Hygrothermal Behavior of Finnish Building Exterior Walls

HAMK
UNIVERSITY OF APPLIED SCIENCES

Bachelor's thesis

Degree Programme in Construction Engineering

Visamäki, spring 2015

Abhishek Subba

HAMK UNIVERSITY OF APPLIED SCIENCES

ABSTRACT

Unit
Name of degree programme
Option

Author Abhishek Subba **Year** 2015

Subject of Bachelor's thesis Hygrothermal behavior of Finnish building exterior walls

ABSTRACT

The main problem with the buildings in Finland is most probably moulds growing inside the building components. Due to the very humid climate of Finland, the chance of mould problems is very large. During winter, the temperature difference between the indoor and outdoor environments is very large. Moisture travels with air currents. When air and moisture moves from warm side to cold side of the wall, moisture condenses onto the cold sheathing or cool drywall. This phenomenon can rot the insulation layer and degrade the thermal transmittance of the wall.

The main objective of this thesis study was to look for the main causes behind the moisture and heat loss problems. The highlight of the research was the position of vapour barrier and the thickness of the insulation layer. The vapour barrier position can always affect the moisture condensation process in the wall. The vapour barrier must be kept in the warm side of the wall so that the moisture flowing through the wall does not condensate. The thickness of the insulation layer affects the thermal transmittance. The heat loss decreases while the insulation thickness increases but at the same time the insulation thickness also increases the cost of insulation. This means that the need of optimization of wall material, especially insulation material can be economical and effective.

This thesis study process was first theoretically analyzed and was practically tested. The wall was designed using Finnish National Code and later tested using the weather simulating chamber. The findings were different in all test phases. When the wall has a construction fault, even a small hole can cause frost to accumulate in the exterior gypsum board. This accumulated frost can melt in warmer days and can rot the insulation. This thesis study can be used as a reference for further studies in the similar topic.

Keywords Lightweight steel framed walls, timber framed walls, building physics, hygrothermal performance

Pages 35 p. + appendices 17 p.

CONTENTS

1 INTRODUCTION

Healthy and comfortable building design is the main aim for a building designer. There is nothing more important than customer's health and the fulfilment of customer's dream structure for a designer. At the same time, designing an eco-friendly and economically viable design is equally important. Almost every construction is meant to be built to take full service out of it. Sustainability of building is one of the important objectives in today's design. Selection of right building materials and optimization of building materials can play a vital role in obtaining a safe and economic building design. During the designing process, appropriate decision in selection of building material can help a lot in obtaining benefit and save construction cost. However, there are many building components that have equal importance and need equal attention.

This thesis focuses on a building external wall design. The objective of this study is to know the behaviour of different types of walls tested under Finnish weather condition. The designed wall is constructed and tested in Sheet Metal Centre (SMC). The wall is tested with the help of weather box chamber in SMC which simulates the required Finnish weather. The main focus of the study is to know the hygrothermal behaviour of the external wall in Finland. The hygrothermal term is related to the movement of heat and moisture through buildings. The main idea of this study is also to know the different kinds of effects in wall structures under different construction faults in wall structures.

Finland is one of the Nordic countries. Finland has long winter and short summer. During winter, Finland is covered with snow and temperature can easily drop down to -10°C or even can get severe down to -30°C. February is the coldest month. Though summer in Finland is short, summer brings warmness and brightness. During summer, temperature can rise to +20°C or more. The warmest month is typically July, with mean temperature between +14°C and +18°C in most parts of the country. Daily maximum temperatures can reach +30°C in July. The coldest months are January and February, with mean temperatures between -4°C in the south and -15°C in the north (Karjalainen 2008, 1238).

"Long-term performance of buildings is governed by their response to the heat, air, and moisture transport processes that are the consequences of ever-changing outdoor conditions. In countries with a cold climate, these transport processes often result in moisture deposition within wall cavities. One major source for moisture that leads to such deposition is the indoor air; for human comfort, it is desirable to maintain a certain level of humidity in the indoor environment. Moisture from the indoor environment is transported into the wall cavity through two mechanisms, vapour diffusion and ex filtration. In countries such as Canada and Finland, it is a code requirement to install a vapour retarder at the warm surface of the wall assembly. Such an installation will effectively retard moisture transport through the mechanism of diffusion, but this does not prevent the other mechanism of moisture transport, which in most buildings is the dominating one {Latta 1976}." (Ojanen & Kumaran 1992, 491)

1.1 Need of a perfect wall

Condensation in a wall is the most commonly known problem especially in exterior walls in Finland. Condensation can create dampness and mould growth problems in walls. These problems can bring many drawbacks in building performance. This problem can be dangerous for occupant's health. Wall condensation problems can lead to:

- Mould growth in wall components.
- Heat and energy loss from wall envelope
- Maintenance and management costs can increase.
- The deterioration of building finishes and fabric.
- Health problem issues for occupants.
- Increased complaints from tenants.

The main principle of designing and constructing external wall structures is that the wall must be airtight. The water vapour permeability of structural layers must increase gradually towards the outside surface of the wall. A water vapour barrier may be needed near the inner surface of a wall (Häkkinen 2012).

2 OBJECTIVE AND DESCRIPTION OF THESIS

This thesis was commissioned by HAMK UAS, Visämaki. The main aim of this thesis is to know the behaviour of different types of walls used in Finnish structures under the Finnish climate. The idea behind the research is to analyze the wall and study the moisture flow and thermal behaviour using the weather box chamber. To check the influence of moisture and temperature on the wall, the constructed wall is placed in a weather box chamber which has sensor implanted in different depth and section. Later the practical test result is compared with the theoretical calculation result of the wall.

A weather box chamber is a climate simulation chamber which was constructed by Sheet Metal Center (SMC). The weather box chamber helps to simulate the Finnish climate and can produce the desired parameters of temperature, relative humidity, solar radiation and rain in laboratory conditions. Sheet Metal Center operates the weather box chamber to test the structures used in construction for educational purposes and also for commercial purposes. The weather box chamber also provides assistance in research and development activities for HAMK UAS and Sheet Metal Center.

"SMC is a research and development unit under the administration of HAMK University of Applied Sciences that works both as an educational and training institute as well as an enterprise. It was established in 1998 to provide various weathering tests and structural analysis on various structures as their service to the customers. Later, SMC started working as a hybrid of a business point and an educational institute. SMC also provides work placement and thesis topics in various fields of construction engineering to many graduating students of HAMK. (HAMK 2011)" (Shakya 2011)

2.1 Objective of the thesis study

The main objective of this thesis study project is to investigate how well the designed walls can perform in practice and to develop a better understanding about the factors that can affect the thermal transmittance (U-value) of the wall and moisture flow in the wall. The objectives of the thesis study are as follows.

- To determine the thermal behavior and moisture flow in wall structures in Finnish climatic condition
- To determine the function of the vapour barrier and analyze the best position for vapour barrier in the wall component
- To use the research result for determining probable mistakes in wall design and wall construction phases
- To apply the research outcomes for the necessary amendment to future projects

For the thesis study, two types of wall were chosen. The timber-framed external wall and light weight steel framed walls were designed for the thesis study. The designed walls were designed so as to cope with the Finnish climate. The designed walls are commonly used in Finland structures.

Since Finland is very rich in forest resources, timber framed walls are most commonly used in Finland. However, thin sheet-framed walls which are lightweight construction are equally being constructed. For this thesis study, Ruukki's Termo Purlins were used in light weight steel framed wall construction.

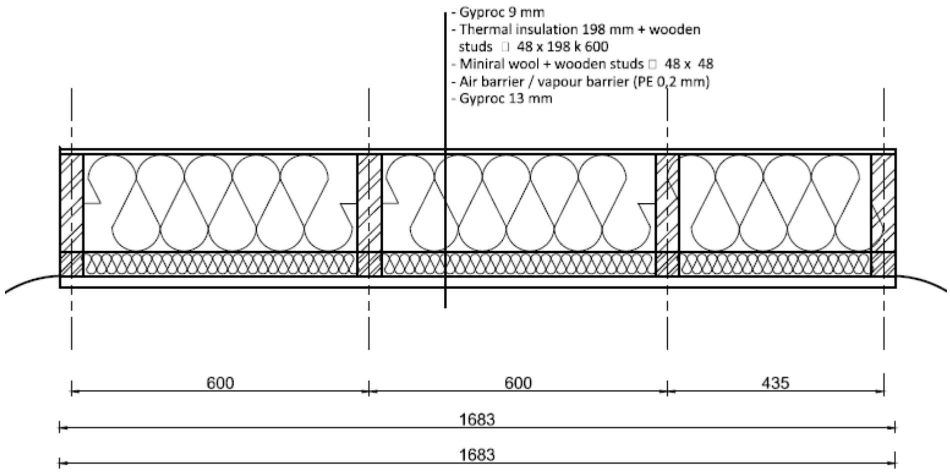


Figure 1 Timber framed wall

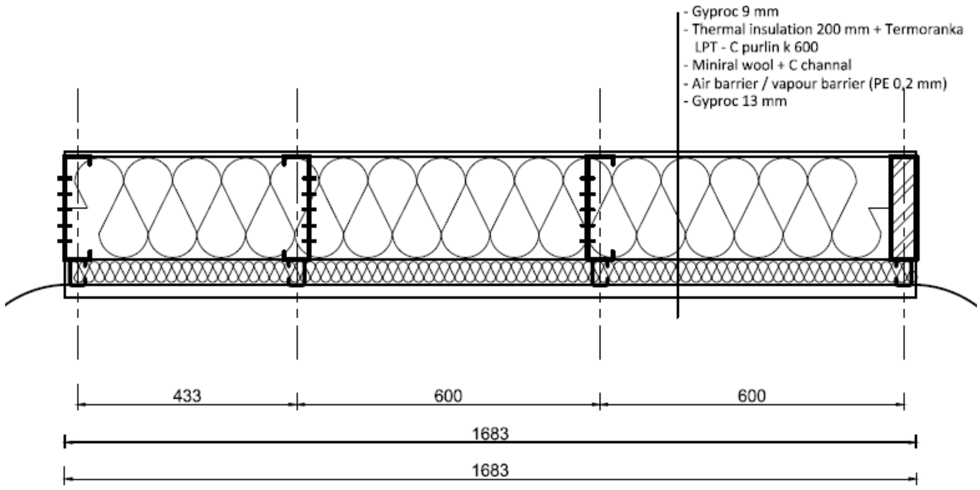


Figure 2 Light weight steel framed wall

Figure 1 & 2 shows the wall designed for the thesis study. The exterior claddings are not included in the figure. Basically, thermal behavior of the wall assembly concerns the outer surface on sheathing layer and the internal finishing layer of the wall structure. There is normally a ventilation gap between thermally functioning wall assembly and external claddings. Though the thermal transmittance of the wall is improved to certain extent with the help of external claddings, the ventilation gap and external claddings are left out in this thesis study.

The walls were constructed in SMC and loaded in the weather chamber for 24 days. The walls were tested in three phases. The testing procedures and results are explained in detail in chapter 2.2.

2.2 Theoretical and practical approach of the study

For the thesis study to be effectively performed, all the necessary required data were allocated. The preliminary plan was established with the collected initial ideas and data. The main idea of the plan was to compare and conclude the result between the theoretical and practical analysis. The study required building physics knowledge and practical construction knowledge.

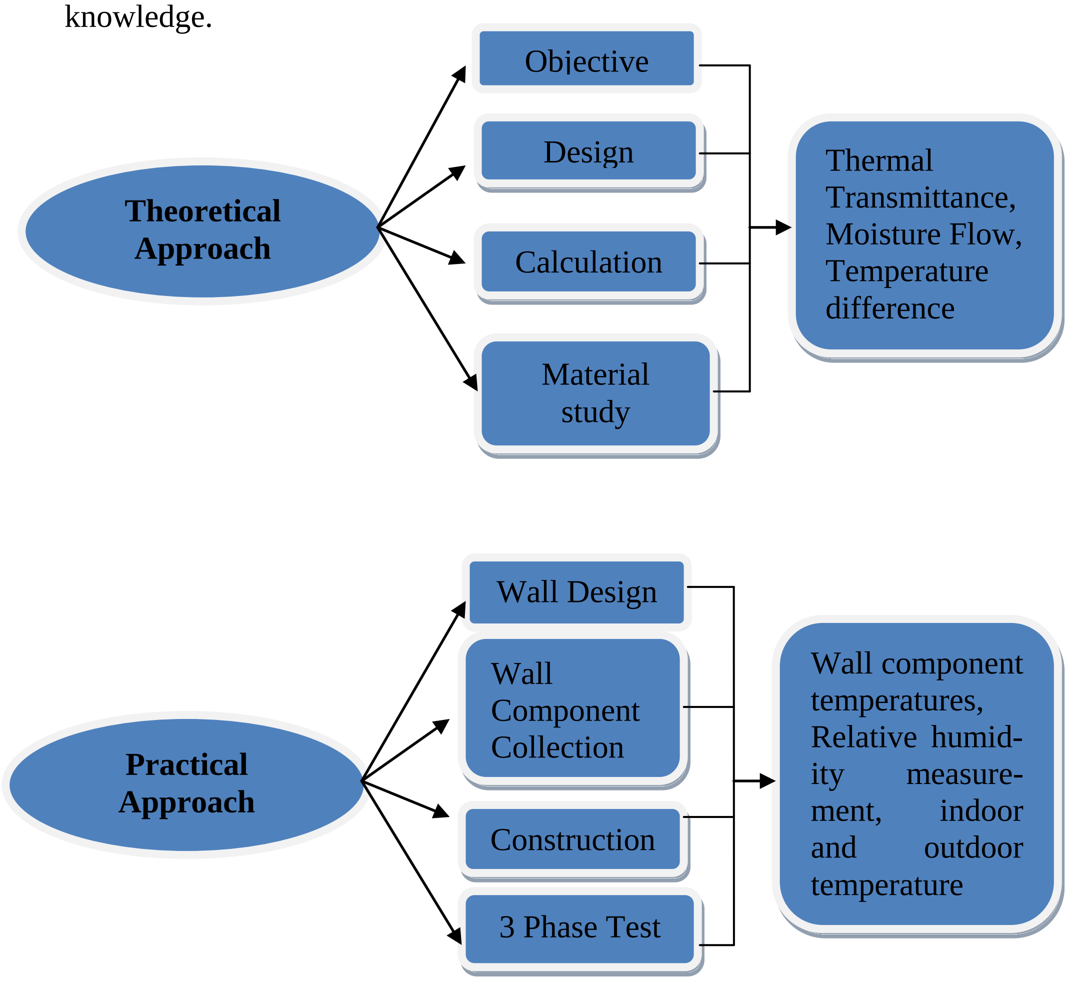


Figure 3 Theoretical and practical approach of the study

Figure 3 shows the thesis study in two sections, the theoretical section covers the theoretical analysis of the wall designed whereas practical part covers the construction and testing work of the study. Both sections will be analysed with a conclusions at the end of the study.

The theoretical part consisted of wall thermal transmittance calculations (U-valve) and calculations regarding possible moisture flow through the wall. The theoretical study also consisted of wall components study. Other important data collection and study of temperature, thermal resistance of material and relative humidity of site were carried out.

The practical part was done at the Sheet Metal Center (SMC). All the required wall components were bought from hardware shop and collected in SMC. The walls were constructed as per the design and were loaded in weather box for test. The test was done in three phase. The temperature of cold side of the wall was adjusted to approx -10 °C and Relative humidity to about 72 to 75%, whereas the warm side was set differently during each phase.

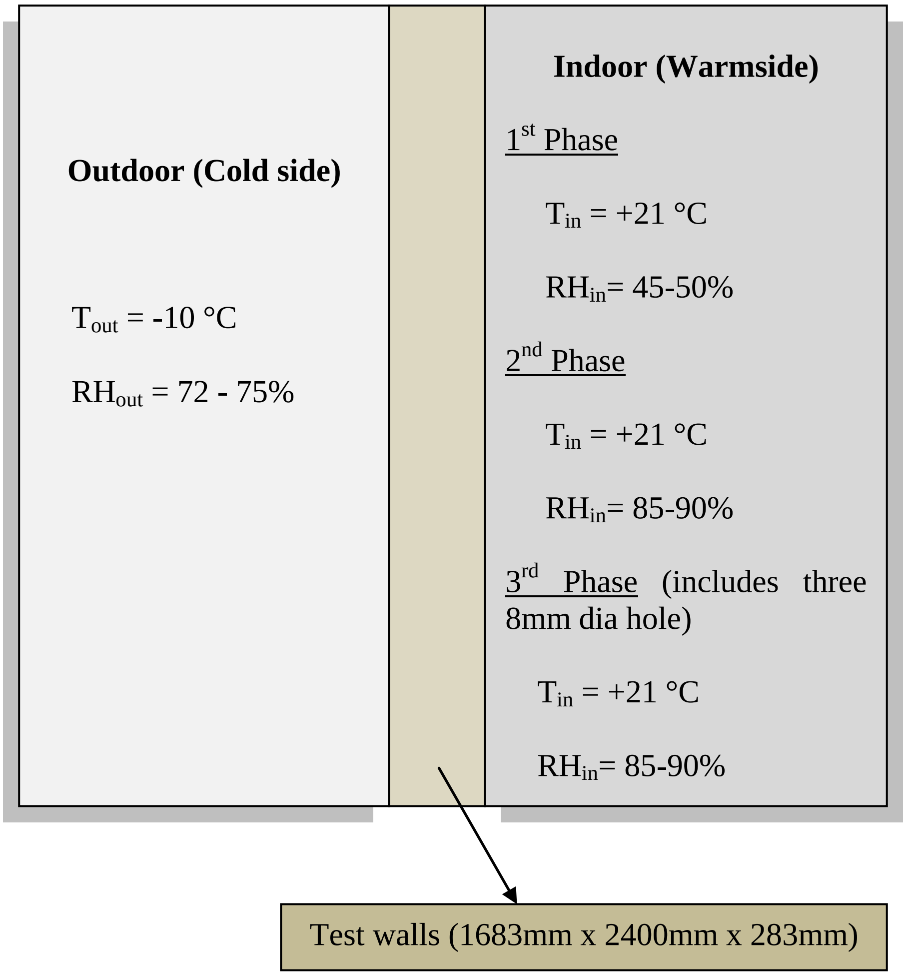


Figure 4 Wall testing plan and different test phases

The warm side of the testing chamber was equipped with heating and humidification units. This helped to simulate the indoor climate of a building. The cold side of the testing chamber was equipped with refrigeration, heating and humidification units that helped to simulate the outdoor climate. The weather box chamber was automatically controlled. The weather box chamber is designed to maintain equilibrium of various climatic parameters. This made test to be conducted as per the designed parameters, i.e. parameters such as air temperature, relative humidity (RH) and air pressure difference were easily maintained as wanted. The interior view of the weather box chamber can be seen in Figure 5.

The outdoor temperature was set to -10 °C and relative humidity to 72-75%. The required temperature and relative humidity was generated with the help of weather box chamber. The temperature and relative humidity of the wall components (wall layers) were recorded every day by using sensors installed in wall. The sensors were installed in different wall depth to get the reading from different wall layers. The sensors required a reading instrument that was used to measure the relative humidity and temperature. More information about sensor will be described in chapter 5.2.

Figure 5 Weather box chamber and external wall

1st phase of the test was done by setting normal indoor room condition. The indoor temperature was set to +21 °C and the relative humidity was 45-50%. The test was conducted for 10 days.

For 2nd phase of the test the indoor temperature was set to +21 °C and the relative humidity was set to 85-90%. The idea was to check the effect of maximum relative humidity on the external wall. The maximum relative humidity was generated with the help of humidifier. The test was conducted for 7 days.

The 3rd phase of the test was conducted with the same setting as the 2nd phase but the setting included holes in a wall. The hole was made so that it breaks the vapour barrier so that moisture can pass through the hole from indoor (warm side) to outdoor (cold side). The test was conducted for 7 days. All the three phases can be understood clearly with Figure 4.

3 CLIMATE AND BUILDINGS

“The main factor influencing Finland's climate is the country's geographical position between the 60th and 70th northern parallels in the Eurasian continent's coastal zone, which shows characteristics of both a maritime and a continental climate, depending on the direction of air flow. The mean temperature in Finland is several degrees (as much as 10°C in winter) higher than that of other areas in these latitudes, e.g. Siberia and south Greenland. The temperature is raised by the Baltic Sea, inland waters and, above all, by airflows from the Atlantic, which are warmed by the North Atlantic Drift (itself an extension of the Gulf Stream).” (Finnish Meteorological Institute 2014.)

3.1 Climate in Hämeenlinna

“The climate in Hämeenlinna is cold and temperate. There is significant rainfall throughout the year in Hämeenlinna. Even the driest month still has a lot of rainfall. The Köppen-Geiger climate classification is Dfc. The average annual temperature in Hämeenlinna is 4.0 °C. About 615 mm of precipitation falls annually.

The driest month is February with 30 mm. Most precipitation falls in August, with an average of 79 mm.

The warmest month of the year is July with an average temperature of 16.2 °C. In February, the average temperature is -7.6 °C. It is the lowest average temperature of the whole year.” (climate-data.org 2014)

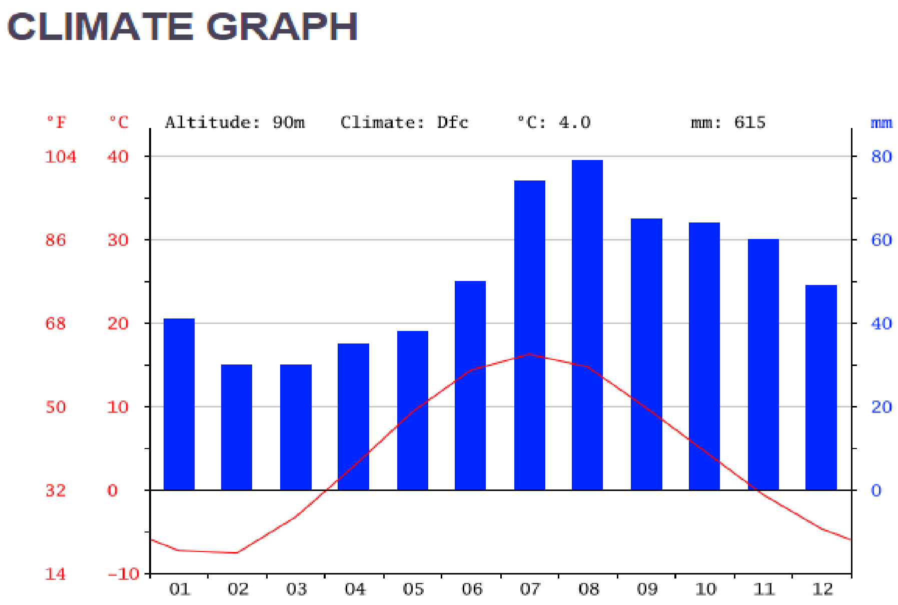


Figure 6 Climate graph of Hämeenlinna, Finland

(Figure and text taken from climate-data.org, Assessed 18.11.2014)

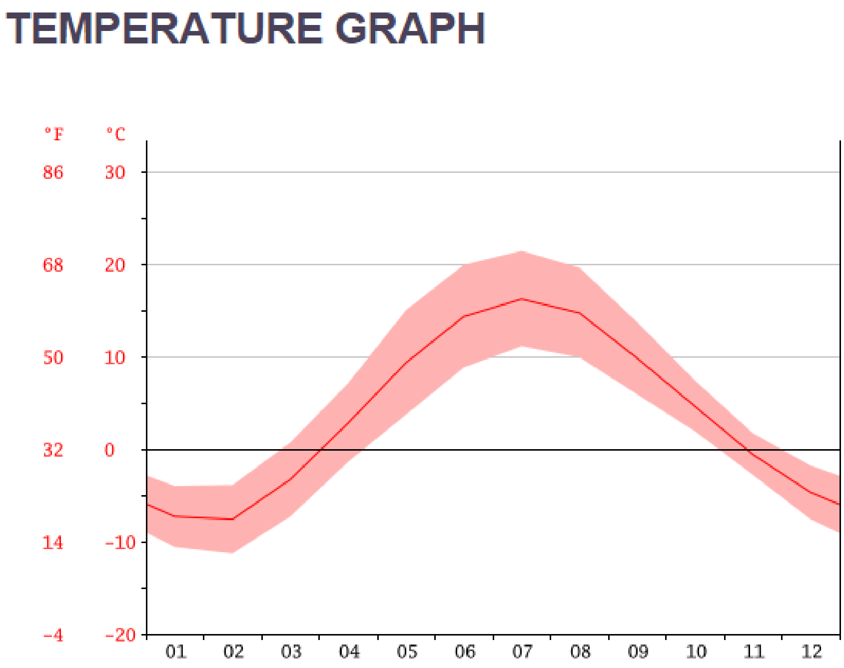


Figure 7 Temperature graph of Hämeenlinna, Finland

(Figure and text taken from climate-data.org, Assessed 18.11.2014)

Figure 6 and figure 7 shows the annual precipitation and temperature of Hämeenlinna. Hämeenlinna has cold humid type of climate. February is a dry month in Finland while August has the higher precipitation of the year.

3.2 Buildings in Finland

"In Europe, Finland is second to Spain in the ratio of blocks of flats to population: some 43 per cent of all residences in Finland are in multi-storey buildings. Of new-build dwellings, some four tenths (12,000–13,000 residences per year) are still built in multi-storey buildings. Concrete has dominated the multi-storey building market for the past 50 years.

Wood-based construction has undergone intense development in Finland since the early 1990s, through close co-operation with other EU countries. Development efforts have focused particularly on building of multi-storey wooden buildings and on enhancing buildings' energy-efficiency." (Karjalainen 2014, 2.)

Residential buildings in Finland are usually timber framed buildings although concrete buildings are dominantly constructed. Since Finland is rich in forest resources, timber is very easily available building material. However, prefabricated concrete buildings and steel structural buildings are equally constructed for both residential and commercial purpose. The buildings are well insulated and equipped with heating systems. The room air temperatures are typically adjusted between 20 °C and 24 °C in the winter period. Heating systems are well set to keep the room air temperature over 20 °C even on the coldest winter days.

The relative humidity inside the residential buildings can range from 21% to 65% (Kalamees, Kurnitski & Vinha 2004, 1).

4 BUILDING PHYSICS MECHANISM OF WALLS

The perfect wall is designed in order to protect the building from exterior environment. A wall is an environmental separator which acts as a barrier between the interior and exterior environment of a building. The wall prevents rain water, wind, heat, moisture and other harmful substance to enter the building. Heat flows from warm side to cold side. In case of Finland weather, the temperature difference between indoor and outdoor environment is large. Moisture travels with air currents. The air flowing through the walls contains moisture in it. Warm air carries more moisture than cool air. When air and moisture moves from warm side to cold side of the wall, moisture condenses onto the cold sheathing or cool drywall. This can degrade the R-value of insulation and can promote mould growth in wall components. Air has a maximum storage capacity for water vapour which depends on temperature. Warm air can carry more moisture than that of cold air. The moisture flow is normally inside out from buildings in Finland (Lstiburek 2008).

4.1 Thermal transmittance (U-value)

"Thermal transmittance U indicates in steady state conditions the density of heat flow which permeates a building component when the temperature difference between the air spaces on both sides of the building component is one unit of temperature. The unit is W/(m2 K)." (C3 NATIONAL BUILDING CODE OF FINLAND 2002.)

C3 National Building Code of Finland gives the requirement of thermal insulation and required thermal transmittance of the structural components.

4.2 Thermal resistance (R-value)

"Thermal resistance of a material layer of a uniform thickness or a layered structure in the thermal steady-state indicates the temperature difference between the isothermal surfaces on both sides of the structure divided by the heat flow density through the material layer." The unit of thermal resistance is (m2 · K)/W. (C4 NATIONAL BUILDING CODE OF FINLAND 2002.)

C4 National Building Code of Finland provides the guidelines to acquire required thermal transmittance of the structural components.

4.3 Factors effecting the thermal transmittance (U-value) of the wall

The thermal transmittance depends on the wall components that are used in the wall design. Thermal insulation is one of the most important components of wall because it has the highest thermal resistance (R-value) in the wall. When the material has higher R-value, it means that the material has greater capacity to resist heat to pass through it. Apart from wall components, the temperature differences, moisture and construction faults can also affect the wall performances (Doran & Carr 2008).

The U-value of a wall can be influenced by followings factors:

- Thickness of the insulation.
- Thermal conductivity of the insulation.
- Loosely packed or presence of any gaps or voids during insulation installation and presence of inhomogeneous section.
- Holes in vapour barrier.
- The accuracy of the estimation of the amount of insulation material needed.
- Bigger drill holes in the wall can let moisture pass through the hole.

4.4 Study of wall components

While designing a wall, there are four important segments of the wall that needs to be well studied. Each wall layers has its own contribution. The four principal layers are;

- a rain control layer
- an air control layer
- a vapor control layer
- a thermal control layer

A rain control layer helps to stop rain water leakages into wall. Water leakage into the structures is harmful. Normally water tends to enter the wall from joints between different structure components. Water can also enter wall structure through connections, construction faults. If the insulation material is foam plastic or if the insulation material is such that can absorb very moisture, water leakages in wall components are very risky. The moisture inside the wall can condensate and eventually rot the insulation and timber frames. Excessive moisture levels may also cause mould to develop in the wall. This can be a risk considering the indoor air quality for the occupants (Häkkinen 2012).

An air control layer helps to create a continuous air barrier between the conditioned living space and the outdoors. Air carries moisture with it and moisture can be bad for structure. Wall construction must be air tight to avoid air to pass through the walls. If air gets into the wall structure it can reach the cold side of the wall because of which moisture can drop its water inside the wall.

Vapour control layer prevents moisture to enter the building from the exterior or interior. Vapour barrier is an impermeable layer of the wall that helps to prevent moisture to enter the wall. Vapour barrier helps to dry the wall components to the exterior or interior part of the wall or both if the assembly gets wet. Vapour barrier is a very essential part of the wall, especially in case of Finland because there is a very high chance for moisture condensation in the wall.

Thermal layer helps to increase the climate efficiency of the space by making it easier to heat and cool the room. Normally in case of Finland, thermal layer is used to prevent the loss of heat and maintaining the probable thermal transmittance of the wall. Depending on the type of wall insulation used, the product may also help to soundproof the space and minimize the amount of noise that enters or escapes from the room.

4.5 Importance of thermal insulation

Thermal insulation can help in improving indoor comfort and also helps in energy savings. Thermal insulation helps to reduce heat flow from warm side to cold side spaces by forming a thermal blanket around a building. Due to good thermal resistance less heating is needed in the winter and less cooling is needed in the summer. The more heat flow resistance insulation provides, the lower the heating and cooling costs are of a building.

“Using low energy design principles, especially good thermal insulation avoiding cold bridges, will result in constant temperature without cold surfaces internally in the rooms. This enhances the comfort level due to the lack of significant air movement. Good thermal insulation will result in reduced temperature differences and fluctuations throughout the year which will make a home drier and more comfortable to live in at a lower average temperature.” (European Manufacturers of Expanded Polystyrene (EUMEPS) 2010.)

C3 NATIONAL BUILDING CODE OF FINLAND contains the necessary regulation concerned with thermal insulation in Finnish buildings. Whereas, C4 NATIONAL BUILDING CODE OF FINLAND contains instructions and guidelines for calculating thermal transmittance (U) for building components and structures. Both codes were used in analysing and designing the projects walls.

3.2 Reference values for building envelope components heat transfer coefficients and window area in a building

3.2.1
When a heated, especially warm or cooled cold space abuts the outside air, an unheated space or the ground, the following values for the thermal transfer coefficients U for the building components are to be used when calculating the building's heat loss comparative value in accordance with part D3 of the National Building Code of Finland:

wall	0.17 W/m²K
log wall (log structure thickness at least 180 mm)	0.40 W/m²K
roof and base floor abutting outside air	0.09 W/m²K
base floor abutting crawl space (total area of ventilation openings a maximum of 8 % of the base floor area)	0.17 W/m²K
building component against the ground	0.16 W/m²K
window, skylight, door	1.0 W/m²K

Figure 8 Requirements for thermal transmittance of building components (C3 NATIONAL BUILDING CODE OF FINLAND)

(Figure and text taken from C3 National Building Code of Finland)

Figure 8 shows the required thermal transmittance (U-value) that the wall must possess. The calculated U-value of timber framed wall is 0,167 W/m2.K. For the U-value calculation of timber framed wall, C3 NATIONAL BUILDING CODE OF FINLAND and C4 NATIONAL BUILDING CODE OF FINLAND were followed. For light weight steel framed wall, the calculated U-value is 0,267 W/m2.K. For the calculation of steel framed wall, Therm 7.2 (Therm finite element simulator) was used. Some results can be seen in figure 7 and figure 9.

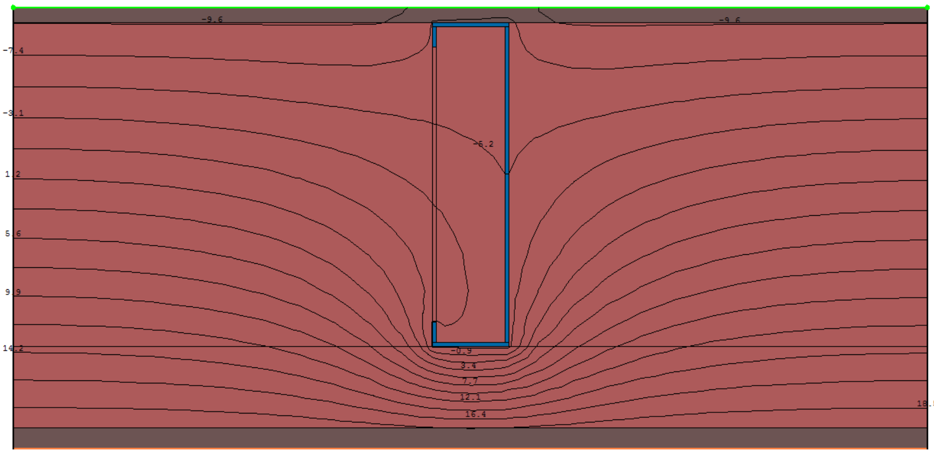


Figure 9 Lightweight steel framed wall Isotherm diagram from Therm 7.2

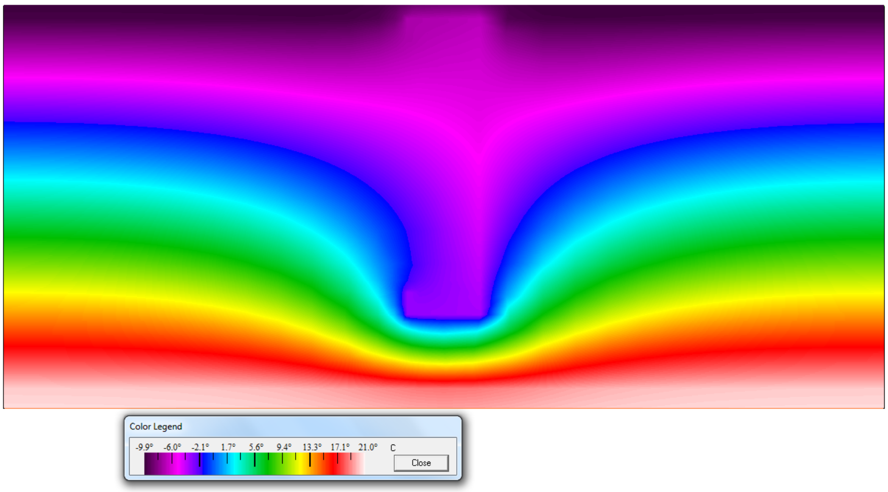


Figure 10 Lightweight steel framed wall Thermo result diagram from Therm 7.2

All the detailed calculation and results are attached in the appendix

"THERM is a state-of-the-art, Microsoft Windows™-based computer program developed at Lawrence Berkeley National Laboratory (LBNL) for use by building component manufacturers, engineers, educators, students, architects, and others interested in heat transfer. Using THERM, you can model two-dimensional heat-transfer effects in building components such as windows, walls, foundations, roofs, and doors; appliances; and other products where thermal bridges are of concern. THERM's heat-transfer analysis allows you to evaluate a product's energy efficiency and local temperature patterns, which may relate directly to problems with condensation, moisture damage, and structural integrity." (Therm 7,2.)

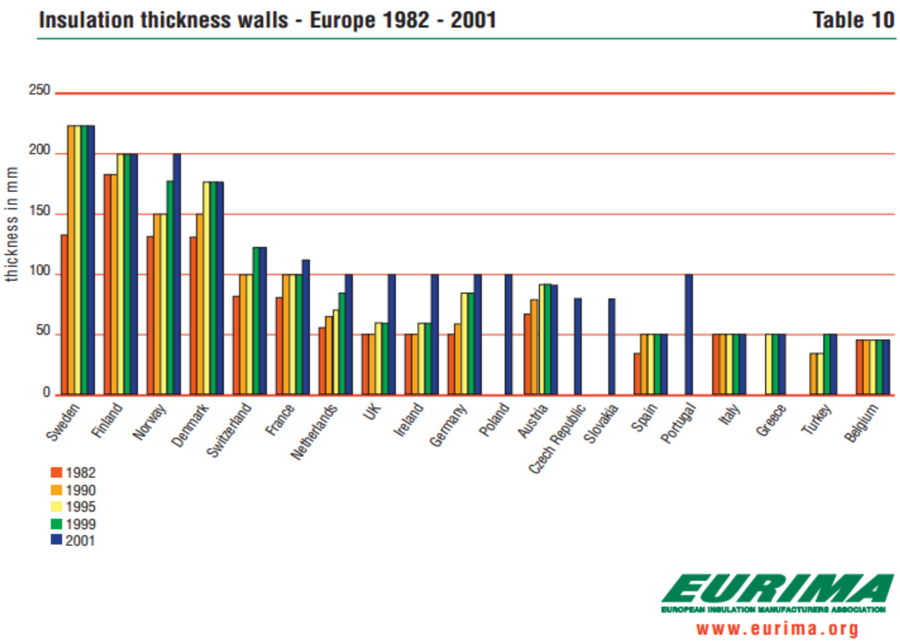


Figure 11 Wall insulation thickness history

(Figure 11 taken from EURIMA brochure)

"For the past 20 years, EURIMA has studied the development of thermal insulation standards in new dwellings in Europe. Traditionally, these studies have focused upon the thickness (mm) of mineral wool insulation prescribed and applied in new construction. An updating survey completed in 2001, showed continued progress in insulation standards in several countries, particularly in central Europe. Unsurprisingly perhaps, in view of their climatic conditions, the Scandinavian countries – headed by Sweden – retain their position at the top of the list, showing how far the rest of Europe needs to go. The south continues to lag behind, despite European regulations demanding improved standards in order to meet Kyoto targets."

Figure 12 Placement of insulation and vapour barrier layers

Thickness of insulation generally affects the wall thickness. The heat loss decreases while the insulation thickness increases. The cost of fuel decreases since the heat losses decrease. On the other hand increasing the insulation thickness also increases the cost of insulation. This means that the need of optimization of wall material, especially insulation material can be economical and effective (Comaklı & Yuksel 2002).

4.6 Placement of vapour barrier

The main aim of a vapour barrier is to oppose the migration of water vapour from warm side to cold side of the wall. The purpose of the vapour barrier is to prevent moisture from entering the wall from the interior or external faces of the wall. In case of Finnish weather, the flow of moisture is often from inside out of the building.

Just in case moisture gets inside the wall, it cannot escape from the wall. It is almost impossible for the moisture to escape from the wall. The moisture tends to flow from the warm side to cold side of the wall. Once the moisture reaches the cold side, it can condensate and freeze in the cold layers.

The vapour barrier must always be installed on the warm side of the wall. The vapour barrier is placed in the interior side of the house. It can also be sandwiched between two layers of insulation, but only if the cold side insulating layer is at least two thirds thicker than the warm. If the vapour barrier is placed in the cold side of the wall, there are always chances of occurring condensation (Forest, T. W.).

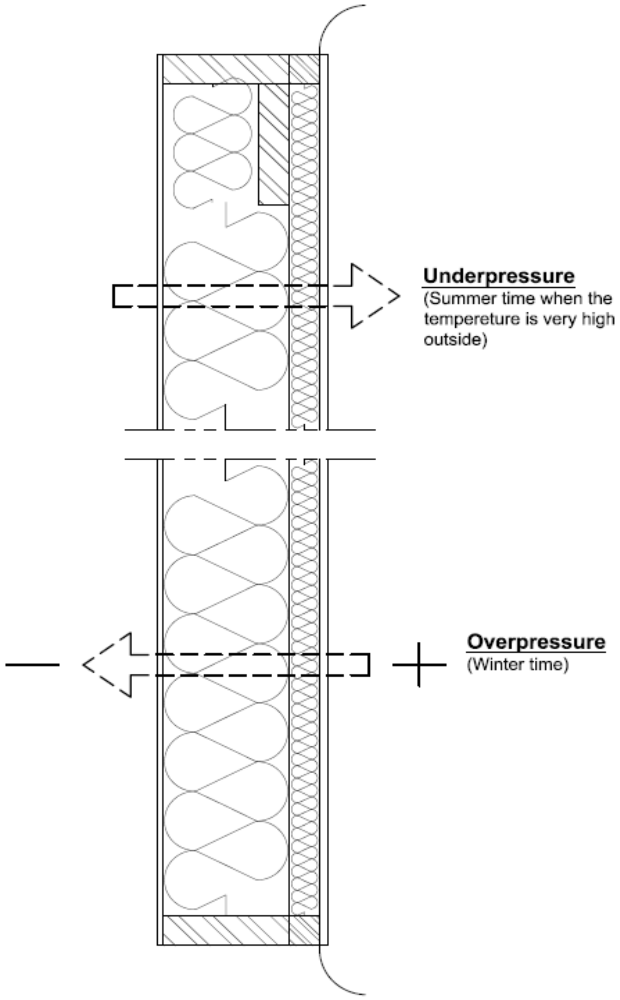


Figure 13 Moisture movement in Summer and Winter

Heat flows from warm side to cold side. In case of Finland weather, the temperature difference between indoor and outdoor environment is large. Moisture travels with air currents. Warm air carries more moisture than cool air. If warm and humid air touches a cold surface, the water will condense out. Condensation degrades the wall performance. If the presence of water continues over a long period of time, this will cause mold to grow within the wall. The presence of moisture reduces the effectiveness of the insulation. It can also cause other problems like attracting bugs who like moist places. The general idea of moisture flow can be seen in figure 13.

The normal practice in Finland is to keep the vapour barrier sandwiched between insulation where the surface temperature is warm. This helps in avoiding condensation problems within the wall. This also provides comfortable space for electrical installation without any danger to vapour barrier. This practice also makes ease in construction phase. For the research there were two possible placement of vapour barrier.

The vapour barrier is sandwiched between the insulation in one wall section and vapour barrier placed next to the internal gypsum board in the other wall section.

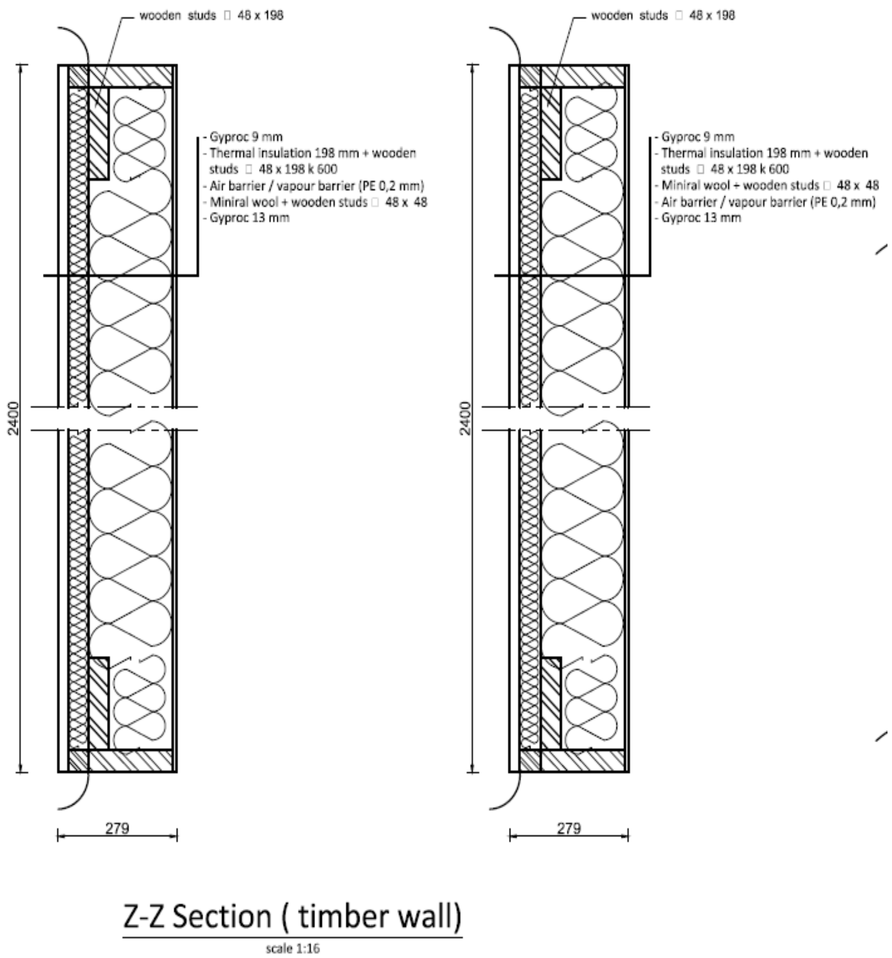


Figure 14 Timber framed wall z-z section

The two different position of vapour barrier can be seen in Figure 14. For the test Polyethylene (PE 0,2mm) was used.

5 WALL CONSTRUCTION AND TEST ARRANGEMENT

After all the research and design work, the light weight steel framed wall was constructed in Sheet Metal Centre. The wall was constructed using the Rukki Termo Purlins as the studs and timber was used as outer frames. All the necessary wall components were estimated initially. This helped in buying the right amount of materials for the wall construction. The weight of the designed wall was also calculated to know if the need of mechanical crane was necessary. Since the weight of the walls were high it was difficult to load the walls in the weather chamber box manually. For loading and unloading, the use of mechanical crane was helpful.

Figure 15 TERMO RANKA PURLINS and timber frame

Figure 15 shows the initial phase of the construction process. The lightweight steel purlins and timber frame can be seen in figure 15. The construction process took about a week to complete. Two walls were constructed for the test. The constructed wall had same wall components except the position of the vapour barrier. The designed walls were then loaded to the weather chamber for the tests. The section of the constructed walls can be seen in Figure 16 and Figure 17.

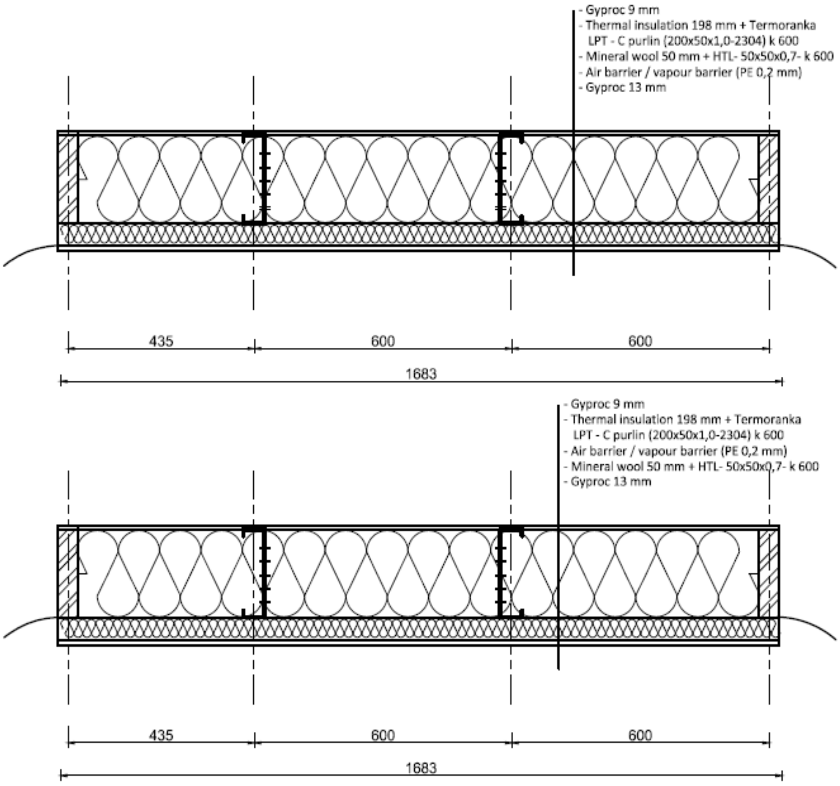


Figure 16 Horizontal section of the lightweight steel framed wall

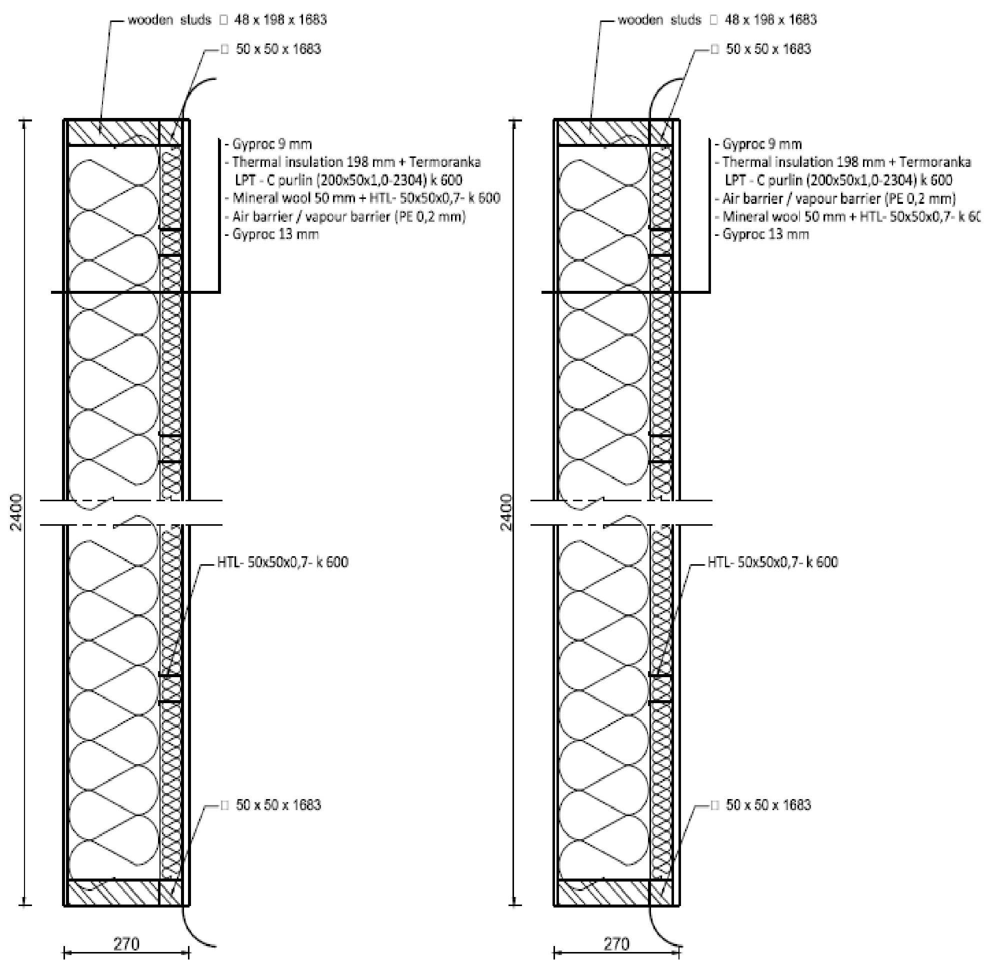


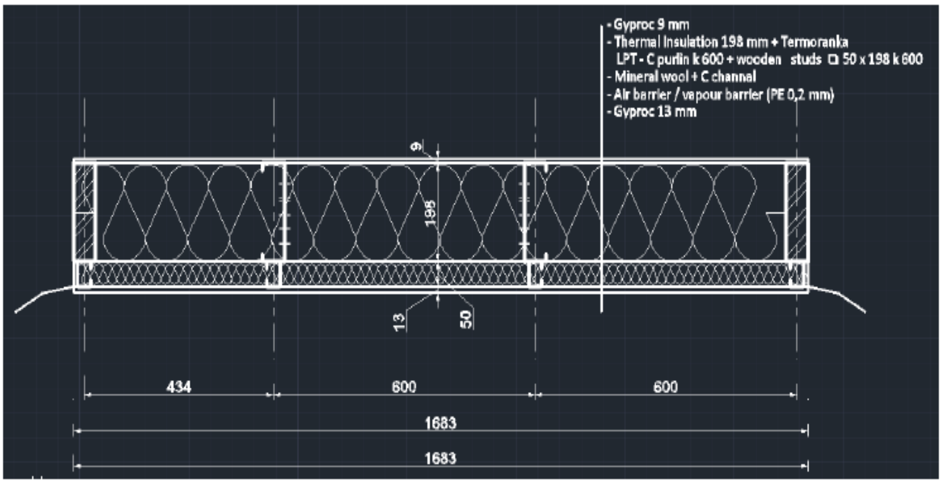
Figure 17 Vertical section of the lightweight steel framed wall

In figure 16 and 17, the vapour barrier can be seen sandwiched between the insulation in one wall section and vapour barrier placed next to the internal gypsum board in the other wall section.

5.1 Wall components material list

For the construction of the designed wall, material list was prepared to estimate the required quantity of materials needed. This helped in saving time for buying the wall materials and also to reduce the material waste. While preparing material list, all the available material sources were searched. The preparation of the list helped in finding the better materials with better properties. This also helped in analysing the materials used commonly in Finnish building's wall construction.

The material list preparation also helped in estimating the approx cost of the wall materials. The material list of the designed walls is as follows;



S/N	Particulars	Qty	Volume/specification	Product description
1	Timber studs	4	50x198x2400	
2	Gyproc 9mm	4	1200x9.5x2700	This comes in a bundle of 40 pcs which might be problematic when our need of gypsum board is low. http://www.gyproc.fi/tuotteet/43/levyt/3176/gyproc-gts-9-tuulensuojalevy
3	Gyproc 13mm	4	1200x12.5x2400	The problem here is same as above. It comes in huge bundle. http://www.gyproc.fi/tuotteet/43/levyt/3141/gyproc-gn-13-normaali
4	Thermal Insulation Isover KL-33 (198mm)	12	610x200x1170	This isover insulation can be found in single pack (4pcs) and multi pack (16pcs) http://www.isover.fi/tuotteet/rakennuseristeet/kevyet-rakennuseristeet/2558/isover-kl-33
5	Thermal Insulation Isover KL-33 (50mm)	12	610x50x1170	We can go for single pack which consists of 16pcs of this product.
6	Termoranka LPT-C purlin	4	15/50/200/50/15 2400 mm long	http://www.ruukki.com/Products-and-solutions/Building-solutions/Lightweight-purlins/Termo-purlin
7	C channal	8	14/30/50/30/14 2400 mm long	http://www.ruukki.com/Products-and-solutions/Steel-products/Cold-formed-steel-sections/C-sections
8	U section	1	70/200/70 1683 mm long	U 70/200/70x6x6000 http://www.ruukki.com/Products-and-solutions/Steel-products/Cold-formed-steel-sections/U-sections

* Ruukki products (Termoranka LPT-C purlins and C channal) are (Minimum length 1600 mm,Maximum length 15000 mm), 2 mm thickness
* Ruukki products , U Section is 6000 mm Long, 6mm thickness

Figure 18 Material list of the designed walls

The material list was prepared to estimate one wall construction. Since the two designed walls were identical, the same list was used for the second wall construction.

5.2 Placement of Sensors

The sensors were installed in different wall depths. The installed sensors helped to record the surface temperature and relative humidity that were needed. The sensors were connected to a reading device that helped in recording the relative humidity and temperature of the certain cross section of the wall. The sensors were installed taking in consideration the thermal bridges and the normal wall cross sections. The cross section areas near the steel studs (non-homogeneous layer) possess some thermal bridge where as the cross section area away from the steel studs (homogeneous layer) has no thermal bridges. The sensors were installed very close to the steel stud to record the temperature and relative humidity of the non-homogenous layer. Figure 19 shows the homogeneous and non-homogeneous layer of the wall.

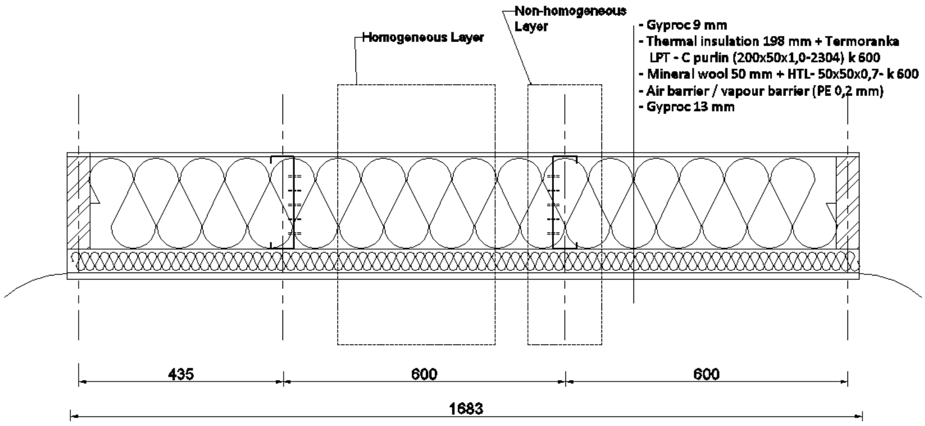


Figure 19 Homogeneous and Non-Homogeneous Layer of the designed wall

For the test, two kinds of sensors were used. The sensors used were Envic THS22 and Almemo FH A646-R. Total 12 sensors were used for the test.

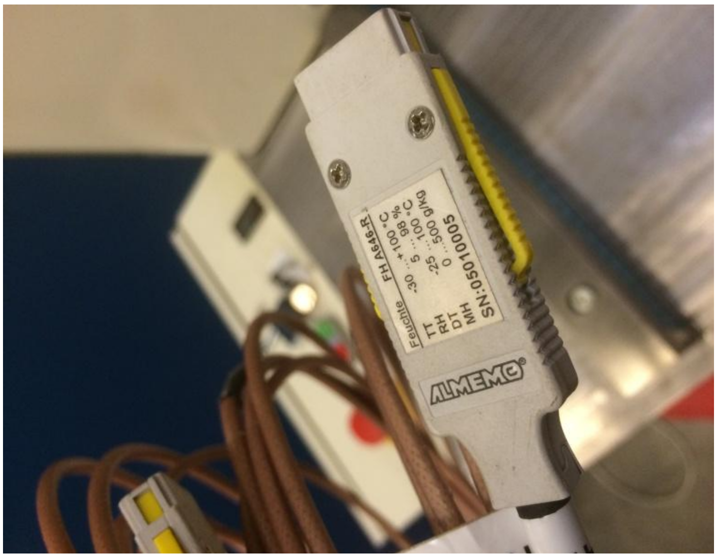


Figure 20 Almemo FH A646-R Sensor

Figure 21   ENVIC THS22 Sensor

The arrangement of the sensors can be seen in the following figure.

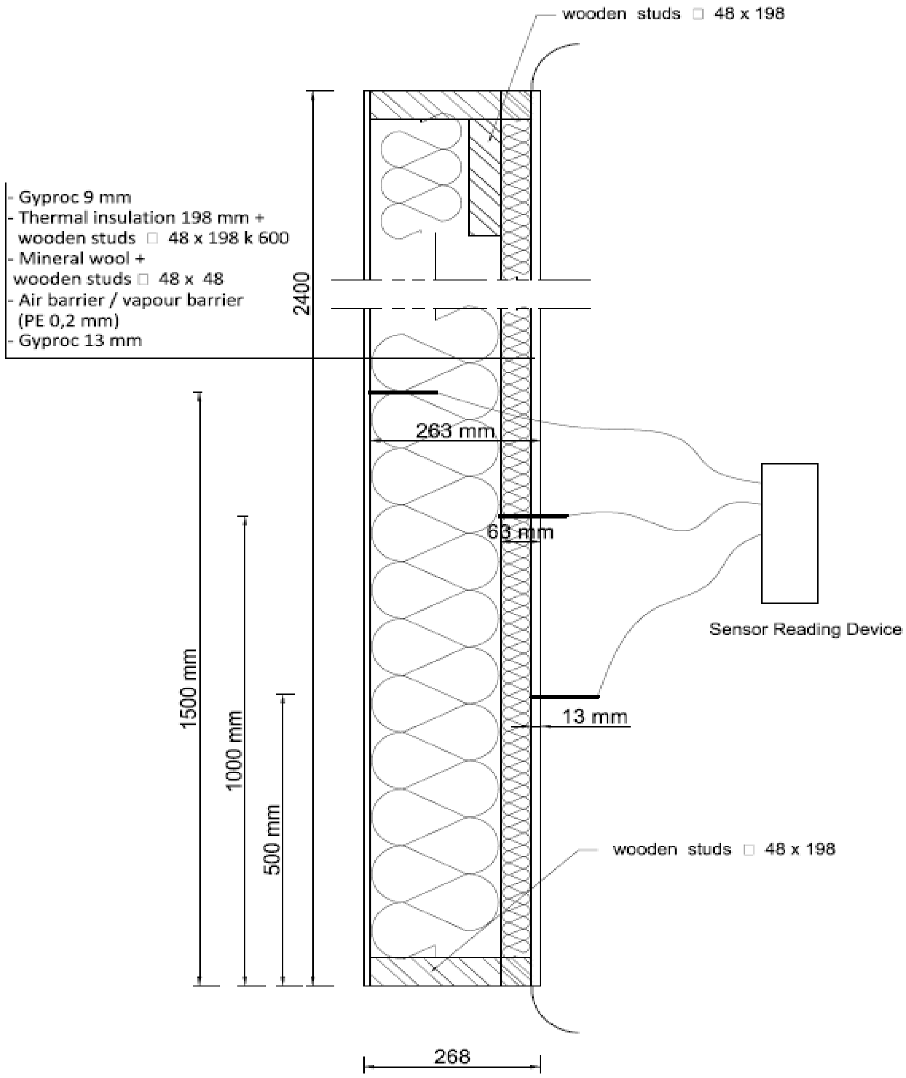


Figure 22   Depth of installed sensors

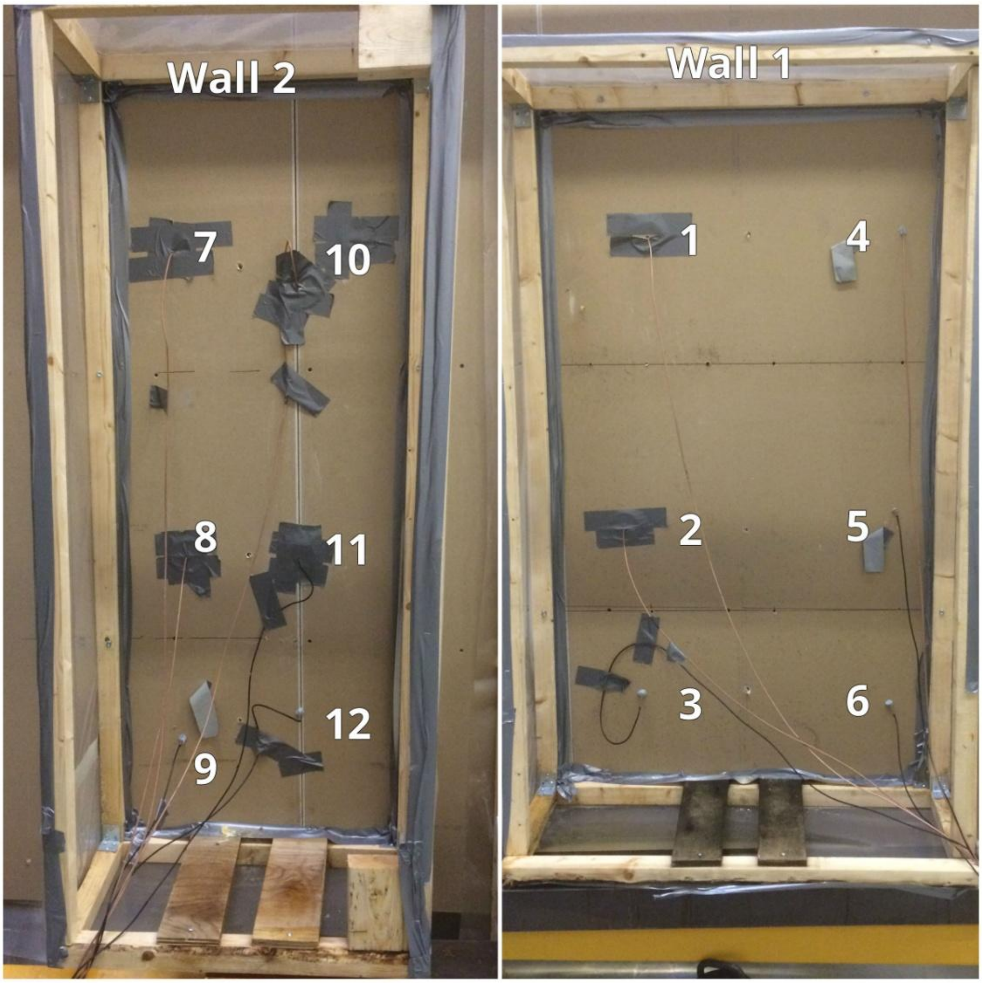


Figure 23 Sensors arrangement and numbering

The installing of sensors was carefully done to get the required depth and position. The sensors were made sure to be kept perpendicular to the gypsum board. When the sensors are installed inclined then the result might not be accurate. It was important to keep the sensors perpendicular with the gypsum board and to the accurate depth to get accurate readings. The required depth for the test can be seen in figure 22.

Figure 23 shows the numbering of sensors. The numbering was important to keep the records for temperature and relative humidity in different wall layers. Wall 1 and wall 2 are identical lightweight steel framed walls. The only difference between the two was the position of the vapour barrier. The vapour barrier in wall 1 is kept just after the interior gypsum board whereas the vapour barrier is sandwiched between the insulation in wall 2. The details about sensors depth and position can be seen in table 1.

Sensor no	Depth	Placement
1,4,7,10	263 mm from interior face	Close to external gypsum board
2,5,8,11	63 mm from interior face	Sandwich point of insulation layer
3,6,9,12	13 mm from interior face	After interior gypsum board

Table 1 Sensor placement and depth

6 TEST RESULTS AND COMPARISONS

After the wall was loaded in the weather box chamber, the weather box chamber temperature was set to -10 °C and relative humidity was set to 72-75%. The required temperature and relative humidity was constantly maintained with the help of weather box chamber. The temperature and relative humidity of the wall components (wall layers) were recorded every day by using sensors installed in the wall. The indoor layer temperature of the wall was recorded with the help of a thermal imaging camera.

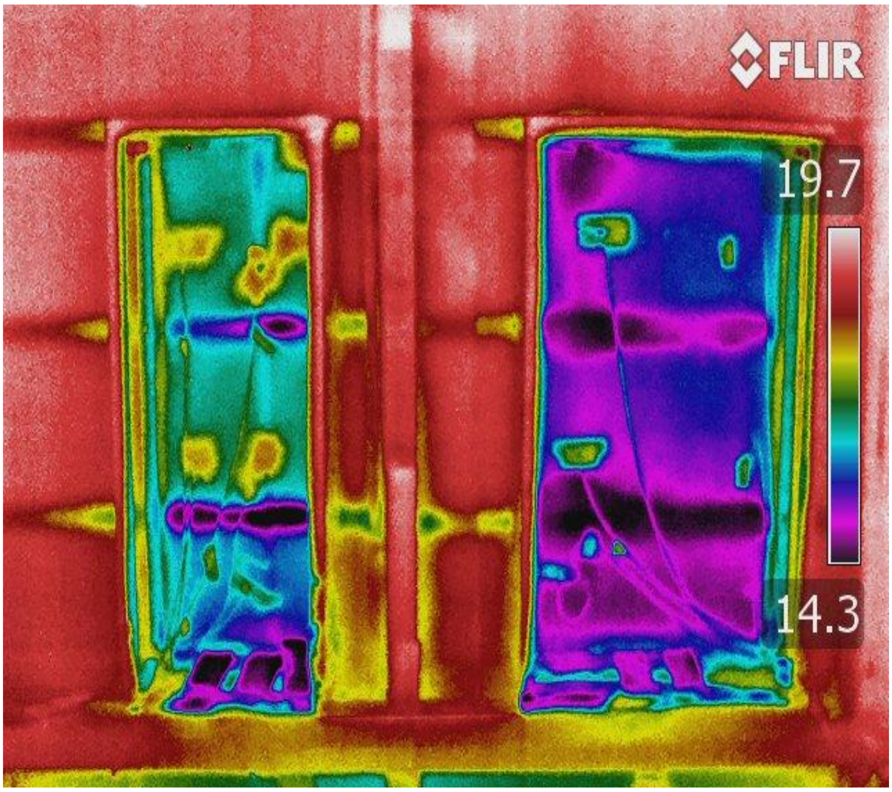


Figure 24 Thermal image of interior layer of tested wall

The thermal imaging camera shows the difference in temperature. This helps in identifying the thermal bridge and heat losses from the wall. Figure 24 shows the image taken from the thermal imaging camera. The low temperature can be seen in the horizontal C channel area. The diversity of temperature can be seen and the faults can be located with the help of thermal imaging camera.

The relative humidity and temperature were recorded everyday with the help of a sensor installed in the wall. The test was conducted in three phases. The test results of the three phases are illustrated below.

6.1 Phase 1, Normal Test

First phase of the test was done by setting normal indoor room condition. The indoor temperature was set to +21 °C and the relative humidity was

45-50%. The test was conducted for 10 days. The mean was taken from all the recorded readings.

Sensor no	Temperature (˚C)	Relative Humidity (RH %)
1	-10	48,46
2	17,4	18,18
3	19,1	41,66
4	-10	47,472
5	18,5	19,84
6	19,3	38,78
7	-5,8	44,664
8	14,3	17,22
9	17,1	38,68
10	-11	28,6
11	16,4	12,78
12	17,4	37,68

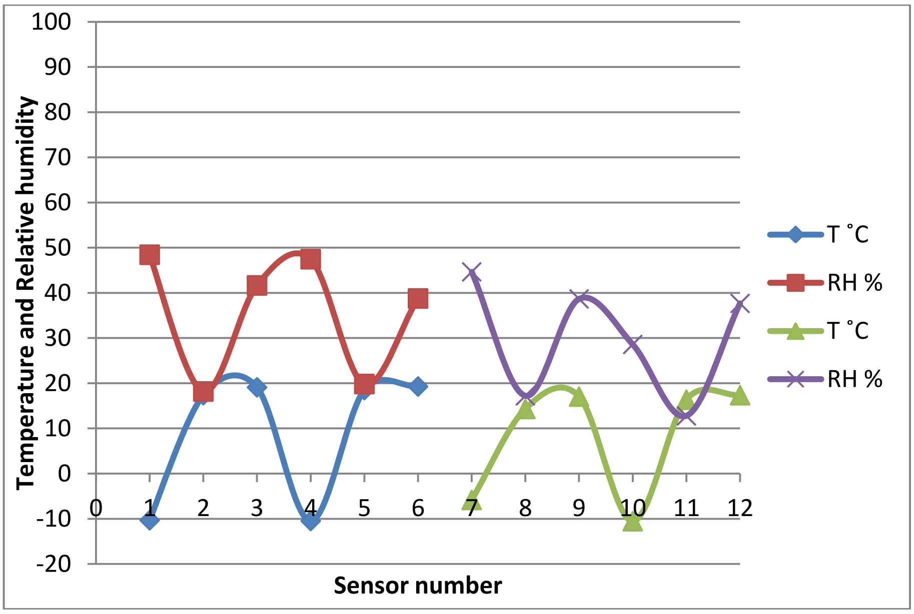


Table 2 Mean temperature and relative humidity of phase 1

Table 2 shows the mean temperature and relative humidity of phase 1. The detailed recording of temperature and relative humidity can be found in the appendix.

6.2 Phase 2, Warmside humidity 85%-90% test

For second phase of the test the indoor temperature was set to +21 °C and the relative humidity was set to 85-90%. The idea was to check the effect of maximum relative humidity on the external wall. The maximum relative humidity was generated with the help of humidifier. The test was conducted for 7 days.

Figure 25 Wall installed with humidifier

The frame was constructed which acted as a base for humidifier. The function of the humidifier was to increase the humidity of the indoor environment (warm side). The frame was wrapped with plastic film. The relative humidity was set to 90%. The humidifier produced the moisture and the plastic film helped to block the moisture to let it out. Figure 25 shows the installed frame and humidifier.

Sensor no	Temperature (˚C)	Relative Humidity (RH %)
1	-10,45	48,275
2	17,225	25,15
3	18,7	94,3
4	-10,2725	48,5675
5	18,375	20,975
6	18,925	82,5
7	-9,35	45,505
8	14,525	19,625
9	17,275	55,55
10	-9,445	29,95
11	16,6825	12,9
12	17,625	54,05

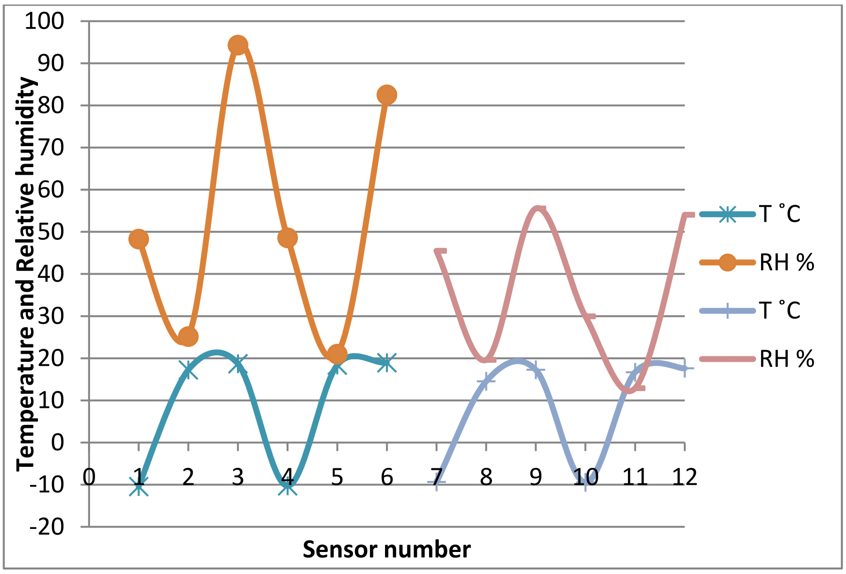


Table 3 Mean temperature and relative humidity of phase 2

Table 3 shows the mean temperature and relative humidity of phase 2.

6.3 Phase 3, Warmside humidity 85%-90%, (with 8mm diameter hole) test

The third phase of the test was conducted with the same setting as the second phase test but the setting included holes in a wall. The hole was made so that it breaks the vapour barrier so that moisture can pass through the hole from indoor (warm side) to outdoor (cold side). The test was conducted for 7 days.

Sensor no	Temperature (˚C)	Relative Humidity (RH %)
1	-11,1	48,575
2	17,29	25,275
3	18,775	95,2
4	-10,2725	48,5675
5	18,08	24,025
6	18,275	82,875
7	-9,65	44,48
8	14,125	18,375
9	16,69	89,6675
10	-9,92	44,375
11	16,0475	17,8
12	17,4125	93,15

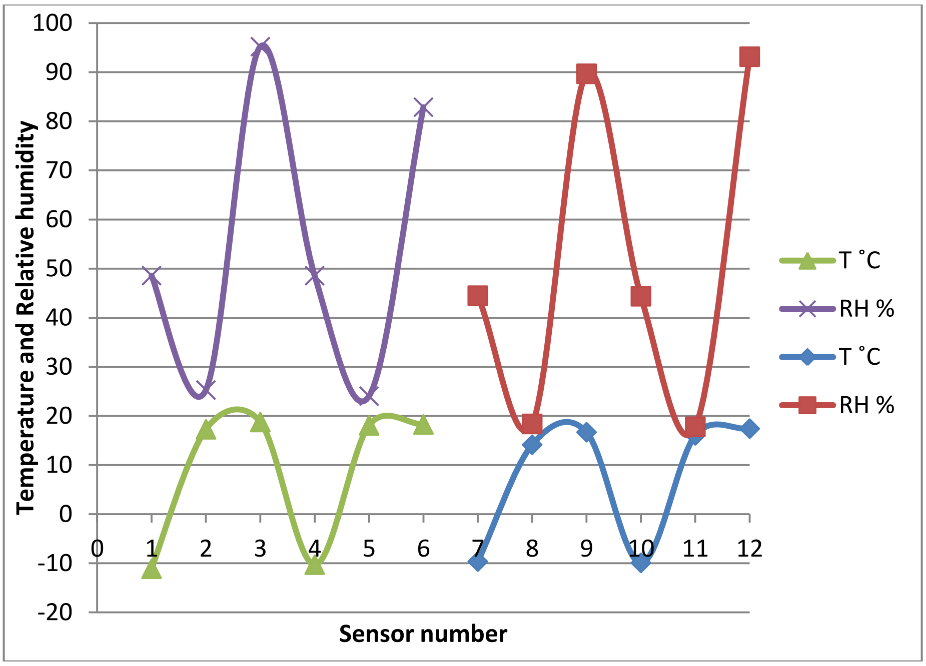


Table 4 Mean temperature and relative humidity of phase 3

Table 4 shows the mean temperature and relative humidity of phase 3.

6.4 Result comparison

The temperature recorded can be seen constant throughout the test. The relative humidity fluctuates and differences can be seen in the three test. Due to the increase in relative humidity in the warm side by humidifier, the relative humidity in wall layers increases too. The humidity level rises more in phase three when the hole was made on the wall.

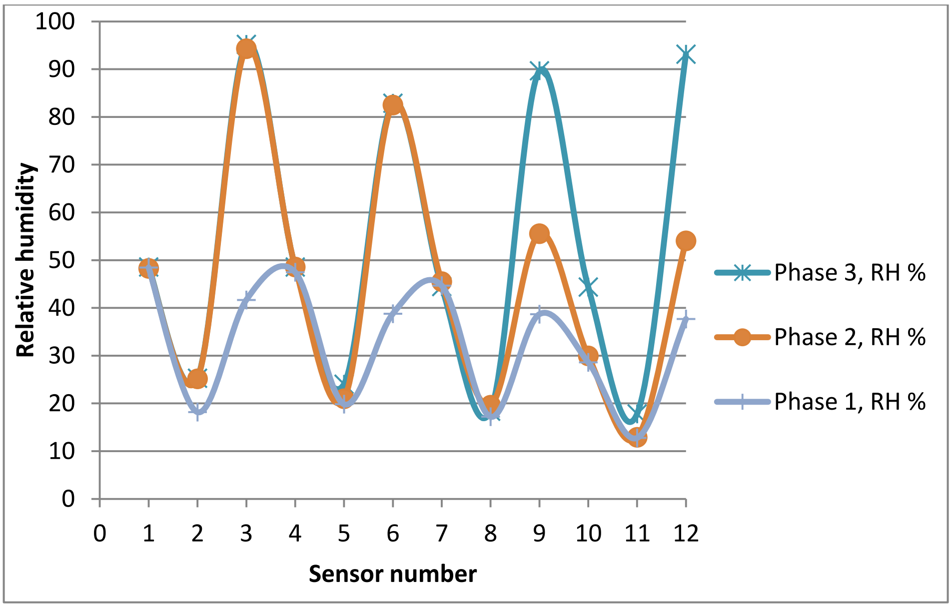


Table 5 Relative humidity of all three phases

The difference in relative humidity in the three phases can be seen in Table 5. The relative humidity is high in phase 3. The moisture produced by humidifier passed through the 8mm hole which increased the moisture content in wall. The position of the vapour barrier also affected the relative humidity in wall layers. In phase one and phase two, the recorded humidity is less in wall 2 than in wall 1. In wall 2 the vapour barrier is sandwiched between the insulation.

The temperatures recorded were constant in all three phases. The results simulated from Therm 7.2 and the test results are approximately same.

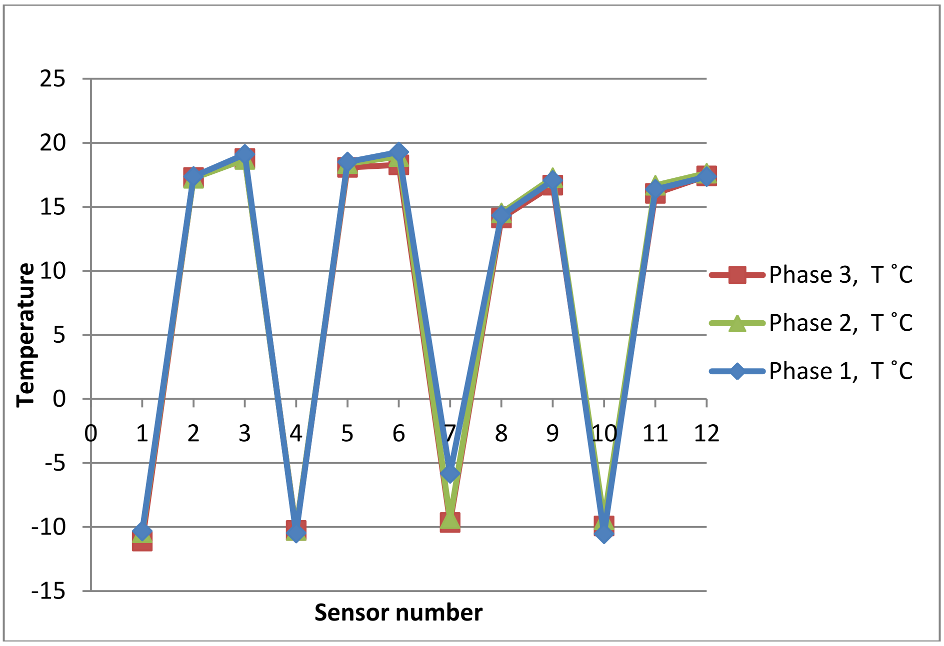


Table 6 Temperature in all three phases

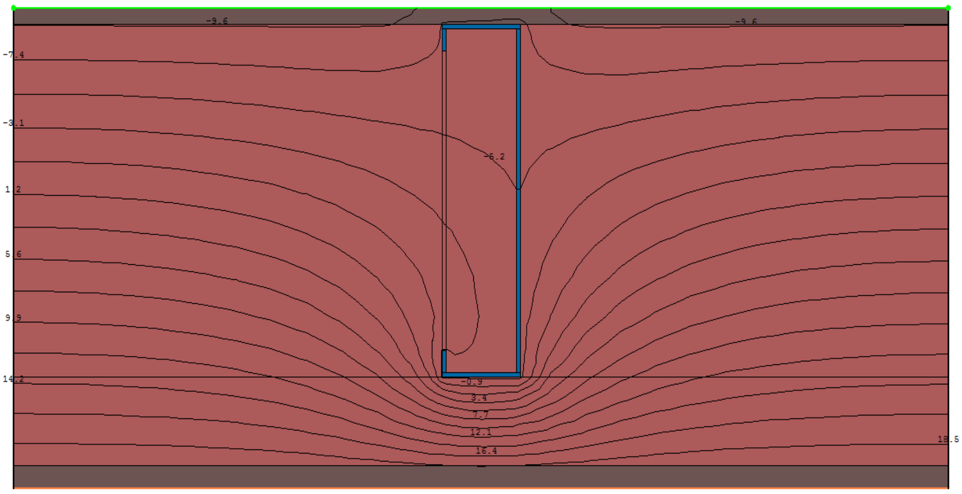


Figure 26 Isotherms result from Therm 7.2

The temperatures recorded in test and Therm 7.2 gave approximately same results. Table 6 shows the mean temperature recorded in all three phases and figure 23 shows the isotherm diagram received from Therm 7.2 thermal simulator.

After the entire test was conducted the check for frost in the wall was done. When moisture flows from the hole and hits the cold surface inside the wall, moisture condenses within the wall. The exterior layer of the wall is always below freezing point in winter, this can cause the condensed water to freeze and change into frost within the walls.

“Especially in Nordic countries, a phenomenon is mentioned that may lead to moisture accumulation in the outer layers of the wall structure. Due to outside weather conditions or diffusion from the inside, the relative humidity in the outside layers of the insulation can rise close to 100%. If then the temperature drops below zero in this area, white frost as commonly observed on foggy winter mornings may form on the inside surface of the outer wall cladding panel. As no sunrays can temporarily melt this frost during the day, the ice layer may build up over time furthermore blocking diffusion to the outside. Eventually this frozen layer will melt down in spring, hence causing significant amounts of moisture accumulation in the insulation layer long enough to enhance mould growth.” (Winter, S. Wrede, M. S. Jebens, K. 2012)

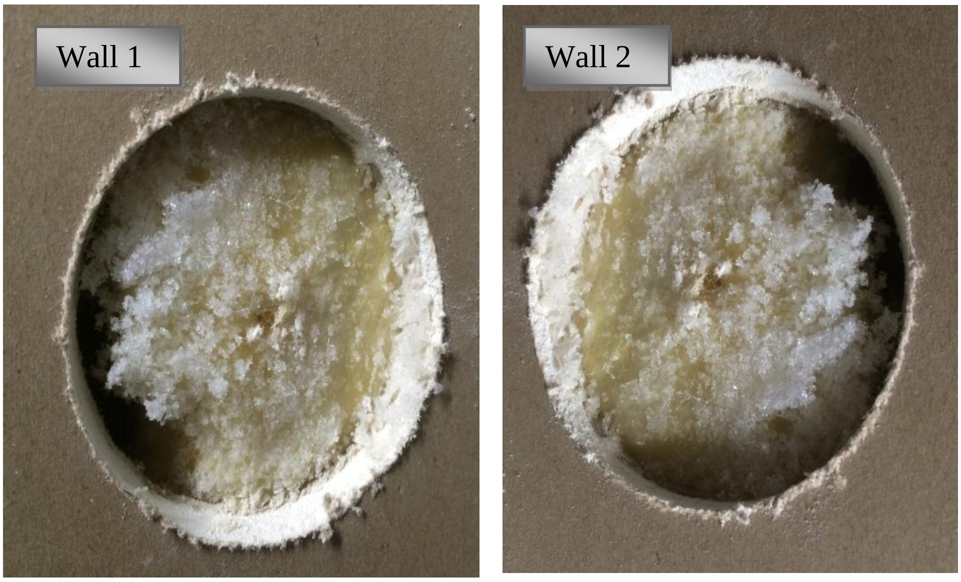


Figure 27 Frost accumulated in between insulation and exterior gypsum board

Figure 27 shows the accumulation of frost in the outer layer of wall. The moisture produced by humidifier passes through the hole which condenses in the cold layers of the wall and changes into frost. The accumulated frost can melt in warm weather and wet the insulation layer. This can rot the insulation and degrade the wall thermal transmittance.

7 CONCLUSION

Moisture damage in a structure is an important subject to be analyzed during structure design and construction phase. Even in the structure servicing phase, precaution is needed to keep structure safe from moisture damages. Moisture damages can get worse in a long run. It is something different than load bearing problems. Load bearing problems can be seen right in the construction phase. It can be seen with human eyes and can be solved in the initial point. But, moisture in the other hand can be unseen for long time. It can only be noticed when the damages has reached the worst point. The test results can clearly show how dangerous can the small hole be to damage the wall structure. Even the 8mm hole can cause frost to accumulate in the exterior gypsum board. The accumulated frost can melt in warmer days and it can rot the insulation and facilitates moulds to grow that can be harmful to human health. Moisture can also damage the wall structure degrading the wall thermal transmittance and the inner and outer wall appearance. It can also increase the heating cost. Thus, special precaution is needed while installing the vapour barrier. Vapour barrier should always be placed in the warm side of the wall. The temperature difference between indoor and outdoor can cause moisture flow. It is a wise decision to place the vapour barrier where the moisture cannot condense. The movement of moisture is inside out during winter and just the opposite during summer time. In summer times, the outdoor temperature rises higher than the room temperature, the moisture flow is from outside to inside. During summer time, due to use of air conditioning the air inside the building can be humidified. When the outdoor temperature is above +32˚C with about 65% of relative humidity and the room temperature is set below +22˚C, moisture may condensate on the exterior side of the vapour barrier, because the wall temperature can be below the ambient dew point (Korkeamäki, T. Thesis meeting 23.12.2014).

While constructing walls, special attention should be made to reduce the construction faults. Even the small hole in vapour barrier can be dangerous for wall. Use of humidifier to increase the relative humidity of the room can be risky. The uneven distribution of insulation in wall surface can also affect the thermal performance of the wall. The loosely packed insulation surface can act as a thermal bridge. The thickness of the insulation layer affects the thermal transmittance. The heat loss decreases while the insulation thickness increases. The cost of fuel decreases since the heat losses decrease. On the other hand increasing the insulation thickness also increases the cost of insulation. This means that the need of optimization of wall material, especially insulation material can be economical and effective.

The use of thermal imaging camera can be helpful to indicate the thermal bridging and heat loss from the walls. The calculation of the thermal transmittance and thermal simulator software can be helpful to understand the behaviour of the wall under different weather conditions. Even though the wall constructed has good thermal transmittance the energy source and building systems can affect a lot. The wall can function well not only with good design and wall construction but also an effective heating, ventilating and air conditioning building service system are needed.

The use of lightweight steel for wall construction is gaining more momentum in compared to timber framed and pre-fabricated walls. Lightweight steel frame is lightweight, economical, fast installation and easily available. The only drawback is that the lightweight steel can act as a thermal bridge. With proper insulation and sheathing layer this problem can be solved.

SOURCES

C3 National Building Code of Finland. Thermal Insulation in a building, Regulation 2003 (Finnish version), pdf-file. http://webcache.googleusercontent.com/search?q=cache:Wn2TLDZVKn4J:www.ym.fi/download/noname/%257B7BF051A7-6436-4724-A1FD-7688A56FB09B%257D/102966+&cd=2&hl=en&ct=clnk&gl=fi

C4 National Building Code of Finland. Thermal Insulation, Guidelines 2003, pdf-file. http://www.ym.fi/download/noname/%7B09D023C7-7562-449E-86A3-859BD06C7BB9%7D/31549

Climate-data.org. Accessed 18.11.2014. http://en.climate-data.org/location/676/

Comakli, K. Yuksel, B. 2002. Optimum insulation thickness of external walls for energy saving. Applied Thermal Engineering 23 (2003) 473–479, pdf-file. Accesed 25.11.2014. https://stuff.mit.edu/afs/athena/dept/cron/project/concrete-sustainability-hub/Optimized%20ICF/Background%20Research/2003_Comakli.pdf

Doran, S. & Carr, B. 2008. Thermal Transmittance of Walls of Dwellings Before and After Application of Cavity Wall Insulation, pdf-file. http://www.decc.gov.uk/assets/decc/11/about-us/economics-social-research/3146-thermal-transmittance.pdf

European Manufacturers of Expanded Polystyrene (EUMEPS). 2010, Low and net zero energy buildings with EPS insulation. ppt-file & pdf-file. http://www.buildup.eu/publications/12992

Finnish Meteorological Institute. Accessed 18.11.2014. http://en.ilmatieteenlaitos.fi/climate

Forest, T. W. Moisture Transfer through Walls, pdf-file. Accessed 25.11.2014. http://web.ornl.gov/sci/buildings/2012/1989%20B4%20papers/044.pdf

HAMK 2011. Sheet Metal Center. Accessed 18.11.2014. http://portal.hamk.fi/portal/page/portal/HAMK/Tutkimus_ja_kehitys/Osaamiskeskittymat/Ohutlevykeskus

Häkkinen, T. Sustainable Refurbishment of Exterior Walls and Building Facades; VTT: Espoo, Finland, 2012, pdf-file. Accessed 29.11.2014. http://www.vtt.fi/inf/pdf/technology/2012/T30.pdf

Kalamees, T. Kurnitski, J. & Vinha, J. 2004. Indoor Temperature, Humidity, and Moisture Production in Lightweight Timber-Framed Detached Houses, pdf-file. Accessed 20.11.2014. http://web.ornl.gov/sci/buildings/2012/2004%20B9%20papers/155_Kalamees.pdf

Karjalainen, M. 2014. The status of wood construction in Finland. pdf-file. http://www.tem.fi/files/40816/Wood_Construction_in_Finland.pdf

Karjalainen, S. 2009. Thermal comfort and use of thermostats in Finnish homes and offices. Building and Environment 44(2009): 1237-1245. Amsterdam: Elsevier

Korkeamäki, T. 2014. Thesis meeting 23.12.2014.

Latta, K. 1976. Vapor barriers: What are they? Are they effective? Canadian Building Digest, Division of Building Research, National Research Council Canada: CBD 175.

Lstiburek, J. 2008. BSI-001: The Perfect Wall, pdf-file. Accessed 21.11.2014. http://www.buildingscience.com/documents/insights/bsi-001-the-perfect-wall

Ojanen, T. & Kumaran, M. K. Air Exfiltration and Moisture Accumulation in Residential Wall Cavities. Thermal Performance of the exterior Envelope of the Buildings V, BTECC/DOE/ASHRAE, 1992.

Persily, A.K. 1998. Airtightness of commercial and institutional buildings: Blowing holes in the myth of tight buildings. Thermal Envelopes VII Conference, Clearwater, Fla.

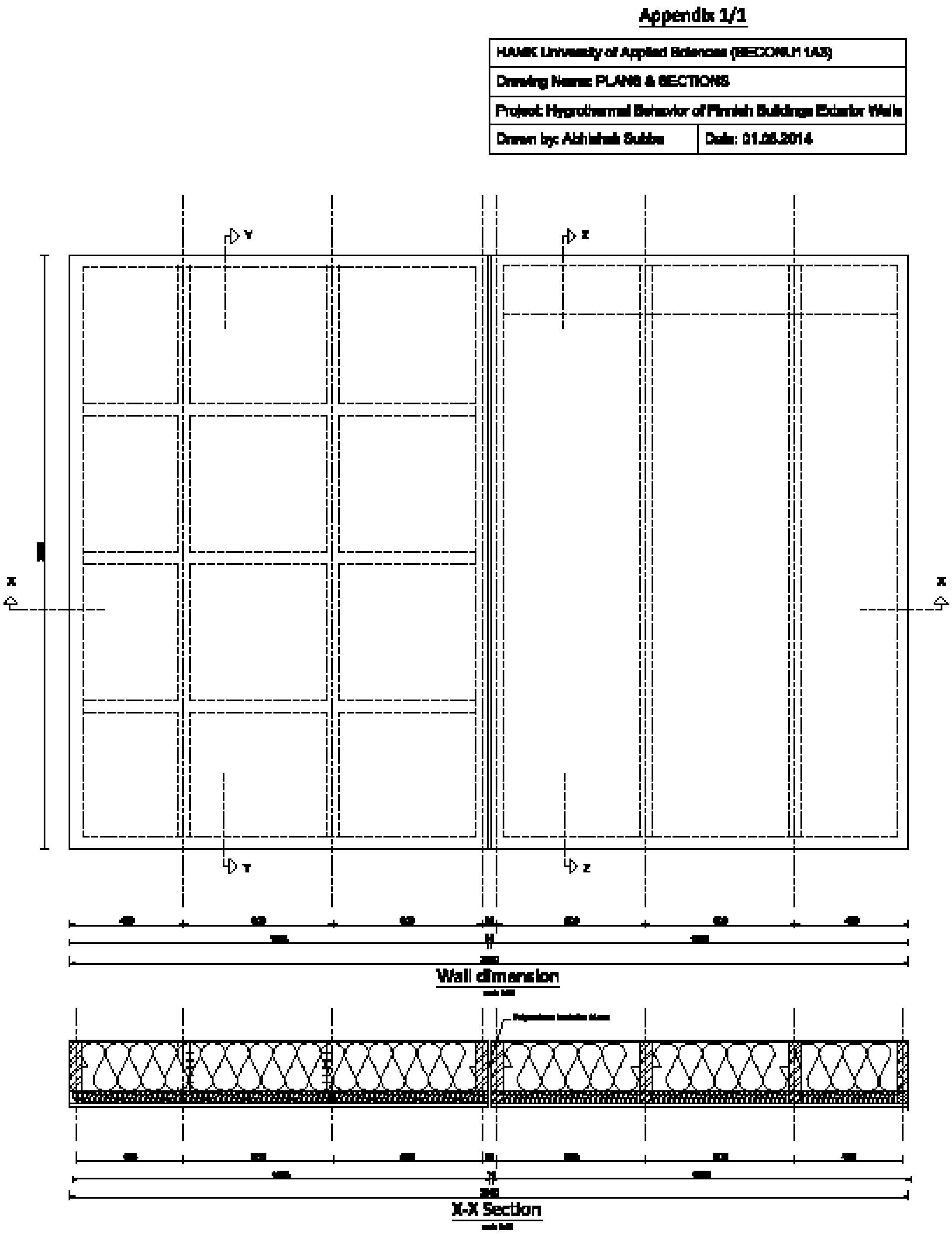
Shakya, S. 2011. Lightweight purlins stiffened with polyurethane foam. HAMK University of Applied Sciences. Construction Engineering Degree Programme. Bachelor’s thesis.

Therm 2014. Accessed 24.11.2014. http://windows.lbl.gov/software/therm/therm.html

Winter, S. Wrede, M. S. Jebens, K. 2012. Highly insulated wooden structures in Nordic climate. World Conference on Timber Engineering 2012. pdf-file. Accessed 28.11.2014. http://www.timberdesign.org.nz/files/00076%20Stefan%20Winter.pdf

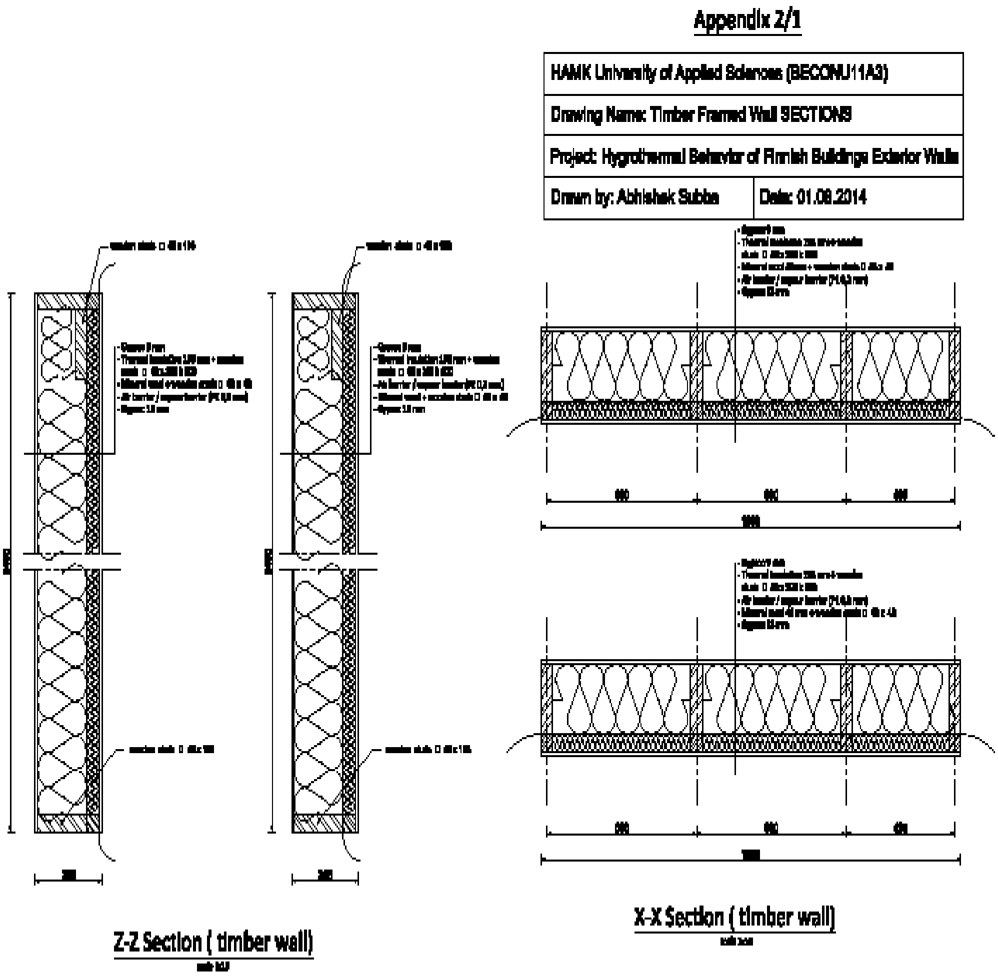
Appendix 1/1

PLAN



Appendix 2/1

Section

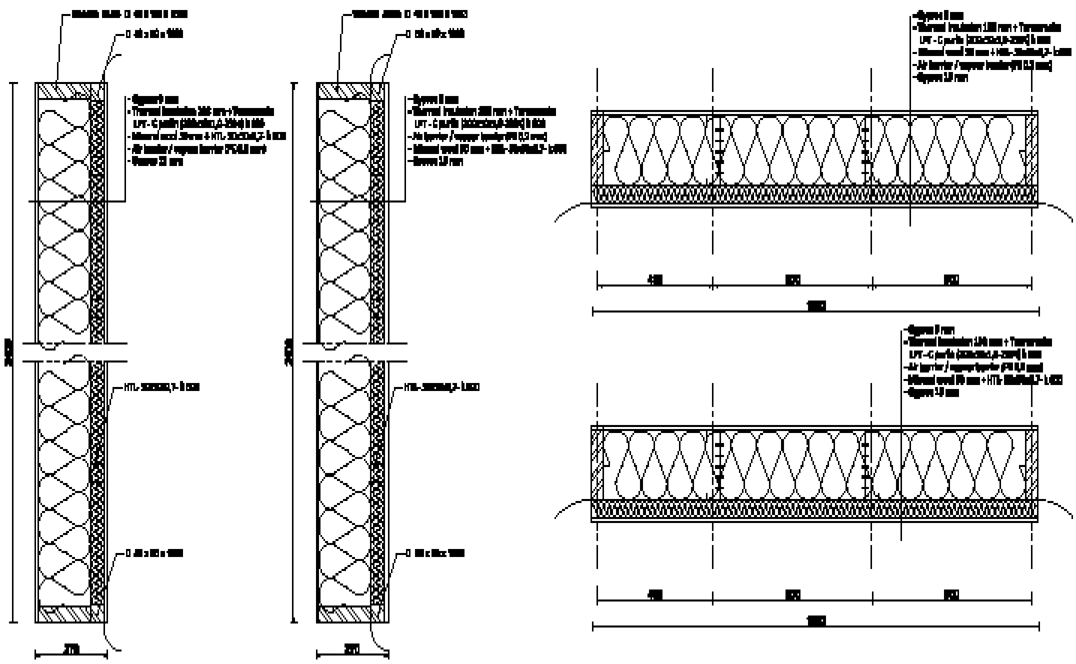


Appendix 3/1

Section

Appendix 3/1

HAMK University of Applied Sciences (BECONU11A3)	
Drawing Name: Timber Framed Wall SECTIONS	
Project: Hygrothermal Behavior of Finnish Buildings Exterior Walls	
Drawn by: Abhishek Subba	Date: 01.08.2014



Y-Y Section (termoranka purlin wall)

Appendix 1/2

Timber wall thermal resistance (timber studs excluded)

			thermal resistance	m²K/W
T_i,inside(°C)	22		R_{si}	0,13
T_e,outside(°C)	-10		R_{se}	0,04
Temp. Diff.	32			

	d (m)	λ_n	R	ΔT(°C)	T(°C)
					-10
outdoor			0,040	0,165	
					-9,835
gyproc	0,009	0,15	0,060	0,247	
					-9,588
thermal insulation	0,198	0,033	6,000	24,700	
					15,112
mineral wool	0,048	0,033	1,455	5,988	
					21,100
vapour barrier	0,002		0,002	0,008	
					21,108
gyproc	0,013	0,15	0,087	0,357	
					21,465
inside			0,13	0,535	
					22,000
total	0,270		7,773		

(U-value) W/m²K U=1/R **0,129**

Termoranka purlin wall thermal resistance (termo purlins excluded)

			thermal resistance	m²K/W
T_i,inside(°C)	22		R_{si}	0,13
T_e,outside(°C)	-10		R_{se}	0,04
Temp. Diff.	32			

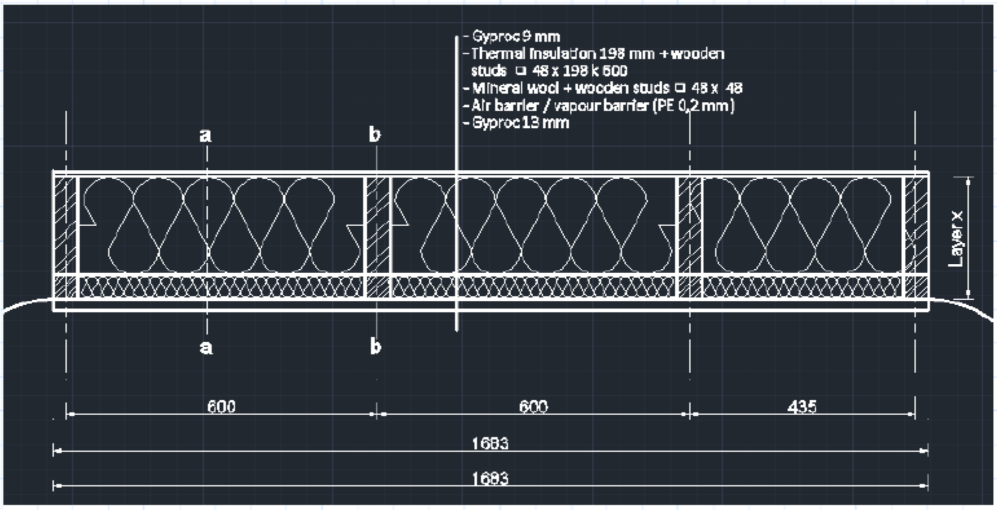
	d (m)	λ_n	R	ΔT(°C)	T(°C)
					-10
outdoor			0,040	0,163	
					-9,837
gyproc	0,009	0,15	0,060	0,245	
					-9,592
thermal insulation	0,198	0,033	6,000	24,509	
					14,918
mineral wool	0,05	0,033	1,515	6,189	
					21,107
vapour barrier	0,002		0,002	0,008	
					21,115
gyproc	0,013	0,15	0,087	0,354	
					21,469
inside			0,13	0,531	
					22,000
total	0,272		7,834		

(U-value) W/m²K U=1/R **0,128**

Appendix 2/2

Thermal Transmittance (Lower and upper case) & moisture flow calculation

Upper and lower limit method



$$R_{gyproc} := \frac{0.009\ m}{0.15\ \frac{W}{m \cdot K}} = 0.06\ \frac{m^2 \cdot K}{W}$$

$$A := 0.6\ m \cdot 1 = 0.6\ m$$

$$A_a := 0.576\ m \cdot 1 = 0.576\ m$$

$$R_{Thermalinsulation} := \frac{0.198\ m}{0.033\ \frac{W}{m \cdot K}} = 6\ \frac{m^2 \cdot K}{W}$$

$$A_b := 0.048\ m \cdot 1 = 0.048\ m$$

$$R_{mineralwool} := \frac{0.048\ m}{0.033\ \frac{W}{m \cdot K}} = 1.455\ \frac{m^2 \cdot K}{W}$$

$$R_{si} := 0.13\ m^2\ \frac{K}{W}$$

$$R_{se} := 0.04\ m^2\ \frac{K}{W}$$

$$R_{vapourbarrier} := 0.002\ \frac{m^2 \cdot K}{W}$$

$$R_{gyproc1} := \frac{0.013\ m}{0.15\ \frac{W}{m \cdot K}} = 0.087\ \frac{m^2 \cdot K}{W}$$

$$R_{studs} := \frac{0.198\ m + 0.048\ m}{0.15\ \frac{W}{m \cdot K}} = 1.64\ \frac{m^2 \cdot K}{W}$$

Appendix 3/2

Thermal Transmittance (Lower and upper case) & moisture flow calculation cont..

Upper Limit

$$R_a := R_{si} + R_{se} + R_{gyproc} + R_{Thermalinsulation} + R_{mineralwool} + R_{vapourbarrier} + R_{gyproc1} = 7.773\ \frac{m^2 \cdot K}{W}$$

$$R_b := R_{si} + R_{se} + R_{gyproc} + R_{studs} + R_{gyproc1} = 1.957\ \frac{m^2 \cdot K}{W}$$

$$R_u := \frac{A}{\frac{A_a}{R_a} + \frac{A_b}{R_b}} = 6.083\ \frac{m^2 \cdot K}{W}$$

Lower Limit

$Layer - X$

$$R_{xa} := R_{Thermalinsulation} + R_{mineralwool} = 7.455\ \frac{m^2 \cdot K}{W}$$

$$R_{xb} := R_{studs} = 1.64\ \frac{m^2 \cdot K}{W}$$

$$R_x := \frac{A}{\frac{A_a}{R_{xa}} + \frac{A_b}{R_{xb}}} = 5.632\ \frac{m^2 \cdot K}{W}$$

Lower limit $R_L := R_{si} + R_{se} + R_x + R_{gyproc} + R_{gyproc1} + R_{vapourbarrier} = 5.951\ \frac{m^2 \cdot K}{W}$

Average thermal Resistance

$$R := \frac{R_u + 2\ R_L}{3} = 5.995\ \frac{m^2 \cdot K}{W}$$

Thermal transmittance, U

$$U := \frac{1}{R} = 0.167\ \frac{W}{m^2 \cdot K}$$

Appendix 4/2

Thermal Transmittance (Lower and upper case) & moisture flow calculation cont..

Difference in air pressures

Since the hole is in a wall, we don't have a uniformly distributed neutral axis. In this case we take ΔP as 0,5Pa or 0,25Pa and work with the calculation.

$\Delta P_1 := 0.5\ Pa$ $\Delta P_2 := 0.25\ Pa$

Air flow through the crack (10mm hole)

$$A_{hole} := \frac{\pi}{4} \cdot (10\ mm)^2 = \left(7.854 \cdot 10^{-5}\right)\ m^2$$

$$Q_1 := 0.8 \cdot A_{hole} \cdot \sqrt{\Delta P_1} \qquad Q_1 := 0.000044\ \frac{m^3}{s}$$

$$Q_2 := 0.8 \cdot A_{hole} \cdot \sqrt{\Delta P_2} \qquad Q_2 := 0.000031\ \frac{m^3}{s}$$

Moisture flow

$T_{i.inside} := 22\ °C$ $R_{si} := 0.13\ \frac{m^2 \cdot K}{W}$ $RH := 65\%$ $V_{k.i} := 19.40\ \frac{gm}{m^3}$

$T_{e.outside} := -10\ °C$ $R_{se} := 0.04\ \frac{m^2 \cdot K}{W}$ $RH := 90\%$ $V_{k.e} := 2.20\ \frac{gm}{m^3}$

water vapour

$$V_{inside} := 0.65 \cdot V_{k.i} = 12.61\ \frac{gm}{m^3}$$

$$V_{outside} := 0.90 \cdot V_{k.e} = 1.98\ \frac{gm}{m^3}$$

$$\Delta V := V_{inside} - V_{outside} = 0.011\ \frac{kg}{m^3}$$

$$g_1 := \Delta V \cdot Q_1 = \left(4.677 \cdot 10^{-7}\right)\ \frac{kg}{s}$$

$$g_2 := \Delta V \cdot Q_2 = \left(3.295 \cdot 10^{-7}\right)\ \frac{kg}{s}$$

Moisture flow through the crack in a month

$$g_1 \cdot 30 \cdot 24 \cdot 3600\ s = 1.212\ kg$$

Appendix 5/2

Weight of Termoranka purlin wall

		no	dimension(mm)	unit	weight (Kg)
1	Timber studs	2	48*198*1685	450 kg / m^3	14,413
		2	50*50*1685		3,791
2	Gyproc 9mm	1	9*1685*2400	7 kg / m^2	28,308
3	Gyproc 13mm	1	13*1685*2400	8,4 kg/m^2	33,970
4	Thermal Insulation	1	198*1685*2400	21,8 kg / m^3	17,456
5	Thermal Insulation Isover KL-33 (50mm)	1	50*1685*2400	21,8 kg / m^3	4,408
6	Termoranka LPT-C purlin	2	C-200*50*1,0-2300	2,5 kg / m^2	11,500
7	HTL-50*50*0,7 k600	3	HTL-50*50*0,7 k600	1,1 kg / m^2	5,561
	Total				119,406

Appendix 1/3

Light Weight Steel Framed Wall Therma 7,2 Figures

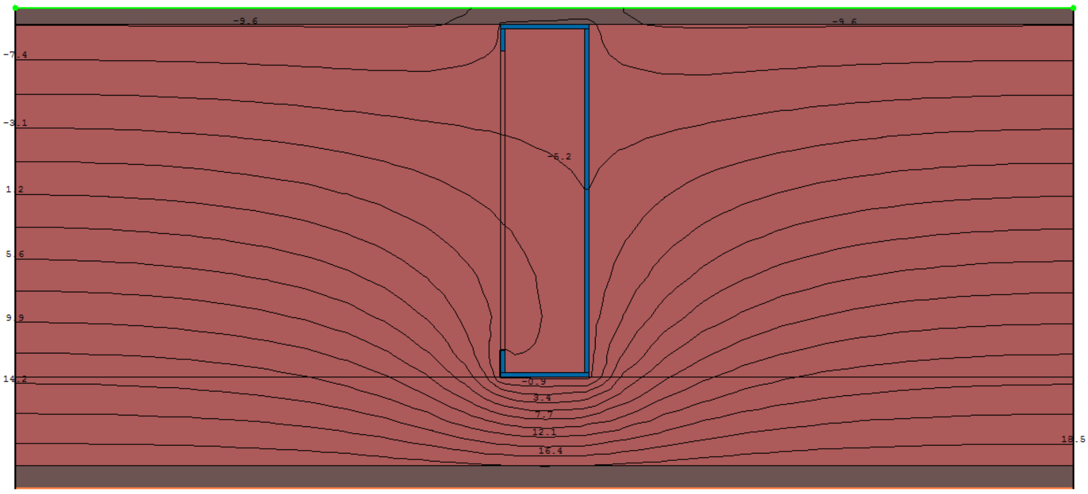


Figure 28 Isotherm Drawing

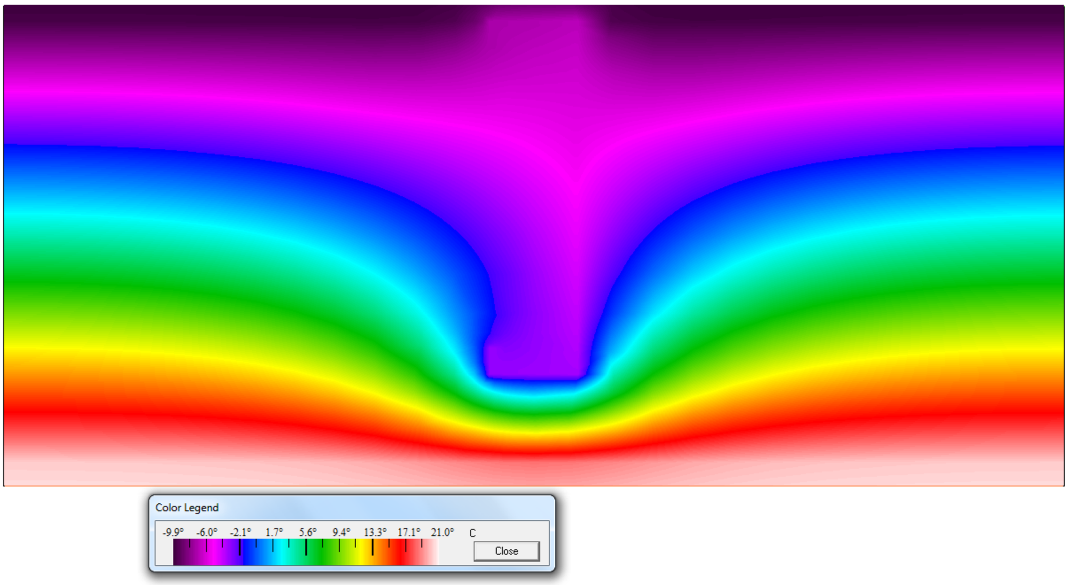


Figure 29 Thermo Drawing

Appendix 2/3

Light Weight Steel Framed Wall Therma 7,2 Figures cont..

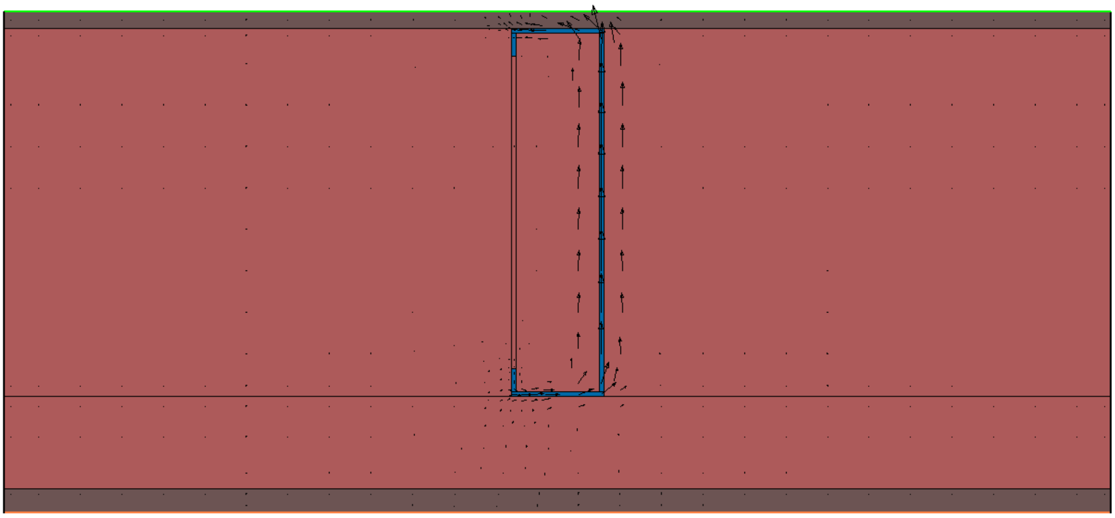


Figure 30 Flux movement

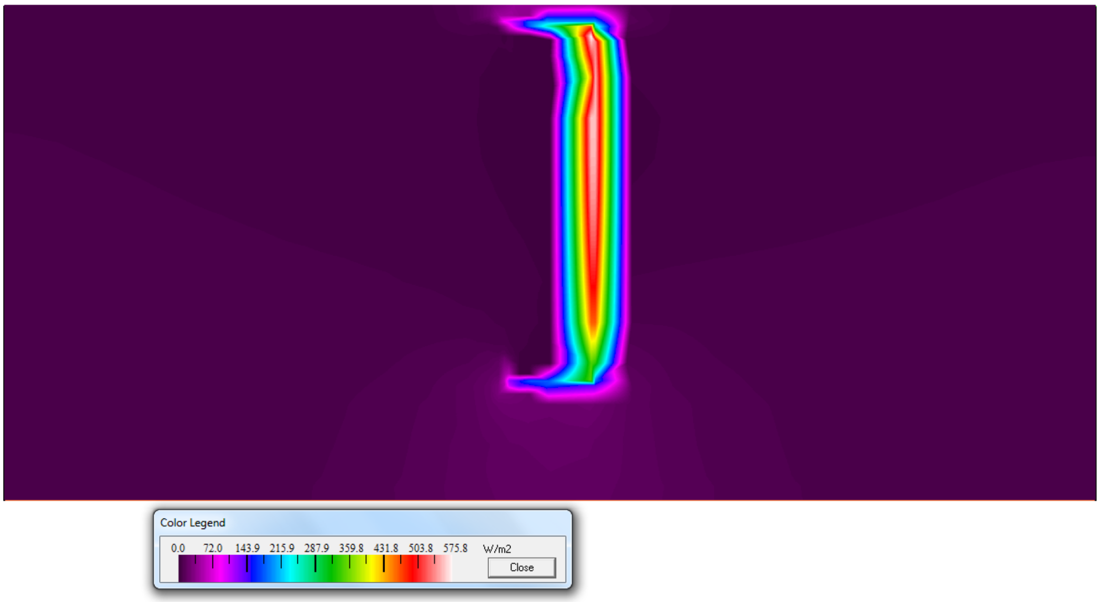


Figure 31 Flux Thermo Drawing

Appendix 3/3

Timber Framed Wall Therma 7,2 Figures

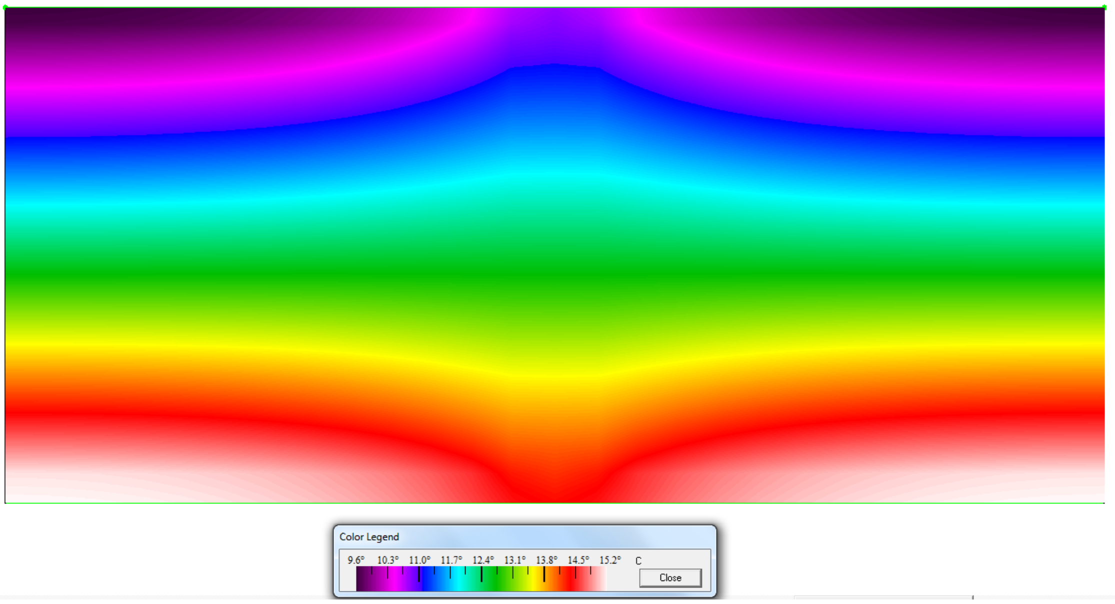


Figure 32 Thermo Drawing

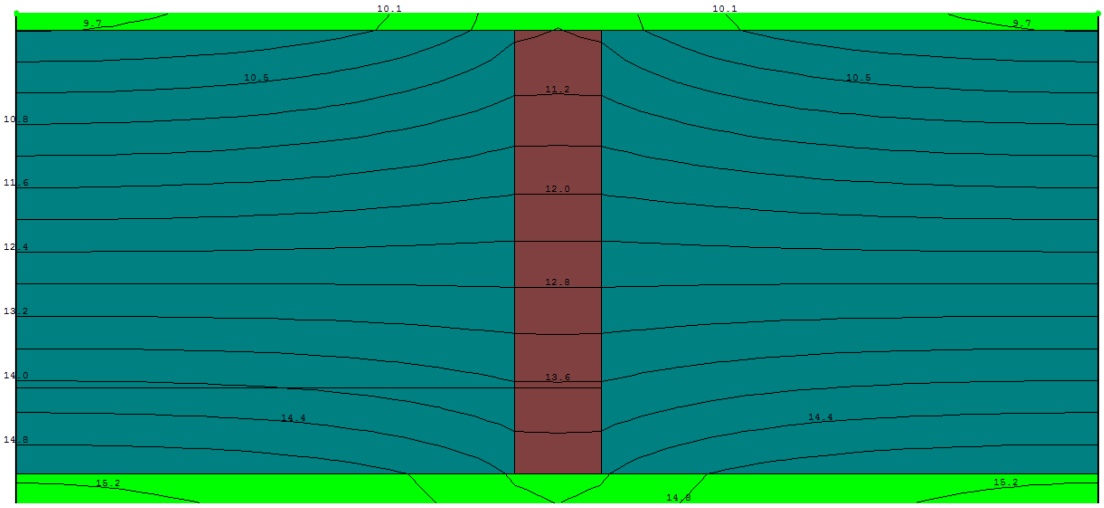


Figure 33 Isotherm Drawing

Appendix 1/4

Construction Phase Pictures

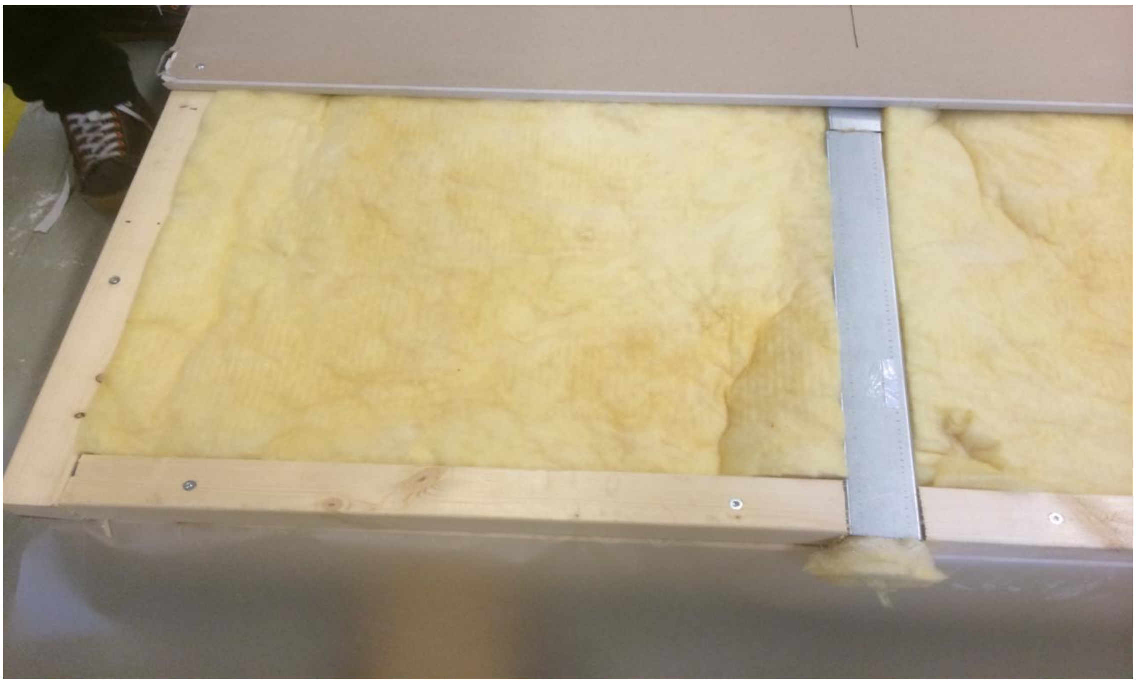


Figure 34 Insulation layer, gypsum board and C-channel

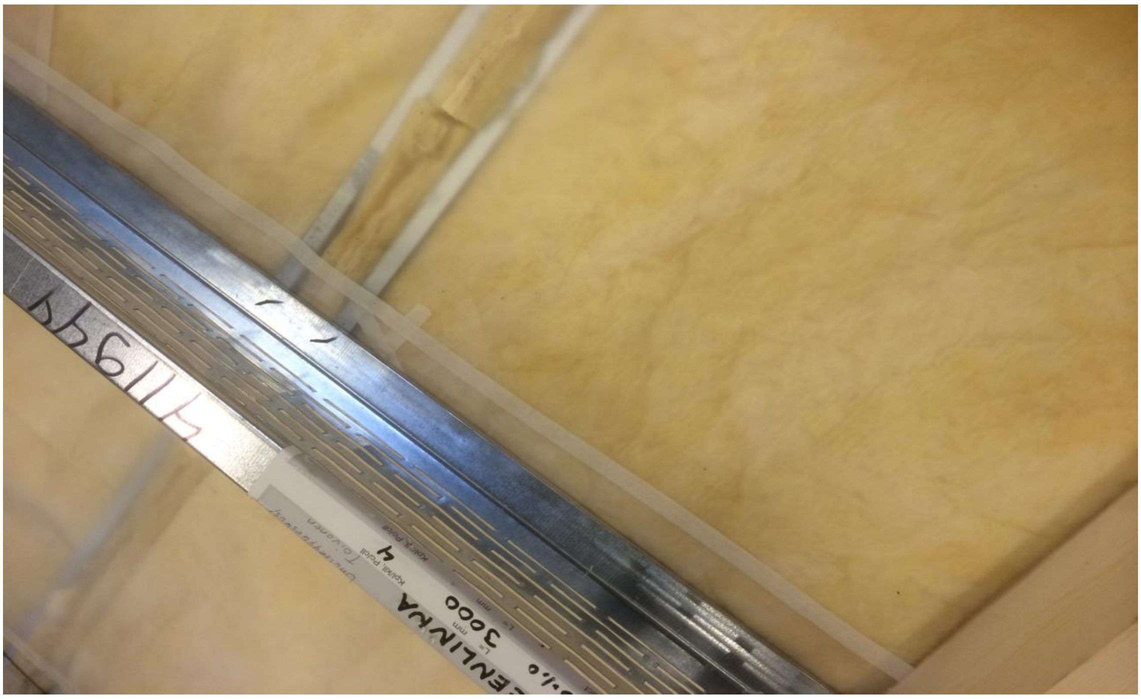


Figure 35 Light weight pulins (Termo Ranka)

Appendix 2/4

Construction Phase Pictures cont..

Figure 36 Arrangement of Sensor

Appendix 1/5

Thermal Imaging Camera Pictures

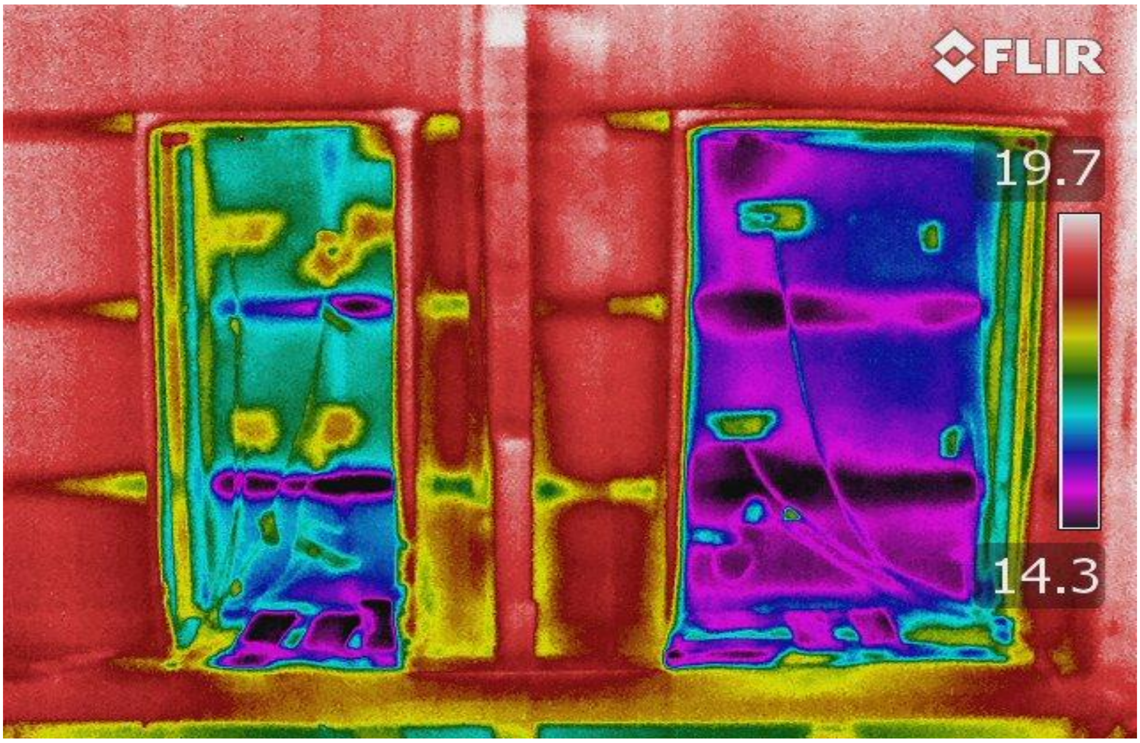


Figure 37 Thermal Imaging Camera Picture

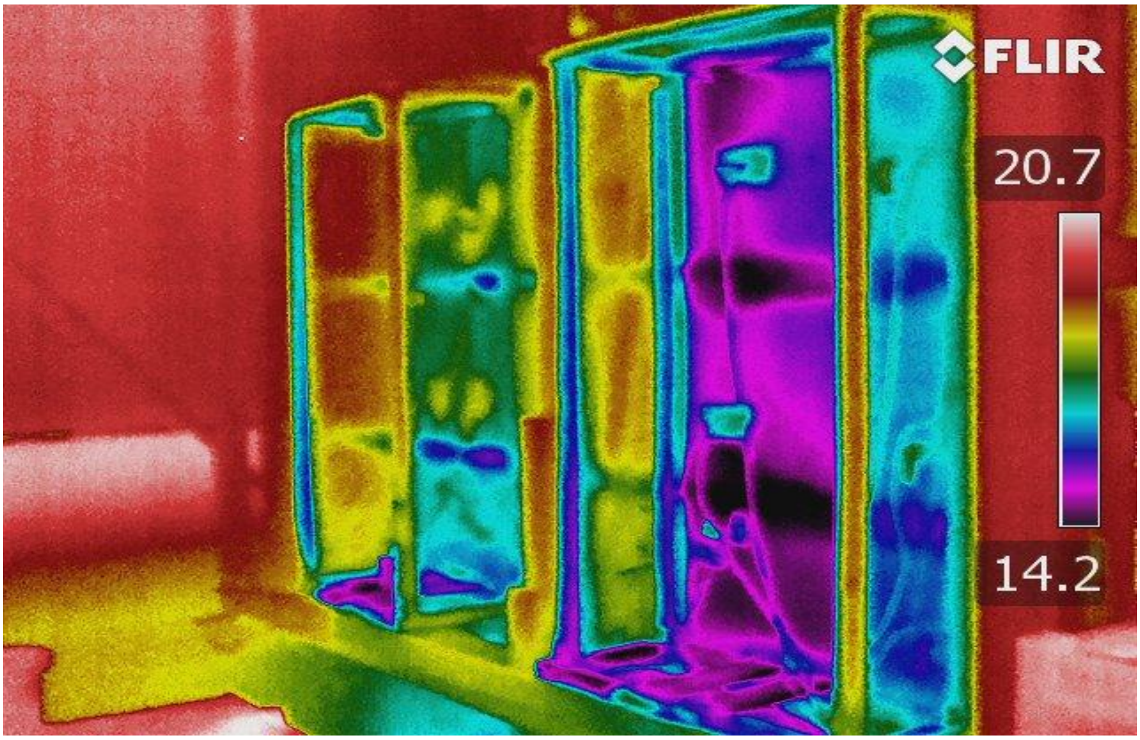


Figure 38 Thermal Imaging Camera Picture

Appendix 1/6

Practical Test Readings

Normal test

Sensor no	29th oct Temperature (T˚C)	29th oct Relative Humidity (RH %)	30th oct Temperature (T˚C)	30th oct Relative Humidity (RH %)	31st oct Temperature (T˚C)	31st oct Relative Humidity (RH %)	3rd nov Temperature (T˚C)	3rd nov Relative Humidity (RH %)	4th nov Temperature (T˚C)	4th nov Relative Humidity (RH %)
Wall 1										
1	-10,1	50,3	-10	49	-10,1	48	-10,1	48	-11,3	47
2	18,2	18,8	17,6	18,2	16,53	16,8	17,2	21,4	17,33	15,7
3	19,8	49,6	19,2	30,5	18,5	50,2	19	52,2	19	25,8
4	-10,1	49,8	-10	47	-10,09	45,26	-10,99	48	-11,2	47,3
5	19,2	21,3	18,6	21,5	17,9	16,9	18,3	20,6	18,5	18,9
6	20	43,7	19,8	42,6	18,5	17,6	19	46,3	19,1	43,7
Wall 2										
7	-8,9	46,7	-9,8	43,2	-9,8	44,62	10,2	47,5	-10,8	41,3
8	14,9	17,8	14,6	17,8	13,7	15,3	14,2	18,6	14,2	16,6
9	17,7	55,2	17,3	33	16,4	19,1	16,9	57,1	17	29
10	-8,9	31,4	-10,1	28	-9,88	28,1	-11,1	31,5	-12,7	24
11	16,88	12,7	17	12,5	15,97	13,2	15,97	13,2	16,03	12,3
12	18	54,7	17,8	30,2	16,7	18,2	17,1	57,1	17,2	28,2
Coldside	-9,8	72	-9,8	73	-9,2	69	-9,5	71	-9,8	73
Warmside	21	48	21	48,3	20,8	47	21	48	20,8	47

Practical Test Readings

Warmside humidity 85%-90% test

	13th nov		14th nov		17th nov		18th nov	
Sensor no	**Temperature (T˚C)**	**Relative Humidity (RH %)**	**Temperature (T˚C)**	**Relative Humidity (RH %)**	**Temperature (T˚C)**	**Relative Humidity (RH %)**	**Temperature (T˚C)**	**Relative Humidity (RH %)**
Wall 1								
1	-10,3	51	-11,3	46,1	-10,1	48	-10,1	48
2	16,91	24,2	17,26	25,3	16,53	25,8	18,2	25,3
3	18	93,8	18,5	94,2	18,5	94,2	19,8	95
4	-10,1	49,8	-10,8	47	-10,09	48,26	-10,1	49,21
5	17,9	23,2	18,5	23,2	17,9	16,9	19,2	20,6
6	18,4	81,1	18,8	83	18,5	82,6	20	83,3
Wall 2								
7	-8,9	46,7	-9,8	43,2	-9,8	44,62	-8,9	47,5
8	14,9	17,8	14,6	17,8	13,7	17,3	14,9	25,6
9	17,7	55,2	17,3	55	16,4	54,9	17,7	57,1
10	-8,9	31,4	-10,1	28	-9,88	28,9	-8,9	31,5
11	16,88	12,7	17	12,5	15,97	13,2	16,88	13,2
12	18	54,7	17,8	52,2	16,7	52,2	18	57,1
Coldside	-9,8	72	-9,8	73	-9,2	69	-9,8	71
Warmside	21	85	21	85	20,8	85	21	85

Practical Test Readings

Warmside humidity 85%-90%, (with 8mm diameter hole) test

	14th nov		17th nov		18th nov		19th nov	
Sensor no	**Temperature (T˚C)**	**Relative Humidity (RH %)**	**Temperature (T˚C)**	**Relative Humidity (RH %)**	**Temperature (T˚C)**	**Relative Humidity (RH %)**	**Temperature (T˚C)**	**Relative Humidity (RH %)**
Wall 1								
1	-11,1	49,2	-11,5	48,8	-11,7	48,3	-10,1	48
2	17,17	25,3	17,26	25,3	18,2	24,7	16,53	25,8
3	18,4	94,8	18,5	95,6	19,7	96,2	18,5	94,2
4	-10,1	49,8	-10,8	47	-10,1	49,21	-10,09	48,26
5	18,3	23,3	16,52	25	19,6	23	17,9	24,8
6	18,7	82,1	17,9	83,1	18	83,7	18,5	82,6
Wall 2								
7	-9,2	44,8	-9,8	44,7	-9,8	43,8	-9,8	44,62
8	14,8	18,5	14	18,5	14	18,3	13,7	18,2
9	16,8	87,2	17,36	86,7	16,2	92,4	16,4	92,37
10	-9,9	45,8	-10,2	44,4	-9,7	43,6	-9,88	43,7
11	16,85	18	15,69	18,4	15,68	17,5	15,97	17,3
12	17,8	93,2	16,85	93,1	18,3	93,1	16,7	93,2
Coldside	-9,8	72	-9,8	73	-9,8	71	-9,2	69
Warmside	21	85	21	85	21	85	20,8	85