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SUMMARY
This study is written as a part of the Build-in-Wood project, in cooperation with the Norwegian Institute of Wood Technology. The goal was to evaluate the condensation and mould growth risk in flax fibre, wood fibreboard and mineral wool, integrated in a timber-based wall system. In addition, it was investigated if the exterior cladding and the convection in the air gap behind the exterior cladding affects the condensation and mould growth risk. The investigations were conducted through experiments and both short-term and long-term numerical simulations, where the short-term simulations were conducted for validation. Both the experimental investigations and the numerical simulations revealed that there is no significant risk for condensation and mould growth in any of the materials. For properties like thermal transmittance and absolute humidity, all materials seem to be within the requirements, and suitable for use in a timber-based wall, even though there were some differences between the materials. Mineral wool had the lowest thermal transmittance, and flax fibre had the highest. In addition, wood fibreboard stood out with a bit higher absolute humidity than the rest of the materials. Nevertheless, both flax fibre and wood fibreboard can be considered good alternatives when choosing insulating material.

3 KEYWORDS
Condensation and mould growth risk
Nature-based insulating materials
Timber-based wall

PREFACE

This master thesis has been written during the spring semester of 2022 and marks the end of a 5-year long study period at Oslo Metropolitan University, also called OsloMet. This study consists of a close collaboration with the Norwegian Institute of Wood Technology and OsloMet during weekly meetings and close cooperation throughout the year. Steady progress has been facilitated with the help of Dimitrios Kraniotis as our supervisor from OsloMet and Stine Lønbro Bertelsen, Samee Ullah and Rolf-William Wik from the Norwegian Institute of Wood Technology.

First, we want to show our big gratitude to Dimitrios Kraniotis for being our rock in the journey towards the submission. We are grateful for frequent meetings and above average follow-up. We are especially grateful for the opportunity to be part of a project in Build-in-Wood of which Kraniotis is already a part of. This has been useful and practical. We have reached our goals by getting specific goals and deadlines we must comply with, which has helped us along the way.

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ABSTRACT

This study is written as a part of the Build-in-Wood project, in cooperation with the Norwegian Institute of Wood Technology. The main goal was to evaluate the risk for condensation and mould growth in different nature-based insulating materials, in comparison to mineral wool. The three materials tested as a part of this study were flax fibre, wood fibreboard and glass wool, integrated in a timber-based wall system. Eight different experimental tests were conducted, as all three materials were tested both with a fully ventilated and an unventilated air gap behind the exterior cladding, and as wood fibreboard was tested both with a cement-based cladding and with a wooden cladding. Each experimental test lasted for approximately five days. In addition, two different simulations were conducted in the software WUFI Pro 1D, where the first one was conducted for validation, and the second one was conducted to evaluate the condensation and mould growth risk after 10 years.

Through both the experimental investigations and the numerical simulations, it was revealed that there were no significant condensation or mould growth risk in any of the material. There were some differences between the three materials in properties like thermal transmittance and absolute humidity, where mineral wool was the property with lowest, and therefore best, thermal transmittance, and flax fibre had highest thermal transmittance. In addition, wood fibreboard stood out with a bit higher absolute humidity than the rest. Nevertheless, all materials were within the requirements for at least thermal transmittance, and they all seem adequate for use in a timber-based wall system. When it comes to the exterior cladding and the convection in the air gap behind this cladding, these factors had less impact on the experimental results than initially expected but seem to impact the simulations greater. In the experimental results, most of the properties were quite similar both with and without convection, and with both types of cladding. In the simulations, on the other hand, it became clear that the desired results came with convection, and that the wooden cladding resulted in smaller amounts of mould growth than the cement-based cladding. Besides this, the experiments and the simulations gave approximately the same results, at least when it comes to the condensation and mould growth risk. As there were no significant risk for condensation or mould growth in any of the materials, flax fibre and wood fibreboard can be considered good alternatives when choosing insulating material.

SAMMENDRAG

Denne oppgaven er skrevet i samarbeid med Norsk Treteknisk Institutt, og er en del av prosjektet Build-in-Wood. Oppgavens mål var å evaluere risikoen for kondens og muggsopp i ulike naturbaserte isolasjonsmaterialer, sammenlignet med mineralull. De tre isolasjonsmaterialene som ble testet var lin, trefiber og glassull, alle som en del av en trevegg. Alle materialene ble testet både med og uten konveksjon, og trefiberisolasjonen ble testet både med en sement-basert kledning og med en trekledning. Dette resulterte i totalt åtte eksperiment. I tillegg ble det kjørt to simuleringer i WUFI Pro, hvor den første ble brukt til å validere eksperimentene og den andre ble brukt til å vurdere kondens- og muggsopprisikoen etter 10 år.

Resultatene fra eksperimentene og de validerende simuleringene viser at det ikke er betydelig risiko for kondens i noen av de testede materialene. Ifølge 10 års-simuleringene er det heller ikke betydelig muggsoppvekst i noen av materialene. Egenskaper som U-verdi og absolutt fuktighet varierer litt fra materiale til materiale, hvor for eksempel mineralull har lavest U-verdi, og lin har høyest U-verdi. I tillegg har trefiber litt høyere absolutt fuktighet enn de to andre materialene. Ingen av materialene overgår likevel kravet for U-verdi fra TEK17, og alle ser ut til å være tilfredsstillende for bruk i trevegger. Når det kommer til den utvendige kledningen og konveksjon, hadde begge disse mindre påvirkning på eksperimentene enn forventet, men de ser ut til å ha påvirket simuleringene i større grad. I eksperimentene er de fleste egenskapene omtrent like både med og uten konveksjon, og med de to ulike kledningene, mens det i simuleringene var tydelig at med konveksjon ga bedre resultater, og at trekledningen ga mindre muggsoppvekst enn den sement-baserte kledningen. Utenom dette ga eksperimentene og simuleringene ganske like resultater, spesielt når det gjelder risikoen for kondens og muggsoppvekst. Ettersom det ikke er noen risiko for hverken kondens eller muggsopp i noen av materialene, kan både lin og trefiber anses som gode isolasjonsalternativer.

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ABBREVIATIONS

Abbreviation/Symbol	Explanation	Unit
BiW	Build in Wood	-
CLT	Cross-Laminated Timber	-
HF	Heat Flux	
MCU	Measurement and Control Unit	-
NTI	Norwegian Institute of Wood Technology	-
RH and ϕ	Relative Humidity	[%] and [-]
TC	Thermocouples	-
A	Area	m^2
B_0	Specific permeability	m^2
c	Specific heat	J/(kgK)
D_v	Diffusion rate of water vapour in air	m^2/s
D_w	Moisture diffusivity	m^2s
D_ϕ	Liquid conduction coefficient	kg/ms
g	Diffused amount of steam per unit of time and area	$kg/(m^2s)$
g_w	Liquid transport	$kg/(m^2s)$
h	Total enthalpy	J/m^3
h_v	Latent heat of phase change	J/kg
k_a	Air permeability (=B_0/η)	$m^2/(Pas)$
L	Amount of air	m^3/s
p_{sat}	Saturation vapour pressure	Pa
R_v	The gas constant for water vapour (=461,4)	(Nm)/(kgK)
T	Absolute temperature	K
t	Time	s
T_s	Surface Temperature	K
T_a	Fluid temperature outside the boundary layer	K
w	Moisture Content	kg/m^3
q_{cv}	Heat transport by convection	W/m^2
q_x	Heat flux	W/m^2
h_c	Convection heat transfer number	$W/(m^2K)$
ϕ_A	Heat flow	W
λ and k	Thermal conductivity	W/mK
η	Dynamic viscosity of air (=$18{,}1*10^{-6}$ by 20°C)	Pa*s
Δv	The gradient in water vapour concentration	kg/m^4
Δp_v	The gradient in the partial pressure of water vapour	$Pa/m = N/m^3$
$\nabla \mathbf{w}$	Gradient in moisture content	$kg/(m^3)$ per m
$(dp_t)/(d_x)$	Total pressure gradient	Pa/m
δ_p	Vapour permeability	kg/(msPa)

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1 INTRODUCTION

1.1 BACKGROUND/STATE OF ART

“A sustainable product is a product, which will give as little impact on the environment as possible during its life cycle” [1]. Sustainability and sustainable products are more important now than ever, due to the worlds limited resources and the serious environmental impacts. The problems are related to all the phases in a product’s life cycle, which includes extraction, refinement, transport, products use phase, recycling, and decomposition. All these phases have different impacts on the environment and must be considered when discussing the sustainability of either a material or a building [1].

Today, the building industry is responsible for about 1/3 of the entire planets greenhouse gas emissions. Therefore, one of the most important challenges in the industry today is to reduce the energy consumption in all of the life phases [2]. In fact, in 2016, about 40% of the energy worldwide was used to heat and cool buildings, and in 2015 the European Union (EU) decided on a target of lowering the energy consumption by 50% in 2050. This value is compared to the energy consumption in 1990. The European Union also decided that by 2030, the emissions of domestic greenhouse gases should be reduced by at least 40%, compared to 1990 [3]. In Norway, this target has been increased to 50-55% [4].

One way of contributing to the reduction of both energy and emissions, is to choose more environmentally friendly materials. One example can be to not use mineral wool as the insulating material, but instead choose a nature-based insulating material. This leads us to the main focus of this study, which is nature-based insulating materials used in wooden wall systems. These insulating materials are not widely used at the moment, but the demand seems to be growing. Back in prehistoric times, materials like flax fibre, sheep wool and other nature-based materials were used for both clothes and dwellings. The lifespan of these materials was not good enough for building purposes though, and as the industrial revolution started, new materials like iron, glass, concrete, and steel emerged. Using these materials resulted in lower thermal insulation capacity, greater heat loss and higher heating demands. In other words, the need for thermal insulation increased when these new materials emerged [5]. During the 19th century and the first half of the 20th century, artificial materials like mineral wool and plastic foams appeared. Due to the low production cost, good durability, and good flammability protection, these materials almost completely replaced the nature-based materials for insulating purposes [5, 6]. This was also due to the appearance of iron, glass, concrete, and steel. These materials, as mentioned, were depending on the use of insulating materials, and mineral wool and plastics seemed to be a good solution together with the new building materials. Now, mineral wool and plastics are still the most commonly used insulating materials. In fact, in 2011, these materials were the leading ones in the market. There are two main problems when using these materials. The first one is that producing these types of insulation requires non-renewable materials. The second one is disposal of these materials in their end-of-life-phase. The latter is maybe most relevant for the materials made from plastics, and also a bigger issue for developing countries, which might not have well-defined recycling policies. In addition, some of these countries are struggling with by-products and waste from agriculture, which can be used in nature-based insulating materials instead of being disposed [2].

When reviewing already existing research conducted on nature-based insulating materials, it can be seen that this research has a short history. According to LiFang et al. [7], the earliest research was published in 1974, and the development up until 1988 was small. The reasons for this slow development might be many, but at this time in history, the buildings were used mostly for living or staying, and the energy use and environmental performance of the buildings were not as important. The nature-based resources were rather used for animal food or fuel. In addition, the indoor air quality was not as important as it is now. Today, the indoor air quality plays a huge role for the comfort of the occupants, which also has an impact on the energy consumption. In order to not let this affect the energy consumption too much, thermal insulators with good properties are important. This can be reflected in the increasing number of papers published about nature-based insulating materials after 1988, and especially after 2010 [7].

In addition to the short research history, already existing research can tell something about which countries are most dedicated and which countries that publish the most research. As already known, some countries have more arable land or more forest than other countries, and it would be reasonable to assume that these countries are some of the leading ones when it comes to the amount of research. This does not seem to be the case though. The countries publishing the most research on nature-based insulating materials in the world are France, United Kingdom, Italy, Turkey, and Algeria. As the countries with most arable land in the world are India, USA, Russia, China and Brazil, and the countries with the most forest in the world are Russia, Brazil, Canada, USA, and China, it can be seen that none of the countries publishing the most research are of the ones with the most arable land or forest. The reasons for this could be many, but the initial though was that the lack of research could be due to lack of research resources, like for example money. At the same time, some of the countries with most arable land and forest are quite big countries and not known for being particularly poor. In other words, money might not be the biggest issue for all the countries, but maybe for some of them. The issue might also simply be that some countries are more interested in fixing the environmental issues than others. Another interesting observation, that also strengthens the theory about some countries being more interested in the environmental issues, is that 4 out of 5 of the countries publishing the most research is located in Europe. Many European countries are more concerned and focussing more on environmental protection than other countries, like for example countries from Asia or Africa [7].

By studying the already existing research, one can also create an impression of the properties of the different materials. The overall impression of the thermal properties from the existing research is that nature-based insulating materials are good materials, but not good enough to be expected to surpass mineral wool's properties. It seems like flax fibre, sheep wool and cellulose are the ones with the best thermal properties, while wood wool board, wood fibreboard and hemp fibre are not as promising, as can be seen in Table 1, where the thermal conductivity of the different materials are listed. The thermal conductivity in this table is taken from the reviewed research discussed in this paragraph. For flax fibre, the thermal conductivity is below 0.05W/mK for many different manufacturing methods [8-11]. For sheep wool, Zach et al. [12] claims that this material has excellent thermal properties that can be compared to mineral wool, while [13] claims that cellulose has a thermal conductivity between 0.040 W/mK and 0.050 W/mK, which is quite good. In fact, Abu-Jdayil et al. [3] talks about fibrous materials in general and claims that these materials are very good thermal insulators, as they capture air within the fibres and in this way prevents heat transmission. They also minimize the collisions between gas molecules, which reduces gaseous heat conduction. For the remaining materials (wood wool board, wood fibreboard and hemp fibre), the properties are not as promising, as mentioned. According to

Boszaky [5], the thermal conductivity of a wood wool board is somewhere between 0.070 W/mK and 0.090 W/mK, while the thermal conductivity of a wood fibreboard is somewhere between 0.040 W/mK and 0.090 W/mK. The thermal conductivity of hemp fibre insulation is between 0.031 W/mK and 0.073 W/mK [10, 11, 14, 15]. As can be seen through these numbers, the thermal conductivity is varying a lot, especially for wood fibreboard and hemp fibre. According to Boszaky [5], a thermal conductivity below 0.070 W/mK can be considered a thermal insulator, meaning that both wood fibreboard and hemp fibre can, in some cases, be categorised as good thermal insulators, and is therefore not as bad as presumed. It should also be mentioned that even though materials like wood fibreboard can have a thermal conductivity as high as 0.090 W/mK, according to the reviewed research, it is possible to find products in Norway with lower thermal conductivity. Examples of this can be found in Table 1.

Table 1: Thermal Conductivity of some nature-based insulating materials, based on the reviewed research.

Material	Thermal Conductivity [W/mK]
Wood fibre	0.040-0.090[1]
Wood wool board	0.070-0.090
Hemp fibre	0.031-0.073
Flax fibre	< 0.050
Sheep wool	< 0.050
Cellulose	0.039-0.050
[1] Wood fibreboards with lower thermal conductivity are found in Norway. One example of this is a wood fibreboard delivered by Hunton with a thermal conductivity of 0.038 W/mK [16].	

Another way of determining the thermal properties of a material is to measure the thermal diffusivity, which is often used in the unsteady state. The thermal conductivity, as mentioned in the last paragraph, is often used in the steady state. According to Durakovic, Yahia and Yildiz [17], which investigates these materials as a group and not as individual materials, the thermal diffusivity of renewable insulating materials is significantly lower than the thermal diffusivity of petrochemical insulating materials. Petrochemical insulating materials are materials like expanded polystyrene and extruded polystyrene. Having a low thermal diffusivity is more desirable than a high thermal diffusivity, as the thermal diffusivity measures how fast heat travels through the material. In other words, you do not want heat to travel fast through your outer wall, so a low thermal diffusivity is desirable [17].

Some properties that are closely connected to the thermal properties are the moisture properties. This can include for example water absorption capacity, moisture content, moisture diffusivity, moisture buffering value, and water vapour permeability. The way that these are connected with the thermal properties of a material is simply that increasing the amount of moisture in a material will worsen the thermal properties for almost every insulating material. In other words, you do not want much moisture in your insulating layer. For the nature-based insulating materials, the moisture properties vary. If you look at flax fibre insulation, the water absorption capacity is 5.02 kg/m2, and the moisture content is about twice as high as it is for mineral wool, according to Jiri and Jitka [10]. As already stated, moisture in the insulation worsen the thermal properties, meaning that both the water absorption capacity and the moisture content should be as small as possible. In other words, according to this study, flax fibre insulation cannot compete with mineral wool when it comes to the moisture properties. In the same study, also insulation made from hemp boards were investigated. The water absorption capacity was measured to be 7.67 kg/m2, which is even worse than for flax fibre [10]. Another material that is included in already existing research is sheep wool. This material was studied by both Ahmed and Qayum [18] and Zach et al. [12]. There it was found that the moisture content in the investigated sample of sheep wool is 10.12%, which is quite high compared to other materials [18]. One of the benefits of using sheep wool though, is that this particular material can handle high moisture content quite well. It is one of the materials that absorbs quite a lot of moisture before it starts affecting the thermal properties. In other words, sheep wool can be a good thermal insulator even if the water content is high [12, 18].

In addition to moisture content and water absorption capacity, other mentioned moisture properties are moisture diffusivity, moisture buffering value and water vapour permeability. When studying already existing research it can be seen that for cellulose, all of these three properties has been measured. According to Hurtado et al. [19], the moisture diffusivity of cellulose is somewhere between $5*10^{-8}$ m/s^2 and $1.2*10^{-7}$ m/s^2, and the moisture buffering value is 3.06 g/(m^2*%RH) [19]. According to Rode et al. [20], a moisture buffering value above 2.0 g/(m^2*%RH) is defined as excellent. This means that the moisture buffering value of cellulose is quite good. Hurtado et al. [19] also measured the water vapour permeability of cellulose which ended up being $177\pm29*10^{-12}$ kg/(Pa*m*s). Comparing this to the water vapour permeability of mineral wool, which is $115*10^{-12}$ kg/(Pa*m*s), it can be stated that cellulose would let more water through the wall than mineral wool would. Another problem about cellulose that has been mentioned is that its reaction to moisture is not good enough. It seems like when cellulose is exposed to moisture it increases the thermal conductivity quite a lot, and it therefore has to be replaced once every five years [3, 13]. According to [21], on the other hand, cellulose is quite durable. In this case, the word durable has not been elaborated, so it is difficult to know how long a durable material is expected to last according to Goyal et al. [21].

As already mentioned, the thermal properties are influenced by the moisture properties of a material. But there are also other properties that affects the thermal properties of a material. One of them is the density. Density is mentioned quite a lot in many of the reviewed studies, and one statement is mentioned several times, by for example Hussein et al. [22] and Lazzaretto et al. [7]. The statement is that increasing the density of a material also increases the thermal conductivity of the material. This happens because when increasing the density, the proportion of solid components increase, compared to the proportion of not solid components [22]. Another way of explaining it is that when the density increase, the porosity decreases, and decreasing porosity also increases the thermal conductivity and worsen the thermal properties [7].

As will be described later, the most important properties in this study are the hygrothermal properties. Despite this, existing research about properties like fire and acoustics of the different nature-based insulating materials should be included. Fire resistance is not directly connected to this study or to the experiments that will be conducted, but fire is an important factor simply due to the safety of human lives. The general impression about the fire properties for nature-based insulting materials is that they are not well suited and that their fire resistance is bad. This impression is supported by Abu-Jdayil et al. [3], who concluded that biobased insulating materials in general have poor fire resistance. In addition, Zach and Hroudová [10] investigated the fire resistance of both flax fibre insulation and hemp fibre insulation, and both ended up in fire class E. This implies that the material has a significant contribution to fire, and that the fire most likely will spread significantly before 2 minutes has passed [10]. Another insulating material with bad fire properties are cellulose. According to Hurtado et al. [19], cellulose is a material that has high flammability and therefore need treatment before it can be installed [19]. In other words, the impression that many of the nature-based insulating materials has bad fire properties seems reasonable. When it comes to the acoustic properties, these do not stand out much, neither as excellent, nor as terrible. Some of the nature-based insulating materials meet the requirements and can therefore be used in civil engineering, while other do not.

As mentioned, the focus for this study will not only be the insulating materials, but the use of insulating materials in wooden wall systems. Wood is, in other words, an important part of this study. Wood is a renewable material that has little negative impact on the environment. Wood also absorbs and stores CO_2. It is easy to produce, and can often be found locally, at least in Norway. In addition, it has relatively good insulating properties, which makes it easier to avoid thermal bridges than it is when using for example concrete or steel. Using wood as a buildings load-bearing system is also possible, as the material has high strength compared to its weight. It is also quite flexible. This flexibility can also be seen when wood is exposed to varying moisture contents. When this happens, the material can change its dimensions. It can either expand or shrink. If the moisture content gets high, normally above 20%, the risk for mould growth increases. If the moisture content stays this high for a long time, the wood can rot. This is one of the challenges with wooden buildings [23, p. 86-91]. As this study will focus on nature-based insulating materials in wooden buildings, mould growth will be an important factor to evaluate. Nature-based insulating materials are not as well-known and used as mineral wool, meaning that their handling of both mould growth and moisture in the wall is not as well known. This is therefore interesting and important to do some research on.

Both in Norway and in the world in general, wood has been used for buildings for many years, actually all the way back to the stone age. Throughout the years, it has been used in different ways though. Some of the wooden constructions throughout the years have been longhouses, log cabins and timber frames. For many years, wooden buildings were built without any insulation, which can be seen in for example the log cabins. These are made from quite big logs, whit no cavity for insulation. Today, most wooden buildings are either made as timber frames, which could also be described as buildings with stud walls, or they are made as for example cross-laminated timber. The buildings made with stud walls has been used for quite a long time and has therefore also gone through some development. In the beginning, this construction type was used mostly for buildings that did not require any heat insulation, like for example boathouses. After a while, when this type of construction became more common for houses, it became normal to use brickwork in the cavities. This was particularly common in Christiania, but not that common in the rest of Norway. Later, it became more common to use insulation in these cavities instead, but the insulation that was used was sawdust, shavings etc. Nevertheless, when mineral wool was introduced in Norway, this became the most common way of insulating the stud walls. Today, the stud walls with mineral wool are still one of the most common ways of constructing buildings in Norway, even though CLT are emerging [23, p. 9-13].

1.2 PROBLEM STATEMENT AND HYPOTHESIS

This study is conducted in collaboration with the Norwegian Institute of Wood Technology (NTI) and the supervisor from OsloMet, Dimitrios Kraniotis. It is a part of the Build-in-Wood (BiW) project and will be an experimental investigation of the hygrothermal performance of wood-based wall systems with nature-based insulating materials. In the process of deciding what the master thesis should include, a big focus area was the use of cross-laminated timber (CLT). During the five years of studying at OsloMet, there has been a lack of courses containing wood and timber, so the interest in learning more about this became even bigger. The initial wish was therefore to include CLT in the experimental investigation, but this was neglected after a while. At the end, it was decided to focus on the insulation materials in a normal stud wall, and also a bit on the exterior cladding. This way, both nature-based insulating materials and wood were included in the study. Considering the environmental issues the world is facing today, this is an important topic, and the industry are always trying to find new and better solutions to fit the world's needs. The problem statement is therefore:

Evaluation of the risk for condensation and mould growth in nature-based insulating materials integrated in timber-based wall systems.

To answer this problem statement, three different insulating materials, mineral wool, flax fibre, and wood fibreboard, will be tested in the laboratory at NTI, measuring the temperature, the relative humidity (RH) and the heat flux in the elements. The elements will also be tested with two different types of cladding: a cement-based cladding and a wooden cladding treated with fire resistance. In addition, all materials will be tested both with and without convection in the air gap behind the exterior cladding. The procedure of the experiments will be explained in detail in chapter 3. The goal is to get enough measurements to be able to evaluate the risk for condensation and mould growth. It is also desirable to investigate and evaluate if the hygrothermal properties of the materials tested in this study can come close to the hygrothermal properties of mineral wool, both placed in a wall made from wood. In addition to the experimental investigations, two different kinds of numerical simulations will be conducted in WUFI Pro 1D, as will be explained in detail in chapter 3.

Based on early investigations in the BiW-project, some thoughts have been done around what results to expect from the experimental investigations. First of all, it is expected that flax fibre will have better hygrothermal performance and less risk for mould growth and condensation than wood fibreboard. Secondly, using cement as the exterior cladding is expected to worsen the condensation and mould growth risk, as wooden claddings, both with and without fire retardant, has had better performance than cement claddings in earlier investigations. Last, but not least, it is expected that natural convection will have a big impact on the moisture problems. From early investigations, it is seen that when the air cavity behind the exterior cladding is fully ventilated through natural convection, the risk for moisture problems is reduced. Through experimental investigations and numerical simulations, these hypotheses will be challenged, and either rejected or strengthened.

1.3 LIMITATIONS AND DELIMITATIONS

When conducting this master thesis, a list of delimitations was decided in order to define the study and make the workload reasonable. In the following subchapter, the delimitations will be explained and accounted for, in addition to the limitations. Some of the limitations were known before hand, while others occurred during the semester.

1.3.1 Delimitations

As already mentioned, one of the big delimitations was to exclude cross laminated timber from the experiments. This was decided in order to investigate the insulating materials thoroughly and not have too many variables in the experiments. Another reason for this decision was that the time was limited. In order to ensure a good progress, a schedule for the whole semester was made. When creating this schedule, it was decided that in order to finish the study in time, all the experiments should be conducted before the easter holiday, or in other words by the end of week 14. The experiments were expected to take approximately 8 weeks, and in order to make the most of those weeks, it was decided to neglect CLT. In addition to neglecting CLT, other nature-based insulating materials were neglected. As mentioned, this study is a part of an ongoing research project with NTI, where several insulating materials are being tested. Due to limited time, only two of these materials are included in this study.

1.3.2 Limitations

As for everything else happening the last two years, Covid19 became a slight limitation for this project as well. The year started with lockdown and home office, making it harder to find motivation in the early stages. After only a few weeks, it was luckily possible to meet in person and work from OsloMet or the office at NTI. Due to the Covid restrictions being taken away, sickness in general, both Covid19 and other sicknesses, became a slightly limiting factor. Both the authors experienced sickness at different times, making the progress of the study slow at times. In addition, time was a limiting factor. The elements to be tested in the laboratory at NTI were delayed, which led to the whole schedule of the study being delayed as well. Nevertheless, this was not a major issue, and the experiments were conducted as planned, just a few weeks later than planned, but still before the end of week 14. In the meantime, other tasks could be conducted, like writing methods and theory.

Another challenge and limitation for this study was to make sure that the numerical simulations and experimental investigations were as identical as possible. In the simulation software, WUFI Pro, the transportation of air and moisture through the elements happens in only one direction. In the experiments, it was reasonable to think that this transportation would happen in several directions. The only way of monitoring this was to mount sensors in two different heights in the elements. Due to limited number of sensors, this was not done and the transportation of air through the element was not monitored. One can therefore not know if this transportation happened in one or several directions, and how big the deviations between the experiments and WUFI are. Another deviation between the experiments and WUFI was the material data. This will be explained in detail in chapter 3.4, but the main issue was that the materials used in WUFI were not identical to the materials used in the experiments. As much data as possible were gathered about the experimental materials, but the input data in WUFI were still not identical. These deviations must be considered when evaluating and discussing the results.

1.4 STRUCTURE OF THE THESIS

This thesis consists of seven chapters: Introduction, Theoretical Background, Materials and Methods, Results, Discussion, Conclusion, and Further Research.

In the first chapter, Introduction, some background information, and already existing research are reviewed, before the problem statement and the goal of the study are described. Then some limitations and delimitations are explained. In chapter 2, Theoretical Background, the most important theory to know when reading this study are presented. This includes some theory about heat transfer, moisture transfer and mould growth.

In chapter 3, Materials and Methods, the methodology used in this study is presented. This includes the experimental procedures and the procedure for the simulations. In addition, some background information about the insulating materials is reviewed. In chapter 4, Results, all the results gathered through experiments and simulations are presented. In chapter 5, Discussion, the results are being discussed in conjunction with the theory and the already existing research from chapter 1.

In chapter 6, Conclusion, a conclusion is made based on the discussions conducted in chapter 5. In chapter 7, Further Research, some suggestions to further research are being presented, based on the research conducted in this study.

2 THEORETICAL BACKGROUND

The ability of the air to emit and absorb moisture is of central importance in the treatment of almost all moisture problems. All materials that come in contact with moisture in vapour or liquid form will absorb more or less moisture. The exception is materials with completely closed pores, such as glass and metals. The materials in building constructions thus always contain a certain amount of moisture. This moisture could come from the production phase, or from contact with moist air in the surroundings or free water from precipitation, leaks, the ground etc. The moisture content of a material depends on the type of material, the properties of the pore system and the form of moisture bonding that occurs. The moisture effects the material has been exposed to before (the moisture history), will also usually have an effect on the moisture content at a given time [24, p. 289-327].

In this chapter, emphasis will be placed on understanding heat transfer, moisture transport and mould growth. By knowing these key concepts, the reader can easier keep track and understand what's being discussed and presented by results. The chapter is divided into three subchapters, where each of the key concepts are mentioned. Heat transfer is again divided into four subchapters which describes the four heat transport mechanism: convection, heat conduction, latent heat, and radiation. Moisture transfer is divided into three subchapter which describes water vapor diffusion, moisture convection and capillary transport. The last chapter about mould growth isn't divided into any subchapters but describes mainly the establishment and growth of mould.

2.1 HEAT TRANSFER

When assessing or calculating the moisture condition or moisture transport, one must have knowledge of the thermal conditions. Several of the moisture properties vary with temperature, like for example the saturation pressure of the water vapour, which is largely dependent on the temperature. In addition to the fact that temperature differences in themselves can give rise to moisture transport. It is therefore necessary to have some basic knowledge from the thermodynamics, so that one can analyse the temperature condition and heat flow conditions in and on the structures. Basic quantities such as temperature, amount of heat, heat flow, specific heat capacity and latent heat, on the other hand, are given that the reader has knowledge of. In this chapter, a brief review of the elementary theoretical basis for calculating heat transport will be given [24, p. 309].

To explain heat transport, it is important to mention the heat transport mechanisms. Heat can be transferred in four different ways in a material or in a building part. These four ways are convection, heat conduction, latent heat, and radiation. All heat transport processes include one or more of these mechanisms [25, p. 53]. In order to understand heat transport in best possible way, an explanation must be given in terms of temperature changes and what role temperature has when it comes to heat transport. Temperature is an expression of the energy state of the molecules and the second law of thermodynamics states that where there is a temperature difference, there will always be a transport of energy, so that heat is transferred from a higher to a lower temperature level, but never the other way around [26]. In this chapter, most emphasis will be placed on convection, heat conduction and latent heat, but a brief explanation of radiation will also be given.

2.1.1 Convection

In a flowing fluid (a liquid or a gas) an energy transport takes place by the fluid with its internal energy moving. The term convection refers to the heat transfer that occurs between a surface and a fluid in motion when the surface and the fluid have different temperatures. Heat transport by convection is a complex process which is partly due to the fluid being heated or cooled by conduction in a thin boundary layer at the material surface, where the flow rate is small, and partly because heat is transferred by the fluid flowing and mixing with surrounding fluid [24, p. 313].

The heat transport by convection depends on the nature of the fluid (in a building context it is usually air), condition, temperature, flow form (laminar or turbulent) and on the surface temperature, orientation in relation to gravity, roughness, shape and dimension [24, p. 309]. Convection can be divided into two main groups where the main force for the flow is the biggest difference. If the flow is due to temperature differences, i.e., buoyancy forces, it is a matter of natural convection. If there on the other hand is external influences, such as a pump, fan or wind, which determines the flow, it is a matter of forced convection. Depending on the flow situation, we also distinguish between external flow, when an unlimited fluid flows over a surface, and internal flow when the fluid is completely enclosed by solid surfaces [25, p. 58].

The convection process exchanges sensible heat in addition to the exchange of latent heat in some situations. For example, by evaporation or condensation on the surface. The heat transport q_{cv} [W/m^2] by convection from a material surface to a fluid is usually described by means of a convective heat transfer number h_c [W/(m^{2}K)], as shown in Eq.1. The heat transfer number h_c can vary within wide limits and must be determined experimentally for given conditions [24, p. 309].

$$q_{cv} = h_c * (T_s - T_a) \qquad [1]$$

2.1.2 Heat Conduction

Heat through conduction, called heat conduction, occurs by the transfer of kinetic energy between the molecules in various substances. In practice, if we consider building materials in a house, it will be from hot to cold side [26]. Heated molecules transfer some of their kinetic energy to colder and more energy-poor molecules through collisions. Heat conduction occurs in both solids, liquids, and gases. Such a net transport of energy due to molecular motion is also called energy diffusion [24, p. 309]. Some materials conduct heat better than others, i.e., they have a higher thermal conductivity. Metal is an example of a good heat conductor, which means that the heat is transferred quickly. Mineral wool, on the other hand, is a poor heat conductor, which makes it a suitable insulating material [26].

The basis for all computational processes of heat conduction is Fourier's heat conduction law. This law states that heat flux q_x [W/m^2] in a given direction, e.g., x – direction, is proportional to the temperature gradient, $\frac{dT}{dx}$, in this direction and opposite of the temperature gradient, shown in Eq.2. The heat flow ϕ_A [W] through an area A [m^2] normally in the heat flow direction becomes as shown in Eq.3. The minus sign on the right side of the equations expresses that the heat always flows towards decreasing temperature. The proportionality factor, λ [W/mK], is a material factor and is called thermal conductivity. The higher the λ of a substance, the easier it conducts heat [25, p. 53].

$$q_x = \frac{dQ_x}{dA*dt} = -\lambda * \frac{\partial T}{\partial x} \qquad [2]$$

$$\phi_A = A * q_x = -A * \lambda * \frac{dT}{dx} \qquad [3]$$

2.1.3 Radiation

Heat radiation can be defined as electromagnetic waves, where the waves propagate in a straight line and at the speed of light, corresponding to light and radio waves. The radiation from a surface occurs over a wavelength range, over a spectrum that depends on the temperature of the surface. The wavelength depends on the temperature, where the higher the temperature of the surface, the shorter the wavelengths are radiated. In the infrared range, radiation is found from surfaces with normal ambient temperatures (-30 to +50°C) that are invisible. They have an energy maximum at about 10 µm. Solar radiation has a spectral distribution corresponding to a surface temperature of about 6000 K. This is a surface temperature with significantly shorter wavelengths, where the energy maximum is at about 0.5 µm. A distinction is made between long-wave and short-wave (solar) radiation in the context of building technology. Heat radiation can occur through most gases and through certain types of liquids and solids. Heat can be transferred through vacuum by radiation, as opposed to by convection and conduction. Radiation occurs both inside the cavities and pores of the building component, and against internal and external surfaces [24, p 314]. To make a more practical example, one can imagine the human body in a house. All surfaces that are heated, radiate infrared radiation. When a material emits heat radiation (infrared radiation), it heats solid, colder materials around it, until they have the same temperature (equilibrium). Unfortunately, there is very little you can do with this radiation, but with good insulation, one can reduce this radiation somewhat [26].

2.1.4 Latent Heat

In case of phase changes, the heat content of the substance changes without changing the temperature. That is, by the transition between solid and liquid or between liquid and gas. This type of change in heat content is called latent heat. Latent heat is often related to mass, so that the unit becomes J/kg [24, p. 290]. When it comes to the convection process, in addition to the exchange of sensible heat, in some situations latent heat will also be exchanged, for example by evaporation or condensation on the surface [24, p. 313]. A factor which may influence the heat loss, is the transport of latent heat, i.e., evaporation or condensation. This effect can be particularly significant in steam-open insulation materials that are moist and exposed to large temperature gradients [24, p. 48].

2.2 MOISTURE TRANSFER

Moisture migration includes both sorption of water vapour from the air and capillary suction. In this chapter, the various forms of moisture transport will be reviewed in more detail. It will be reviewed which physical processes take place and which parameters determine how large amounts of moisture are transported. The transport mechanisms will first be presented in general and then separately. This will hopefully form the necessary basis for later being able to carry out computational analyses of the moisture condition in building structures [24, p. 327].

Vapour diffusion, capillary transport and to a certain extent convection are the transport mechanisms that are relevant and possible to treat computationally in connection with building structures. In addition, these are the modes of transport that have the greatest practical significance. Water vapour diffusion and effusion are due to the natural movements of the water vapour molecules. Differences in the partial pressure of water vapour are here usually dominant as a driving force [24, p. 328].

Moisture convection occurs by air flow through a structure or a material where the water vapour content of the air will give rise to moisture transport. The driving force for such an air flow is differences in the total air pressure. In terms of calculation, such moisture transport is difficult to handle as local irregularities such as cracks, fissures, leaks in joints etc., has a great impact on the course of the air flow [24, p. 328].

Capillary conduction is defined as the transport of water in water-filled pores due to differences in pore water negative pressure. Even at low moisture content in the hygroscopic area, the smallest pores will be filled with water. Transport speed and then transported water volume is therefore correspondingly small. Its only with moisture content that provides a continuous network of water-filled pores ($w > w_{cr}$) that the capillary conduit becomes dominant [24, p. 328]. In addition to the three mentioned mechanisms for moisture transport, there are several mechanisms that may have practical significance in a building context, but the focus will mainly be on these three.

2.2.1 Water vapour diffusion

The water molecules have an enormous freedom in the vapour phase which means that the speed they have will always tend towards an equalization of the concentration in an enclosed space. Any differences in the partial pressure of water vapour will gradually level out. This applies regardless of whether the water vapour is mixed with other gases, and even if the total pressure and temperature are constant throughout the room. The result of this is that water vapour molecules penetrate into a dry, porous material when this is placed in moist air. Such transport of water vapour is called diffusion [25, p. 323].

In a space where the vapour concentration varies for different coordinate points, it will diffuse vapour molecules from higher to lower concentration. Under isothermal conditions, this current can be expressed by Eq.4 (Fick's law of diffusion) [25, p. 323]. With a constant temperature, the steam flow will only depend on the diffusion number of the water vapour and the change in concentration per unit length. The minus sign on the right is due to the steam flow going towards lower concentration/partial pressure. By looking at the one-dimensional case, the analogy with the heat conduction equation is $\mathrm{q} = -\lambda * \mathrm{dT}/\mathrm{dx}$. One can see that the temperature gradient drives the heat flow and the concentration gradient drives the steam diffusion [25, p. 324].

$$g = -D_v * \Delta_v = -D_v * \frac{1}{R_v * T} \Delta p_v \left(\frac{kg}{m^2 s}\right) \qquad [4]$$

2.2.2 Moisture convection

There are other forms of moisture transport in the steam phase than diffusion which can play a large role in real buildings, like for example moisture convection [25, p. 325]. Moisture convection means that water vapour is transported with an air flow from high air pressure to low air pressure. In some situations, convection can lead to the transport of large amounts of air and thus also large amounts of water vapour. Moisture convection can occur in cracks, holes and porous materials. To determine the moisture transport, one must first determine the air flow [24, p. 331]. By Darcy's law, one can calculate the amount of air flowing through a porous material due to an air pressure difference, as shown in Eq.5. The minus sign on the right side of the equation indicates that the air flow takes place in the direction of decreasing pressure. Darcy's law applies only to laminar power. Calculation of air flow through cracks and holes is therefore somewhat more complicated [24, p. 332]. By knowing the air volume R and the air vapour content v of the air, it is possible to calculate how large amounts of moisture can be transported through a material, a leak or a construction due to forced convection as shown in Eq.6. Moisture transport by convection is in practice a much more frequent cause of condensation problems in the outer structures than moisture transport by diffusion. Air tightness is therefore incredibly important to protect against moisture damage [25, p. 326].

$$L = -A * \frac{B_0}{\eta} * \frac{dp_t}{d_x} = -A * k_a * \frac{dp_t}{dx} \qquad [5]$$

$$G = R * v \ (kg/s) \qquad [6]$$

2.2.3 Capillary transport

The capillary forces provide fluid transport in the narrowest pores even at a relatively low moisture content. The total moisture transport in the hygroscopic moisture content range is described by means of the diffusion as shown in Eq.7, despite the fact that flow in narrow pores gives small and slow transport. The vapour permeability varies with the moisture content [24, p. 334].

The liquid transport becomes dominant at higher moisture content and in part much larger than the water vapour transport. The process takes place by a combination of surface creep and capillary conduction. Capillary conduction is strictly defined for moisture content above the critical level (w_{cr}), but it is practically impossible to distinguish these processes from each other. The total liquid transport, g_w [kg/(m^{2}s)], is often described as a potential current, corresponding to diffusion, with the moisture content, w [kg/m^3] (possibly u [kg/kg]), as potential and a transport coefficient, D_w [m^2/s], which varies with the moisture content, as shown in Eq.8. This assumes that the liquid flow at any location is proportional to the gradient in moisture content. If one considers the absorption of water in a single capillary, this condition is not fulfilled. The gradient in the moisture content is therefore equal to zero everywhere, apart from the meniscus, where the gradient is "infinitely large" [24, p. 334].

$$g = -\delta_v * \frac{dv}{dx} = -\delta_p * \frac{dp_v}{dx} \qquad [7]$$

$$g_w = -D_w(w) * \nabla w \qquad [8]$$

2.3 CONDENSATION

By condensation, liquid is formed by densification of vapour or gas [27]. Condensation is the transition from gas to liquid or solid. In the process of condensation, both gas and liquid or solid are present. When the temperature of the gas drops to the boiling point for the liquid or to the sublimation point of the solid, condensation occurs [28]. A common example might be when boiling water in a kettle and the lid is filled with water droplets beneath.

When speaking of humidity, heated air can absorb more moisture than cold air, but at a given temperature, there is an upper limit to how much water vapour in the air can hold. By increasing the water vapour content, the air can no longer hold and some of the water vapour will condense into water droplets. Since heated air can hold more moisture than cold air, condensation occurs when the water vapour gets cooled. This happens when the temperature has reached dew point [29]. Condensation can cause rot damage and mould growth on organic materials such as stud wall of wood, explained in more detail in the next chapter.

2.4 MOULD GROWTH

Moulds are fungi that grow at an enormous rate while producing large amounts of fungal spores, various organic compounds, and toxins (mycotoxins). Spores are the reproductive units of the fungus. In comparison, rot-fungi do not grow as fast, but can be very harmful in the sense that they break down the wood and can cause serious damage that impairs the load-bearing capacity. For the fungus to grow, it needs nutrients, moisture, a favourable temperature, and time [30].

Moulds thrive in buildings, as the nutrition they live on are organic materials that are abundant in buildings. Cellulose-containing material is the material that is mainly attacked indoors. Inorganic surfaces can also be an exposed area, where binders, plasticizers and dust contaminants can settle and provide a sufficient nutritional basis for growth. Under favourable growth conditions, all materials and surfaces can in principle be attacked by moulds [30]. When it comes to moisture, the moulds have different levels at which they thrive to grow in. Most moulds require over 80-85% relative humidity (RH) indoors on the material surface or in pores in the material surface to grow. In such a situation you get a water content of approx. 20% by weight in wood at 20°C. At higher RH, you get more species with good growth conditions where the growth rate increases with the moisture level. When you reach a humidity of over 90%, you will find a mixture of different organisms, where yeast and rot fungi, bacteria, mites, and various insects often occur at the same time as mould. The growth stops when it dries out but does not disappear completely. The spores can survive and start new growth with access to new moisture [30].

The different moulds have different temperatures they thrive in to grow. Most species thrive around 25-30°C, but some species can also thrive at lower temperatures. At 0°C the growth stops, but the moulds do not die out. The moulds only go dormant and usually survive the freezing. If, on the other hand, we get higher temperatures up to 40-50°C, most moulds die. At temperatures 25-30°C the growth rate is reduced. This also applies to rot fungi [30].

Something that can lead to immediate growth conditions for moulds is water damage indoors. Fungal infections can occur just after a few days. Spores that by natural indoor occurrence are accumulated in dust, or that have been supplied through the air, can germinate at almost the same moment, and quickly lead to the development of damage [30]. With high or varying humidity over a long period of time, mould can grow over weeks or months. Exposed places can be in unheated attics and crawl spaces. By being aware, one can detect the mould early and take countermeasures. This due to a slow and gradual development of damage [30].

3 MATERIALS AND METHODS

3.1 EXPERIMENTAL INVESTIGATION AND NUMERICAL SIMULATION

In this study, the two research methods used are experimental investigations and numerical simulations. An experimental investigation is a quantitative method, and "seeks to determine if a specific treatment influences an outcome" [31, p. 13]. In other words, the observers manipulate the variables expected to influence the outcome and are then able to observe the outcome. This way, the observers can manipulate only the factors they think will affect the results, based on their hypothesis. A numerical simulation is, in one way, quite similar to an experimental investigation. In both research methods, different variables are changed to see which effect these variables has on the result. The biggest difference between a simulation and an experiment is that a simulation is a representation of a real system on a computer, while an experiment is a representation of a real system in a laboratory. An experiment is also often scaled down to make it possible to conduct, while a simulations is not [32].

For this study, the experimental investigations conducted will be described in detail later, but the main idea is to change the insulating material and the exterior cladding in a stud wall to examine the changes in temperature, relative humidity, and heat flux. In addition, the convection in the air gap behind the exterior cladding will be a manipulated variable. When it comes to the numerical simulations, these will mainly be used to investigate how the different materials behaves after 10 years, as the experimental investigations only lasts for 5-6 days. Before doing this though, the numerical simulations must be validated to make sure that they are similar enough to the experimental investigations. In other words, there will be two different types of numerical simulations: short-term simulations and long-term simulations. All numerical simulations will be conducted in WUFI Pro 1D. In addition, in the long-term simulations, WUFI Bio will be used to extract data.

3.2 INSULATING MATERIALS

In this subchapter, the insulating materials to be tested in the experiments are presented. These materials are flax fibre insulation, wood fibreboard insulation and mineral wool. The mineral wool will function as a reference material, and both flax fibre and wood fibreboard will be compared to the properties of mineral wool, in addition to being compared to each other.

3.2.1 Flax Fibre

One of the materials that will be studied is flax fibre. Flax fibre is a material that has been used both in buildings and in clothes for a long time. Back in prehistoric times, flax was used for clothing and ropes, but also for dwellings. After a while, using flax for dwellings were not desirable anymore, as its lifespan was limited and the need for more durable materials started to grow. Now, using flax fibre in insulation is becoming more relevant again. Flax fibre used as insulation is made from flax stalks and are available as both rolls and boards. The first products made of flax for insulation purposes were developed in the United States around 1910 and it has been developed since then. In the 19th century, artificial materials like mineral wool, were developed. This resulted in a setback for the research and development of nature-based insulating materials like flax fibre, but it now seems like the interest and focus is returning to these materials again [5]. In Norway, the cultivation of flax was important until around the 1800s, when cotton arrived. Cotton was cheaper and easier to produce, and therefore preferable.

Even though the cultivation of flax increased again around World War II, it has now decreased, and is cultivated in a smaller scale than earlier [33]. In other words, flax is not a material that is easy to obtain without some transport costs and emissions.

Some of the benefits of using flax fibre insulation is that the flax fibres are hollow. This makes the material better at keeping the insulating air inside the fibres, which results in good thermal properties. In addition, flax fibre insulation can handle quite a lot of water. In fact, it can store twice of its own weight. Also, when the flax fibre insulation gets wet, it will still keep its thermal properties, even with high humidity, and it also dries out fast. The flax fibres will always try to keep the moisture content constant and natural, and the moisture will be transported towards the exterior side of the wall. It is therefore important that the moisture is able to leave the wall through the exterior side, and that the wall is more open for diffusion on this side than on the interior side. The best way to do this is by using a wind barrier with low water vapour diffusion resistance, and to have an air layer behind the outer cladding [34]. In Figure 1, an example of flax fibre insulation can be seen.

Figure 1: Flax Fibre

3.2.2 Wood Fibreboard

The second nature-based insulating material tested in this study is wood fibreboard. Wood fibreboards were originally produced as a sidestep from the production of paper and they were made of unreliable materials. Later, the steam explosion process and the steam-pressurized refining process led to a huge success making fibreboards. William Mason was the developer of the steam explosion process in 1924 and Arne Asplund the developer of steam-pressurized refining process in 1931. Both methods had their advantages, but a common disadvantage was that they had high water consumption, in addition to using a lot of electricity [5].

Wood fibreboards are made of wood chips which are treated in a wet or dry process where the fibres are extracted. The next step in the production process is to add glue before mat formation and heat pressing happens. Mat formation and heat pressing are suitable for adjusting the bulk density of the end product. At final, conditioning, edge-finishing, and grinding remains. Thermal insulation fibreboards usually have a bulk density of 200-400kg/m^3 [5]. Wood fibreboards with low density have good thermal and sound insulation and is also recyclable. According to Boszaky [5], the thermal conductivity of a wood fibreboard is somewhere between 0.040-0.090 W/mK. Bozsaky also claims that a material with thermal conductivity lower than 0.70 W/mK is usually considered a thermal insulator, which means that wood fibreboard can be either depending on the specific case [5].

When it comes to the moisture properties, wood fibreboard has low water absorption capacity in addition to resistance to vapour permeation. In [14], Andzs and Skrupsis measured the water absorption capacity in several insulation materials including wood fibre. The study shows that the different insulation materials had different water absorption capacity and the test proved that more moisture in the insulation would reduce the thermal properties for most materials, meaning that a high-water absorption capacity is not wanted [14]. Figure 2 shows the wood fibreboard used in this study.

Figure 2: Wood Fibreboard

3.2.3 Mineral Wool

The last insulating material included in the experimental investigations are mineral wool. Mineral wool is a group of insulating materials that arrived during the 19th century. Before its arrival, the common insulating materials were based on natural materials, but from the 19th century mineral wool became the new standard. This was due to the low production cost of mineral wool, in addition to these materials not having the same durability and flammability issues as natural materials had [5]. Today, mineral wool is still the most common material used for insulation. Mineral wool includes, among other things, glass wool and rock wool. Neither glass wool nor rock wool are combustible, but rock wool's melting point is higher than glass wool's, making it even more fireproof. In addition, none of them absorbs moisture or smell. When these insulating materials are produced, the glass or the rock is grinded into small particles, before it is melted at high temperatures. The melted material is then blown through a nozzle and shaped in the same way as you make cotton candy [35]. The temperature used for melting glass wool is about 1400°C, while the temperature used for melting rock wool is about

1500°C. In addition to glass wool and rock wool, slag wool is another type of mineral wool. Slag wool is produced by molten furnace slag and is not as commonly used in Norway as glass wool or rock wool [36]. The mineral wool used in the experiments of this master thesis is glass wool.

One of the main issues with mineral wool is the ability to reuse or recycle it. Mineral wool is rarely recycled, mainly because there are lacking both systematic collection systems and potential reuse solutions. In addition, ensuring purity and steady availability of recycled mineral wool is challenging, and so is managing the transportation costs effectively. Nevertheless, there are some ways for mineral wool to be recycled. The waste could simply be returned to the mineral wool manufacturing process. It seems like this recycling method works better with rock wool than glass wool, but the method is not widely used. Recycled mineral wool can also be used as raw materials in other products, for example indoor ceiling tiles. In addition, rock wool waste can be used in cement-based composites, as for example aggregate, cementitious material, or ultrafine filler. Even though there are ways to recycle mineral wool, none of these ways are much utilized. Therefore, the volume of mineral wool waste becomes a problem [37]. Figure 3 shows mineral wool integrated in one of the elements used in this study.

Figure 3: Mineral wool inside one of the elements.

3.3 EXPERIMENTAL INVESTIGATION

In this study, eight different experiments are conducted. Through these experiments, a hygrothermal analysis of two nature-based insulating materials in a stud wall is conducted, with the main goal of evaluating the condensation and mould growth risk. The materials that are tested are flax fibre and wood fibreboard, in addition to the reference material mineral wool. In addition, two different types of cladding are tested. One of them is cement-based, while the other one is made from wood and treated with fire retardant. The experimental investigation take place in the laboratory at Norwegian Institute of Wood Technology in Oslo and the hygrothermal analysis are performed in a climate chamber. In order to create two different climatic zones in the climate chamber, a stud wall is built inside the chamber, with an opening to place the elements with the different insulating materials in. These elements are exposed to different climatic stresses in the form of humidity and temperature. There are 8 different experiments, and each analysis takes about 5 days to complete. In addition to changing the insulating material and the exterior cladding, each element is tested both with and without convection. With and without convection will in this study correspond to the air gap behind the exterior cladding being ventilated and unventilated, respectively. In this subchapter, the experiments will be explained in detail. This includes the climate chamber, the separating wall, the different elements, the sensors, and a detailed description of how the experiments are conducted.

3.3.1 Climate chamber

As mentioned, the experiments are conducted in a climate chamber. This chamber is divided into two zones, the cold zone, and the warm zone. In Figure 4, the zones are marked in blue colour (cold zone) and red colour (warm zone), to easier keep track. The dimension of the chamber is described in Figure 4 and the chamber has the height of 2400mm. What separates the zones are the wall which will be described in chapter 3.3.2. This wall should function as an exterior wall and be airtight.

The blue zone represents the exterior climate and has a cooling aggregate from an Italian producer from Angelantoni Industrie called A1 climatic module, shown in Figure 5. This aggregate can moisten the air through a steam generator, but it can only give moisture to the air when the temperature is 4 degrees or more. In other words, when the temperature is below 4 degrees, it is not possible to have full control over the RH. The compressor itself is placed on the outside of the climate chamber and emits cold and moisture through a battery on the inside, shown in Figure 6. The compressor has a heat exchanger on the outside of the building. This controls the cold zone [38].

The red zone has three components that controls the indoor climate. The indoor climate is limited to an air temperature of 16-35 degrees and RH of 0-100 %. The first component is a heat pump of 3.6 kW which controls the air temperature, shown in Figure 7. The main part of the heat pump, which is the compressor and the heat exchanger, are placed outside the building. The second component is the humidifier shown in Figure 8, which provides humidification and dehumidification. The dehumidification takes place through an adsorption dehumidifier. The humidifier and the dehumidifier are of different brands. The humidifier is a Cotes C35E-3.8 PLC-B and the dehumidifier is a HygroMatik Steam Humidifier FLH03-T, which is placed outside the climate chamber behind the heat pump in red zone. It is important to mention that the brain of the moisture control is located in the humidifier and that the dehumidifier works as a slave for this. The dehumidifier collects fresh air for the dehumidification process through the ventilation pipe to the exterior wall. It has a capacity of 3.8 kg/hour at 20°C and 60% RH, a nominal dry air volume of 1000 m^3/hour and a regular air volume of 135 m^3/hour [39]. In addition, a recirculation system is installed which is controlled from a speed regulator at the humidification system. The job of the recirculation system is to get the largest possible mix of the air masses in the room [38].

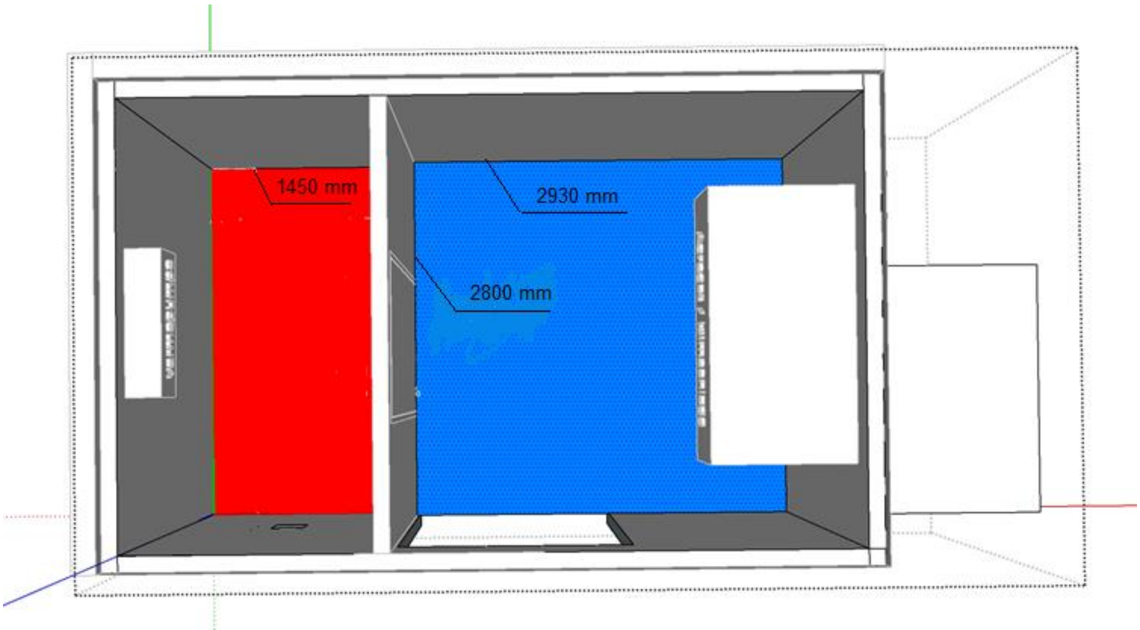

Figure 4: Climate chamber, Screenshot from Sketchup, 25.01.2022

Figure 5: Cooling aggregate from Angelantoni Industrie called A1 climate module

Figure 6: Cooling aggregate from inside of the climate chamber on cold (blue) side.

Figure 7: Heat pump on warm (red) side.

Figure 8: The humidifier, HygroMatik Steam Humidifier FLH03-T.

3.3.2 Separating wall

In order to separate the warm and cold zone in the climate chamber, a separation wall is built. This wall is airtight and is built like any other stud-wall, starting with the studs, and filling the gaps with mineral wool. A vapour barrier is mounted on the interior side of the wall, and a wind barrier is mounted on the exterior side of the wall, both mounted with battens. The process of building the wall can be seen in Figure 9 and Figure 10. In the middle of the wall, an opening, with a size of $1020mm \times 1020\ mm$, is made. This is where the elements are placed. As can be seen in Figure 10, the wall around this opening is thicker than the rest of the wall. This is to make sure that the thickest element fits in the opening. Because of this, the thickness of the wall is 448.15mm at its thickest. In addition to the opening, a small door is built, as can be seen in Figure 9. This door is used to access the warm zone of the climate chamber, as the main entrance to the chamber is in the cold zone. The finished separation wall can be seen in Figure 10.

Figure 9: Separating Wall - Building process

Figure 10: Separating Wall - Finished product

3.3.3 Elements

In order to make the experiments as easy as possible to conduct, the insulating materials to be tested are placed in elements. These elements fit in the opening in the separation wall and has a dimension of $990mm \times 990mm$. As the opening in the wall is $1020mm \times 1020mm$, there is a small gap around the element which are filled with insulation and sealed around the edges after the element is mounted. By creating these elements, one can avoid tearing down and rebuilding the separation wall inside the climate chamber when changing the materials. It also requires less material, which among other things has an economical benefit. In these elements, sensors that measures temperature and RH are placed. Table 2 shows the structure of the different elements which are going to be tested. From this table, it can be seen that each insulating material are tested two times in a row. This is because the same material is tested both with and without convection in the air cavity. It should also be mentioned that even though three different materials are tested, only two elements are used. This means that the material in one of the elements has to be changed at one point.

Every element is built as a stud wall with the same thickness of 336.7 mm excluded the exterior cladding. For all the elements, gypsum board is used as interior cladding, while the exterior cladding is varying between cement and wood, as already mentioned. For the test conditions, the desired interior climate is 21-23°C and 65% RH, and the desired exterior climate is 5-6°C and 75-80% RH. A detailed description of the elements can be seen in Figure 11, and Figure 12 shows one of the elements filled with mineral wool. The only difference between the elements is the insulating material, and the exterior cladding. The first element is tested with mineral wool and cement cladding, the next with flax fibre and cement cladding, followed by wood fibreboard and cement cladding, before testing with wood fibreboard again but this time with wooden cladding at the end. Table 2 shows the order of the different experiments.

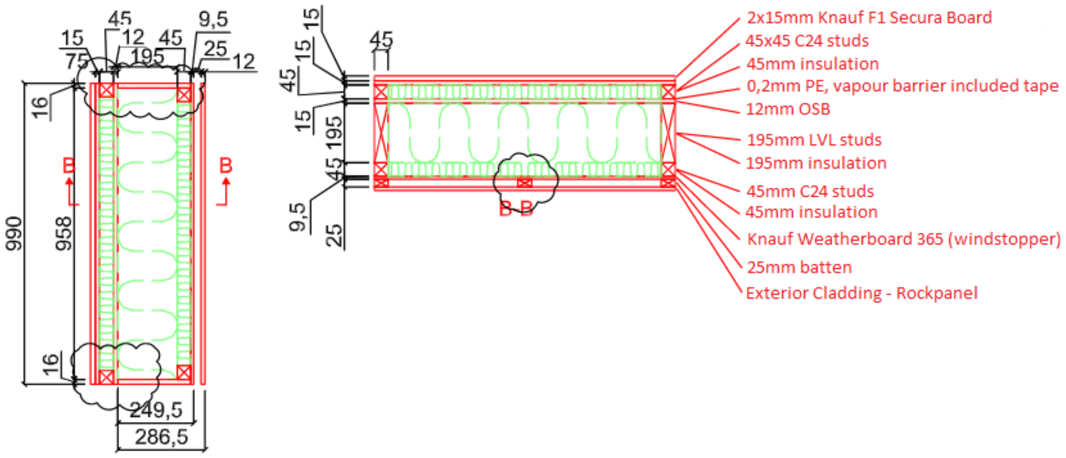

Figure 11: Cross-section of the elements

Figure 12: Element filled with mineral wool

Table 2: A detailed description of the experiments

Test order	Insulating material	Thickness Insulation	Thickness Element	Interior Cladding	Exterior Cladding	Convection
1	Mineral Wool	45+195+45	336.7	Gypsum Board	Cement-based	Yes
2	Mineral Wool	45+195+45	336.7	Gypsum Board	Cement-based	No
Installing new element						
3	Flax Fibre	45+195+45	336.7	Gypsum Board	Cement-based	Yes
4	Flax Fibre	45+195+45	336.7	Gypsum Board	Cement-based	No
Installing new element						
5	Wood Fibreboard	45+195+45	336.7	Gypsum Board	Cement-based	Yes
6	Wood Fibreboard	45+195+45	336.7	Gypsum Board	Cement-based	No
Installing new element						
7	Wood Fibreboard	45+195+45	336.7	Gypsum Board	Fire treated wood	Yes
8	Wood Fibreboard	45+195+45	336.7	Gypsum Board	Fire treated wood	No

3.3.4 Sensors

In order to evaluate the different materials and solutions, there is a need for concrete measurements and numbers about its performance. To do this, different sensors are mounted inside the elements, in addition to some sensors monitoring the climate inside the climate chamber. This subchapter will describe all of these sensors, how they work, where they are located and what they are measuring.

Temperature and Relative Humidity sensors

The only sensors located inside the elements are the five sensors used to measure temperature and relative humidity. The specific location for each of the sensors will be explained later. These smart sensors are from the brand Onset, the model used is S-THC-M008, and they are 8m long. They can measure temperatures between -40°C and 75°C, and relative humidities between 0% and 100%, as can be seen in Table 3. Table 3 also shows the expected measurement error for both the temperature and the relative humidity [40]. When using these smart sensors, they should be used together with a logger in order to collect and extract data. For these experiments, the logger used is HOBO H22-001 data logger. This logger can connect six smart sensors at a time, which fits good for these experiments as they require five smart sensors. In addition, this logger allows extracting data while still gathering information from the smart sensors. There is no need to stop the measurements in order to extract the data and control the already gathered information. The logger supports a long list of measurements, including temperature and relative humidity. The other measurements are not needed for this study. It has a slightly smaller operating range than the smart sensors, as the range is from -20°C to 50°C with the use of alkaline batteries, and from -40°C to 60°C with the use of lithium batteries, both being enough for the experiments conducted in this study. The logger can also be powered by a wall adapter instead of batteries. The logging interval can be specified by the user, based on the wanted interval, but a smaller interval will reduce the lifetime of the batteries. When extracting data from this logger to a computer, the software HOBOware is used, together with a Keyspan USB to Serial Adapter [41].

Table 3: Measurement range and error for Onset S-THC-M008 [40].

	Measurement range	**Accuracy**	
		Temperature/RH range	**Error**
Temperature	-40°C to 75°C	-40°C to 0°C	±0.25°C
		0°C to 70°C	±0.20°C
		70°C to 75°C	±0.25°C
Relative Humidity	0% to 100%	10% to 90%	±2.5%
		Below 10% and above 90%	±5%
Note: If the temperature is below -20°C or the relative humidity is above 95%, the maximum RH error might be increased by 1%.			

Hukseflux

In addition to the temperature- and RH-sensors, Hukseflux TRSYS02 thermal measuring system are used to gather data from the experiments. When using this system one can find the thermal resistance (R), the thermal conductance (Λ), and the thermal transmittance (U-value) of a building envelope. The system consists of four heat flux sensors (plates) of model HFP01 and four pairs of thermocouples, as shown in Figure 13, in addition to a measurement and control unit (MCU01), as shown in Figure 14. The MCU01 is connected to a computer through either a USB-port or a RS232-port in order to download the measured data. On this computer, the software LoggerNet has to be downloaded for the measured data to be extracted. In this study, the hukseflux system will measure heat flux and temperature difference, which will be used to calculate the U-value without surface resistance for the different elements. TRSYS02 has both high accuracy and high sensitivity and can conduct measurements in low heat fluxes and low temperatures. This makes the system more reliable, as it will detect the low heat fluxes and temperatures as well as the higher ones. In addition, the thermocouples are quite accurate, and can measure a temperature difference with an uncertainty better than 0.1°C [42].

As mentioned, the hukseflux measuring system used in this study consists of, among other things, four heat flux sensors. These are called HF1-HF4. According to the supplier, you should use at least two heat flux sensors in order for the results to be reliable enough. In other words, when using four heat flux sensors, the results are expected to be more than reliable enough. Also, in the worst-case scenario, if one of the sensors should stop working, the other three sensors will be enough for the results to still be reliable. The heat flux sensors measure the heat flux through the wall, in W/m^2, and must be mounted in the correct way in order for the measurements to be correct. As there are four heat flux sensors, two of them are located on the interior side of the element, and two on the exterior side of the element. To make sure that the direction of the heat flux is shown correctly through the signs, it is important to install the heat flux sensors in the correct direction. When installed on the interior side of the element, the red face of the sensors should be facing towards the interior side, which will give a positive output signal when the heat flux direction is from interior to exterior. When installed on the exterior side of the element, the blue face should be facing towards the exterior side [42].

In addition to the four heat flux sensors, the hukseflux measuring system consists of four pairs of thermocouples, which in total gives 8 sensors. These sensors are installed in pairs, four on each side of the element. The thermocouples are linked to the heat flux sensors, as shown in Table 4. For example, when HF1 is installed, TC11 is installed next to it and TC12 is installed at the same location but on the other side of the element. The same system goes for the rest of the sensors as well. Table 4 also mentions the temperature differences, DT1-DT4. DT1-DT4 shows the temperature difference between the different thermocouples, as the table explains [42].

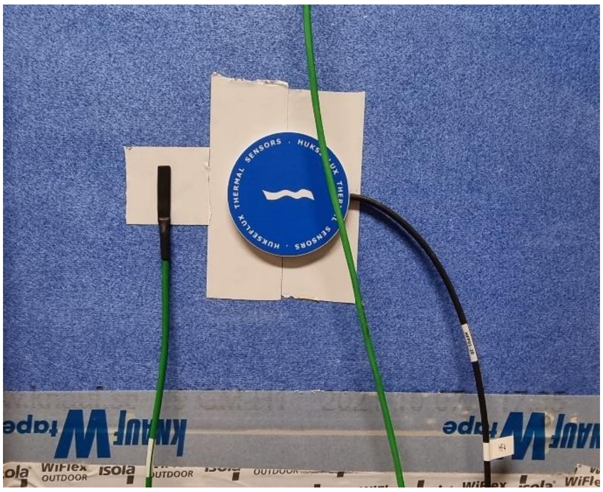

Figure 13: Heat flux sensors and thermocouples (HFP01).

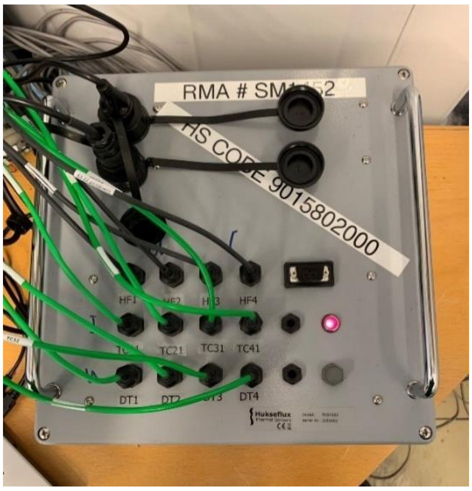

Figure 14: Measurement and control unit (MCU01).

Table 4: Link between thermocouples, heat flux sensors and temperature differences.

Heat Flux Sensor	**Thermocouples**	**Temperature Difference**
HF1	TC11 and TC12	DT1 – Measures the temp. difference between TC11 and TC12
HF2	TC21 and TC22	DT2 – Measures the temp. difference between TC21 and TC22
HF3	TC31 and TC32	DT3 – Measures the temp. difference between TC31 and TC32
HF4	TC41 and TC42	DT4 – Measures the temp. difference between TC41 and TC42

Air velocity

The air velocity sensor used in this study is called Testo 440dP. It is located in the air gap behind the exterior cladding, as can be seen in Figure 15, and it can measure air velocity, temperature, and relative humidity. As both the temperature and the relative humidity are measured by other sensors, the interesting data from this sensor is the air velocity, which can be measure accurately between 0-30m/s by this sensor. By documenting the air velocity in the air gap, one can make sure that the air gap is ventilated and unventilated at the correct times. Testo 440dP is a practical and easy to use measuring system, as it is handheld, and battery driven. This makes it easy to bring along and use in different locations. For the experiments conducted in this study though, Testo 440dP is only mounted in one location. The batteries used are AA, 1,5V batteries, which with average use gives about 12 hours of battery time. As the experiments lasts for more than 12 hours, the batteries of Testo 440dP must be exchanged a few times during the experiments. This will result in some gaps where there is no measured data. This is not ideal of course, but as the air movement in the climate chamber should be quite identical throughout the entire experiment, this should not be a major issue. After each experiment, the data needs to be extracted, which is simply done through a USB-port on a computer [43].

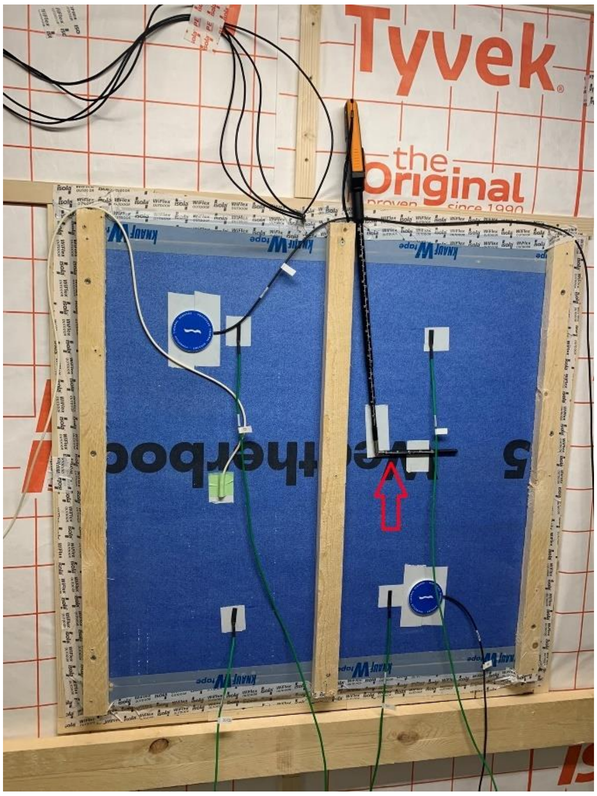

Figure 15: Air velocity sensor.

Climate inside the chamber – warm and cold zone

In addition to the sensors used to monitor the elements, there is a need for sensors to monitor the climate inside the climate chamber as well. The sensors used for this are called Celsicom and can measure both temperature and relative humidity. There are two of these sensors, one located on the cold side, and one located on the warm side. The location of these can be seen in Figure 16, both mounted approximately 50cm from the roof. In this figure, the interior sensor is called L5, while the exterior sensor is called L6. These sensors can measure temperatures between -30°C and 70°C, and they can measure relative humidities between 0% RH and 100% RH. They are quite accurate and only has a temperature error at ±0.4°C and a RH error of 3%. In addition, they are battery driven, with a battery that can last up to five years [44].

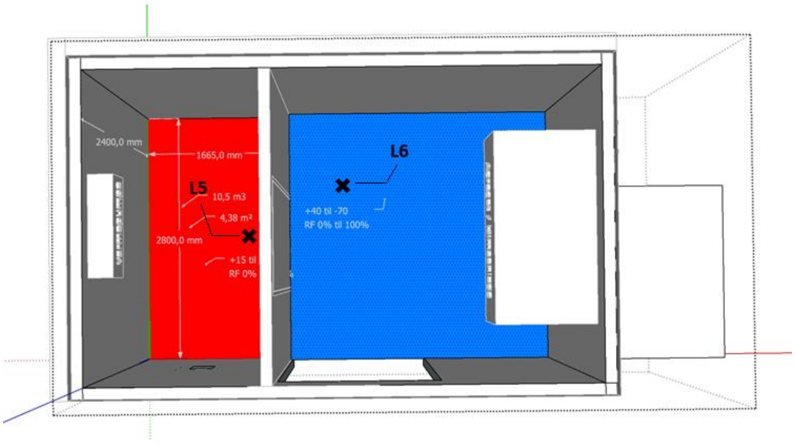

Figure 16: Location Celsicom sensors.

3.3.5 Experiment procedure

As already mentioned, the climate chamber consists of two zones, warm and cold, which are separated by a wall. The first step in conducting the experiments were to build this separation wall. In addition, the climate chamber was initiated with the correct temperatures and relative humidities, as shown in Table 5, to make sure that everything was working as planned. One challenge with the climate chamber was the risk for ice growing on the cooling aggregate on the cold side, as demonstrated in Figure 17. This is because the aggregate sends through colder air than needed, trying to keep the temperature as desired. This cold air leads to ice growing on the aggregate. To prevent this ice from growing, the cooling aggregate needs defrosting. Initially, this defrosting was set to 14 min every 3rd hour, but as can be seen in Table 5, the interval was reduced after the first experiment. From the second experiment and throughout the rest of the experiments, the defrosting is set to 14 min every 2nd hour and 55 min. In other words, the settings for the temperature and RH are only activated for 2 hours and 55 minutes at a time. After this time, there are 14 minutes of defrosting where the cooling aggregate is turned off. During this defrosting time, the temperature will rise a little bit, giving a mean temperature a bit higher than the value chosen in the settings.

After a few days of acclimatizing of the climate chamber, it was noticed that the moisture content of the wood in the first element was too high. The moisture content even varied between the different studs in the element, and the highest moisture content was between 17-20%. The lowest moisture content was 11-12%. The desired moisture content in the wood is somewhere around 11-12%, so 17-20% is not ideal. The reason for this high moisture content could either be the use of too moist materials when building the elements, or due to moisture damage during transportation. As the elements were quite thoroughly wrapped during transportation, it is most likely that the materials used to build the elements had a higher moisture content than wanted. In order to try to reduce this moisture content a bit, the elements were left drying for four days. As reducing the moisture content from 17-20% to 11-12% would take weeks, it was not expected that the moisture content would be notable reduced during these four days though. While the elements were drying, preparations like unwrapping and numbering the sensors, were done.

Table 5: Experimental procedure and details.

Test nr.	Insulation	Exterior cladding	Convection	Exterior conditions	Interior conditions	Duration
1	Mineral wool	Cement	Yes	Temp: 5.5°C RH: 90% [1]	Temp: 21°C RH: 65%	5 days, 18 hours
2	Mineral wool	Cement	No	Temp: 5.5°C RH: 90% [2]	Temp: 21°C RH: 65%	5 days, 16 hours
3	Flax fibre	Cement	Yes	Temp: 5.5°C RH: 90%	Temp: 21°C RH: 65%	5 days, 22 hours
4	Flax fibre	Cement	No	Temp: 5.5°C RH: 90%	Temp: 21°C RH: 65%	6 days, 17.5 hours
5	Wood fibreboard	Cement	Yes	Temp: 5.5°C RH: 90%	Temp: 21°C RH: 65%	6 days, 17 hours
6	Wood fibreboard	Cement	No	Temp: 5.5°C RH: 90%	Temp: 21°C RH: 65%	7 days, 20.5 hours
7	Wood fibreboard	Wood – fire retardant treated	Yes	Temp: 5.5°C RH: 90%	Temp: 21°C RH: 65%	6 days, 20.5 hours
8	Wood fibreboard	Wood – fire retardant treated	No	Temp: 5.5°C RH: 90%	Temp: 21°C RH: 65%	6 days, 21.5 hours

Figure 17: Ice growing on the cooling aggregate.

Experiment 1

After the four-day drying period, it was time to start the first experiment. The moisture content did not decrease significantly, but it was decided to start the experiments anyway. The insulating material in the first experiment is mineral wool, as this is the reference material. The first step in starting the experiments were to mount the temperature/RH-sensors inside the insulation in the first element. Figure 18 shows the planned location for the five temperature/RH-sensors, while Figure 19 shows the actual location of four of these sensors. Figure (a) to the left shows the location of sensor number four, figure (b) in the middle shows the third and second sensor, while figure (c) to the right show sensor number one. The plastic shown to the left in figure (b) is only there for practical reasons while inserting the insulation and the sensors. It was removed after the sensors were mounted in their location. Figure 20 shows the element after the first four temperature/RH-sensors had been mounted. The location of the fifth, and last, sensor is shown in Figure 21, together with the hukseflux-sensors and the air velocity-sensor. These were mounted at the end and will be explained in the next paragraph. After the first four temperature/RH-sensors were mounted, the element could be placed in the separation wall. To make sure that all gaps between the element and the separation wall were sealed, the gaps were filled with mineral wool and sealed with tape, both from the exterior and the interior side. In addition, on the interior side, the vapour barrier of the separation wall was taped to the vapour barrier of the element. This was to make sure that the vapour barrier was sealed as well.

The last thing left before the experiment was ready to start, was to mount the last of the sensors. The remining sensors were the hukseflux-sensors, the last temperature/RH-sensor, and the air velocity sensor. All of these sensors were mounted in the air gap behind the exterior cladding, as can be seen in Figure 21. Some of the hukseflux-sensors were also mounted on the gypsum board on the interior side of the element, as can be seen in Figure 22. Figure 21 and Figure 22 also shows the name of each of the sensor (HF1-HF4, TC11-TC41 and DT1-DT4), and where each of them is located. How the hukseflux-sensors should be mounted is explained in chapter 3.3.4, but the distance from the edge of the element to the middle of the heat flux sensors are shown in Figure 22-Figure 24. The thermocouples are located approximately at the same location in the remaining corners, in addition to one thermocouple alongside each heat flux sensor. Then the exterior cladding was screwed back in place, and the experiment started. The experiment lasted about 5 days and 6 hours, and the only interfering during this time was to check that everything worked as it should, and to insert new batteries in the air velocity-sensor. On the fifth day of the experiment, data were extracted, the experiment were stopped, and the element was prepared for the next experiment. Information about materials, start conditions and duration of the different experiments can be found in Table 5.

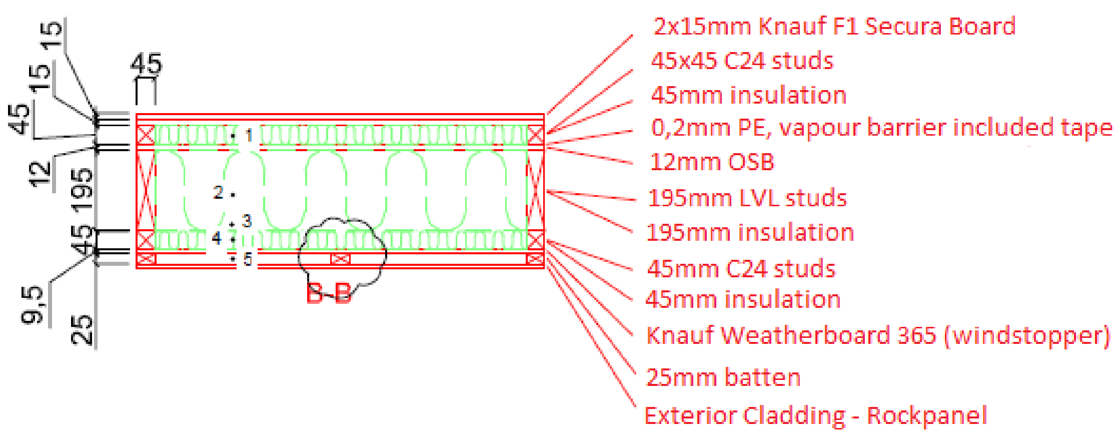

Figure 18: Planned location of Onset S-THC-M008 sensors.

Figure 19: Actual location of Onset S-THC-M008 sensors. (a) left, (b) middle, (c) right.

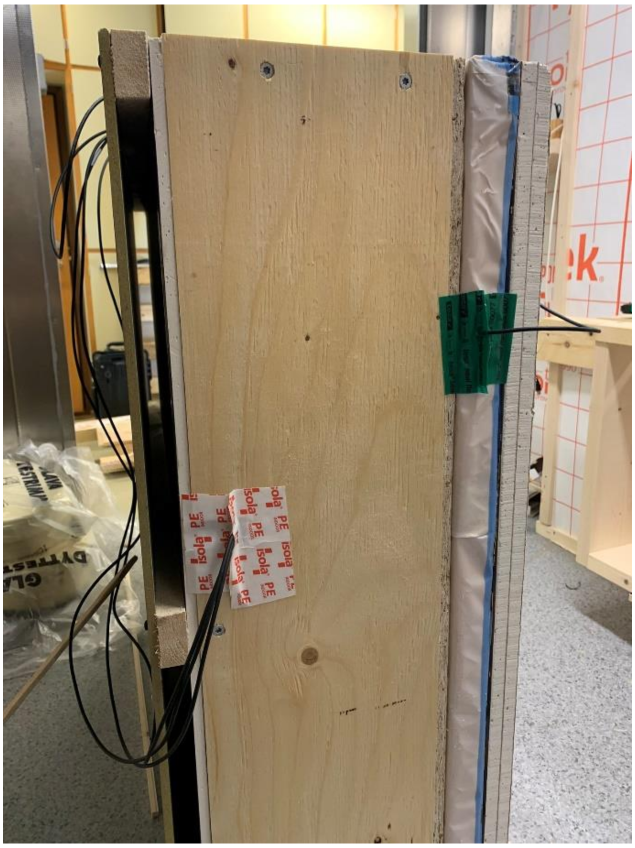

Figure 20: Sensor nr.1-4, Onset S-THC-M008

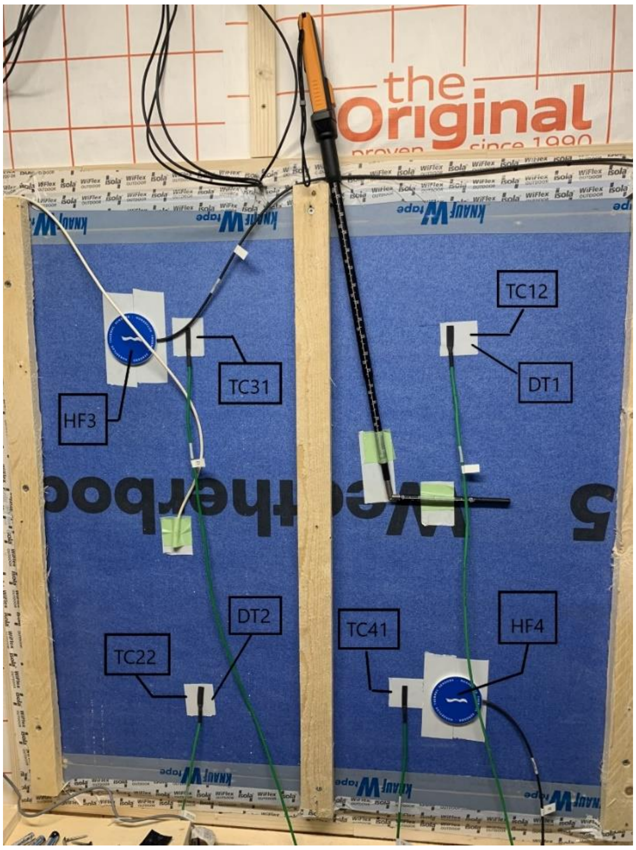

Figure 21: Sensor nr.5 Onset S-THC-M008, and hukseflux-sensors.

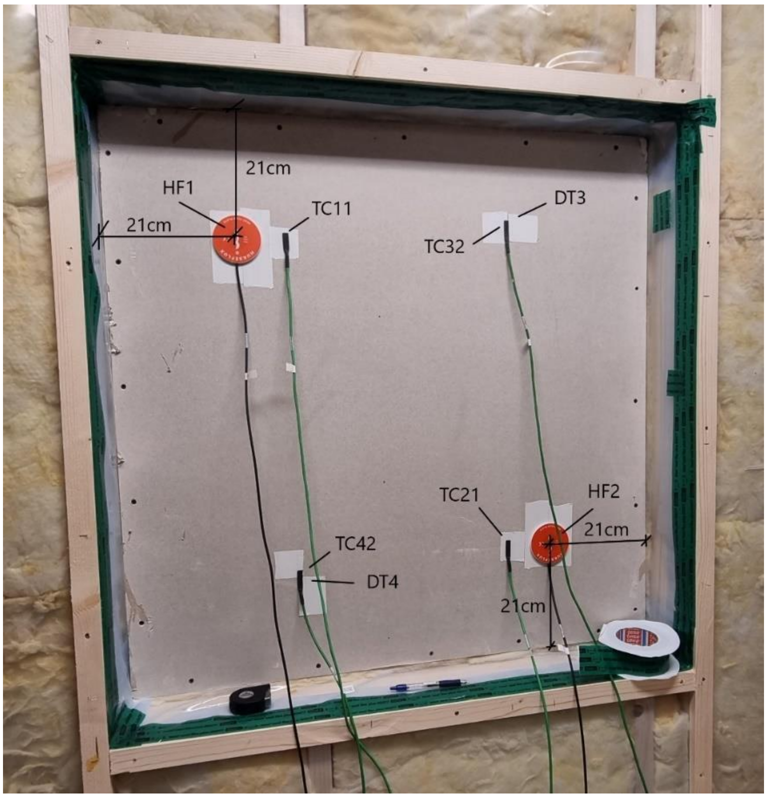

Figure 22: Location of Hukseflux-sensors, interior side.

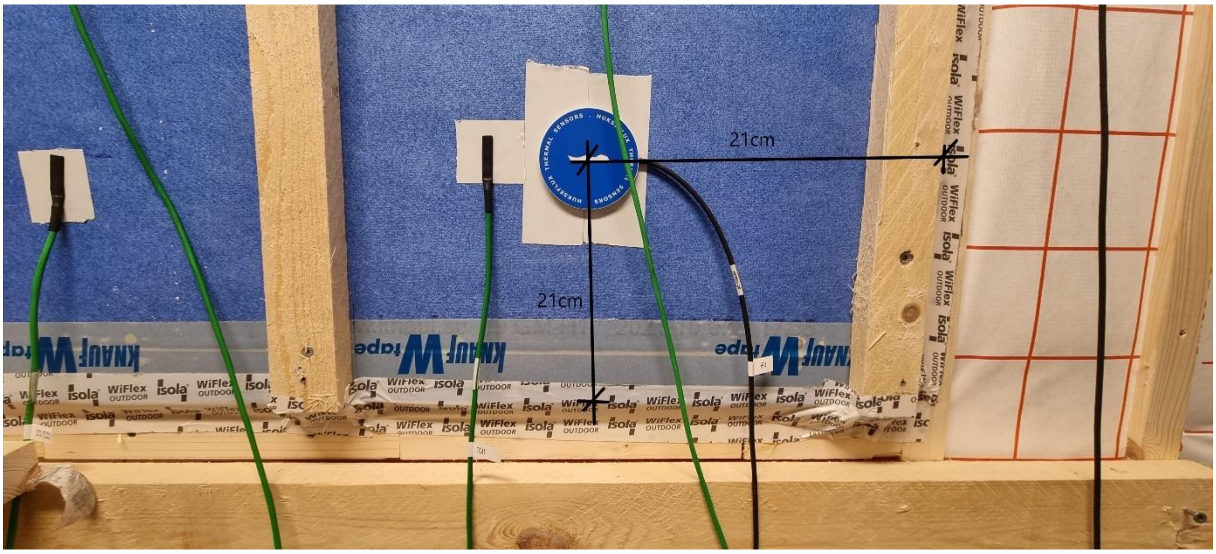

Figure 23: Location of hukseflux-sensors.

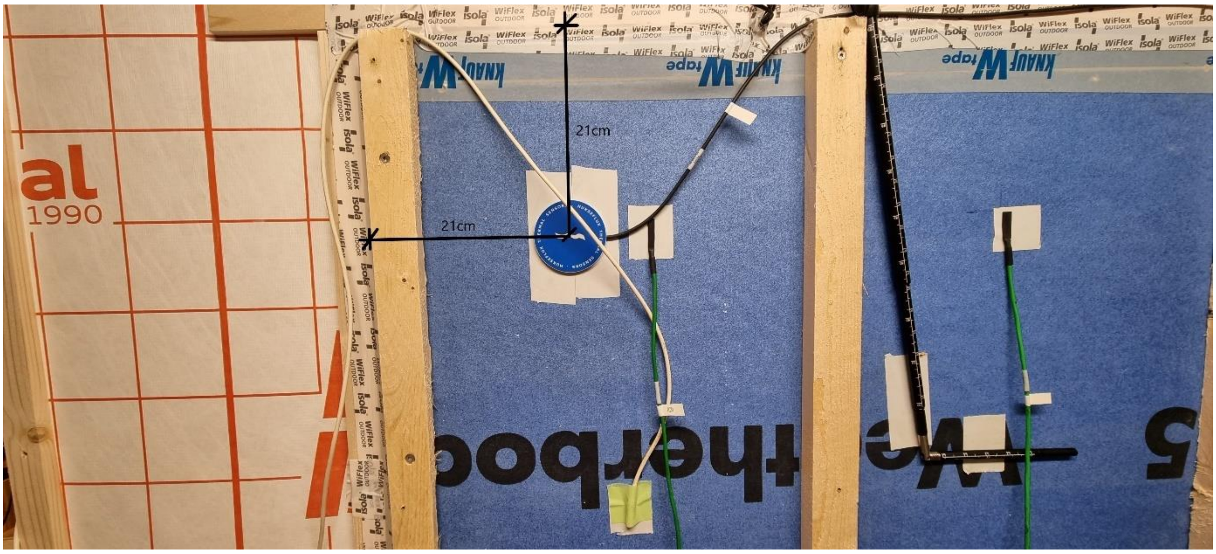

Figure 24: Location of hukseflux-sensors.

Experiment 2

The second experiment started the same day as the first experiment ended. This experiment was in many ways identical to the first experiment as the insulating material is the same and all the sensors are located in the same place. The only differences were in the air gap behind the exterior cladding, and in the defrosting time, as already mentioned. In the first experiment, this air gap was ventilated so that the air could move and be exchanged at any time, which in this study is called “with convection”. In the second experiment, the goal was to make this air gap unventilated, or as it is called in this study “without convection”. To practically accomplish this, the air gap was sealed with tape, making it approximately impossible for air to enter. This makes the air gap unventilated, but it does not remove the convection. As long as there are different temperatures on either side of the element, there will always be some convection. This convection is neglected though, as it will not significantly impact the results. When starting this experiment, there were some issues with the software connected to the climate chamber, so the start of the experiment was a bit delayed.

Experiment 3

Now that the two reference tests are conducted, the experiments including nature-based insulating materials can start. The material tested in the third experiment is therefore flax fibre. When preparing for experiment nr. 3, it was decided to change the insulating material while the element was still in the wall, as this was assumed to be more efficient than removing the element. The exterior cladding, the wind barrier and the interior gypsum boards were therefore removed, in order to reach the insulation behind and remove the mineral wool. In order to save even more time, all the sensors mounted on the interior gypsum boards and on the wind barrier were left on the plates. These sensors include the fifth temperature/RH-sensor, all the hukseflux-sensors and the air velocity sensors. The plates were simply lifted off with all the sensors still on them. This way, all the sensors are automatically mounted when the plates are screwed back in place, and the location of the sensors is therefore exactly the same as in experiment 1 and 2. Then, the flax fibre insulation was inserted, bit by bit, and the temperature/RH-sensors were mounted in the correct location as the insulation were inserted, as can be seen in Figure 25. When all the flax fibre insulation were inserted, the gypsum boards, wind barrier and exterior cladding were mounted back in place. As all the remaining sensors are already mounted on the interior gypsum boards and on the wind barrier, experiment nr.3 were now ready to start.

Figure 25: Mounting of flax fibre and Onset S-THC-M008 sensors.

Experiment 4

The fourth experiment is quite similar to the third experiment. As for experiment one and two, the only difference between the third and fourth experiment is in the air gap. In this experiment, the air gap is unventilated. This includes sealing the edges and making it approximately impossible for air to enter the air gap. The rest of the experiment is identical. The materials are the same and the sensors are located in the exact same place. After sealing the edges around the air gap, the experiment was started.

Experiment 5

The second, and last, nature-based insulating material to be tested in this study is wood fibreboard. This material is shown in Figure 26. In the fifth experiment, this type of insulation is tested with a cement-based cladding. In order to start this experiment, a new element had to be placed in the separation wall. Therefore, the element used for experiment 1-4 had to be removed first. This was done by removing the tape and mineral wool used to seal the edges around the element, before simply pushing and lifting the element out of the separation wall. When the first element had been removed, the preparing of the new element containing wood fibreboard could start. At first, the first four temperature/RH-sensors were placed in their location. Figure 26 shows some of the process of placing the sensors in the correct location. The element was then lifted and pushed in its place in the separation wall, and as for all the other experiments, the gaps between the element and the separation wall was sealed with mineral wool and tape. Then, the hukseflux-sensors and the air velocity sensor were mounted inside the air gap behind the exterior cladding, in addition to the last temperature/RH-sensor. All these sensors were mounted in the same location as for the earlier experiments. At last, the cement-cladding were screwed back in its place, and the experiment were started.

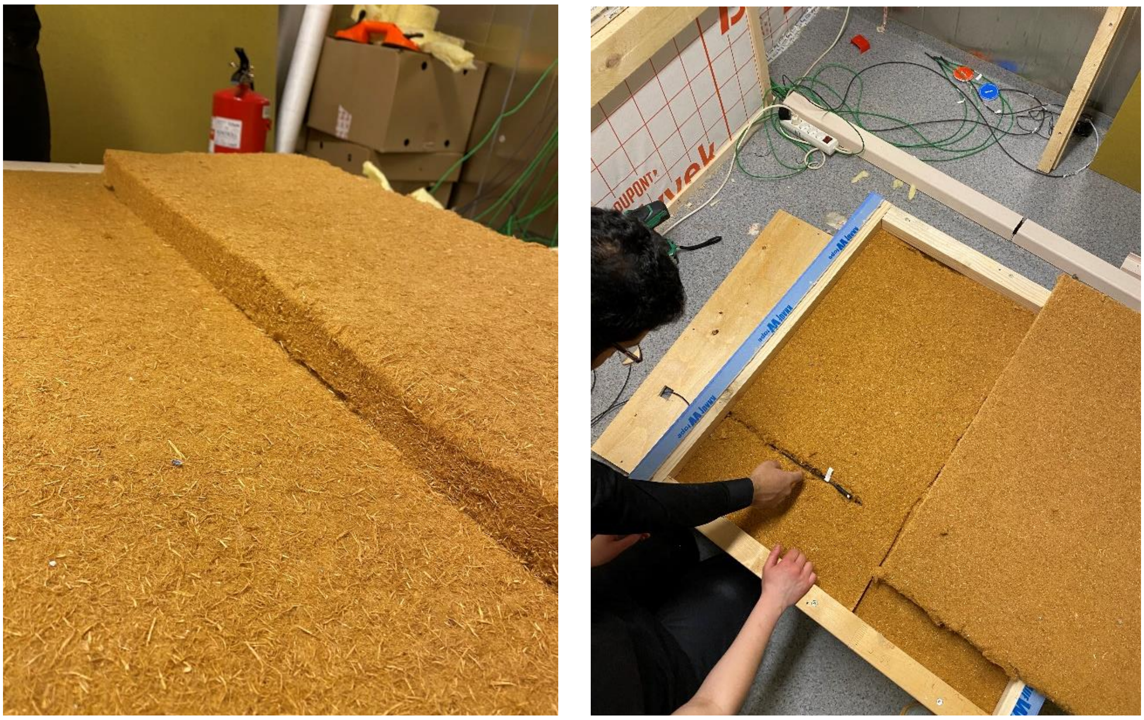

Figure 26: Mounting of Onset S-THC-M008 sensors in wood fibreboard.

Experiment 6

In the sixth experiment, wood fibreboard is tested again, but this time with an unventilated air gap (without convection). As for all the other experiments with an unventilated air gap, the gap is sealed with tape, making it approximately impossible for air to enter. The rest of the experiment is identical to experiment 5, with the sensors located in the exact same location and the element and the cladding being the same.

Experiment 7

In experiment 7, wood fibreboard is still the insulating material to be tested. The only difference between this experiment and experiment 5 is that the cement-based cladding is replaced with a wooden cladding treated with fire retardant. This experiment is also conducted with convection in the air gap. The first steps when conducting this experiment were to remove the cement-based cladding, monitor if all the sensors were still in their locations and change batteries in the air velocity sensor. As all sensors were still in their location, the wooden cladding could be mounted. This cladding was delivered in eight pre-cut parts, that had to be mounted on the battens using screws. This can be seen in Figure 27. After mounting, the experiment was ready to start.

Figure 27: Mounting of the wooden cladding.

Experiment 8

The last experiment conducted in this study is conducted with wood fibreboard and the same wooden cladding as in experiment 7. The difference between this experiment and experiment 7 is that now there is no convection in the air gap. In other words, the air gap is unventilated. As for all the other experiments conducted without convection, the air gap is sealed with tape to make sure that approximately no air can enter the air gap. This can be seen in Figure 28.

Figure 28: Sealing of the air gap behind the exterior cladding.

3.4 HYGROTHERMAL NUMERICAL SIMULATIONS

In addition to the experimental investigations, two different kinds of numerical simulations are conducted in this study: short-term simulations and long-term simulations. The main goal of the long-term simulations is to investigate the condensation and mould growth risk in the insulating materials after 10 years. In order to do this, a model that is quite similar to the experimental investigations is needed. This model is created through the short-term simulations and validated using the experimental investigations. If the short-term simulations are similar enough to the experimental investigation, the model is good enough. All these simulations are conducted in WUFI Pro 1D, which is the standard program for evaluating moisture conditions in building envelopes [45]. In this chapter, some theory behind WUFI Pro will be explained, in addition to the procedure used when conducting both the short-term and the long-term simulations.

3.4.1 WUFI Pro 1D

As mentioned, the simulations in this study will be conducted in the software WUFI Pro 1D, version 5.3. WUFI Pro is one of many products in the WUFI software family and is normally used for one dimensional hygrothermal calculations of building components [45]. From the software's in the WUFI software family, using WUFI Pro is the best way to gain quick results when you have pre-defined indoor climates [46]. The WUFI software family is also a well-known and accepted software family in the field of heat- and moisture transport in building components exposed to natural weather, which makes it a wise first choice of simulation software for this study. This subchapter is dedicated to explaining how heat transport and heat storage are connected to moisture transport and moisture storage in WUFI Pro, as it is well known that heat and moisture in a building component affects each other quite a lot. In WUFI, this connection can be explained through a couple of equations, called the governing transport equations.

Governing Transport Equations

The two equations used in the hygrothermal calculations in WUFI Pro are Eq.9 and Eq.10. Eq.9 represents the moisture transfer, while Eq.10 represents the heat transfer. In both equations, the left-hand side shows the storage terms of the equation, while the right-hand side shows the fluxes. These two equations create an understanding of how heat- and moisture transport and heat- and moisture storage affects each other [47].

In Eq.9 about moisture transfer, the left-hand side represents the moisture storage, and the right-hand side represents the liquid flux and the vapour flux. On the right-hand side of Eq.9, there are coefficients like D_ϕ, which is the liquid conduction coefficient, δ_p, which is the vapour permeability, and p_{sat}, which is the saturation vapour pressure. The liquid conduction coefficient is one of the coefficients describing the liquid flux, while the vapour permeability and the saturation vapour pressure describes the vapour flux. Both these fluxes are dependent on moisture and temperature. The liquid flux is only slightly influenced by the temperature, as the liquid conduction coefficient is only slightly influenced by the temperature, while the vapour flux is strongly dependent on both temperature and moisture. This is partly because of the saturation vapour pressure, which is strongly dependent on the temperature [47].

For Eq.10, which describes heat transfer, the storage term on the left-hand side describes the heat/energy storage. This term is dependent on the temperature difference, which is dependent on time. The fluxes on the right-hand side of this equation represents the conductive heat flux and the enthalpy flux, which are both strongly dependent on the moisture fields and the moisture fluxes. The conductive heat flux is also dependent on the temperature. This is partly due to the thermal conductivity, which is quite dependent on both temperature and moisture. The term that represents the enthalpy flux consists of, among other things, the term $\delta_p \nabla(\phi p_{sat})$. This term describes the phase change. During a phase change, energy is either added or released. This is dependent on moisture because moisture in a material also implies that there is energy stored in the material. Summed up, it can be seen that the two transport equations (Eq.9 and Eq.10) are dependent on each other [47].

Moisture transfer:

$$\underbrace{\frac{\partial_w}{\partial_\phi} * \frac{\partial_\phi}{\partial_t}}_{\text{Moisture storage}} = \underbrace{\nabla * (D_\phi \nabla \phi}_{\text{Liquid flux}} + \underbrace{\delta_p \nabla(\phi p_{sat}))}_{\text{Vapour flux}} \qquad [9]$$

Heat transfer:

$$\underbrace{\frac{\partial H}{\partial T} * \frac{\partial T}{\partial t}}_{\substack{\text{Energy/heat} \\ \text{storage}}} = \underbrace{\nabla * (k\nabla T)}_{\substack{\text{Conductive} \\ \text{heat flux}}} + \underbrace{h_v \nabla * \left(\delta_p \nabla(\phi p_{sat})\right)}_{\text{Enthalpy flux}} \qquad [10]$$

3.4.2 Short-term analysis – Validation

The first part of the simulations was to create a project in WUFI Pro. This project was to include all the experiments that had been carried out in the climate chamber. Then the job was to create a variant inside this project, which was to represent the first element. Here, the element's construction, time/profile and climate were entered. Since the elements had pretty much the same structure, the first variant could function as a template for the others and be further duplicated to facilitate the work.

To create the element, the materials used in the different layers had to be added. The layers were placed in order from left to right. The left side represented the cold side, and the right side represented the warm side. The thicknesses of the different layers were defined, in addition to the material data. The material data was retrieved by NTI, which provided information on the various properties of the materials. Table 6 shows an overview of which properties are plotted in the different materials. Due to lack of information about the materials, it became necessary to find materials that were as similar as possible to the ones used in the experiments. This was done by using materials from the material database in WUFI Pro. The materials were selected in the best possible way, and some properties were exchanged with the ones gathered from NTI. Table 7 shows which materials and databases that were chosen in WUFI Pro.

As mentioned, one of the sensors used in the experiments is the air velocity sensor. The measurements from this sensor are used to calculate the air exchanges in the air gap behind the exterior cladding, which is one of the input values in WUFI Pro. The air exchanges were entered in the layer of the air gap in WUFI Pro as an air exchange source in hygrothermal sources. The calculated air exchanges can be found in the results, in chapter 4.1.2. To be able to compare the simulations in WUFI Pro to the experiments, data must be gathered from approximately the same locations in the elements. Therefore, the monitoring positions in WUFI Pro are added in the same locations as the sensors in the experiments. The monitoring positions gives information about the temperature, relative humidity, and partial pressure in the chosen locations inside the building component. Since it was only possible to place monitors in one material at a time, it was necessary to place two monitors in the transitions between each material to find the value in the transition phase after taking the average value. In layers where it was not possible to place the monitoring positions in the middle, the same method was used as well.

Since the experiment took place inside a climate chamber with a stable climate and without rain, no building height or rainfall coefficient was added. The orientation was chosen in a southerly direction and the slope was set to 90 degrees. Since the element is not as exposed to an outdoor climate, but at the same time not to an indoor climate, the outdoor heat transfer resistance is changed from 0.04 to 0.1 m^2K/W as an assumed value. Internal heat transfer resistance is set to 0.125 m^2K/W, which is a value set by WUFI. The sd-value remains unchanged, as the surface treatment of the materials in question is already included in the material data in WUFI Pro. No radiation or rainwater absorption figures have been included. To find the initial humidity in the structure for each individual layer, an overview of the RH value in the beginning of each experiment in each layer had to be made, as shown in Table 8. This information was used to determine the moisture content of the materials by reading the sorption curve of the material, shown in Table 9. The sorption curves are provided by WUFI Pro. The initial temperature in the structure was calculated by taking the average value of the measured values in the sensors from the experiment, shown in Table 10. For the starting conditions in WUFI, this information was necessary.

When adding the calculation period in WUFI Pro, this is decided based on the climate data from the experiments. The climate data from the experiments are measured every ten minutes, while in WUFI Pro the climate data are added per hour. Due to this, the calculation period in WUFI Pro is set to last around 30 days instead of five days like the experiments. Climate data for five days with measurements per ten minutes corresponds to about 30 days with measurements per hour in WUFI Pro. The start period was set to be from 01.01.2022 at 00:00 for each experiment and ended when around 30 days had elapsed. Having an exact date on when the experiments were carried out was not important for the simulations in WUFI Pro, rather that the number of days was correct to get the same amount of data. To add the climate data in WUFI Pro, climate files were made, containing the time period in which the experiments were carried out. Separate climate files were created for the warm and cold side of the element, and imported into WUFI Pro. The climate files were created in Excel, using a template created for use in WUFI Pro. When it comes to the numeric values, these were set to default.

After the first element was ready for simulation, all that remained was to duplicate the element until eight elements were created. The rough work had been done and all that remained was to change the insulation material, cladding, start conditions, time/profile and climate data, which wasn't that much of work. Then it was time to run the simulations, which didn't take long. In fact, it only took two seconds per element. The data was exported as ASCII files and processed in Excel. The results were later compared with the experimental data.

Table 6: Material data inserted in WUFI Pro.

	Material Data				
	Bulk density [kg/m^3]	**Porosity [m^3/m^3]**	**Spec. heat capacity, dry [J/kgK]**	**Thermal conductivity 10°C [W/mK]**	**Water vapour diffusion resistance [-]**
Cement board	1250	0.48	840	0.55	28
Wood cladding	465	0.9	1880	0.086	552
Air gap	1.3	0.99	1000	0.155	0.51
Plasterboard (wind barrier)	850	0.65	850	0.25	10
Mineral wool	60	0.95	850	0.037	1.3
Flax Fibre	39	0.95	1600	0.038	2
Wood fibreboard	50	0.97	2100	0.038	5
OSB	600	0.6	1500	0.13	200
Vapour retarder	130	0.001	2300	2.3	100000
Plasterboard	774	0.65	850	0.25	10

Table 7: Materials and material databases.

	Material Name	Material Database			
		North America Database	BiW	Generic Materials	Fraunhofer – IBP – Holzkirchen, Germany
Cement board	Cement board	x			
Wood cladding	5 - Spruce - Woodsafe FirePRO fireretardant solid wood _ 12 mm		x		
Air gap	Luftsjikt 25 mm			x	
Plasterboard (wind barrier)	Gipsplate				x
Mineral wool	Mineralull (Varme-konduktivitet: 0.04 W/mK)				x
Flax Fibre	12 Flax Insulation Board - Isolina Linen insulation - Flax fibre		x		
Wood fibreboard	07 AiF Flexible Wood-Fiber Insulation WF - Steico therm, flex 036 - Wo		x		
OSB	OSB-plate (Densitet: 630 kg/m³)				x
Vapour retarder	Vapour retarder (sd=100m)				x
Plasterboard	Gipsplate				x

Table 8: Initial RH-values in the different layers.

	Initial RH – Value In Different Layers [%]							
	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 6	Exp. 7	Exp. 8
Exterior cladding	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Air gap	0.90	0.85	0.90	0.74	0.63	0.90	0.45	0.80
Wind barrier	0.82	0.80	0.69	0.72	0.60	0.85	0.65	0.81
45mm insulation	0.75	0.75	0.47	0.70	0.56	0.80	0.85	0.83
195mm insulation	0.46	0.54	0.27	0.47	0.63	0.67	0.67	0.68
12mm OSB	0.46	0.54	0.27	0.47	0.63	0.67	0.67	0.68
Vapour barrier	0.46	0.54	0.27	0.47	0.63	0.67	0.67	0.68
45mm insulation	0.44	0.64	0.47	0.69	0.61	0.70	0.72	0.73
Plasterboard	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
Plasterboard	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60

Table 9: Initial water content in the different layers.

	Initial Water Content in Different Layers [kg/m³]							
	Exp. 1	**Exp. 2**	**Exp. 3**	**Exp. 4**	**Exp. 5**	**Exp. 6**	**Exp. 7**	**Exp. 8**
Exterior cladding	45.0	45.0	45.0	45.0	45.0	45.0	50.0	50.0
Air gap	4.0	2.5	4.0	1.2	0.6	4.0	0	2.0
Wind barrier	6.5	6.3	5.5	5.7	4.9	8.65	5.2	6.4
45mm insulation	0.7	0.7	2.1	3.8	4.4	9.0	12.5	14.0
195mm insulation	0	0	1.0	2.1	4.9	5.1	5.1	5.1
12mm OSB	45.0	60.0	30.0	55.0	70.0	75.0	75.0	79.0
Vapour barrier	0	0	0	0	0.0001	0.0001	0.0001	0.0001
45mm insulation	0	1.0	2.1	3.8	4.9	6.0	7.0	7.0
Plaster board	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Plaster board	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0

Table 10: Initial temperature in the elements.

	Initial Temperature in Component [°C]
Experiment 1	11.14
Experiment 2	11.24
Experiment 3	11.92
Experiment 4	14.94
Experiment 5	13.76
Experiment 6	11.91
Experiment 7	15.81
Experiment 8	12.93

3.4.3 Long-term analysis

In addition to validating the short-term analysis, WUFI Pro is in this study used to investigate if there are any changes to the results if the experiments are left running for more than 5-6 days, like for example 10 years. As this takes too long to investigate through an experiment, WUFI Pro is the perfect tool for this. For the long-term analysis, all the material properties and thicknesses are the same as for the validation, in addition to the interior and the exterior climate. The only difference is the duration of the simulations.

When creating the long-term simulations in WUFI Pro, the construction, orientation, surface transition coefficient and starting conditions remained the same as for the short-term simulations. The calculation period was changed to a 10-year period from midnight 01.01.2022 to midnight 01.01.2032 and the outdoor climate was set to be in Oslo. The reason for choosing Oslo, was the interest of choosing a Norwegian climate due to writing for OsloMet. The indoor climate was derived from the outdoor climate in Oslo using the algorithm specified by DIN EN ISO 13788. Since this indoor climate was assigned to the right side of the component, and a climate file was already assigned to the left side as the outdoor climate, it was only to check the option *"use left climate"* to get the indoor climate derived from that file. This was done for all cases. After making these changes, the model was ready for new simulations. In this case the simulations would last longer, but fortunately only 4 minutes and 17 seconds per element. The simulations were again exported as ASCII files and processed in Excel.

When extracting data from the long-term simulations, both WUFI Bio and WUFI Pro is needed. The most interesting results from the long-term simulations are the mould index, which is gathered from WUFI Bio. The mould index indicates how much mould growth that is expected in a certain location and is given as a number from 0 to 6, as shown in Table 11. In this table, 0 indicates no mould growth at all, while 6 indicates a tight coverage of mould growth. In order to obtain the best possible use of this table, the mould index should be used together with Table 12. This table shows which mould indexes are acceptable and which are not. This table is valid only for surfaces inside a construction that has no direct contact to indoor air and is used actively in WUFI Bio through the signal lights. All information about the mould index and the signal lights are gathered from WUFI Bio.

Table 11: Mould Index. This table is taken from WUFI Bio [48].

Mould Index	Description
0	No growth.
1	Some growth visible under microscope.
2	Moderate growth visible under microscope, coverage more than 10%.
3	Some growth detected visually, thin hyphae found under microscope.
4	Visual coverage more than 10%.
5	Coverage more than 50%.
6	Tight coverage, 100%.

Table 12: Signal lights and Mould index. This table is taken from WUFI Bio [48].

Signal Light	Mould Index	Assessment
Green	≤ 2	Usually acceptable
Yellow	2 < Mould Index ≤ 3	Additional criteria or investigations are needed for assessing acceptability
Red	> 3	Usually not acceptable

3.5 DATA ANALYSIS

After gathering data through the experiments, this data must be analysed. The purpose of analysing data is to provide information about the variables and how they affect each other. In this study, information like temperature, relative humidity and heat flux are gathered through the different experiments and simulations. In order to evaluate the risk for condensation and mould growth, this data is analysed through graphs and tables, showing the temperature- and relative humidity profiles of the elements and the thermal transmittance of the different elements. In addition, air exchanges, absolute humidity, and partial pressure is calculated. This subchapter describes how data from the experimental investigations and numerical simulations are being analysed, and which equations that are being used.

3.5.1 Thermal transmittance

As mentioned, one part of the data analysis is to calculate the thermal transmittance of each element. The thermal transmittance is measured in W/m^{2}K. In this case, the thermal transmittance is calculated based on the measurements from the hukseflux sensors, as will be described later, and it is calculated without the surface resistances R_{si} and R_{se}. This is, among other things, because of the turbulence inside the climate chamber. When calculating the thermal transmittance, Eq.11 and Eq.12 are used. In Eq.11, HF represents the four heat flux sensors located on both the interior and the exterior side of the element, as explained in chapter 3.3. DT represents the temperature difference between the thermocouples, also located on both the interior and the exterior side of the element, and also explained in chapter 3.3. As there are four heat flux sensors and four pairs of thermocouples, the thermal transmittance is calculated four times. Firstly, HF1 and DT1 are used, then HF2 and DT2 are used, and so on. As can be seen in Eq.11, the different HFs should be added up, and so should the DTs. By doing this, the measurements from the entire experiment are used when calculating the thermal transmittance. The result is then four thermal transmittances, calculated using all the data from the experiments. These four calculations are then used to calculate the average thermal transmittance of the element, as shown in Eq.12. In this equation, TT stands for thermal transmittance, and TT1, TT2, TT3 and TT4 represents the four thermal transmittances calculated using Eq.11. In Eq.12, the absolute values of the thermal transmittances are used.

$$Thermal\ transmittance = \frac{\sum HF}{\sum DT} \qquad [11]$$

$$Average\ thermal\ transmittance = \frac{|TT1|+|TT2|+|TT3|+|TT4|}{4} \qquad [12]$$

3.5.2 Absolute Humidity

From the experimental investigation and the numerical simulations, data like relative humidity inside the elements are gathered. When evaluating how each of the elements and insulating materials are reacting to moisture, comparing only the relative humidity is not sufficient. This is because the relative humidity is dependent on the temperature in the exact moment, and it is relative, as the name says. Therefore, the absolute humidity is calculated. The absolute humidity is a more comparable variable, and is according to Mander [49], calculated using Eq.13. In this equation, T represents the temperature, and RH represents the relative humidity measured in percent, which are values gathered through the temperature- and relative humidity sensors located inside the elements. The absolute humidity is calculated for all of the measured values in the experiment, and presented in a graph, showing the development of the absolute humidity throughout the experiment in five different locations.

$$Absolute\ Humidity = \frac{6{,}112 * e^{\left(\frac{17{,}67*T}{T+243{,}5}\right)} * RH * 2{,}1674}{273{,}15+T} \qquad [13]$$

3.5.3 Partial Pressure

In addition to the thermal transmittance and the absolute humidity, the partial pressure is calculated. The partial pressure is used to evaluate if there is a risk for condensation in the elements in the five different locations. Before calculating the partial pressure, the saturation pressure must be calculated. These two calculations are shown in Eq.14 and Eq.15. Eq.15, for the saturation pressure, is only valid for temperatures ≥ 0°C. When evaluating the risk for condensation it is expected that the risk is increasing throughout the experiment, meaning that for the calculations of the partial pressure and the saturation pressure, only the last measurements are of interest. In other words, the partial pressure and the saturation pressure are only calculated once for each location in the element. In order to evaluate the risk for condensation, the partial pressure is compared to the saturation pressure. If the partial pressure is lower than the saturation pressure, no condensation is expected in that location. If the partial pressure reaches the saturation pressure on the other hand, this location is guaranteed to have condensation.

$$Partial\ pressure = p_{sat} * RH \qquad [14]$$

$$p_{sat} = 610{,}5 * e^{\left(\frac{17{,}269*T}{237{,}3+T}\right)} \qquad [15]$$

3.5.4 Air Exchange

In addition to measuring temperature, relative humidity, and heat flux, also the air velocity in the air gap behind the exterior cladding are measured. In order to use these measurements in the simulations, the air exchanges must be calculated. Air exchanges are calculated per hour and is in WUFI Pro used to control the movement of air in the air gap behind the exterior cladding, or in other words used to control if there is convection or not in the air gap. The formula used to calculate the air exchanges can be seen in Eq.16. In this formula, the air velocity is gathered through the experiments, A is the area of the opening of the air gap, and V is the volume of the air gap. In the experiments, the volume of the air gap is divided into two parts, due to a batten in the middle of the air gap. Because of this, the air velocity is only measured in half of the air gap, meaning that also the area and the volume is divided into two.

$$Air\ Exchange = \frac{Air\ velocity * A}{V} \qquad [16]$$

3.5.5 Validation

The last part of the data analysis is the validation of the simulations. This is done by running simulations in WUFI Pro and validating the simulations with the experiment, in order to use the simulations for the long-term analysis. In order to make sure that the experiments and the simulations are identical enough, the deviations between them must be calculated. This is done using Eq.17. This equation is used in all of the five locations measuring the temperature and the relative humidity. In order to summarize the results, the average for each location in every experiment is calculated.

$$Difference\ [\%] = \left(\frac{x_{i,sim} - x_{i,meas}}{x_{i,meas}}\right) * 100 \qquad [17]$$

4 RESULTS

The purpose of this chapter is to present the results gathered through both the experimental investigations and the numerical simulations. Firstly, in chapter 4.1, the experimental results are presented. Then, in chapter 4.2, the results from both the short-term and the long-term simulations are presented. Later, in chapter 5, these results will be discussed.

4.1 EXPERIMENTAL RESULTS

This subchapter presents the experimental results. Firstly, the results that has been used as input-values in WUFI Pro are presented, meaning the exterior and the interior climate in the climate chamber, in addition to the air exchanges in the air gap behind the exterior cladding. Then, the results used for evaluating the condensation and mould growth risk are presented. This includes the thermal transmittance of the elements, the temperature and relative humidity inside the elements, and the absolute humidity and partial pressure inside the elements.

4.1.1 Exterior and Interior Climate

This subchapter shows the temperature and the relative humidity inside the climate chamber throughout all eight experiments. These results are used to evaluate if the climate chamber is working as it should, in addition to being used as input-values in WUFI Pro. The settings for the climate chamber are shown in Table 5, and the graphs shown in this subchapter are the real-life measurements from the sensors Celsicom. Due to defrosting of the cooling aggregate, some variations in both the temperature and the relative humidity were expected. Looking at Figure 29, which is the climate from experiment 1, all climate data seem correct compared to the set values. As this were the case for almost all experiments, the rest of the climate graphs can be found in attachment A1. The only deviation was in experiment 6, wood fibreboard with cement-based cladding and no convection in the air gap, where there was some trouble with the cold side of the climate chamber during the first two days of running the experiment. Due to this issue, the experiment was left running for a few extra days, providing enough measurements for five whole days without using the data from the first two days. The issue with the climate chamber is visible in all of the results for this experiment though.

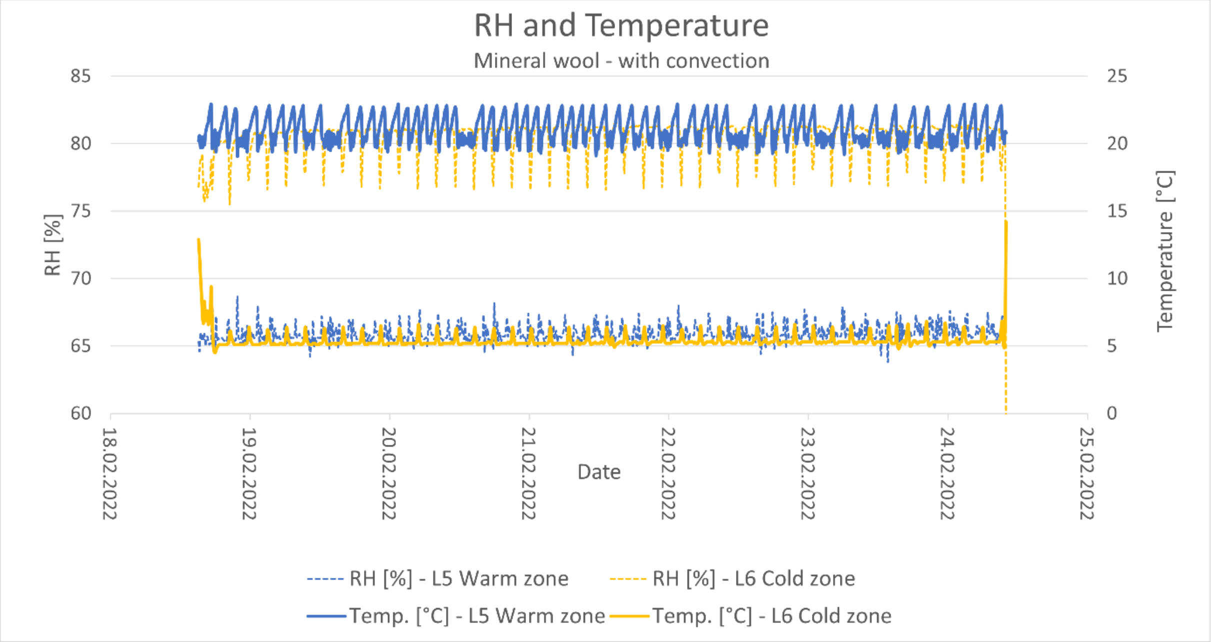

Figure 29: Interior and exterior climate for experiment 1.

4.1.2 Air Exchange

Another part of analysing the data from the experiments were to calculate the air exchanges in the air gap behind the exterior cladding, in order to use them in the WUFI Pro simulations and to monitor the air movements in the air gap. These results will tell if the air gap is ventilated or unventilated. The calculations were done using Eq.16, and the results can be seen in Table 13.

Table 13: Air exchanges.

Test nr.	Air Exchange [1/s]	Air Exchange [1/h]
1	1.53	5.49
2	0.03	0.11
3	1.38	4.98
4	0.04	0.15
5	1.12	4.04
6	0.03	0.11
7	1.53	5.49
8	0.03	0.11

4.1.3 Thermal Transmittance

Through Eq.11 and Eq.12, and the data gathered by the Hukseflux-sensors, the thermal transmittance without surface resistance for each experiment has been calculated. Originally, the results from these calculations were presented through graphs, but in order to make them easier to compare, the results have been summarized in Table 14. The original graphs can be found in attachment A2. For some of the experiments, there were some acclimatisation time which were visible in the measurements. In order to have comparable results, the measurements showing the acclimatisation were removed from the calculations. This way, all experiments are having the same start-conditions in the calculations. In other words, all calculations shown in Table 14 are without acclimatisation, but the graphs in attachment A2 includes both with and without acclimatisation.

Table 14: Thermal transmittance from the experiments.

Experiment	HF1 [W/m²K]	HF2 [W/m²K]	HF3 [W/m²K]	HF4 [W/m²K]	Average [W/m²K]	Theoretical [W/m²K]
T1 (Mineral Wool)	0.11	0.10	-0.11	-0.12	0.11	0.1231
T2 (Mineral Wool)	0.14	0.15	-0.11	-0.11	0.13	0.1207
T3 (Flax Fibre)	0.15	0.17	-0.19	-0.16	0.17	0.1263
T4 (Flax Fibre)	0.17	0.20	-0.16	-0.14	0.17	0.1237
T5 (Wood Fibreboard)	0.15	0.16	-0.16	-0.15	0.15	0.1263
T6 (Wood Fibreboard)	0.15	0.17	-0.15	-0.13	0.15	0.1237
T7 (Wood Fibreboard)	0.15	0.17	-0.11	-0.11	0.14	0.1263
T8 (Wood Fibreboard)	0.16	0.17	-0.10	-0.11	0.13	0.1220

4.1.4 Temperature and Relative Humidity

Some of the most interesting results gathered from the experiments are the temperature and relative humidity inside the elements. This has been measured in five different locations, using the sensors from Onset, as showed in Figure 19. In this subchapter, the results from these measurements are presented through Figure 30-Figure 37. Firstly, the results from the reference material are presented, then the results from flax fibre, and lastly the results from wood fibreboard, both with a cement cladding and a wooden cladding. In all the graphs, the relative humidity is marked with a dotted line, while the temperature is marked with a solid line.

Mineral Wool

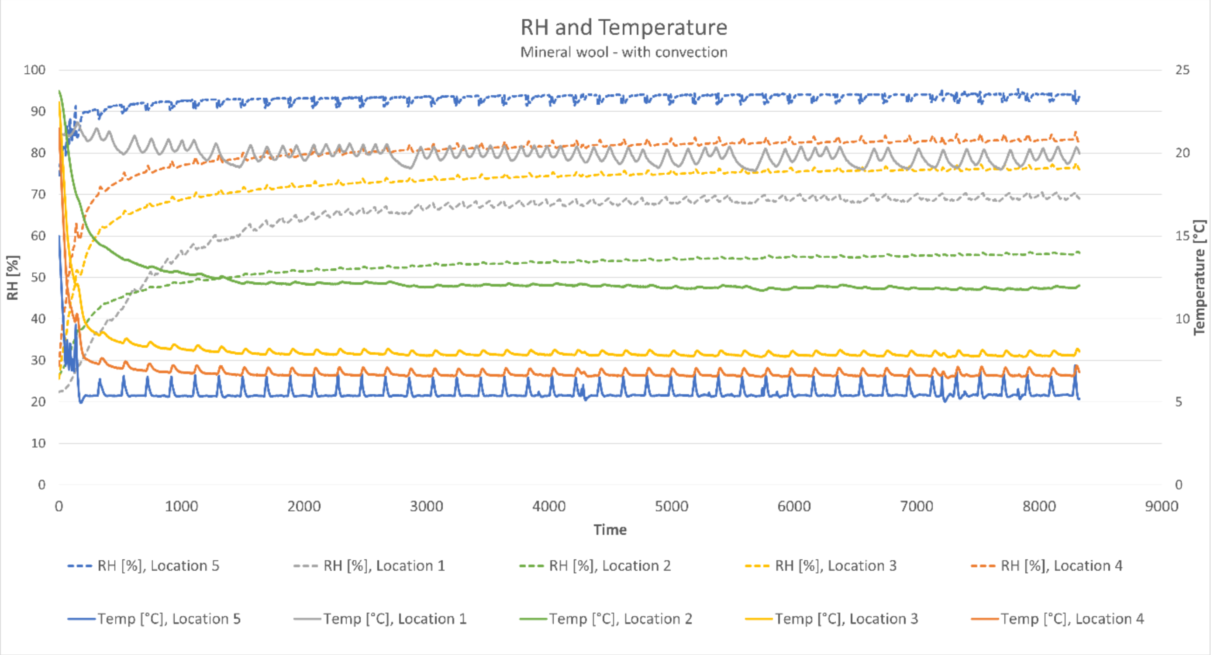

Figure 30: Relative humidity and temperature, Experiment 1.

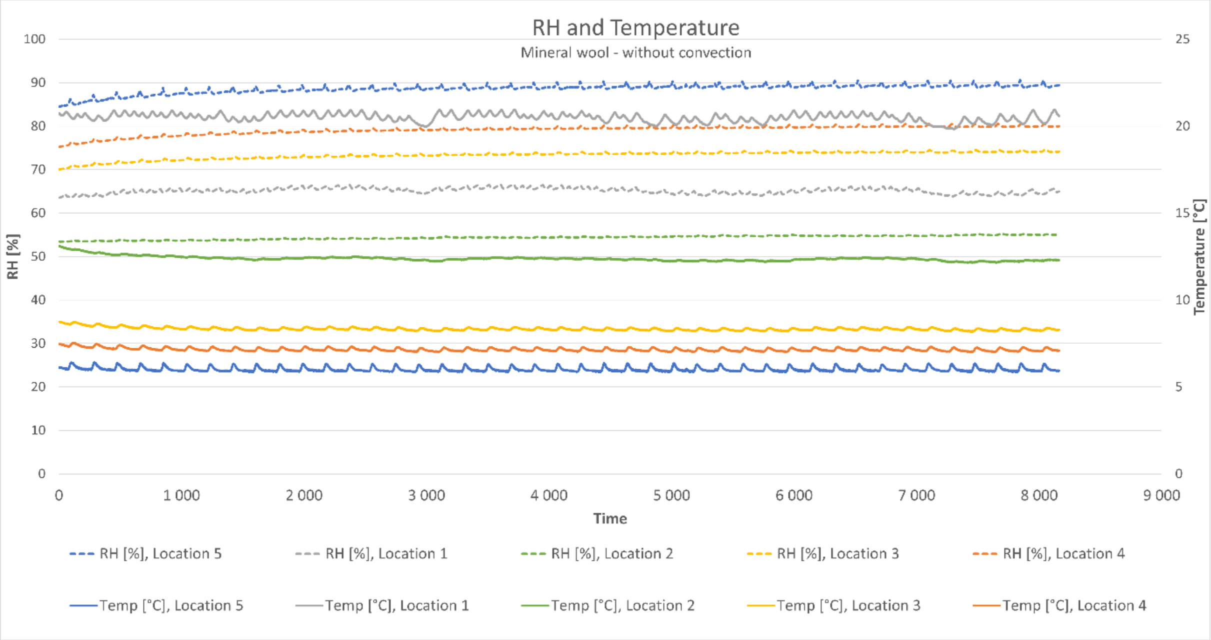

Figure 31: Relative humidity and temperature, Experiment 2.

Flax Fibre

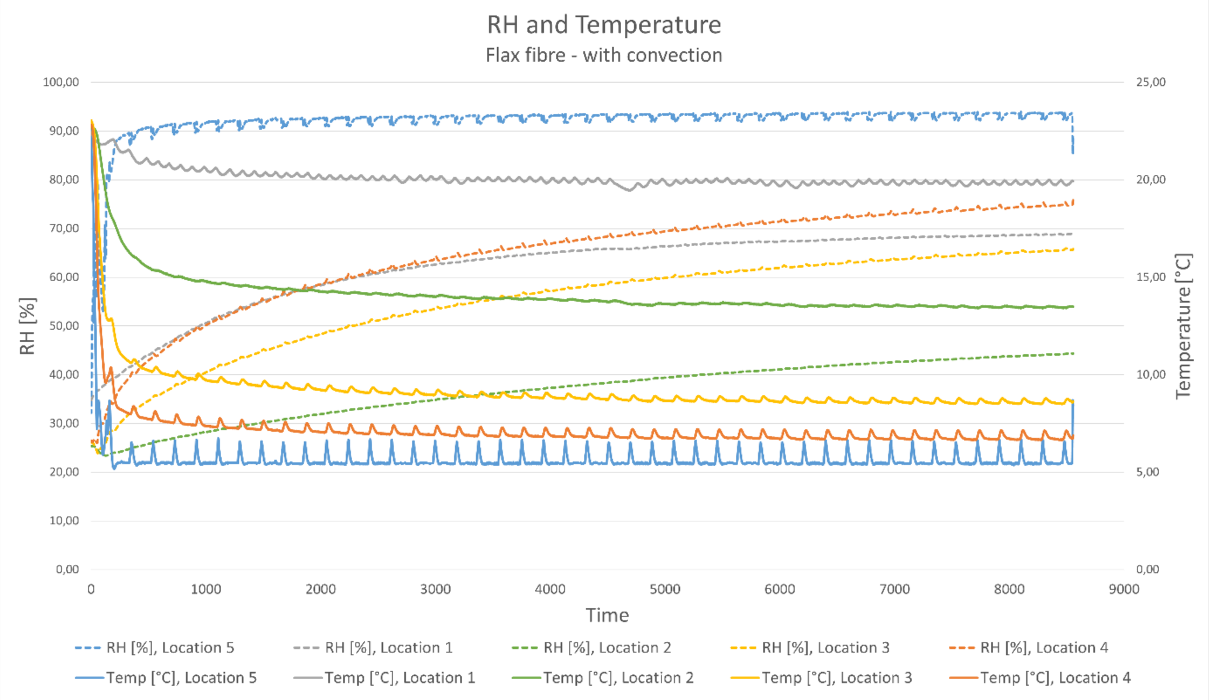

Figure 32: Relative humidity and temperature, Experiment 3.

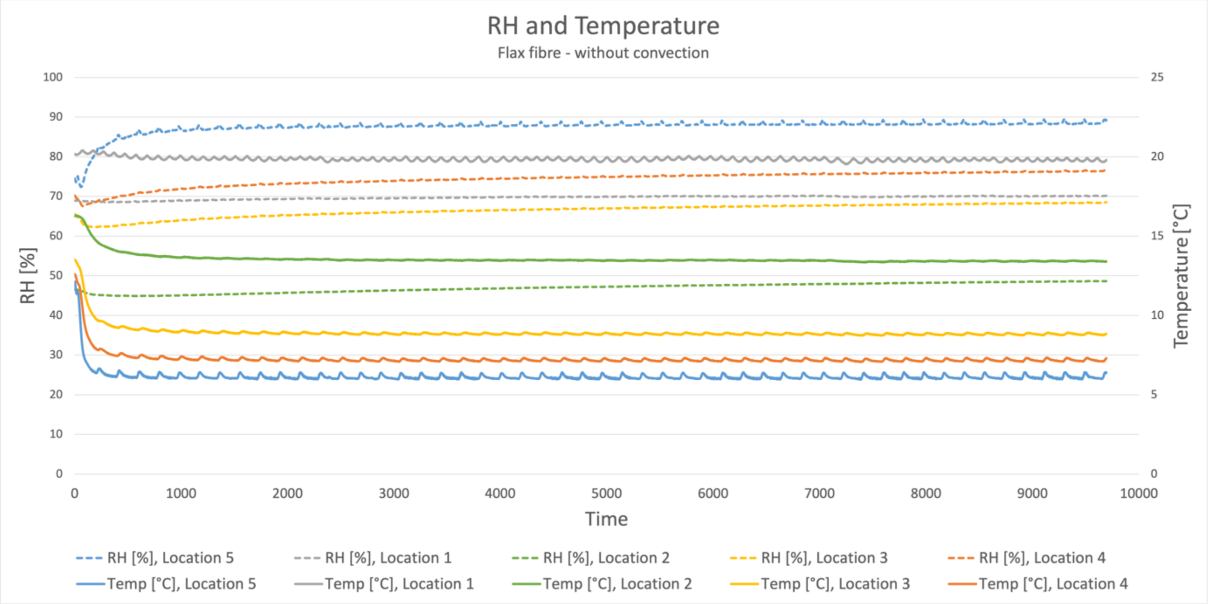

Figure 33: Relative humidity and temperature, Experiment 4.

Wood Fibreboard

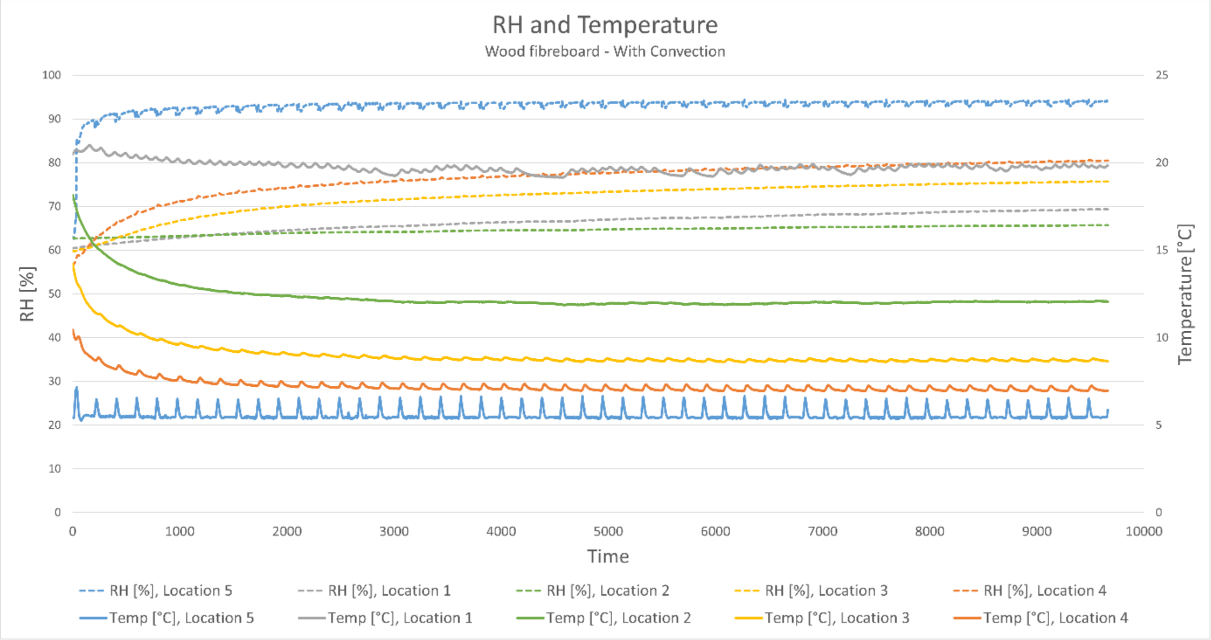

Figure 34: Relative humidity and temperature, Experiment 5.

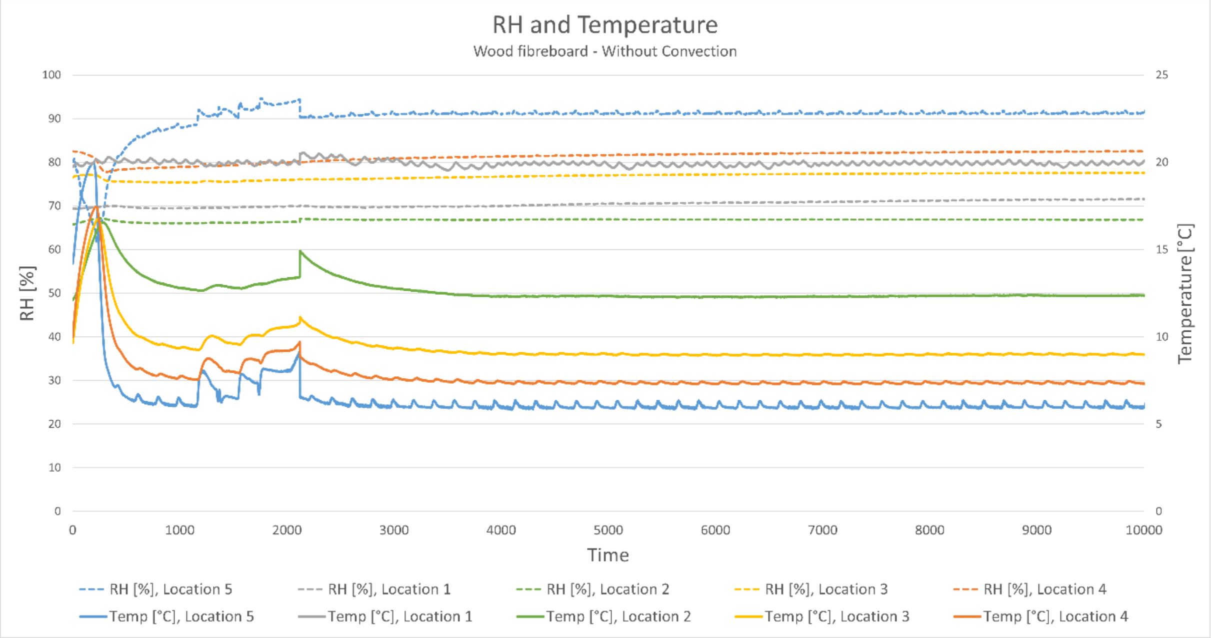

Figure 35: Relative humidity and temperature, Experiment 6.

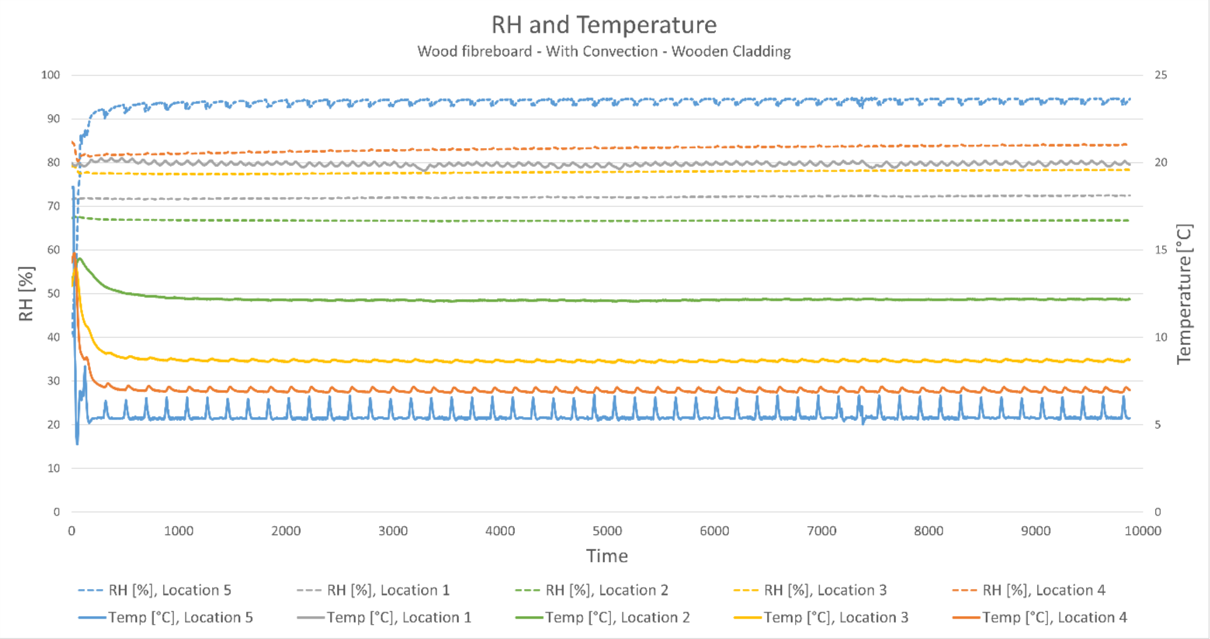

Figure 36: Relative humidity and temperature, Experiment 7.

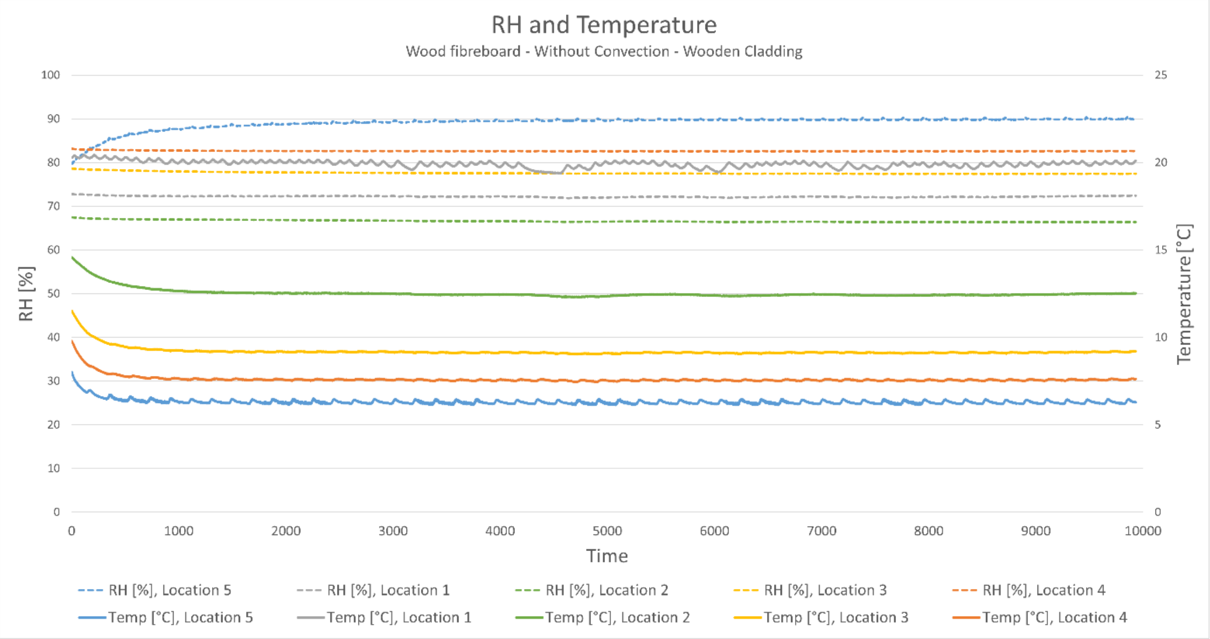

Figure 37: Relative humidity and temperature, Experiment 8.

4.1.5 Absolute Humidity

Even though the temperature and relative humidity presented in the previous subchapter are important and interesting results, they are not the most comparable results. At least not the relative humidity. Due to this, the absolute humidity is calculated and used to compare the different experiments. The absolute humidity is calculated using Eq.13 and is dependent on both the temperature and the relative humidity. The results can be seen in Figure 38-Figure 45. As for the temperature and the relative humidity, the results are presented by material with mineral wool as the first, flax fibre as the second, and lastly wood fibreboard both with a cement cladding and a wooden cladding.

Mineral Wool

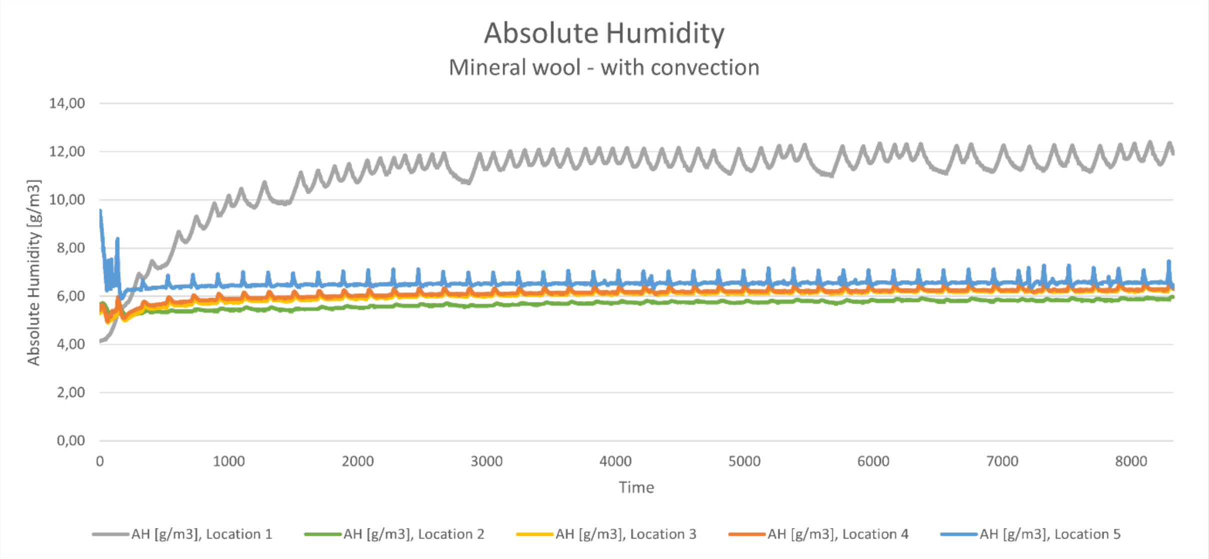

Figure 38: Absolute humidity, Experiment 1.

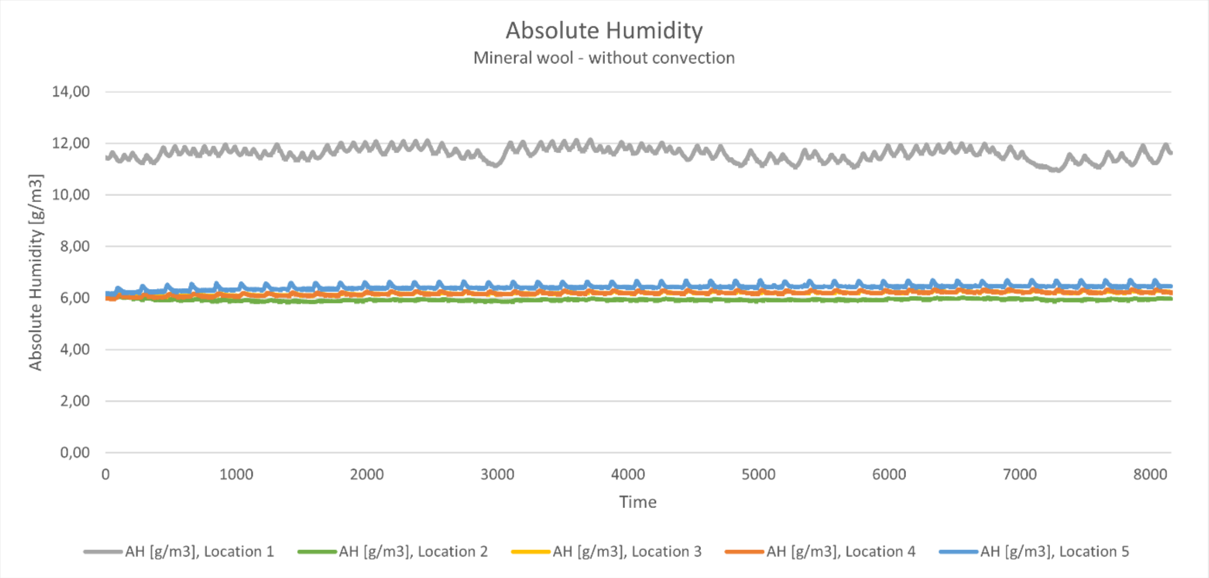

Figure 39: Absolute humidity, Experiment 2.

Flax Fibre

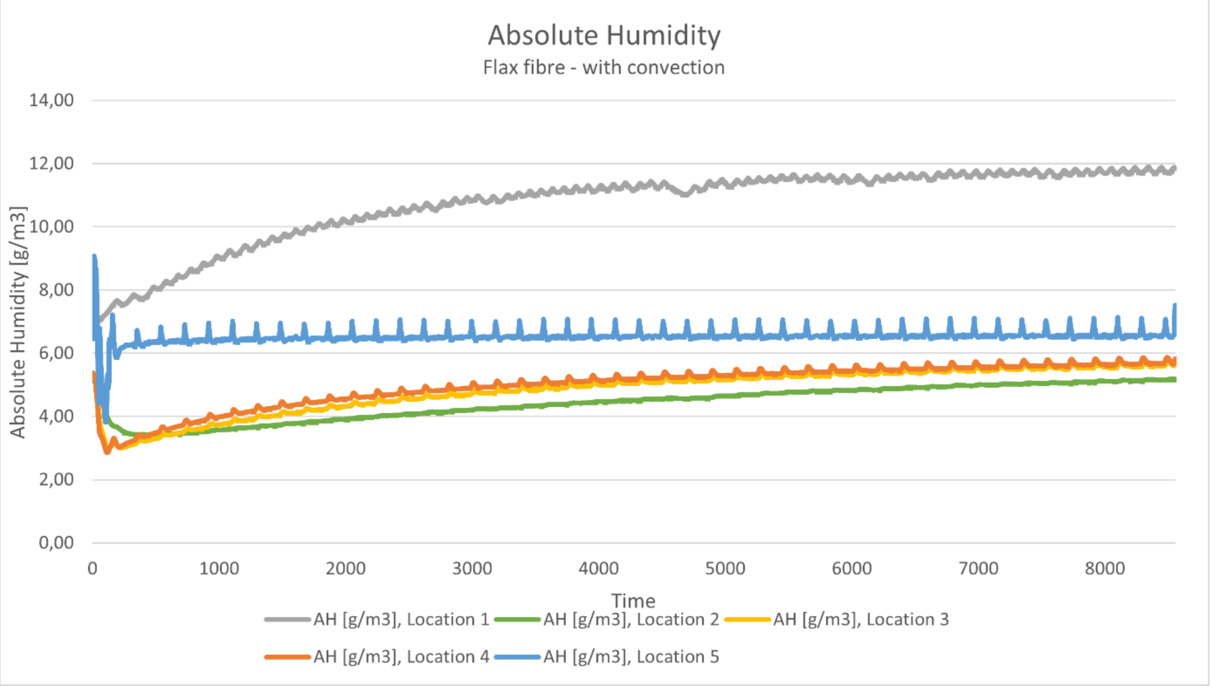

Figure 40: Absolute humidity, Experiment 3.

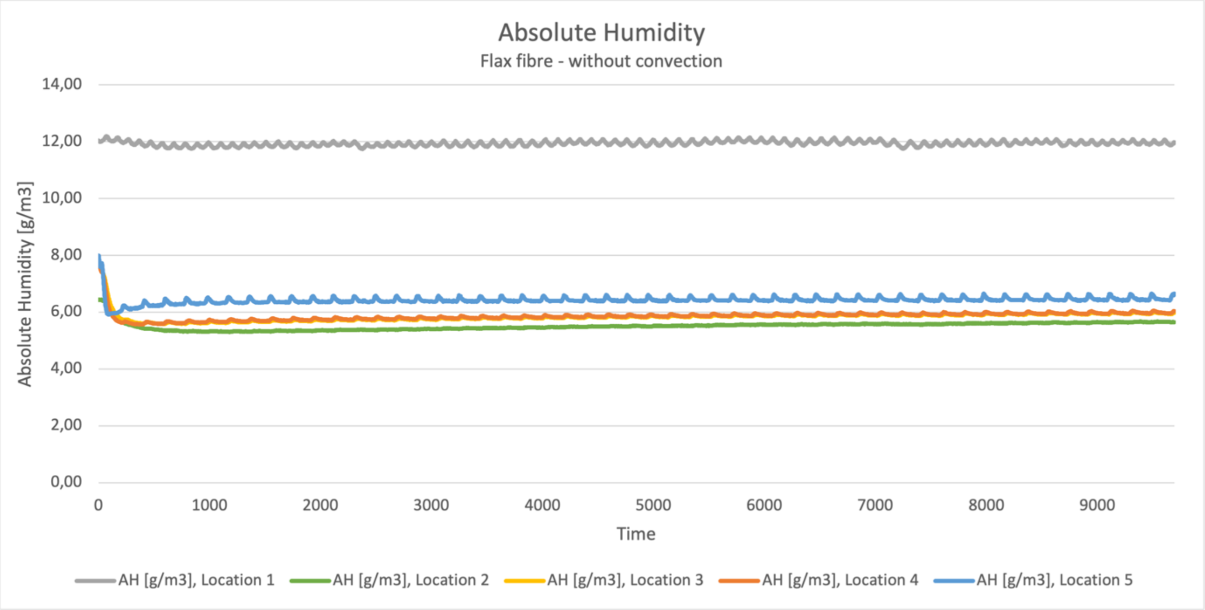

Figure 41: Absolute humidity, Experiment 4.

Wood Fibreboard

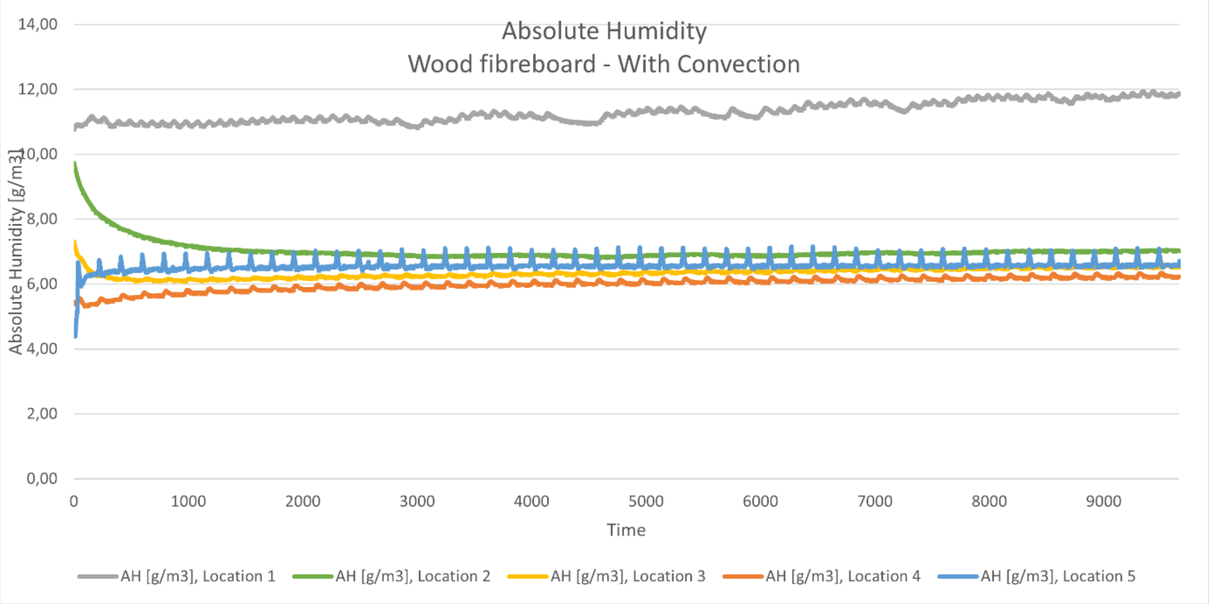

Figure 42: Absolute humidity, Experiment 5.

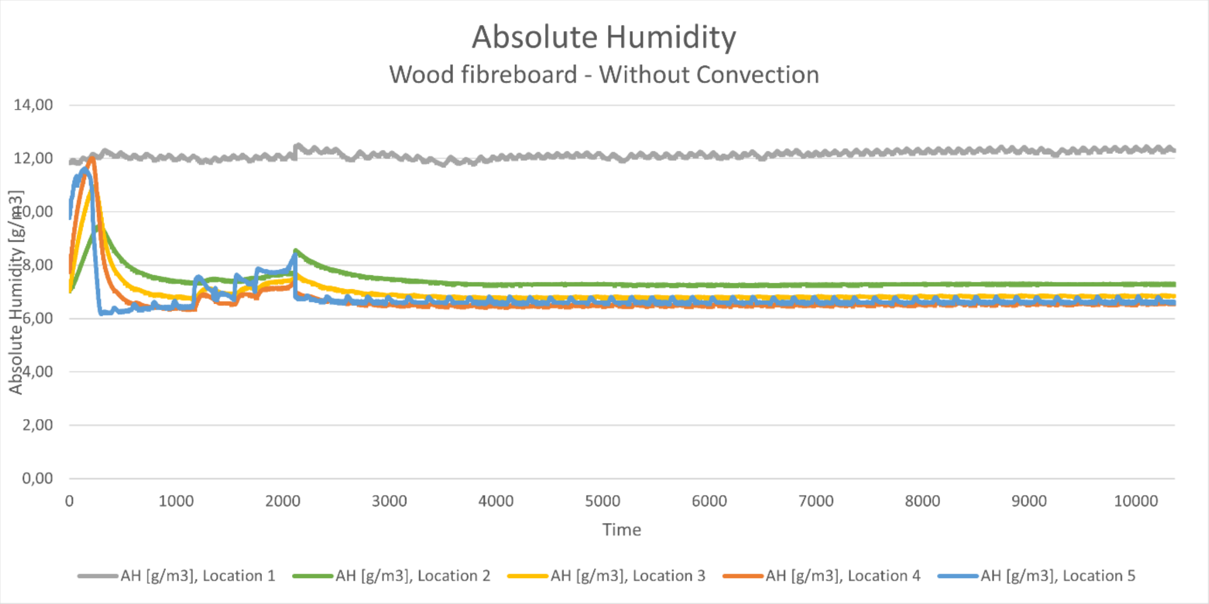

Figure 43: Absolute humidity, Experiment 6.

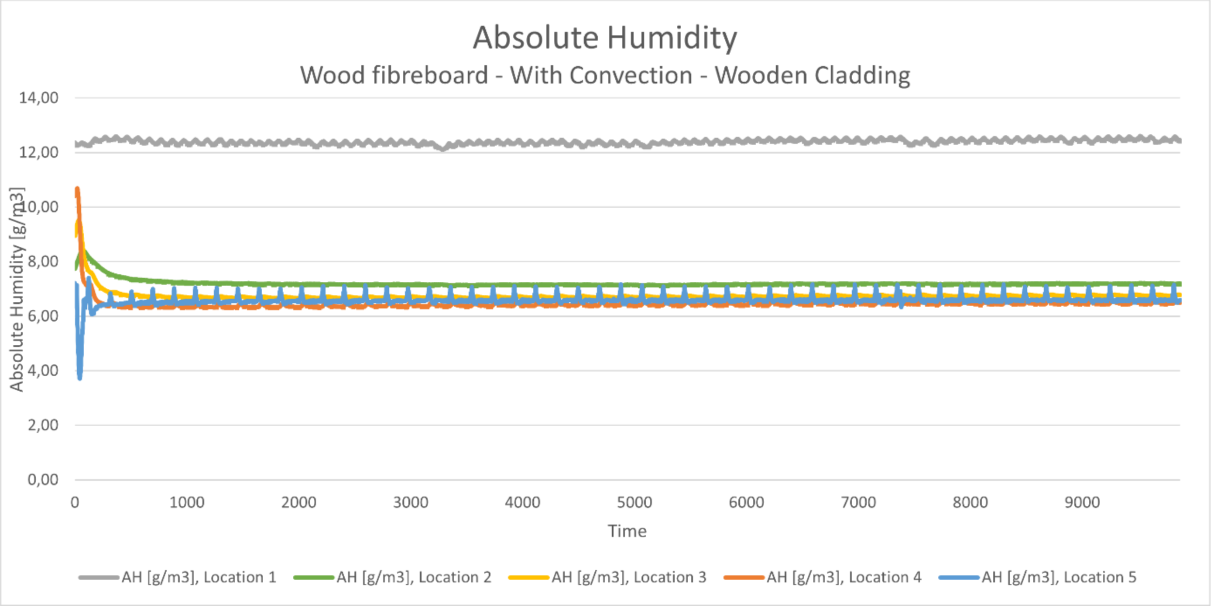

Figure 44: Absolute humidity, Experiment 7.

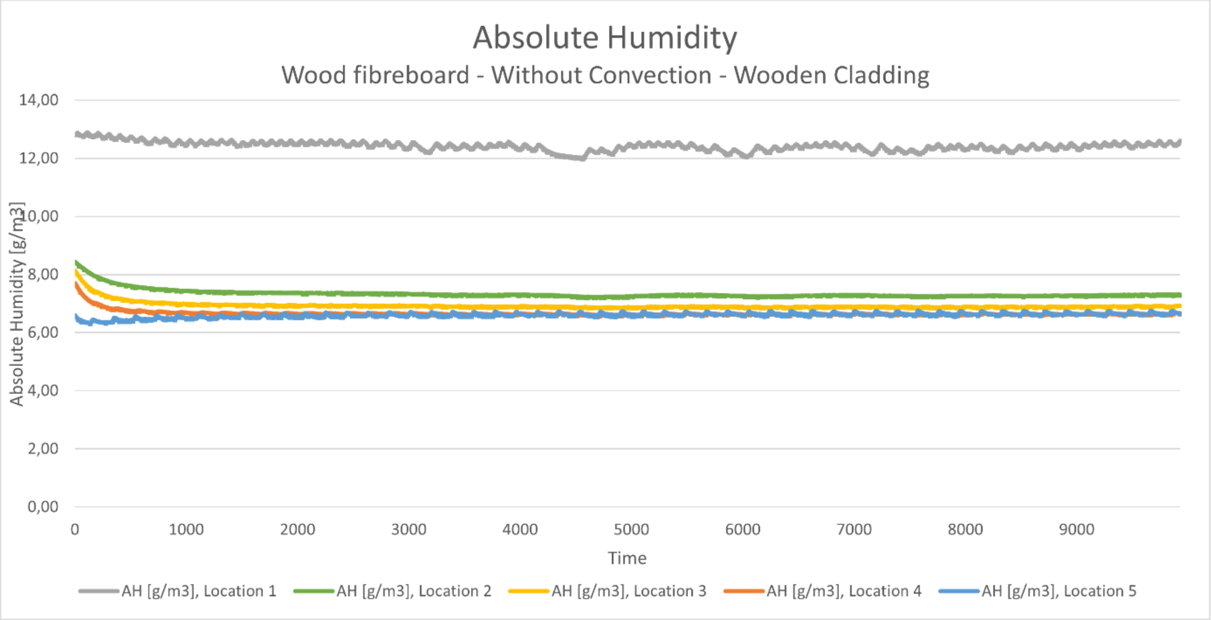

Figure 45: Absolute humidity, Experiment 8.

4.1.6 Partial Pressure

As the main purpose of this study is to evaluate the condensation and mould growth risk in the different elements, the partial pressure is calculated. The partial pressure is, together with the saturation pressure, used for exactly this purpose. Comparing these two values will help evaluate the risk for condensation, and later mould growth. These calculations are conducted using Eq.14 and Eq.15 and are dependent on both the temperature and the relative humidity in the chosen location. In other words, the measurements presented in chapter 4.1.4 are used for these calculations as well. The partial pressure and the saturation pressure are presented in Figure 46-Figure 53, in the same order as for the temperature and relative humidity, and the absolute humidity.

Mineral Wool

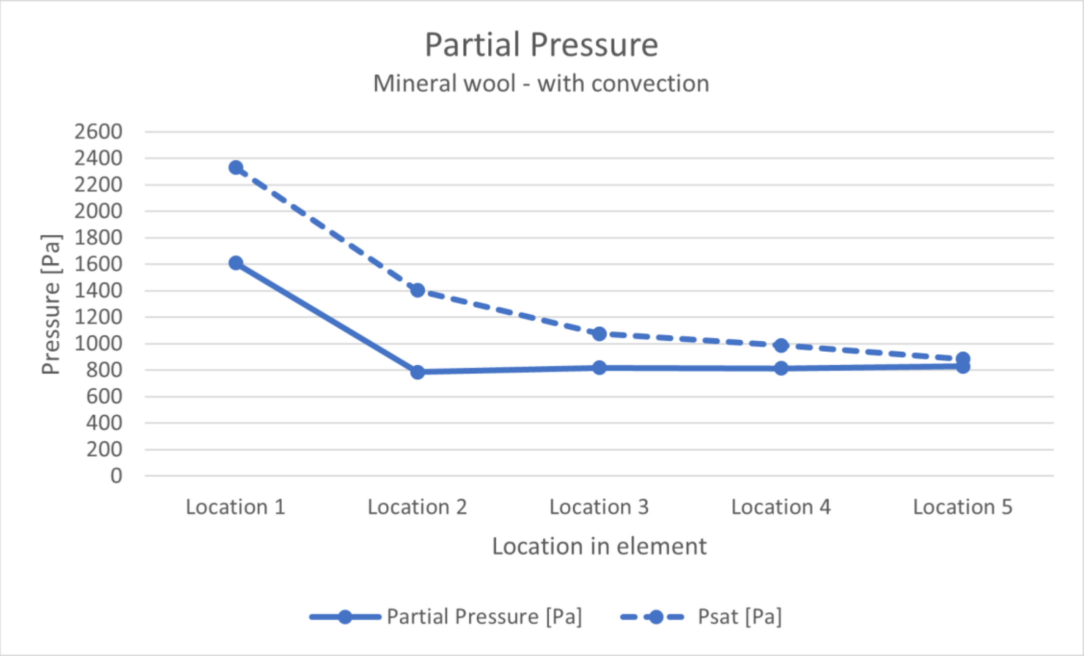

Figure 46: Partial pressure, Experiment 1.

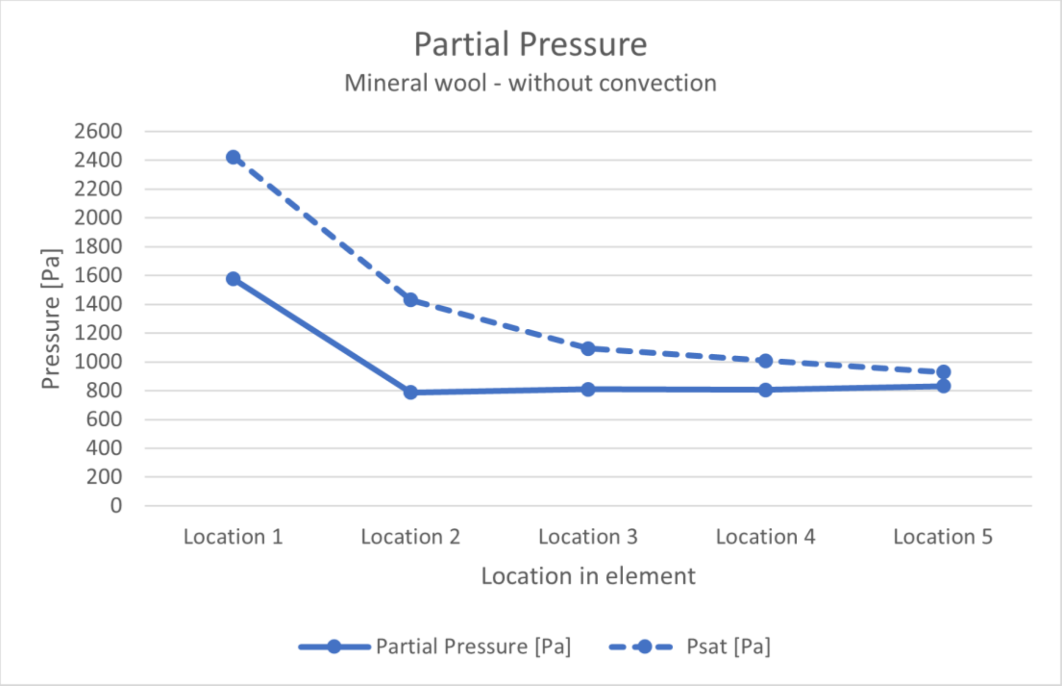

Figure 47: Partial pressure, Experiment 2.

Flax Fibre

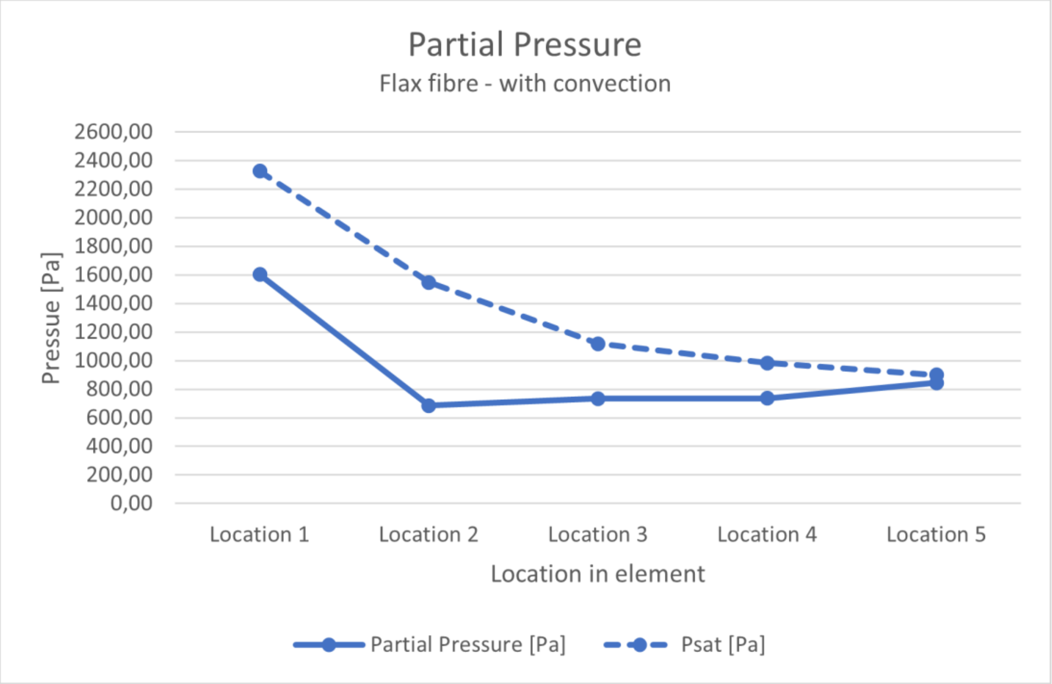

Figure 48: Partial pressure, Experiment 3.

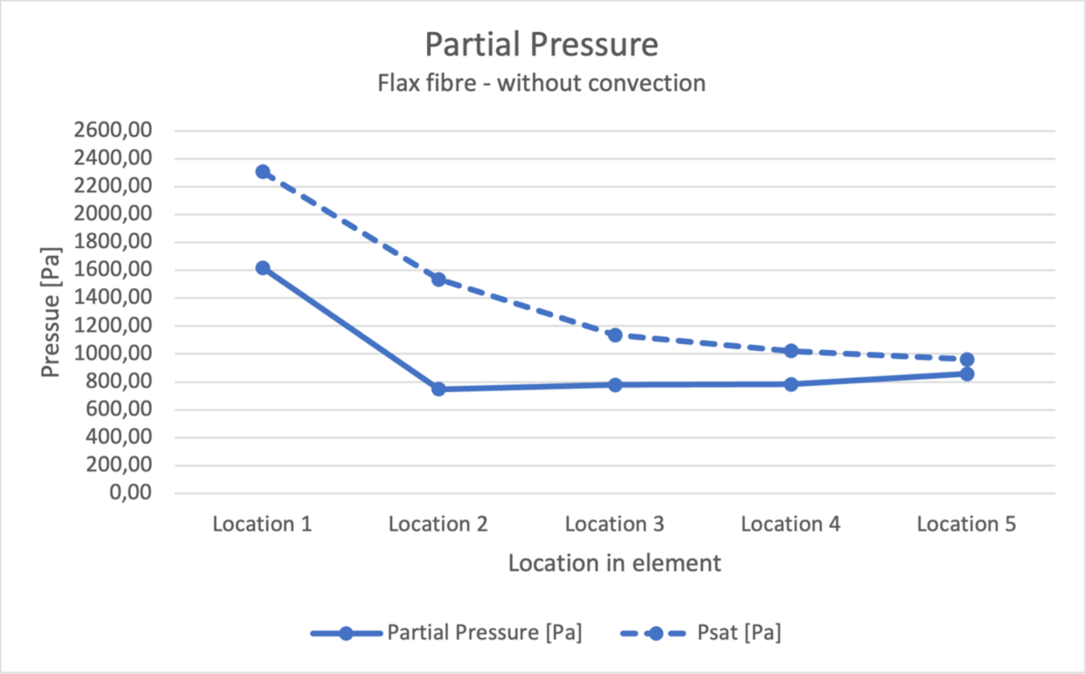

Figure 49: Partial pressure, Experiment 4.

Wood Fibreboard

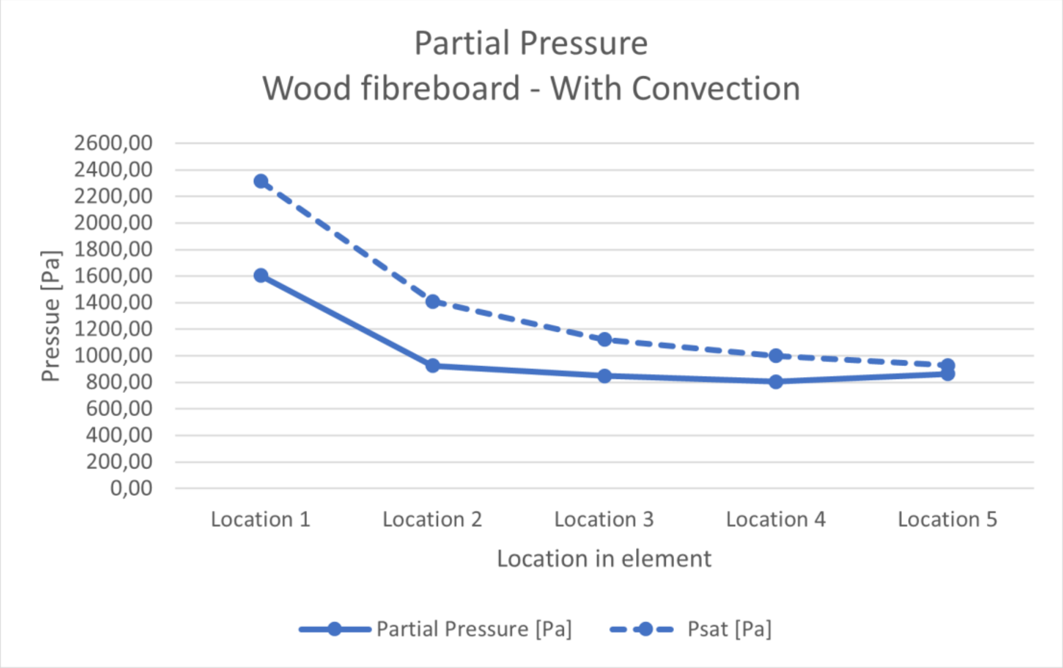

Figure 50: Partial pressure, Experiment 5.

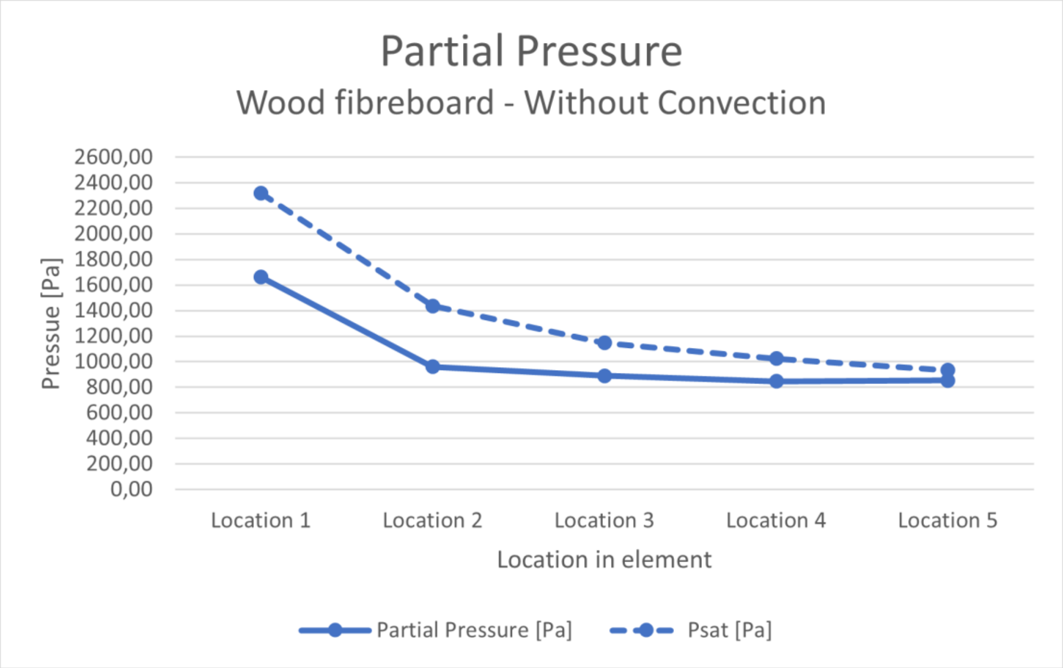

Figure 51: Partial pressure, Experiment 6.

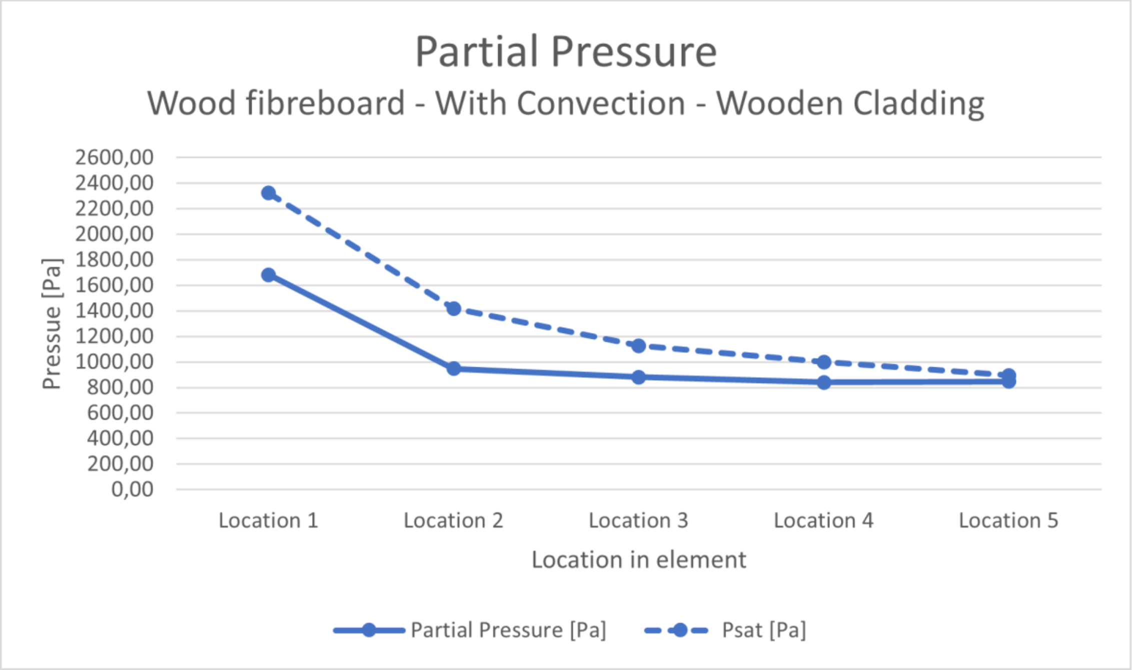

Figure 52: Partial pressure, Experiment 7.

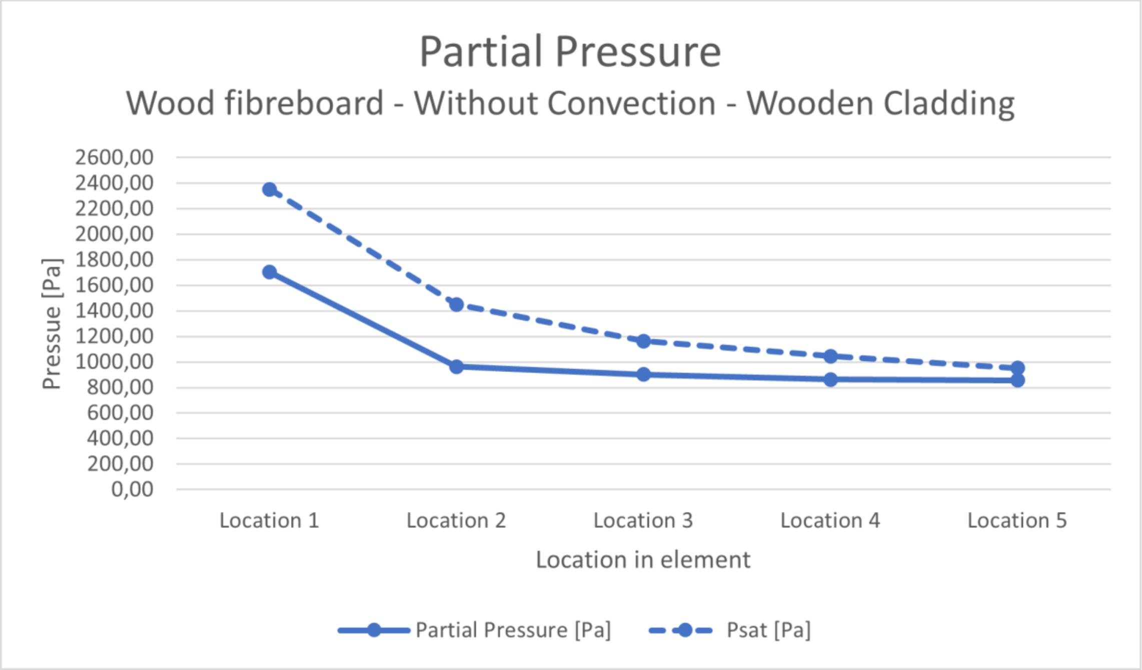

Figure 53: Partial pressure, Experiment 8.

4.2 Results from the Numerical Simulations

Now that the results from the experimental investigations have been presented, the results from the numerical simulations should be presented. This includes results from both the short-term and the long-term simulations.

4.2.1 Short-term simulations

This subchapter presents the results from the short-term simulations. These simulations are as identical as possible to the experimental investigations, which includes the material input, the climate, the start-conditions, and the duration. The main reason for conducting these short-term simulations has been to validate the model in WUFI Pro, in order to use this model for the long-term simulations and evaluate the condensation and mould growth risk after 10 years. Most of the collected data has been used to calculate the differences between the experimental investigations and the numerical simulations and are therefore not directly used in this study. This includes the temperature and relative humidity, the absolute humidity, and the partial pressure in different locations in the elements. This data can be found in attachment A3-A5. The calculated deviations between the experimental investigations and the short-term simulations can be seen in Table 15. These deviations are calculated in percent, and the calculation method can be seen in chapter 3.5.5.

Table 15: Deviation between experiments and short-term simulations, calculated in percent.

	Temp. Loc.1 [%]	RH Loc.1 [%]	Temp. Loc.2 [%]	RH Loc.2 [%]	Temp. Loc.3 [%]	RH Loc.3 [%]	Temp. Loc.4 [%]	RH Loc.4 [%]	Temp. Loc.5 [%]	RH Loc.5 [%]
T1	-3.74	32.37	4.07	-4.47	1.26	-6.06	4.3	-8.71	4.98	-14.43
T2	-3.17	7.34	9.71	-11.23	1.47	-9.74	1.19	-9.25	-4.19	-10.58
T3	0.53	6.49	0.16	-3.86	-2.73	-4.27	6.59	-8.56	5.38	-19.87
T4	0.61	1.79	0.61	5.45	-4.84	0.19	0.31	-3.19	-5.52	-10.23
T5	0.03	3.72	8.87	-6.85	-5.8	-4.42	1.02	-5.74	5.65	-16.41
T6	-0.22	-1.1	9.95	-3.87	-2.27	-2.68	4.42	-3.43	6.34	-8.82
T7	-0.09	-0.82	10.99	-3.76	-1.3	-1.54	6.7	-3.43	11.41	-14.6
T8	-1.8	-1.86	2.35	-2.92	-11.69	0.22	-7.02	-0.53	-7.17	-3.94

4.2.2 Long-Term Simulations

In addition to the short-term simulations from WUFI Pro, long-term simulations for each of the experiments has been conducted. These simulations have the same input-values as the short-term simulations, except for the exterior and interior climate, and the duration. The most interesting results from the long-term simulations are the mould index. The mould index indicates how much mould growth you can expect to find in the chosen location, through a scale consisting of six points. This scale is described in chapter 3.4.3. In the long-term simulations, the mould index has been measured in two different locations, location A and B, as shown in Figure 54. The results are presented, material by material, in Figure 55-Figure 58. In addition to the mould index, the water content could be of interest when evaluating the long-term simulations. The results showing the water content of the different experiments in location A can be found in attachment A6.

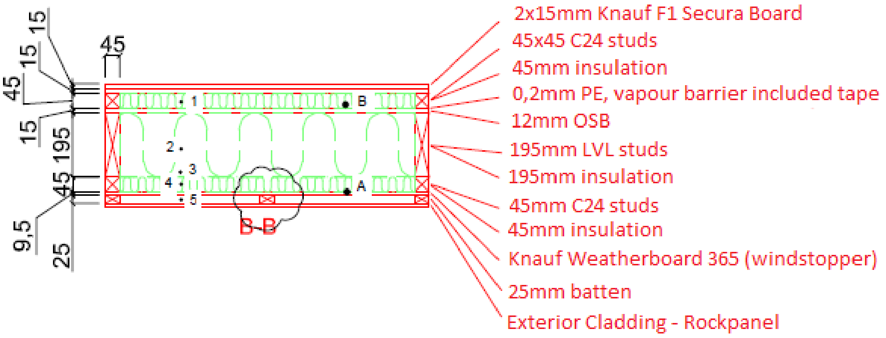

Figure 54: Location A and B

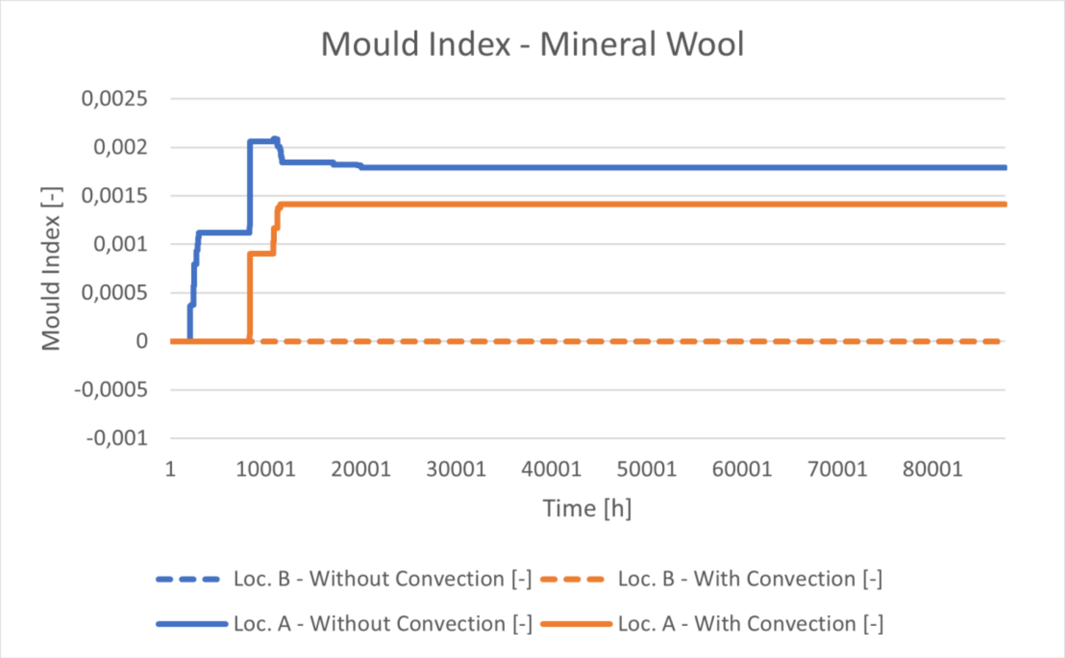

Figure 55: Mould Index - Experiment 1 and 2

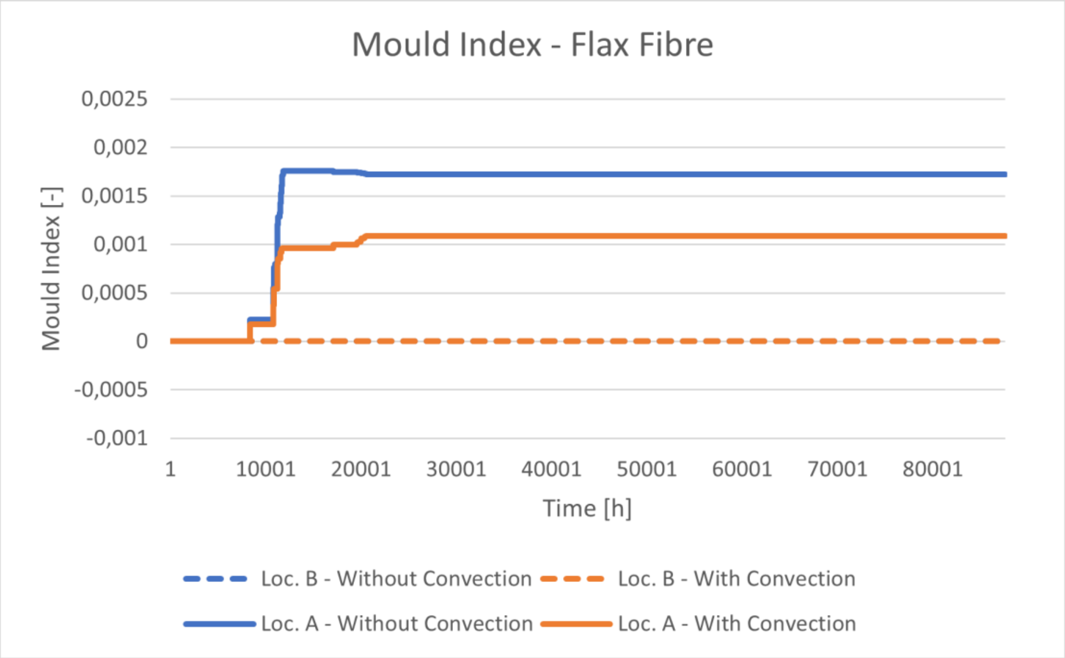

Figure 56: Mould Index - Experiment 3 and 4

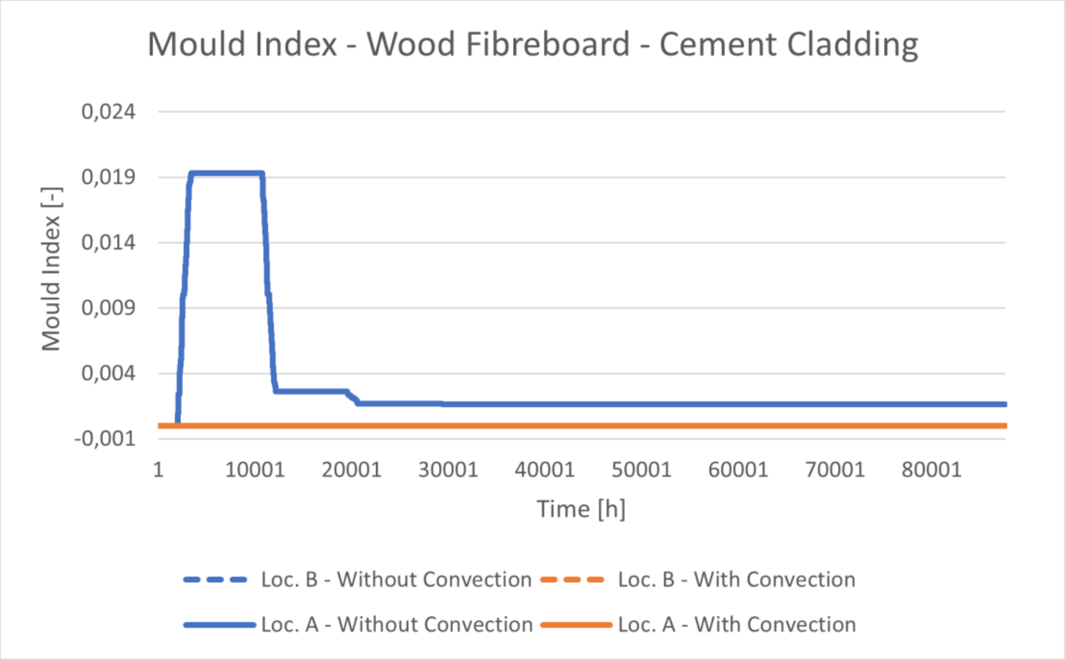

Figure 57: Mould Index - Experiment 5 and 6

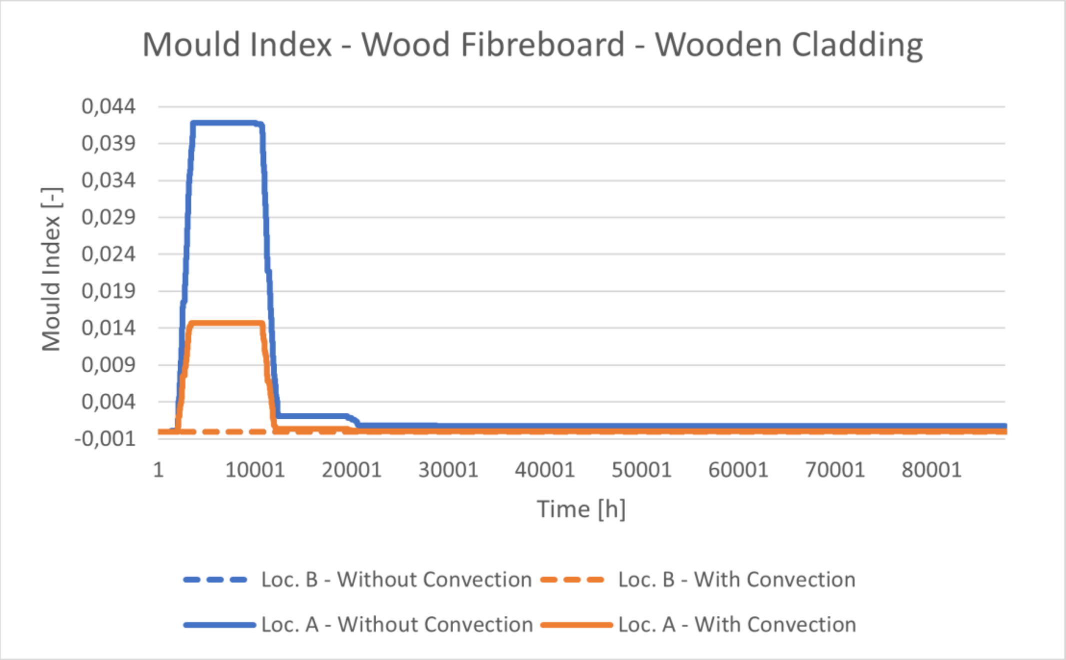

Figure 58: Mould Index - Experiment 7 and 8

5 DISCUSSION

By conducting experiments and simulations, a lot of information has been gathered about the two nature-based insulating materials flax fibre and wood fibreboard, in addition to the reference material mineral wool. In order to answer the research question, these results will be discussed and evaluated in connection to the theory, the expected results and already existing research. An attempt to discuss the risk for condensation and mould growth will be given, looking at the different variables from the experiments and their effect on the hygrothermal properties of the elements. After discussing the experimental results, the results from the simulations will be discussed and compared to the experiments.

Before diving into the categories affecting the condensation and mould growth risk, some general comments to the results will be discussed. These comments are valid for all experiments, unless else is told. First of all, the acclimatisation in the beginning of some of the experiments should be addressed. In the experiments where a new insulating material is inserted, there seem to be some acclimatisation time before the measurements stabilizes around a certain value. This acclimatisation is most visible in experiment 1 and 3, which is mineral wool and flax fibre both with convection in the air gap, respectively. For experiment 5, wood fibreboard with a cement-based cladding and convection in the air gap, the same tendencies were expected, but looking at the results, the acclimatisation time seems shorter and not as present as for experiment 1 and 3. This might simply be due to the starting time of the experiment. When conducting the experiments, there were in some cases an issue with the software connected to the climate chamber. To avoid this issue, the temperature in the climate chamber were activated a few hours before the relative humidity, for some of the experiments. As the gathered data is from the moment the relative humidity was activated, it could be reasonable to assume that the element had already gone through some of the acclimatisation at that point, which might be the reason for the short acclimatisation time in experiment 5. Secondly, the absolute humidity in location 1 for all experiments should be addressed. As can be seen in Figure 38-Figure 45, the absolute humidity in this location is about twice as high as in the rest of the locations. Looking at the location of the different sensors in Figure 19, one can see that this sensor is located with quite a bit of distance to the rest of the sensors. In addition, both the temperature and the relative humidity in the same location are quite high. As the absolute humidity is dependent on both the relative humidity and the temperature, it makes sense that the absolute humidity is high in this location as well.

5.1 INSULATING MATERIAL

The first factor expected to influence the hygrothermal properties and the risk for condensation and mould growth, are the insulating materials. The type of material used are expected to influence the thermal transmittance, the temperature, relative humidity, and absolute humidity throughout the element, in addition to the partial pressure. Looking at for example the thermal transmittance, one can see that this property is varying with the insulating material used, as shown in Table 14. As expected, this table shows that mineral wool is the insulating material with lowest, and therefore best, thermal transmittance. The thermal transmittance of mineral wool is measured to be 0.11 W/m^{2}K and 0.13 W/m^{2}K, respectively with and without convection in the air gap. The next insulating material in line is wood fibreboard, with a thermal transmittance of 0.15 W/m^{2}K, both with and without convection in the air gap. Lastly, flax fibre has a thermal transmittance of 0.17 W/m^{2}K, both with and without convection in the air gap. One of the hypothesis of this master thesis was that flax fibre would have better thermal- and moisture properties than wood fibreboard. As mentioned, flax fibres are hollow, which makes the material better at keeping the insulating air inside the fibres. In addition, flax fibre can handle quite a lot of water before it starts affecting the thermal properties. Based on this, early investigations in the BiW-project, and the existing research, flax fibre was expected to have better properties than wood fibreboard. Looking at the results, this does not seem to be the case though. Flax fibre is, in fact, the insulating material with highest thermal transmittance, and therefore the worst thermal properties. That being said, even though flax fibre was expected to have good thermal properties, it was also expected that wood fibreboard could deliver some good results. As wood fibreboard now seems to deliver better results than flax fibre, this seems reasonable to expect. It should also be mentioned that all three insulating materials are within the requirements from TEK17, which for exterior walls is 0.18 W/m^{2}K, even without the surface resistances.

In addition to affecting the thermal transmittance, the insulating material also affects the temperature- and relative humidity development through the construction. From the experimental results, one can see that the material with the lowest relative humidity is flax fibre, with 40-50% RH. This is measured in the middle of the element, using sensor nr.2, as shown in Figure 32 and Figure 33. Both mineral wool and wood fibreboard has higher relative humidity in the same location, with 50-60% RH and 60-70% RH, respectively. The reason for flax fibre having lower relative humidity than the two others might be flax fibre's ability to always try to keep the moisture content constant and natural. As mentioned, the fibres therefore transport moisture towards the exterior side of the wall, and lets the moisture exit there. For this mechanism to work it is important that the exterior side is quite open for diffusion, for example through a wind barrier with low water vapour diffusion resistance, and that there is an air layer behind the exterior cladding, which both is the case for this study. When looking at the temperature in the same location, one can see that the temperature for flax fibre is a bit higher than for mineral wool and wood fibreboard. This higher temperature might also be a reason for the low relative humidity. It is well known that warm air can hold more moisture than cold air, which can be adapted to this scenario. In other words, as the temperature rises, the relative humidity decreases. As mentioned, the temperature in location 2 for flax fibre is higher than for mineral wool and wood fibreboard, and the relative humidity is lower than for mineral wool and wood fibreboard. In other words, higher temperature leads to lower relative humidity also in this scenario.

When speaking of flax fibre, it is important to mention the acclimatisation. In every experiment where new insulation is inserted, some acclimatisation time is expected. What makes flax fibre special is that this acclimatisation time seems longer than it is for mineral wool and wood fibreboard. This can for example be seen through the relative humidity in Figure 32 and the absolute humidity in Figure 40. It looks like it takes longer for moisture to travel through flax fibre than it does for materials like mineral wool and wood fibreboard. This might come from the fact that the fibres are always trying to keep the moisture content constant and natural. In Figure 40, showing the absolute humidity, this acclimatisation can be seen through the values of sensor 2, 3 and 4. Because of the short duration of the experiment, it looks like the absolute humidity is lower for flax fibre than it is for mineral wool and wood fibreboard, but the more likely explanation is that it takes longer for the humidity to stabilize in flax fibre and that the values are moving towards an equilibrium close to the values for mineral wool and wood fibreboard. In Eq.13 one can see that the absolute humidity is dependent on both the relative humidity and the temperature, and as the relative humidity is affected by acclimatisation, the absolute humidity is expected to be as well.

Up until now, flax fibre has been the insulating material that stands out the most and has important properties to comment. That being said, the absolute humidity of wood fibreboard is also worth noticing. In all four figures containing results about absolute humidity for wood fibreboard, one can see that the absolute humidity seems to go towards an equilibrium around 7 g/m^3. For both mineral wool and flax fibre, this equilibrium seems to be around 6 g/m^3. In other words, the absolute humidity of wood fibreboard is higher than the absolute humidity for the other two materials. This might be connected to the high relative humidity and the low temperature of wood fibreboard, for example in location 2 in Figure 34-Figure 37, as mentioned earlier. The absolute humidity is, as mentioned, calculated through Eq.13, which includes both the relative humidity and the temperature. When using this formula, a high relative humidity together with a low temperature will give higher absolute humidity than it would if the relative humidity was lower, like it is for mineral wool. This can play a role in explaining why the absolute humidity is higher for wood fibreboard than it is for mineral wool and flax fibre. Even though the absolute humidity is high, it does not seem to have affected the thermal transmittance that much, as one might expect. As mentioned earlier, the thermal transmittance of wood fibreboard is better than the thermal transmittance of flax fibre, despite the fact that the absolute humidity is higher for wood fibreboard.

5.2 CONVECTION

The second factor expected to affect the hygrothermal properties and the risk for condensation and mould growth is convection. In this case, convection is relevant for the air gap behind the exterior cladding, and every insulating material is tested both with and without convection. With convection refers to a fully ventilated air gap, while without convection refers to an unventilated air gap. To determine if the air gap is ventilated or unventilated, the number of air exchanges per hour is calculated, as shown in Table 13. These calculations are based on the air velocity in the air gap, which has been monitored throughout all experiments. When looking at these calculations, one can see that all experiments with convection have an air exchange above 1, which in practice refers to fully ventilated. In addition, all experiments without convection have an air exchange around 0.1, which in practice refers to unventilated. In other words, the experiments seem to have been executed correctly, regarding the convection.

As mentioned, the convection is expected to impact the hygrothermal properties quite a bit. This is based on early investigations in the BiW-project. That being said, the findings from the experiments tells otherwise. The first thought when interpreting the results is that there is no obvious pattern in how convection affects the different materials. Looking at for example the thermal transmittance, one can see that for mineral wool, the thermal transmittance is lowest with convection in the air gap, while for wood fibreboard the thermal transmittance is lowest without convection in the air gap. For wood fibreboard this applies for the experiment with a wooden exterior cladding. For wood fibreboard with cement cladding and flax fibre, there is no difference between the thermal transmittance with and without convection in the air gap. As convection were expected to affect the hygrothermal properties quite a bit, these results are surprising. Trying to interpret these results and forming some sort of theory or reason why the results turned out different than initially though, the first explanation that comes to mind is that convection affects the moisture properties more positively than it affects the thermal properties. Looking at for example wood fibreboard, where the thermal properties are worse with convection, this might be explained by the fact that exchanging the air in the air gap gives access to new and colder air, which cools down the surface and increases the heat transfer. This will reduce the thermal properties. That being said, when looking at mineral wool, the results tell the opposite. In this case, the thermal properties are better with convection than without convection. This does not support the theory just presented.

In addition to the thermal transmittance, the temperature and relative humidity in five different locations inside the element has been monitored. The temperature in these locations seems quite independent of the convection, except for mineral wool where the temperature is a bit higher without convection than with convection. This difference applies for all the locations, but it is bigger and more visible for location 5 in the air gap. Looking at this in connection to the theory presented in the last paragraph, where it was suggested that convection affects the moisture properties more positively than it affects the thermal properties, this makes sense. In this case, the temperature is higher without convection, where the air is not exchanged that often. This makes it easier to keep the warm air inside the air gap, instead of exchanging it with colder air, resulting in a higher temperature. It should also be mentioned that the temperature in the air gap is varying more when there is convection than when there isn’t. This is probably due to the defrosting of the cooling aggregate, which will affect the air gap more when there is convection than it will when there isn’t, as the air has easier access to the air gap when the gap is fully ventilated through convection.

Based on the theory just presented, convection is expected to affect at least the moisture properties positively, meaning that moisture in the wall is expected to be reduced when there is convection. Looking at for example the relative humidity for mineral wool and flax fibre, the results are opposite of the expected results. The relative humidity is lower without convection than with convection, for all locations except location 2. It should be mentioned though, that due to the long acclimatisation for flax fibre, the results are a bit difficult to evaluate and might not be as reliable as the rest. For wood fibreboard, o in the air gapn the other hand, convection does not seem to affect the relative humidity as much. The only difference can be found in location 5 in the air gap. Here, the relative humidity is lower without convection than with convection, which is the same development as for mineral wool and flax fibre. The reason why convection affects the moisture properties opposite of what was expected is not known. The only reason that comes to mind is that the experiments could be executed wrongly. Based on the air exchanges though, this does not seem to be the case. To investigate this further, the experimental results should be compared to the results from the simulations, which will be done later. When talking about moisture, it is important to remember that the absolute humidity is a more comparable variable than the relative humidity, and that this variable should be evaluated as well. Looking at the results for absolute humidity, one can see that there is almost no difference when there is convection and when there is not. This might indicate that the convection does not play that big of a role as initially thought. What should be mentioned though, is that there seem to be some more variation in the absolute humidity in the air gap when there is convection. As the temperature in the air gap is varying with convection as well, this makes sense.

5.3 EXTERIOR CLADDING

The third and last factor expected to affect the hygrothermal properties and the risk for condensation and mould growth is the exterior cladding. As mentioned, the cladding used for most of the experiments were a cement-based cladding. During the last two test though, a wooden cladding treated with fire retardant was tested as well, in order to examine if the exterior cladding would have any effect on the hygrothermal properties. Due to limited time, the wooden cladding was only tested together with wood fibreboard. Before conducting any tests, the initial though was that the exterior cladding would not affect the results in any significant amount. As mentioned in the theoretical background, all surfaces can in principle be attacked by mould, so both a cement-based cladding and a wooden cladding can be at risk. After reading some of the earlier investigations done in the BiW-project, the expectations changed. Some of the results in these investigations showed that the cement-based cladding increased the risk for condensation and mould growth, compared to the wooden cladding. The expectations were therefore that the wooden cladding would give the best results.

Looking at the results from the experiments, the effect of the exterior cladding looks almost insignificant. There is approximately no difference in either the relative humidity, absolute humidity, or the temperature inside the element. Looking at the thermal transmittance though, the wooden cladding seems to result in a bit lower thermal transmittance than the cement cladding. The thermal transmittance is reduced from 0.15 W/m^{2}K to 0.14 W/m^{2}K with convection, and from 0.15 W/m^{2}K to 0.13 W/m^{2}K without convection. In other words, the reduction is 0.01 and 0.02. This reduction might seem small, but a reduction of 0.01 from 0.15 is somewhere between 6% and 7%, while a reduction of 0.02 from 0.15 is a reduction of about 13%. These reductions are in other words not as insignificant as initially though. In other words, the thermal properties when using a wooden cladding is better than the thermal properties when using a cement-based cladding. In addition to affecting the thermal transmittance, the exterior cladding also affects the mould growth risk in the long-term simulations. This will be discussed later.

5.4 CONDENSATION AND MOULD GROWTH

The last, and probably the most important topic to discuss in this study is the risk for condensation and mould growth in the different experiments. In order to evaluate the risk for condensation and mould growth, the saturation pressure and the partial pressure is calculated, as shown in Figure 46-Figure 53. If the partial pressure reaches the saturation pressure, there will be condensation. As mentioned, mould requires nutrients, moisture, and the correct temperatures to grow. If there is access to these over a longer period of time, mould will grow. This means that over time, if the partial pressure reaches the saturation pressure and condensation occurs, this will create good growing terms for mould. In other words, condensation and mould growth are closely linked together. Therefore, when evaluating the risk for condensation, the risk for mould growth is evaluated as well.

5.4.1 Experimental Investigation

From the experimental results one can see that at the time being, there is no condensation in any of the locations in the elements, as the partial pressure never reaches the saturation pressure. This can be seen in Figure 46-Figure 53. Due to the short duration of the experiments though, it is desirable to evaluate the long-term simulations from WUFI as well, before concluding that there is no condensation. This will be evaluated later in this subchapter. It should also be addressed that the risk for condensation is smallest on the interior side of the element, and that the risk increases towards the exterior side. Looking at the absolute humidity though, one can see that for all materials, this is highest on the interior side, so one could assume that the risk for condensation would be biggest here. But as this location also has the highest temperature, the air and material can hold more moisture before condensation occurs. On the exterior side, the temperature is lower, meaning that the amount of moisture needed for condensation to occur is lower as well. When talking about the condensation risk on the exterior side, one can see that for sensor in location 5, the difference between the partial pressure and the saturation pressure is quite small. Location 5 is the sensor located in the air gap behind the exterior cladding, and therefore closest to the exterior side out of all the sensors used. As the partial pressure and the saturation pressure is not equal or crossing each other in this location, there might not be any condensation, but the risk is higher here than it is in the remaining locations.

As already mentioned, there is no obvious condensation in any of the locations in the elements. This applies for all the different insulating materials. Nevertheless, there are some differences between the materials. The differences are minor, but they are present. For wood fibreboard, the partial pressure is closing in on the saturation pressure more than it is for flax fibre and mineral wool. In other words, the condensation and mould growth risk are a little bit higher for wood fibreboard than it is for flax fibre and mineral wool. It should also be addressed that between mineral wool and flax fibre, the risk is highest for mineral wool. As mentioned, the differences are minor, but the risk for condensation- and mould growth are smallest for flax fibre. These results coincide with the expected results. The reasons for flax fibre being the insulating material with the smallest risk for condensation and mould growth could be many. As mentioned in chapter 3.2.1, flax fibre is an insulating material that dries out fast when exposed to moisture. If the material can avoid being moist for a long period of time, the risk for, at least, mould growth will decrease. Another reason might be that flax fibre tends to transport moisture towards the exterior side of the wall, and if the moisture is able to escape there, the moisture problems in the wall might be reduced. It seems like flax fibre is a material that, despite its other challenges, can handle moisture quite well.

In addition to the insulating materials, factors like with or without convection in the air gap, and the type of exterior cladding might affect the risk for condensation and mould growth. Looking at the convection, this seems to have less impact than originally thought. Through early investigations in the BiW-project, it was discovered that a fully ventilated air gap behind the exterior cladding would have a big impact on reducing the moisture problems. The experiments conducted for this study tells otherwise though. First of all, the difference between the partial pressure and the saturation pressure is smaller with convection than it is without convection, meaning that the risk for condensation is increasing with convection. This is opposite of what was expected. Secondly, the difference between with and without convection is not that big. For all materials, the pressure difference without convection is maximum 50 Pa bigger than it is with convection. This can also be seen in Figure 46-Figure 53, where there is a slightly smaller gap between the saturation pressure and the partial pressure when there is convection in the air gap. In addition to convection, the exterior cladding was expected to affect the condensation and mould growth risk. Again, based on early investigations in BiW-project, the cement-based cladding was expected to have a higher risk for condensation and mould growth than the wooden cladding. Looking at the results from the experiments though, this was not the case. The exterior cladding does not seem to affect the risk for condensation and mould growth as much as initially thought. In fact, the risk seems approximately the same for both the cement-based cladding and the wooden cladding.

5.4.2 Long-term simulations

In order to properly evaluate the risk for condensation and mould growth, the long-term simulations must be included. The experiments conducted in this study is only lasting for 5-6 days, meaning that the results are not telling anything about the long-term properties of the elements and materials. Hence, long-term simulations are needed. What should be mentioned about the long-term simulations though, is that the interior and exterior climate is not identical to the interior and exterior climate in the experiments and the short-term simulations. This means that the long-term simulations might not be directly comparable to the experiments and the short-term simulations. Nevertheless, they are able to tell something about the different properties after 10 years.

Through the long-term simulations the mould index has been monitored in two locations in the element, location A and location B, as shown in Figure 54. Firstly, it should be addressed that in location B, the mould index is zero for all tests. In other words, there is no mould growth in this location, for any of the test during the 10 years of simulation, as explained. Secondly, the mould index is highest when there is no convection, for all tests. This is opposite of the experimental findings, but it coincides with the expected results. As the difference between with and without convection were quite small in the experimental results, this might indicate that a fully ventilated air gap will lead to less risk for mould growth than an unventilated air gap. As the risk is highest without convection in the simulations, the rest of this subchapter will only include the tests without convection.

As mentioned, the mould index in location B is zero, but the mould index in location A is varying some more, as seen in Figure 55-Figure 58. Nevertheless, it never exceeds 1. Looking at Table 12, one can see that a mould index below 2 is usually acceptable for surfaces inside the construction. Looking at Table 11, one can see that a mould index of 0 means no mould growth, while a mould index of 1 means some mould growth visible under a microscope. As the mould index for all tests in location A are somewhere between 0 and 1, there might be some mould growth, but a very small amount. When evaluating the mould index throughout the whole simulations, it is clear that for all simulations, the mould index has its peak during the first 10 000 measurements, which corresponds to a bit more than a year. During these 10 000 measurements, the mould index is quite a bit higher than it is after a couple of years of simulation. What is interesting though, is that the highest mould index during this first year is found when using wood fibreboard as the insulating material, but wood fibreboard is also the material with lowest mould index after a few years has passed. In other words, the peak in the beginning of the simulations is highest for wood fibreboard, but the value stabilizes, and wood fibreboard ends up having lowest risk for mould growth at the end. The material with the lowest mould index during the first year of simulations is flax fibre. When looking at the experimental results, one can see that flax fibre has the lowest risk for mould growth and wood fibreboard has the highest risk for mould growth. Comparing this to the long-term simulations, this makes sense. Flax fibre being the one with lowest risk and wood fibreboard being the one with highest risk coincides with the first year of the simulations. As the experiments only lasts for 5-6 days, there is no way of telling if the mould growth risk would change after a year, other than trusting the simulations. It should also be mentioned that the wooden cladding has the same development as wood fibreboard. The peak in the beginning of the simulations is high, but then it stabilizes at the lowest value of them all. This coincides with the expected results based on early investigations in the BiW-project, which were that the wooden cladding would have better moisture properties than the cement-based cladding.

5.5 VALIDATION

As mentioned, the main purpose of the short-term simulations in WUFI Pro were to validate the model and therefore be able to use this model in the long-term simulations. By calculating the deviations between the experimental results and the results from the short-term simulations, it is possible to evaluate how identical the simulations are to the experiments, and if the deviations are too big. In this case, the deviations have been calculated in percentage, and summarized in Table 15. The formulas used to calculate these deviations are shown in chapter 3.5.5. Usually, a deviation of 3% is considered a good validation, but higher deviations can be approved as well, at least for a master thesis. For the simulations done in this thesis, about half of the deviations exceeds 3%. Nevertheless, only a few of them exceeds 10%, meaning that the deviations are not that big. It should also be mentioned that these calculations are not completely trustworthy. This is due to the acclimatisation in the beginning.

When calculating deviations, both the simulated values and the experimental values are used. In the experiments, the acclimatisation has been removed and are not used in the calculations, while in the simulations, there seems to be some acclimatisation in the early stages of every simulation. This difference will give higher deviations in the early stages of the experiments and simulations, which will affect the average deviations. In other words, the deviations between the experiments and the simulations are in fact lower than calculated and should therefore be considered adequate. This means that the simulations are similar enough to the experiments, and that the model from the short-term simulations can be used in the long-term simulations.

6 CONCLUSION

The main goal of this study was to evaluate the condensation and mould growth risk for different nature-based insulating materials integrated in a timber-based wall system. In addition, it has been investigated if factors like convection and exterior cladding would affect the hygrothermal properties. All investigations have been conducted through both experiments and simulations. Firstly, it should be addressed that there is no obvious condensation or mould growth in any of the experiments or simulations. There is a difference between the insulating materials though, where wood fibreboard seems to be the one with highest risk and flax fibre the one with smallest risk at the early stages in both the experiments and the simulations. For wood fibreboard, this risk decreases and stabilizes as the one with smallest risk after a couple of years in the long-term simulations. None of the two remaining materials experiences significant amounts of mould growth after a couple of years, but a bit more than wood fibreboard.

Secondly, it should be addressed that the thermal transmittance for all insulating materials were within the requirements from TEK17, with mineral wool as the leading one and flax fibre as the worst one. When it comes to the exterior cladding, this does not seem to change any of the properties significantly. The only difference was found in the long-term simulations, where the mould index was a bit smaller with a wooden cladding than with a cement-based cladding. It should also be addressed that there seem to be small differences in the absolute humidity for the different experiments. The only experiments that stand out is the ones including wood fibreboard. Here, the absolute humidity is slightly higher than for mineral wool and flax fibre in certain locations, but it does not seem to have affected any other properties. Lastly, it should be noted that the convection plays a bigger role in the simulations that it does in the experiments. In the experiments, there are approximately no difference in any of the properties with and without convection, and if there are some differences, these difference are opposite of what was expected. In the long-term simulations, the mould index is visibly higher when there is no convection than when there is convection.

To sum up, it can be concluded that the experiments and simulations are quite similar but does not provide the exact same results. The long-term simulations seem to coincide more with the expected results than the experiments do. It can also be concluded that there is no risk for mould growth in any material, which makes wood fibreboard and flax fibre good options when choosing insulation. Other properties like thermal transmittance, absolute humidity, and such, also seem adequate for all materials tested.

7 FURTHER RESEARCH

In this study, the main focus has been the hygrothermal properties and the risk for condensation and mould growth. Factors like environmental impact and economics has not been included. One suggestion for further research is therefore to conduct life cycle analyses of different insulating materials, and comment on the environmental benefits of using nature-based insulating materials. As the environmental impact of different materials and solutions has become a big focus area in the industry, this could influence people to choose nature-based. In addition, economics is an important factor when choosing materials and solutions. Nature-based insulating materials are expected to be more expensive than mineral wool, due to lower demand and accessibility. Another interesting suggestion for further research is therefore to investigate the economic benefits or disadvantages of choosing nature-based insulating materials.

Besides environmental impact and economics, it is advised that further researchers dedicate more time to the WUFI Pro-model, in order to make it more similar to the experiments. It should also be mentioned that as this study is a part of the Build-in-Wood project, some further research is already planned and initiated. This includes running experimental tests using the same insulating materials as in this study but integrated in a CLT-wall instead of a stud-wall. It also includes at least one more nature-based insulating material than this study. In addition to the tests conducted in the climate chamber, the BiW-project are also planning a full-scale test with nature-based insulating materials in a real-life building, with real exterior- and interior climate, in Denmark.

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9 ATTACHMENTS

A1: Interior and Exterior Climate – Experiment

Mineral Wool

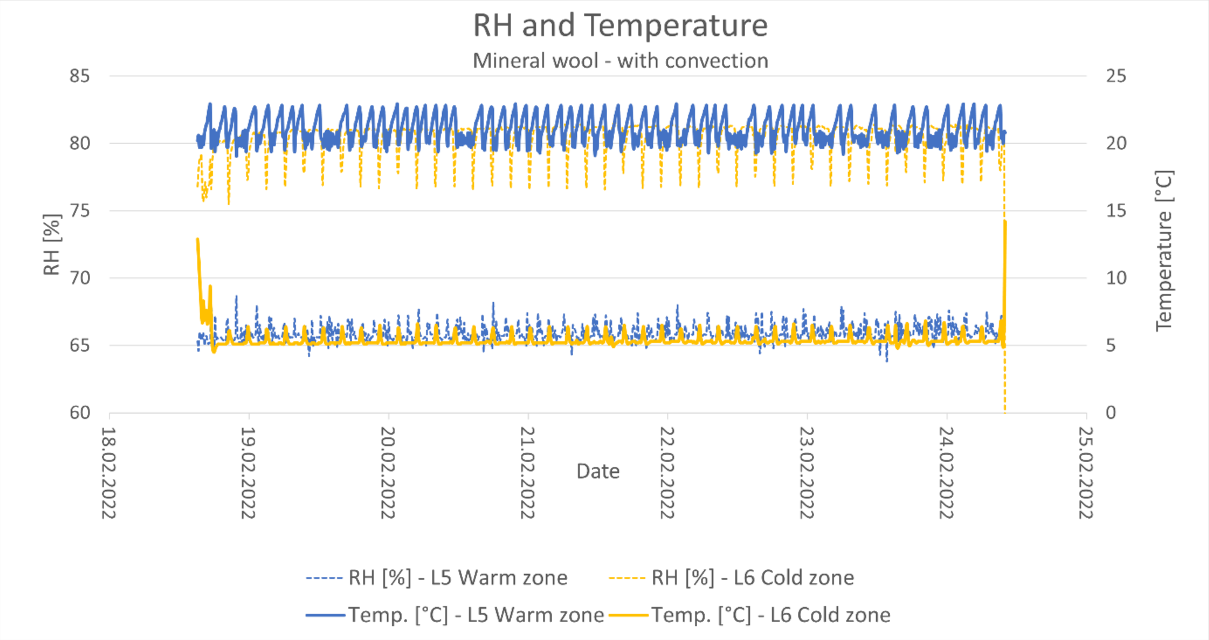

Figure A1.1: Relative humidity and temperature – Experiment 1.

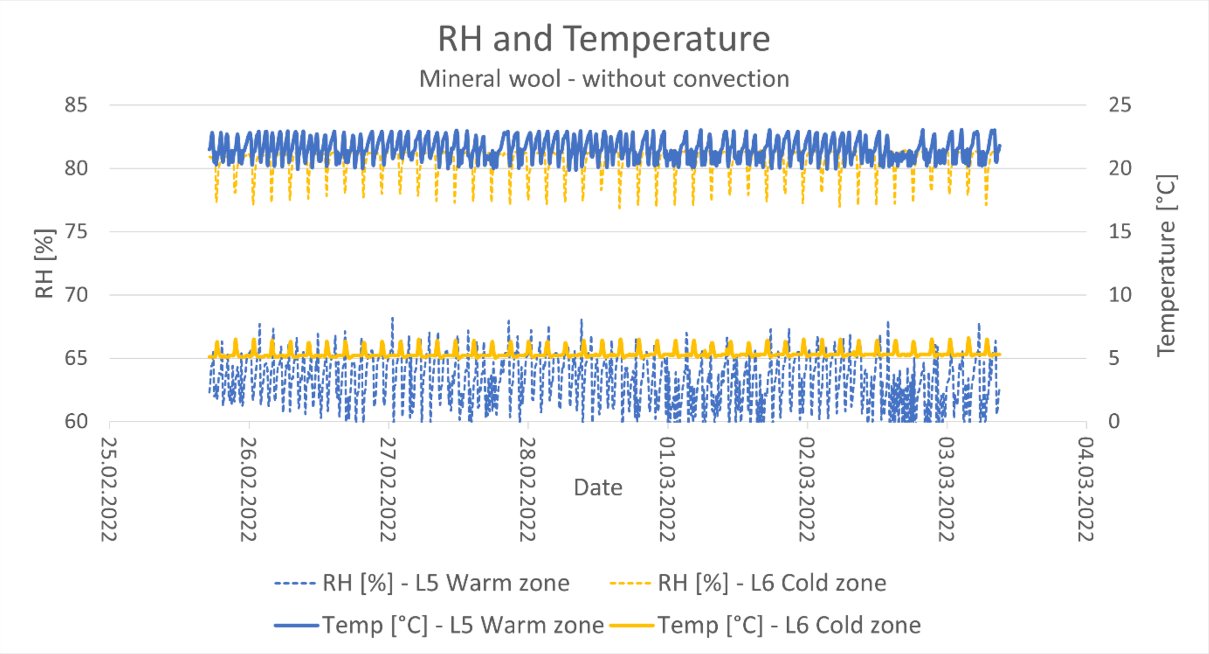

Figure A1.2: Relative humidity and temperature – Experiment 2.

Flax Fibre

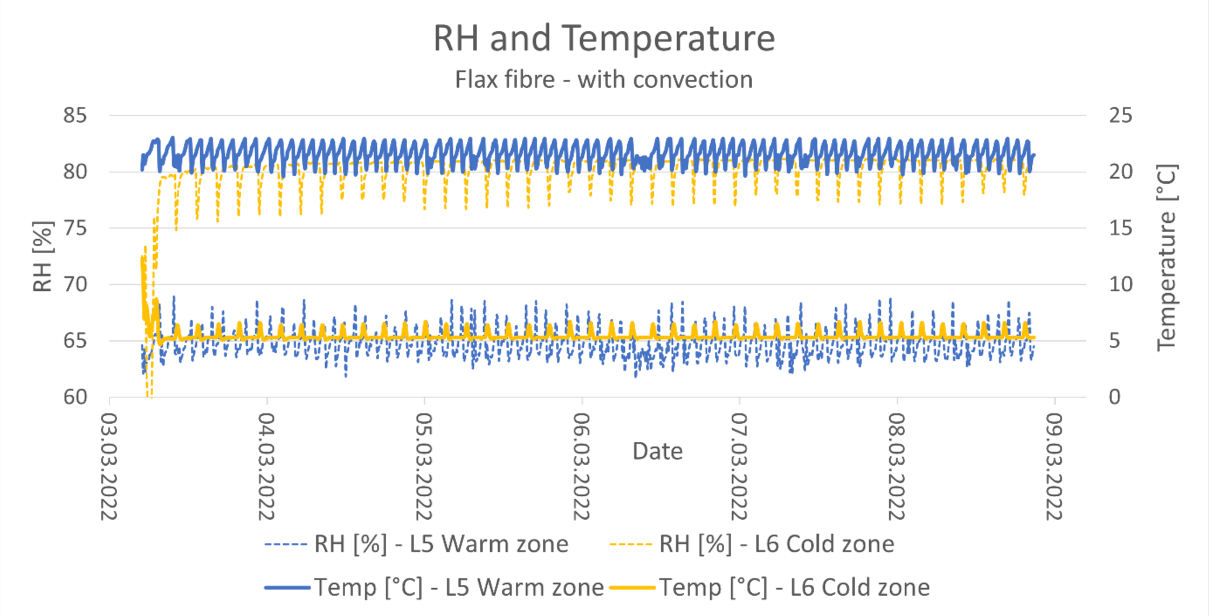

Figure A1.3: Relative humidity and temperature – Experiment 3.

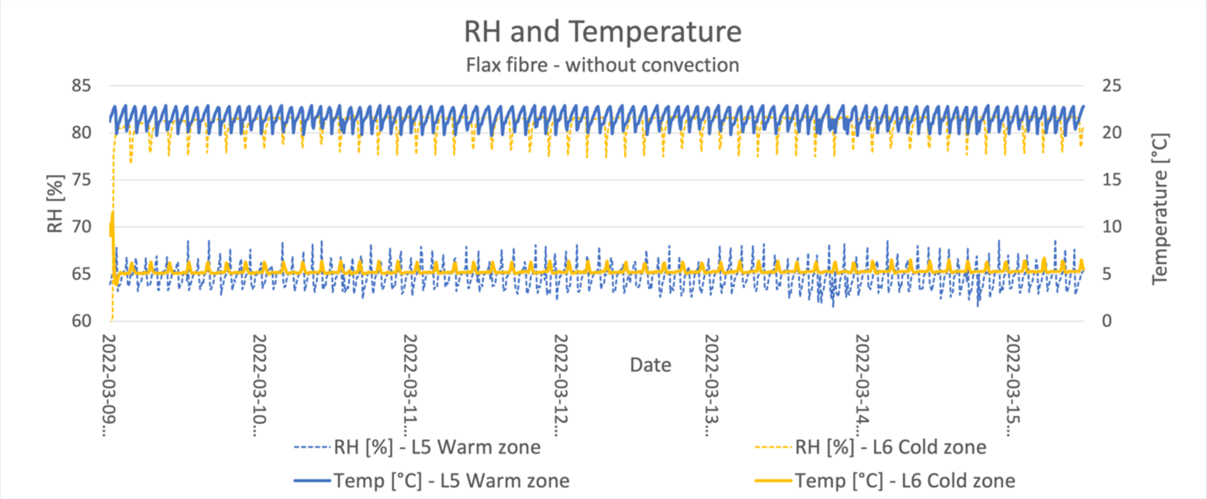

Figure A1.4: Relative humidity and temperature – Experiment 4.

Wood Fibreboard

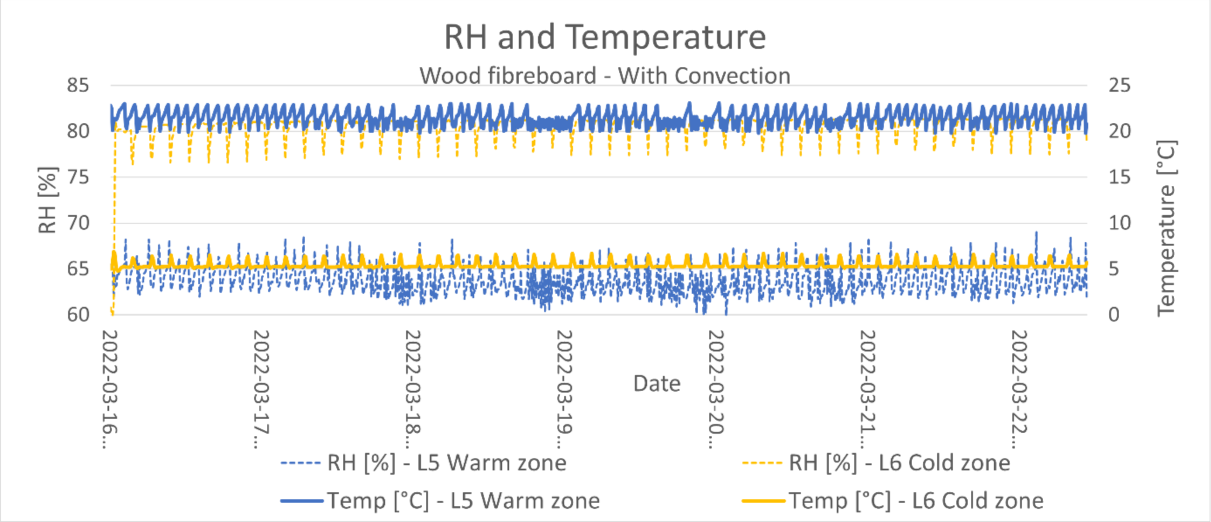

Figure A1.5: Relative humidity and temperature – Experiment 5.

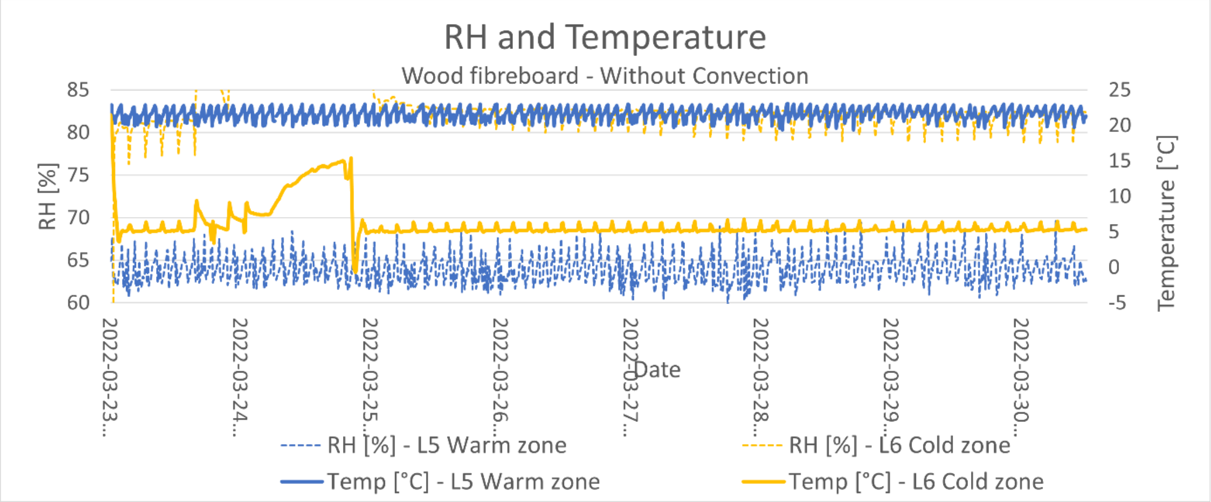

Figure A1.6: Relative humidity and temperature – Experiment 6.

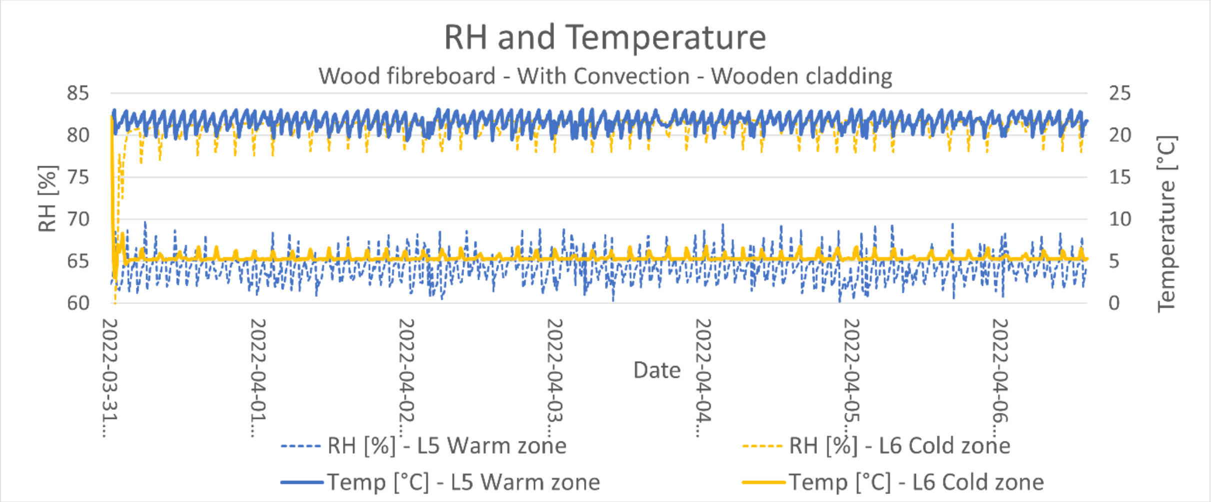

Figure A1.7: Relative humidity and temperature – Experiment 7.

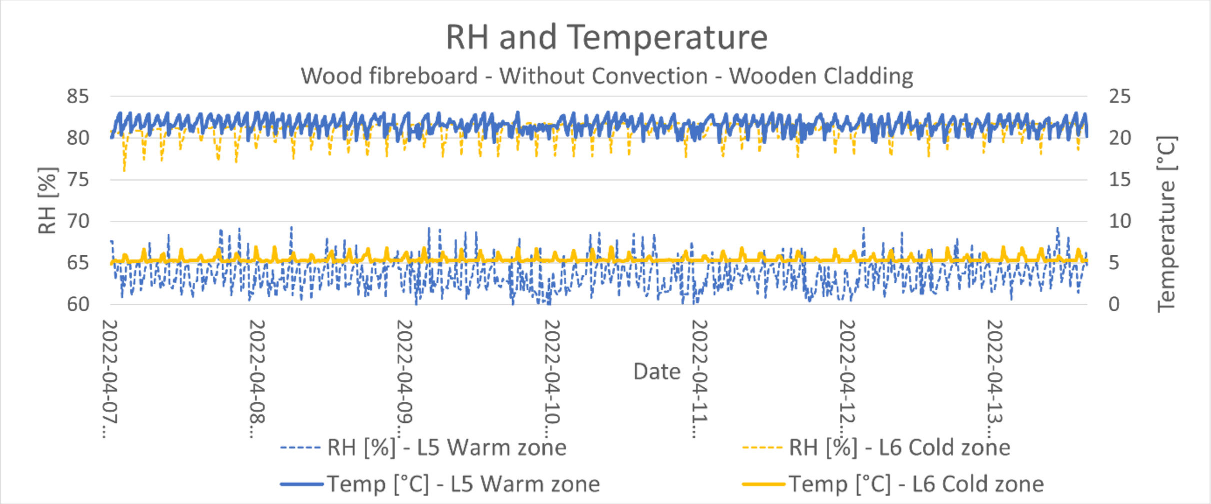

Figure A1.8: Relative humidity and temperature – Experiment 8.

A2: Thermal Transmittance – Experiments

Mineral Wool with Convection

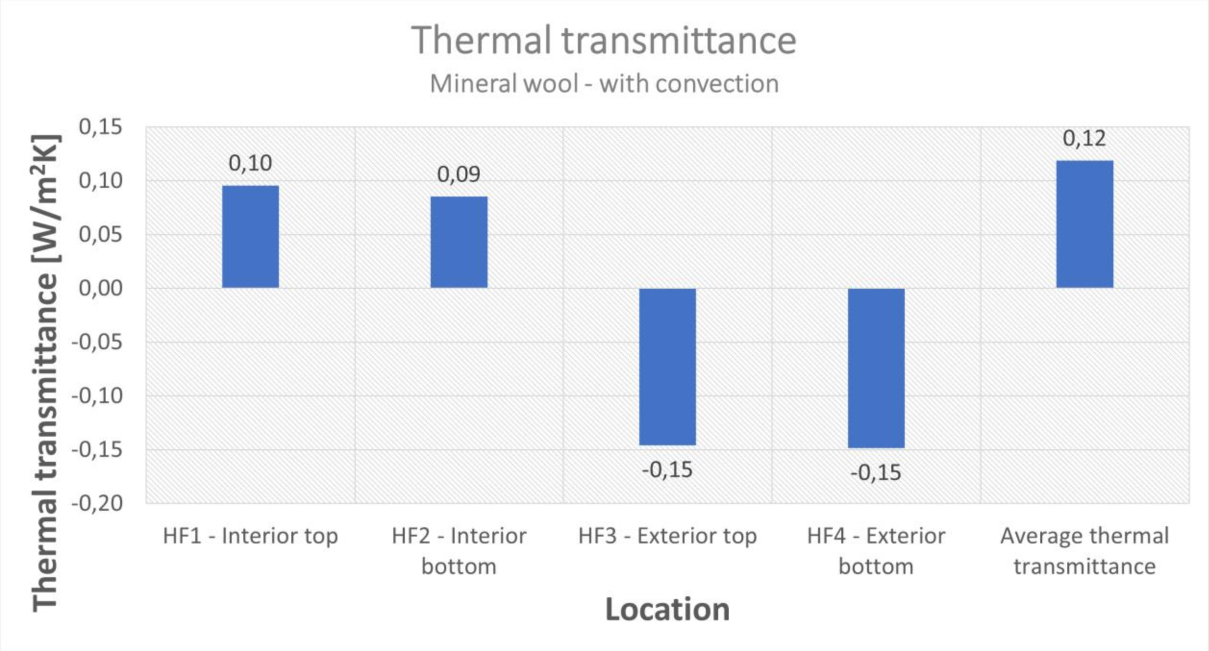

Figure A2.1: Thermal Transmittance with acclimatisation – Experiment 1.

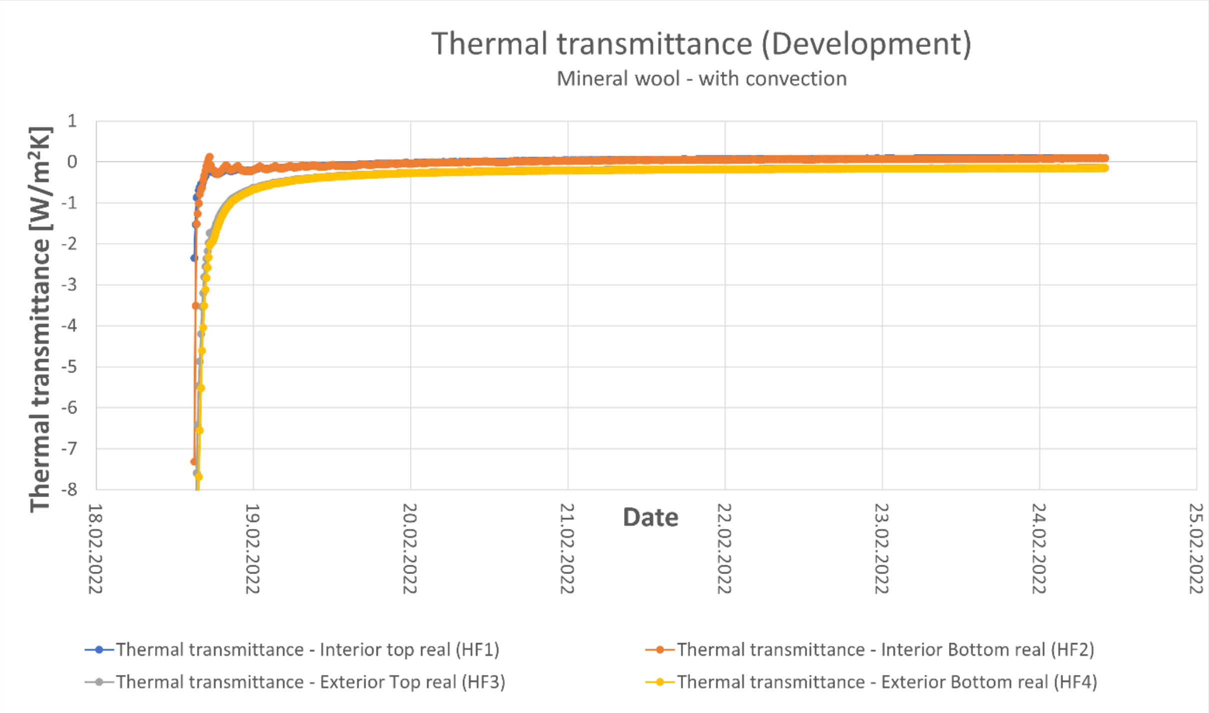

Figure A2.2: Thermal Transmittance Development – Experiment 1.

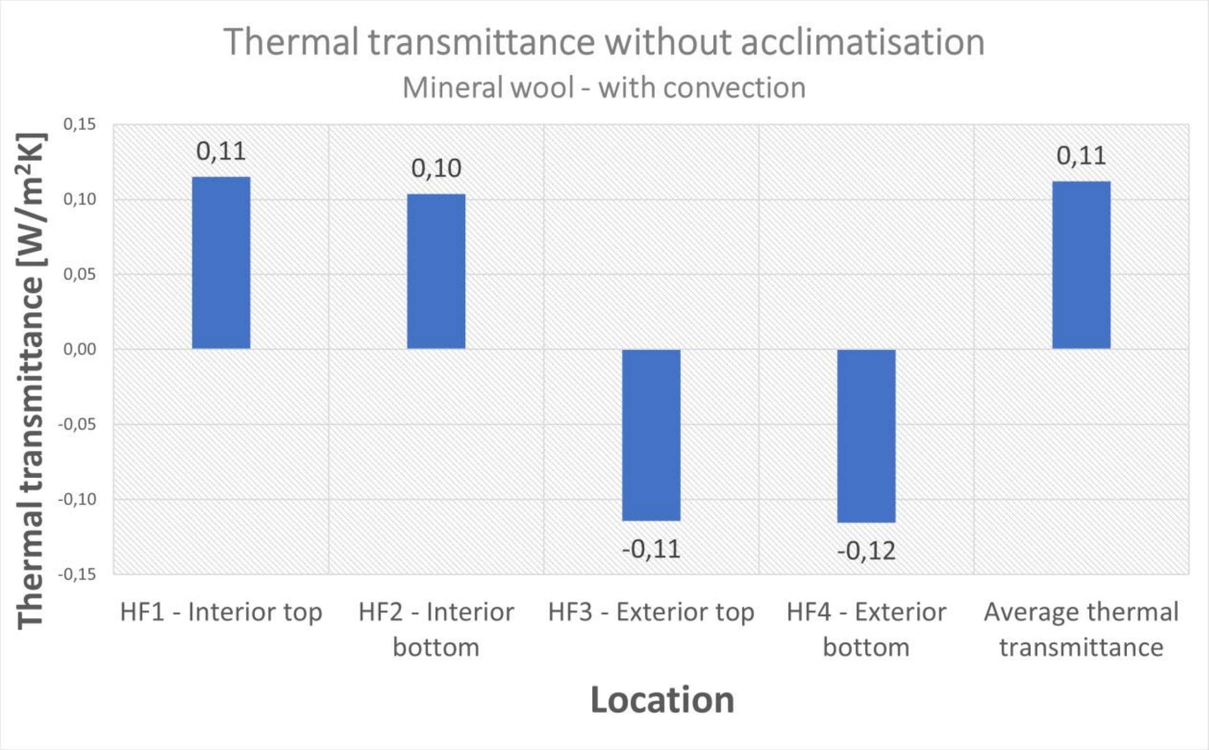

Figure A2.3: Thermal Transmittance without acclimatisation – Experiment 1.

Mineral Wool without Convection

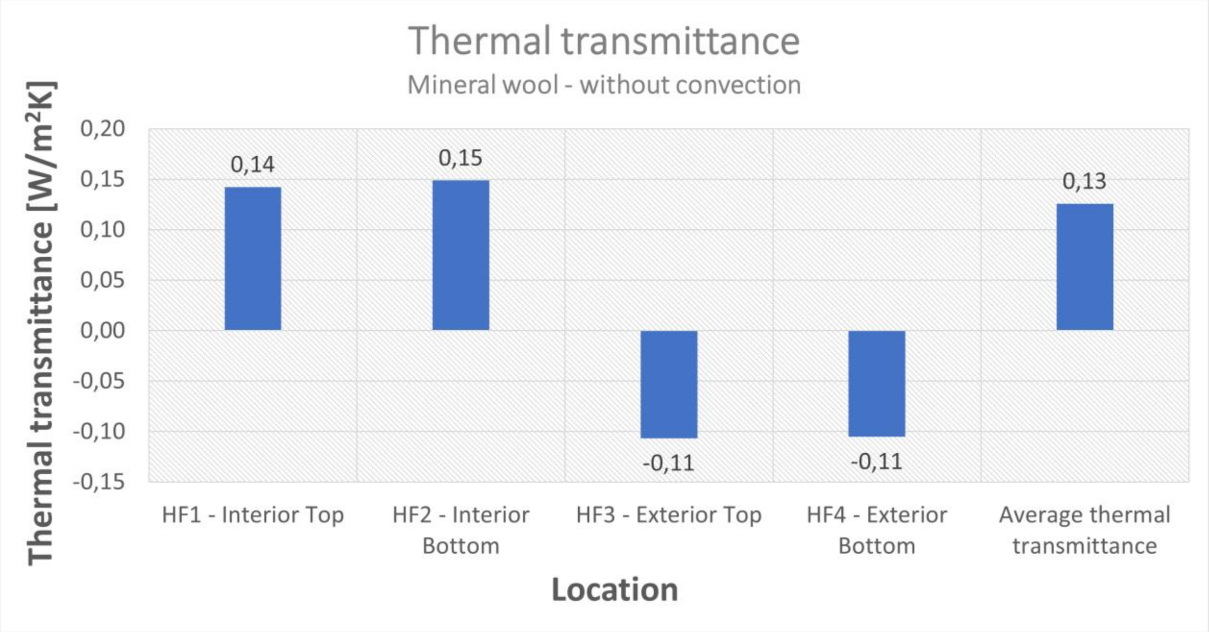

Figure A2.4: Thermal Transmittance – Experiment 2.

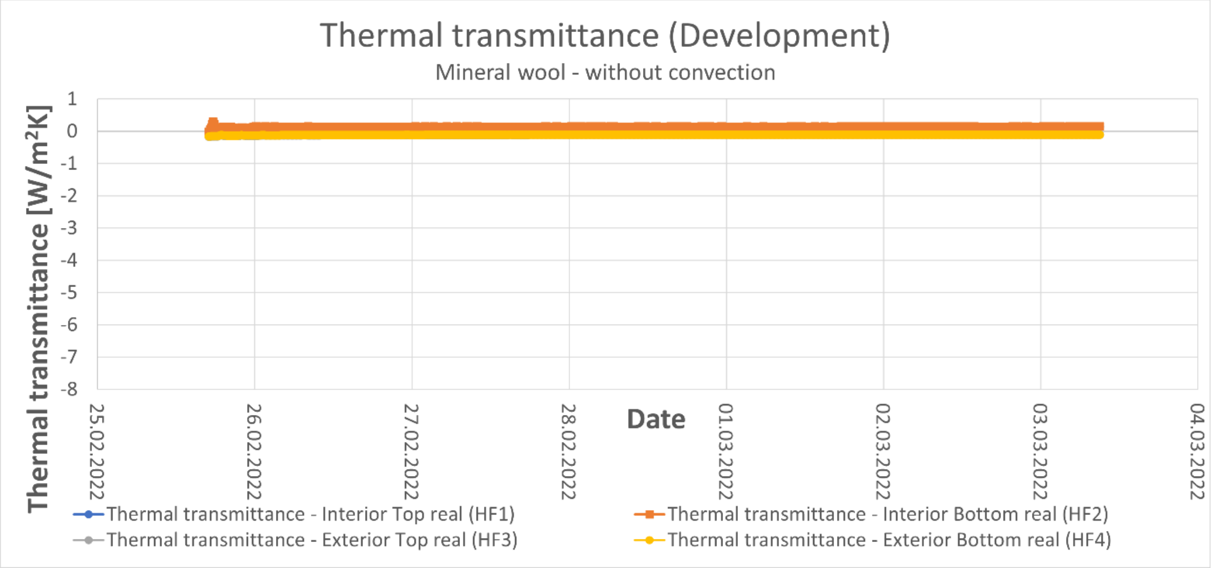

Figure A2.5: Thermal Transmittance Development – Experiment 2.

Flax Fibre with Convection

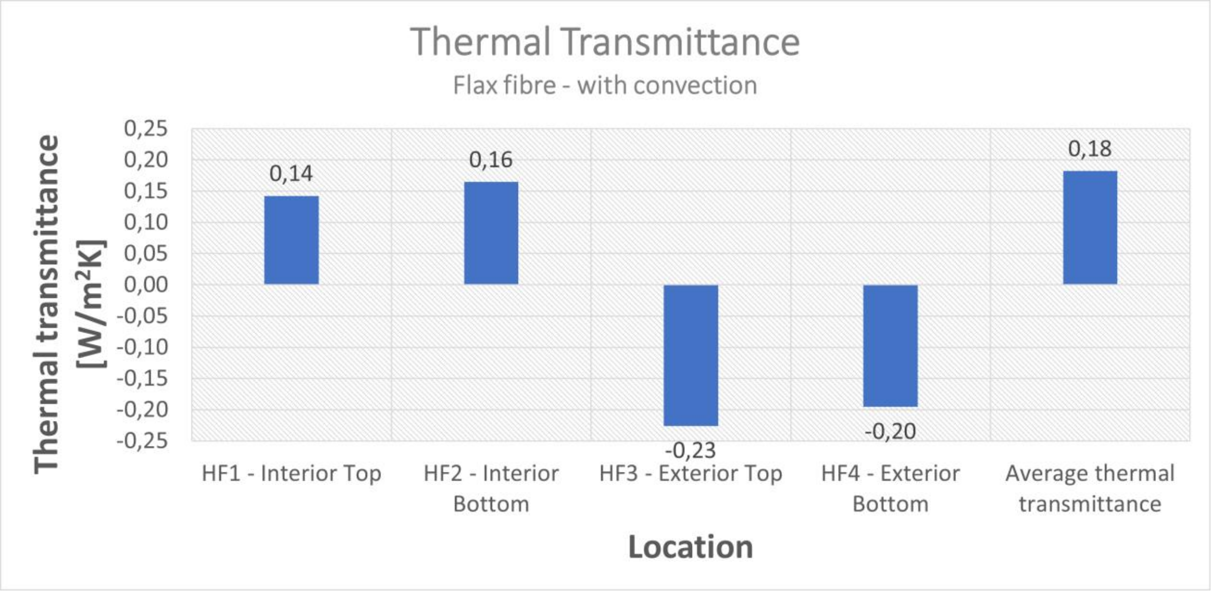

Figure A2.6: Thermal Transmittance with acclimatisation – Experiment 3.

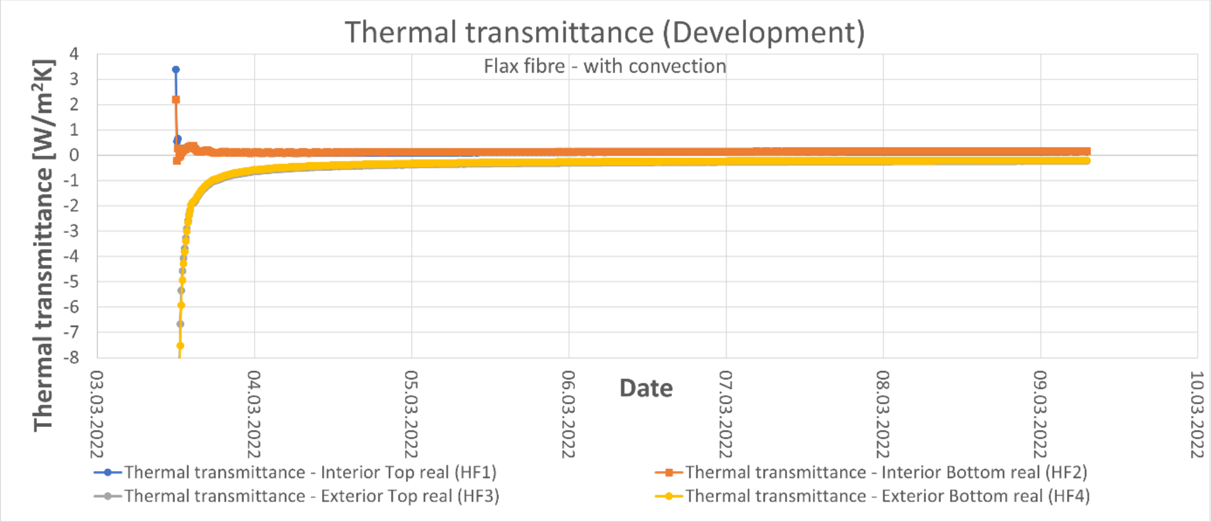

Figure A2.7: Thermal Transmittance Development – Experiment 3.

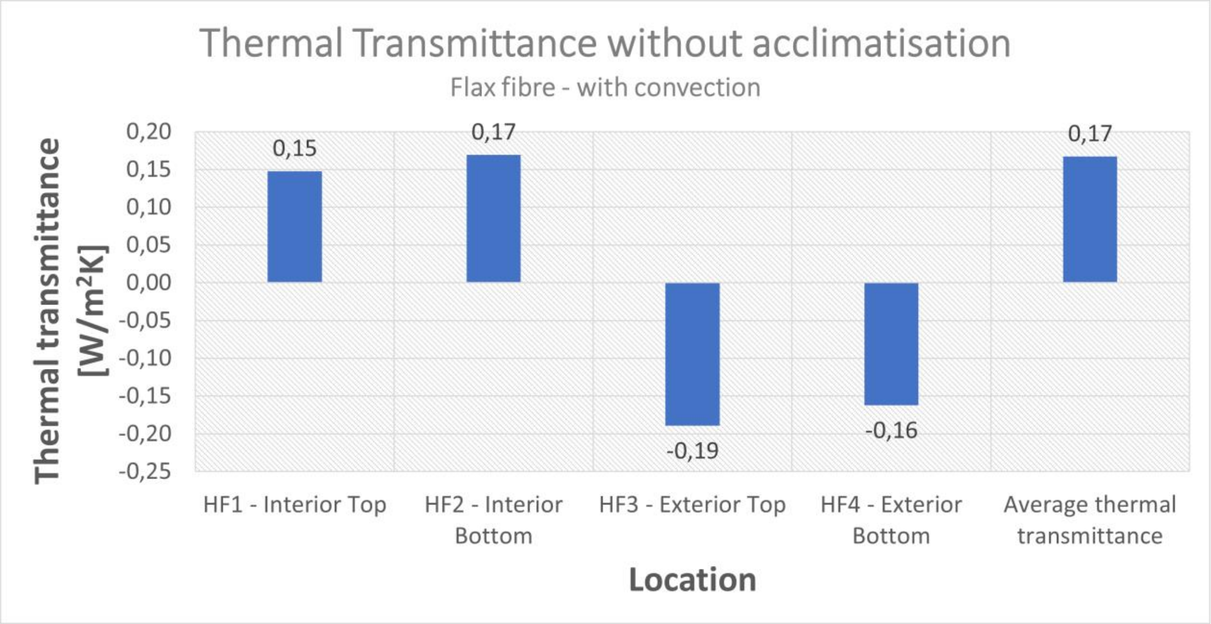

Figure A2.8: Thermal Transmittance without acclimatisation – Experiment 3.

Flax Fibre without Convection

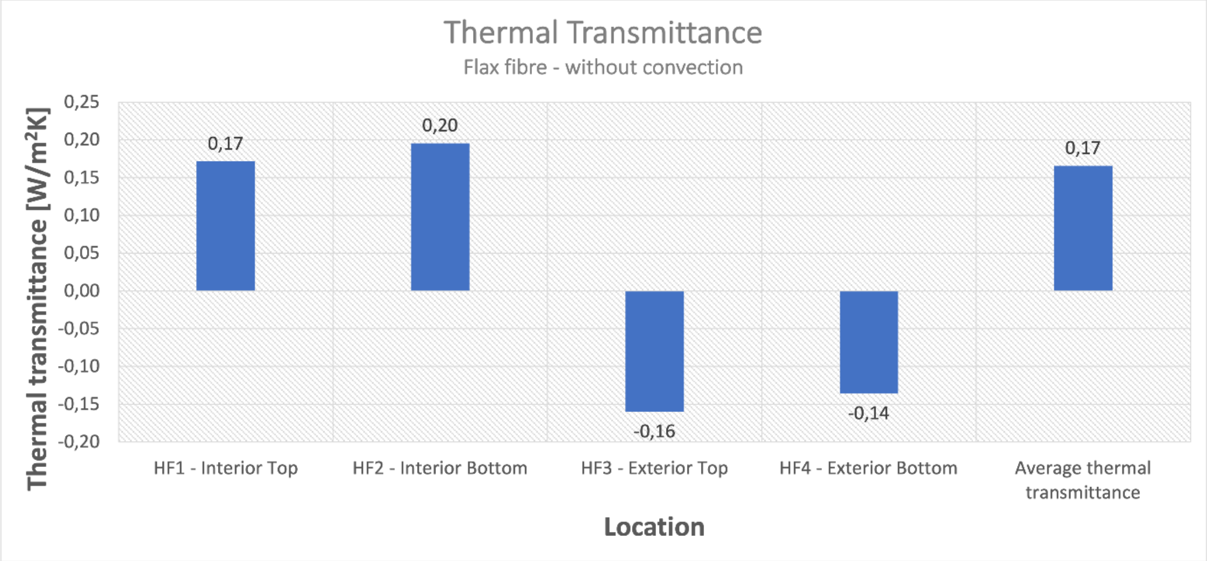

Figure A2.9: Thermal Transmittance – Experiment 4.

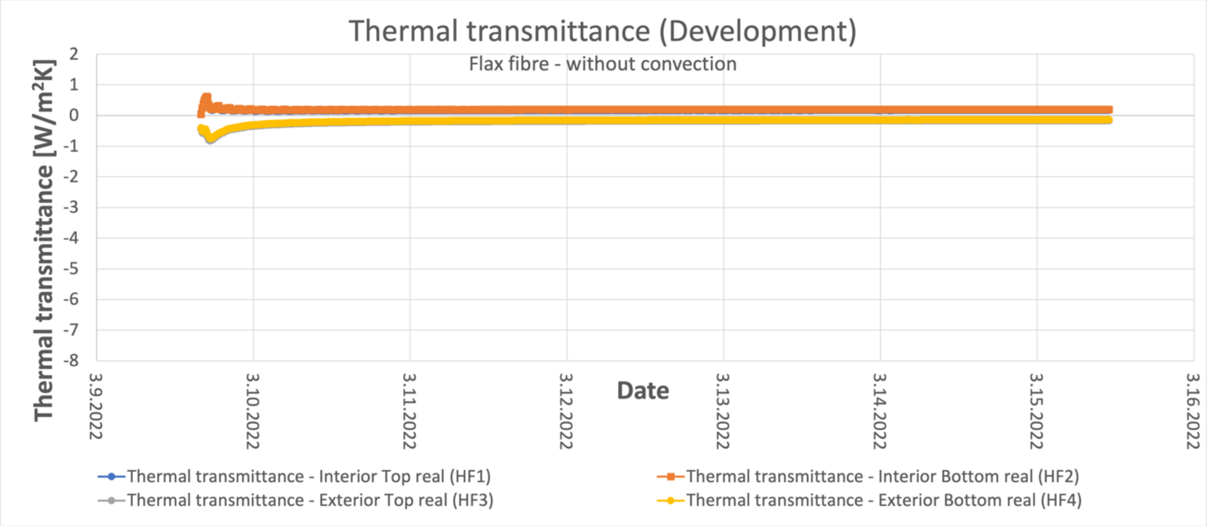

Figure A2.10: Thermal Transmittance Development – Experiment 4.

Wood Fibreboard (Cement-based cladding) with Convection

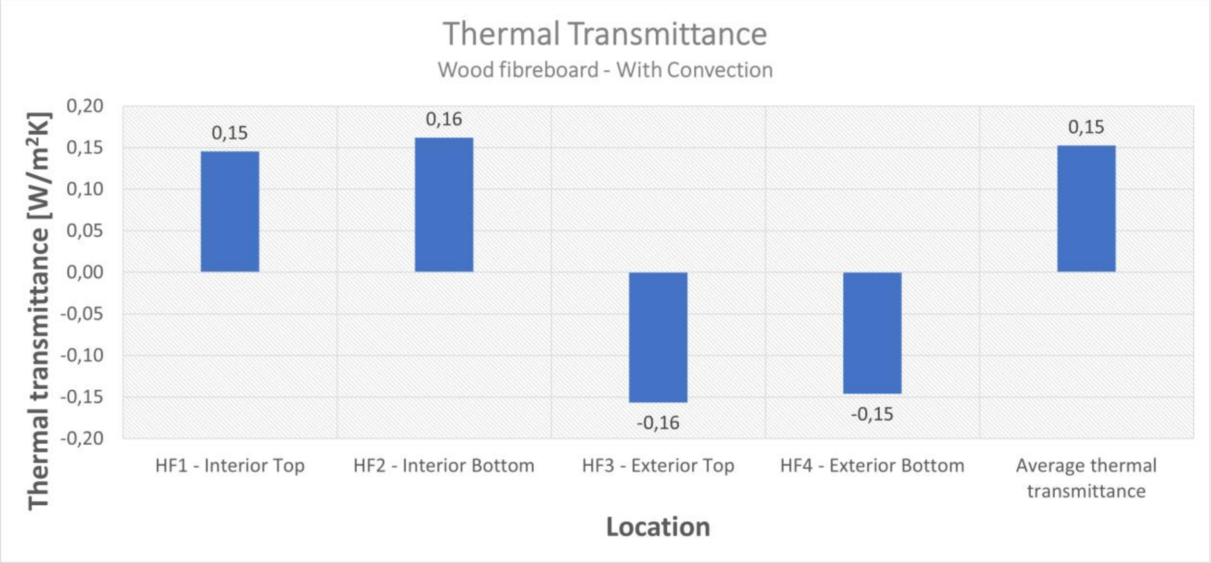

Figure A2.11: Thermal Transmittance – Experiment 5.

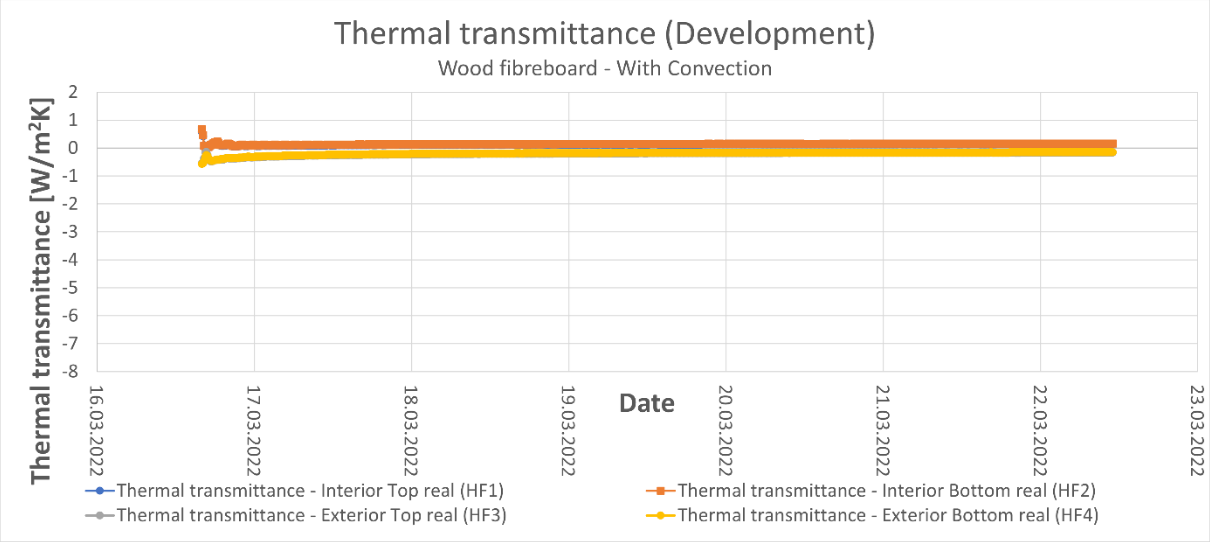

Figure A2.12: Thermal Transmittance Development – Experiment 5.

Wood Fibreboard (Cement-based cladding) without Convection

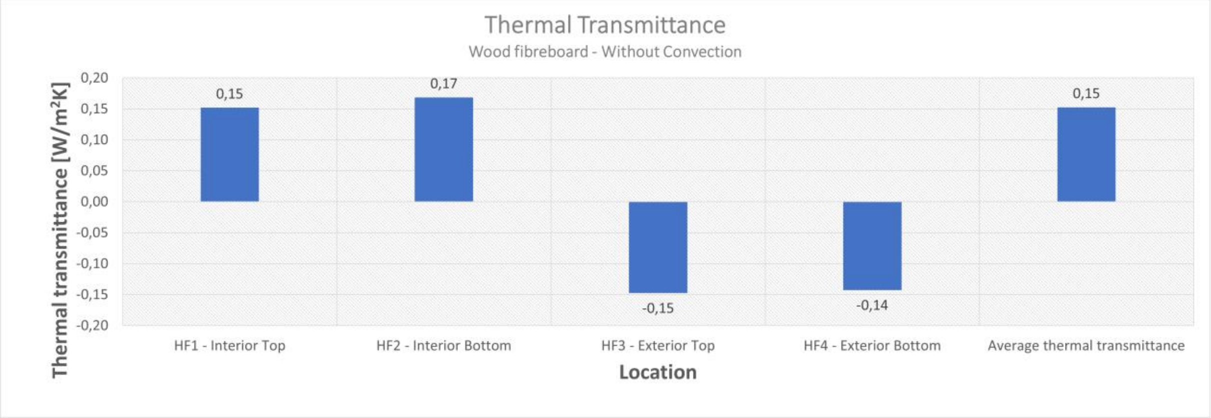

Figure A2.13: Thermal Transmittance with acclimatisation – Experiment 6.

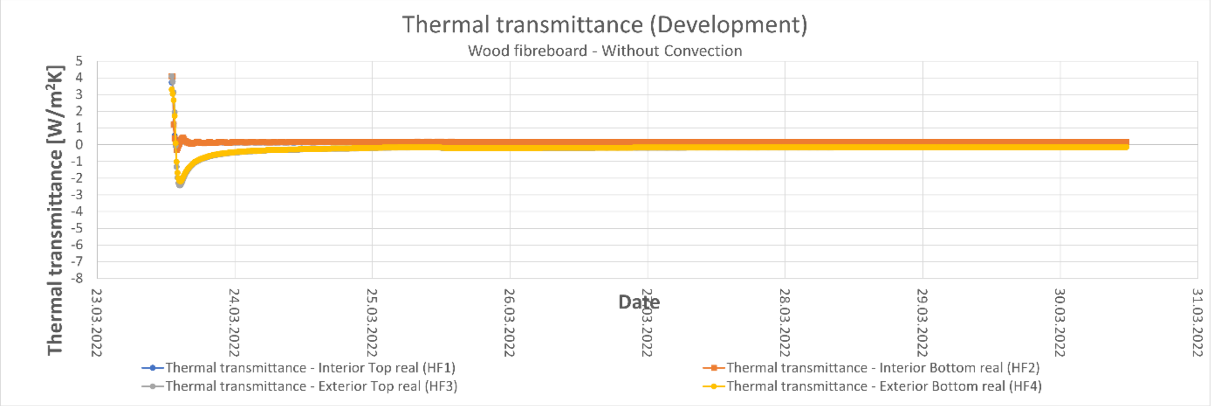

Figure A2.14: Thermal Transmittance Development – Experiment 6.

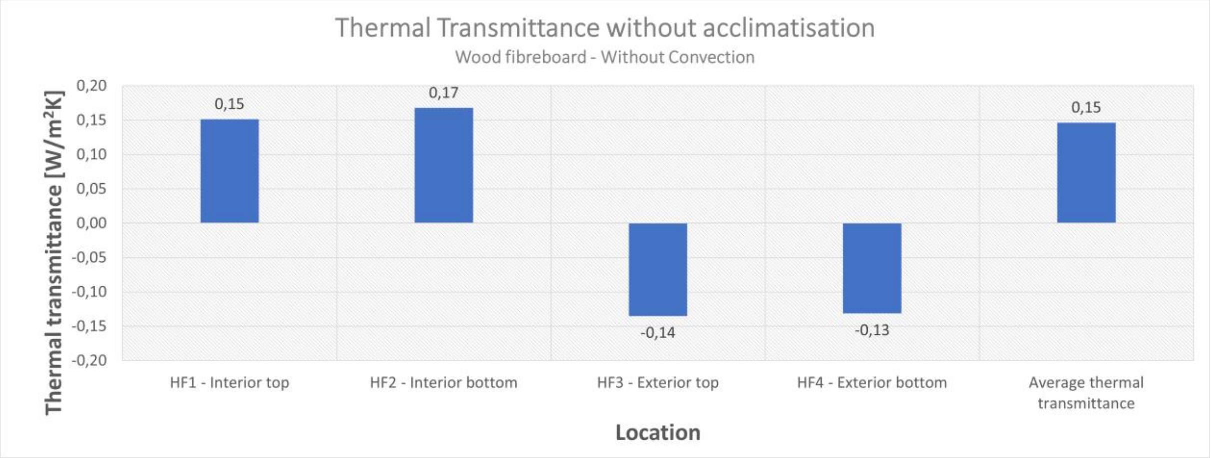

Figure A2.15: Thermal Transmittance without acclimatisation – Experiment 6.

Wood Fibreboard (Wooden cladding) with Convection

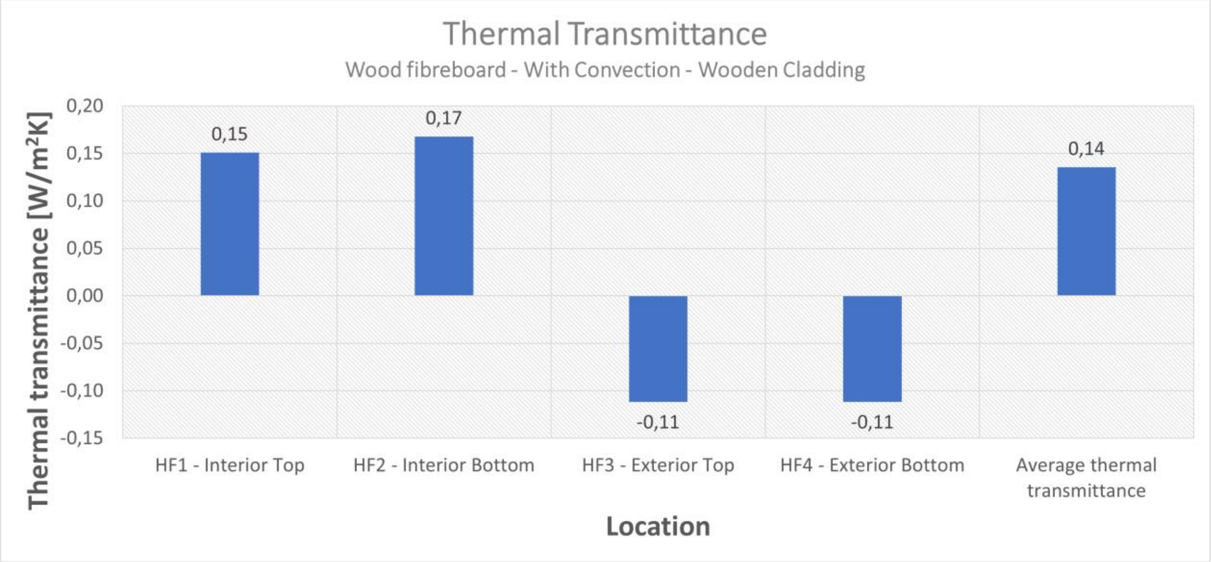

Figure A2.16: Thermal Transmittance – Experiment 7.

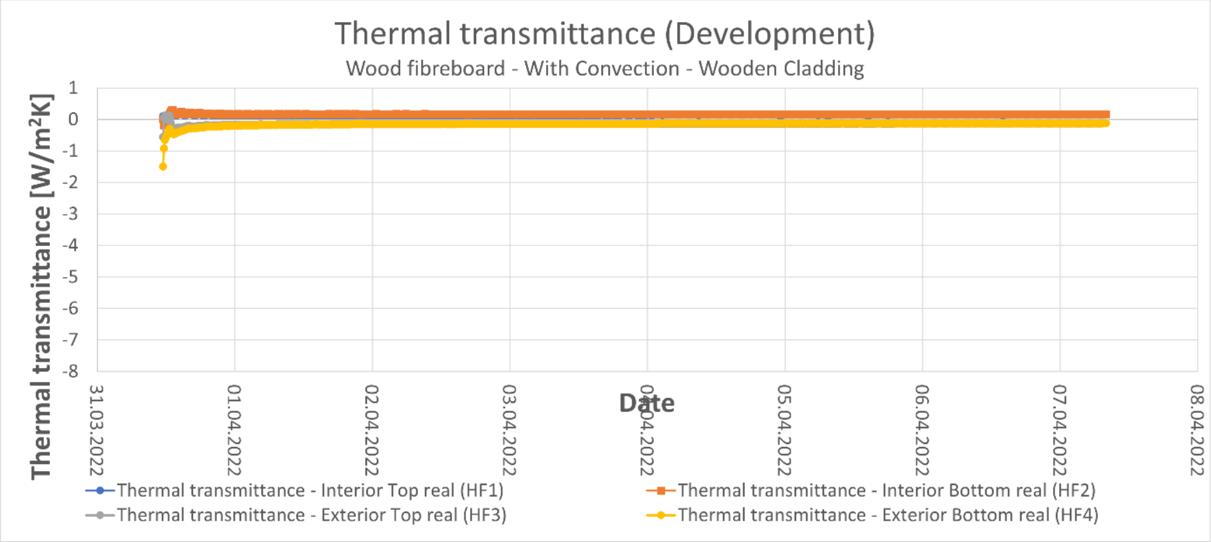

Figure A2.17: Thermal Transmittance Development – Experiment 7.

Wood Fibreboard (Wooden cladding) without Convection

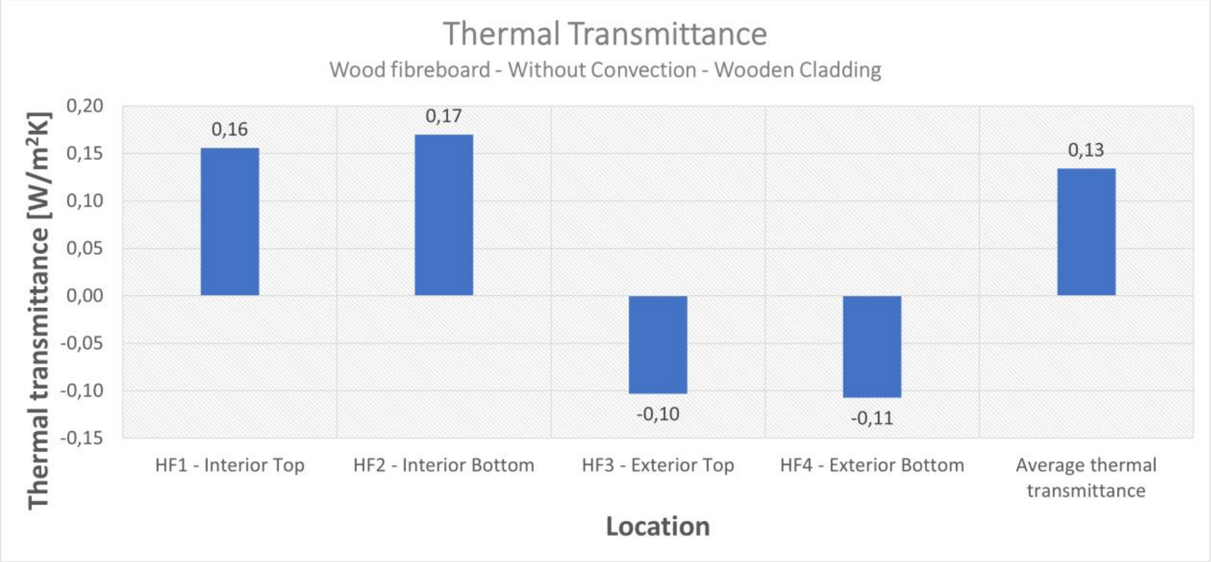

Figure A2.18: Thermal Transmittance – Experiment 8.

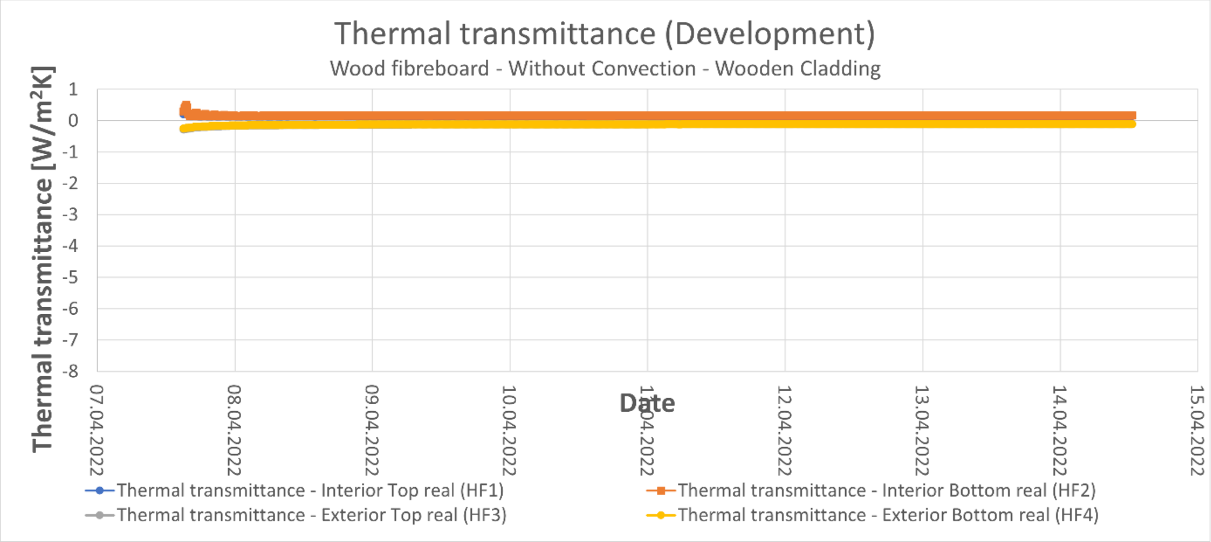

Figure A2.19: Thermal Transmittance Development – Experiment 8.

A3: Temperature and Relative Humidity – Short-term simulations

Mineral Wool

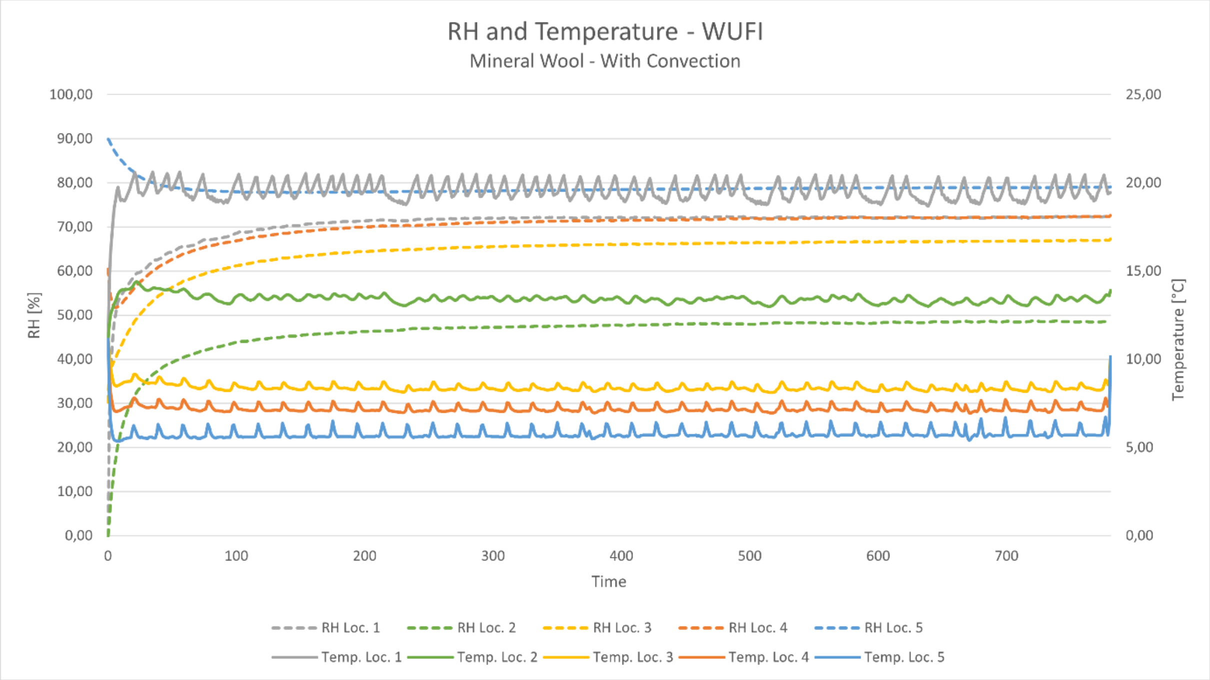

Figure A3.1: RH and Temperature – Short-term simulation 1

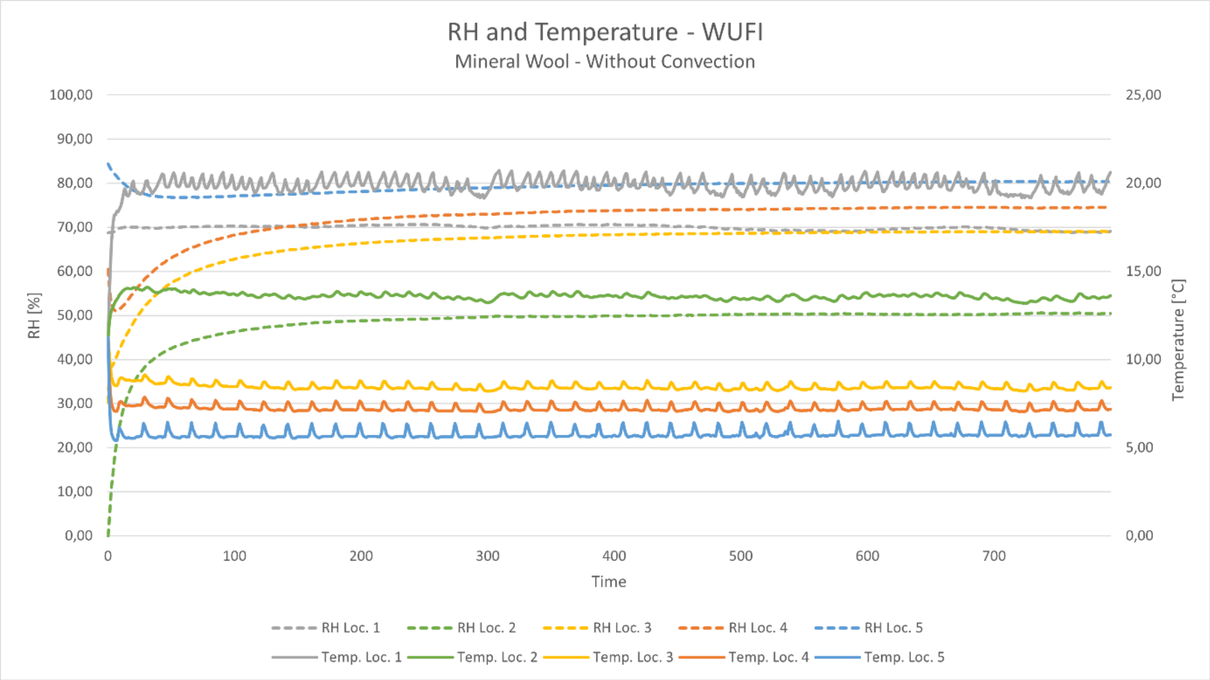

Figure A3.2: RH and Temperature – Short-term simulation 2

Flax Fibre

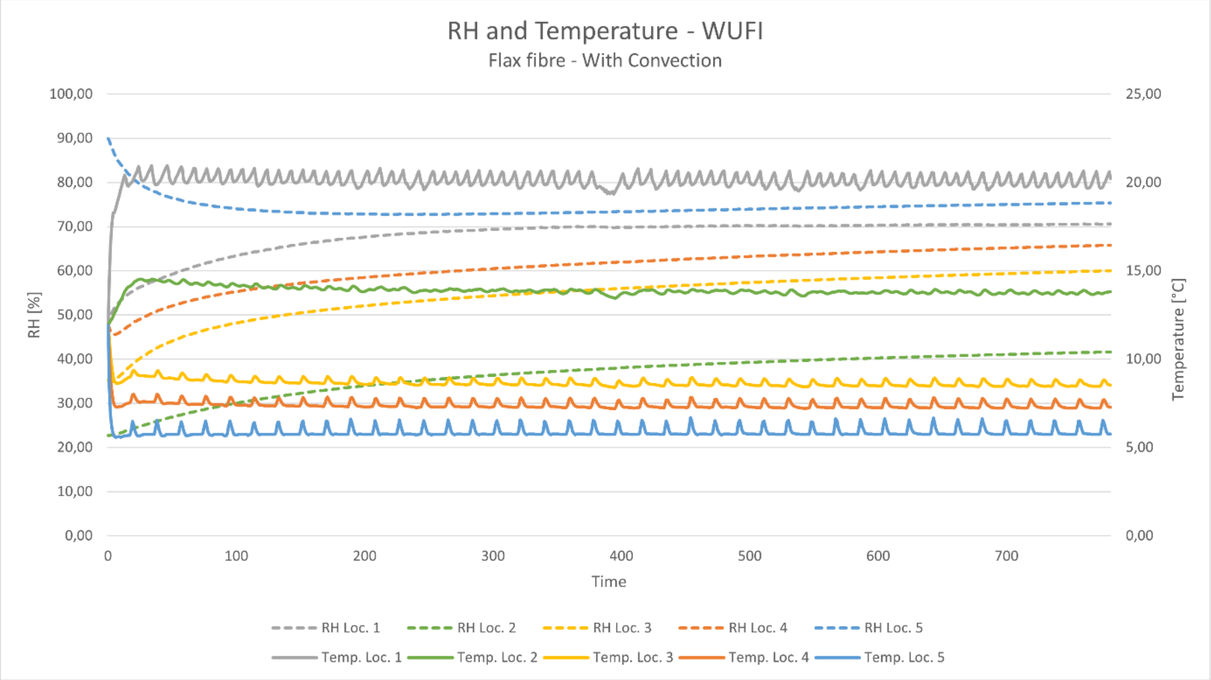

Figure A3.3: RH and Temperature – Short-term simulation 3

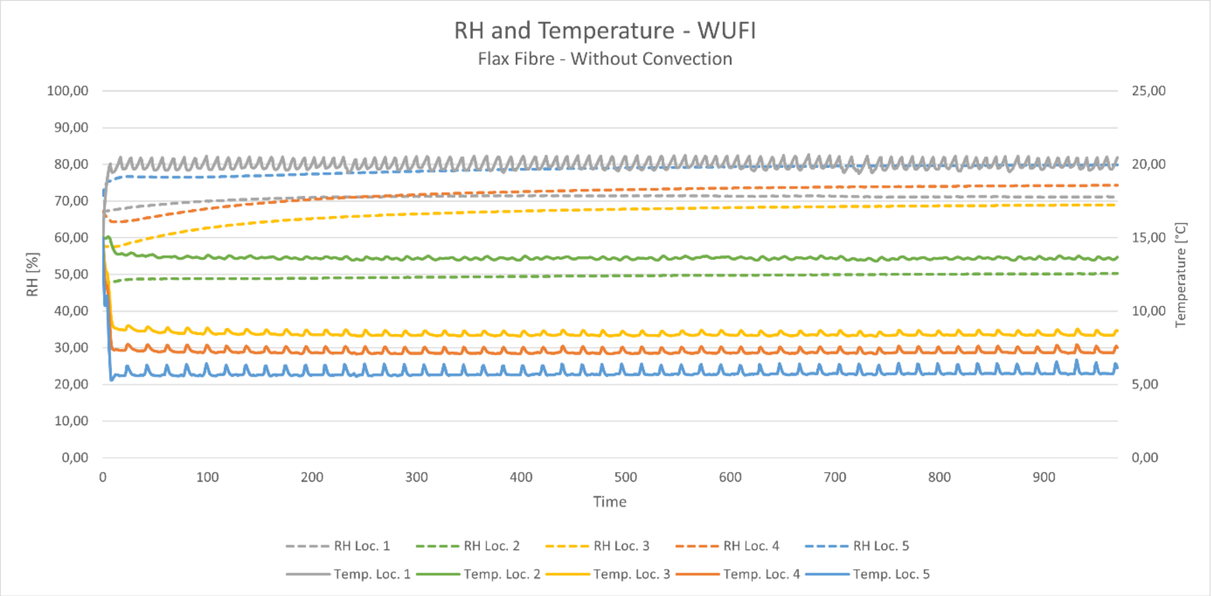

Figure A3.4: RH and Temperature – Short-term simulation 4

Wood Fibreboard

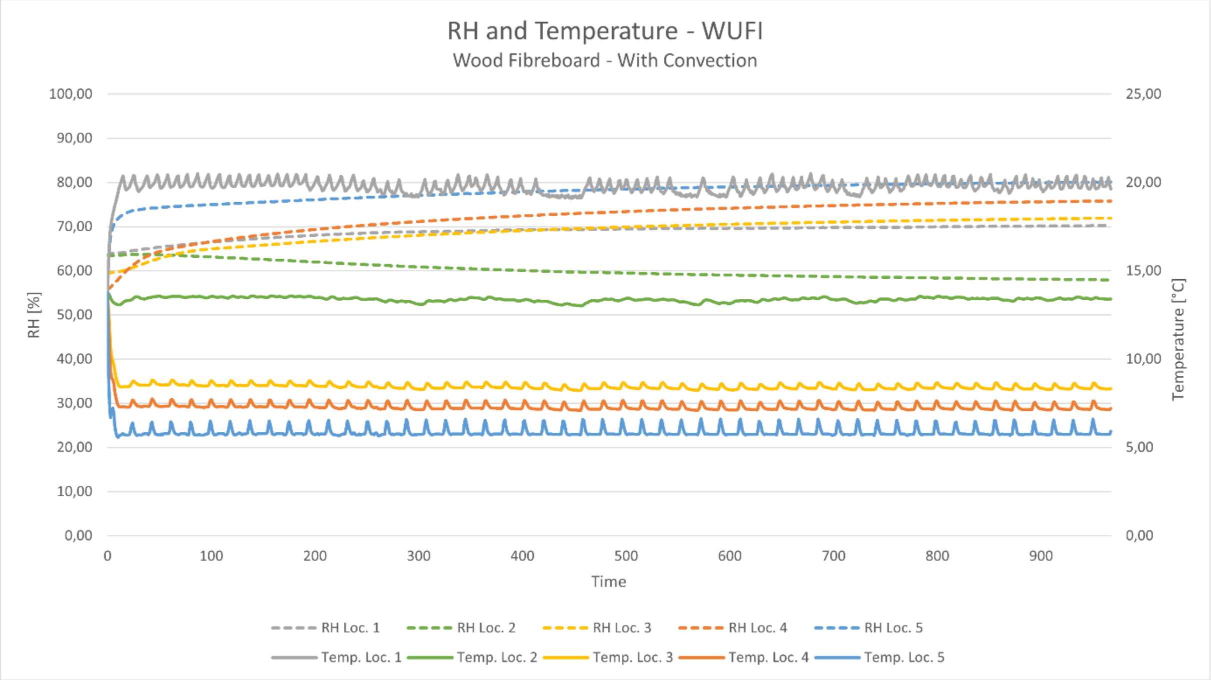

Figure A3.5: RH and Temperature – Short-term simulation 5

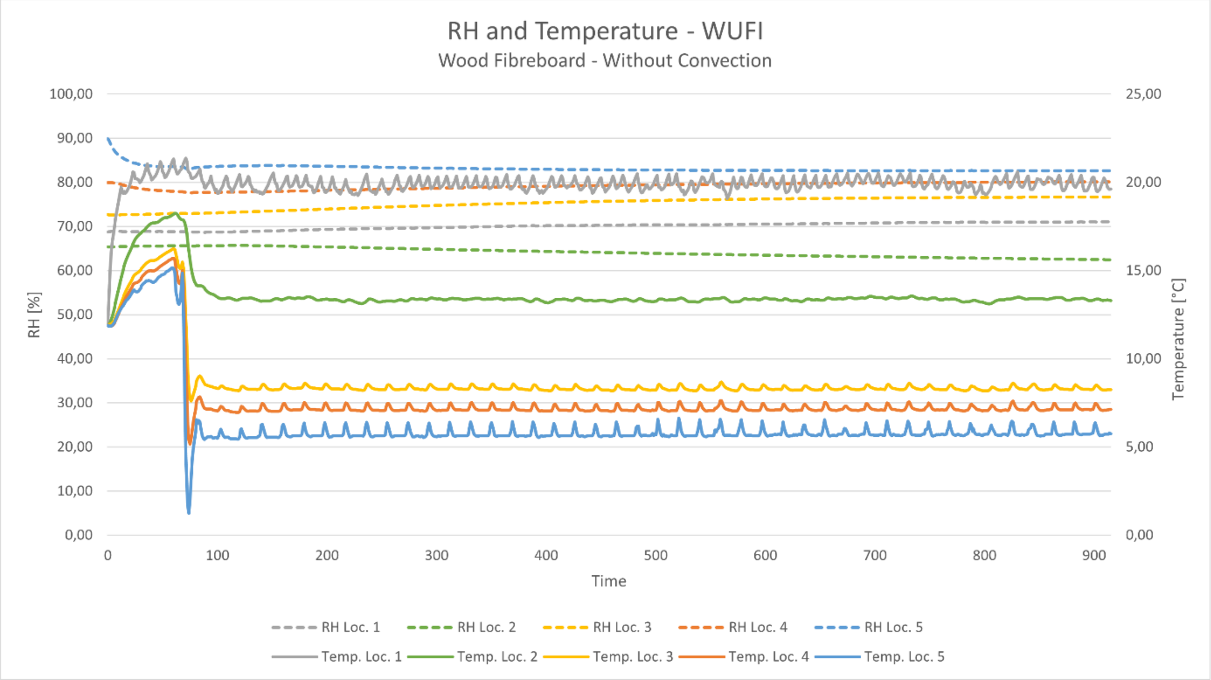

Figure A3.6: RH and Temperature – Short-term simulation 6

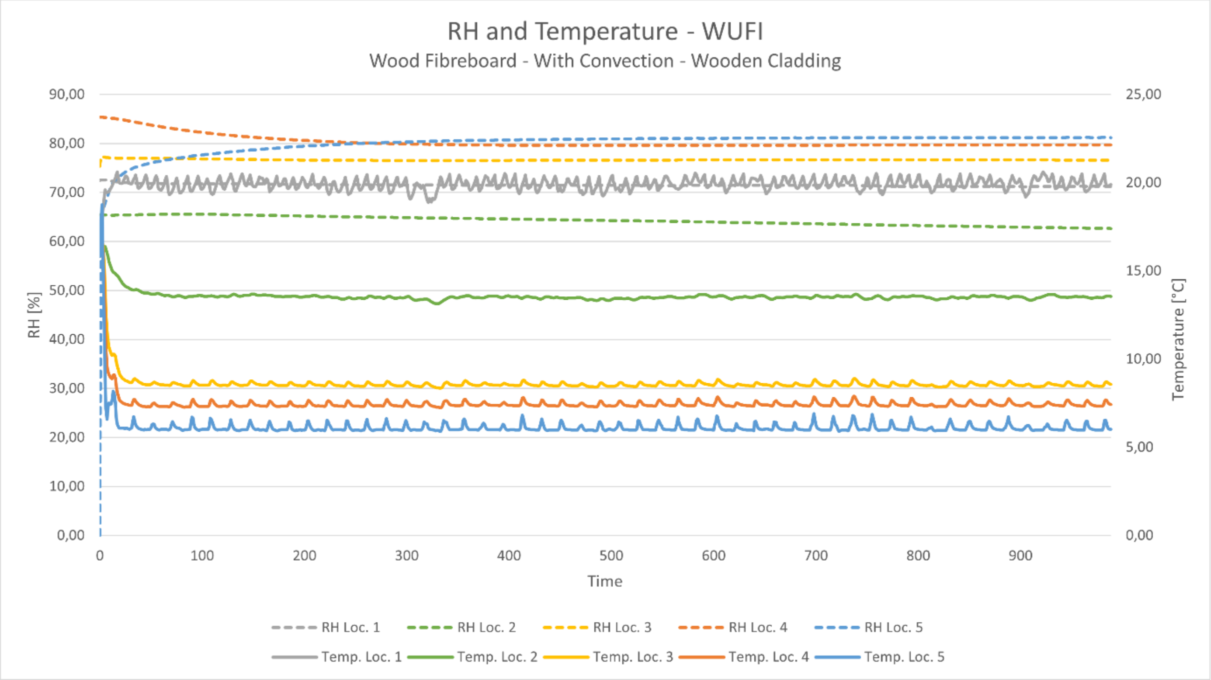

Figure A3.7: RH and Temperature – Short-term simulation 7

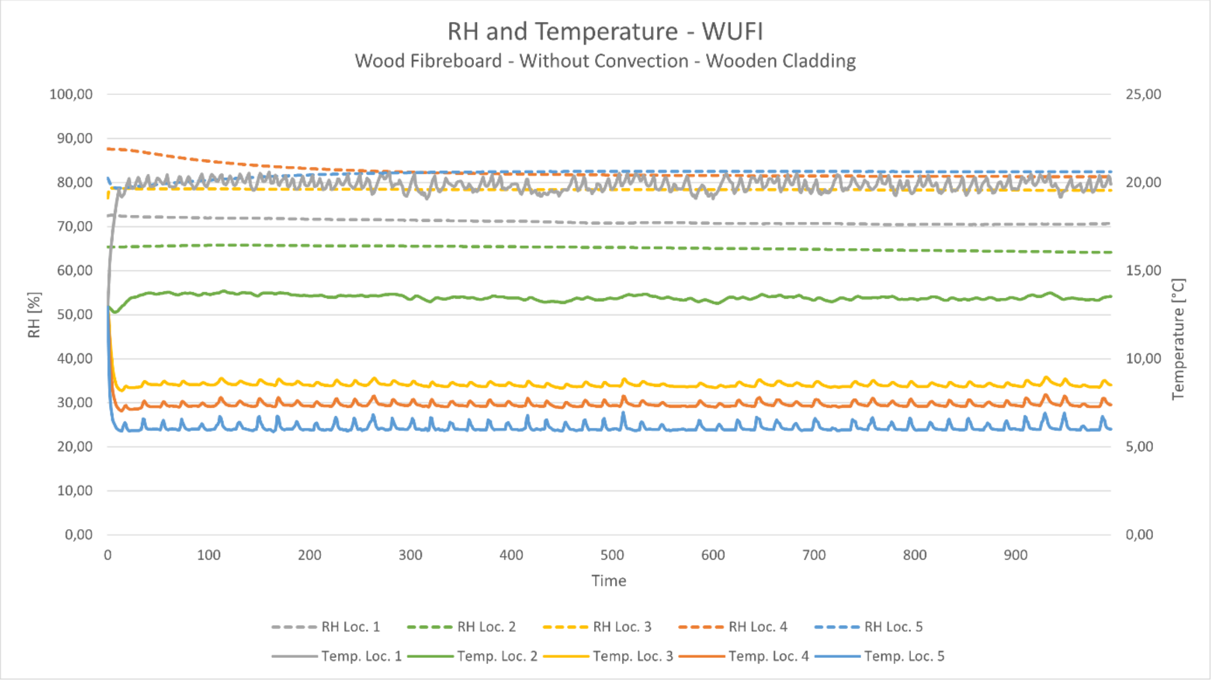

Figure A3.8: RH and Temperature – Short-term simulation 8

A4: Absolute Humidity – Short-term simulations

Mineral Wool

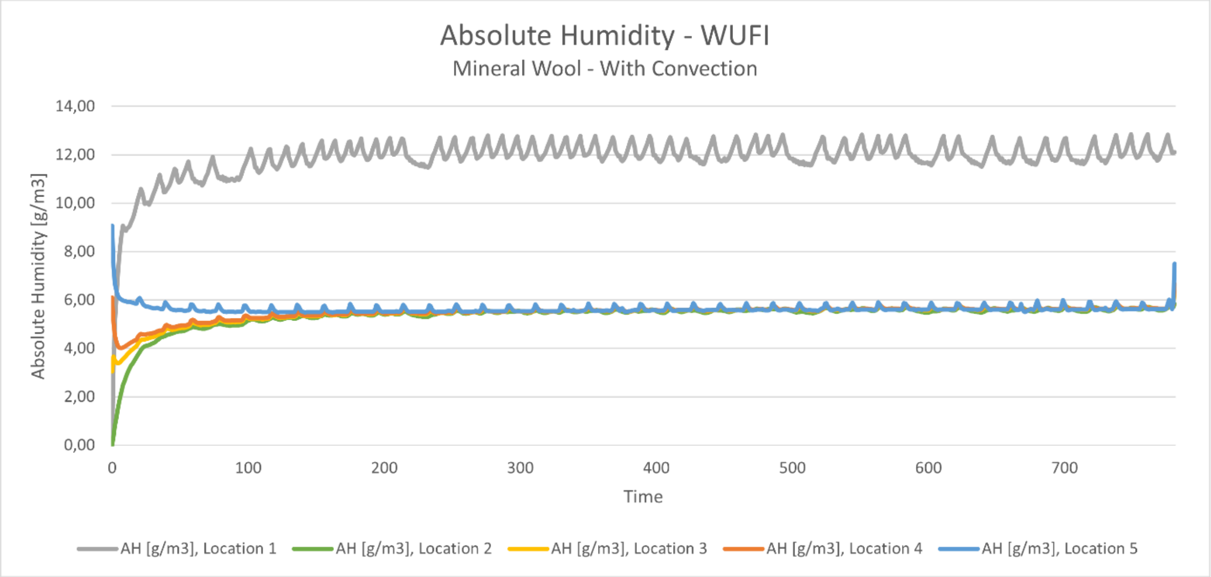

Figure A4.1: Absolute Humidity – Short-term simulation 1

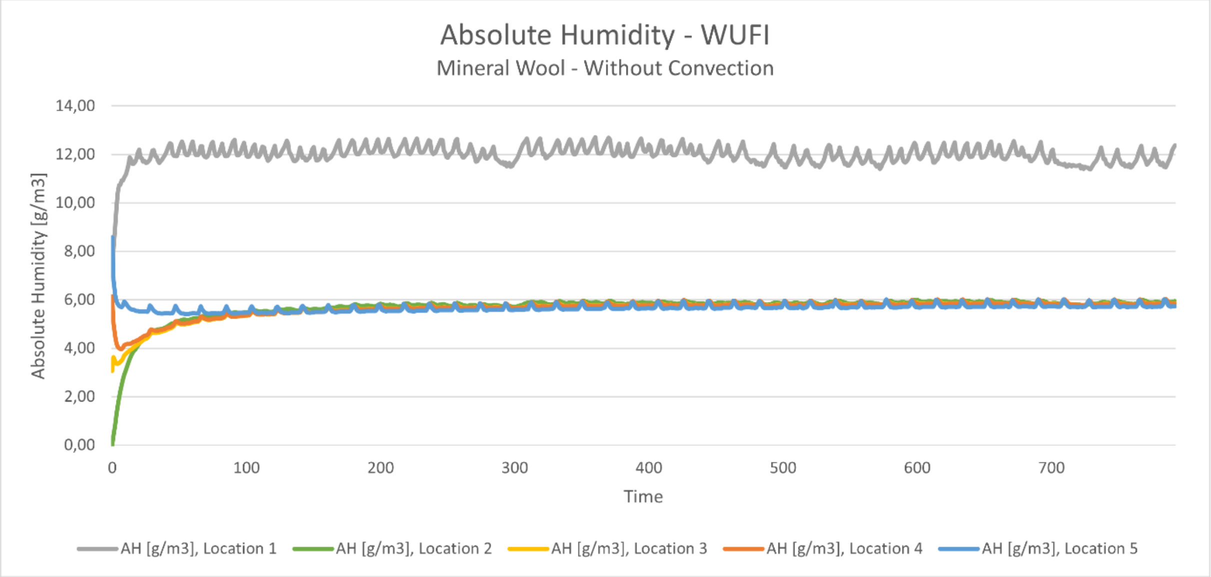

Figure A4.2: Absolute Humidity – Short-term simulation 2

Flax Fibre

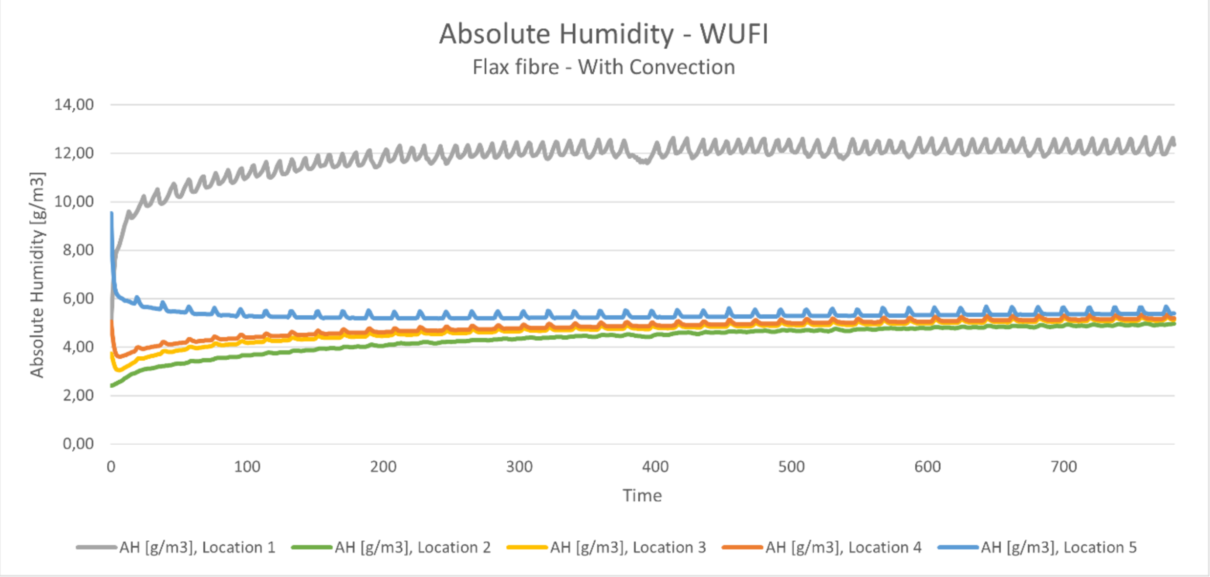

Figure A4.3: Absolute Humidity – Short-term simulation 3

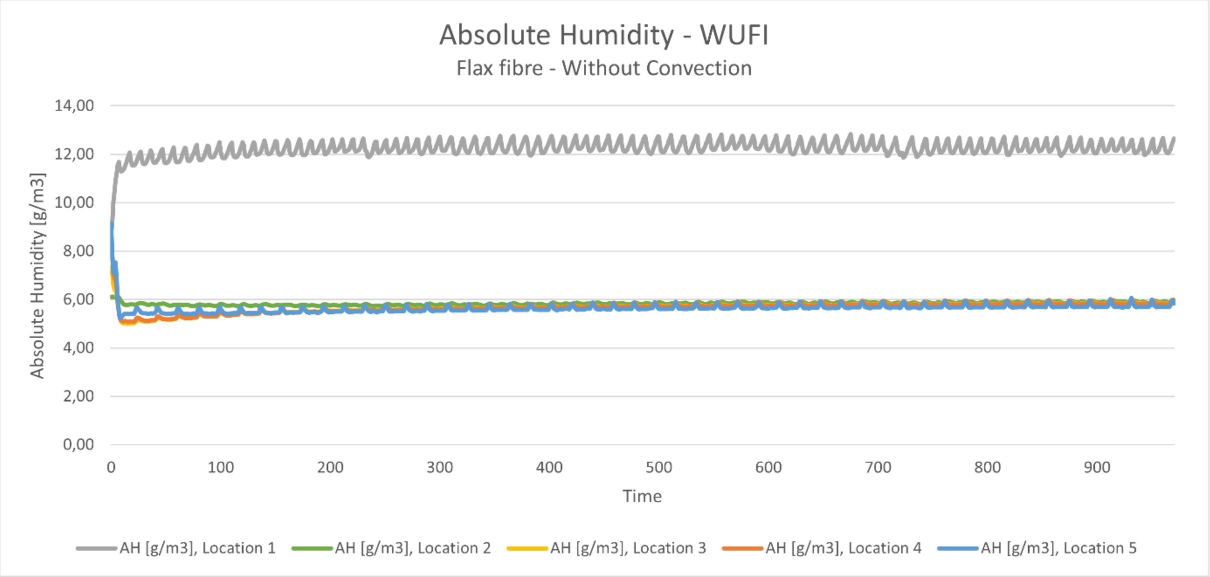

Figure A4.4: Absolute Humidity – Short-term simulation 4

Wood Fibreboard

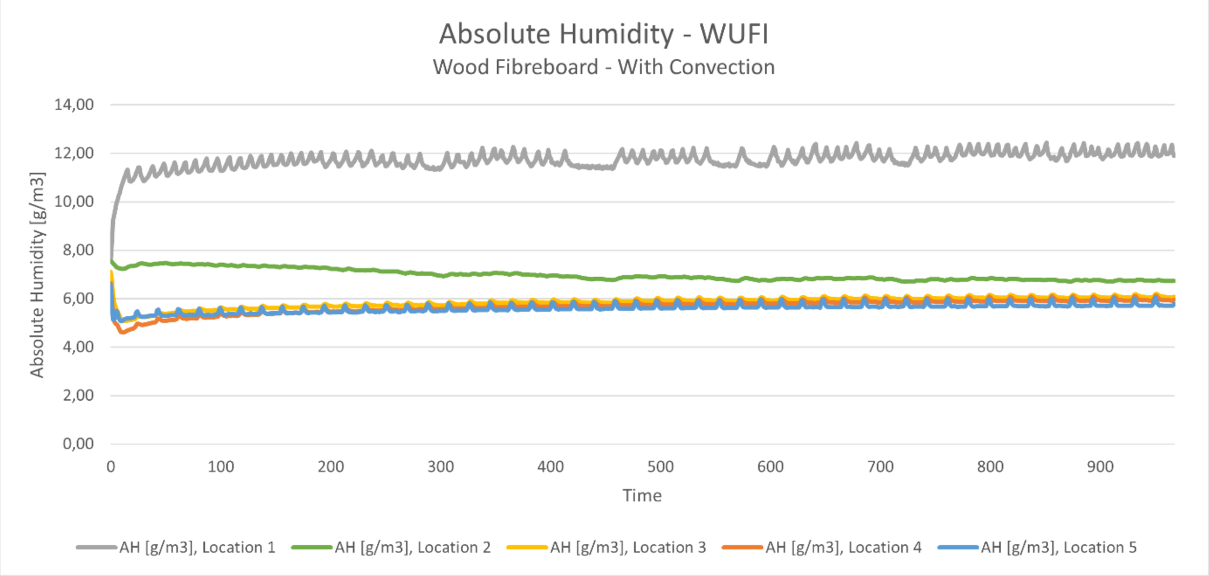

Figure A4.5: Absolute Humidity – Short-term simulation 5

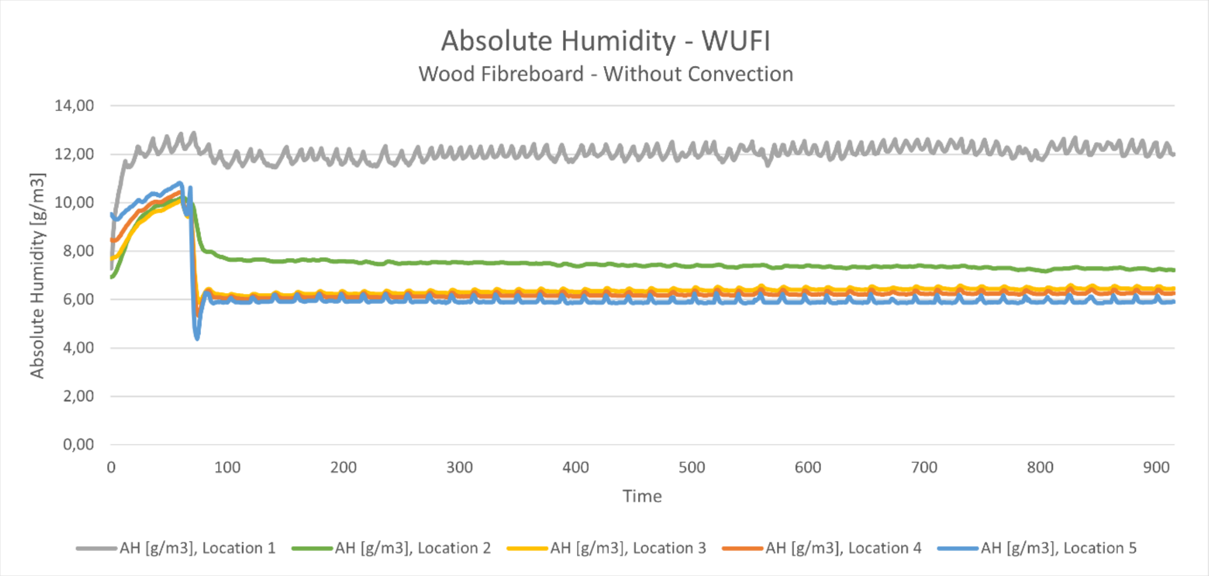

Figure A4.6: Absolute Humidity – Short-term simulation 6

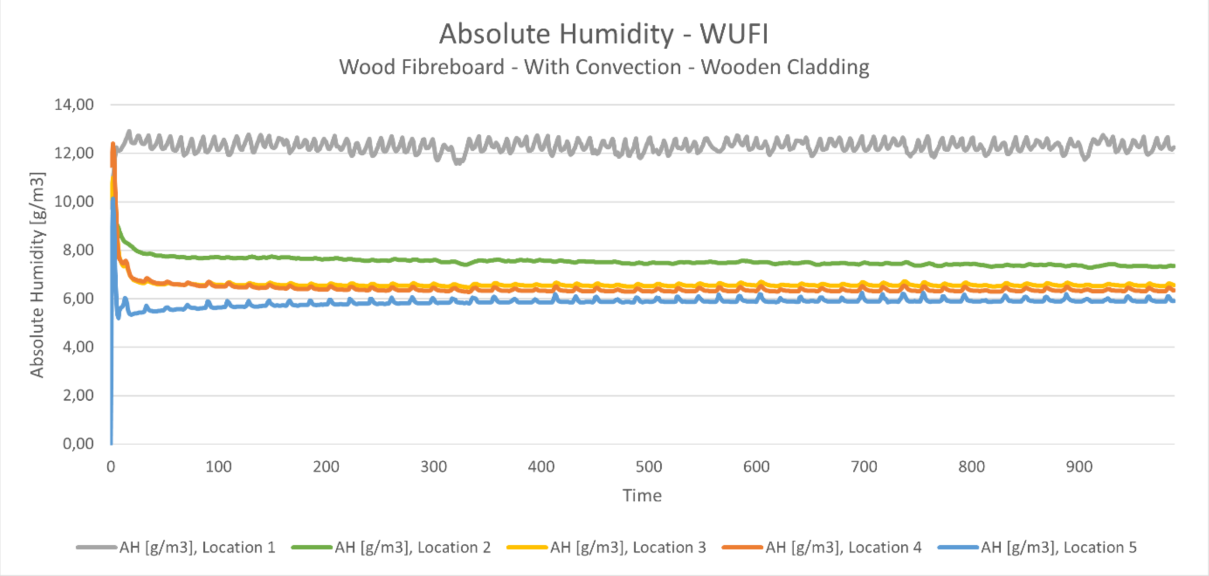

Figure A4.7: Absolute Humidity – Short-term simulation 7

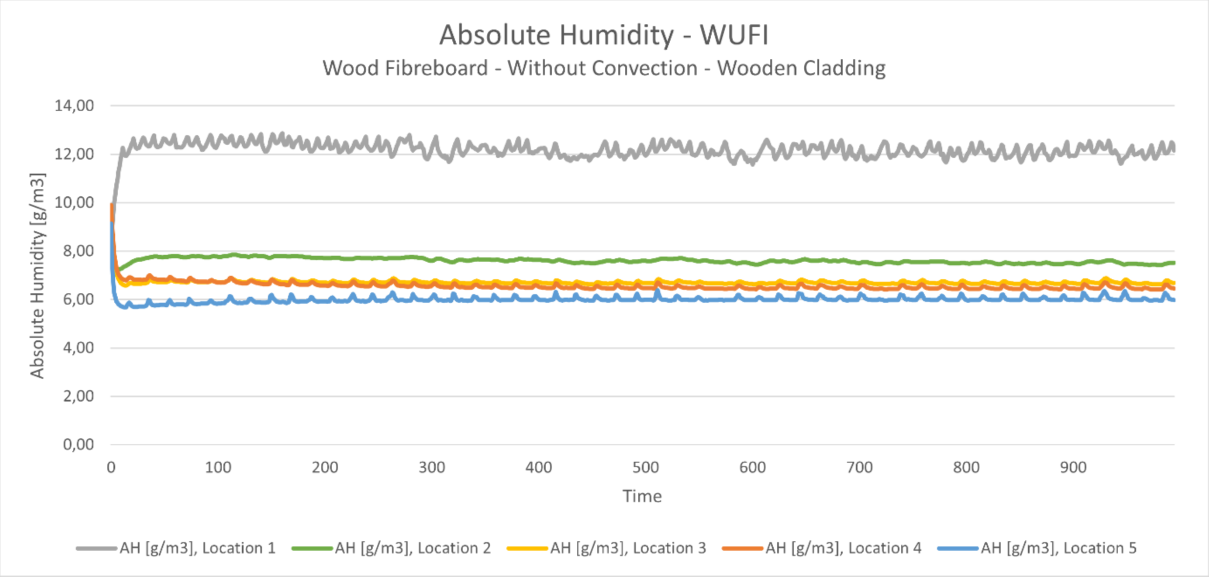

Figure A4.8: Absolute Humidity – Short-term simulation 8

A5: Partial Pressure – Short-term simulations

Mineral Wool

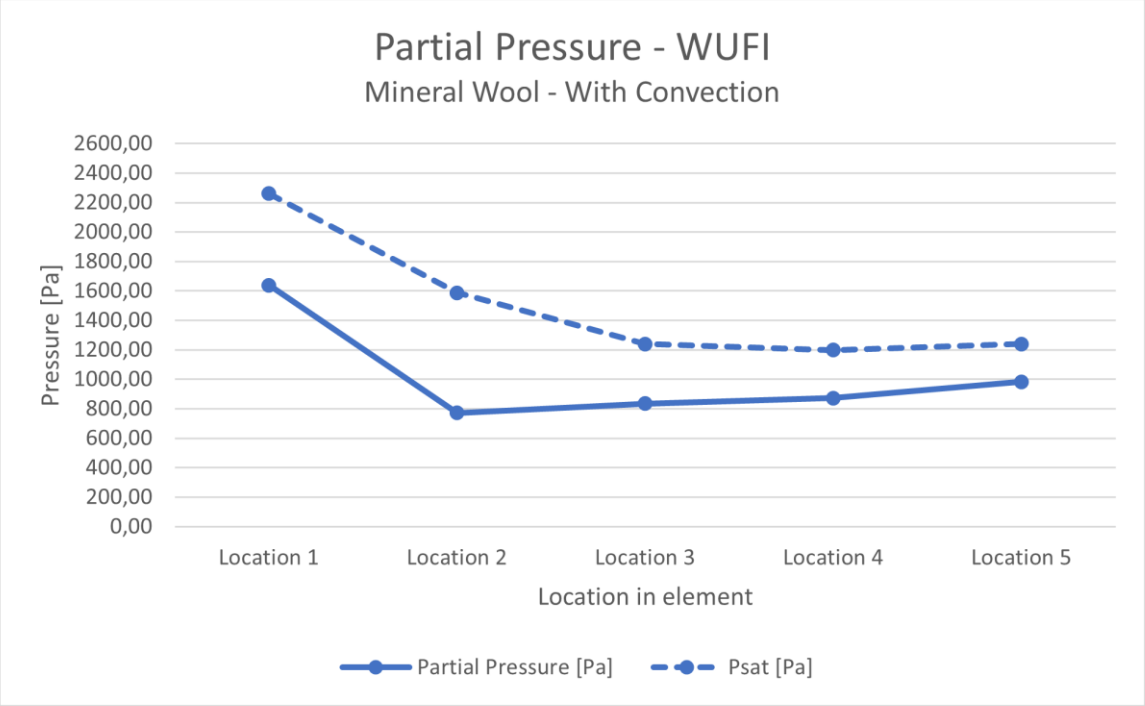

Figure A5.1: Partial Pressure – Short-term simulation 1

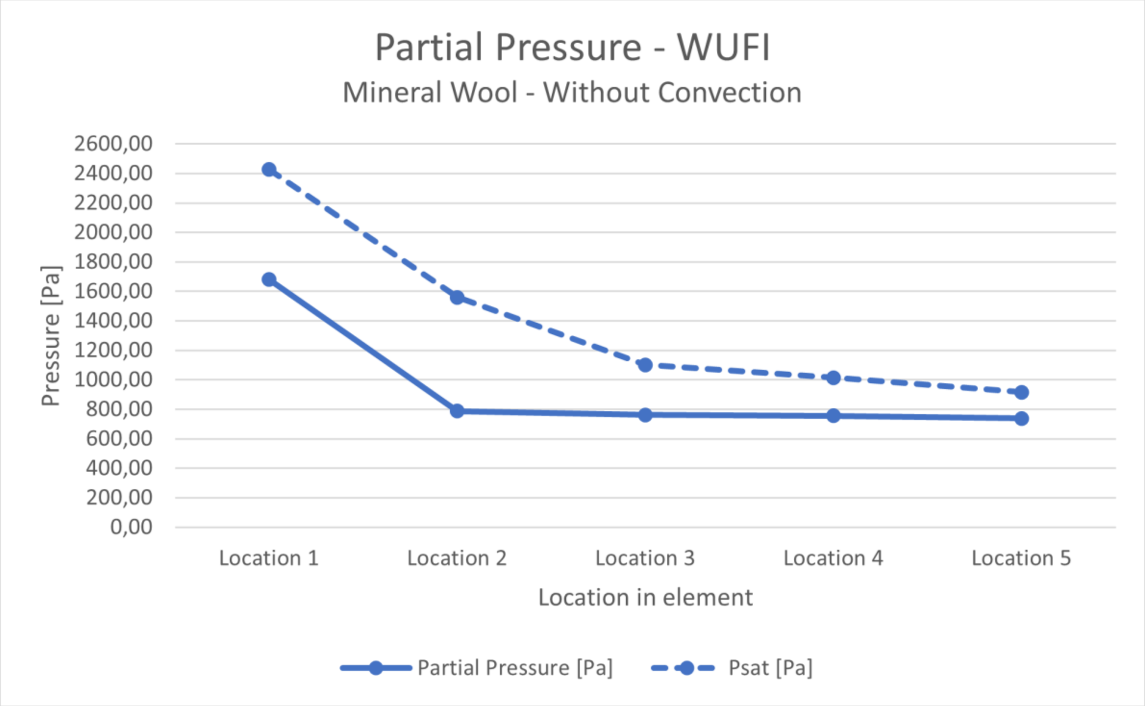

Figure A5.2: Partial Pressure – Short-term simulation 2

Flax Fibre

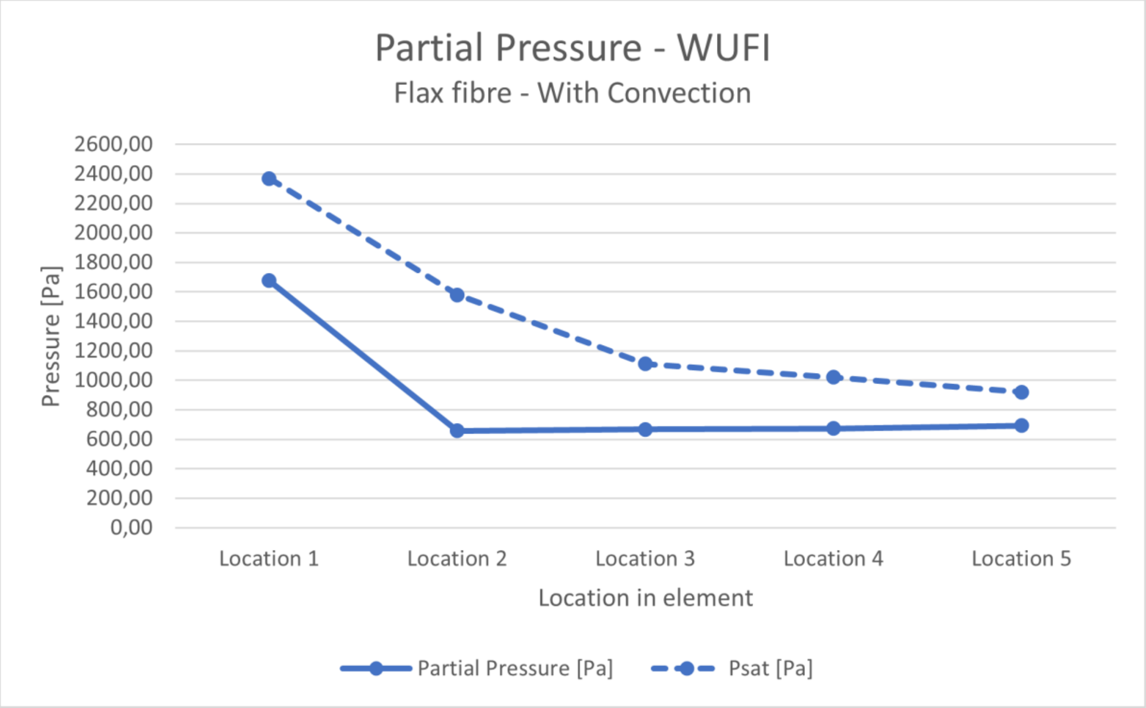

Figure A5.3: Partial Pressure – Short-term simulation 3

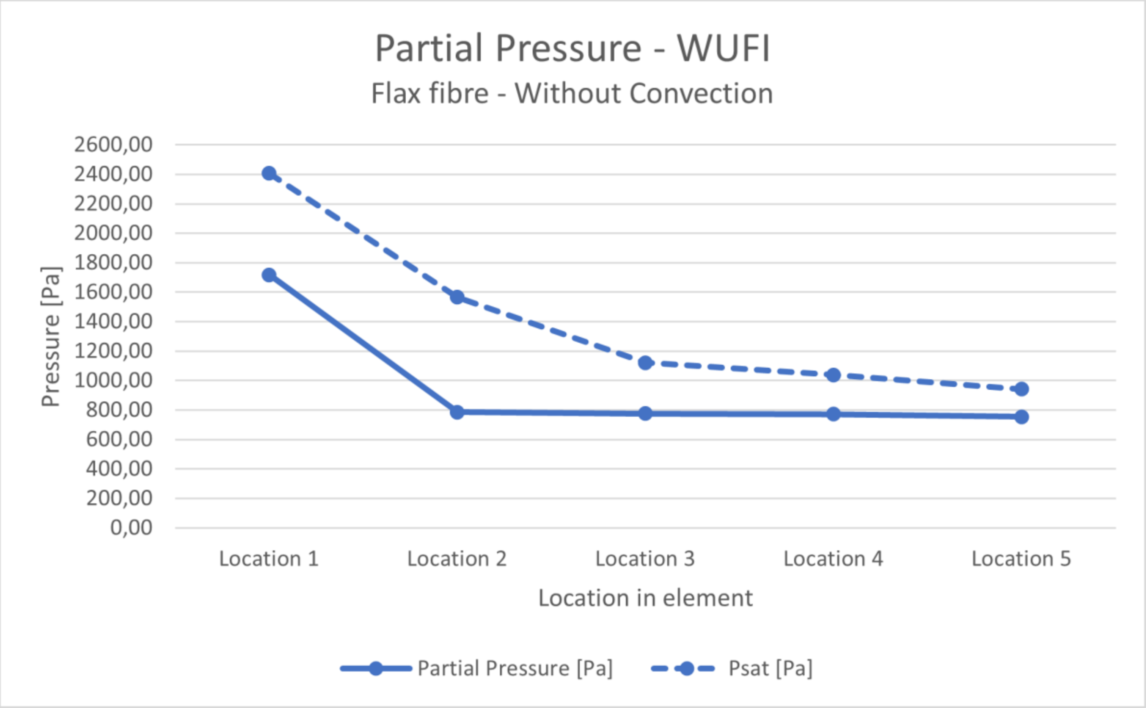

Figure A5.4: Partial Pressure – Short-term simulation 4

Wood Fibreboard

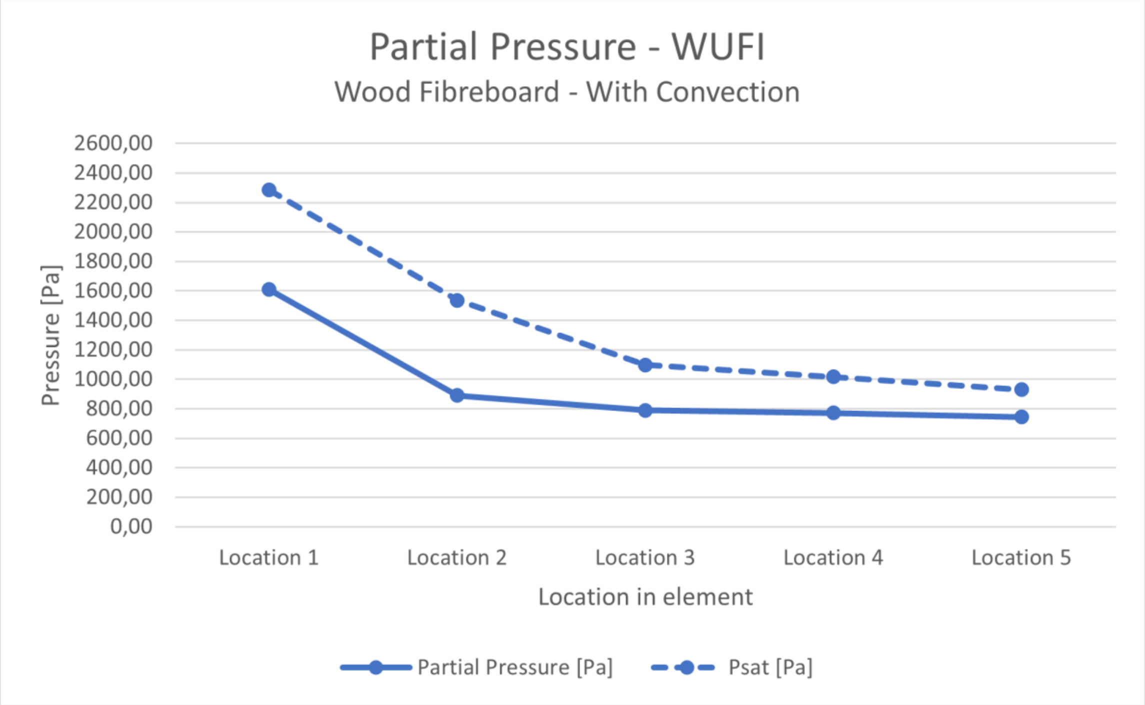

Figure A5.5: Partial Pressure – Short-term simulation 5

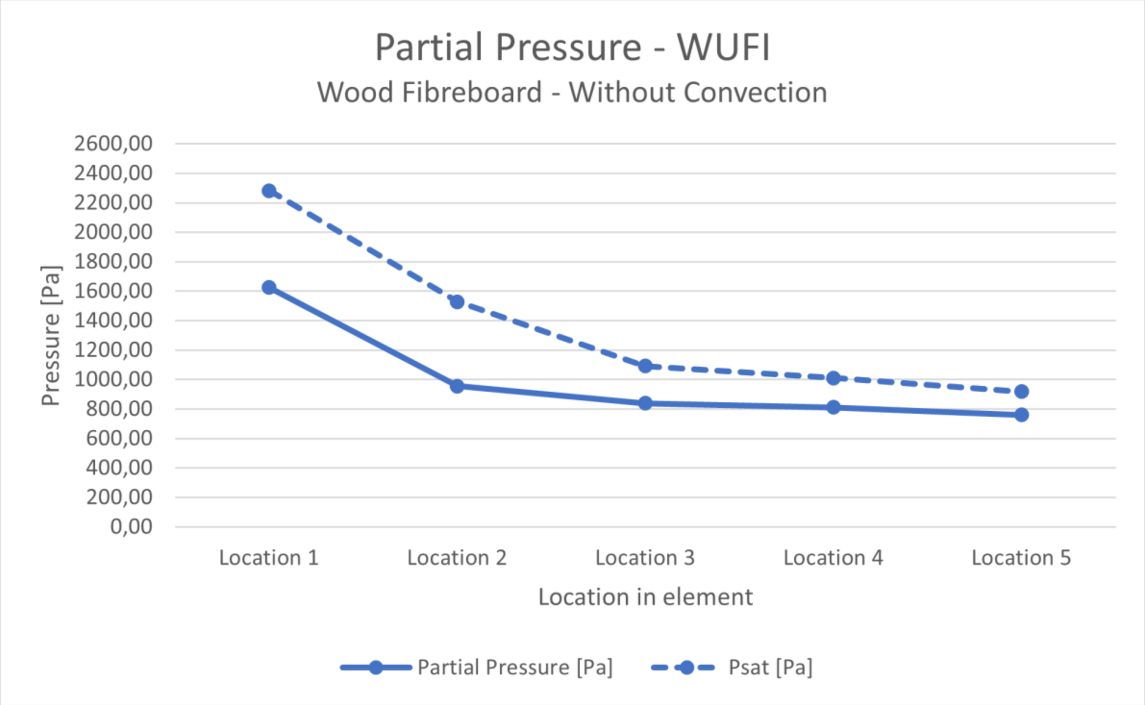

Figure A5.6: Partial Pressure – Short-term simulation 6

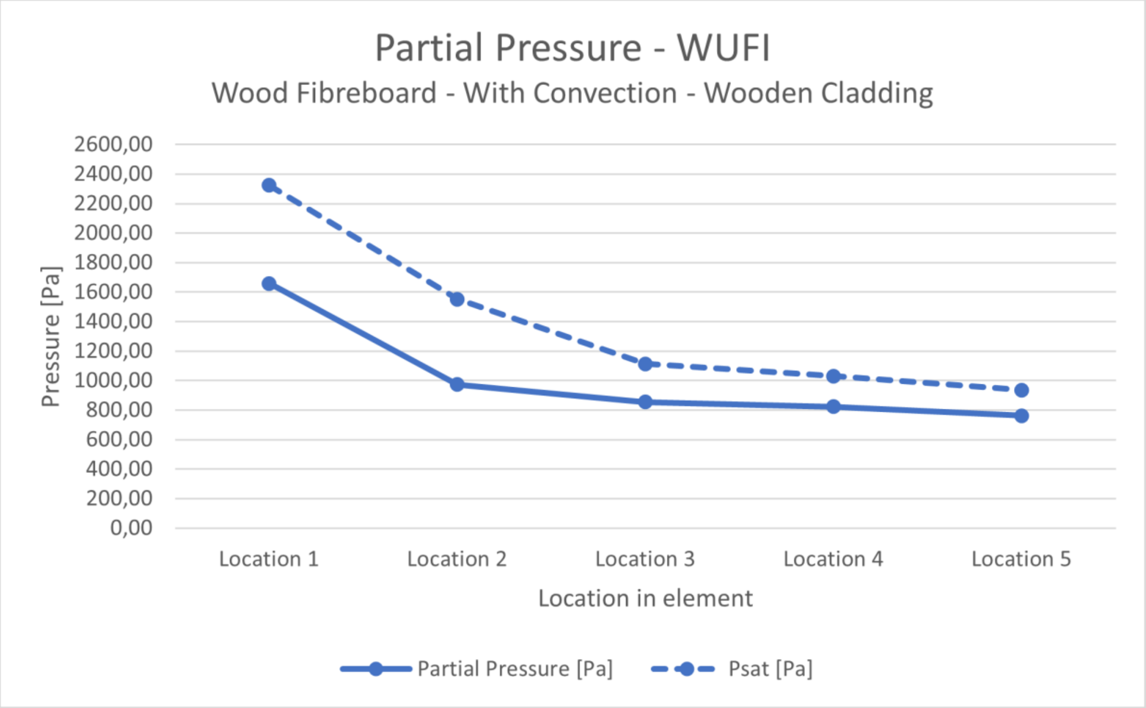

Figure A5.7: Partial Pressure – Short-term simulation 7

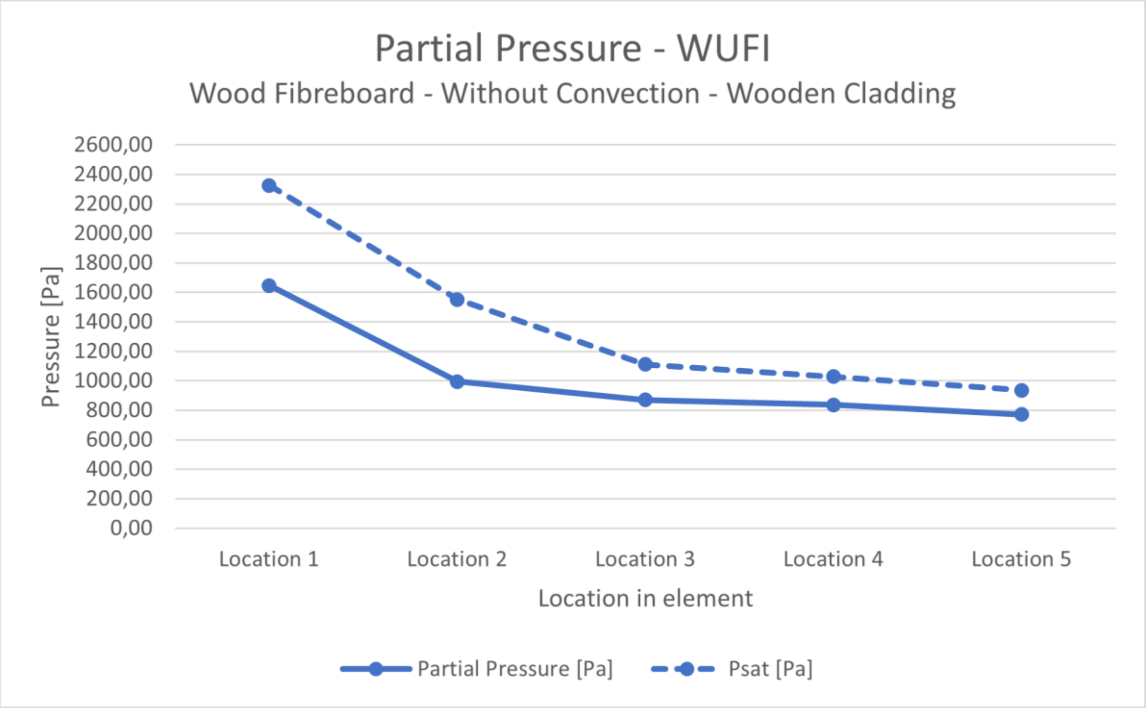

Figure A5.8: Partial Pressure – Short-term simulation 8

A6: Water Content – Long-term simulations

Mineral Wool

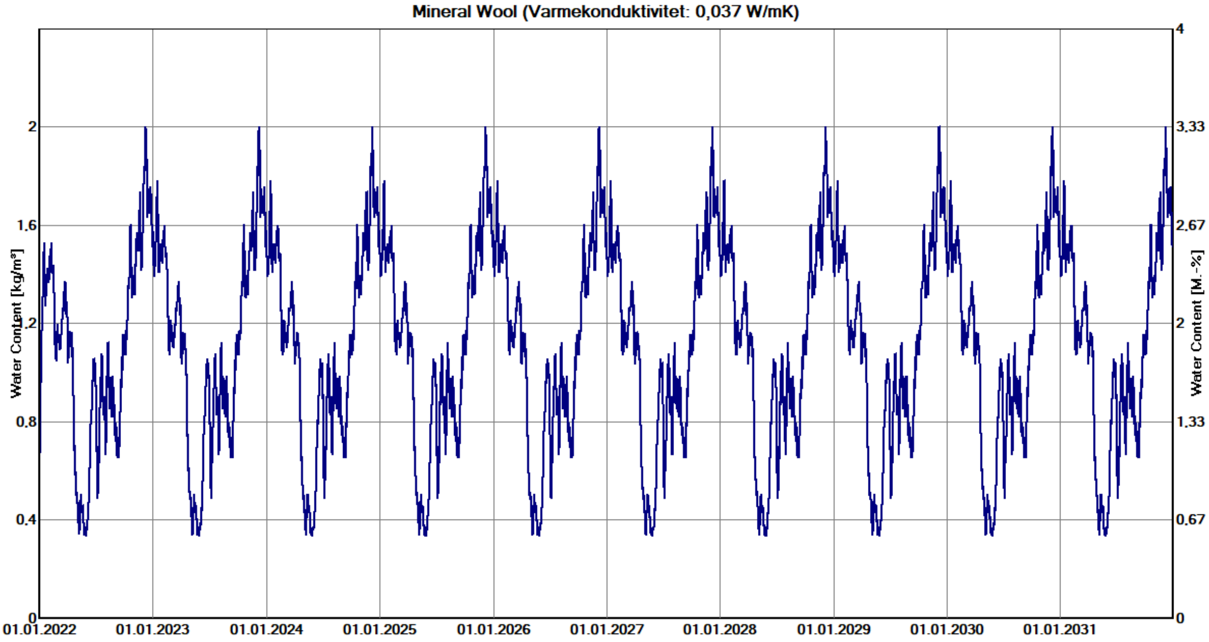

Figure A6.1: Water Content Mineral Wool with convection – Long-term simulation 1

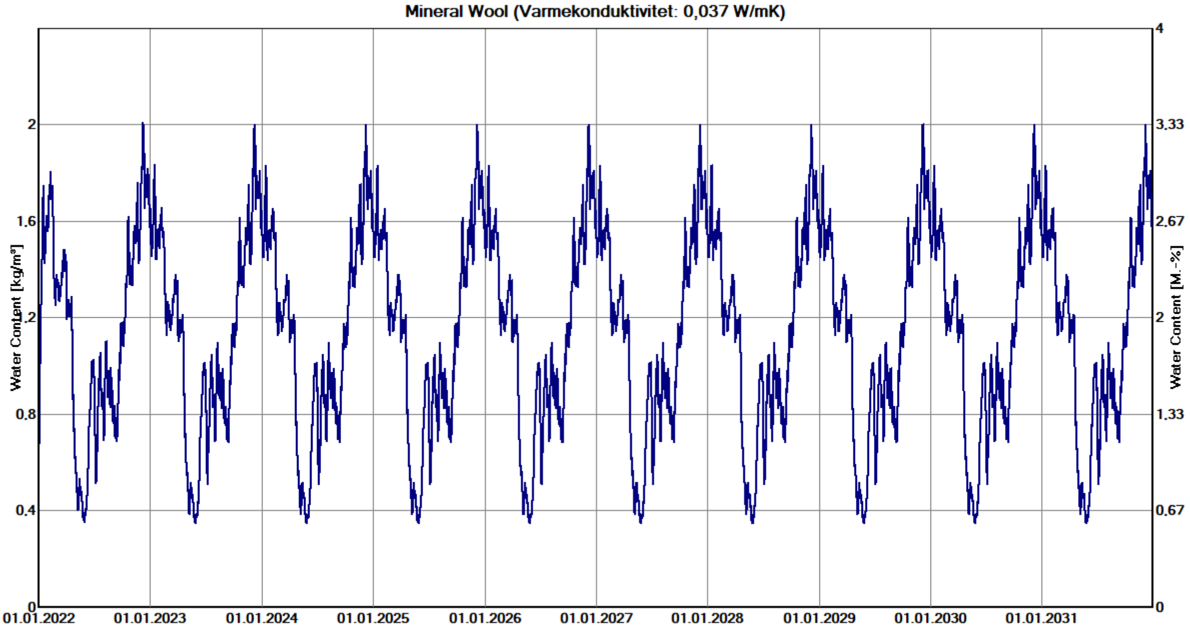

Figure A6.2: Water Content Mineral Wool without convection – Long-term simulation 2

Flax Fibre

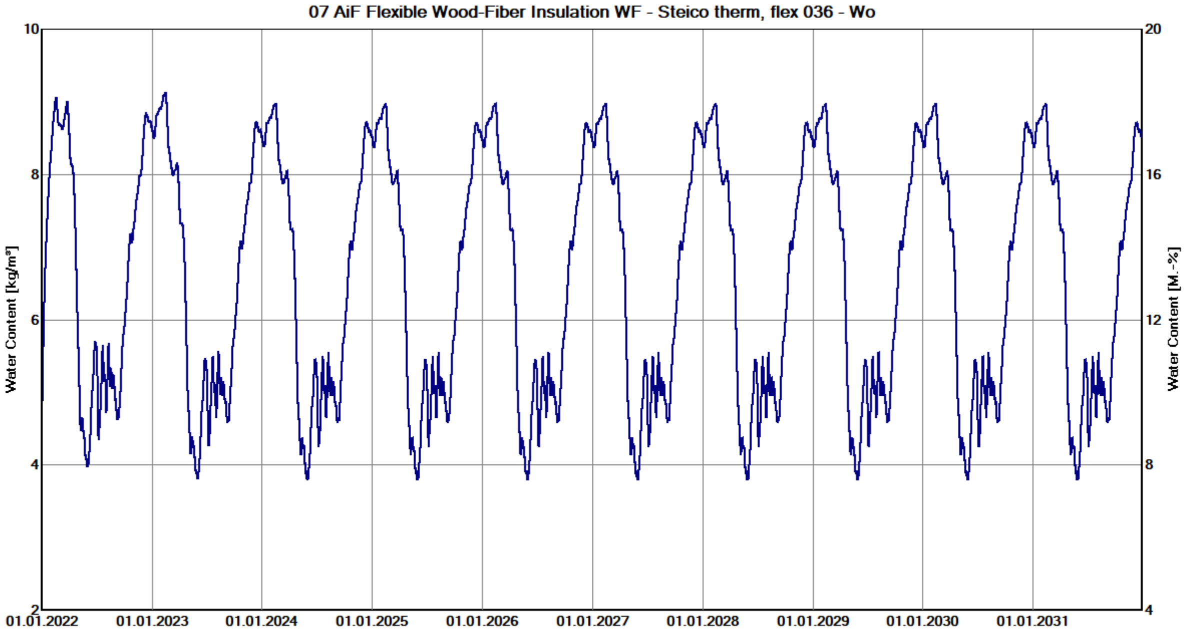

Figure A6.3: Water Content Flax Fibre with convection – Long-term simulation 3

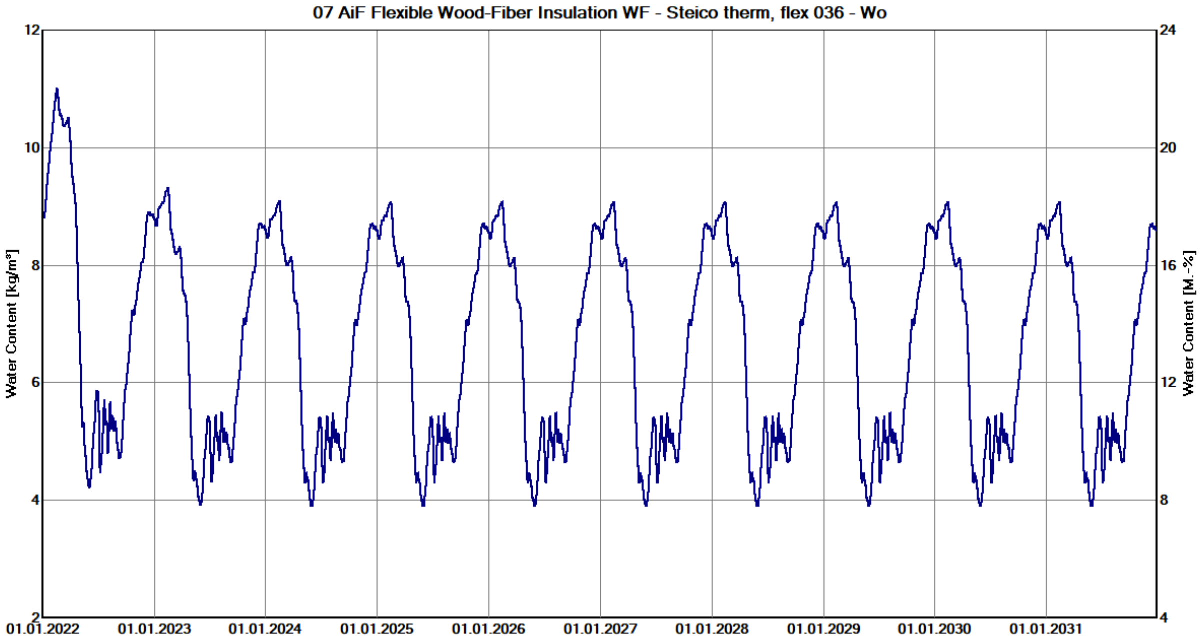

Figure A6.4: Water Content Flax Fibre without convection – Long-term simulation 4

Wood Fibreboard

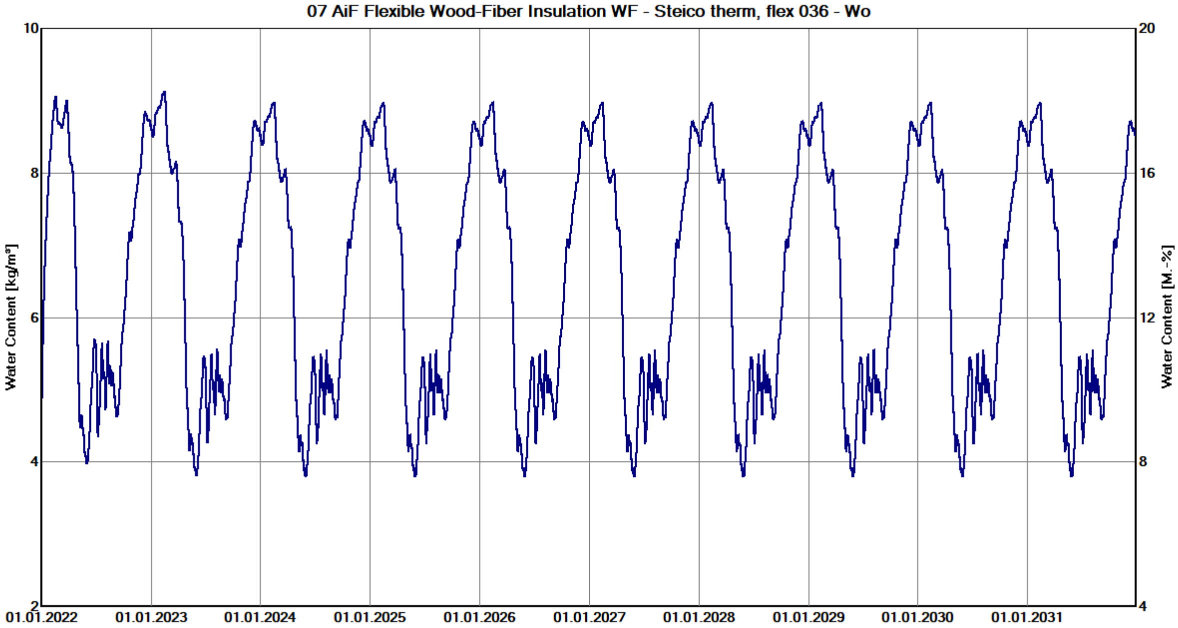

Figure A6.5: Water Content Wood Fibreboard (Cement cladding) with convection – Long-term simulation 5

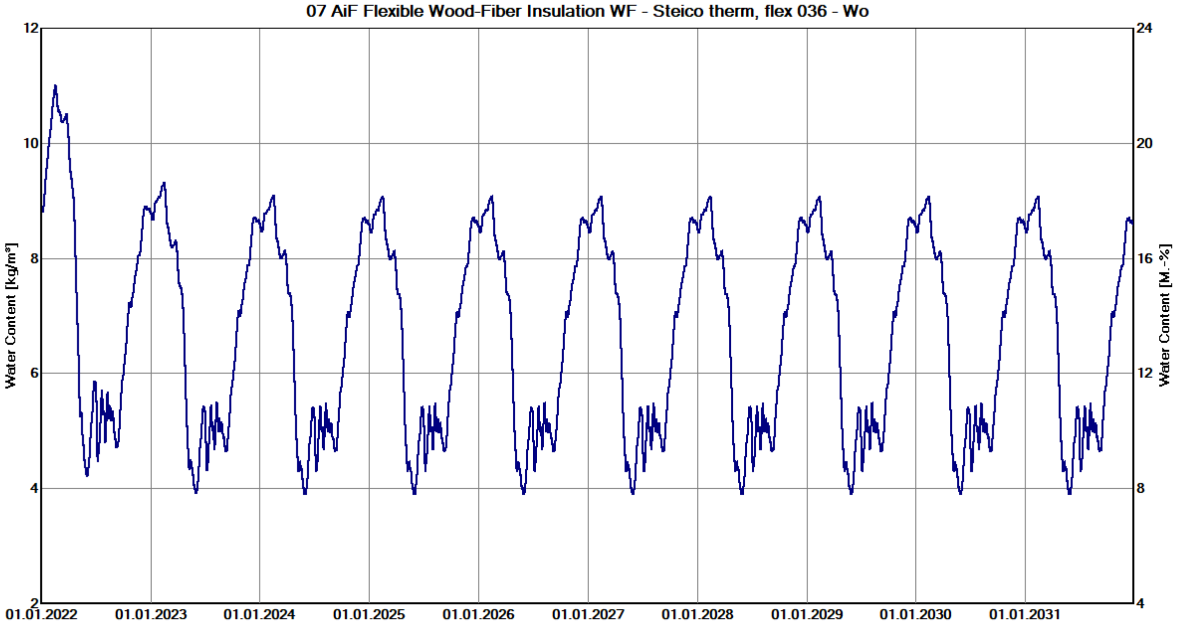

Figure A6.6: Water Content Wood Fibreboard (Cement cladding) without convection – Long-term simulation 6

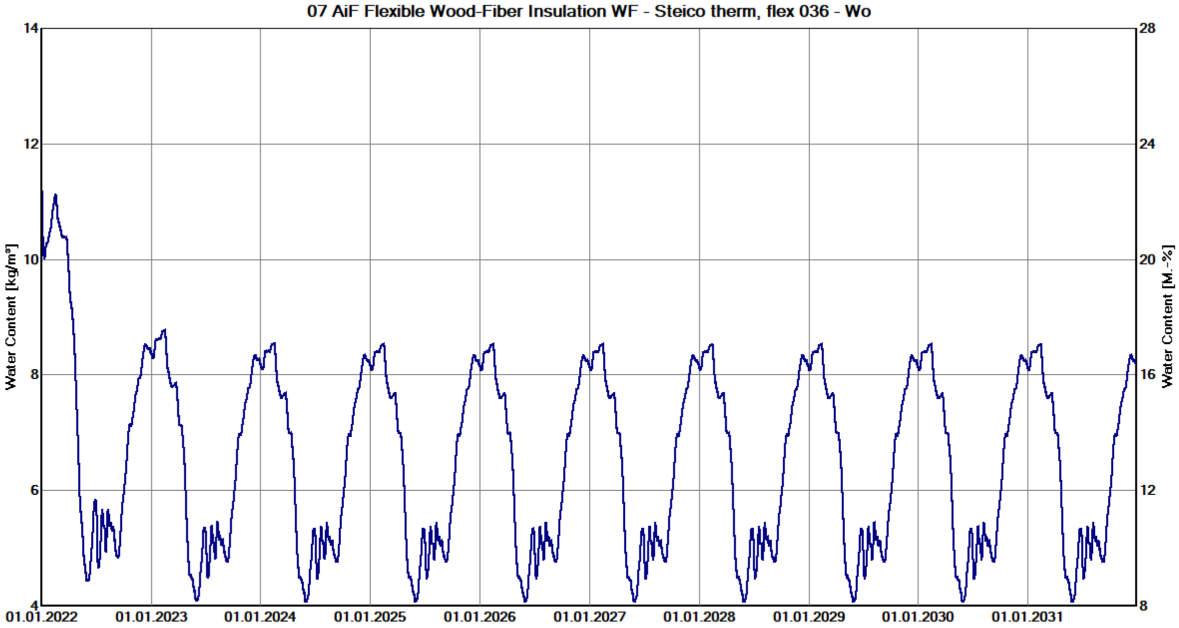

Figure A6.7: Water Content Wood fibreboard (Wooden Cladding) with convection – Long-term simulation 7

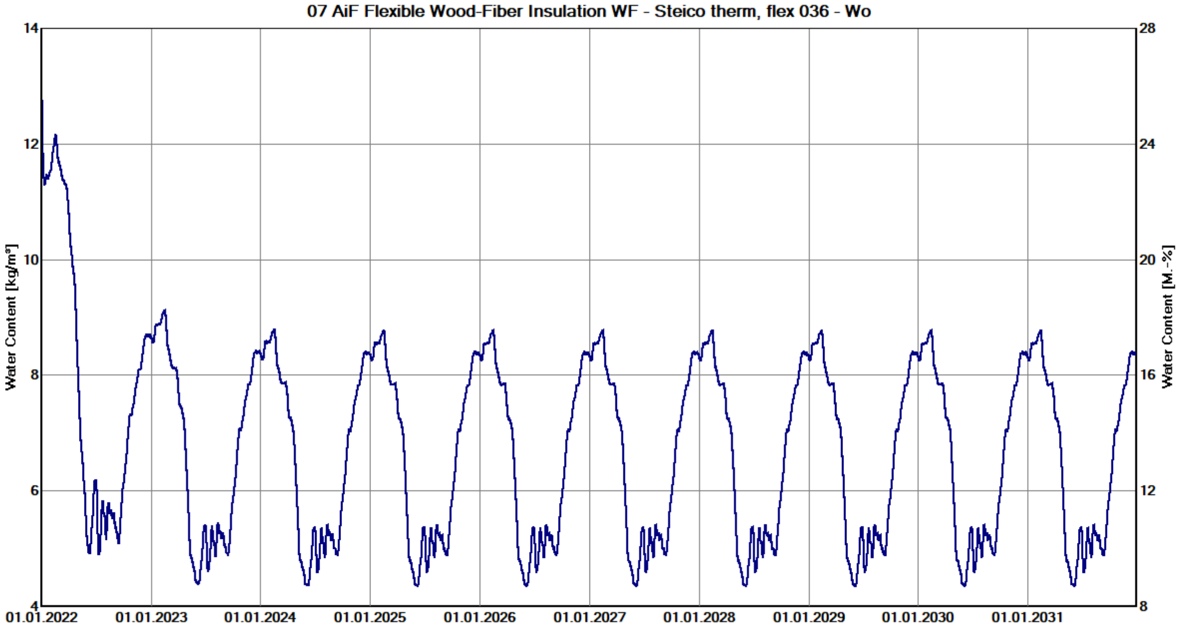

Figure A6.8: Water Content Wood Fibreboard (Wooden Cladding) without convection – Long-term simulation 8