is continuously transferred to the outside of the building through the wall component. The assumption is that the heat lost is in the normal direction of the wall, and the transfer in other directions is ignored. Isothermal wall components are where the temperature difference between the top and bottom as well as right and left is equal to zero. Heat is transferred due to the temperature gradient between both sides of the wall component, the small distance between the inner and outer surfaces governs the transfer in the normal direction of the wall. Steady-state heat transfer occurs when the temperature difference between both sides of the building remain constant. In heat transfer, there is only energy conservation where no added heat is generated. Figure 1.1 illustrates the direction of heat flow which is due to the temperature difference.

$$\begin{pmatrix}\text{Rate of}\\ \text{heat transfer}\\ \text{into the wall}\end{pmatrix} - \begin{pmatrix}\text{Rate of}\\ \text{heat transfer}\\ \text{out of the wall}\end{pmatrix} = \begin{pmatrix}\text{Rate of change}\\ \text{of the energy}\\ \text{of the wall}\end{pmatrix} \qquad \textit{Equation 1.1}$$

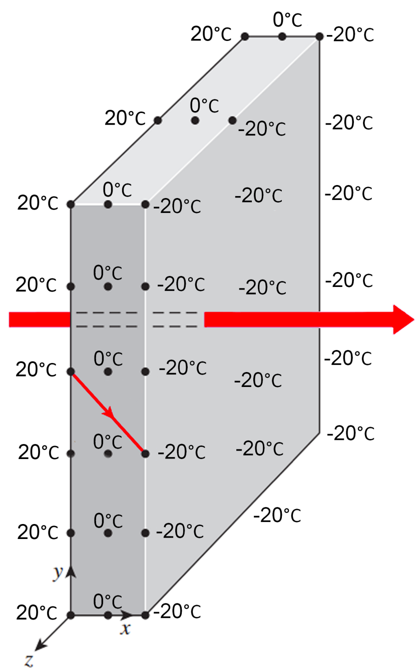


Figure 2.1. Heat flow direction in the wall component from the warm to colder side.

The total resistance of the wall is equal to the sum of the resistance of the wall component plus the surface resistance with surrounding air from both sides of the wall. The temperature difference needed between the surfaces and surroundings to produce unit rate of heat flow through unit area is quantitatively defined as thermal resistance per unit area, the direction of heat flow is normal to the unit area. The definition of the conductance per unit area which is the reciprocal of the latter, is the rate of heat flow produced by 1 K temperature difference between the system boundaries. The two other important quantities are thermal conductivity and transmittance. Thermal conductivity is material property and defined as the rate of heat flow through unit area when the temperature difference is 1 K in the perpendicular direction of to the area. Transmittance is the reciprocal of the total resistance from air to air and it's described as the overall heat transfer from air to air.

The quantities defined above endures variations in their values with the change in the mean temperature and the temperature differences. However, the amount of this variation is small and therefore for the sake of simplicity these quantities are considered constant and the change is neglected. The variation is taken into consideration if it's necessary in the solution of the actual problem. Furthermore, there are very few studies that investigates the change in these quantities such as, conductivity and the ones found are subjecting the material to high (warm) temperatures. Unlike this study where the material is subjected to low temperature ranges. Hence, some explanations in this research are derived from the knowledge about the heat transfer and might be subjected to further questioning.

2.2 Calibration and uncertainty analysis

Calibration is a method to calibrate a sensor or a measured quantity to a true value. The remaining expected deviation after a calibration determines the accuracy of the results in experimental testing, it is important to maintain the instrument accuracy. The main principle is to exclude the factors that increase the potential for inaccurate results. Uncertainty analysis of the climate chamber determines the amount of expected deviation between the measured and calculated temperatures.

The usual procedure of the calibration is to perform the experiment on test samples with known values (properties), then construct a relationship between the results of the test sample and the results of the actual test object. Different test samples can be used to establish a correlation and gain an understanding of the instrument operating interval. However, in the case of the climate chamber, it may not be possible to prepare and test several test samples due to the time and effort constraints. Hence, the acceptable range of values must be defined before starting the calibration.

Laboratories base their calibration analysis on national and international standards which are quite relevant for climate chambers. The differences are in the degree of details and purpose of the experiment [9]. These standards provide guidance and specify the technical requirements needed to assure reliable and accurate calibration results.

In order to perform uncertainty analysis some of the following parameters shall be determined to assess their influence on the results [9]:

- Temperature and humidity dimensional distribution in the chamber.
- The steady state of temperature and humidity readings.
- Radiation effect due to the temperatures difference on the exterior wall of the chamber and air temperatures, which will affect the emissivity of the temperature sensors. This might have a large influence on measured temperatures.
- Time-dependent temperature differences between air and moisture load within the chamber.
- Sensitivity temperature changes in the air.
- Effect of the ambient conditions.
- Resolution of indicators.

The standard used for the calibration analysis and measurements of specimen U-values in Sweden is, SVENSK STANDARD SS-EN ISO 12567-1:2010 [10]. Thermal performance of windows and doors- Determination of thermal transmittance by hot-box method- Part 1: complete windows and doors. This standard is based on the INTERNATIONAL STANDARD ISO-8990 [8].

The description of the apparatus, measurement technique, and the required data is provided. The standard mentions the two alternative methods to perform laboratory measurements on homogeneous specimens for calibration and validation. The calibrated hot box (CHB) and guard hot box (GHB). In the guarded hot box (see figure 2.1), the area under the guard box covers the test specimen and some parts of the surround wall. However, in the calibrated hot box, the area only covers the test specimen hence the total power generated passes through the test specimen only. Both methods are applicable for large vertical specimens such as walls and for horizontal specimens such as, ceilings and floors.

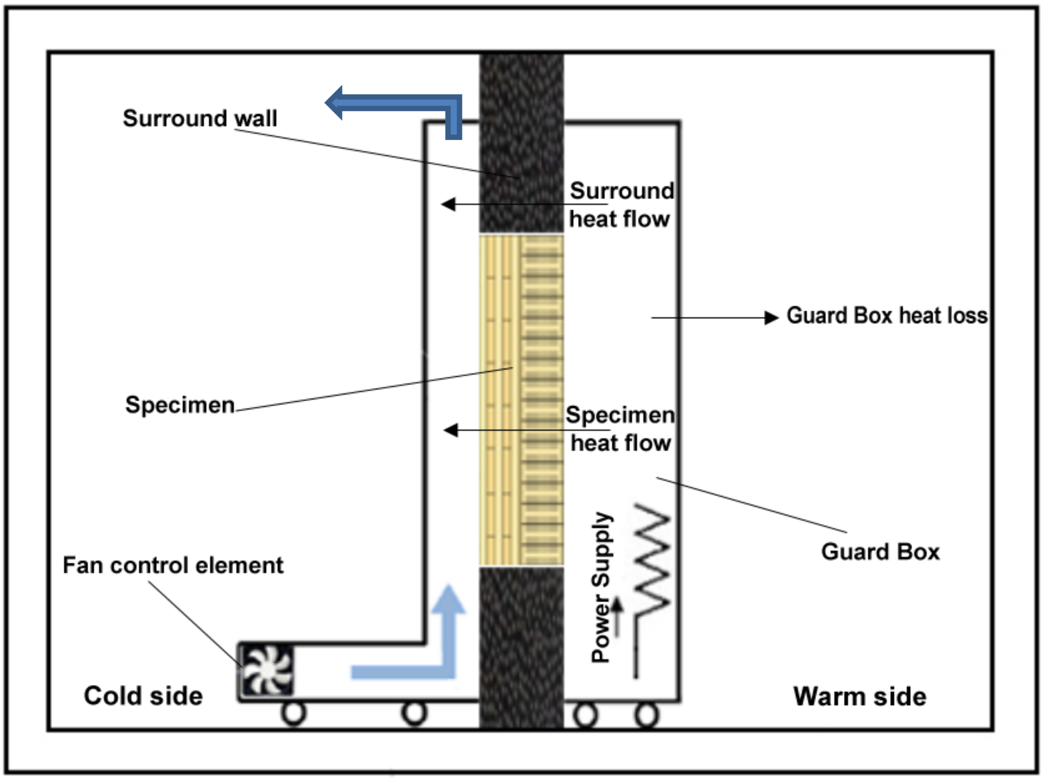


Figure 2.2. GHB climate chamber configuration for a set up according to the guard box principle [8].

However, the international standard does not provide the requirements for special components such as, windows which require an additional procedure. Furthermore, the effect of moisture transfer on the heat flow through the specimen is excluded.

The principle is to perform measurements on two or more calibration panels that have known thermal properties i.e. conductivity. Then, calculation of the surface coefficient of the heat transfer (conductive components) on both sides of the calibration panel. These tests shall ensure that adequate test conditions are met by checking the reliability of the surround panel heat flow (UA-Value) with respect to the known heat transfer coefficients of the calibration panel. Furthermore, by means of interpolation or analytical iteration procedure, the measurement results of wall testing are corrected to standardize the surface heat transfer coefficient.

2.2.1. SP calibration

A previous calibration analysis on the climate chamber was performed by SP at Dalarna University [11]. The calibration experiment was according to [8]. The experiment used two glass sheets with different thicknesses (20mm and 30mm) as the calibration panels. The equations from the standard were inserted into excel evaluation sheet called "Specimen Analysis.xlsx". The measurements are inserted into this file, the plot between the thermal resistant value of the calibration panel and the heat flux through will define the uncertainty of the measurements. Moreover, the file provides sheets for calculation of the actual U-value of the test object.

The calibration procedure for the thermocouples is made separately for the cold and warm side. The thermocouples shall be placed in a water bath for the warm side and glycol bath for the cold side where beater motor provides mixing for the baths. To obtain the thermocouples readings, the temperature of the water bath should stabilize with the temperature of the warm chamber. Then, five readings are obtained with respect to the same time interval as Agilent data logger recordings and inserted into an excel sheet where calibration polynomials are developed. The acceptable deviation of the calibrated and measured temperature shall be less than 0.3 K.

Steady state condition considered by SP
In this calibration, the stability of the power generated by the heater in the guard-box is the indication that defines the steady-state. However, according to [11], and at the time of the experiment, the power supplied was interrupted due to instruments incompatibility and the measurements were discontinuously appearing. Hence, the alternative approach was to use the temperature measurements to define the steady-state conditions which also was hard due to small variations between the measurements.

Generally, the time needed to reach steady-state condition depends on the thermal inertia of the test specimen. Material properties such as density, thermal conductivity, heat capacity and material thickness [7].

2.3 Timber in wall components

Walls are essential elements in the building envelope and they are important for maintaining the energy balance within the structure boundary, using the proper material will result in higher thermal comfort and enhanced indoor environment. Wood buildings are widely used in Sweden, the oldest buildings are preserved and date back to the 13th century [12].

Nowadays, wood construction uses advanced technologies and focuses on prefabrication which will reduce the construction time, detailed design analysis to improve the quality and guarantee the reliability of the product. Using timber material for external walls is an environmentally friendly choice, it will reduce energy demand and works as high efficient insulation material. Typical exterior timber wall configuration consists of manufactured timber board in the outer cover panel and plaster in the inner panel.
Heating is responsible for the higher energy demand in residential buildings in Sweden [12].

Hence, to achieve high energy efficient building, heat losses must be minimized and well analyzed. Walls take a large portion of the total heat losses in buildings, using adequate insulation material will lower the heat transferred through the walls and help to keep balanced moisture content between two ends of the wall.

2.3.1. Indoor Climate

Providing adequate indoor climate by controlling the temperature and relative humidity can influence comfort, health and productivity. According to Simonson [13], people spend about 90% of their time indoors. Hence, more consideration has been given nowadays to improve the indoor quality by analyzing the interaction between the building materials and the indoor air. Also, several studies on the ability of building materials to passively dampen the changes in temperature and relative humidity have been conducted. Many approaches, systems and materials have been investigated to minimize the daily and annual variations in indoor climate.

The promising approach is to use massive wood layers in the floor and wall components due to its ability to pump, store and release moisture to the surroundings. The hygroscopic material, when interacted with the indoor climate, tends to absorb moisture when the relative air humidity is high and releases moisture back to the air when relative humidity falls [14]. This will enhance the thermal comfort by providing under pressure indoors in summer season [14]. Furthermore, the accumulated water on the porous of the hygroscopic material will enhance the insulation and reduce the heat losses to the outside of building in winter and lower the sum of heat gains in summer [14].

Moisture and temperature fluctuation

Nowadays, an increase in the use of massive wood components in the floor and wall system can be noticed. The hygroscopic structural material has the ability to buffer the moisture and heat fluctuation in the indoor environment which will passively enhance the thermal comfort and result is lower energy demand. Hameurya and Lundström [15] have conducted an experimental study on four occupied apartments that consists of large massive wood surfaces (walls, floors). The study analyzed the interaction between the indoor exposed massive wood material and the indoor climate by assessing the effect that the exposed massive wood has on regulating the relative humidity and temperature indoor.

The study results showed the effect of considering large wood surfaces in buildings on factors such as, indoor thermal comfort, energy requirement, material properties and thermal and moisture transfer. The values were verified with ASHARE standard 55.

According to the authors, measuring temperatures at different depths is necessary in heat transfer analysis. Hence, the T-type thermocouples have been inserted at different depths in the massive wood wall to measure the temperature fluctuation. The relative humidity is measured in the outside and inside of the building based on the capacitive technology, the moisture content in the wall is measured instantaneously at different depths using moisture meters. The measurements were taken in summer and winter on an hourly basis for a period of one week.

The researchers have confirmed previous findings of [13] which stated that using large surfaces of exposed wood material will result in dry indoor conditions in winter compared to other type of building materials such as, concrete. The dry indoor conditions occur when indoor relative humidity is lower than the limit specified in the standard which is 25 %. However, for the summer week, the humidity remains within the limit of the acceptable range and does not exceed the limit of 60 %. Also, the study mentioned that using massive wood surfaces in buildings shall reduce the annual energy demand.

According to [16], the purpose of the computation shall be identified to a proper selection of the values of the properties. The values selected for insulation level computation differ from the values selected for effective heat capacity level computations, the ones presented in the Swedish building code are based on the heat capacity level.

Furthermore, the authors have described the diffusion mechanism of moisture transfer in the wood material which is divided into three main processes: water vapor diffusion in the lumen, diffusion through the pit chamber and bound water diffusion within the cell wall of the wood material [14]. This research assumed that moisture is transferred through the cell cavities without any capillary forces of free water acting on it, this is considered as the hygroscopic moisture range. The governing moisture transfer process under the hygroscopic range is bound water diffusion within the cell wall of wood material [17-18].

The wood material when interacted with the indoor environment endures variations in moisture content and temperature to maintain the energy balance within the structure. When the variation of humidity reaches approximately one third the variation of the indoor climate in 24 hours period, the presented distance is known as the moisture penetration depth. According to previous studies done by [15-19], the penetration depth of moisture in the wood material is estimated at around 3 mm during daily humidity fluctuations. The moisture is stored in the wood material a few millimeters behind the surface which means that the capacity of the hygroscopic wood medium to store moisture is partly activated in the experiment by [15]. Furthermore, when increasing the air exchange rate indoor the moisture content within the wood material decreases during the daily period.

The group of scientists has concluded that using a hygroscopic material in the building envelope shall provide the adequate indoor environment without the need to increase the ventilation rate. Also, due to the wood dimensional instability, the designer must consider balancing the moisture content inside the wood material and maintain it under the fiber saturation point. The results also illustrated that the variations in the indoor relative humidity levels between summer and winter are approximately 30%, and this change causes a change of 4 % in the moisture content in the wood wall.

2.3.2. Influence on heating and cooling demand

The wood material has a relatively low conductivity compared to other building material such as concrete, which reduces the heat loss to the outside of the building. According to Hameury [4] as well, the high thermal inertia of the massive wood tends to reduce the temperature fluctuation indoor which will result in lower heating/cooling demand. The massive wood is classified as heavyweight material in the building envelope due to its high thermal inertia. However, it shows lower specific heat requirements than the low weight insulation materials. Accordingly, it can't be concluded that low ventilation rate is needed since the capability of wood to buffer the temperature indoors is higher than humidity.

Latent Heat of sorption phenomena

The latent heat is the heat released when water condenses and changes the state from vapor to liquid. The vaporization latent heat of water in a typical indoor environment temperature which ranges between 10 - 30 C° varies between 2477.7 to 2430.5 J/kg [20]. However, in order to measure the total heat of sorption H_m released when water content accumulates in the wood wall porous, the differential heat of sorption ΔH_s has to be added to the latent heat of vaporization of water, this is due to the enthalpy of absorbed water is less than the one of liquid water and the differential heat of sorption, the theoretical equation of the total heat of sorption is shown below [20].

$$H_{\mathrm{M}} = H_{\mathrm{V}} + \Delta H_S \qquad \textit{Equation 2.1}$$

Kraniotis and Langouet [20], have investigated that using wooden surfaces in buildings will reduce the heating demand due to the latent heat of sorption phenomena in wood, the paper presents quantification of the amount of heat loss compensated by released sorption heat from wooden surfaces [21]

The experiments on the test house were for period 24h and divided into two phases, humidification for the first 8h and drying for the rest of the period. The internal volume is approximately 8.7 m^3, i.e. 2.44 m × 1.44 m × 2.5 m. The indoor parameters such as temperature, RH and the moisture content at different depths were continuously recorded. Also, the latent heat of sorption released is calculated based on the state of art equation below.

$$H_{\mathrm{s}} = \frac{S \cdot \rho_{\mathrm{m}} \cdot d_{\mathrm{m}} \cdot \Delta MC \cdot H_{\mathrm{v}}}{t} \qquad \textit{Equation 2.2}$$

where H_{s} is the heat of sorption [kWh] released or absorbed within a time interval t [s], S is the surface area of the hygroscopic structure [m2], ρ_{m} is the density of the hygroscopic material [kg/m3] , ΔM is the increase/decrease of the moisture content in the material in the volume of interest [%] and d_{m} is the penetration depth [m].

The researchers have set the area of the hygroscopic structure equal to the area of walls and ceiling since these are the components which will absorb the moisture. The penetration depth was set to 10 mm, the change in the moisture content within the 10mm was equal to 0.6 % during the humidification phase.

The latent heat of sorption is found to be 0.3 kWh during the humidification phase. This heat that is released is relativity small amount. However, by calculating the conduction heat losses through the building envelope for a period of one day and at ΔT=15 K. It was found that the latent heat of sorption compensates for approximately 30% of the heat losses.

Penetration Depth
It can be clear that the penetration depth considered by Kraniotis and Langouet [21], is higher than the one estimated by [19-20] previously. The penetration depth depends on the type of hygroscopic material used and how it withstands the variation in the indoor climate. A clear method to calculate the penetration depth for semi-infinite wood material was presented by Arfvidsson [22]. The semi-infinite solid model is facing the heat flux and the change in the RH on the top exterior surface, and the temperature thermocouples are placed on the same exterior surface [23]. Figure 2.2 represents a semi-infinite material model with the thermocouples placed on the surface facing the heat flow.

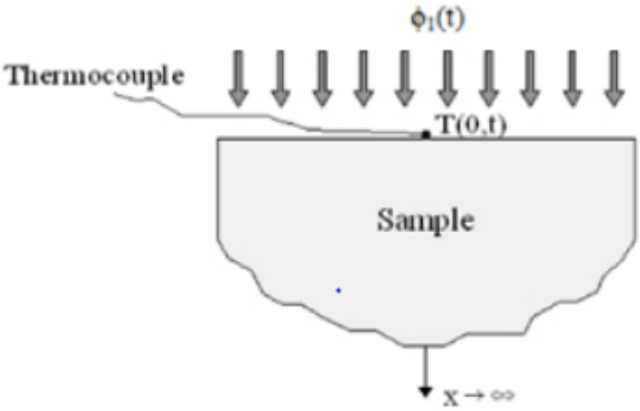


Figure 2.3 Semi-infinite material model subjected to heat flux [23].

The penetration depth is determined by defining the amplitude, the total difference between the maximum and minimum moisture content at each point x through the depth of the wood material. The difference decreases at deeper points in the material. When the amplitude value shows a difference of less than 1% at a significant point in the material, the distance between the point and surface of the material is equal to the penetration depth.

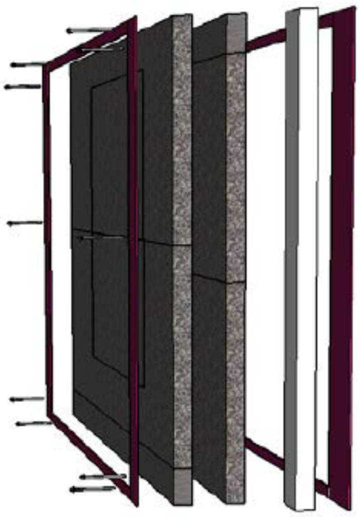
3 Experimental setup

The experimental full-scale test room CLIMATE CHAMBER is located in the machine lab at Dalarna University. The main principle is to provide boundary conditions such as extreme temperatures and for the wall specimen to be tested. Climate chamber consists of warm and cold chambers and a hot box according to figure 2.1, the warm side is accustomed to simulate indoor climate and the cold side simulates outdoor temperatures. The dynamically controlled temperatures are variable between -22 °C minimum and 35 °C maximum. The installation method for the equipment is based on the file provided by Persson [11], which is based on the Swedish Standard [10]. The climate chamber consists of the following components; separation wall, guard box, cold side baffle and power supply element.

The separation is the wall separating the cold and warm side of the climate chamber. The separation wall have an opening where the test specimen can be inserted, the original thickness of the separation wall is 200 mm (**Error! Reference source not found.**), but it was also extended to 300 mm to test a 300 mm timber wall. The material used in the wall is BeWi grey EPS S100. The EPS sheets are supported by 12 mm thick plywood at the corners to enhance stability and minimize air gaps. An opening is constructed in the separation wall to place the test wall specimen, the hole was in the center with respect to the warm guard box, the size of the gap is approximately 2.12 m^2. , the accuracy of the gap dimensions is determined according to the Swedish standard [10]. The dimensions and specifications for the single EPS layer that were provided from the manufacturer are shown in table 3.1.

Table 3.1. EPS material specifications from the manufacturer.

BeWi Grey EPS	
Quality	S100
Thickness	100 mm
Sheet size	2400 mm x 1200 mm
Thermal conductivity	0.031 W/(m·k)
Density	Ca 20 kg/ m^3



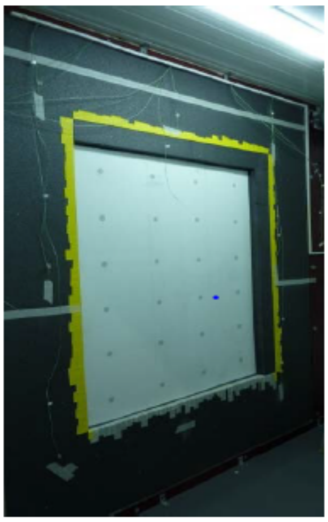


Figure 3.1. To the left typical configuration of separation wall with two layers of black EPS compressed between wooden frame, the white pillar is to enhance stability of the separation wall. To the right a photo of the separation wall from the warm side with a specimen mounted [11].

The guard-box in the warm side consists of 40 mm thick Polyurethane and the surface is covered with a sheet made of painted steel. The height of the guarded box is 220 cm and the width is 240 cm. The edges are sealed with rubber for air tightness to focus the heat flow through the specimen, the inner compartment is disconnected by baffle wall which is the main component that faces the test specimen and responsible for the occurrence of the natural convection, the radiator element is located behind the baffle at the lower end. Figure 3.2 shows a diagram of the guard box and the cold side baffle.

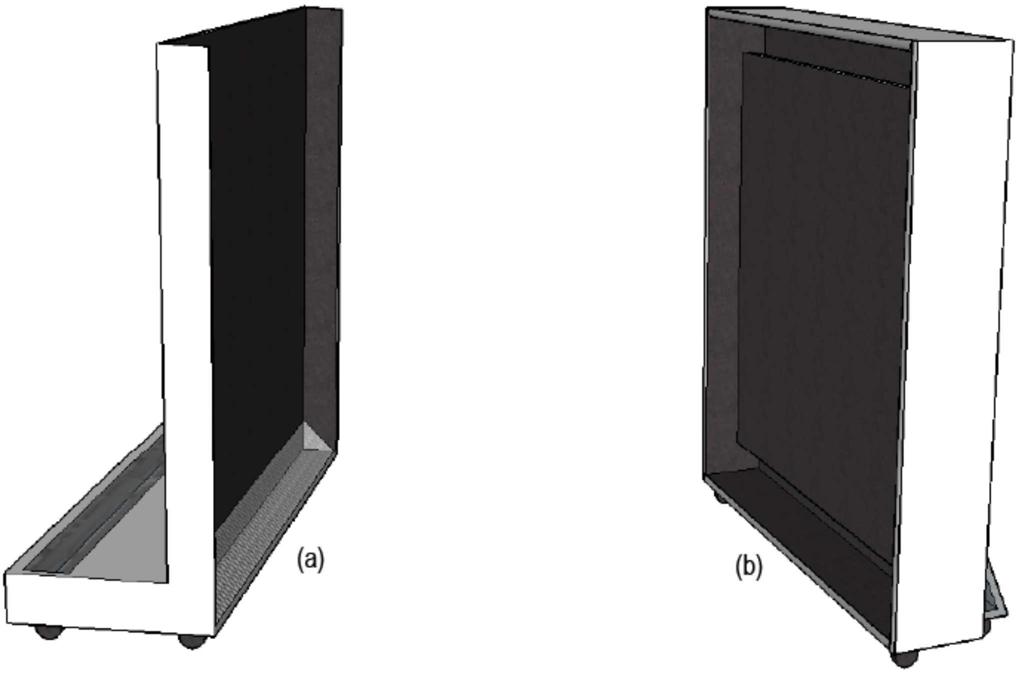


Figure 3.2. (a) The cold side baffle, radial fans allow the air to flow vertically along the test specimen. (b) Guard-box of the warm side with baffle wall inside, sealed at the edges to reduce heat losses [11].

The temperature measurements are according to SS-EN ISO 12567-1:2010. The standard specifies the number of measurement points and the position of each thermocouple.
The thermocouples are K-type with a diameter of 0.51mm. The air temperatures inside the guard box are captured from thermocouples hanging along a horizontal wire on the guarded-box. All thermocouples are wired to the terminal blocks (figure 3.4) of the data logger on the warm side. Figure 3.3 shows an image of the two types of thermocouples.

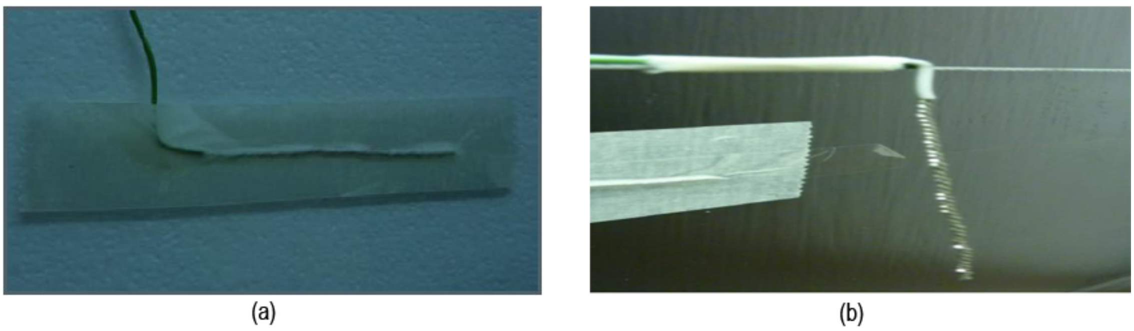


Figure 3.3. (a) The thermocouple taped to the surface with paper masking tape to capture the temperature in the surface of the baffle. (b) The hanging sensors to capture the air temperature.

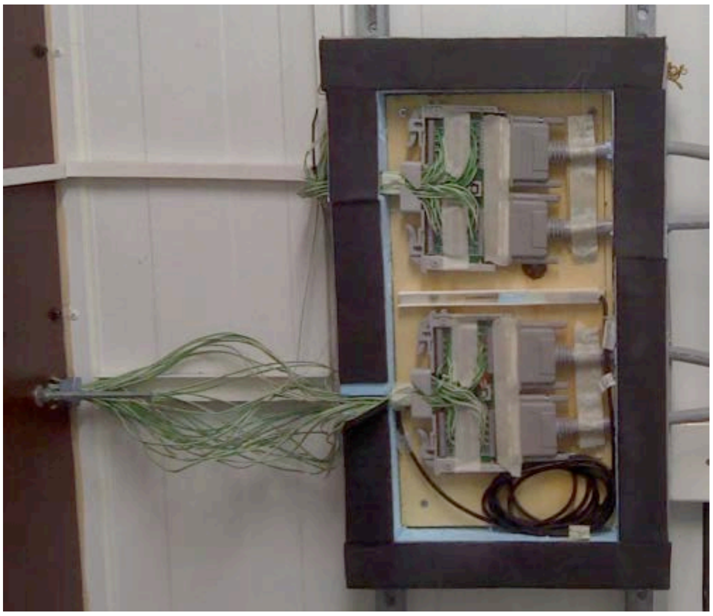


Figure 3.4. Terminal block located in the hot-chamber.

The locations of sensors are according to the Swedish standard [10]. There are 6 vertical layers in addition to the surround panel reveal where temperatures are captured. Figure 3.5 illustrates the locations of sensors. A fan element was positioned facing the terminal block to lower the temperature of the wires and minimize the effect of the heat generated on the air temperature.

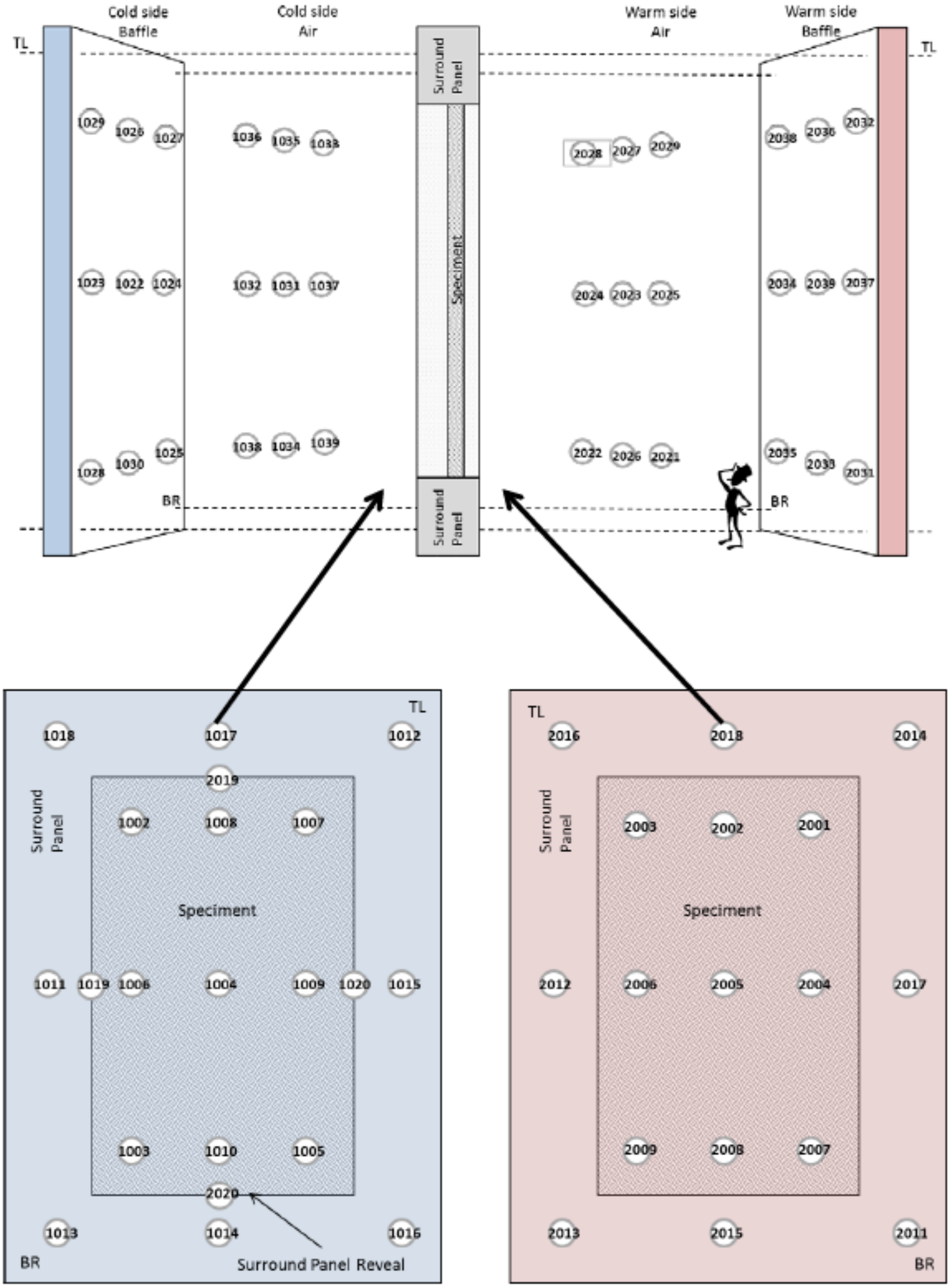


Figure 3.5. Sensors positions [11].

From the graph above it is clear that the main sensor positions are [11]:

- Cold side surface temperature of baffle.
- Cold side air-temperature between the baffle and the separation wall.
- Cold side surface temperature of surround panel.
- Cold side surface temperature of surround panel reveals.
- Warm side surface temperature of the surround panel.
- Warm side air-temperature between the baffle (inside guarded-box) and separation wall.
- Warm side surface temperature of baffle inside guarded-box.

The cold side baffle is responsible for directing air flow to flow vertically along the test specimen, the baffle is not sealed at the edges since it has no thermal function. According to the Swedish standard [4], an air-flow sensor shall be installed in the midway of the flow-path, this sensor shall control the air-velocity supplied by the fans to maintain the specified speed, which is higher than 1.5 m/s. The thermal air-flow sensor (Testo 0635 1024) which is connected to stand alone instrument called Testo 480 Multi-instrument. In this study, the air flow sensor was not installed, but the cold side baffle was attached with fan operation to the test specimens during experiments to ensure more uniform distribution of the temperatures on the cold side surface.

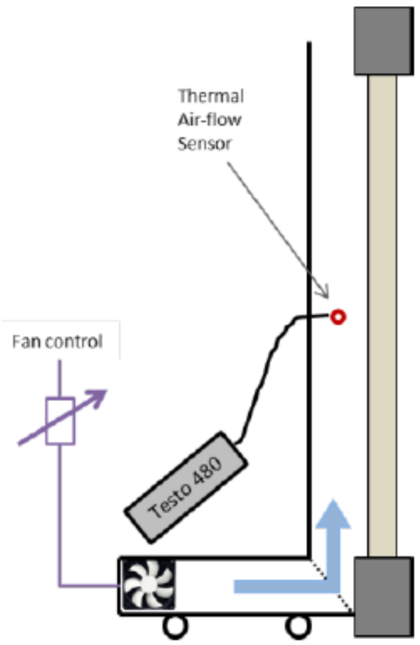


Figure 3.6. Fan control element [11].

Power in the warm side is generated by an electrical heating radiator that is positioned inside the guard-box. In order to maintain steady state heat flow in the guard-box, the radiator must generate power equal to the power lost through the specimen and surround wall. The temperature sensor PT100 is placed approximately 35 cm above the radiator. Hence, The PID regulator receives the measured temperature from the PT100 sensor and controls pulse-width modulation of the power provided to the radiator. Power is supplied at small time intervals to reach to the average power needed and the maximum value that can be supplied is 1500 W.

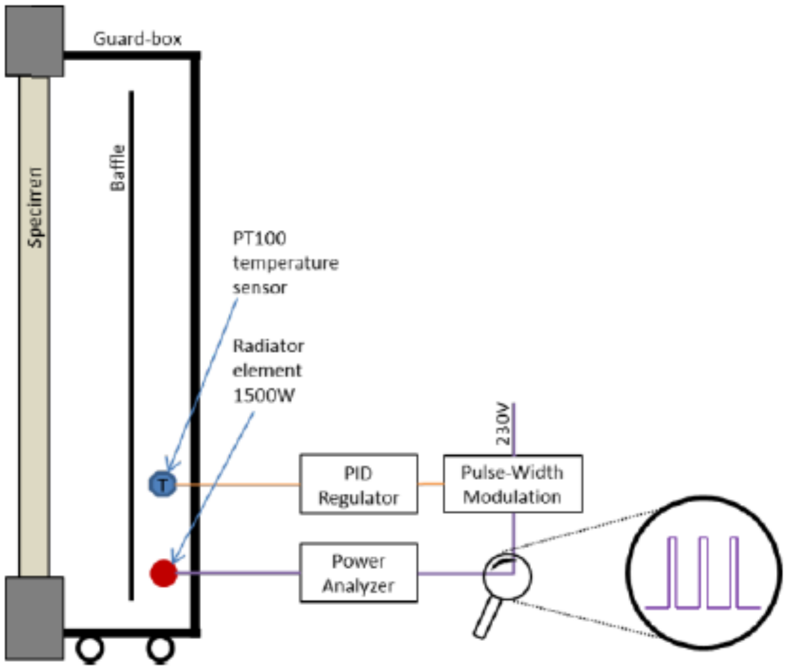


Figure 3.7. Radiator element inside guard-box [11].

Figure 3.8. YOKOGAWA 310WT power analyser.

According to the Swedish standard [8], the electric power supplied to the radiator should have an accuracy of ±1 %. To achieve this accuracy, YOKOGAWA 310WT power analyzer is used, it minimizes the voltage drops along the supplying lines.

Note that when adjusting the control temperature to for example 20 °C within the guard-box, the control system will regulate for 20 °C at the position of PT100 sensor. Hence, the temperature may vary at other locations within the guard-box. Also, due to the large size of the radiator, the needed maximum average power for calibration is less than 120 W. Moreover, the uncertainty of the actual average power measurements is increased because of the pulse width modulation and this will prevent data collection from the Agilent data logger and it will be obtained from a separate measurement file.

Installment of test specimen for EPS tests (200 mm)
The standard EPS sheet that is described in table 3.1 was obtained to be placed in the separation hole, EPS is made into shapes that will fit inside the hole separating the cold and hot side. Saw was used to cut EPS and then the pieces were combined using glue, the parts were kept for three days in a rigid position to enable the glue to reach its maximum strength. The main issue was trying to fit EPS inside the hole since the edges of the hole were irregular and uneven, a trimmer was used to trim the edges of EPS and with a couple of trials, EPS was placed successfully in the hole. Mineral wool was stuffed surrounding the edges of the test specimen to make it airtight and reduce the heat loss from the

boundary which shall affect the results. Then, the sensors were attached to EPS according to the specification in figure 3.5, the tape used for attachment of sensors is low thickness adhesive paper tape with high emissivity (>0.8) to enable the sensors to produce adequate electrical fluxes and result in more accurate reading.

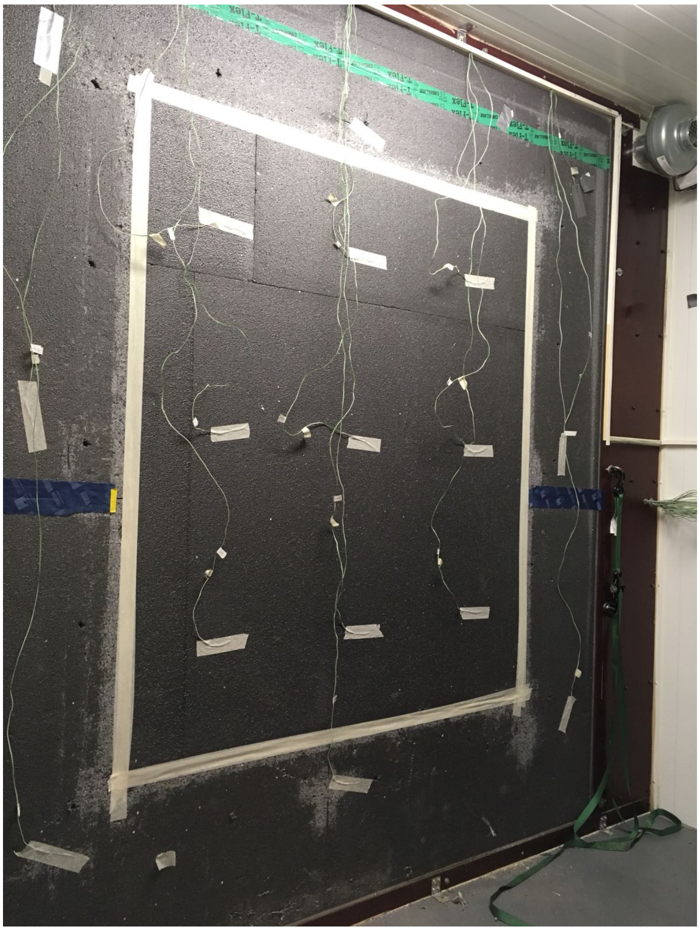


Figure 3.9. EPS specimen placed in the surround wall.

Installment of test specimen for EPS tests (300 mm)

Determination of the reliability of the climate chamber to perform tests on walls with a thickness higher than the standard shall be investigated, to examine the possibility of testing 300 mm massive wood wall, calibration analysis on test specimens with the same thickness shall be done.

The standard thickness for the surround wall is of 200 mm of EPS which is used to test specimens with this maximum thickness. In order to test walls beyond this thickness, an extra layer of 100 mm EPS was placed installed on the surrounding wall and the on the calibration specimen. The wood frame that supports the surround wall is fixed with strong nails, the procedure to remove the wooden frame to place a new one with 300 mm thickness requires manpower and time to be done. Hence, the decision was to attach an extra layer of EPS above the existing layer using plastic nails and stuff the mineral wool in the air gaps to reduce the air leakages.

Figure 3.10. extra 100 mm of EPS is attached to the surround wall from the warm side.

Figure 3.11. Plastic nails used to attach the extra 100 mm EPS layer.

4 Methods

4.1 Preliminary checks and adjustments

Before starting the experimental work, an investigation into the possibility of performing an accurate calibration test procedure was performed. The climate chamber was verified for its reliability and accuracy. Manual inspection on the machine equipment's was performed to detect any operational defects or failures. Also, checking the compatibility of sensors and the data-logger was done to ensure systematic practical work and minimize the risk for errors.

4.1.1. Checking sensors readings

In order to proceed with the calibration, all temperature sensors were tested for their accuracy and reliability. After locating the sensors and labeling them, the climate chamber was kept running for a period of three days to ensure that the steady state condition on both sides is met. The climate chamber was turned on and an observation on the deviation between each sensor (cold and warm sensors) reading is made. The readings obtained showed a large deviation from the true value for several sensors which implied the need for calibrating the thermocouples. This deviation was found to be caused by the inaccurate calibration polynomials for each temperature sensor in the data-logger. Studying the original calibration coefficients, it was found that several sensors were compensated more than what would be possible for a correct Thermocouple. The reason was found to be that several thermocouples were not properly connected to the datalogger. The compensated sensors were separated from each other and fixed back to the terminal block again.

Calibrating the reference sensor

The solution for deviated sensors was to perform calibration on the main reference sensor instead and determine the calibration polynomials for it. The calibration polynomials are coefficients inserted in the data logger to account for the uncertainties and produce the calibrated values. The measured temperatures are adjusted based on the equation. The location of the reference sensor (1001) is shown in the figure 4.1.

Figure 4.1. Location of the reference sensor in the terminal block.

$$T_{\text{corrected}} = T_{\text{meas}} + [\![k_2.(T_{\text{meas}})^2 + k_1.T_{\text{meas}} + k_0]\!] \qquad \textit{Equation 4.1}$$

The reference sensor is placed in a Fluke dry well calibrator with specified accuracy of ±0.1C, but repeatable comparison with a calibrated PT100 sensor indicate that the repeatability and accuracy is higher than specified. calibration points were taken at 15 °C, 20 °C, 22.5 °C and 25 °C accordingly. The data logger kept operating and the period for each temperature set was about 15 minutes long. Then, the readings obtained for each temperature set are compared with the true value and the difference is calculated. The calibration polynomials are developed by plotting the average differences against the true set-temperatures in Kelvin. The function of the curve yields the value of the coefficients accordingly. Figure 4.2 shows the calibration curve for the reference sensor and table 4.1 states the calibration polynomial values.

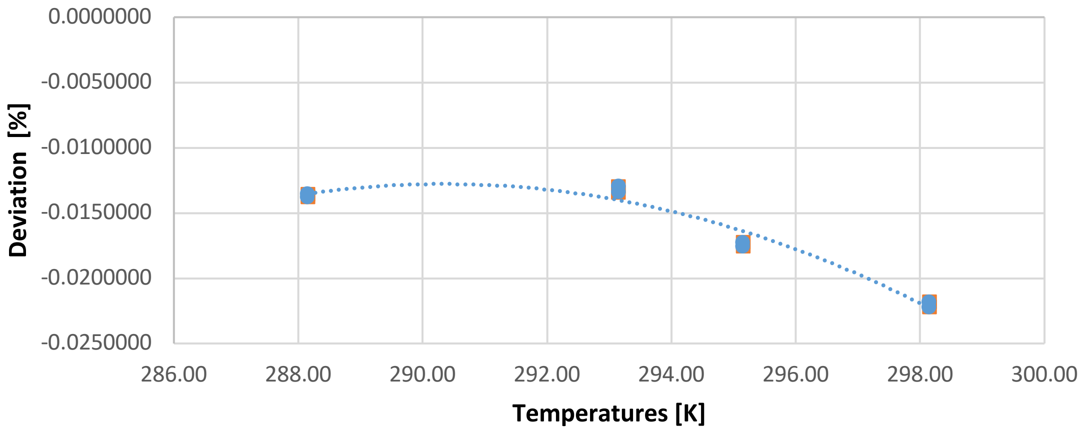


Figure 4.2. Calibration curve for the reference sensor.

Table 4.1. Reference sensor calibration coefficients according to equation 4.1.

Coefficients	***Value***
k_0	-13.1385370648
k_1	0.0904170892
k_2	-0.0001557101

The accuracy of the obtained calibration polynomials was then confirmed theoretically by equation 4.1 above. The resulted difference between the measured and corrected temperatures was relatively small (0.014 K) which indicates the reliability of the calibration polynomials.

Then, the calibration polynomials were inserted into the log-file for the reference sensor and the data logger was turned on. The results show that the difference between the calibrated temperatures and measured temperatures in the data logger was equal to the theoretical difference which is 0.014 K.

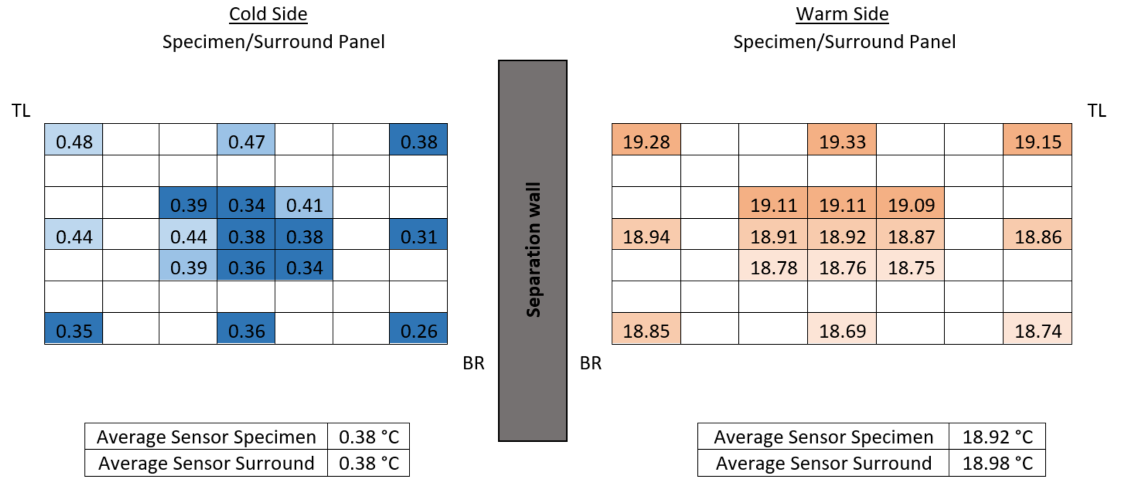


Figure 4.3. Average readings for each sensor and the total average all sensors for 200 mm calibration and ΔT =20 K.

Figure 4.3 illustrates the set of average temperature readings for each sensor at one temperature difference range ΔT =20 K, 0 °C in the cold chamber and 20 °C in the warms side. This representation helps in the determination of deviated sensors from the group and detecting failures in sensors by analyzing patterns when repeating the tests. However, most sensors give close values to the average group value ± 0.3 °C which indicates the consistency of the recorded measurements [8]. Due to time constraints it was decided not to do further calibration of the individual thermocouples.

4.1.2. Defining guard box heat losses or gains

The metering chamber is the volume surrounded by the guard box in which the environment is controlled. The sensor 2040 consists of combined thermopiles distributed across the surface of the guarded-box, these thermopiles are responsible for measuring the difference between the temperatures inside the guard-box and the temperature outside it. This difference is important in the calculations of the heat losses through the guard box which are necessary for the determination of the total heat loss through surround wall. Hence, in order to determine the direction of the heat flow based on the sign of the measured reading of 2040 sensor, the temperature of the guard-box was set to 25 °C and the temperature of the warm room to 20 °C, and for a period of 3 days to ensure steady state condition. The values of the 2040 sensor readings were negative which implies that heat is lost to the warm chamber since heat is transferred from the warmer region to the colder region.

4.2 Measurements on EPS material

4.2.1. Determination of deviation

The philosophy behind the experiments is to determine the accuracy of the climate chamber to test the timber wall component. From the U-value measurements on the 300 mm test specimens, a U-value is measured for the surround wall. This U-value is used in the determination of the power lost from the surround wall which is necessary to determine the timber wall U-value. The unique method shall reduce the error in the U-value measurements for the timber wall component.

In order to quantify the reliability of the climate chamber, an uncertainty analysis was done to account for the heat losses that do not pass through the specimen. These deviated heat fluxes are due to edge effects at the boundary between the specimen and the surround wall, heat flux against the surround panel and the heat exchange of the guard box with the rest of the warm room. However, the case in this experimental work is to neglect the edge loss since the thickness of the test specimen is equal to the thickness of the surround wall which will reduce the thermal bridge value to almost zero [10]. In addition, the mineral wool stuffed in the edges will reduce the air leakages and lower the potential for cold thermal bridges, figure 4.5 shows the edges between the specimen and surround wall. Also, by setting the guard box as shown in figure 4.4, the heat flow is focused in the direction perpendicular to the test components and hence the heat loss to the side of the guard box is minimized.

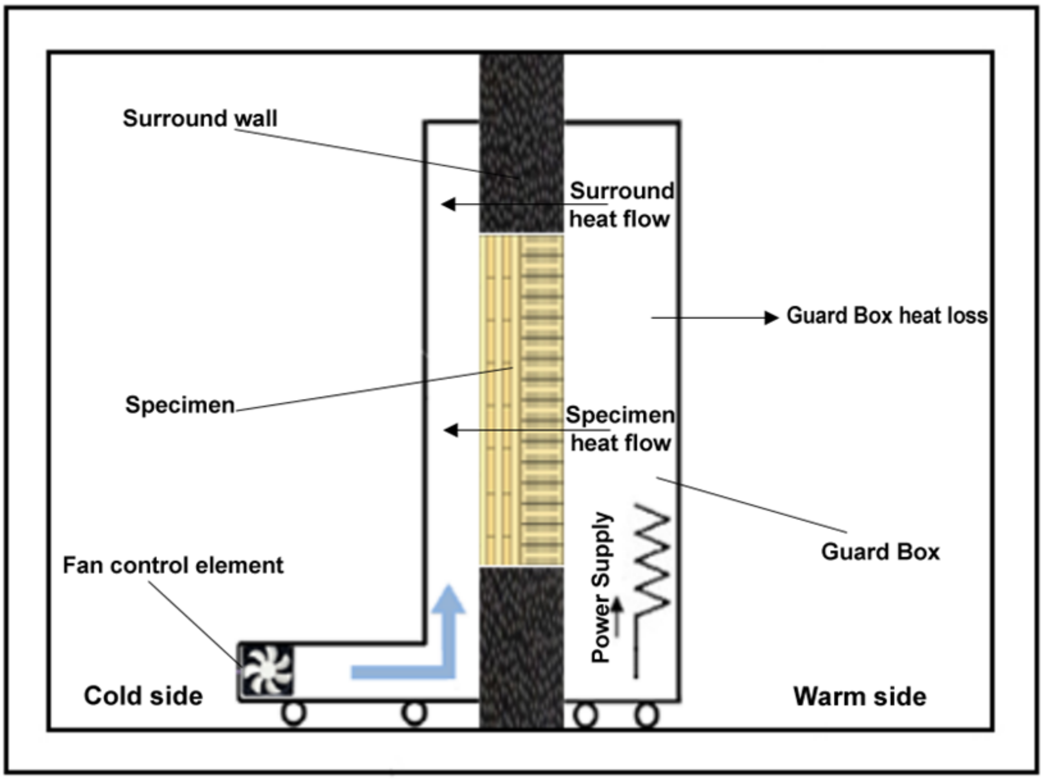


Figure 4.4. Guard-box configuration in the climate chamber [8].zz

Figure 4.5. Mineral wool is stuffed at the boundary between the surround wall and the specimen to reduce the edge heat loss.

4.2.2. U-value measurements for 200 mm and 300 mm EPS.

The method that was followed in this analysis, is to measure the U-value of both the test specimen and surround considered as one unit since they are made from homogenous material. A conductivity value has been derived for the EPS material based on power measurements and surface temperature readings and a thermal transmittance value is obtained. Hence, the measured U-value are then compared with the "true value". Since the true value cannot be absolutely determined, in practice an accepted reference value is used. The accepted reference value is the value obtained from the manufacturer data. Accuracy is the closeness of agreement between a measured value and the true value.
The deviation between measured U-value and the manufacturer data was calculated according to equation 4.2.

$$Deviation = \left| \frac{U_{Manufacturer} - U_{Measured}}{U_{Manufacturer}} \right| \times 100$$ *Equation 4.2*

Flourier law for heat conduction is used to obtain the thermal transmittance of this material, the equation is rearranged to calculate the U-value based on the measured surface temperature differences. The area is for the test specimen and surround wall are represented in figure 4.6.

$$P = U \cdot A \cdot \Delta T_s$$ *Equation 4.3*

Generally, P is the heat flow through the component, U is the overall heat transfer coefficient, A is the area of the test component and ΔT_s is the surface temperature difference between both sides of the component.

Equation 4.3 was rearranged to calculate the U-value for the EPS material, which is a uniform value for both the specimen and surround wall. The power that is lost from the guard box is subtracted from the average electrical power transmitted through the EPS material i.e. specimen and surround wall. Temperature difference is taken from the surface sensor reading on the cold and warm side of the component. Equation 4.4 below, is used to calculate the U-value for the EPS material. The area considered is the combined area for the specimen and surround wall.

$$U_{EPS\ material} = \frac{P_{\text{electric}} - P_{\text{guard-box}}}{\Delta T_s \cdot A}$$ *Equation 4.4*

Then, the calculated U-value based on measured temperature differences is compared with the theoretical U-value from the manufacturer. Theoretical U-value is calculated by obtaining the labeled conductivity according to equation 4.5

$$U = \frac{\lambda}{d}$$ *Equation 4.5*

Areas of, test specimen, surround wall and the guard box are calculated, table 4.2 show the dimensions of the components as well as thermal conductivity values.

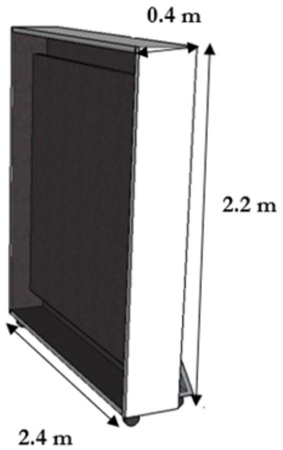


Figure 4.7. Guard-box dimensions "Reprinted from [11]".

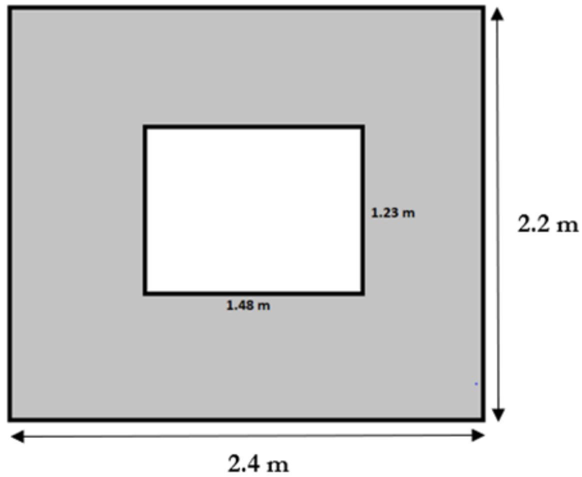


Figure 4.6. Area of surrounding wall and test specimen.

Table 4.2. Parameters and properties of the test components.

Location	***Thickness [m]***	***Area [m]***	***Conductivity [W/(m·K)]***
Test specimen	0.2/0.3	2.12	0.03
Surround wall	0.2/0.3 attached	3.16	0.03
Guard box	0.04	8.96	0.025*

* The value refers to Polyurethane which is the insulation material of the guard box

4.2.3. Test conditions

To measure the U-value of the EPS wall a combination of three temperature measurements are required [8]. Single U-value is measured under each temperature set and then deviation from the labeled value is calculated. The temperatures differences were set to simulate Sweden's outdoor temperatures during cold seasons (20 °C, 0 °C), (20 °C, -10 °C) and (20 °C, -20 °C). These temperature differences are then applied to measure the steady-state thermal transmittance of the timber wall element.

The experiments were performed on two different thicknesses of test specimens, first they were conducted on 200 mm EPS material. Then, an extra layer of 100 mm of EPS material was added to increase the thickness of the material to 300 mm. Note that when increasing the thickness of the wall the U-value decreases.

The accuracy of the power measurements obtained from the data logger were verified by calculating the theoretical electrical power that shall be supplied when the temperature difference is equal to 10 K. The value of the theoretical power calculated using the equation 4.3 was close to the measured value taken from the data logger which implies the reliability of the power instrument.

When performing the experiment, the climate chamber was kept operating for a period of 24 hours for each temperature difference set to ensure the steady state condition [24], the time step for data recording was set to be each 90 second. The steady-state condition was considered by achieving uniform power readings from the electrical power element.

Readings were taken from different periods during the test period to ensure accurate U-value measurements. A delay has occurred on several occasions due to the sudden disconnection of the data logger which resulted in longer experimental time.

Note that, when setting the temperature difference between the chambers to a certain value, for instance, 20 K. The difference is accounted for the ambient room temperatures. However, in the power calculations, the recorded surface temperatures are obtained to measure the heat flow through the test component. Surface temperatures vary due to the convective and conductive surface resistance and is smaller than the air to air temperature difference.

4.3 **Heat Transfer tests on the timber wall component**

The wall component was built and delivered by ISO-Timber in. The company specializes in constructing ready-made timber walls with improved insulation properties by providing air gaps and eliminate the need for plasticization. The wall components reduce the air leakages through buildings due to the presence of discs on the internal and outer surfaces of the walls. Also, wall components provided by ISO-Timber are classified as passive buildings elements due to their high density which maintains balanced interaction with the indoor climate. The wall layer consists of two types of layers combined into single element, one layer is made from CLT and the other layer is from timber named iso-timber, figure 4.9 below shows a diagram of the wall component. The U-value obtained for the surround wall from the EPS tests previously was applied in the calculations of the power that is subtracted from the average electrical power in equation 4.4. This shall increase the accuracy of the test results by applying the actual measured U-value of the surround wall instead of the manufacturer value. Figure 4.8 shows the steps followed to calculate the U-value of the timber wall specimen by substituting the calculated U-value of the surround wall in EPS 300 mm testing.

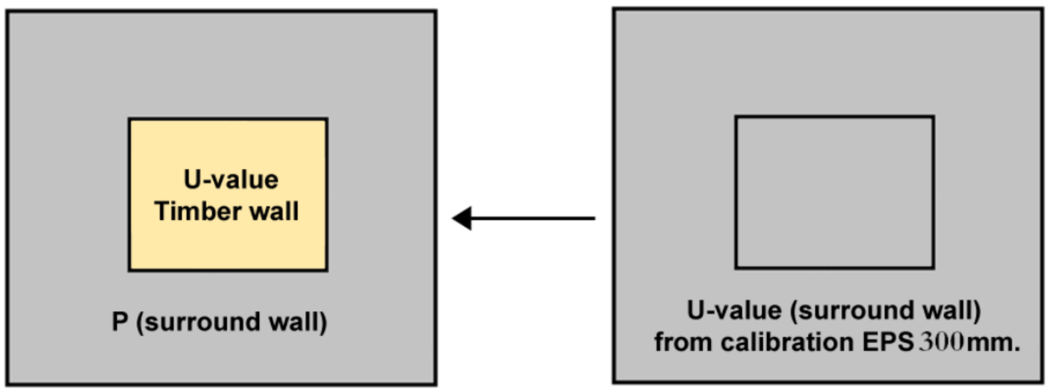


Figure 4.8. U-value calculated for the surround wall from the EPS 300mm tests is applied to calculate the power lost from it in the timber wall testing

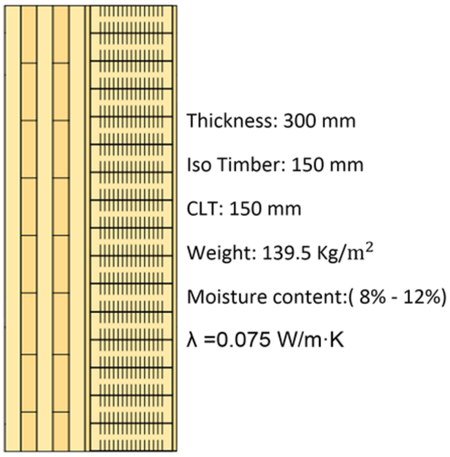


Figure 4.9. Diagram of the timber wall component including the thermal properties, CLT layer is to the left and iso-timber component is to the right.

4.3.1. Installation of wall component

The installation of the wall took place on the 4th of July 2018 in the climate chamber. Figure 4.10 and 4.11 illustrates the mounting procedure of the timber wall. The process required the power of three men and the tools used were a lifter and mobile surface. After placing the wall, mineral wool was stuffed at the boundary between the surround wall and the timber wall to reduce the edge heat losses. Note that the timber wall is a couple of centimeters smaller than the previous test specimen hence larger amount of mineral wool is used to make it airtight. Furthermore, a high strength tape with great temperature and moist resistance was used to seal the edges to prevent the occurrence of any small air leakages.

(a) (b)

Figure 4.10. (a) lifter is used to carry the timber wall and place it on mobile surface, (b) mineral wool is stuffed at the boundary between the surround wall and the wall specimen.

Figure 4.11. Wall specimen is sealed at the edges with high tensile strength tape to increase the air tightness and reduce edge losses.

4.3.2. Steady state U-value measurements

The timber wall component is exposed to three temperature differences which are the same sets as the tests of 300 mm EPS, the U-value for each test is calculated according to equation 4.6 below and based on the measured surface temperature differences. The variation in the U-value when increasing the temperature difference is evaluated. Iso-timber Company claims that the wall component can perform efficiently at high-temperature differences between indoor and outdoor temperatures.

U-value for the timber wall is calculated according to equation 4.6 which is derived from Fourier law. It's similar to equation 4.4. However, in this experiment the test specimen (timber wall) and surround wall are made of different materials. Hence, the power that passes through the surround wall is also subtracted from the total power generated to determine the power that only passes through the timber wall. The U-value for the wall specimen is calculated based on the measured temperature readings.

$$U_{wall\ specimen} = \frac{P_{\text{electric}} - P_{\text{Surround wall}} - P_{\text{guard-box}}}{(\Delta T_s \cdot A)_{wall\ specimen}} \qquad \textit{Equation 4.6}$$

The steady state condition is considered by achieving uniform power and U-value calculations over the sequence of test periods. Evaluation of the measurements after each day to determine the time required to reach to a constant U-value. This timber wall structure has a higher time constant due to its higher density and thus requires more time to reach the steady state condition. An observation on the time required to obtain stable readings of the U-value for each set of temperature differences is noted, an estimation yields that it takes approximately three days to achieve the steady state condition for this wall component. The time constant of the wall is affected by certain factors such as, moisture content, humidity and radiation. Therefore, these quantities were frequently measured while testing using a handheld digital moisture meter for wood.

4.3.3. Dynamic testing

Test is performed by setting the temperature in the warm side (indoor) to 20 ºC and changing the temperatures of the cold side (outdoor). The initial temperature in the cold side is set to be -20 ºC, increase to reach 0 ºC in the middle and return to -20 ºC at the end of the test. Graph 4.12 below shows the air temperatures that were performed in this part of experiment. However, the actual change in the temperature is not instant and takes extra time to reach uniform value. The time required for the temperatures to change is taken into consideration to obtain the total evaluation period which is discussed in the following section. The original plan was to apply the test for a minimum of two cycles of cold and warm temperatures, yet due to instrument disconnections and to ensure the equilibrium point is reached, only last two cycles were considered were considered for the evaluation of the average and instant U-values.

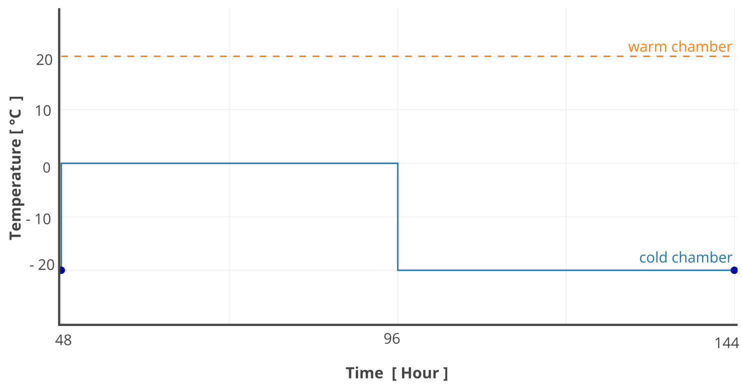


Figure 4.12. Temperature setpoints during testing

The temperature change is made every 2 days as seen in the graph above since this wall has a time constant of three days. This time constant was obtained from the steady-state heat transfer testing and will be further discussed in the following section. Temperature will take extra time to reach to the targeted value and this is considered by evaluating the temperature readings and checking the period it takes to stabilize. The average value of the U-value is measured for a period of four days to ensure the dynamicity of the test. First case, time needed when increasing the temperature from -20 °C to zero at the beginning of the cycle. Secondly, the number of hours that was taken to reach – 20 °C from 0 °C at the start of the last cycle.

The average U-value was calculated using equation 4.6, the average temperature readings were obtained for each temperature difference (cycle). Then, a U-value was calculated for each time period (2 days) which yielded two values, the average value is the mean of the two calculated values. Consideration was taken for the time required for the temperature to stabilize, the total evaluation period is obtained by observing the change in the surface temperatures from the cold side. This time gap was measured to be around 5 hours and it was eliminated in the calculations of the average U-value.

Also, the instant U-value was calculated using equation 4.6, during the test the instant reading of the temperature and power during the test was taken. The values were single values selected at the 48 hour and 144 hours. Then, the instant U-values were plotted in graph and compared with the average U-value.

5 Results and Discussion

5.1 Measurements on EPS material

5.1.1. Measurements on EPS 200 mm

The U-value based on manufacturer data are calculated for the specimen and the surround wall combined as one unit according to equation 4.5, these values are to be compared with the measured values from heat transfer tests, table 5.1 below show the calculated U-values. Note that the surround wall and test specimen are considered as one unit and referred to with the term EPS material. The guard box U-value is calculated to determine the heat loss through it.

Table 5.1. Calculated U-values for the 200 mm EPS material, and the guarded box based on the conductivity from manufacturer data.

Component	*U-value [W/(m^2·K)]*
EPS material	0.150
Guard box	0.625

The power that is lost from the guarded box is calculated based on equation 4.3 and are presented in the tables (5.2,5.3 and 5.4) below, the average power supplied from the radiator is taken from the data-logger readings and presented in the tables as well. Power values that are represented in the tables below are then used to obtain the U-value for the 200 mm EPS material according to equation 4.4. The temperature difference sets applied for test specimen shall be equal to the temperature difference sets applied for testing the real element (timber wall) in steady state the testing.

Table 5.2. power values for the first temperature test ΔT= 20 K, ΔT_s=18.567 K.

Component	*Power [W]*
Guard box (Lost)	0.753
Average electrical power	15.223

Table 5.3. power values for the second temperature test ΔT= 30 K, ΔT_s=28.077 K.

Component	*Power [W]*
Guard box (Lost)	0.782
Average electrical power	23.096

Table 5.4. Power values for the third temperature test ΔT= 40 K, ΔT_s=37.519 K.

Component	*Power [W]*
Guard box (Lost)	0.829
Average electrical power	30.789

The calculated U-value of the EPS material according to the equation 4.4 is shown in table 5.5.

Table 5.5. Calculated U-values of the EPS material (Surround wall+ Specimen) from heat transfer tests, EPS thickness 200 mm.

Ambient Temperature difference [K]	*Surface temperature difference ΔT_s [K]*	*U-value [W/(m^2·K)]*

20	18.567	0.147
30	28.077	0.150
40	37.519	0.151

By plotting the measured U-values against the temperature differences it can be seen from the graph 5.1 below that the amount of deviation is within the acceptable range for the EPS 200 mm tests where the acceptable range for 200 mm specimens is ±5 % according to the international standard [8]. The deviation percentage from the manufacturer data was calculated according to equation 4.2. For the test of $\Delta T = 20$ K temperature difference the deviation from the manufacturer data was about 1.60 %, the $\Delta T = 30$ K temperature difference yields approximately 0.35 % deviation and the $\Delta T = 40$ K results in 0.83 % deviation. The deviations for each temperature difference are shown in diagram 5.2.

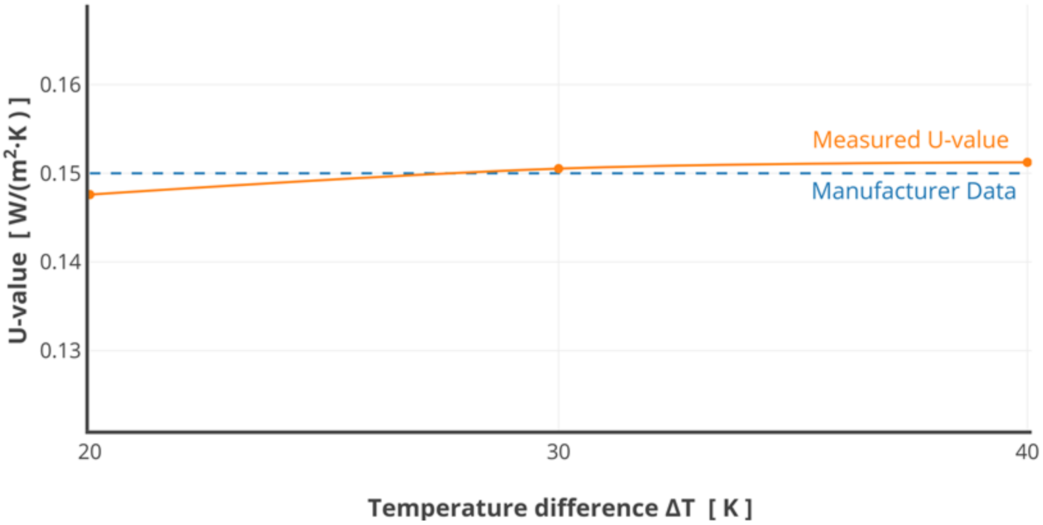


Figure 5.1. plot of measured U-values as a function of temperature difference ΔT for the EPS 200 mm tests.

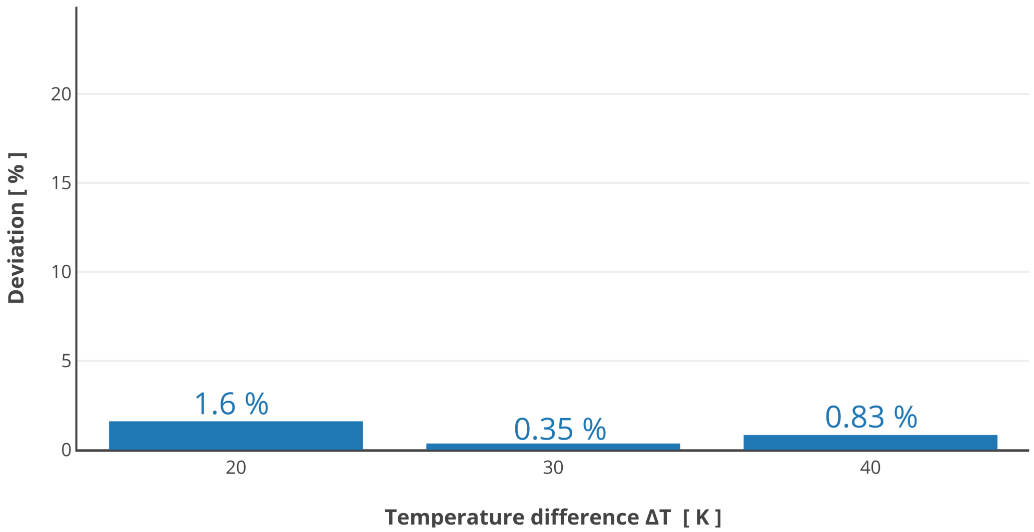


Figure 5.2. Diagram represents the deviation of the measurements at each temperature difference ΔT for the EPS 200mm tests.

Results from testing 200 mm EPS material have showed that the deviation from the manufacturer data is very small. Hence, the climate chamber has proven to be reliable for testing the 200 mm wall components. Which implied the possibly of performing accurate tests on 300 mm test material.

5.1.2. Measurements on EPS 300 mm.

In the same manner for testing the EPS 200 mm material, the U-values based on the labeled conductivity are determined for the EPS material and guarded box according to equation 4.5. Table 5.6 below show the calculated values. Note that the U-value of the EPS material is reduced since the thickness is increased by adding the extra 100 mm layer.

Table 5.6. Calculated U-values for the 300 mm EPS material, and the guarded box based on the conductivity from manufacturer data.

Component	***U-value [W/(m²·K)]***
EPS material	0.100
Guarded-box	0.625

The power lost from the guard box is determined based on equation 4.3 and the average electrical power is taken from the data-logger readings. Power values for each temperature different test are presented in tables 5.7, 5.8 and 5.9.

Table 5.7. Power values for the first temperature test $\Delta T= 20$ *K,* $\Delta T_s=18.950$ *K.*

Component	***Power [W]***
Guard box (Lost)	1.789
Average electrical Power	10.477

Table 5.8. Power values for the second temperature test $\Delta T= 30$ *K,* $\Delta T_s=28.570$ *K.*

Component	***Power [W]***
Guard box (Lost)	2.031
Average electrical Power	15.582

Table 5.9. Power values for the third temperature test $\Delta T= 40$ *K,* $\Delta T_s=38.217$ *K.*

Component	***Power [W]***
Guard box (Lost)	2.892
Average electrical Power	21.469

The measured U-value of the EPS material according to the equation 4.4 is shown in the table below.

Table 5.10. Calculated U-values of the EPS material (Surround wall+ Specimen) from heat transfer tests, EPS thickness 300 mm.

Ambient temperature difference [K]	***Surface temperature difference*** ΔT_s ***[K]***	***U-value [W/(m²·K)]***
20	18.950	0.087
30	28.570	0.090
40	38.217	0.092

However, for the case of testing EPS 300 mm the deviation calculated was slightly higher than the standard. For the test of 20 K temperature difference the deviation was about

13.17 %, the 30 K temperature difference yields approximately 10.17 % deviation from the manufacturer data and the 40 K results in 7.93 % deviation.

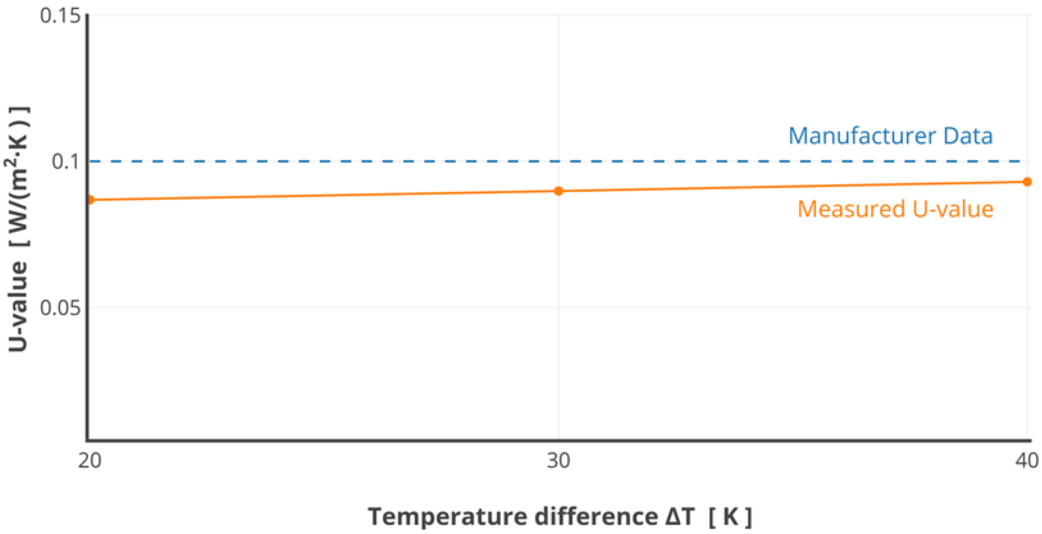


Figure 5.3. plot of measured U-values as a function of temperature difference ΔT for the EPS 300 mm tests.

These uncertainties are due to several factors such as, equipment design, material properties and operation, which affect the power dissipated through the EPS material and results in a deviation in the measured U-value for the surround wall. Figure 5.4 shows a diagram of the deviation percentage resulted from each temperature set.

The thermal transmittance U-value is a function of the temperature differences across the material itself, the temperature difference is affected by the heat fluxes that do not pass through the specimen. These lost heat fluxes are due to the edge effect at the boundary between the specimen and surround wall, the heat losses are minimized by adding insulation material within the boundary and sealing it with tape. Also, the heat loss through the borders of the guard box causes uniformity in the distribution of the temperatures within the guard box volume as well as on the specimen surface which may lead to an increase of the lateral heat loss along the specimen and heat lost to the outside of the guard box.

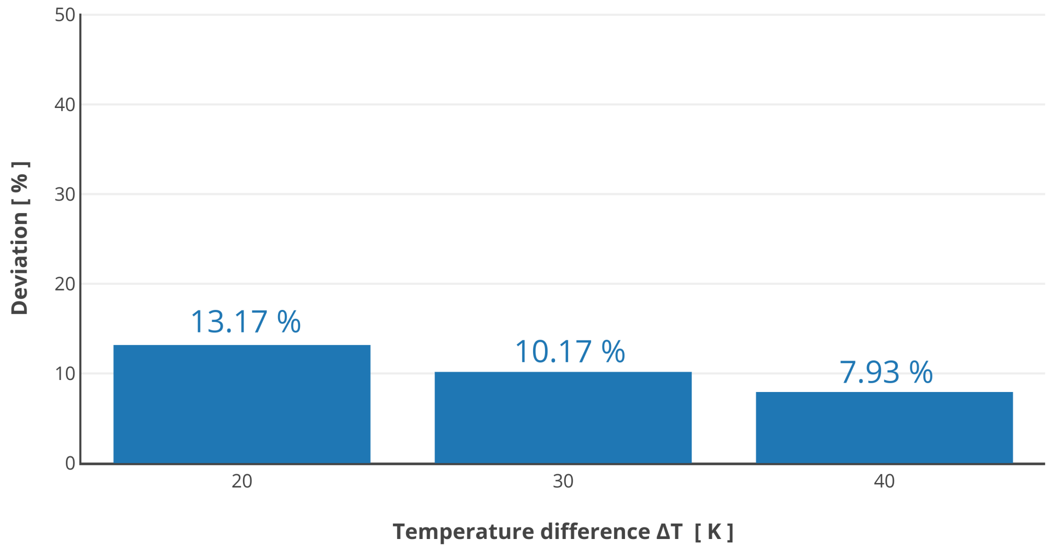


Figure 5.4. Diagram represents the deviation percentage of the measurements at each temperature difference ΔT for the EPS 300mm tests.

From the diagram 5.4, the average deviation for the U-value measurements in the three temperature differences is around 10 %. This increased deviation from the labeled value might be due to the small air cavities behind the attached 100 mm EPS layer, these air cavities generate natural convection which causes an imbalance in the heat flow rate that passes through the specimen and result in a higher inaccuracy in the U-value measurements, please see figure 5.5 below. Furthermore, it can be understood from the graph above that the measured U-value is lower than the manufacturer data due to, the small cavities which act like air gaps preventing the total heat flow to be transferred through the specimen which shall result in a lower measured U-value [8].

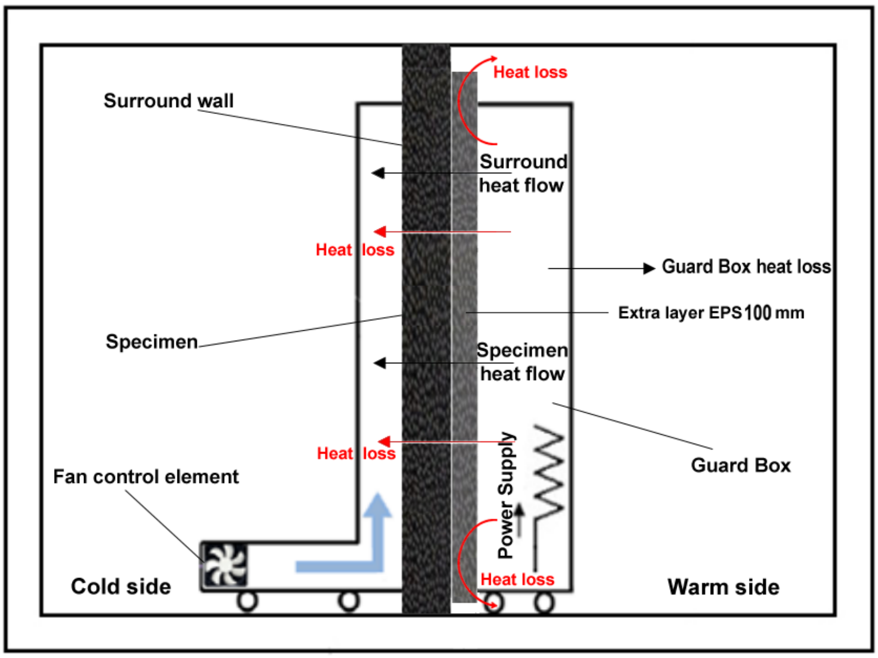


Figure 5.5. Side view of the separation wall along with the extra attached 100 mm EPS, the small thickness air cavities between the original surround wall and the extra EPS layer, creates natural convection which affects the heat flow rate through the specimen.

This deviation can be minimized by removing the wooden frame that holds the separation wall and placing the extra 100 EPS layer and then fix the wood frame back, by compressing the extra layer of EPS the air cavities are reduced and the heat flow is not affected.

Thought, the high deviations in the tests of the EPS 300 mm analysis, a decision was made to proceed with testing the massive timber wall component. This can be justified by comparing the U-value of the timber wall with the thickness of the EPS material. From equation 4.5, solving for the thickness of the EPS by setting the U-value equal to the one of timber wall and the conductivity is kept the same for the EPS material. The results show that the massive wood wall is equivalent to approximately 120 mm EPS material thickness which implements that the error resulted from the heat transfer tests on the massive wood wall tests shall be lower than the errors from calibrating EPS 300 mm. The ratio between the EPS thickness and the timber wall is about 0.4 which indicates that the error of testing 300 mm timber wall will be significantly low the different temperature differences.

Moreover, the massive wood wall shall compress the extra attached layer of EPS due to the higher weight of the wood material. Hence, this will reduce the cavities within the surround wall and help increase the uniformity of heat flow which shall enhance the reliability of the test results.

5.2 Heat transfer test on timber wall

Previous experiments on EPS material has given clear insight into the confidence level of the measured U-values for the timber wall. The measurements of the thermal transmittance of the timber wall yield a single numerical value for each test period. Hence, the U-value of the timber wall was calculated based on the calculated U-value of the surround wall from the 300 mm EPS testing.

5.2.1. Steady state tests

The calculated U-values of the surround wall from the EPS tests are presented in table 5.11. These temperature dependent U-values will be used in the following calculations of the power transmitted through the surround wall according to equation 4.3. The power transmitted through the surround wall is then subtracted from the average electrical power in equation 4.6 to calculate the U-value of the timber wall specimen.

Table 5.11. Calculated U-values of the surround wall obtained from the EPS test results for 300 mm at different temperature differences.

Temperature Difference* ΔT *[K]	***U-value [W/(m²·K)]***
20	0.087
30	0.090
40	0.092

To obtain the measured U-value of the wall component using equation 4.6, the power transmitted through surround wall and lost from the guard box are calculated according to equation 4.3. The average electrical power that is supplied from the radiator is obtained from the data logger readings. The power that is lost from the guard box is calculated from equation 4.3, the U-value and areas of the guard box are shown in table 4.2 in the methods. The tables 5.12, 5.13 and 5.14 below show the power values for the three different temperature tests.

Table 5.12. power values for the first temperature test $\Delta T = 20$ *K,* $\Delta T_s = 18.616$ *K.*

Component	***Power [W]***
Surround wall	5.329

Guard box	3.383
Average electrical power	20.647

Table 5.13. power values for the second temperature test ΔT= 30 K, ΔT_s =28.075 K.

Component	***Power [W]***
Surround wall	8.308
Guard box	3.117
Average electrical power	28.794

Table 5.14. Power values for the third temperature test ΔT= 40 K, ΔT_s =37.640 K.

Component	***Power [W]***
Surround wall	11.406
Guard box	3.894
Average electrical power	35.895

The U-values of the wall component are calculated according to equation 4.6, values are presented in the table 5.15.

Table 5.15. Measured U-values of the timber wall for the three temperature sets.

Temperature difference ΔT [K]	***Surface temperature difference ΔT_s [K]***	***U-value [W/(m²·K)]***
20	18.616	0.302
30	28.075	0.292
40	37.640	0.258

Surface moisture content reading were taken frequently during the steady-state heat transfer testing to determine the effect on steady state condition. Table 5.16 below shows the values of moisture content during this experimental work with the respected dates.

Table 5.16. Surface moisture content of the timber wall component at 3 mm penetration depth.

Date	***Surface moisture content of warm side [%]***
July 09, 2018	8.4 %
July 17, 2018	8.4 %
July 19, 2018	8.4 %
July 23, 2018	8.4 %
July 26, 2018	8.4 %
July 27, 2018	8.4 %
July 29, 2018	8.4 %
August 02, 2018	8.4 %
August 03, 2018	8.5 %
August 05, 2018	8.5 %

Higher experimental time was consumed in this phase since the wall component requires higher time to reach to the steady-state condition compared to the EPS material. The higher density of the timber wall reduces conduction heat flow along the thickness of the wall which increases the time constant. An approach to estimate the time required to reach steady-state is based on the stability of the measured U-values.

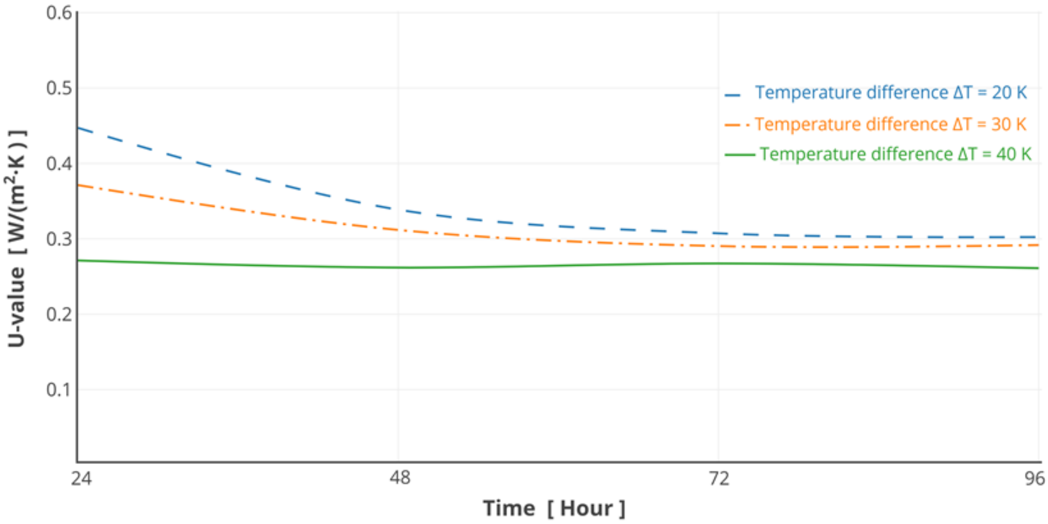


Figure 5.6. Time required to achieve steady-state heat transfer for three temperature sets (time constant of the wall).

Graph 5.6 above shows the stability of U-value measurements over the test sequences for different cold side temperatures. It can be understood that the time required to achieve uniform U-value measurements is approximately 72 hours for all temperature differences. Also, the measured U-values for the temperature difference of 40 K shows small oscillation compared to other temperature differences, this stability in higher temperature differences are due to higher heat flow which accelerates the time to reach steady-state condition. Furthermore, from the graph 5.6, it can be seen that the U-value measurements are stable for the higher temperature difference ΔT=40 K. This stability is due to higher power supply from the radiator element which will faster the time to reach steady-state condition.

Furthermore, the time constant of the wall can be affected by the moisture content and the air relative humidity levels. By taking the readings of these quantities frequently, it was concluded that the moisture content remained constant from the warm surface of the wall as can be seen from figure 5.7 below. Hence, the effect of the moisture content was ignored. Also, air relative humidity readings were not accurate due to the interruption caused when the door was opened. Although, the relative humidity is assumed to be constant since the moisture content did not vary. Moisture content is affected by the relative humidity indoor and since the wall was tested in controlled environment (climate chamber) where the change in relative humidity is small unlike in outdoor conditions. Hence, more time is taken for the moisture content to change within the thickness of the wall. Also, the time required for the moisture content to change might be affected by certain factors such as, hygroscopic material used in the wood, the size of air voids that contain the water molecules and presence of vapor barriers or airgaps.

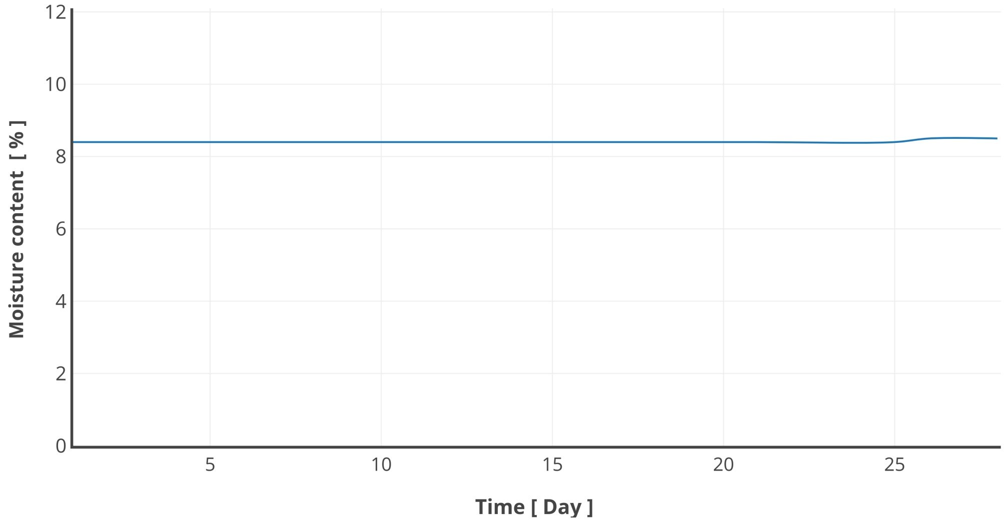


Figure 5.7. moisture content at 3 mm surface penetration during the one-month testing period.

The calculated U-values from the steady-state heat transfer tests are plotted against the temperature difference in figure 5.8.

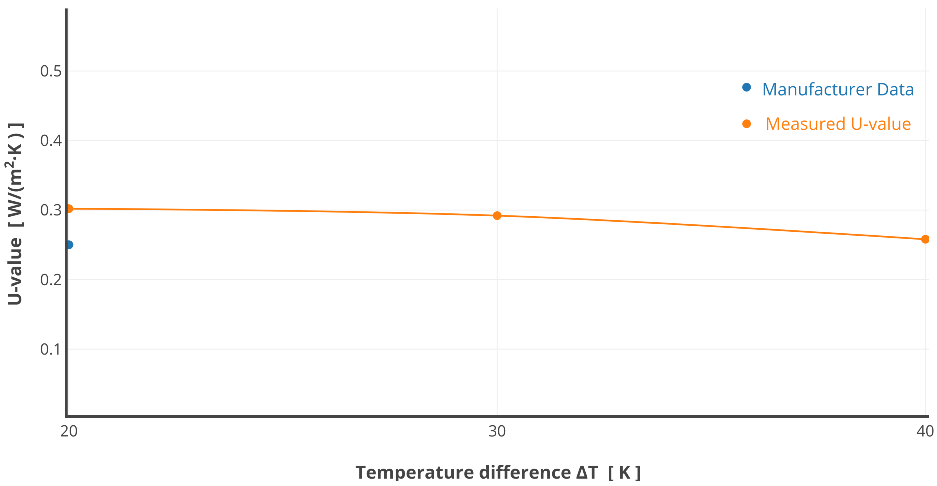


Figure 5.8. The change in the measured U-values with respect to increased temperature difference.

The measurement results show that the measured U-value for the wall component decreases with increasing temperature difference. From graph 5.8, it can be understood that the measured U-value has the highest value at the lowest temperature difference. The measured values gradually decrease with increasing the temperature difference to reach the value of the manufacturer data. At 40 K temperature difference, the U-value is minimum with 0.258 W/(m^2·K) which implement the high thermal insulation property of the wall. Also, the reduction in U-value when increasing the temperature difference shall lower the overall heat transfer coefficient and thus the heat loss through the wall. Wall component density and porosity affect the thermal conductivity and lower the conduction heat flow through voids and cell boundaries. Moreover, when decreasing the absolute temperature in the cold side the moisture inside the voids extends and with continuous reduction in temperature, it turns into ice. This formed ice from the cold side reduces the conductivity of the wall component and thus lower the heat loss.

Furthermore, increasing the temperature difference might result in an increase of the air convection in the air voids of the wall component which shall increase the heat flow. On the other hand, reduced absolute temperature will result in a higher viscosity of the air inside the voids of the wall component. The higher viscosity will counteract the occurrence of air convections inside the air voids which shall lower the amount of heat transferred to the outside of the wall. This shall result in lower thermal transmittance value which was the case for this timber wall component.

Photos taken with the IR-camera instrument showed that the timber wall component have maintained a close surface temperature to the indoor air temperature (warm chamber) when the cold chamber temperature was set to – 10 °C.

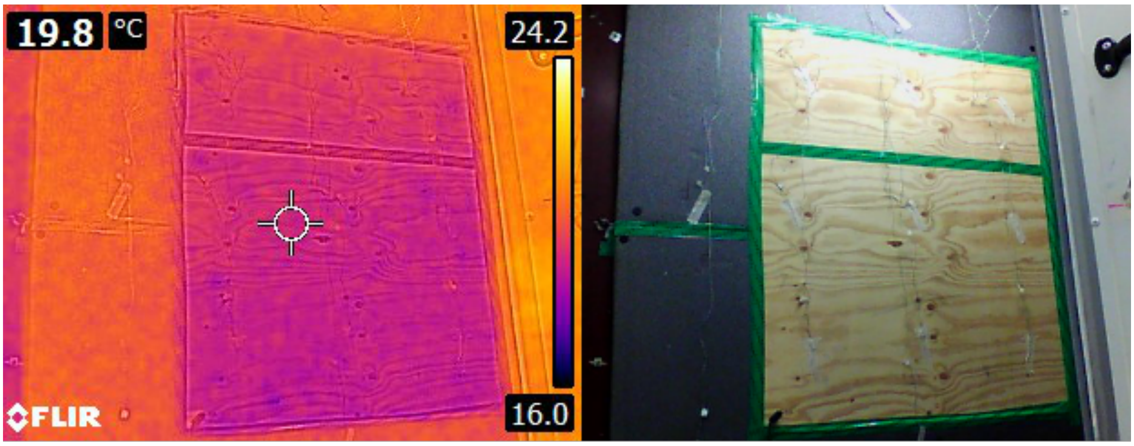


Figure 5.9. Thermal image of the wall component taken from the warm side at 20 °C air temperature.

Figure 5.9 shows that the timber wall have maintained a surface temperature of about 19.8 °C where the air temperature was 20 °C. Since surface temperature values are close to the air temperatures, this will reduce the occurrence of convective air currents on the surface and thus lower the heat transfer from air to wall surface. Hence, the heat loss to the cold side is minimized as can be seen from the thermal image from the cold side in figure 5.11.

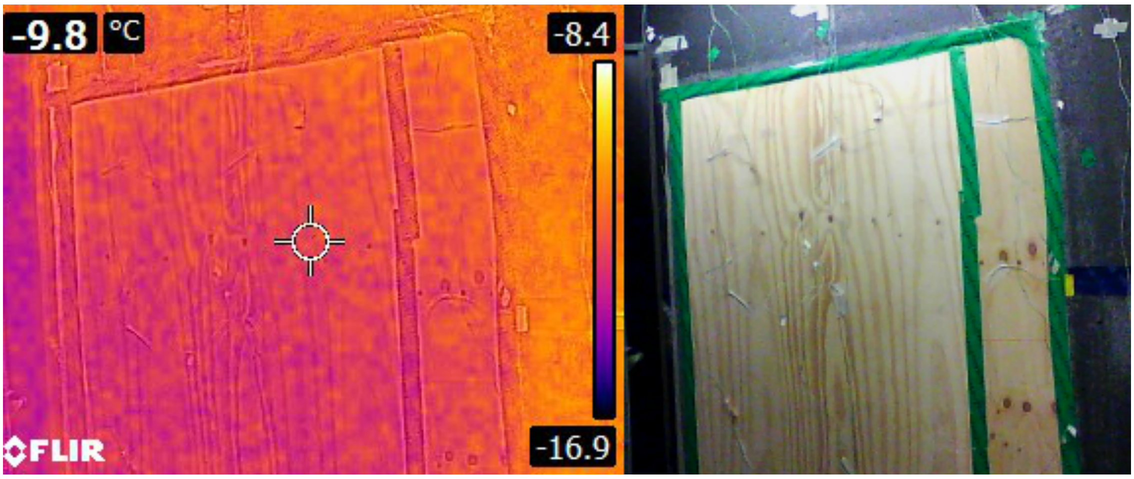


Figure 5.10. Thermal image of the wall component taken from the cold side at -10 °C air temperature.

As can be seen from graph 5.10, the surface temperature is almost the same as the air temperature which indicates that less heat is transferred from the warm side. Higher surface temperatures from the cold side implements more heat loss through the thickness of the wall which was not the case for this wall component.

5.2.2. Dynamic tests

The table below represents the measured data and the calculated average U-values during the test. Each U-value is calculated based on average power and surface temperature readings for the two days, the total average U-value is for the four days which is the period considered for this evaluation. Only the last 4 four days were considered to ensure the dynamicity of the test and the equilibrium point is achieved. The average electrical power was obtained from the data-logger readings and inserted in equation 4.6.

Table 5.17. Average U-value for the evaluation period (four days).

Period [Days]	***Temperature difference ΔT [K]***	***Surface temperature difference ΔT_s [K]***	***$P_{electric}$ [W]***	***$P_{Surround\ wall}$ [W]***	***$P_{guard-box}$ [W]***	***Average U-value [W/(m²·K)]***
0-2	20	18.190	24.070	6.050	3.200	0.405
2-4	40	37.230	32.790	12.190	3.640	0.227
						Total average=0.316

The instant U-value is calculated based on single readings at the middle of each cycle, the readings were taken randomly at different time frames. Table below show single values taken during the test. The instant U-values were calculated according to equation 4.6.

Table 5.18. Instant U-value measurements based on temperatures readings at the middle of each cycle.

Temperature difference ΔT [K]	***Surface temperature difference ΔT_s [K]***	***$P_{electric}$ [W]***	***$P_{Surround\ wall}$ [W]***	***$P_{guard-box}$ [W]***	***Instant U-value [W/(m²·K)]***
20	18.170	24.300	6.050	2.940	0.418
40	37.100	33.100	12.160	3.860	0.229

The total average U-value for the evaluation period showed a deviation of approximately 26.6 % higher than the U-value from the manufacturer data. This increase is expected when walls are subjected to sudden temperature changes due to higher air convection movements inside the wall air voids. However, this wall component showed a tolerant change according to the company, which implements lower heat losses to the outside during sudden temperature fluctuation.

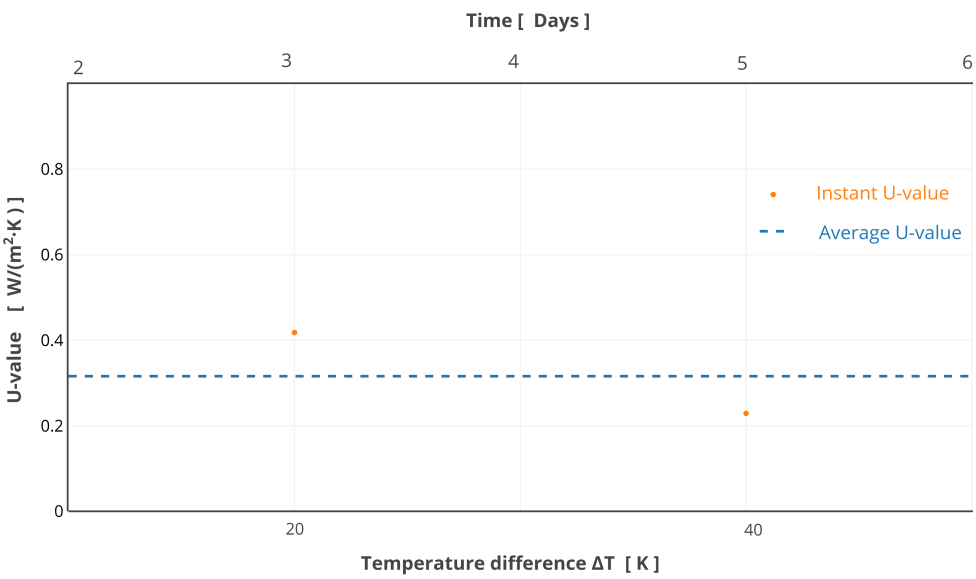


Figure 5.11. Instant and average U-value plotted against the temperature difference for the four days testing,

From the graph 5.11, it can be seen that the instant U-value measured in the two cycles, vary significantly along the test period. This variation is due to the higher thermal mass of the timber wall which allows the temperature to be stored within the thickness of the component. Hence, the conductivity may be affected and varies during the testing and result in a change in the measured U-value.

For example, when changing the temperature of the cold side to 0 °C at the beginning of the cycle, the instant U-value measured was significantly high and gave a value higher than the one obtained from the previous tests "steady-state". This was due to the high thermal mass which maintained a low temperature inside the wall even after increasing the temperature, the heat flow has increased and accordingly the power supplied which resulted in an increase in the nominator in equation 4.6, thus higher instant U-value was obtained.

Furthermore, the frozen moisture content on the cold side of the wall melts when increasing the absolute temperature and thus higher heat flow occurs. Since more heat is lost to the cold side, the radiator element increases the amount of the average power supplied to compensate for the lost heat. As a result, the calculated instant U-value increases due to higher power readings in equation 4.6.

Timber walls have high thermal mass which increase the resistance to temperature changes, as it can be seen from the following figure 5.12, the time required for the surface temperatures to stabilize when increasing the temperature on the cold side to zero was about approximately three hours. Also, almost the same time was required when decreasing the temperature to -20 °C at the start of last cycle.

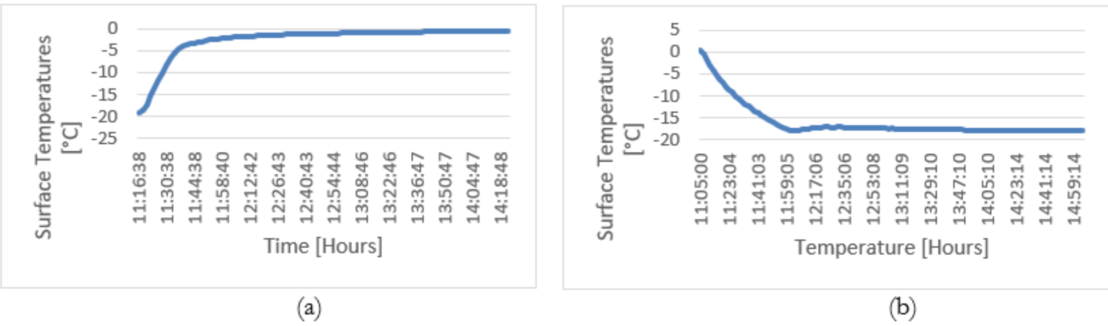


Figure 5.12. (a) Time required for the surface temperatures to stabilize when increasing the temperature in the cold side to zero. (b) Time needed to stabilize when decreasing the temperature in the cold chamber to-20 °C.

Timber walls have high thermal mass which increase the resistance to temperature changes, as it can be seen from the following graphs, the time required for the surface temperatures to stabilize when increasing the temperature on the cold side to zero was about approximately three hours. Also, almost the same time was required when decreasing the temperature to -20 °C. Thus, this wall component has high resistance to the temperature changes and peaks and shall increase the thermal inertia of the building envelope when integrated.

6 Conclusion

In conclusion, this project has studied the thermal properties of timber-structure wall component. Heat transfer tests on a massive timber wall component provided by the Iso-timber company was performed and the behavior of the wall component when subjected to different temperature variations was analyzed. This study also mentioned about the effect of phenomena's such as, moisture buffering and latent heat of sorption on regulating the indoor temperatures and reduce energy demand. Pointed out about the change in thermal transmittance properties of the wall component when subjected to steady state and dynamic heat transfer. The unique method described in this research to determine the variation in the thermal properties such as, conductivity of the timber material shall be further analyzed and discussed. The outcome of this project may encourage valuable knowledge for the use of massive wood element in wall components through a design that also considers physical and economic factors related to indoor thermal comfort.

6.1 Limitations and/or Applicability of the Study

Over the course of this thesis work, several obstacles and limitations have prevented from further studies and investigations. The tremendous time that was spent on determination of deviation and preparation of the climate chamber is more desirable to be consumed in studies related to the topic. Scope of this thesis work has been changed on several occasions due to the sudden emergence of complexities during the test period.

For example, the Agilent data-logger was disconnecting and stop to take measurements during testing, time was consumed to wait for the problem to be fixed and to be able to repeat the tests. However, this issue appeared also when testing the timber wall also, the data-logger disconnects after several hours of operating which complicated the process of taking measurements. Also, the YOKOGWA power analyzer have shown some disturbance during testing. The error message was displayed several times and the power readings were either unrealistic high or equal to zero. Furthermore, when performing temperature fluctuation tests, the minimum temperature that can be set was – 22 °C and the objective was to test the wall for a minimum of -30 °C. At the beginning of the test, the minimum temperature that could be achieved from the cold side was -10 °C, this was due to the accumulated ice in the pipes of the evaporator which prevented the gas from circulating inside. Hence, a decision was made to stop the machine for a period of 24 hours to allow the melting of ice, doors were opened, and water containers were placed behind the chamber to collect the discharged water from the machine.

Such errors and delays are expected in similar experiments where multiple types of equipment are involved. Future students must have a clear insight on the degree of preparation of the climate chamber in order to determine the scope of work. Also, the student shall be prepared to expect high practical work and be flexible with emerging errors.

6.2 Recommendations for Future Work/Further Study/Avenues for future research

This project can be expanded to include experimental testing on wall components with different insulation materials. Comparing the thermal properties of various insulation materials by calculating the U-values using the same procedure presented in this work. Also, adding vapor barriers and air gaps to the wall components. Analyze the effect of these layers on heat transfer through the thickness of the wall. Moreover, the influence of moisture buffering property in the wood material on regulating the relative humidity levels can be investigated. Fixing relative humidity sensors inside the chambers in such a way the readings can be taken from the outside, this shall reduce the error resulted from opening the door of the chamber. This can be achieved by increasing the experimental time to a period of six months at least, and daily recording of the relative humidity variations inside the chambers.

Acknowledgment

Firstly, we would like to express our sincere gratitude to our advisor Tomas Persson for the continuous support of our thesis work, for his patience, motivation, and immense knowledge. His guidance helped us in all the time of research and during experiments.

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Also, we thank Johan Vestlund and Neeraj Vijay Bedmutha for their technical support over the course of this research. Without they precious support it would not be possible to conduct this research.

Reflection minutes

During this project we have both performed the experimental tasks equally, attended the meeting with the supervisor and performed laboratory work. The work load was divided equally, we both have made the research work about the heat transfer subject and cooperated to write and present the thesis paper.

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List of Equations

(Rate of heat transfer into the wall) − (Rate of heat transfer out of the wall) = (Rate of change of the energy of the wall)	*Equation 1.1*
$H_{\mathrm{M}} = H_{\mathrm{V}} + \Delta H_S$	*Equation 2.1*
$H_{\mathrm{s}} = \frac{S \cdot \rho_{\mathrm{m}} \cdot d_{\mathrm{m}} \cdot \Delta MC \cdot H_{\mathrm{v}}}{t}$	*Equation 2.2*
$T_{\mathrm{corrected}} = T_{\mathrm{meas}} + [\![k_2.(T_{\mathrm{meas}})^2 + k_1.T_{\mathrm{meas}} + k_0]\!]$	*Equation 3.1*
$Deviation = \left\lvert \frac{U_{Manufacturer} - U_{Measured}}{U_{Manufacturer}} \right\rvert \times 100$	*Equation 4.2*
$P = U \cdot A \cdot \Delta T$	*Equation 4.3*
$U_{EPS\ material} = \frac{P_{\mathrm{electric}} - P_{\mathrm{guard-box}}}{\Delta T \cdot A}$	*Equation 4.4*
$U = \frac{\lambda}{d}$	*Equation 4.5*
$U_{wall\ specimen} = \frac{P_{\mathrm{electric}} - P_{\mathrm{Surround\ wall}} - P_{\mathrm{guard-box}}}{(\Delta T \cdot A)_{wall\ specimen}}$	*Equation 4.6*
$R = \frac{1}{U}$	*Equation 5.1*