CHALMERS

Retrofitting an old warehouse using vacuum insulation panels

Hygrothermal analysis and life cycle cost assessment

Master of Science Thesis in the Master's Programme Structural Engineering and Building Technology

AUGUSTINE LAUBY

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Building Physics
CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover:
The former warehouse Kajskjul 113 in the port of Gothenburg (photo: Augustine Lauby

Department of Civil and Environmental Engineering Göteborg, Sweden 2013

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ABSTRACT

Due to global warming and climate change, it is now pressing to reduce the harmful anthropogenic impacts on environment. The daily consumed energy is still mainly from fossil fuels so it represents a major source of greenhouse emissions. Therefore, the building sector, which accounts for 35% of the final energy consumption in the OECD countries, is a sector with a strong potential for abatement measures. In particular, re-insulating old buildings, which are usually not or poorly insulated, is considered as a promising measure for energy savings. Today, the new Swedish and European thermal regulations are getting stricter and keep inciting building owners to retrofit their old deficient building façades. To fulfill these new requirements, several new insulation materials have been developed over the last decades. One of them is the vacuum insulation panel (VIP), a state-of-the art system, containing vacuum encased in a polymer laminate envelope. Thus, VIPs present very efficient thermal properties with a low thickness. This report focuses on a case study: Kajskjul 113, a former warehouse whose retrofitting was ordered by its building owner, a municipal company willing to move there its headquarters. This thesis sought to determine if by using VIPs for the retrofitting, the building owner would fill its most relevant requirements: hygrothermal improvements in the façade materials and cost efficiency. First, a pre-study has established a promising internal insulation following feedback from previous research experiments. Then, the overall cost of the solution has been evaluated using a Life Cycle Cost analysis (LCC) and the thermal improvements as well as the new hygrothermal conditions in the retrofitted façade has been controlled using the software WUFI 2D. It results that the VIPs offer an efficient thermal solution but the implementing VIPs is more expensive that insulating with conventional materials. Owing to this, it seems that re-insulating Kajskjul 113 with VIPs is not the most optimal solution. Indeed, due to their high purchase price, the VIPs are still too costly for conventional insulation measures. It is most probable that due to their thinness and excellent thermal properties, the VIPs would be more adapted to insulating façade elements where the space is limited such as windows or door frames and windows casings.

Key words: insulation, building envelope, brick facade, vacuum insulation panels, retrofitting, hygrothermal conditions, life cycle cost

Rénovation d’un ancien entrepôt avec des panneaux à vide isolant
Analyse hygrothermique et analyse du coût du cycle de vie

Master of Science Thesis in the Master’s Programme Structural Engineering and Building Technology

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RESUME

Les sérieuses conséquences du réchauffement climatique sur notre environnement ne sont plus contestables. Il est donc nécessaire de réduire ces effets néfastes et notamment de diminuer les émissions de gaz à effets de serre. L’énergie consommée au quotidien provient encore principalement de combustibles fossiles et contribue donc au réchauffement climatique. Dans les pays de l’OCDE, le secteur du bâtiment consomme 35% de l’énergie disponible, ainsi, dans ce secteur, des mesures d’économie d’énergie doivent être entreprises. En particulier, l’une des mesures les plus prometteuses est de ré-isoler les bâtiments anciens qui ont été peu ou pas isolés au moment de leur construction. Ainsi, en Suède comme dans le reste de l’Europe, la réglementation thermique, plus en plus stricte, incite les propriétaires à revoir l’isolation de leurs bâtiments. Depuis quelques décennies, de nouveaux matériaux isolants ont été développés et permettent d’atteindre ces nouvelles normes. Les panneaux à vide isolant (PVI) sont un nouveau système d’isolation ultramoderne. Le vide maintenu à l’intérieur des panneaux permet une très bonne isolation dans un système très fin. Ce rapport présente une étude de cas: la rénovation thermique de la façade d’un ancien entrepôt, Kajskjul 113 pour que son propriétaire puisse y emménager le siège de son entreprise. Ce travail a cherché à déterminer si la rénovation de la façade avec des PVI était à la fois une solution thermiquement efficace et économiquement intéressante. Il en ressort que l’utilisation de PVI n’est pas la solution la plus optimale. La pré-étude et les modélisations informatiques montrent que l’utilisation de PVI offre une solution thermiquement efficace. De bonnes conditions hygrothermiques dans les différents matériaux de la façade seront maintenues. Cependant, l’analyse du cout du cycle de vie de cette isolation indique que le système est encore beaucoup plus cher qu’une isolation classique. Les PVI sont encore très chers à l’achat et il semble donc qu’ils soient plus adaptés à l’isolation d’éléments de façades où la place est restreinte comme les caissons de volets roulants ou les cadres de fenêtres ou de portes.

Mots-clés: isolation, enveloppe de bâtiment, façade de briques, panneaux à vide isolant, rénovation, thermique, conditions hygrothermiques, coût du cycle de vie.

Contents

Notations and Abbreviations

Notations relative to the heat and water transfer

Roman letters

A	[m²]	Surface
d	[m]	Thickness of vacuum insulation panels
E_a	[$J.mol^{-1}$]	Activation energy
E(T)	[-]	Transport extinction coefficient
g	[$kg.m^{-2}.s^{-1}$]	Water vapour flow
h_c	[$W.m^{-2}.K^{-1}$]	Convective heat transfer coefficient
h_r	[$W.m^{-2}.K^{-1}$]	Radiative heat transfer coefficient
Kn	[-]	Knudsen number
l	[m]	Thickness of the insulation materials
l_k	[m]	length of the thermal bridges.
l_{mean}	[m]	Mean free path
L	[$m^3.m^{-2}.s^{-1}$]	Air flow
n	[-]	Refraction index
p	[m]	Perimeter
p_{ei}	[m²/s]	Surface permeability
q	[$W.m^{-2}$]	Density of heat flux
Q	[W]	Heat flux
s_d	[m]	Diffusion thickness
R	[$m^2.K.W^{-1}$]	Thermal Resistance
R	[$J.K^{-1}.mol^{-1}$]	Gas constant
T	[K] or [°C]	Temperature
U	[$W.m^{-2}.K^{-1}$]	Thermal Transmittance
X	[$W.K^{-1}$]	Point thermal bridges
Z	[$s.m^{-1}$]	Water resistance

Greek letters

δ	[m]	Characteristic pores diameter
δ_v	[$m^2.s^{-1}$]	Vapor permeability
ε	[-]	Emissivity
λ	[$W.m^{-1}.K^{-1}$]	Thermal conductivity
λ_{init}	[$W.m^{-1}.K^{-1}$]	Thermal conductivity of a new VIP
λ_{eff}	[$W.m^{-1}.K^{-1}$]	Effective thermal conductivity of a VIP
$\lambda_{evacuated}$	[$W.m^{-1}.K^{-1}$]	Thermal conductivity of a VIP when punctured
μ	[-]	Water vapor convection resistance
σ	[$W.m^{-2}.K^{-4}$]	Stefan-Boltzmann constant
φ	[%]	Relative humidity
ψ	[$W.m^{-1}.K^{-1}$]	Linear transmittance
v	[$kg.m^{-3}$]	Humidity by volume
ω	[$kg.m^{-3}$]	Water content

Notations relative to cost analyses

Roman letters

A	[m²]	Surface covered by insulation
$ac_{maintenance}$	[€.year^{-1}]	Annual maintenance cost
C_{ad}	[€/m²]	Installation Costs
$C_{cooling}$	[€.year^{-1}]	Annual energy cost for cooling
CDD	[-]	Cooling Degree Day
C_e	[€.kWh^{-1}]	Electricity cost
C_{energy}	[€.m^{-2}.year^{-1}]	Cost of energy
C_f	[€.m^{-3}]	Price of fuel
$C_{heating}$	[€.year^{-1}]	Annual energy cost for heating
C_i	[€.m^{-3}]	Cost of the insulation material
$C_{investment}$	[€.m^{-2}.year^{-1}]	Cost of investment
$C_{maintenance}$	[€.m^{-2}.year^{-1}]	Cost of maintenance
COP	[-]	Cooling system's performance
$C_{rental\ income}$	[€.m^{-2}.year^{-1}]	Cost of rental income or loss
g	[%]	Inflation rate
h	[m]	Height of a storey
h	[%]	Real cost of capital
HDD	[-]	Heating Degree Day
H_u	[J. m^{-3}]	Lower heating value of the fuel
i	[%]	Interest rate
$\mathrm{K_{R:spec}}$	[€.m^{-4}.W^{-2}]	Cost per thermal transmittance
LCC_{total}	[€.m^{-2}.year^{-1}]	Cost of the Life Cost Circle
L_i	[m]	Insulation thickness
N	[yr]	Period of calculation
p_b	[yr]	Pay Back Period
PWF	[-]	Present worth factor
U	[W.m^{-2}.K^{-1}]	Thermal Transmittance of the wall

Greek letters

η	[-]	Heating system's efficiency
λ_{vip}	[W.m^{-1}.K^{-1}]	Thermal conductivity of the VIP
δd	[m]	Difference of façade thickness
ΔKa	[€.m^{-2}]	Difference in cost of the thermal insulation materials

Abbreviations

AF	Aluminium Foil
BBR	Swedish Building Regulation
EPS	Expanded Polystyrene
LCC	Life Cycle Cost
MF	Metalized Films
PE	Polyethylene
PET	Polyethylene Terephthalate
PUR	Polyurethane
VIP	Vacuum Insulation Panel
XPS	Extruded Polystyrene

Introduction

This part is an introduction to the thesis. It gives general background information about the European and Swedish legislative context and the current requirements regarding the thermal insulation of buildings. It also defines the purpose, methodology and limitations of this Master's Thesis.

1.1 Background Information

Today, there is no denying the global warming and the climate change taking place all around the world. Therefore, it is now pressing to undertake the necessary measures to reduce or at least limit our production of greenhouse gases. By 2020, the European Union has targeted a reduction of greenhouse gas emission to a level at least 20% lower than the level of 1990 (European Commission 2008). McKinsey&Company (2009) has evaluated reduction emissions opportunities. They have reported 200 opportunities across ten different sectors, all of them are considered as promising since they have a cost inferior to 60 euros per ton of CO_2 equivalent (tCO_2e[1]) saved. In 2005, the building sector accounted for about 18 percent of the world greenhouse gas emission by releasing 8,3 $GtCO_2e$. This value is even higher in developed countries where around 30% of the emissions are produced by the building sector. Without any abatement measures, the emissions are expected to rise by 53% between 2005 and 2030. Therefore, it is now urgent to reduce our greenhouse gas emissions and important opportunities should be found in diverse energy efficiency measures (McKinsey&Company 2009).

The building sector is an heavy-energy consumer. In every developed country, it accounts for more primary energy than any other sector, such as transportation or industry. Thus, in the OECD countries, in 2008, the buildings for residential and tertiary purposes accounted for 35% of the final energy consumption, half of it used for space heating (Bouquerel et al. 2012). And even though, today, in Europe, the energy needs of new dwellings are three to four times lower than the ones of an average building built in the 1970s, the overall energy consumption of the sector keeps increasing due to the growth of the building stock. On the long run, it is not viable since energy consumption produces greenhouse gases. Furthermore, the energy used is mainly the energy from fossil resources and its availability is lessening. The Energy Information Agency (EIA) predicts that the natural gas stocks will last less than 70 years and the crude oil reserves only 43 years. Their scarcity contributes to their increasing prices, an upward trend which is expected to continue in the following decades. In addition, most of the fossil resources brought by the European Union are imported from countries politically unstable, which intensifies the uncertainties regarding the availability and prices of the resources. Most of EU members are now willing to decrease their dependency on fossil fuels by reducing their energy consumption. As a consequence, over the last years, the building energy codes and policies have changed to favor an overall decrease of energy consumption.

Thus, many new regulations have been adopted for the last fifteen years. With the Kyoto Protocol ratified in 1998, the European countries aimed at cutting of greenhouse gas emissions by 8% compared to the levels of 1990 for the period 2008-

[1] The ton CO_2 equivalent (tCO_2e) is the unit defined by the Kyoto Protocol to measure the contribution of every type of gas to global warming.

2012 but the targets have not been reached (Janson 2010). In 2009, during the last meeting in Copenhagen to discuss a new worldwide framework after Kyoto no agreement was found (Janson 2010). However, in 2008, the European Union agreed "to reduce, by 2020, overall greenhouse gas emissions by at least 20% below 1990 levels" and in 2010, a new directive was passed to further regulate the energy performance of buildings (European Parliament 2010).

In Sweden, the housing sector accounts for around 40% of the total energy use and heating and domestic hot water represent a large part of it, 57% and 19% respectively (Gross 2010). Electricity, gas and fuel are the main sources of energy used in the country. Their prices, as the ones within the rest of Europe, have been increasing during the last decades (see Figure 1.1). Between 1990 and 2008, the prices of electricity and oil have been multiplied respectively by 2.5 and 3.6 and the gas price have been multiplied by 2.5 during the period 2001-2008. In order to follow the Swedish Building Regulations (BBR) and the European agreements, the energy use should decrease by 50% before 2050 (Boverket 2010).

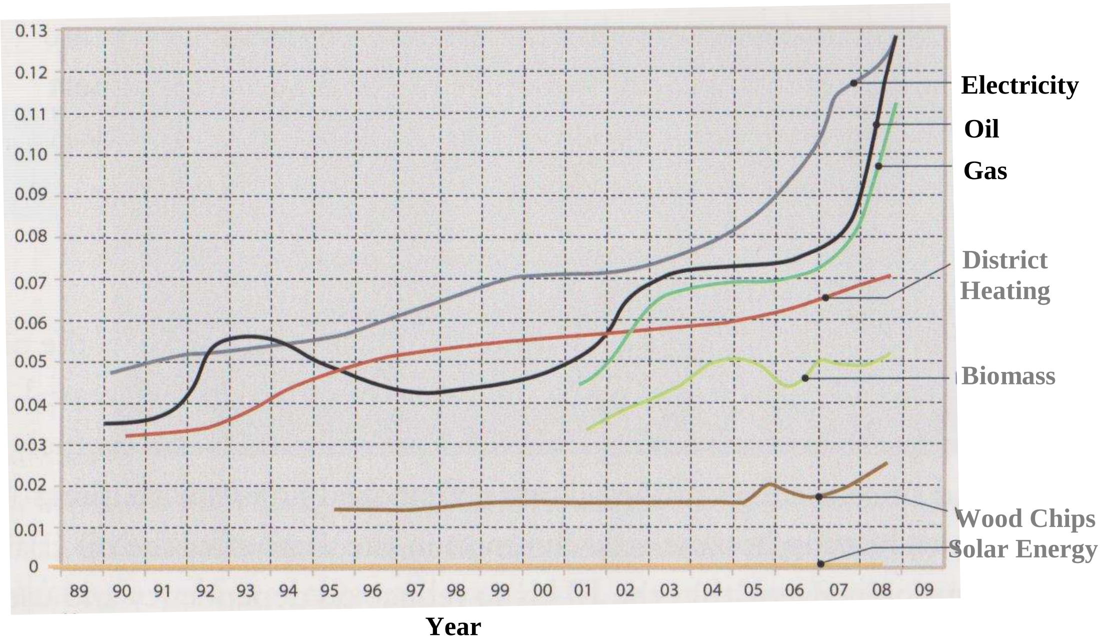

Figure 1.1 Evolution of the energy prices for Swedish house customers (Gross 2010)

To implement energy consumption reduction in the building sector, McKinsley&Company (2009) has identified several options including "Retrofit Building Envelope" which represents a strong tCO_2e abatement potential. Indeed, well-insulated building envelope enables important energy savings, in particular heating savings. Furthermore, thermal insulation is one of the most cost-effective measures, far more efficient than the use of solar photovoltaic or energy wind (McKinsley&Company 2009). The efficiency of the insulation systems can be improved using the new materials, techniques or technologies which have been developed during the last decades. In particular, various new insulation materials for building envelopes have been investigated. Among them, the use of vacuum insulation panels (VIPs), a state-of-the-art insulation system, is considered as a promising alternative.

The VIPs were introduced in the building sector in the 1990s when the insulation systems containing harmful gases had to be replaced (Brunner et al. 2012). They consist of an envelope containing a filling nanostructured porous material at a very low gas pressure, between 0.02 and 3 mbar (see Figure 1.2) (Johansson 2012). Therefore, the thermal conductivity of the panels is extremely small. It ranges typically from 0.003 to 0.008 $W.m^{-1}.K^{-1}$ when newly installed (Berge and Johansson 2012) up to 0.020 $W.m^{-1}.K^{-1}$ at the end of their life span (Simmler et al. 2005). In comparison, the thermal conductivity of conventional insulation materials is between 0.03 and 0.04 $W.m^{-1}.K^{-1}$. Many research projects have been carried out to study the use of VIPs and all of them discuss their great potential.

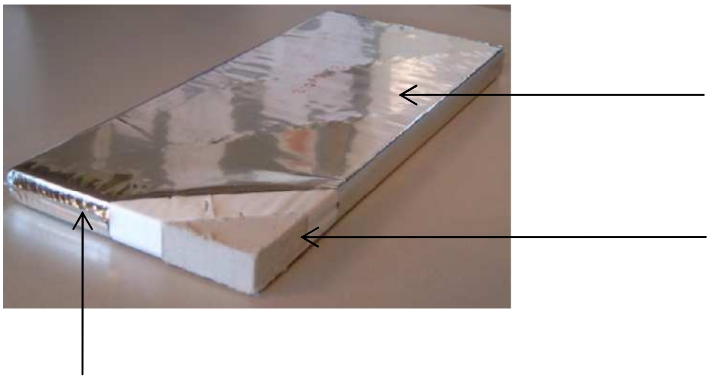

Figure 1.2 Example of vacuum insulation panel (Tenpierik 2009)

Today, most of the building owners want efficient building envelopes and are more willing to use new materials and systems to achieve it. However, the cost of the selected materials and systems is very often as determining as the searched thermal efficiency. Thus, many buildings owners could be dissuaded by the high prices of purchase of the VIPs.

1.2 Scope

This master´s thesis is based on a study case and focuses on the implementation of VIPs to retrofit the insulation system of a façade. The hygrothermal performances will be discussed as well as the costs of its installation and maintenance.

The study case concerns the installation of VIPs on an exterior wall of a former warehouse in Gothenburg Port: Kajskjul 113. The housing company, Älvstranden utveckling AB wants to retrofit the warehouse to move in their company headquarters within 5 years. They were willing to test new materials. However, as for every company, the decision of using VIPs to retrofit the entire façade cannot be undertaken without being sure of the thermal and hygrometric improvements carried out by the system and of the profitability of the new system.

Therefore, the aim of this master’s thesis is to give home builders all the necessary knowledge and tools so they will be able to evaluate if VIPs can be successfully implemented in their projects. The key question answered by this reports is “By implementing a thermal insulation system with vacuum insulation panels, will my project be thermal efficient and profitable?"

1.3 Methodology

This project has been conducted following distinct steps.

Firstly, a comprehensive literature of scientific papers and reports has been read to establish a short literature review that gathers background information about the function, use and main stakes concerning vacuum insulation panels. It also contextualizes the study case which follows.

Then, a pre-study, based on the literature review has been carried out to design a promising insulation system with which refurbish Kajskjul 113. The pre-study also evaluates the thermal and economical potentials of the use of VIPs in this case. The thermal efficiency is roughly estimated in term of U-value. The economical potentials are evaluated with a Life Cycle Cost analysis (LCC). The LCC is mainly based on literature review and the results were obtained with a short model created with Excel.

Finally, to definitely validate the expected performances of the selected insulation system, a detailed hygrothermal analysis was realized with the computer software WUFI 2D. The performances of the retrofitted wall are compared to the ones of the older wall to evaluate the improvements. What is more, the influence of different parameters has been studied to evaluate potential improvements to the new insulation system.

1.4 Limitations

This thesis only focuses on the use of the vacuum insulation panels as a solution to retrofit the insulation of the exterior walls.

The main tool used was the software WUFI 2D. Thus, the temperature, moisture control and moisture durability have been studied. The air flow and air pressure control have not been taken into consideration. The main limitations were due to the level of accuracy of the model. In particular, since the VIPs are a rather new technology, the materials VIP is not available in the data base of WUFI 2D. Therefore, the models including VIPs are not as accurate as they could have been. Furthermore, the windows cannot be modeled with WUFI although they play a prominent part in the functioning of the façade.

Regarding the Life Cycle Cost analysis, the study is only carried out on the use of VIPs with an internal insulation. The results reported in this report are as accurate as possible. Nevertheless, there are strongly dependent on the input data such as the energy prices, the different money rates.

1.5 Outline of the thesis

This Master's thesis is divided in 6 chapters.

The first chapter is the introduction of the thesis. The second presents some background information about the role of the building envelope, the heat and water transfers through the building envelope. The third chapter gives a short literature review focused on the thermal properties of the vacuum insulation panels and the stakes due to their use. Chapter 4 is a pre-study concerning the case study of the thesis. Its purpose is to propose feasible solutions to retrofit the insulation system of the façade of Kajskjul 113. The solutions use VIPs and are designed to be thermal and cost efficient. Chapter 5 presents a detailed analysis of the solutions regarding the thermal and hydrothermal behavior of the new façade. Finally, the last chapter discusses the results, in particular the results can be used and their validity.

2 Background Information

2.1 Role of the building envelope

The building envelope refers to all parts of a building that form a barrier against the outdoor climate: external walls, roof, foundations, windows and doors. Today, most of the heat losses in buildings, approximately 85%, occur through the building envelope including 30% of the heat lost through the windows and external doors and 17% through the external walls (Gross, 2010)

A good, well-insulated and airtight façade construction is a first compulsory step to decrease the use of heating and cooling, a factor of global warming. Indeed, it prevents from too large daily temperature oscillation. Thus, in the building process of passive houses, Gross (2010) advices “first and foremost” the construction of an air tight and well insulated building envelope. Only after that, technical installation measures, such as the system of heat and ventilation, can be undertaken.

The potential of energy-efficient measures is even more important when retrofitting old building façade. Indeed, the use of thermal insulation material became widespread only after the 1973 oil crisis. In 1995, in the European Union, 72% of the dwellings were built before 1975 and 50% of the total building stock were not insulated at all (Binz et al. 2005). Furthermore, since 1995, the turnover of the existing building stock renewal is slow: nowadays, there is one new construction for 100 to 200 older constructions (Simmler et al. 2005). Retrofitting building envelopes is almost certain to produce an abatement of about 740 $MtCO_2e$ per year. In cold area, it is assumed to reach 48% savings (McKinsley&Company 2009). Therefore, the thermal retrofitting of the old building stock appears to be a new obligation.

Today, the U value [$W.m^{-2}.K^{-1}$] representing the total surface thermal resistance is internationally used to evaluate the thermal performance of a building envelope. The U value represents how well a building section insulates against heat leaks. A U value of 1 $W.m^{-2}.K^{-1}$ means that the façade is losing 1 watt per meter square for a temperature difference of 1 Kelvin between its faces.

In Sweden, for Passive House, the mean U-value for opaque façades (façades without windows) is 0.10 $W.m^{-2}.K^{-1}$ whereas in the Mid-Europe, a U-value inferior to 0.15 $W.m^{-2}.K^{-1}$ is enough to reach the standards of Passive Houses (Janson 2010). The current values imposed by the Swedish Building Regulations for a façade including windows are much bigger: 0.40 $W.m^{-2}.K^{-1}$ for dwellings and 0.60 $W.m^{-2}.K^{-1}$for non residential buildings (Boverket 2011). For opaque façades, most many European regulations advise a value of 0.20 $W.m^{-2}.K^{-1}$ (Simmler et al. 2005).

2.2 Heat Transfer through the Building Envelope

Heat transfer is the process by which energy is transported from one region to another due to a temperature difference. In various fields, including the building sector, it is important to accurately understand and quantify heat transfer in order to better control it.

In building applications, three modes of heat transfer have been identified (see Figure 2.1)

- Conduction
- Convection
- Radiation

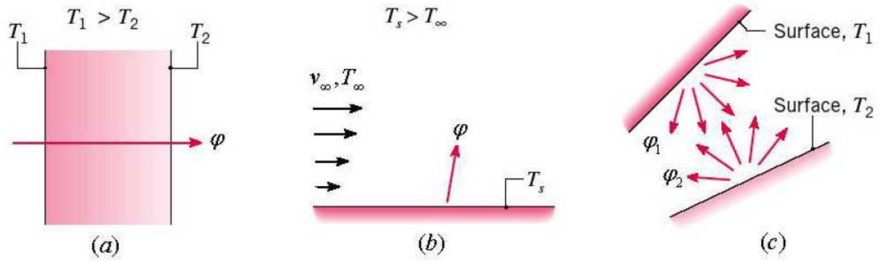

Figure 2.1 Illustration of the modes of heat transfer: a) conduction, b) convection, c) radiation (Ghiaus and Brau 2011)

The heat transfer is estimated either with the heat flux, denoted Q, expressed in watt [W] or with the density of heat flux, denoted q calculated in watt per meter square [$W.m^{-2}$].

In conduction, the heat is transported by diffusion inside a solid material or between solids in contact. It also takes place in liquids and gases. There, its effect is less important than in solids except in viscous liquids and in gases enclosed in materials pores. In walls, partitions and floor, heat is mainly transferred by the conduction process.

The Fourier´s Law is the constitutive law for conduction. It relates the heat flux, Q [W] and the temperature difference, ΔT [°C or K] and is expressed as follows:

$$Q = -\frac{\lambda}{l}.A.\Delta T \qquad (2.1)$$

$$q = -\frac{\lambda}{l}.\Delta T \qquad (2.2)$$

where λ the thermal conductivity [$W.m^{-1}.K^{-1}$], l the thickness of the materials [m], A the surface of the solid perpendicular to the heat flux [m^2] and ΔT [°C or K] is the temperature difference between the two sides of the solid.

Therefore, decreasing the density of the heat flux through a building envelope can be achieved either by implementing thick insulation materials or by selecting materials with a low thermal conductivity.

In contrast, in convection, the heat is transferred by the movement of molecules inside a fluid. It is very common in gases and liquids. The constitutive law is the Newton's Law, expressed as follows:

$$q = -h_c.\Delta T \qquad (2.3)$$

where q the density of heat flux [$W.m^{-2}$], h_c the convective heat transfer coefficient [$W.m^{-2}.K^{-1}$] and ΔT the temperature difference [T or K] .

Radiation is a heat transfer due to electromagnetic radiation between surfaces which are not in contact. The flux emitted by a surface, due to radiation effects is expressed with the Stefan-Boltzmann relation:

$$q = h_{\mathrm{r}}.(T_{\mathrm{s}} - T_{\mathrm{me}}) = \varepsilon.\sigma.(T_{\mathrm{s}}{}^4 - T_{\mathrm{me}}{}^4) \qquad (2.4)$$

where and h_r the radiative heat transfer coefficient [W.m^{-2}.K^{-1}], T_s the surface temperature [K] and T_{me} the temperature of the ambient air [K], ε the emissivity [-], σ the Stefan Boltzmann constant (σ.=5.670.10^{-8} W.m^{-2}.K^{-4}). ε is a number between 0 and 1 which represents the capacity of a material to emit radiation.

2.3 Traditional Insulation Materials versus VIPs

According to the European Insulation Manufacturers Association (EURIMA 2006), the European insulation materials market is currently composed for 60% of inorganic fibrous materials: glass and stone wool, and for 27% of organic foamy materials: polystyrene (EPS and XPS) and polyurethane. Thus, the use of “conventional insulation materials”, materials with a thermal conductivity higher than 0.025 W.m^{-1}.K^{-1} is widely developed across Europe (Bouquerel et al. 2012a). Mineral wool, expanded polystyrene (EPS), extruded polystyrene (XPS), polyurethane (PUR), loose-fill cellulose and cork are the most commonly used ones. Their thermal conductivity ranges from 0.025 W.m^{-1}.K^{-1} for the PUR to 0.050 W.m^{-1}.K^{-1} for the cork (Jelle 2011). Their robustness and adaptability on site are greatly appreciated by home designers. Moreover, they can be perforated without reducing their thermal properties.

Recently, in Sweden, various passive houses have been achieved with a conventional insulation system. For instance, the external insulation of the façade of a passive house, outside Linköping was made of mineral wool and EPS. The external wall consists of prefabricated structural wood wall elements, insulated with 20 centimeters of EPS, supplemented with mineral wool insulation on the outer and inner face. The total insulation thickness is more 44 than centimeters (Gross 2010). In the same way, the houses from Brogården in Alingsås, built during the Million Program, between 1963 and 1975, were the first multi-family houses to reach the passive houses standards. To achieve it, the renovation measures consisted in changing the façade, setting efficient doors and windows and better insulate the balconies. The old brick façade was demolished and new walls were erected and insulated with 44 centimeter of mineral wool (Energi Princip n.d).

Therefore, in order to achieve the new thermal regulations, the insulation thickness required becomes thicker and thicker. Indeed, it is now usual to implement insulation system of more than 30 centimeters. Today, the conventional materials are opposed to what is called the “super insulation materials”, materials with a thermal conductivity below 0.025 W.m^{-1}.K^{-1} which enable thinner insulation systems (Bouquerel et al. 2012a). Their properties are compared in Figure 2.2.

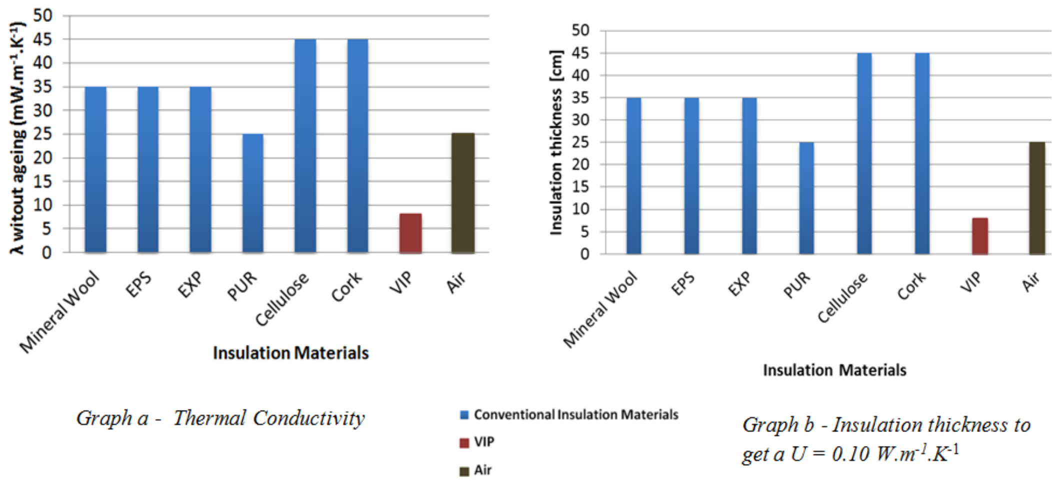

Figure 2.2 Thermal properties of Insulation Materials (adapted from the values from Jelle 2011)

The thickness required to get a U value of 0.10 W.m^{-2}.K^{-1}, which is considered as an efficient value for a passive house's façade largely differs from a material to another (Gross 2010). The VIPs allow an 8 centimeter thickness whereas the use of mineral wool constrains to insulation four times bigger. In comparison, 600 centimeters of bricks would be necessary to obtain the same insulation efficiency. One of the main explanations is exposed in Figure 2.3 which represents the heat transfer in conventional insulation materials. The gas conductivity (blue line) takes an important part in the heat transfer. The gas conductivity is possible when some pressure stands inside a material, which is not the case in VIPs when a very low pressure is maintained.

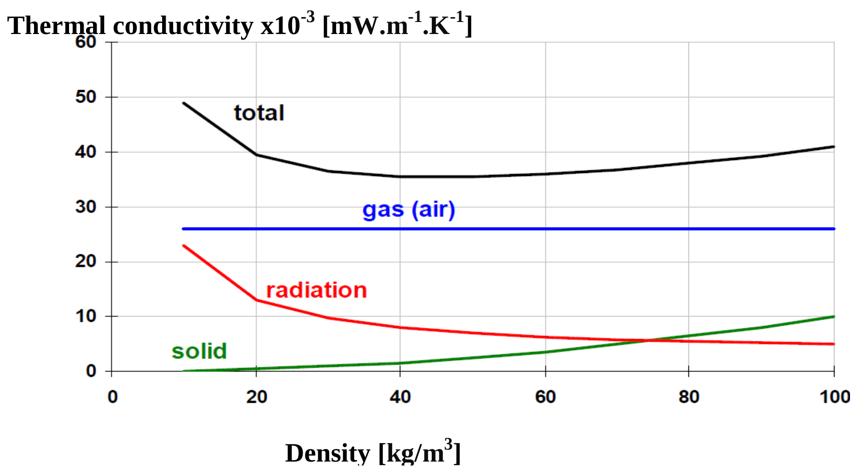

Figure 2.3 Heat transfer in conventional insulation materials (Simmler et al. 2005)

Therefore, the main advantage of VIPs is their high thermal performance with smaller thickness than with conventional materials. In the case of external insulation, the thickness of the thermal insulation is usually not problematic since it does not affect the living space. However, when an internal insulation is implemented, the thinner the system is the better. The internal insulation is mainly set up to protect building façades with historical features or for aesthetics reasons. Moreover, in most parts of Europe, urban areas face high real estate prices. Therefore, the living space is valuable and the insulation thickness is limited. In this case, the use of VIPs represents a great advantage. For instance, when considering a room of 10 meters by 5 meters and the insulation thickness described in Figure 2.2, we can get an idea of the surface saving: if the walls are internally insulated with 35 centimeters of mineral wool, EPS or XPS, the available living area will be 36.1m^2 whereas with 8 centimeter VIPs the surface will be 30% larger.

2.4 The Insulation Systems

Insulation systems are set up on exterior walls, ground floor, in attic, around non heated locals and in every element in contact with the outside. For exterior walls, there are mainly two options: internal or external insulation. Both systems face the same challenges which are principally the reduction of thermal bridges and the risk of moisture and mould growth. The following sections present these risks and draw a short comparison between internal and external insulation.

2.4.1 Thermal bridges

Thermal bridges mean the areas where a material with conductive properties or low thermal properties comes in contact with a material with better thermal properties (Abel and Elmroth 2007). Thus, most of the thermal bridges are found at structural junctions between different materials. These junctions can be the areas with plane change (wall with cantilevered balconies) or with partition change (between walls and roof or walls and windows). These thermal bridges can be calculated as follow (Abel and Elmroth 2007):

$$\Sigma\psi_{\mathrm{k}}.\,l_{\mathrm{k}} \tag{2.5}$$

where ψ_k [W.m^{-1}.K^{-1}] is the linear thermal transmittance for thermal bridges of type k and l_k [m] the length of this thermal bridges. All the different thermal bridges of a wall must be added to get an overall value. The ψ-values can be found in many handbooks.

There are also point thermal bridges to consider. They are created by the fixation systems used to fix the insulation to the building. Their values are denoted X [W.K^{-1}] and can found in many handbooks (Abel and Elmroth 2007).

The overall linear and point thermal bridges effects must be considered when calculating the average thermal transmittance of the building envelope, U$_m$ as follow (Boverket 2011):

$$U_{\mathrm{m}} = \frac{\sum Ui.Ai + \sum \psi\mathrm{k.lk} + \sum Xj}{A_{\mathrm{om}}} \tag{2.6}$$

Where U_m is the average U-value of the building envelope [W.m^{-2}.K^{-1}], U_i the U-value for a single part of the building envelope [W.m^{-2}.K^{-1}] and A_i its surface [m²], ψ_k the thermal transmittance for the linear thermal bridge k [W.m^{-1}.K^{-1}] and l_k its length [m] X_j the point thermal bridges j [W.K^{-1}] and A_{om} the overall surface [m^2].

The thermal bridges have two major consequences: a rising heat flow through the building envelope and a depletion of the surface temperatures (see Figure 2.4) (Hagentoft 2001).

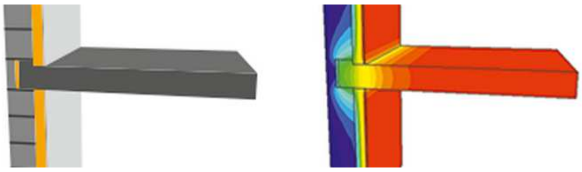

Figure 2.4 Example of a thermal bridge between a wall and a slab. The wall in made of concrete blocks with a gypsum board of one-centimeter thick. Red represents the warmer surfaces whereas blue represents the colder surfaces, one can observed that the junction is colder than the rest of the wall and slab. (source: www.cellumat.fr 2013)

The low surface temperatures are problematic. Indeed, if the surface temperature is lower than the dew point, then condensation occurs. For instance, with an indoor temperature of 20°C a relative humidity of 60%, the dew point is only 11.8°C, a temperature that can easily be reached on a poorly insulated concrete wall (Pouget 2011). According to the Fourrier law, the surface temperature, T_s [°C], is expressed as follows:

$$T_s = T_i - \frac{\mathrm{Rsi}}{\mathrm{Rtot}}.(T_i - T_e) \qquad (2.7)$$

where T_i is the indoor temperature [°C], T_e the outdoor temperature [°C], R_{si} the thermal surface resistance at the inner surface [$m^2.K.W^{-1}$] and R_{tot}, the total resistance of the structure [$m^2.K.W^{-1}$]. The usual value of R_{si} is 0.13 $m^2.K.W^{-1}$ (Abel and Elmroth 2007). Equation 2.7 underlines the influence of the insulation quality.

We are used to condensation on windows, where the insulation is weak, because the liquid water is visible. However, although the condensation is invisible on porous materials such as walls, the consequences are serious. Wet surfaces are more likely to attract solid particles, such as dust so mould will develop. Mould can cause various health hazards. Moreover, the thermal bridges can lead to an unjustified heat demand and extra energy consumption if the thermostat, used to regulate the interior conditions, is placed on cold surfaces.

Therefore, it is important to reduce the thermal bridges effects to achieve a good building envelope and thermal comfort for the building occupants. According to Abel and Elmorth (2007), the overall effects of the thermal bridges cause till 20-30% of the total heat losses of a building.

2.4.2 Mass transfer through the exterior walls

The external walls are subject to numerous humidity sources: water vapour in outdoor and indoor air, rain falls, leakages, moisture from the ground, and occupants' indoor activities such as breathing, cooking and showering. The walls are porous materials so they can transfer and store humidity. However, a high relative humidity and water content can damage the materials. It is therefore important to control the moisture behavior in walls.

In this report, the relative humidity is denoted φ [%] and the water vapour content is denoted ω [$kg.m^{-3}$]. They are calculated as follows:

$$\boldsymbol{\varphi = \frac{v}{vs}} \qquad \boldsymbol{\omega = \frac{mass\ of\ moisture}{1\ m^3\ of\ gas}} \qquad (2.8 – 2.9)$$

where v is the humidity by volume [kg.m^{-3}] and v_s the humidity by volume when the saturation point is reached [kg.m^{-3}].

In façade walls, three different moisture transfer modes can be identified:

- The water vapour diffusion
- The water vapour convection
- The capillary suction

They can occur at the same time but not necessary in the same direction.

The water diffusion is due to a difference of vapour concentrations between two sides of a wall. The diffusive flux is expressed with the Fick's law as follows (Hagentoft 2001):

$$g_{\mathrm{d}} = -\delta_{\mathrm{v}} \,.\, \frac{v_1 - v_2}{l} \qquad (2.10)$$

where g_d is the diffusive flow [kg.m^{-2}.s^{-1}], δ_v the vapor permeability [m^2.s^{-1}], v_1 and v_2 is the humidity by volume on the first and second side [kg.m^{-3}] and l is the width of the layer [m].

The Fick's law is analogous to the Fourrier's law. In the same way, a water resistance, Z_v can be defined as $Z_v = \frac{d}{\delta v}$ [s.m^{-1}]. Furthermore, the equation is only valid if $v < v_s$. Then, the saturation point is reached and condensation occurs.

The water vapour convection is due a difference in air pressure caused by winds, ventilation or thermal driving forces. This pressure difference between the internal and external side of a wall leads to air flow through the building envelope which is not perfectly airtight. The flux is from high pressure to low pressure and it is calculated as follows (Abel and Elmroth 2007):

$$g_{\mathrm{c}} = L\,(v_{\mathrm{i}} - (v_{\mathrm{s}})_{\mathrm{e}}) \qquad (2.11)$$

where L is the air flow through the structure [m^3.m^{-2}.s^{-1}], v_i is the humidity by volume inside the structure [kg.m^{-3}] and $(v_s)_e$ is the humidity by volume at saturation point on the cold surface [kg.m^{-3}].

As a consequence, in winter the moisture transfer is usually transferred from the internal to the external side whereas, in summer, it is in the opposite direction. Thus, condensation is likely to occur in winter since there is a high risk that the air goes through temperatures inferior to their dew point. Condensation is especially important when there are cracks or holes in the walls (Abel and Elmroth 2007).

Each material has its own resistance to water vapor diffusion. It is a no dimensional number denoted μ. In order to evaluate, the water vapor diffusion of a material, a diffusion thickness, s_d, expressed in meter is calculated as follows:

$$s_{\mathrm{d}} = \mu \,.\, l \qquad (2.12)$$

where l is the thickness of the materials [m].

Vapor barrier has high value s_d whereas materials that are water permeable have low s_d value. This risk of condensation can be avoided in a construction opened to water diffusion, its materials should have a decreasing resistance from the internal to allow drying to the external side. Vapour barrier on the internal side can also be a solution.

The capillary suction is due to a difference in moisture content. It is strongly depending of the materials properties as proven by the following expression of the flux due to capillary suction (Hagentoft 2001):

$$g_s = \frac{A.B}{2.l} \tag{2.13}$$

where A is the water sorption coefficient [kg.m^{-2}.s$^{-0.5}$], B the water penetration coefficient [kg. m^{-2}] and l the thickness of the materials [m]. The values for A and B are found in handbooks.

Most of building materials withstand temporary condensation. Nevertheless, for longer periods, condensation can decrease the thermal and structural properties of materials. In particular, condensation increases the thermal conductivity of insulation materials. In cold areas, if the water inside the wall freezes, deformations, cracks and failures can occur. Moreover, condensation also causes mould growth. However, it is important to notice that mould growth can start before condensation appears, when the relative humidity exceeds a limiting value, usually 70% (Abel and Elmroth 2007).

As a consequence, a critical moisture levels should not be overstepped. The critical moisture condition is the limit over which changes in materials occurs. It depends of each materials and it is usually expressed as φ_{crit} [%], the critical relative humidity or ω_{crit} [kg/m^3], the critic water content.

Moisture induces changes in materials such as changes of their properties: strength, creep, thermal conductivity or physical, chemical and biological deterioration. It can also cause discolouring, unwanted swelling, shrinkage, smell and even health risks.

Re-insulating existing walls will change their moisture conditions and behavior. Therefore, before implementing any new insulation systems, it is essential to deeply understand the wall behavior and to foresee the consequences in terms on relative humidity and water content inside the walls. The changes in term of structural and thermal properties in materials must be controlled.

2.4.3 Internal or external insulation

A building façade can be insulated from the inside or from the outside. Figure 2.5 presents the main difference of the two systems and how the thermal and hygrothermal conditions differ between both cases.

Concerning the façade retrofitting, external insulation presents many advantages over internal insulation. It is usually more easily implemented since it can be installed without disturbing the building inhabitants. The thickness of the insulation system is less problematic because it will not lead to any space living loss and the thermal bridges are better reduced. Nevertheless, external insulation cannot always be implemented, for instance when the façade is protected for historical purposes but internal insulation is not usually recommended. The thermal bridges effects cannot really be suppressed and the moisture transfer is more problematic. The outer part of the façade which is not protected gets colder because the inside part of the wall is insulated (see Figure 2.5). As a consequence, the façade is more likely to be subjected to the action of freeze and thaw and to develop mould growth. However, various solutions are already available and broadly used to reduce these harmful effects, such as the use of vapour barrier or the setting of radiators close to the windows. It is also possible to entirely re-insulate a room from the slab to the ceiling. In this “box in the box", the thermal bridges are suppressed (Plouget). The choice of the type of insulation depends on every project.

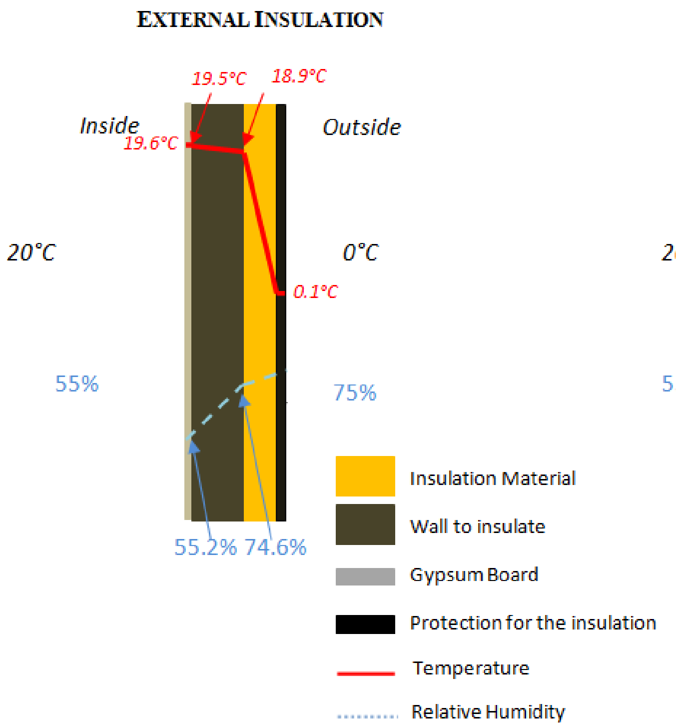

Figure 2.5 Principal differences between an internal insulation and an external insulation

Table 2.1 summarizes the main characteristics of both insulation systems.

Table 2.1 - Comparison between internal and external insulation system (adapted from Gallauziaux and Fedullo 2010)

TECHNICAL CRITERIA	INTERNAL INSULATION		EXTERNAL INSULATION	
THERMAL INERTIA	-	The thermal inertia of the wall cannot be used	+	The heat can be accumulated in walls which improve the indoor conditions
THERMAL BRIDGES	-	There will still be thermal bridges	+	They will be almost completely disappeared
PROTECTION AGAINST THE DRIVING RAIN	≈	The external wall does not let the water to reach the insulation system	+	The external layer of the insulation system offers an efficient rain protection
DRYING OF THE EXTERNAL WALL	-	The wall dries more slowly in winter and the water penetrates deeper in the wall. During winter, if the water is not evaporated, there is a risk of froze and therefore degradation of the wall.	+	The external wall is protected from the rain and its temperature is rather constant all around the year.
HUMIDITY	-	The risk of condensation must be handled. The use of vapour barrier can be the solution	≈	Humidity must be able to move to the outdoor through the insulation system.

3 Thermal properties of the VIPs

3.1 Description of the VIPs

VIP stands for Vacuum Insulation Panel. It is a rather new insulation system introduced in the building sector in the 1990s when insulation systems containing harmful gases had to be replaced (Brunner et al. 2012). They were firstly developed in the sixties to insulate different cooling systems such as fridges, refrigerators or shipping boxes. Indeed, the very small thickness of these panels enabled the preservation of extra storage (Fricke et al. 2008).

They are considered as a promising state-of-the-art insulation material since their thermal conductivity is very small. It ranges from 3 to 8 $mW.m^{-1}.K^{-1}$ in the center of a prestine panel (Berge and Johansson 2012). This is up to 10 times less than the corresponding number of equally thick conventional insulation materials such as mineral wool or expanded polystyrene (Baetens et al. 2009). These excellent thermal properties are mainly due to the very low gas pressure maintained inside the panel.

The VIPs should be considered as a thermal insulation system made of two components: a filling material, the core, encapsulated in a thin barrier envelope.

The core can be made of different materials: glass wool, polyurethane, polystyrene or silica (Berge and Johansson 2012). However, since it is essential to keep the vacuum and prevent any pressure increase to preserve the good thermal conductivity, the best materials are the one which are less sensitive to pressure increase. Thus, nanostructured porous materials fit the best. In Europe, fumed silica (SiO_2) also called pyrogenic silica in some reviews, is the most commonly used material. It is produced with the pyrolysis of silicon tetrachloride ($SiCl_4$), a material usually used in the semi-conductor industry (Berge and Johansson 2012). Compared to the other possible materials, it has the advantages to have a lower thermal conductivity at higher internal pressure. Their thermal conductivity varies from 0.003 $W.m^{-1}.K^{-1}$ when new, at a very low pressure, to 0.020 $W.m^{-1}.K^{-1}$ at atmospheric pressure (Simmler et al. 2005). In the sections that follow, only VIPs with fumed silica will be described.

The envelope plays an essential role since it maintains low gas pressure inside the core, initially around 0.2-3 mbar. There is no existing envelope that is perfectly air tight which leads to an irreversible pressure increase and the ageing of the panels. Two types of envelopes are usually described in the literature: the aluminium foil (AF) and the multi-layered polymer laminate (MF) (see Figure 3.1). However, these names are not generic names and the exact meaning of AF and MF is specified in each report.

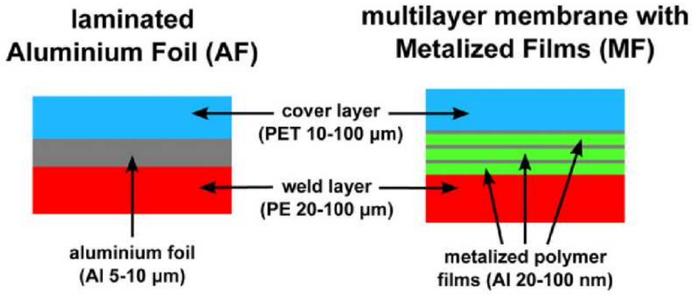

Figure 3.1 Design of VIPs envelope: Aluminium Foil and Metalized Films (Bouquerel et al. 2012a)

The AF membrane is made of laminated aluminium foils of 5-10 μm protected by two different materials. On the exterior side, the cover layer is usually made of PET[2] (represented in light blue in Figure 3.1) and on the interior side, the weld layer is, in most cases, made of PE[3] (in red in the Figure 3.1) (Bouquerel et al. 2012a). These aluminium foils have a very low gas and water vapour permeation rate (Baetens et al. 2009) but due to the high thermal conductivity of pure aluminium layer, around 210 $W.m^{-1}.K^{-1}$, the overall envelope is highly conductive (Binz et al. 2005). Historically, the AF membranes were the first kind of envelope used. Nevertheless, due to their bad thermal properties, the MF envelopes are now preferred (Simmler and Brunner 2005)

The MF membrane uses metalized multi-layers polymer films, usually produced with aluminum. This type of laminates encloses a high density of defects, mainly pinholes, which decrease the air tightness of the envelope. Consequently, several foils are required to limit permeation phenomenon (Bouquerel et al. 2012a). Furthermore, the permeation properties can be improved by adding layers of inorganic material on the polymer films, for instance a layer of 10-100 nm of silica, metal oxide or pure metal or by integrating special getter to the systems. Getters are a material that continually absorbs gases (Bouquerel et al. 2012b). As the AF membrane, the MF membrane is coated with a cover layer usually made of PET and with a PE weld layer. Today, most of the MF membranes are made of three metalized polymer films with a thickness of 30-100 nm each. The MF membranes reach a life span of more than 50 years since the exterior conditions in which they are used are not extreme. Indeed, oxidation might damage the very small foils and so affect the total service life of the envelope. However, oxidation effects get critical only for high humidity levels (superior to 60%) and high temperatures (above 80°C). These conditions are not the ones of building applications.

In order to improve their mechanical properties, VIPs are often used encapsulated, in structural sandwiches or with edge spacers.

VIPs can be encapsulated with EPS or mineral wool so they get extra protection against mechanical damages. There are two types of encapsulated panels: the panels wrapped with insulation materials on every side and the panels encased only on one or both surfaces. This system enables some adjustments on the construction site since the edges on the panels can be slightly cut. Furthermore, the thermal bridges effects due

[2] PET : Polyethylene Terephthalate
[3] PE : Polyethylene

to the envelope are reduced (Tenpierik 2009). Wrapping VIPs in such a way does thicken the size of the whole insulation system. Nevertheless, the system remains thinner than with the use of only conventional materials. For instance, Nussbaumer *et al.* (2005) used a 60 mm insulation system made of 40 mm-thick insulation panels encapsulated in EPS. If they had only used EPS, the total thickness of the insulation would have been 3.5 times bigger.

The use of VIPs integrated in sandwich components also improves their protection. The sandwiches are made of thin tape or a weak profile, in concrete or in non-metallic materials that do not have any structural properties. Besides, the thermal conductivity is very good and the system very thin although additional structural elements are required (Tenpierik 2009).

The spacer panels are VIPs whose top and bottom facing are linked with edge spacers. Unlike the sandwiches, these spacers have structural properties used to connect the VIPs to the load bearing structure (Baetens et al. 2009). The overall system is thinner than sandwich VIPs. However, the space edges cause more thermal losses and the spacers have to be chosen carefully. More details are given in section 3.2.5.1. The spacer panels are often used as an insulation façade system and their thermal properties can be improved by the use of double layered VIP (Brunner et al. 2012b).

3.2 Heat transfer in VIP

As pointed out in Figure 2.2, VIPs have a very low thermal conductivity compared to conventional insulation systems. It is due to their composition which leads to a reduction of each component of the thermal conductivity.

In VIPs, the three heat transfer processes: radiation transfer, solid conduction and gaseous transfer have been identified (Bouquerel et al. 2012a). The transfer due to the thermal bridges inside and between the panels must also be taken into account. Thus the thermal conductivity of a VIP can be estimated as the sum of different values as follows:

$$\lambda_{\text{vip}} = \lambda_{\text{cop}} + \psi_{\text{vip}}.d.\frac{p}{A} \tag{3.1}$$

$$\text{with} \quad \lambda_{\text{cop}} = \lambda_{\text{rad}} + \lambda_{\text{sol}} + \lambda_{\text{g}} \ (+\lambda_{\text{cpl}}) \tag{3.2}$$

where λ_{vip} represents the overall thermal conductivity of a VIP, λ_{cop} the one of the core and $\psi_{vip} \,.\, d \,.\, \frac{p}{A}$ the one of the envelope due to thermal bridges effects, λ_{rad} stands for the radiation transfer, λ_{sol} for the solid conduction, λ_g for the gas conduction and λ_{cpl} for the coupling effects (Bouquerel et al. 2012a). All the processes are represented in Figure 3.2 specified in the following to better understand the potentials and challenges related to the use of VIPs.

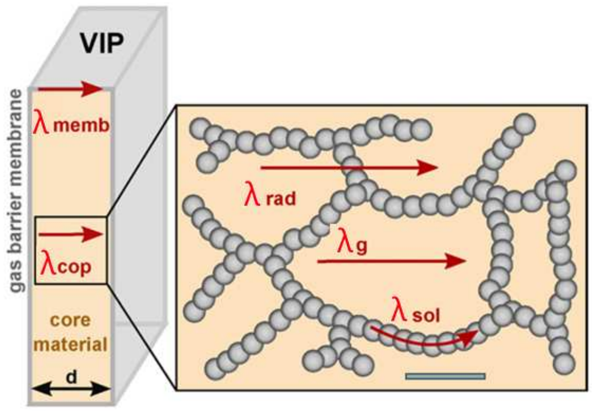

Figure 3.2 Heat transfer through a VIP: influence of the different thermal conductivities (adapted from Bouquerel et al. 2012a)

3.2.1 Radiation heat transfer

The transfer due to radiation is from the gray Rosseland approximation. In most reports, it is calculated as follows (Bouquerel et al. 2012a):

$$\lambda_{rad} = \frac{16}{3} \cdot \frac{\sigma\, n^2\, T_r{}^3}{E_{(T)}} \tag{3.3}$$

where σ = 5.67.10^{-8} W.m^{-2}.K^{-4} is the Stefan-Boltzmann constant, n is the refraction index (for fumed silica, n≈1), T_r is the Rosseland temperature expressed by $T_r{}^3 = \frac{T_1{}^2+T_2{}^2}{4}.(T_1+T_2)$ (T_1 and T_2 are the temperature on the VIP surfaces) and $E_{(T)}$ is the transport extinction coefficient.

For fumed silica, λ_{rad} ranges from 0.001 to 0.004 W.m^{-1}.K^{-1} at 1 mbar pressure. With the use of opacifers, this value decreases to 0.001 W.m^{-1}.K^{-1} (Baetens et al. 2009).

3.2.2 Solid Conduction

Empirical modeling with a guarded hot plate apparatus has established the following dependence between the thermal conductivity due to solid conduction, λ_{sol}, and the temperature, T, for fumed silica filling materials (Bouquerel et al. 2012a):

$$\lambda_{sol} = 0.021(-8.5.10^{-12}.T^4 + 2.1.10^{-8}.T^3 - 1.95.10^{-5}.T^2 + 0.00883.T) \tag{3.4}$$

The value “0.0021” refers to a coefficient proper to fumed silica.

Usually, for core made of fumed silica, λ_{sol} varies between 0.0021 and 0.0034 W.m^{-1}.K^{-1} (Baetens et al. 2009)

Given that both radiation and solid transfer are temperature dependent, Baetens (2009) combines equations 3.3 and 3.4 to calculate the thermal conductivity due to both solid conductivity and radiative transfer:

$$\lambda_{sol} + \lambda_{rad} = (0.0124.T + 0.0808).10^{-3} \tag{3.5}$$

Thus, the temperature influences the radiative transfer and the solid conduction. Simmler *et al.* (2005) have investigated the temperature effects on the thermal conductivity: an increase in temperature leads to a rise of the conductivity. However, in the range of the usual conditions of temperature in which a building is in use, this influence is not significant.

3.2.3 Gaseous Transfer

Gaseous conduction is the main component of the heat transfer in conventional insulation materials (see Figure 2.3) and accounts for more than half of the thermal conductivity value. It is due to the presence of non-convective gas within the materials hollows. There is so a great potential to reduce the heat transfer by limiting gaseous conduction.

Simmler *et al*. (2005) has studied the thermal conductivity of air due to gas conductivity and it appears that it is a function of the gas pressure and the pore diameter of the materials (see Figure 3.3). In particular, it decreases when the pores size are small and the inside gas pressure is low.

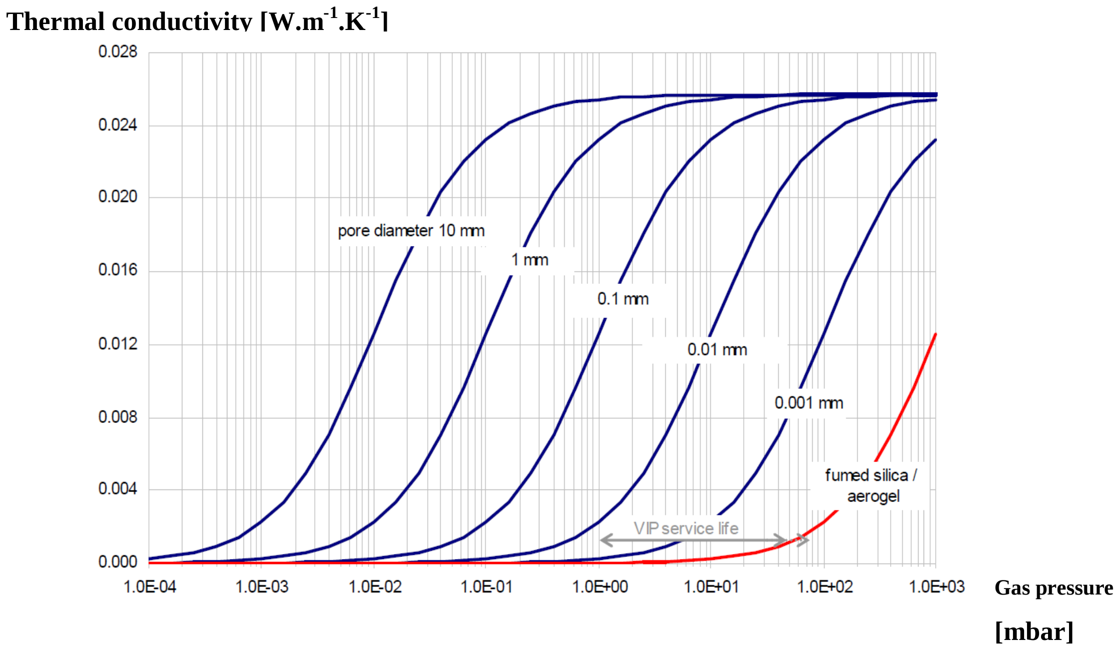

Figure 3.3 Thermal Conductivity of air due to gas conductivity as a function of pore diameter (Simmler et al. 2005)

For VIPs, a very effective measure would be to reach a perfect vacuum inside the VIP or at least to strongly decrease the internal gas pressure to only a few mbar. Indeed, when the inside pressure decreases, the mean free paths of particles, that is to say the average distance they travel between successive impacts, is longer. Thus, fewer collisions between particles can take place and the λ_g value decreases. In VIPs, the gas pressure is between 0.02 and 3 mbar which corresponds to a gas thermal conductivity of approximately 0.003 $W.m^{-1}.K^{-1}$ (Berge and Johansson 2012). Moreover, thanks to the very tiny size of the silica pore, even at atmospheric pressure, the core has a low gas thermal conductivity, around 0.020 $W.m^{-1}.K^{-1}$. Indeed, as represented in Figure 3.3, the gas conductivity decreases also with the pore size of materials. Very low λ_g

values can be obtained when the size of the largest pore of the material is in the same order of magnitude as the free mean path of the gas. Thus, the molecules can only collide with the pores surface.

In most reports and experiments, The Knudsen effect which emphasizes these two characteristics is used to calculate λ_g (Baetens et al. 2009). In porous materials, λ_g is written as follows:

$$\lambda_g = \frac{\lambda_{g,0}}{1+2.\beta.K_n} = \frac{\lambda_{g,0}}{1+\frac{P_{½}}{Pg}} \qquad (3.6)$$

where $\lambda_{g,0}$ is the thermal conductivity of free air [W.m^{-1}.K^{-1}], K_n the Knudsen number and a β constant between 1.5 and 2.0 depending on the gas, the solid material and the temperature, $p_{1/2}$ represents the pressure at which the air thermal conductivity in the material is half the one of the still air and p_g is the gas pressure in the VIP.

The Knudsen number is a dimensionless ratio between the mean free path of the air molecules: l_{mean} and the characteristic pores diameter of the core: δ. It is calculated as follows:

$$K_n = \frac{l_{\text{mean}}}{\delta} \qquad (3.7)$$

Equations 3.6 and 3.7 show in detailed how the inside gas pressure of a materials, its pore size and the free mean path of air molecules are linked. In VIPs, since the free mean path of atmospheric gas molecules is larger than the characteristic pore size, the free gas thermal conductivity is consequently reduced (Simmler and Brunner 2005).

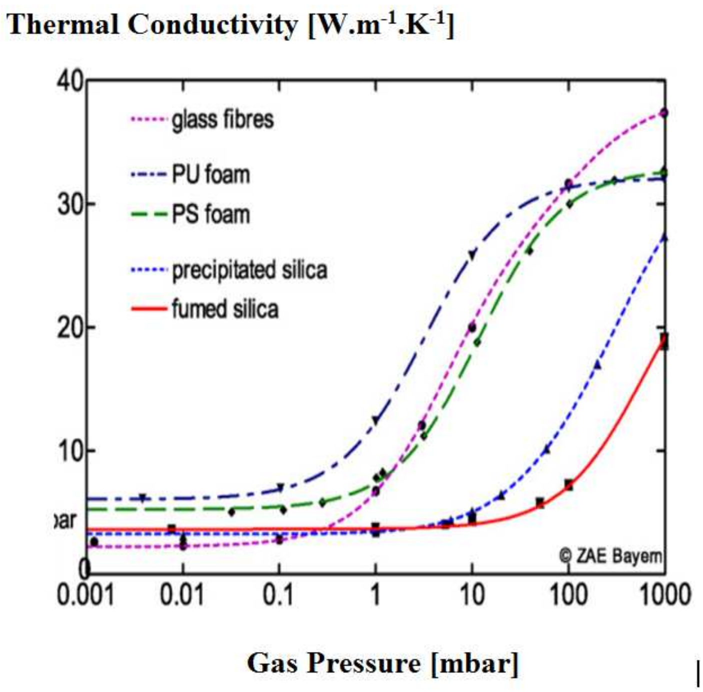

Figure 3.4 Thermal conductivity of several porous materials as a function of gas pressure at 20°C (Simmler et al. 2005)

As a consequence, VIPs have a higher thermal potential compared to conventional materials (see Figure 3.4). Indeed, their gas conductivity significantly increases only when gas pressure is superior to 10 mbar whereas this limit is lessened to 0.1 mbar for different foams and glass fibers materials.

However, the Knudsen effect underlines an important weakness of the system: the envelope around the filling materials should be airtight enough so the service life of the panel can be extended. Obviously, a perfect airtight envelope is impossible to obtain and the air and vapour permeation that the envelope allows is one of the main ageing factors. More detailed are given in section 3.2.5.2.

3.2.4 Coupling Effects

The coupling effects, λ_{cpl}, are a rather complicated phenomenon (Baetens et al. 2009). In most reports, λ_{cpl} is neglected which simplify the VIP's heat transfer model: every heat transfer will be considered as caused independently. In reality, it is not the case, especially in filling materials where the radiative transfer is important. There, the coupling effects can greatly influence the total value of the thermal conductivity. However, Bouquerel *et al.* (2012a) point out that, in fumed silica, the coupling effects can be neglected without leading to significant errors.

Thus, the overall thermal conductivity of the core, in the center of a pristine panel, ranges from 0.003 and 0.008 $W.m^{-1}.K^{-1}$ (Berge and Johansson 2012). The advised design value is 0.008 $W.m^{-1}.K^{-1}$ for panels smaller than 1m x 1m (Simmler et al. 2005). However, this value increases with the thermal bridges due to the envelope.

3.2.5 Heat transfer through the envelope

The envelope is responsible of two phenomenons that lead to an increase of the thermal conductivity: thermal bridges and permeations of air and water vapour. These phenomenons are described in the following.

3.2.5.1 Thermal bridges

The barrier is responsible of thermal bridges, also called edge effects which reduce the thermal performance of the VIPs. These thermal bridges are mainly due to the continuity of the thin envelope which is in contact with the cold and the warm side of the VIP and also due to the small air gaps between two adjacent panels. The heat losses are more consequent through the corners and edges of the panels (Baetens et al. 2009). The following expressions can be used to calculate their effects (Binz et al. 2005):

$$\psi_{\text{vip}}.\, d.\frac{p}{A} \qquad (3.8)$$

where ψ_{vip} [$W.m^{-1}.K^{-1}$] represents the linear thermal transmittance, d [m] represents the thickness of the panel in the heat flux direction, p [m] the perimeter of the panel surface A [m^2].

The linear thermal transmittance, ψ_{vip} , is a measure of linear thermal bridges. It is function of the envelope material, its effective thermal conductivity, its thickness, the type of seams and the materials immediately surrounding the VIP (Binz et al. 2005). Many experiments have been carried out to estimate the linear transmittance and

Simmler and Brunner (2005) advise a design value of 0.007 $W.m^{-1}.K^{-1}$ for an AF envelope and of 0.01 $W.m^{-1}.K^{-1}$ for a MF envelope.

Bouquerel *et al.* (2012a) have investigated different configurations of panels to figure out the thermal conductivity due the edge effects. Their findings are reported in Table 3.1.

Table 3.1 Thermal conductivity due to edge effects (adapted from Bouquerel et al.2012)

Type of membrane	Aluminium Thickness	Size [m.m.m]	$\psi_{vip} \cdot d \cdot \frac{p}{A}$	$\psi_{vip} \cdot d \cdot \frac{p}{A} / \lambda_{cop}$ [%]
MF	90 nm	1 x 1 x 0,02	**0,6**	13
MF	300 nm	1 x 1 x 0,02	**0,7**	19
MF	60 nm	1 x 1 x 0,02	**0,1 - 1,1**	3-27
MF	-	0,9 x 0,9 x 0,02	**2,1**	38
MF	3 x 100 nm	1 x 1 x 0,02	**1**	25
MF	3 x 100 nm	1 x 1 x 0,03	**1,2**	30
AF	8 µm	1 x 1 x 0,018	**3,8**	96
AF	9 µm	1 x 1 x 0,02	**3,3-4,4**	66-88
AF	8 µm	1 x 1 x 0,02	**3,4-8,4**	89-210
AF	-	0,9 x 0,9 x 0,02	**6,7**	120

The MF envelopes produce less thermal bridges than AF membranes so this type of VIPs reaches better thermal efficiency. As displayed in Table 3.1, when taking into account the edge effects from the envelope, the total thermal conductivity might double compared to the single conductivity of the core. This is mainly due to the composition of the envelope: the effective thermal conductivity of an aluminium envelope is around 200 $W.m^{-1}.K^{-1}$ whereas the polymers conductivity only ranges from 0.1 to 0.5 $W.m^{-1}.K^{-1}$ (Bouquerel et al. 2012a).

The thickness of the membrane should also be considered. Although, table 3.1 does not point out any clear results, other studies have underlined a link between a thinner envelope and smaller edge effects (Baetens et al. 2009).

Another important factor is the size of the panel. Indeed, to decrease the edge effects, it is possible to minimize the ratio $\frac{p}{A}$ by using large square-shaped VIPs rather than smaller rectangular-shaped ones. A general recommendation advices the use of panels bigger than 0,50 m x 0.50 m (Binz et al. 2005). Thus, large panels should always be preferred.

On the scale of the whole systems, thermal bridges due to edge spacers should be considered. When not used in sandwich, the component facings of the VIPs are mechanically jointed with edge spacers. The Subtask B of the Annex 39, an internal research project on VIPs, proposes a detailed study of the influence of the edge spacer (Binz et al. 2005). It reveals that aluminium spacers are not suitable because of a linear transmittance which ranges from 0.010 to 0.020 $W.m^{-1}.K^{-1}$ (Baetens et al. 2009). Plastic spacers or reinforced non-metallic tapes offer better performance.

3.2.5.2 Permeation of gas and water vapour

Since it is impossible to manufacture a perfectly airtight envelope to wrap in the filling material, the inside pressure will continually increase over the time due to permeation of air and water vapour. The moisture and gas pressure rise leads to a deterioration of the thermal properties of the VIPs also called the “ageing effects”.

Therefore, it is crucial to select envelope with small permeation rate. The permeation rates are usually separated in Gas Transmission Rate (GTR) and in Water Vapour Transmission Rate (WVTR). Many studies has been carried out to determine the permeation rates of the current membranes and to evaluate the higher rates that can occur without compromising the VIP life expectancy. For a typical VIP with a MF envelope, the GTR is around $2\text{-}5.10^{-10}$ m^3(STP[4])/m.day at 50% relative humidity and the WVTR around $1\text{-}5.10^{-6}$ kg/ m^2.day (Baetens et al. 2009). The air permeation is a bigger in the corners of VIPs (Simmler et al. 2005).

The water vapor penetration is a major problem since it causes both pressure and mass increase. However, due to their high porosity, silica materials have some hydrophilic properties which explain their sensitivity to water content changes. The presence of water inside the silica core leads to conduction due to water vapour and to absorbed water (Bouquerel et al. 2012a). A linear correlation between the total thermal conductivity of the VIPs and the mass content u [kg/kg] has been established by Simmler *et al*. (2005). Thus, in order to take into account the influence of the water mass increase, the supplementary term: “0,0024.u” should be added to Equation 3.2 (see Equation 3.10), u is the water mass increase. After many experiments, a saturation level has been noticed. The water mass content stabilizes between 0.03 and 0.07 kg/kg which means a thermal conductivity increase of 0.0015-0.0035 $W.m^{-1}.K^{-1}$(Baetens et al. 2009).

The increment of gas pressure has also been established as a linear relation. It mainly intervenes through the gaseous transfer. An increase of 30mbar of dry gas pressure contributes to a thermal conductivity increase of 0.001 $W.m^{-1}.K^{-1}$ (Baetens et al. 2009). Since, no saturation level exists for this thermal conductivity rise, it is important to limit the rate of pressure increase. It is linked to the envelope properties and greatly influenced the life expectancy of the panel.

Special getters can be added to increase the VIPs life span since they prevent from the internal increase of gas and water vapour gas pressure (Fricke et al. 2008). Thus, if the core has not a function of getters, it is advised to add them although the

[4] STP : Standard conditions for Temperature and Pressure : 273 K and 1 bar

manufacturing of the panels will be more expensive. Fumed silica does not need any greeter (Baetens et al. 2009).

The temperature is the main influencing parameter for ageing. In most of the studies mass transfer phenomena is evaluated with a sorption-isotherm model. In this case, GTR, WVTR or the surface permeability p_{ei} can be adequately approximated with the Arrhenius type of equation (Baetens et al. 2009). For instance the permeability of the envelope can be calculated as follows (Bouquerel et al. 2012b):

$$p_{ei} = p_{ei}{}^{0}.\, exp\,(\frac{-Ea}{R.T}) \tag{3.9}$$

where p_{ei} is the surface permeability [m²/s], E_a the activation energy [$J.mol^{-1}$], R the gas constant ($R \approx 8.314\ J.K^{-1}.mol^{-1}$) and T the temperature [K].

Thus, the aging of the panel is accelerated by high temperatures. It is even quicker when both high temperatures and high relative humidity levels are gathered (Simmler et al. 2005). Under 1 MPa, there is no significant influence of pressure and concentration (Bouquerel et al. 2012b).

The permeation rate also depends on the envelope materials and the size of the panels. In general, AF membranes are less permeable than MF ones because there are less pinholes in the foils. Figure 3.5 presents the pressure increase and moisture accumulation in different panels, all with a MF envelope. These values were observed in a laboratory at 23°C with 50% RH, at 1 bar pressure. Therefore, it is obvious that the permeation effects are smaller for larger panel surfaces.

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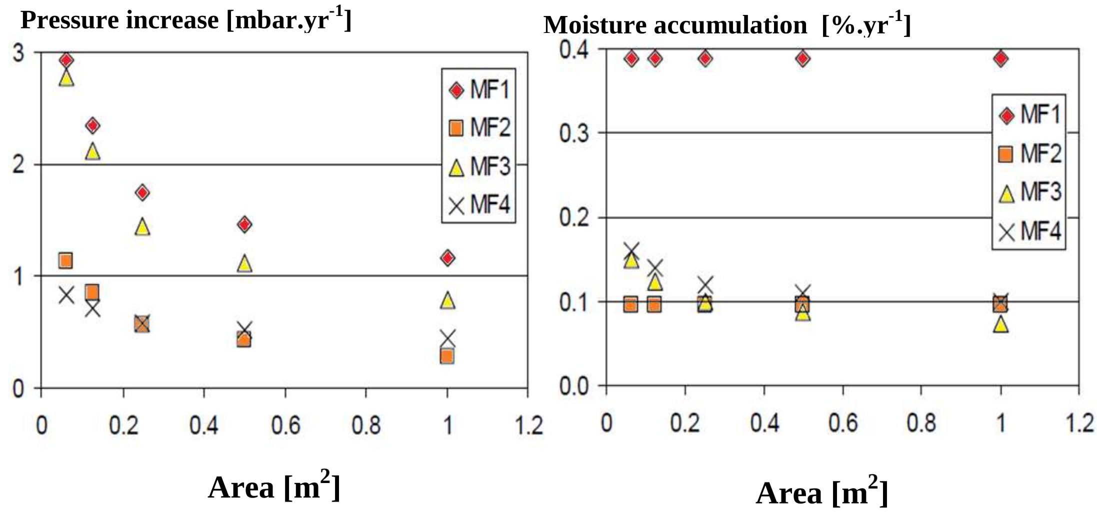


Figure 3.5 Moisture accumulation and pressure increase in VIP with MF envelope (23 °C, 50% RH, 1bar) (Simmler et al. 2005)

MF1, MF2, MF3 and MF4 represent different envelope design.

3.2.6 General expression for λ_{vip}

Assuming that the coupling effects can be neglected and that the influence of the moisture increase must be considered, the following expression for the precise calculation of λ_{vip} can be used (Bouquerel et al. 2012a):

$$\lambda_{\text{vip}} = (0.0124.T + 0.0808).10^{-3} + \frac{\lambda g,0}{1+\frac{P½}{Pg}} + \psi_{\text{vip}}.d.\frac{p}{A} + 0.0024.u \quad (3.10)$$

Consequently, the components have to fulfill special criteria so the thermal properties are good. The core must have small pores diameter, an open cells structure so gas can evacuate and it must be resistant to compression to resist the atmospheric pressure. The envelope must be as air and vapour tight as possible to maintain good thermal performances and be mechanically resistant to stress and strain to resist puncturing and tear during the life span.

3.3 Use for building application

3.3.1 Examples of constructions with VIPS

Many examples of how the VIPs have been used for building applications can be found in the literature. A few examples from the Annex 39 are briefly summarized here to present the great potential of VIPs (Binz et al. 2005). The following examples only concern refurbishment measures for façade since it is the main focus of this master's thesis.

Until now most of the applications in the building sector are realized for research projects and in Germany and Switzerland, the VIPs market is at its early stage (Simmler et al. 2005).

3.3.1.1 First use of the VIPs for an entire façade

The first privately financed building entirely insulated with VIPs was built, in Munich, Germany, in the beginning of 2000s. It has seven floors, the three bottom ones dedicated to offices and the upper floors for residential purpose. The insulation was made of around one hundred panels with a core of fumed silica (Pool, n.d). A conventional insulation would have been 25 centimeters thick resulting in 10% of the living area consumed only by the insulation system. The VIPs used were only 2 centimeter thick and protected with 8 centimeter covering material (va-Q-tec 2013).

3.3.1.2 External insulation façade

In 2000, in Nuremberg, Germany, a semi-detached house needed façade retrofitting. Special limitations regarding the insulation thickness were imposed by the German Federal Department for Preservation of Historical Monuments. A system of 15mm VIPs glued to 35mm polystyrene boards with a plaster on top was mounted on the existing façade (see Figure 3.6). The U value was improved by more than 60% decreasing from 0.6-0.75 $W.m^{-2}.K^{-1}$ to 0.19 $W.m^{-2}.K^{-1}$. After three years, infra-red pictures pointed out that no panels had failed but in this case, the U value would have reached 0.32 $W.m^{-2}.K^{-1}$, which is still less that the initial value.

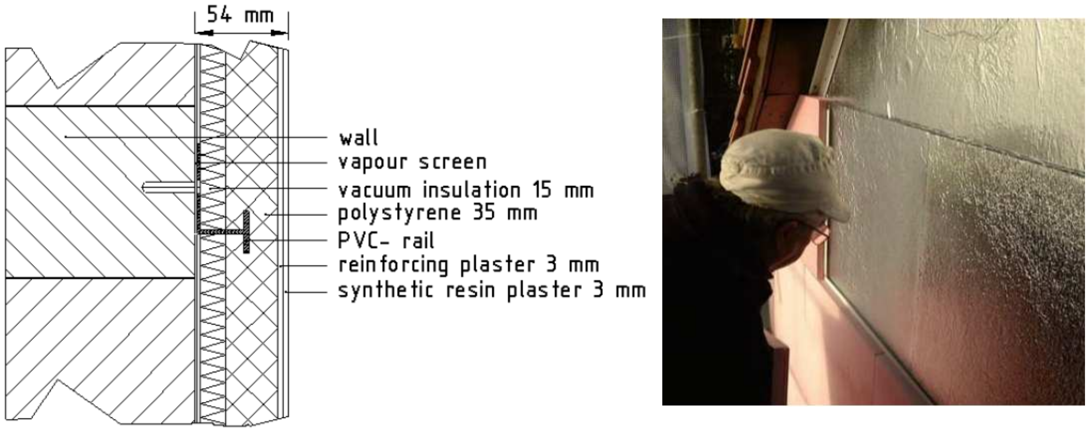
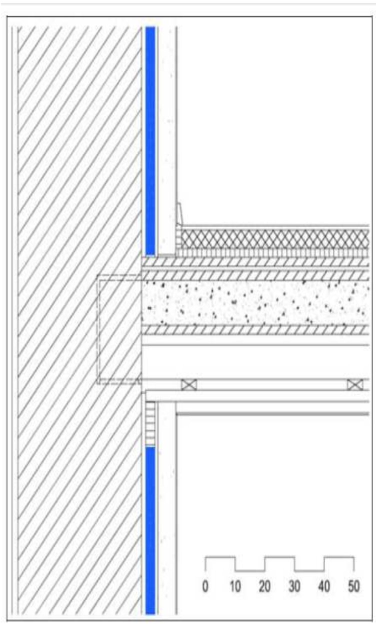


Figure 3.6 VIPs for an external insulation, Germany. On the left, a cross section of the facade. On the right, during the installation (Binz et al. 2005)

3.3.1.3 Internal insulation façade

In 2003, a property in Zürich, Switzerland was retrofitted. The use of VIPs to refurbish the thermal insulation was chosen as part of a pilot and demonstration project. The space saving was the clincher for the implementation of VIPs. The system chosen is described in Figure 3.7. The VIPs were directly assemblied on the existing plaster. Then, an air gap of around 1 centimeter was left between the VIPs and the solid gypsum board. A new interior plaster was applied on the gypsum board (see Figure 3.7). The air gap and the gypsum board were installed as a protection against the daily use of the occupants.



<u>Wall Structure:</u>

External rendering, *existing*: 20 mm

Quarry Stone wall, *existing*: 430 mm

Interior plaster, *existing*: 15 mm

VIP, *new*: 30 mm (in blue)

Air gap: 10 mm

Solid Gypsum board, *new*: 60 mm

Interior plaster, *new*: 5 mm

Figure 3.7Interior Insulation with VIPs in Zürich (Binz et al. 2005)

Since the insulation was internal, the thermal bridges could not be suppressed. Thus, the architects chose to use cork in these areas because it also has a good influence on the humidity level. The architects also set up a mechanical ventilation. As a result, the risk of condensation was limited although in the areas of the thermal bridges, the cork insulation was weaker than the one of VIPs. Due to the retrofitting, the building has reached the passive house standard regarding insulation.

3.3.1.4 Façade elements

Nowadays, the building envelope must be much more thermal efficient so new façade elements which used to be not or very few insulated have to be insulated.

Today, more and more façades are built with sandwich elements, usually made of aluminium and glass that are not materials with good thermal properties. This type of façade is very thin and there is no place for extra insulation so they might not be thermal efficient enough to reach the thermal regulations. Since the VIPs are very thin, they can be introduced inside the façade elements to insulate façade (Porextherm 2013).

VIPs can also be installed on windows and door frames where a thick but efficient insulation is crucial. Baetens et al. (2009) have related an improvement of 50% of the windows and door transmittance with the use of VIPs. Usually, most of the system modules for shutters are not insulated. VIPs can be set inside the modules, for example in roller shutter casings or lamellar blind boxes. This insulation reduces the thermal bridges caused by the conductive materials of the modules for shutters (Porextherm 2013).

3.3.2 Main drawbacks

3.3.2.1 On the construction site

The installation of VIPs on a building is a delicate intervention. Indeed, since the panels are a fragile system, they have to be handled with care. It is recommended that the setting up be realized by skilled workers with adapted tools. The VIPs supplier might propose some of his trained workers as a part of his supply agreement.

Furthermore, the installation of the panels should be planned before the setting. The VIPs are prefabricated systems and they cannot be adjusted on site. Otherwise, they will lose their inside vacuum and consequently most of their thermal properties. Therefore, during the planning phase, laying plans should be drawn, in collaboration with the VIPs supplier (Binz et al. 2005). Every detail concerning possible technical issues should be considered before the installation.

3.3.2.2 Durability

As all equipment used for buildings construction, VIPs have to be durable, that is to say they must not fail unexpectedly due to chemical or mechanical impacts. However, their envelope is fragile and can be easily damaged. The major risk is the loss of the vacuum in case of puncturing or tearing. It can happen during the installation as described in the previous section or during the service life. In the case of an interior insulation, if the panels are not specially protected, there is a higher risk that the inhabitants inadvertently puncture the panels by screwing shelves, hanging decoration on the walls or with impacts against the wall. As a consequence, a good way to improve the durability of the VIPs is to use them encapsulated in EPS and to educate the inhabitants to this type of system.

3.3.2.3 Life Span

The life expectancy of VIPs is a particularly challenging point. Indeed, most buildings are erected for 50 years and with little maintenance, they often reach a life expectancy of 100 years. Thus, thermal insulation is expected to have approximately the same life span, especially for retrofitting measures that are expensive. Today, the life span of VIPs reaches 50 years old (Binz et al. 2005) and some VIPs suppliers announce a life expectancy up to 60 years (va-Q-tec 2013).

The life time of VIPs is usually represented by a bathtub curve (Simmler et al. 2005) where the most fatal moments are the early and late ages, as plotted in Figure 3.8.

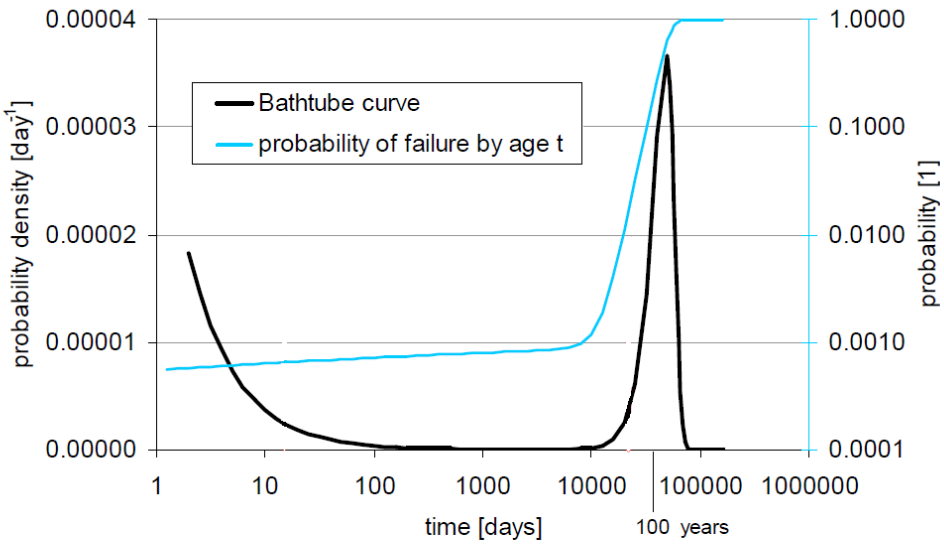


Figure 3.8 Bathtube curve (adapted from Simmler et al. 2005)

The failures at early age are called “infant mortality”, a term borrowed from the reliability statistics to describe the decreasing failure rate in the beginning of the bath curve. It represents all the defects and mistakes caused by errors in the design, the assembly or the production such as defective seams or an excess of pinholes in the envelope. Today, only less than one percent of the panels are deficient just after their production and most of the failures occur during the transport and the installation (Simmler et al. 2005).

During the service life, the life expectancy depends mainly on the envelope since the envelope keeps the low pressure inside the panel. This low pressure is necessary to get a small thermal conductivity. However, during the VIPs life time, since there is no absolutely airtight membrane, thermal conductivity aging effects will take place (Tenpierik 2009). According to Simmler *et al.*(2005), aging designs “the continuous process of performance degradation due to normal slow permeation of atmospheric gas molecules through the imperfect barrier”. This results in a non-reversible degradation of the thermal properties. It is the principal cause for ageing. Figure 3.9

clearly presents the increase of thermal conductivity for fumed silica due to air pressure and water content.

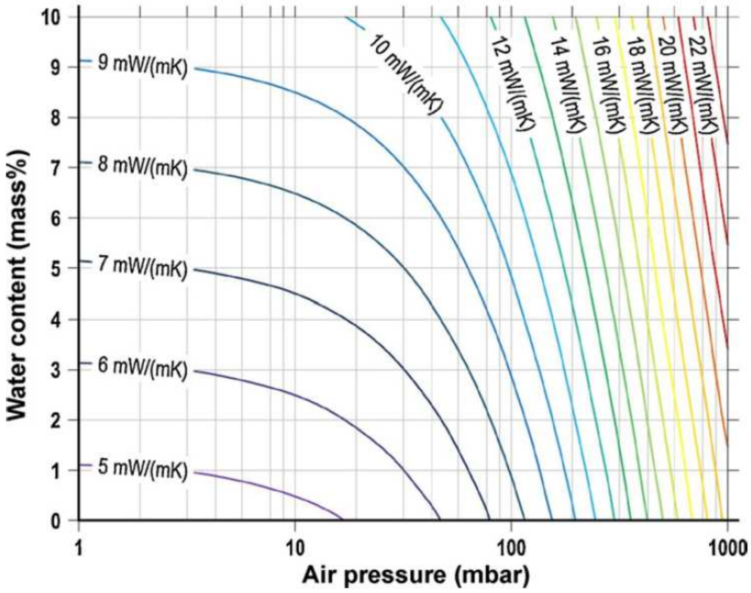


Figure 3.9 Thermal conductivity of fumed silica as a function of air pressure and water content, at external pressure of 1 bar and external temperature 20 ℃ (Baetens et al. 2009)

Concerning the VIPs, the service life usually means the time until the thermal conductivity λ_{vip} exceeds a certain limiting value λ_{lim}. There is no common value for λ_{lim} or any standardized criterion to establish the end of life of the panels. Nevertheless, most specialists recommend a limiting value of 0.008 $W.m^{-1}.K^{-1}$ for the core thermal conductivity at 296 K (Simmler et al. 2005). Another limitation used is when the inside air pressure increases of 100 mbar. If we expect a life span of 50 years, the annual pressure increase should be inferior or equal to 2 mbar (Berge and Johansson 2012).

However, once set up, it is still hard to control the quality of the panels. It is easy to check if the panels are totally failed by visual and haptic control, a good panel is a plane and soft panel but it is more difficult to evaluate the state of the panel between its pristine age until its total failure. The reliable existing methods are either too slow, too expensive or too sensitive and usually hardly implemented on site. Therefore, it might be difficult to detect the end of service life of VIPs.

3.3.2.4 Cost

The cost of VIPs is a second challenging aspect for a broader use. The purchase price varies a lot depending on the choice of the core, the envelope and the manufacturing. Indeed, the panels have to be prefabricated so it is more economical for a building designer to order panels of the same size. However, compared to conventional materials, the VIPs are far more expensive. One cubic of VIP is 27 times higher than the average price of mineral wool and 14 times higher than cork (Binz et al. 2005).

A more precise comparison can be made when analyzing the specific thermal insulation cost, denoted $K_{R:spec}$ (see Figure 3.10) which is calculated as follows (Tenpierik 2009):

$$K_{R:spec} = C_i \cdot \lambda_{eff} \qquad (3.11)$$

where C_i stands for the price of the thermal insulation per cubic meter [€.m^{-3}] and λ_{eff} is the effective thermal conductivity of the materials [W.m^{-1}.K^{-1}].

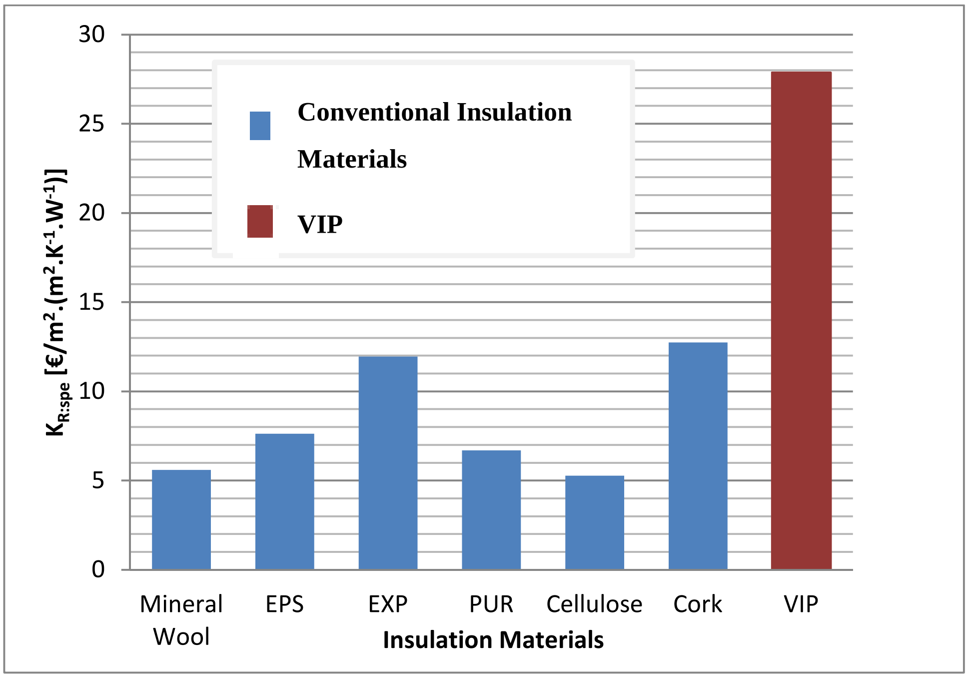


Figure 3.10 Values of the cost per thermal transmittance for different materials.

Price Base: October 2004. The price of installation and support structure are not taken into account (adapted from Binz et al. (2005))

Figure 3.10 points out that VIPs are still around 5 times more expensive than mineral wool and twice more expensive than cork. Therefore, the use of VIPs is still too expensive for ordinary houses. Nevertheless, they can be cost efficient when a minimal level of thermal performance is required in the current context of high prices of the real estate or when the building absolute size is limited. Their slimness enables the gain of living space and the rent gained from this "extra" area will rapidly pay back their extra cost (Jelle 2011).

The minimum required annual rent Ct [€.m^{-2}.year^{-1}] of the living area can be estimated with the following formula (Tenpierik 2009):

$$\sum_{t=1}^{N} \frac{Ct}{(1+i)^t} \geq \frac{\Delta Ka \, . \, h}{\delta d} \qquad (3.12)$$

where i is the interest rate, t the time [years], ΔKa is the difference in cost of the thermal insulation materials compared [€.m^{-2}][5], h is the height of one storey [m] and δd is the difference of façade thickness with the two insulation materials [m]. ΔKa

[5] The surface here refers to the surface of the facade

and δd are usually calculated when comparing VIPs with a conventional insulation material.

This equation does not take into account the price variation of the materials. A first approximation of the annual rent can be done by neglecting the interest year and by considering that the price of the real estate will stay constant (Pool n.d).

Consequently, to rightly evaluate the price of the implementation of VIPs, it is important to consider the system during its entire life span: a Life Cycle Cost assessment (LCC) would give more precise values. Indeed, some other factors such as the risk of early failure, the change of defective panels, the extra-cost of skilled workers to set up the panels would also be considered. A LCC is proposed in Section 4.3 for the building Kajskjul 113.

Specialists expect the price to decrease in the future. For them, the relatively young age of the panels largely contribute to the high costs. The production line is not optimized yet and a mass production of the envelope should lead to cost reductions (Binz et al. 2005, Simmler et al. 2005).

3.4 The VIPs market today

There are three main producers of VIPs in Europe: va-Q-tec, Porextherm and Microtherm. This part aims at describing briefly their products in order to get an overview of the VIPs market today.

Va-Q-tec is a German company created in 2000. It specializes on eco-friendly thermal solutions by developing vacuum insulation panels and heat and cool storage containers made of phase change materials. One of their VIP products, *va-Q-vip B*, received an official approval for building applications from the Deutsches Institut für Bautechnik (DIBT, German Institute for Civil Engineering) in June 2007. The approval was recently extended to June 2015. Its design thermal conductivity is 0.008 $W.m^{-1}.K^{-1}$, it includes the thermal bridges effects and the ageing. More details about this product are given in Table 3.2 (va-Q-tec 2013). On their official website, they provide technical documentation, instructions and recommendations for a successful installation as well as references (see Figure 3.11).

Figure 3.11 Warning labels designed for the va-Q-tec VIP (va-Q-tec 2013)

Porextherm Dämmstoffe GmH is also a Greman company. It has been developing innovative thermal insulation solutions since 1989 such as VIPs and microporous high-performance thermal insulation materials for national and international projects. Their research and development department works on the extension of standardized performed elements and products for individual applications. Their range of VIPs, the *Vacupor,* has an official approval from the DIBT. Futhermore, *Vacupor* VIPs are submitted to an Environmental Products Declaration which is part of a European norming project to develop a sustainable label for the building sector (Porextherm 2013).

Microtherm International Ltd is a worldwide provider of insulation solutions. The VIPs they offer are developed under the brand Microtherm®. This brand belongs to a Belgian industrial group that historically proposes insulation for passive fire protection and high temperature protection and it is now developing a range of products made of advanced microporous insulation solution (Microtherm 2013).

Table 3.2 Comparison of VIPs products

PRODUCTS NAMES	CORE	ENVELOPE	THICKNESS [MM]	THERMAL CONDUCTIVITY[1] [$W.M^{-1}.K^{-1}$] (THICKNESS 20MM)	U VALUE[2] [$W.M^{-1}.K^{-1}$] (THICKNESS 20MM)	INTERNAL GAS PRESSURE AT DELIVERY [MBAR]	SERVICE LIFE	TEMPERATURE STABILITY [°C]	HUMIDITY STABILITY [%]	OFFICIAL APPROVAL
va-Q-vip (va-Q-tec)	Fumed silica	High barrier film	10 to 50	$\lambda_{initial} < 0{,}005$	$U_{initial} = 0{,}22$	< 5	Up to 60 years	-70 to +70	0 to 60	none
va-Q-vip B (va-Q-tec)	U[3]	High barrier film + mechanical protection made of glass fiber textile	10 to 50	$\lambda_{initial} = 0{,}0043$ $\lambda_{eff} = 0{,}007$ $\lambda_{aerated} = 0{,}020$	$U_{initial} = 0{,}22$ $U_{eff} = 0{,}35$	< 5	Up to 60 years	-70 to +70	0 to 60	DIBT [4]
va-Q-plus B (va-Q-tec)	Fumed silica + Opacifiers	High barrier film + mechanical protection made of glass fiber textile	5 to 20	$\lambda_{initial} < 0{,}0035$	$U_{initial} = 0{,}18$	< 5	Up to 60 years	-70 to +70	0 to 60	None
Vacupor NT-B2-S (Porexxtherm)	Fumed silica + opacifiers	Laminated aluminium foil	10 to 50	$\lambda_{initial} \leq 0{,}005$ $\lambda_{eff} = 0{,}007$ $\lambda_{aerated} \leq 0{,}019$	$U_{initial} < 0{,}22$ $U_{aerated} = 0{,}94$	≤5	U	-50 to +120	U	DIBT
Vacupor XPS-B2-S (Porexxtherm)	Fumed silica + opacifiers	Laminated aluminium foil + sheet of 3mm-XPS on both sides	10 to 50	$\lambda_{initial} \leq 0{,}005$ $\lambda_{eff} = 0{,}007$ $\lambda_{aerated} \leq 0{,}020$	$U_{initial} < 0{,}22$ $U_{aerated} = 0{,}94$	≤5	U	-50 to +120	U	DIBT
Vacuspeed (Porexxtherm)	Fumed silica + opacifiers	Laminated aluminium foil	15 to 25	$\lambda_{initial} = 0{,}0043$ $\lambda_{eff} = 0{,}008$ $\lambda_{aerated} = 0{,}019$	$U_{initial} < 0{,}22$ $U_{aerated} = 0{,}94$	<5	U	-50 to +120	U	DIBT
Microthern Slim Vac (Microtherm)	Reinforced silica + opacifier	Multiple metalized polymer layers	6 to 40	$\lambda_{initial} = 0{,}0042$ $\lambda_{aerated} = 0{,}021$	NS	< 5	U	U	U	None

$\lambda_{initial}$ = initial thermal conductivity, λ_{eff}= thermal conductivity included aging and edge effects, $\lambda_{aerated}$= thermal conductivity when the panel is aerated,
$U_{initial}$ = initial U-value, U_{eff}= U-value included aging and edge effects
U: unspecified
Deutsches Institut für Bautechnik (German Institute for Civil Engineering)

4 Results of the Pre study

The following part briefly presents the building Kajskjul 113 and how its façade can be insulated with VIPs. Furthermore, a short Life Cycle Cost analysis is carried out in order to investigate if the VIPs system could be a cost effective measure. The purpose is to propose a solution which fits with the clients' requirements, their financial constraints and the current limitation on energy use. Indeed, until now, the VIPs have been mainly used for research projects so in order to extend their use, it is essential that the VIP system is cost efficient to make the companies willing to use it.

4.1 Presentation of Kajskjul 113

The study case focuses on the thermal retrofitting of Kajskjul 113. It is a former warehouse for steel products which stands in Gothenburg harbor (see Figure.4.1). It has been abandoned since the 1990s and today, the building owner, Älvstranden utveckling AB, plans to move its headquarters there within 5 years. Älvstranden utveckling AB is a municipal company whose purpose is to develop the northern and southern river banks of Gothenburg.

Figure 4.1 Kajskjul 113 (Anderson and Olin 2008)

4.1.1 Historical fact

Frihamnen, which means "The Free Port", is Gothenburg inner harbor on the Göta Älv. It was inaugurated in 1922. At that time, most European cities had their own free port and it was therefore important for the economical development of Gothenburg that the city have its own. Thus, Frihamnen was used as an international port where it was possible to exchange goods without paying taxes. However, when Sweden joined the European Union in 1995, the area lost its importance and was abandoned in 1996 (Anderson and Olin 2008, Sepehr 2010).

Frihamnen is composed of three piers: Södra Frihamnen, the easternmost, Norra Frihamnen and Kvillepriren, the westernmost. They cover an area of approximately 60 hectares (Sepehr 2010). Kajskjul 113 is located on Norra Frihamnen, as described in Figures 4.2 and 4.3. Its construction was ordered by the port of Gothenburg which had chosen Alexander Ericsson to be the architect. It was completed in 1964 and served as a warehouse for metal items until the nineties. Then, it was abandoned except for the ground floor which is still used as a yacht parking (Anderson and Olin 2008). Since 2008, the city of Gothenburg is willing to reconvert the area for its development.

Figure 4.2 Bird view. From the left to the right: Kvillepriren Peer, Norra Frihamnen Peer, Södra Frihamnen Peer. Kajskjul 113 is hooped in yellow (Sepehr 2010)

Figure 4.3 Air view. From the left to the right: Kvillepriren Peer, Norra Frihamnenn Peer, Södra Frihamnen Peer. Kajskjul 113 is hooped in yellow (source: Google Map)

4.1.2 Materials and techniques of the construction

Kajskjul 113 is a three-floor rectangular building with 25 meters width and 125 meters length (see Figure 4.4). The building site is an open site and Kajskul 113 is not protected by any other buildings (see Figures 4.2 and 4.3).

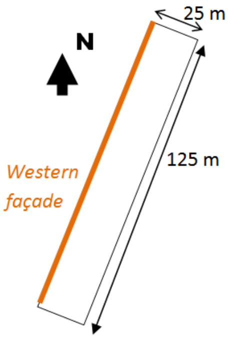


Figure 4.4 Representation of Kajskjul 113's orientation

The building structure is made of circular concrete beams which support the floors and the roof. The former use of the building as a warehouse imposed a framework with large spans and vast open spaces (Anderson and Olin 2008). This structure gives to Älvstranden utveckling AB flexibility to arrange its offices. The ground slab is made of 240 mm thick concrete, designed to carry the loads of the entire building. The foundations are wooden friction piles dung in clay. The external walls are made of 80 mm thick yellow bricks, insulated with mineral wool. Supporting pillars are placed every four meter inside the external walls (Anderson and Olin 2008). More detailed of the composition of the façade is given in Section 4.2.1. The brick façade has been damaged by the weather: the annual temperature variations and the rain (see Figure 4.5). Around the windows and doors, the brick beams are rusting and corrosion can be observed in various areas of the façade. Therefore, the damage bricks will certainly be changed and a protection against the capillary transport through the wall will be installed. Indeed, as detailed in Section 2.4.2 the consequences of water vapour transfer can be serious. This yellow brick façade is considered as a part of the historical heritage of Gothenburg and consequently must be preserved (Anderson and Olin 2008).

Figure 4.5 Damaged brick on the façade (Anderson and Olin 2008)

The windows and doors have not been changed since the erection of the building. For this reason, it is rather obvious that they are not energy efficient enough to reach the current thermal regulation. Moreover, both doors and windows are leaking. As a result, they will be replaced during the retrofitting (Anderson and Olin 2008).

The roof is a lightweight concrete roof on pre-stressed concrete beams spaced of four meters. The main problem of the roof is that it is not completely airtight and waterproof. Similarly as for the external walls, the insulation of the roof is not sufficient (Anderson and Olin 2008) and will be retrofitted.

As a result, the existing building envelope of Kajskjul 113 is facing three main problems: a poor insulation, air leakage and mechanical damages of the bricks (Anderson and Olin 2008).

4.2 The thermal retrofitting of the façade

4.2.1 The façade before the renovation

The western and eastern façades of Kajskjul 113 are the longest ones. The openings, windows and doors, represent a large part of the façade, 21% of the eastern façade and 29% of the western façade including a quarter of the façade is windows. The case study only focuses on these two façades since the northern and southern facades are not made with bricks.

Figure 4.6 presents a cross-section of the façade before the retrofitting.

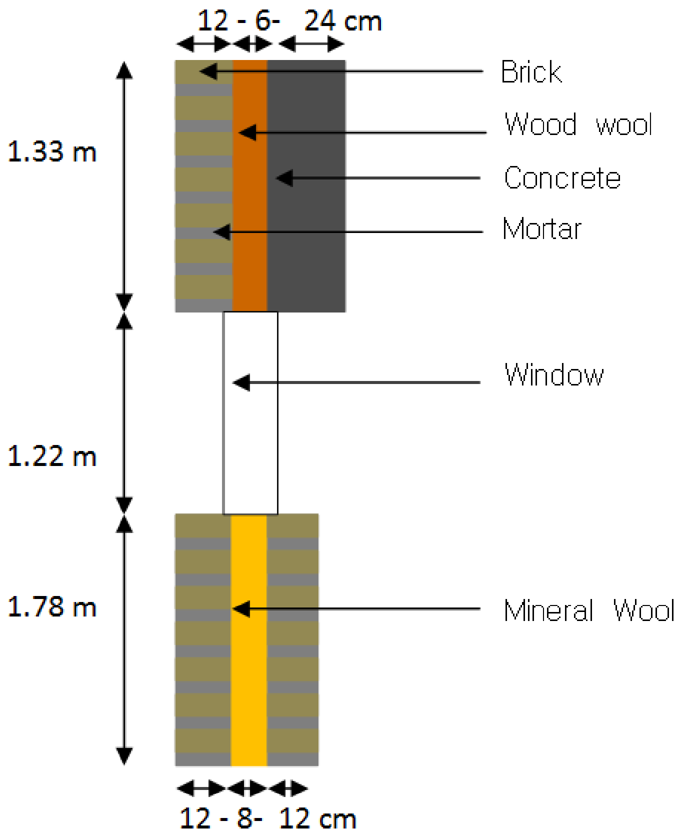


Figure 4.6 Schematic representation of the exterior wall before the retrofitting - Vertical projection

Before the retrofitting, the bricks were damaged by the wind, the driving rain and the freeze and thaw. With the cross section of the eastern and western façade, given in Appendix 1 and the schematic representation in Figure 4.6, a U-value can be estimated. Table 4.1 summarizes the material properties used for the calculation.

Table 4.1 Materials properties (from Anderson and Olin 2008 and WUFI 2D data base)

material	**l [m]**	λ_{init} [W.K^{-1}.m^{-1}]	λ_{wet} [W.K^{-1}.m^{-1}]
bricks	0.12	0.6	1.2-1.8
concrete	0.24	1.6	2.1
mineral wool	0.08	0.04	0.055
wood wool	0.06	0.08	0.2
mortar	0.12	0.08	0.08

materials	**U** [W.K^{-1}.m^{-2}]
Windows	3.0

In order to evaluate the U-value of the wall, the following hypotheses have been made: the bricks are considered as solid bricks for masonry, the concrete is a C35/45 concrete and the wood wool is considered to be in form of boards. The U-value of the windows is from Anderson and Olin (2008) and represents the value of the overall window: glass, glazing and frame included. The indoor surface heat resistance and the outdoor surface heat resistance are 0.13 $m^2.K.W^{-1}$ and 0.04 $m^2.K.W^{-1}$ respectively.

Two calculations were made: one considering that the materials were new (λ_{init} values in Table 4.1) and another considering that the materials were deteriorated by moisture accumulation in materials (λ_{wet} values in Table 4.1). Thus, the U-value before retrofitting is between 1.07 and 1.86 $W.m^{-2}.K^{-1}$. As a reminder, the limit U-value set by the Swedish Building Regulations for a façade of nonresidential buildings is 0.60 $W.m^{-2}.K^{-1}$ that is to say three times less than the estimated U-value of Kajskjul 113 before the refurbishment (Boverket 2011). The retrofitting of the thermal insulation of the façade is therefore necessary.

4.2.2 How to use the VIPs for the retrofitting

The use of VIPs to retrofit the thermal insulation of Kajskjul 113 must lead to the new thermal regulations and preserve the historical features of the façade.

From the main feedbacks from research and demonstration projects explained previously, it has been established that different ways of implementing VIPs are possible. The most challenging aspects of these uses of VIPs are:

- the life span and the ageing processes,
- the fragility
- the thermal bridges
- the impossibility to adapt the panels on site.
- the price

These aspects should be handled before implementing the VIPs on site to be sure that the solution is efficient. Today, the producers of VIPs produce panels whose life expectancy is more than 50 years and whose ageing effects does not affect too much the thermal properties of the panels when use in the usual conditions. The fragility of the panels and the thermal bridges issues can be tackled by choosing an adapted way to install the VIPs. Eventually, the price concern will be further studied in Section 4.3. Indeed, it is the same for all VIP products, independently on the way they are set up. However, the cost is still one of the most important criteria for a company planning to implement a solution. Thus, special care is necessary.

First to get the most efficient thermal properties of VIP as possible, the filling materials should consist of fumed silica. Opacifiers might be used to reduce the effect of the radiative heat flow. To decrease the thermal bridge effect, the envelope should be a MF-envelope. Today, both types of envelopes are available through the trade (see Table 3.2). Moreover, the size of the panels should exceed 0.50 m x 0.50 m. Then, in order to avoid damaging the panels during their setting up and to strengthen their mechanical properties, encapsulated VIP could be used. Some VIP producers offer VIP already encapsulated on their two larger surfaces. Another advantage of such an encapsulation is the ease of fixation on the wall: the panels can simply be glued on the existing walls. In some projects, the VIPs have been fixed with wooden laths or timber battening but these elements create more thermal bridges effects and wood is a material very sensitive to humidity and mould growth.

Most of the VIP products presented in Table 3.2 fit all the previous conditions for our case-study. For Kajskjul 113, the panels used will be encapsulated on both sides with 10 mm thick polystyrene coating and fixed on the walls with polystyrene adhesive that is available in the commerce (see Figure 4.7). Two of standard sizes available correspond to the dimensions recommended by Binz et al. (2005). Table 4.2 displays its main characteristics. The data sheet of the product is shown in Appendix 2.

Figure 4.7 VIP Vacupor®PS-B2-S from Porextherm (Porextherm 2013)

Table 4.2 Characteristics of the Vacupor®PS-B2 (Porextherm 2013).

λ_{init} stands for the thermal conductivity of a panel at the pristine age, λ_{eff} is the designed value advised by Porextherm and λ_{init} is the thermal conductivity of a panel when aerated.

Core	main component: Fumed silica other: opacifiers, fiber filaments
Envelope	alumimium foil
Materials for encapsalution	polystyrene
Standard sizes	1m x 0,5m - 0,5m x 0,5m - 0,5m x 0,25m
Standard thicknesses	10 - 15 - 20 - 25 - 30 - 40 - 45 - 50 mm
Density [kg.m^{-3}]	150-300
λ_{init} [W.M^{-1}.K^{-1}]	0,005
$\lambda_{aerated}$ [W.M^{-1}.K^{-1}]	0,019
λ ef$_f$ [W.M^{-1}.K^{-1}]	0,007
Theoretical pressure rise [Pa.yr^{-1}]	0,5

Obviously, on request, Porextherm can design and produce VIPs with different thickness and sizes than the standard ones but the price will increase. For this reason, panels with standard size thickness will be used. Since the panels are not adjustable on site, a detailed layout for every wall should be established to order the exact number of panels with the right dimension. According to the available dimensions, panels with different size should be used in order to cover the largest surface as possible. The parts of the wall that could not be covered with VIP will be insulated with conventional insulation materials.

4.2.3 The façade after the retrofitting

Before the retrofitting, preceding work is essential. The damaged bricks should be changed and the mortar joints renovated so there will be no cracks or holes that might lead to air and liquid water leakage. For the same reason, Binz et al. (2005) advice that the cavities between the walls and the VIPs should be filled in with fiber insulation so the surface of the brick be even. Finally, the internal bricks surface should be cleaned (Brandt et al. 2012).

The insulation refurbishment measure proposed is presented in Figure 4.8

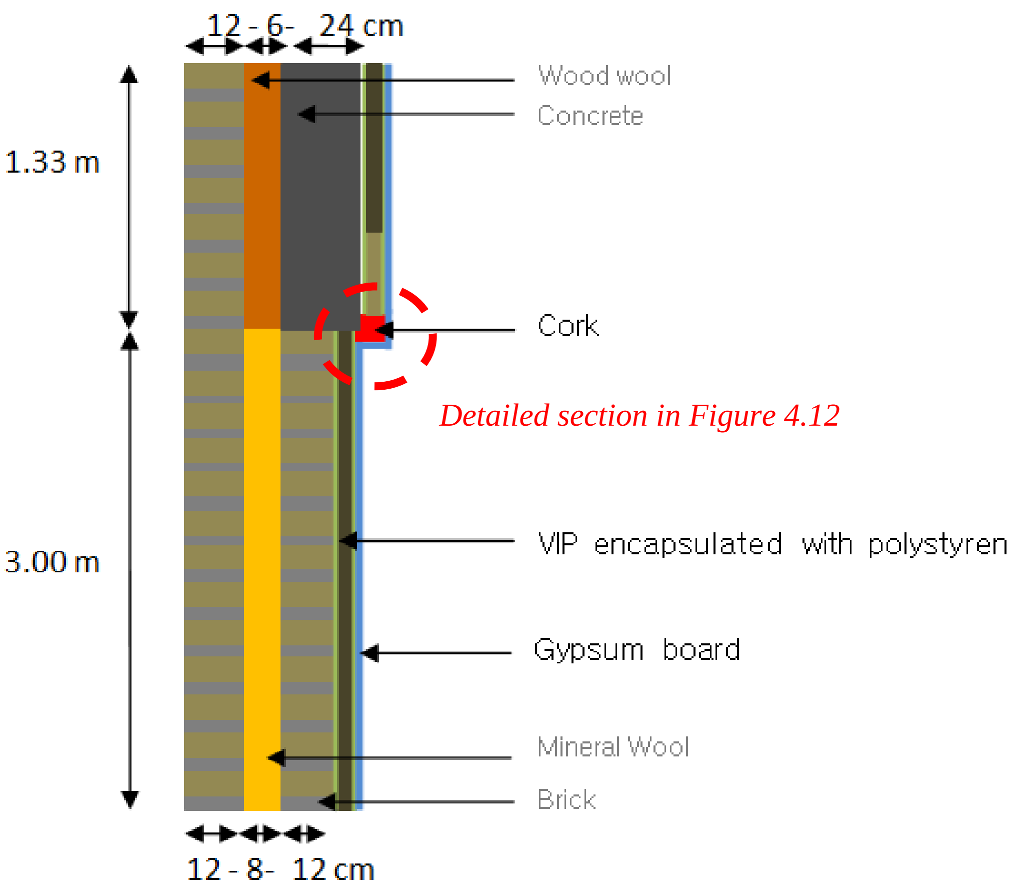


Figure 4.8 Solution for the retrofitting of the façade – Vertical projection

The upper and lower parts of the walls are refurbished in the same way. The polystyrene encapsulating VIPs is glued on the existing inner walls and to complete the parts of the wall without VIPs, cork is used. Cork gives more flexibility to adapt the VIPs on the walls since there are tolerances of few millimeters about the real measurements of the panels. Cork is also interesting for its efficient hygrometric and thermal properties. A gypsum board is set to further protect the VIPs against the risks of punctures during the VIPs life span. It will also contribute to decrease the thermal bridges due to the edges of the panels. Figure 4.9 represents the layout of the insulation system. The parts concerned by the cork insulation are the two bands of 8 and 3 centimeters above and below the windows, represented in red in Figure 4.8.

According, to the interior arrangement realized by Älvstranden utveckling AB and the placement of the interior partition walls, cork will also be set up around the windows to fit with the size of the rooms.

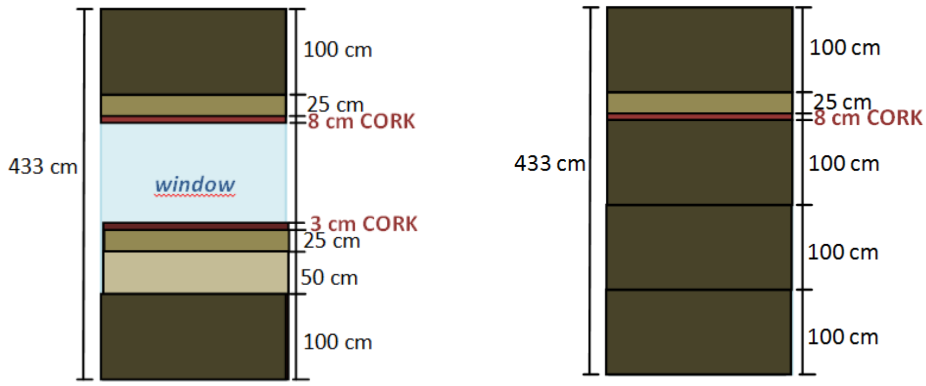


Figure 4.9 Layout of the VIPs. On the left, layout for the part of the facade with windows. On the right, layout for the opaque facade

The thickness of the panels will be chosen in order to reach the current level of thermal efficiency. The material properties used for the calculation are presented in Table 4.3.

Table 4.3 Properties of the materials used for the estimation of the U-value of the retrofitted wall (WUFI 2D data base and Jelle (2011)).

The value of the thermal conductivity of the mineral wool and wood wool take into account the effects of ageing

material	**λ [W.K^{-1}.m^{-1}]**
bricks	0.6
concrete	1.6
mineral wool	0.055
wood wool	0.08
mortar	0.08
VIP	0.007
polystyren - EPS	0.035
cork	0.04
Gypsum board	0.2

material	**U [W.K^{-1}.m^{-2}]**
Windows	1.2-1.5

Figures 4.10 and 4.11 present the U-value of the façade as a function of the thickness of the panels.

The U-value of the façade, including the windows has been evaluated with the same method as in Section 4.2.1. The windows represent a large surface of the wall so their thermal properties greatly influence the overall value of the façade. They are expected to be changed for current double-glazing and triple glazing windows[6] whose U-value ranges respectively from 1.2 to 1.5 W.m^{-2}.K^{-1} and from 0.9 to 1.2 W.m^{-2}.K^{-1} (Sapa 2008). As can be seen in Figure 4.10, only by changing the old windows for new ones with double glazing, the required thermal level is reached even if all the panels are punctured.

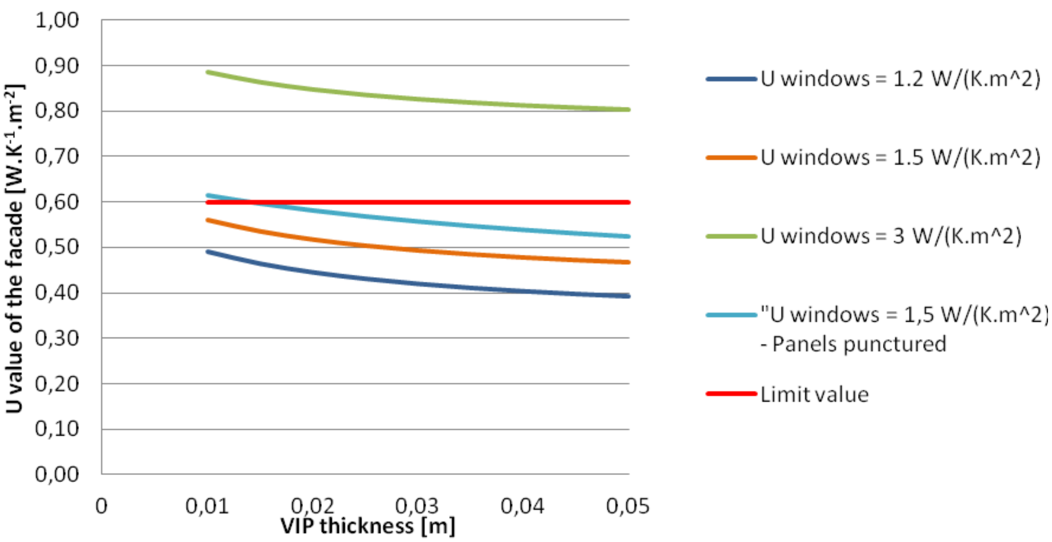


Figure 4.10 U-value of the façade with windows

An estimation of the U-value for the opaque retrofitted façade is displays in Figure 4.11 and indicates the appropriate thickness of the panels. To get a U value inferior to 0.20 W.m^{-2}.K^{-1}, the VIPs should be 3 centimeter thick which leads to a U-value of 0.16 W.m^{-2}.K^{-1} for the opaque façade and 0.53 W.m^{-2}.K^{-1} for the façade with windows. It is interesting to notice that to reach the standard value for Passive House, 0.10 W.m^{-2}.K^{-1}, an extra-insulation with conventional materials is needed. The solution proposed in this thesis is a realistic alternative due to technical and economical reason (see Figure 4.8).

[6] Values given for an opening window with a height of 1.2 meters and for the entire window system : profile, glass, edge zone (Sapa 2008).

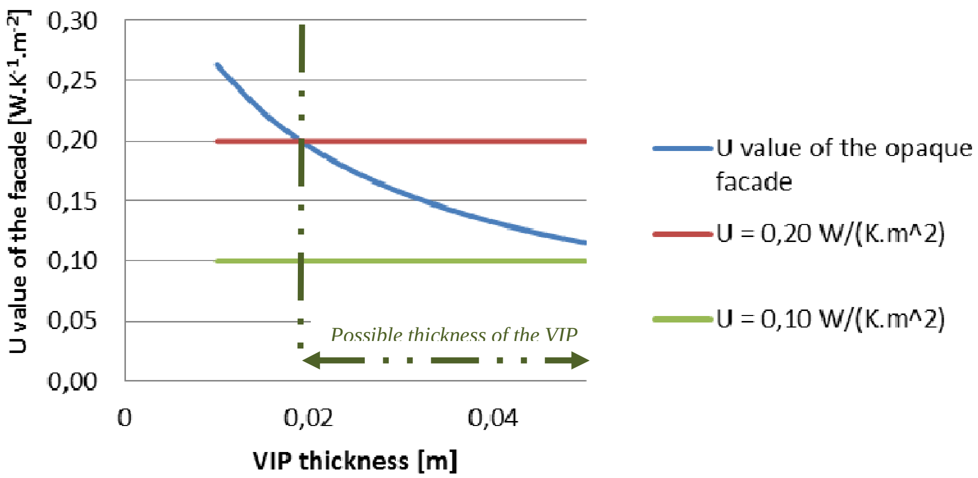


Figure 4.11 U value of the opaque facade

Figure 4.12 illustrates more accurately the new insulation system that will be set up and the connection between the lower and upper parts of the wall. The inner surface of the wall is not flat since the extra thickness of the concrete part is not lined up with the lower part of the wall. It could have been suppressed by adding a 10 centimeter additional-insulation between the inner brick façade and the VIPs. However, this solution is more expensive and results in the loss of living space. It should not be problematic that the wall is not lined up since this happens at three meters height.

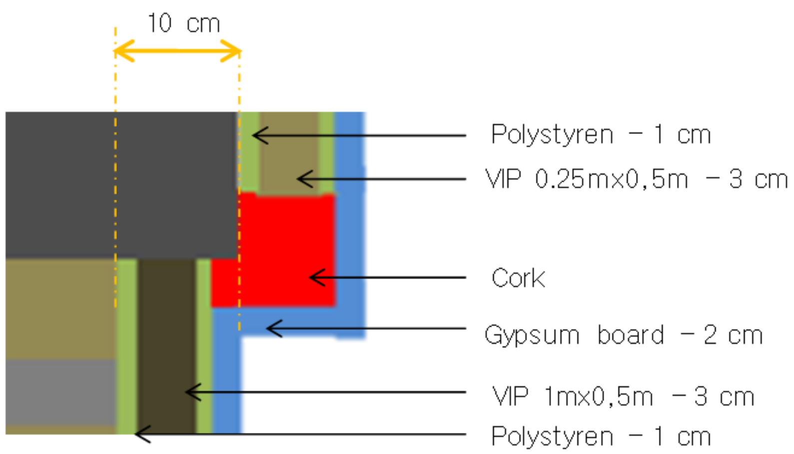


Figure 4.12 Detailed Section of the retrofitted facade

4.2.4 Challenging aspects of the retrofitting

Setting new materials on the existing façade leads to a change of its hygrothermal properties. In order to be sure that these modifications will not affect the thermal and structural properties of the wall, the following aspects should be carefully studied.

First, the temperature of the surface and inside the wall should be considered. Indeed, it is important that the temperatures of the surface stay higher that the dew point of the ambient air to avoid any risk of condensation which might lead to mould growth. Bricks are also sensitive to condensation but for different reasons: if the condensate freezes, the repeated actions of freeze and thaw will damage the bricks. The risk of condensation is higher in winter when the air is more likely to be colder so the dew point is lower. Indeed, in winter, due to the pressure difference, the water vapour flow is often from the inside to the outside which means that the air is cooling down and may get inferior to its dew point. The risk is also higher on the thermal bridges areas such as the joints between the ceiling and the wall, the floor and the wall and around the window frame.

Then, the critical moisture levels should not be reached. When the critical relative humidity value, φ_{crit} is overstepped for a long period of time, shrinkage, swelling, mould growth and rot are likely to appear. Furthermore, an increase in moisture content contributes to the increase of the thermal conductivity.

Interior insulation also increases the risk of condensation since the cold part of the exterior wall will be colder. Therefore, it is essential to control that the water vapour can well evacuate in the outdoor direction. Bricks and cork have good capillarity but the envelope of VIPs is vapour tight (Pouget 2011). Thus, water transfer should be cautiously controlled.

These verifications will be carried out with a computer model with the software WUFI 2D. The results are presented in the Chapter 5. However, before going this step further, companies are willing to know more precisely about the cost of the system considered. Indeed, in most cases, if the cost is considered as too expensive, it is very likely that the solution will not be implemented.

4.3 Life Cycle Cost

The financial situation of the building's owner is a crucial point when considering the type of renovation measures undertaken. Indeed, from a full renovation to the demolition, different levels of renovation can be undertaken with a very large price difference. It is therefore important for the building owner to be sure that the budget fits with the cost of the planned renovation. The purchasing price is often the most important part of the client's budget but additional costs such as the maintenance or the replacement costs must also be considered since they might greatly influence the total costs. Thus, a Life Cycle Cost Analysis (LCC) is recommended to precisely evaluate the total cost of a product or a measure.

4.3.1 Definition

A Life Cycle Cost is a common tool for decision support for a long term perspective. It provides guidance to decision makers when they need to buy a product, an engine or an installation or when they need to choose between different conceptions.

To achieve this, the LCC considers the total cost of the product or service, that is to say that the investment cost and the operational costs, from the purchase until the dismantling are considered as (IMdR 2009):

$$total\ cost = investment\ cost + operational\ costs \qquad (4.1)$$

The investment cost is well known since it is present cost such as the cost of purchase. The operational costs have to be estimated, the inflation and the interest rates must be used to predict the future evolution of the costs. For instance, the energy cost is an operational cost subjected to monthly variations of energy prices. These adjustments are important since the period of calculation can be rather long.

Usually a LCC is carried out to compare different worth considering solutions in order to select the most cost effective one. Since all the costs are considered, the less expensive solution after a LCC is the optimal solution. However, a LCC is only an economical tool and some differences might be observed between the theory and the reality (Gustafsson 2010).

4.3.2 Proposition of a LCC for our study case

In the literature, different LCC methods have been developed to evaluate the cost of the thermal insulation systems. The common idea is that the use of thermal insulation decreases the operational costs by reducing the energy consumption. However, the investment costs are increased due to the purchase of an adequate insulation system (Gustafsson 2010 and Ozel 2012).

The following LCC method is based on the reports from Alam (2011), Ozel (2012). The total cost of the insulation system, LCC_{total}, is calculated as follows:

$$LCC_{total} = C_{investment} + C_{maintenance} + C_{energy} \qquad (4.2)$$

where $C_{investment}$ is the investment's initial cost, $C_{maintenance}$ is the value of the maintenance cost, C_{energy} the cost of energy for heating and cooling. All the costs are expressed in €.year^{-1}.

4.3.2.1 Cinvestment

The investment cost includes the purchase and the installation. It is expressed as (Ozel 2012) :

$$C_{\text{investment}} = \frac{(\Sigma Ci.Li + Cad\ )}{N}.A \qquad (4.3)$$

where C_i is the cost of the insulation material per cubic meter [€.m^{-3}], L_i the insulation thickness [m], C_{ad} represents the costs of installation [€/m²], N the period of calculation [years] and A the surface covered by insulation [m²].

4.3.2.2 Cmaintenance

The maintenance cost is calculated as an annual cost and can be estimated as follows:

$$C_{\text{maintenance}} = ac_{\text{ maintenance}}.\frac{\mathbf{1-(1+h)^{-N}}}{\mathbf{h}} \qquad (4.4)$$

where $ac_{maintenance}$ is the annual maintenance cost [€.year^{-1}], h the real cost of capital [%] and N the period of calculation [years]. The real cost of capital, h, also called the discount rate is a rate representing the additional profit that the company is expected from its investment.

Usually, there is no expensive and heavy maintenance to realize on an insulation system.

4.3.2.3 Cenergy

For insulation systems, service life costs are approximated to the costs of energy. Ozel (2012) distinguishes the cost of heating and cooling as follows:

$$C_{\text{energy}} = (C_{\text{heating}} + C_{\text{cooling}}).PWF \tag{4.5}$$

where $C_{heating}$ and $C_{cooling}$ are respectively the annual energy cost for heating and cooling [€.year^{-1}] and *PWF* is the present worth factor [-]. Indeed, since the energy prices undergo regular variations, it is important to consider the evolution of their prices in the calculation.

The annual energy cost for heating and cooling are calculated as follows (Alam 2011):

$$C_{\text{heating}} = \frac{\mathbf{86400} \,.\, \boldsymbol{HDD} \,.\, \boldsymbol{U} \,.\, \boldsymbol{A} \,.\, \boldsymbol{Cf}}{\boldsymbol{Hu} \,.\, \boldsymbol{\eta}} \tag{4.6}$$

$$C_{\text{cooling}} = \frac{\mathbf{86400} \,.\, \boldsymbol{CDD} \,.\, \boldsymbol{U} \,.\, \boldsymbol{A} \,.\, \boldsymbol{Ce}}{\mathbf{3.6.10^6} \,.\, \boldsymbol{COP}} \tag{4.7}$$

where *HDD* is the Heating Degree Day, *CDD* the Cooling Degree Day, *U* the thermal transmittance [W.m^{-2}.K^{-1}], *A* the surface towards the indoor air [m²], C_f the fuel price [€.m^{-3}], C_e the electricity cost [€.kWh^{-1}], H_u the lower heating value of the fuel [J. m^{-3}], η the efficiency of the heating system [-] and COP the performance of the cooling system [-]. The value 86400 is the number of seconds in a day and $3.6.10^6$ is the conversion from kilo watts per hour for joules (1kWh = $3.6.10^6$J).

The Heating Degree Day (HDD) represents the number of degrees that an outdoor day's average temperature is below a base temperature. Thus, 1HDD means that the outside temperature is, in average, one degree under the base temperature during one day. The HDD can be calculated over any period of time but in most of the available data bases, the HDD is calculated for one year. In the same way, the Cooling Degree Day (CDD) represents the number of degrees that an outdoor day's average temperature is above a base temperature. The base temperature is different depending on the location and calculations due to historical reasons and due to the thermal characteristics of the buildings. However, it is usually between 16°C and 19°C below which the heating system is considered to be in use and above the one, the cooling system might be required. The value of HDD and CDD can be found in text books for different type of buildings depending on their structure.

When using an individual heating system, the consumer directly pays the price of fuel, C_f. The fuel consumption depends on the efficiency of the heating system, η, and the lower heating value of the fuel, H_u [J. m^{-3}]. H_u is a common parameter used to compare the efficiency of different fuels. It represents the lower amount of heat produced during the combustion of one cubic meter of fuel. In Sweden, heating district system is largely used. It is a centralized district heating plant which produces energy by burning fossil fuels, waste from households and from biomass so it participates to greenhouse gases emissions (Gross 2010). There are different tariffs according to the locations and the price is calculated in €.kWh^{-1} (Gustafsson 2010). The Swedish electricity market is interconnected to the European market so Sweden cannot determine its own electricity price (Gross 2010).

The prices of energy: fuels or electricity broadly varies from one year to another. For decades, the current trend has been an increase of the prices (Gross 2010). Therefore, it is important to consider this evolution during the period of calculation which is done when using the present worth factor, PWF (Ozel 2012):

$$\mathrm{PWF} = \begin{cases} \dfrac{(1+r)^N - 1}{r(1+r)^N} \begin{cases} \boldsymbol{if\ i} > g,\ r = \dfrac{i-g}{1+g} \\ \boldsymbol{if\ i} < g,\ r = \dfrac{g-i}{1+i} \end{cases} \\ \dfrac{N}{1+i}\ \boldsymbol{if\ i = g} \end{cases} \tag{4.8}$$

where N is the period of calculation [year], i is the interest rate [%] and g the inflation rate [%]. The interest rate, i, is the rate applied by the banks when money is borrowed whereas the inflation rate, g, is the rate of the annual price increase.

4.3.3 **Analysis of the model**

The LCC is carried out to evaluate the total cost of the insulation system described in Section 4.2.3. The software Excel was used.

The LCC is run for 50 years since it is the minimum life span expected for a building. The calculation was realized for a part of the façade which corresponds to the area presented on the right in Figure 4.8. This area is 4.33 meter height, that is to say the height of one storey and 0.50 meter wide, the width of a panel. Then, to ease the reading of the results, the LCC results are given in €.yr^{-1}.m^{-2}. The common input data of the calculations are presented in table 4.4. All the other values and results are presented in the Appendix 3.

Table 4.4 Input data used for the LCC (Andin 2011, Anderson and Olin 2008)

Input Data		
	Money exchange: 1€	8,5 [sek]
	N	50 [years]
	A	2,165 [m²]
	U	0,16 [W.m^{-2}.K^{-1}]
	Height of a storey	4,33 [m]
	h	7 [%]
	i	6 [%]
	g	2 [%]

It was rather difficult and time consuming to find the exact type of data required by the Equations 4.2 to 4.8 that were also reliable. Therefore, some formulas have been lightly adapted. For instance, the price of the gypsum board was available in €.m^{-2} whereas Equation 4.3 requires a value in €.m^{-3}. The price used for a VIP is 150€.m^{-2}, the price given by Porextherm for a Vacupor® PS-B2-S.

For the cost of investment, the costs of the VIPs, the cork and the gypsum board were considered. The cost of the installation was calculated as the price of the skilled workers employed to set up the insulation system. The price of an hour of work should be higher for the setting of VIPs than the price for the setting of conventional materials (Tenpierik 2009).

The cost of maintenance is hard to predict. With the insulation proposed, no special maintenance is required during the 50 years of calculation but early failure of the panels can happen during their early age. Thus, the maintenance cost takes into account the change of the failed panels during their early age. In agreement with Simmer et al. (2005), it has been considered that only one percent of the panels will be evacuated. The cost of the workers employed to change these panels is also considered.

The energy prices were calculated considering that the heating is obtained with district heating system. The weather data, HDD and CDD, are from the website Bizee Degree Days (2013) which gathers weather data for energy professionals. The base temperature is 17°C and the year reference is the previous year, from March 2012 to March 2013.

Two LCC were carried out: one for the promising insulation system with VIPs and one for an insulation made of 17 centimeter mineral wool. Both insulation systems present the same level of thermal efficiency, a U value of 0.16 $W.m^{-2}.K^{-1}$.

The LCC for the VIPs system indicates that this system will cost 10.9 $€.yr^{-1}.m^{-2}$ (see Figure 4.13) whereas the insulation with mineral wool will cost 8.8$€.yr^{-1}.m^{-2}$ (see Figure 4.14).

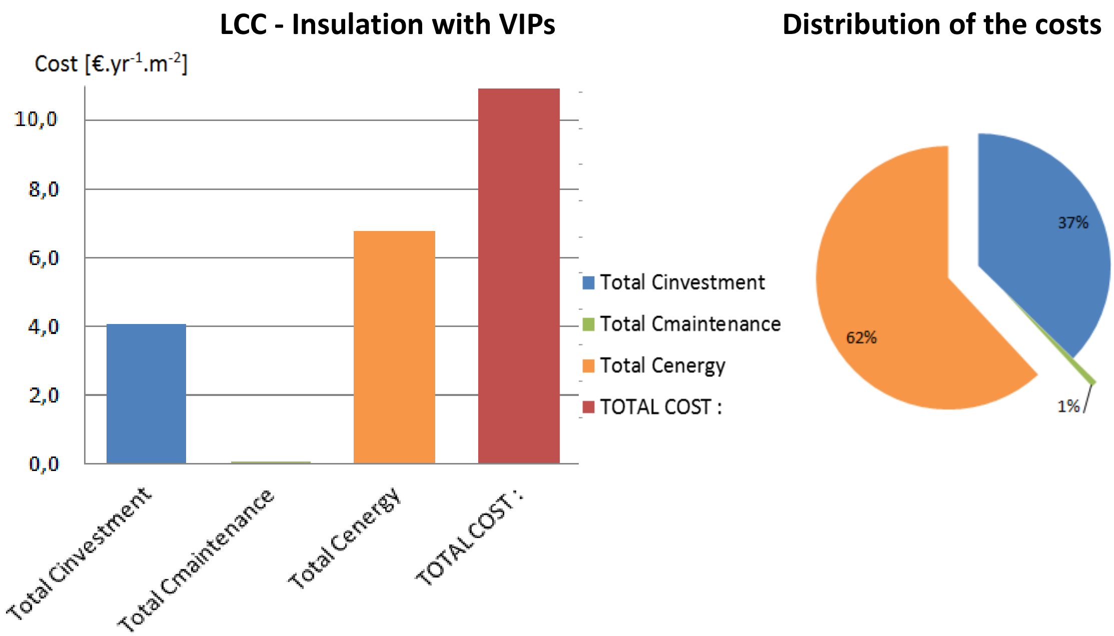


Figure 4.13 Results for LCC with an insulation system with VIPs (N=50 years)

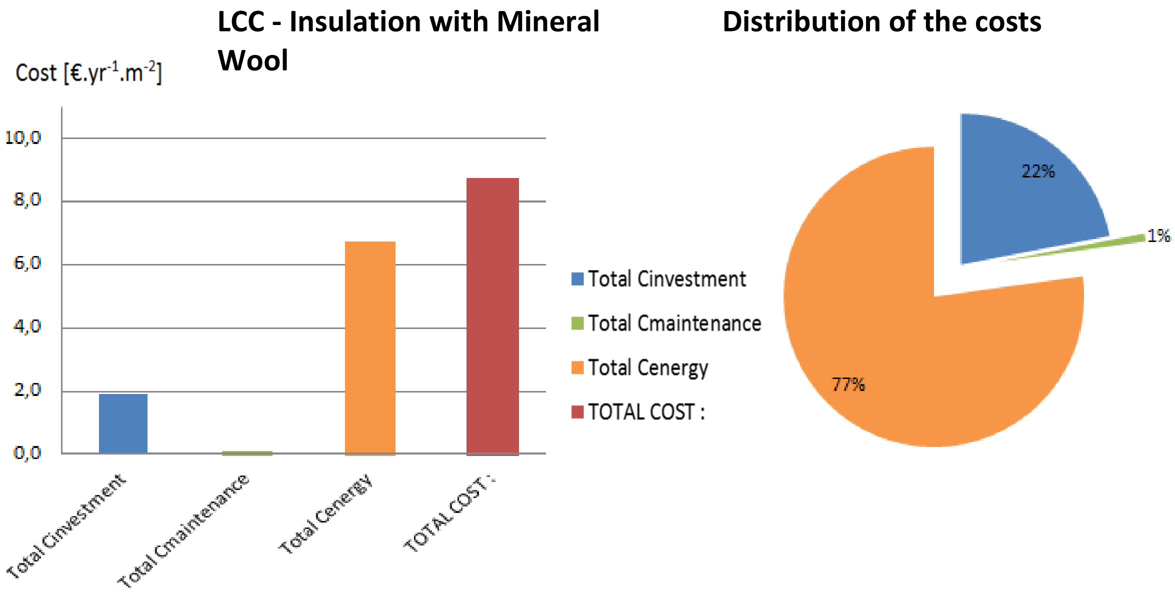


Figure 4.14 Results of LCC with a mineral wool insulation (N=50 years)

The total cost of the insulation with the mineral wool remains cheaper than the system with the VIPs, around 25% less expensive. Thus, when considering the whole facade concerned by the retrofitting, the VIP insulation costs 5 500 € more per year which represents after 50 years an extra cost of around 275 000 €. As a result, it seems that the solution with VIPs is not economically interesting for Älvstranden utveckling AB.

It has been assumed that thermal efficiency imposed by the Swedish Building Regulations should be reached with both systems. As a consequence, the energy costs are the same in both cases: 6.76 €.yr^{-1}.m^{-2}.

The difference of costs is mainly due to the investment cost. The VIP insulation system has an investment cost more than twice more important, 4.1 €.yr^{-1}.m^{-2}, with mineral wool, it only costs 1.9 €.yr^{-1}.m^{-2}. Most of the investment costs are represented by the purchase price and as underlined by Binz et al (2005), the purchase price of the VIP is higher than the ones of conventional insulation materials. Concerning the materials used for Kajskjul 113, the VIP is twenty times more expensive than gypsum board and six times more expensive that cork so the purchase price of the VIPs explains the higher investment costs of this solution. The price of VIPs is expected to decrease (Binz et al. 2005). However, even when the purchasing price it is divided by two, the investment cost would still be 1.5 more expensive than with mineral wool so, after 50 years, the total cost difference will still be important, around 144 000 €.

Over the years, for both systems, the cost of maintenance is low because no expensive maintenance has to be regularly realized. The system is designed to last 50 years without too much reparation. The major uncertainty concerns the early failure of the panels but this rate is low, less than one percent today (Simmler et al. 2005). As a consequence, the maintenance cost is mainly due to the cost of the workers paid to change the few defective panels. However, when the influencing parameter, the time of reparation, is increased, the impact on the total cost stays small. For instance, when the time of reparation is doubled, the maintenance cost represents between 1 and 2% of the total cost.

The cost of energy is only 6.73 €.$yr^{-1}.m^{-2}$. It is a very reasonable sum of money for the opaque parts of the façade because the new insulation is thermally very efficient. Indeed, without retrofitting measures, the energy cost would between four to ten times bigger due to a poorer U value comprised between 0.55 and 1.5 $W.m^{-2}.K^{-1}$. It is also interesting to notice that since the climate is rather cold in Gothenburg, the number of Cooling Degree Day is quite low, 82 compared to 4174 Heating Degree Day (Bizee Degree Days 2013). Therefore, the impact of the cooling system cost is not important.

The LCC assessments points out two main results: the purchase price of the VIP will be the main part of the client's investment but the thermal efficiency of the insulation will have positive effects on the energy costs that will get rather low. Nevertheless, the main advantage of the VIPs system is its thickness. The VIPs system is more than three times smaller than the insulation with mineral wool. If Kajskjul 113 was earmarked for renting, the extra living space earned would have made the VIPs system more economically efficient. This calculation is realised in the next section.

4.3.4 Other economical factors

4.3.4.1 The payback period

Another interesting economical factor that can be estimated is the payback period, it is an "indication of the time required to recover the cost of insulation" (Alam 2011). It is a ratio between insulation cost and the annual energy savings. Different formula can be found in the literature but the one proposed by Ozel (2012) is more accurate since it takes into account the interest and inflation rates. The payback period, p_b is calculated as follows:

$$p_b = \frac{\ln(1-r \,.\, \frac{(Ci.Li+ Cad)}{S})}{\ln\frac{1}{1+r}} \tag{4.9}$$

where C_i, L_i, C_{ad} are described in Equation 4.3, r in Equation 4.8 and S is the annual energy saving, that is to say the difference of energy cost without and with the insulation.

The calculation of the payback period is particularly relevant when different scenarios are studied, especially when different insulation materials are considered. Due to its still high purchasing cost, the payback period of the VIP is still longer than the one of conventional materials (Alam 2011). Consequently, implementing insulation with VIP is more often realised due to technical constraints than for its economical attractiveness.

4.3.4.2 Minimum required annual rent

Kajskjul 113 will be retrofitted by its building owner so Älvstranden utveckling AB will move its headquarter there within some years. Thus, the building is not assigned to rent. The LCC has pointed out that an insulation system with VIP is expensive. However, to obtain a reasonable payback period, Älvstranden utveckling AB could rent out some part of the realized offices.

The minimum annual rent required to pay back the setting of the VIPs has been calculated with the method described in Section 3.3.2.4. It is often used by building owners who use VIPs. In this thesis, three comparisons have been made between VIP and mineral wool, VIP and EPS and between VIP and PUR. Table 4.5 presents the characteristics of each insulation system. The thickness has been calculated to get a U-value of 0,16 $W.m^{-2}.K^{-1}$, the value calculated in Section 4.3.3. The extra cost is calculated with the following expression presented in Equation 3.12:

$$\boldsymbol{Extra\ Cost} = \frac{\boldsymbol{\Delta Ka\ .\ h}}{\boldsymbol{\delta d}} \qquad (4.10)$$

where Ka is the difference in cost of the compared thermal insulation materials [$€.m^{-2}$][7], h is the height of one storey [m] and δd is the difference of façade thickness with the two insulation materials [m]

Table 4.5 Input data for the calculation of the minimum annual rent with a U value of 0.15 $W.m^{-2}.K^{-1}$.

materials	λ [$W.m^{-1}.K^{-1}$]	thickness [m]	δd [m]	**Extra cost [$€.m^{-2}$]**
VIP	0.008	0.03	-	-
Mineral Wool	0.035	0.17	0.14	**3061**
EPS	0.035	0.17	0.14	**2835**
PUR	0.025	0.12	0.09	**4679**

The minimum annual rent has been calculated for different payback periods, from one to ten years. It can be seen from Figure 4.15 that VIPs are economically profitable for buildings assign to rent when the real estate is high.

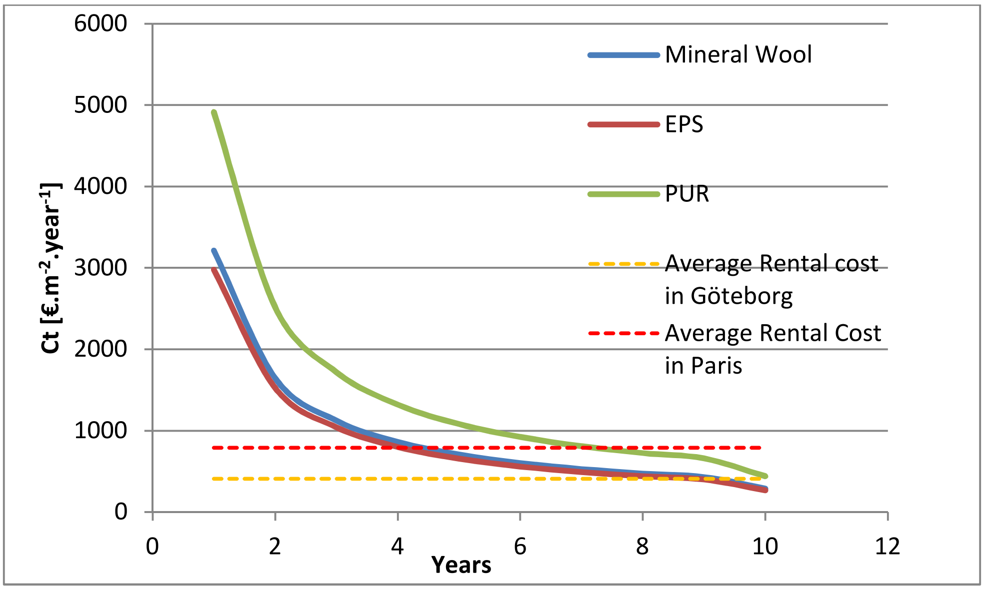


Figure 4.15 Minimal required annual rent to pay back the extra-cost of an insulation with VIPs.

The average rental cost for offices in Gothenburg is 410 $€.m^{-2}$ which corresponds to an average value of the European real estate (The Times 2013). Therefore, the extra

[7] The surface here refers to the surface of the facade

cost of setting VIP compared to mineral wool or EPS will be paid back after 8 to 10 years. When comparing with the use of 12 centimeter thick PUR, no payback can be expected before ten years. A pay-back period between eight to ten years might be considered as a rather long for a insulation system. That is the reason why, the setting of VIPs is more profitable in areas where the real estate is high, such as Paris. In Paris, the average rental cost for offices is 790 €.m^{-2}, one of the most expensive in Europe (The Times 2013). There, the payback periods are shorter: between five and six years compared to the use of mineral wool or EPS and a little more than 9 years compared to the implementation of PUR.

As a consequence, the implementation of VIPs remains expensive if no rental income is received to pay back the extra cost. The price of purchase is much higher than the one of the conventional materials is still the main explanation. However, for Kajskjul 113, annual rental income would pay back the extra cost after less than 10 years. In this case, the use of VIPs can be cost efficient. Nevertheless, it is not the project of Älvstranden utveckling AB who wants to retrofit warehouse for its own purpose.

5 Computer modeling and results

This chapter presents the results of several computer models realized in order to control the thermal and hygrometric conditions in the retrofitted façade. The influence of punctured panels and the air gaps between the panels are also discussed.

5.1 Empirical design

5.1.1 Presentation of WUFI 2D

In order to control the thermal and hygrometric conditions after the retrofitting, computer models have been realized with the software WUFI 2D. It is a commercial hygrothermal analysis software to numerically calculate the simultaneous heat and moisture transport in multi-layer building components, in one or two dimensions. The results can be viewed with graphs or animations.

It is not possible to model windows with WUFI 2D so the following parts only deal with the opaque parts of the façade.

In WUFI 2D, a large range of parameters should be specified before the start of the computation. They are presented in the following sections.

5.1.2 Materials properties

WUFI 2D offers a large data base of materials. The materials used for the models are presented in Table 5.1.

Table 5.1 Characteristics of the materials used in WUFI models (from the WUFI 2D data base)

	Materials Properties					
Materials	thickness [cm]	λ [$K.W^{-1}.m^{-2}$]	ρ [$kg.m^{-3}$]	porosity [$m^3.m^{-3}$]	cp [$J.kg^{-1}.k^{-1}$]	μ [-]
Brick	12	0.6	1900	0.24	850	10
Concrete	24	1.6	2220	0.18	850	248
Mineral Wool	8	0.04	60	0.95	850	1.3
Wood Wool	6	0.08	450	0.55	1500	9
Polystyren	1	0.025	40	0.95	1500	50
Cork	4.1	0.04	150	0.9	1180	10
Gypsum Board	2	0.2	850	0.65	850	8,3

For most of the materials, the moisture storage function, the thermal conductivity as a function of the water vapour content and the diffusion resistance as a function of the relative humidity are also informed and taken into consideration for the calculation by the software.

The VIPs cannot be found in WUFI 2D data base so a new material with the properties of the VIPs has been created. The characteristics of the modeled VIP are presented in Table 5.2, below. They are from the data sheet of the product Vacupor® PS B2-S by Porextherm (see Appendix 2).

Table 5.2 Characteristics to model the VIPs (Porextherm 2013)

	Materials Properties					
Materials	thickness [cm]	λ [$K.W^{-1}.m^{-2}$]	ρ [$kg.m^{-3}$]	porosity [$m^3.m^3$]	cp [$J.kg^{-1}.k^{-1}$]	μ [-]
VIP - new	3	0.007	200	0.96	850	inf
VIP - punctured	3	0.019	200	0.96	850	inf

The VIPs are made of two components, the core and the envelope which have very different properties. In WUFI 2D, the panels are modeled as only one material because the minimal thickness that can be modeled with the software is only one millimeter whereas the real thickness of the envelope is around 10µm (Bouquerel et al. 2012a). The main property of the envelope is its diffusion resistance factor, µ, which makes the VIPs vapour tight. For this reason, the modeled VIP gets a very high µ value.

5.1.3 Initial conditions

For each material, the initial temperature and relative humidity must be defined. Since the temperature in building materials usually reaches the steady state in short period of time the choice of the initial temperatures will not influence much the results. The moisture flow reaches the steady state in a longer period of time, sometimes after several years. As a consequence, in order to avoid too long time of simulation, it is important to start with initial relative humidity levels not too far from the reality. The initial conditions used in the models are presented in Table 5.3.

Table 5.3 Initial Conditions

	Materials	Usage of Kajskjul 113	Initial Temperature	Initial Relative Humidity
Before the retrofitting	All materials	Warehouse	15°C	80%
After the retrofitting	New materials	Offices	20°C	80%
After the retrofitting	Older materials	Offices	Defined with the results of the model of the former facade	

5.1.4 Boundary conditions

For each model, three different boundaries conditions are defined: outdoor, indoor and adiabatic conditions.

Two different indoor conditions are defined: the first one "Before the retrofitting"

Table 5.4 Values for the Boundary conditions (From the data base of WUFI and Hagentoft (2001))

	Interior - Before the retrofitting	Interior - After the retrofitting	Exterior
Materials	Concrete and Bricks	Gyspsum board	Bricks
Surface Coefficient			
Sd value	0	0	0
Heat transfer coefficient	8	8	25
Short Wave Radiation Absorptivity	-	-	0.55
Long Wave Radiation Emissivity	-	-	0.93
Rain water Absorption Factor	-	-	0.7
Climate			
Climate File	Sine Curves	Sine Curve	Gothenburg
Mean Temperature [C]	15	20	8.8
Mean RH [%]	40	55	74
Azimuth	-	-	45
Inclination	-	-	90
Driving Rain Coefficient - R1	-	-	0
Driving Rain Coefficient - R1	-	-	0.07

represents the climate in the warehouse and the second one "After the retrofitting" models the climate in the future offices. The outdoor climate is the one of Gothenburg (see Appendix 3), available in WUFI 2D data base. The values used are summarized in Table 5.4.

The S_d-value represents the vapour resistance at the surface. The natural diffusion caused by the air is already computed but a value can be added if a surface layer has to be considered. In our models, no surface layers are considered. The heat transfer coefficients are calculated with the resistance values of the indoor and outdoor air defined by Hagentoft (2001). The indoor and outdoor resistances used are 0.13 $m^2.K.W^{-1}$ and 0.04 $m^2.K.W^{-1}$ respectively. The short wave radiation absorptivity stands for the fraction of incident solar radiation which is absorbed by the material. The long wave radiation emissivity represents the portion of solar radiation that is reflected by a material. The rain water absorption factor takes into account the part of the rain water that will not be available for capillary suction because it splashes off due to the impact on the façade. For instance, on horizontal surfaces, all the rain water contributes to the capillary suction, the coefficient is 1. For the vertical walls of our model a standard value of 0.7 is used.

The indoor climate is not known and the values presented in Table 5.4 are reasonable estimations for the indoor climate. The relative humidity is set between 30 and 60% and the temperature in the offices is set up to 20°C which are considered as comfortable indoor conditions. The azimuth corresponds to the real orientation of Kajskjul 113 and the inclination is the inclination of the façade. Eventually, the driving rain coefficients are standard values to evaluate the driving rain load on the surface.

The calculation starts on the 1st of October. The period of calculation is set to 2 years with a time step of 1 hour.

5.2 The older wall

The first model realised is a model of the façade before the retrofitting. The purpose of this section is to evaluate the main defects of the older façade and to determine the thermal and hygrometric conditions in the different materials once the steady state is reached. These data are necessary in order to create an accurate model of the retrofitted façade and to estimate the improvements due to the retrofitting.

5.2.1 Mean temperature and relative humidity in the different materials

According to the results from the computer model, a period of calculation of two years is sufficient to reach the steady-state in the older façade. Thus, it is possible to search the mean temperature and relative humidity in each material in the beginning of October, the starting date of the calculation. The data are presented in Table 5.5, they will be reused in Section 5.3 as the initial conditions in the retrofitted façade, in bricks, concrete, mineral wool and wood wool.

Table 5.5 Temperature and relative humidity in the beginning of October based on a two year hygrothermal simulation

MATERIALS	TEMPERATURE [C]	RELATIVE HUMIDITY [%]
Bricks – exterior layer	14.5	86
Mineral Wool	15	85
Bricks –interior layer	14	63
Wood Wool	14.5	88
Concrete	12	71

5.2.2 **Thermal bridges and surface temperatures**

According to the input data used, the average dew point of the surface is between 5°C and 9°C. Figure 5.2 shows the temperature on the different surfaces, the surfaces are identified in Figure 5.1. It can be seen that the dew point is never reached since all the surface temperatures are over 10°C. Thus, very little condensation might have occurred on the surface during the usage of Kajskjul 113 as a warehouse.

However, it is important to remember that this statement is only based on hypothesis. Indeed, no accurate data were available about the indoor conditions of Kajskjul 113 as a warehouse so the input data used are only reasonable estimations[8]. For instance, if the indoor conditions were 20°C with 60% relative humidity, the dew point would be 11.6°C; if it was 20°C with 65% relative humidity, the dew point would be around 13°C. In these cases, as it can be observed in Figure 5.2, condensation might have occurred on the surfaces.

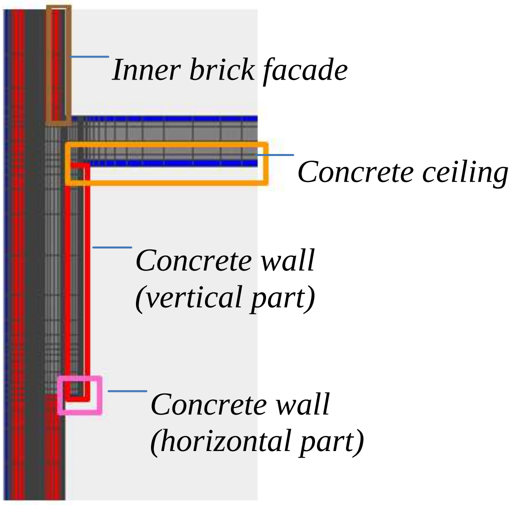


Figure 5.1 Location of the surface where the surface temperatures have been calculate

[8] The estimations is based on a English law that state a minimum temperature in workplace between 13°C and 16°C according to the type of work (Health and Safety Executive 2013)

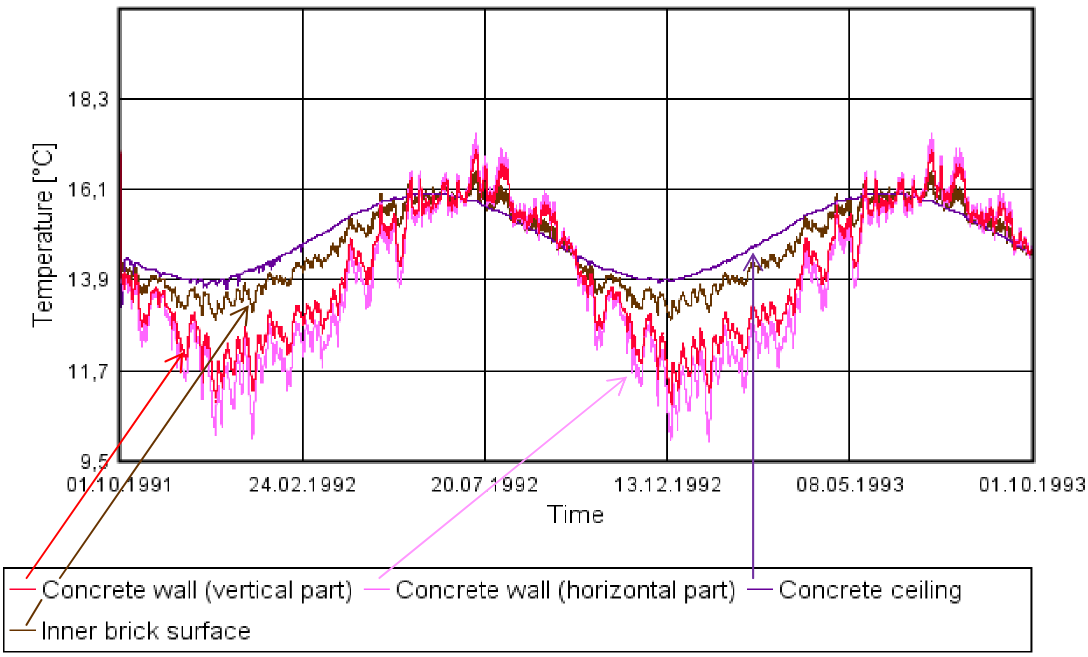


Figure 5.2 Temperature on the surface for the different materials

As it can be seen from the diagram, these surface temperatures are rather high since the indoor air is 15°C ± 1°C because there are no dominating thermal bridges in the façade, even before the thermal refurbishment. As shown in Figure 5.3, the insulation, made of mineral wool and wood wool and set all along the façade, reduces the thermal bridges effects. The mineral wool is represented in yellow and the wood wool in light green. The resistance value of wood wool, 0.75 m².K.W^{-1}, is lower than the resistance of the mineral wool, 0.2 m².K.W^{-1}. Therefore some thermal bridges effects can be expected in the areas of the details A and B (see Figure 5.3). However, the results of the model do not reveal thermal bridges effects on the area of detail B and very few effects on the area of detail A. These effects can be observed during the warmer season so their consequences are not too serious.

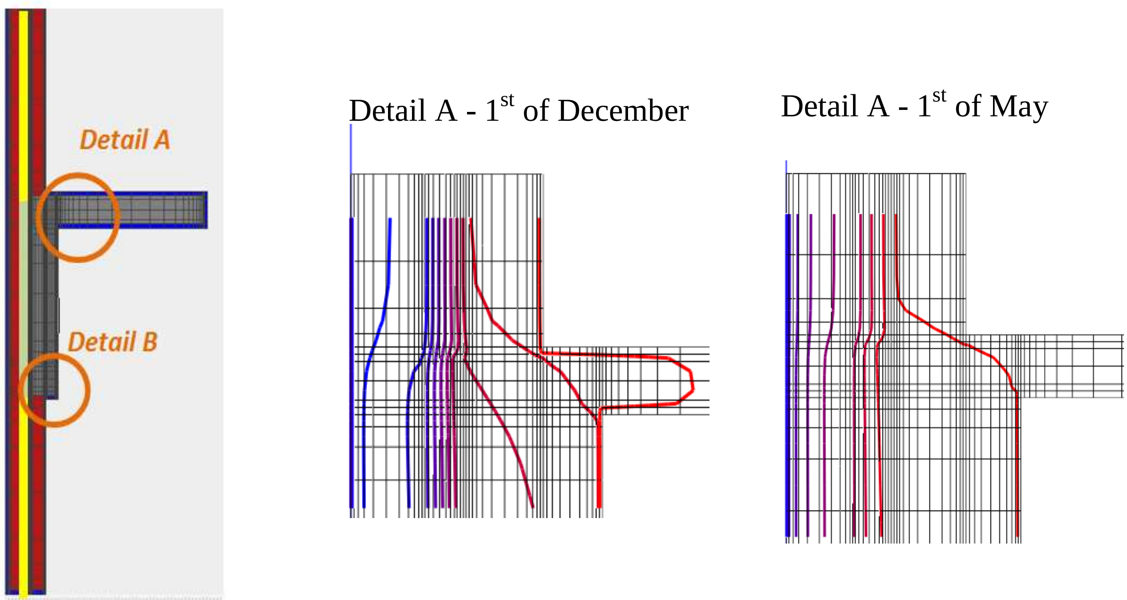


Figure 5.3 Study of the thermal bridges effects in the façade before the retrofitting

5.2.3 Hygrothermal behavior

Over the time, in the façade of Kajskjul 113, it has been noticed that the bricks have been damaged by the action of freeze and thaw (Anderson and Olin 2008). This can be explained with the WUFI 2D model. Indeed, in Figure 5.4, the temperatures, represented in red, and the relative humidity, represented in blue, in the outer brick façade are displayed. It can be noticed that there are rather long periods, marked in orange in the figure, where the relative humidity in the bricks are high and the temperatures are low. There, the risk of condensation and by consequence of freeze appearance is important. Then, the temperatures increase again, thaw occurs and later, the external brick layer will start to dry out. The inner brick layer does not face this issue since due to the layer of mineral wool, the temperatures are higher, superior to 11°C, and the relative humidity lower, inferior to 71% all around the year (see Figure 5.5)

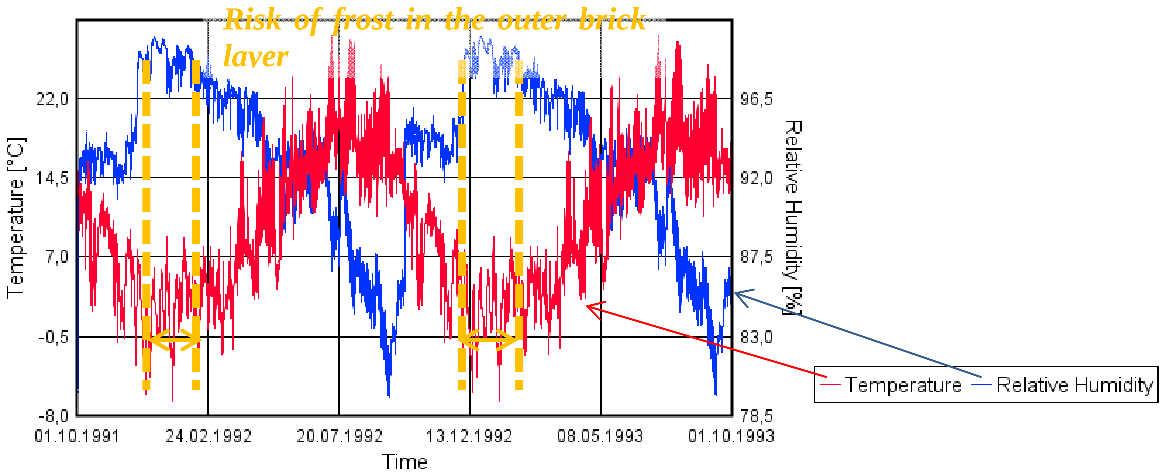


Figure 5.4 Temperature and relative humidity in the outer brick façade

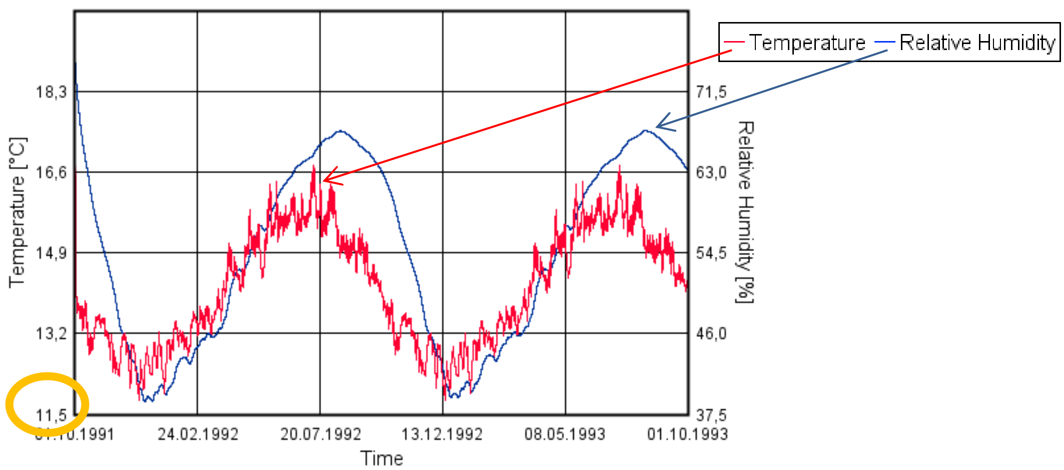


Figure 5.5 Temperature and relative humidity in the inner brick façade

Another hazardous effect due to a poor insulation system is the risk of mould growth. WUFI 2D can display graphs called "isopleths". The isopleths are used to represent the average temperature of a selected part of the insulation over the temperature. On the same graph, two limit lines are represented: Limit 1 and Limit 2 which indicate the minimal level for the appearance of mould growth on interior surface. Limit 1 is the limit for biodegradable material whereas Limit 2 is the limit for non-biodegradable materials. The evolution of the relative humidity over the temperature is plotted for the full time of calculation, the lighter colours, in yellow tones, represent the beginning of the calculation time whereas the darker colours, in dark green tones, represent the end of the calculation time. In the façade of Kajskjul 113, the limit conditions for the appearance of mould growth are overstepped in both insulation materials: the mineral wool and the wood wool (see Figure 5.6). The insulation materials have no capillary properties so in summer when the bricks release water, the mineral wool and wood wool load up with this water. Later, they can hardly evacuate it. As a consequence, these problems must be solved with the new insulation system.

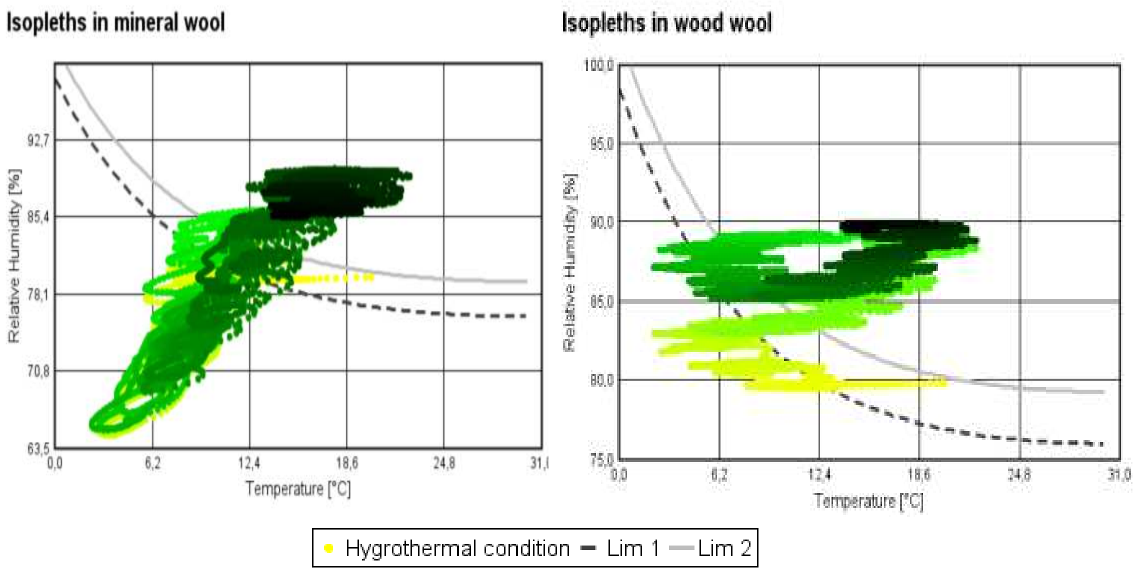


Figure 5.6 Risk of mould growth in the insulation materials

In the outer brick layer, the same type of problem is detected. However, for bricks it is not relevant to talk of problem of mould growth and since it is the outer layer it does not cause any health hazards but only aesthetics issues. With a regular maintenance and cleaning of the façade, this matter could have been easily solved. In the inner brick layer, the limit conditions for mould appearance are not overstepped.

As a consequence, the main issues with Kajskjul 113 are due to the water vapour transfer. It seems that the façade is not water tight so the capillary suction is important when raining whereas then the water vapour evacuates too slowly. Therefore, it leads to serious problems of moisture and rot in insulation materials and also to damages of the bricks and the mortar joints because of freeze and thaw.

The new insulation system integrates VIPs whose envelope is vapour tight. Therefore, it is important to control that the hygrothermal conditions of the façade will not get worse with the setting of the VIPs.

5.3 The retrofitted façade

The following step is to model the new insulation system proposed in the Figure 4.8, Section 4.2.2, to control the changes in thermal and hygrothermal conditions. The new insulation must be more thermal efficient and the issues due to vapour water transfer and moisture in the older façade must be suppressed. However, internal insulation can cause serious problems of mould growth since the temperatures get lower and the relative humidity higher in the cold parts of the external wall.

5.3.1 The challenges of using a vapour barrier

The VIPs are modeled with a very high S_d-value so the VIP surfaces have the same role as a vapour barrier. In reality, the vapour barrier is created by the envelope of the panels.

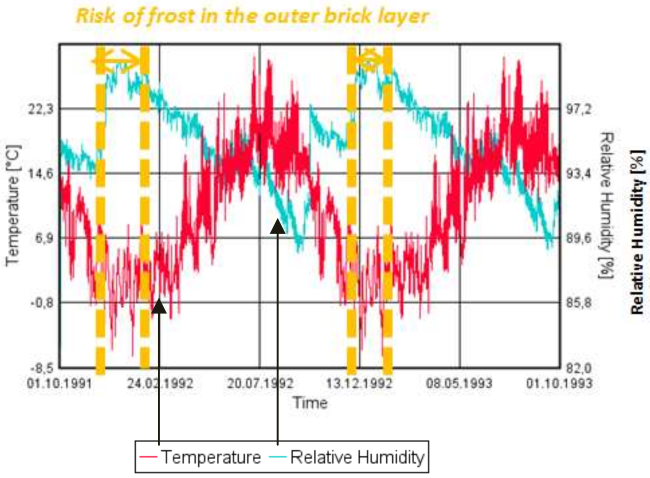
Usually, a vapour barrier is used to avoid the risk of condensation in the wall. They are traditionally placed on the warm side of the insulation material so there is no risk of condensation in the wall (Brandt et al. 2012). However, they are a rather fragile membrane that should not be punctured to be efficient. Indeed, if the vapour barrier is punctured or not absolutely airtight, the humid and warm air from the indoor can circulate in the façade and condensation may occur depending on the pressure and vapour concentrations gradients.

The panels are set up on the wall as close as possible of each other to reduce the air gap between them. Usually the size of the air gap ranges from 1 to 5 millimeters due to the tolerances of the size of the panels (Porextherm 2013). Therefore, the vapour barrier created by the envelope is not continuous. The influence of the air gap is studied in the Section 5.3.5.

5.3.2 Alternative 1

The first alternative is a model of the solution established following the pre-study (see Figure 4.8). The air gap between the VIPs is set to one millimeter to make the model more realistic.

The results from the model prove that the issues of the former wall are not solved with this system. As it is displayed in the Figures 5.7 and 5.8, the outer bricks layer, the colder part of the external wall, is still subjected to the action of frost and thaw which is one of the main drawback of the internal insulation. The temperatures have not changed but the level of relative humidity has worsened.



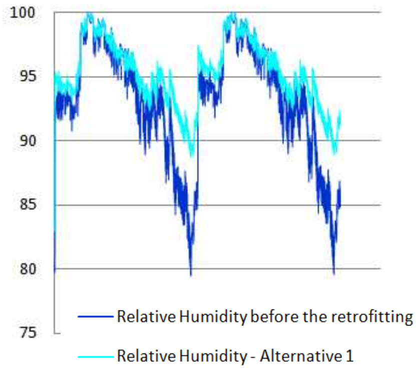


Figure 5.7 Temperature and relative humidity in the outer brick façade

Figure 5.8 Relative Humidity in the outer brick layer before retrofitting and with the alternative 1

Furthermore, the existing insulation materials have a higher relative humidity level and the limit for the appearance of mould growth is overstepped.

The first reason of the bad thermal and hygrometric performance may be due to the poor evacuation of the rain water entering the façade. A solution is to apply a hydrophobic impregnation treatment on the façade to make the surface water repellent.

Another reason might be the air gaps since they enable air leakages from the inside to the outside. Brandt et al (2012) advise the use of a real non-punctured vapour barrier or the setting of an insulation material with high capillary properties. The vapour barrier should be set between the VIPs and the gypsum board and the additional insulation could be glued between the bricks and the VIPs to limit the problems of mould growth. Adding extra insulation is an efficient solution used for decades since the capillary properties of the materials enable a safe equilibrium situation to be reached. However, it will consume extra living space that is the reason why, for the second alternative a vapour barrier will be set up.

5.3.3 **Alternative 2**

For the second alternative, as advised by Brand et al. (2012), a vapour barrier is installed between the gypsum board and the VIPs (see Figure 5.9). The outdoor surface is considered to be water-repellent due to the application of an hydrophobic impregnation.

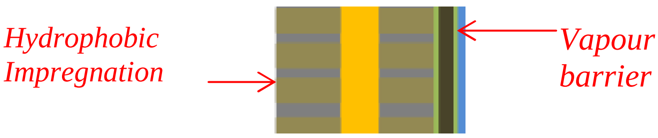


Figure 5.9 Localisation of the vapour barrier and the hydrophobic impregnation for the Alternative 2

Hydrophobic impregnations are a treatment for surfaces made for mineral substrates such as concrete, mortar, bricks, stones or tiles. It is a liquid protection made of silicon resin network whose organic components are responsible for the water repellent properties. Once applied on surfaces, the surfaces get water-repellent but stay opened to water vapour diffusion. Using on building facades, the hydrophobic impregnation improves the aesthetics aspects and the thermal insulation by decreasing the risk of efflorescence and micro-organisms growth and by reducing the water absorption (Sika 2013). The hydrophobic impregnation is modelled by decreasing the rain water absorption factor which represents the portion of water that is available for capillary suction.

The vapour barrier and the water-repellent impregnation have an effect on the relative humidity and water content in the outer materials. Figure 5.10 illustrates the improvements of the hygrothermal conditions in the outer brick layer. In average, the relative humidity is 14 percentage points lower after the refurbishment measures and the water content is 82 % inferior. There is a particular reduction of the water content in winter since it is in winter that the liquid water is more likely to freeze. Thus, it can be expected that the action of freeze and thaw is reduced. To analyze the water content data, the manual of WUFI 2D advices to only compare general long term trends and not the numerical values which are not relevant.

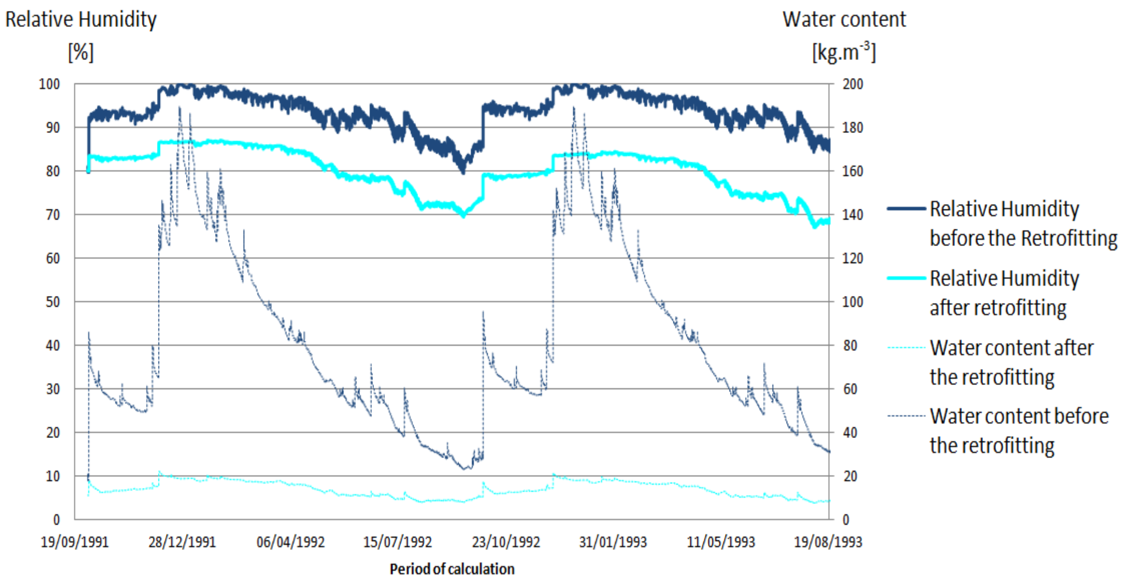


Figure 5.10 Effects of the retrofitting on relative humidity and the water content in the outer brick layer

In contrast, the temperatures have not changed. This is due to the type of insulation set up: an internal insulation often leads to lower temperatures in the outer part of the façade than before retrofitting. However, as it can be seen in Figures 5.11 and 5.12, the risk on mould growth is decreased since the level of relative humidity is lower. The isopleths in the outer brick layer are under the critical limit which represents good conditions for the durability of the façade.

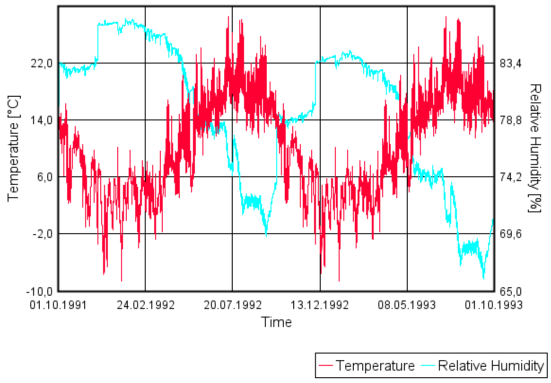


Figure 5.11 Temperature and relative humidity in the outer brick layer.

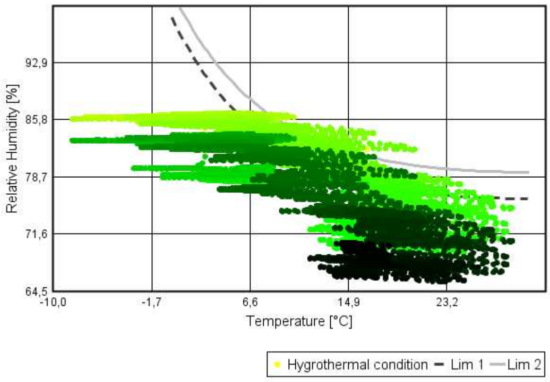


Figure 5.12 Isopleths in the outer brick layer (the lightest colours represent the conditions in the start of the calculation time whereas the darkest colours represent the end of the calculation)

In the same way, the hygrothermal conditions are now acceptable in the mineral wool and wood wool (Figure 5.13) because the insulation materials now face the same temperatures as before but with lower relative humidity levels. The relative humidity has decreased because the hydrophobic impregnation sprayed on the façade limits the absorption of the rain water inside the façade. In the same way, there is no issue in the gypsum board.

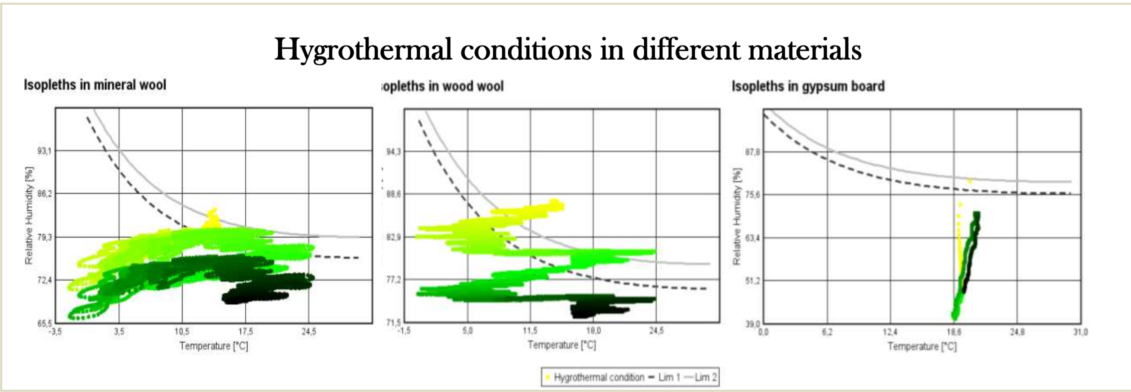


Figure 5.13 Isopleths in different materials (the lightest colours represent the conditions in the start of the calculation time whereas the darkest colours represent the end of the calculation)

The temperatures on the indoor surface are very close to the temperature of the indoor air, around 20°C. They are shown in Figure 5.14 in different position of the wall. In these indoor conditions: 20°C ± 1°C and a 55 % ± 15% relative humidity, the dew point ranges from 4°C to 14°C. As a result, the risk of condensation is consequently reduced with the retrofitting measures.

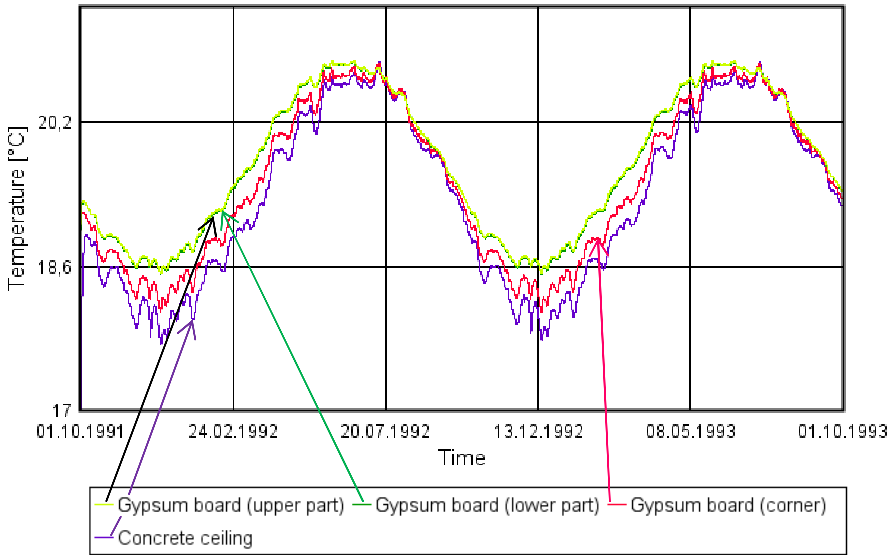


Figure 5.13 Surface temperature

5.3.4 Influence of a punctured panel

In this section, the influence of punctured panels on the hygrothermal conditions in the façade is studied. Once set up on the walls, few panels are expected to early fail. These failures can be due to manufacture defects or to damages caused by the occupants' behaviour. Thus, to make a realistic study, only one VIP is modeled as punctured. The punctured panels have a higher thermal conductivity, 0.19 $K.W^{-1}.m^{-1}$ (Porextherm 2013). Two different scenarios are modeled with two different positions for the punctured panel: alternative A and alternative B (see Figure 5.15).

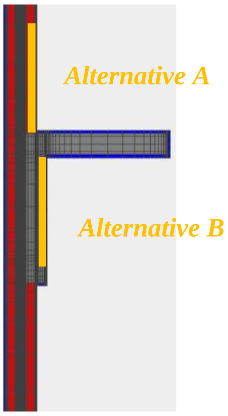


Figure 5.15 The different scenarios studied

Figure 5.16 displays the surface temperature on the gypsum board for the different alternatives. When the panel B is punctured, the surfaces are a slightly colder, in average; the difference is 0.17°C. There is no difference when panel A punctured.

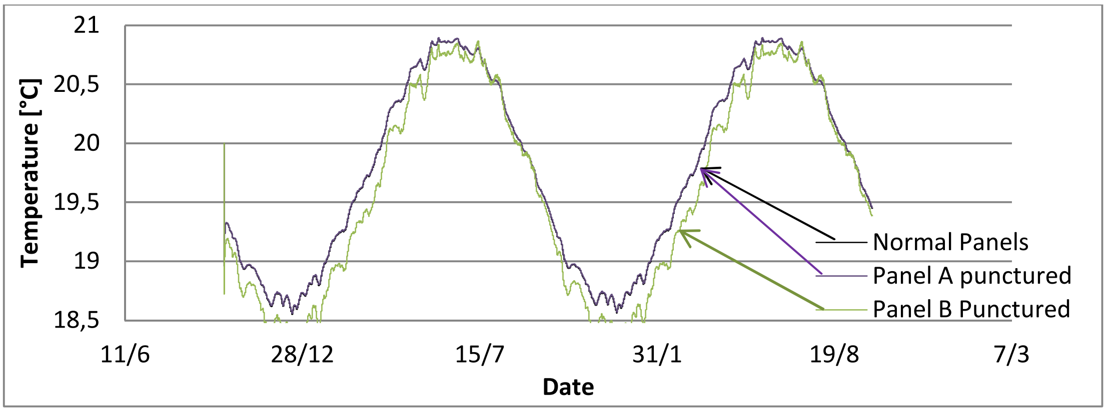


Figure 5.16 - Surface temperature on the gypsum board

Furthermore, there is no important temperature difference inside the concrete slab which is a possible area for thermal bridges. In winter, when the thermal bridges affects are the most consequent, the temperature is only 1°C inferior when one panel is punctured. In the outer part of the façade, there is no perceptible change, the hygrothermal conditions are identical. Therefore, one punctured panel does not lead to perceptible changes for the users.

Although, punctured panels have a thermal conductivity which is four times bigger than when evacuated, their thermal conductivity stays better than the one of conventional materials. Moreover, a failed panel represents only a small portion of the façade. As a consequence, the influence of a failed panel on the overall thermal conductivity is low. Furthermore, in these models, it has been considered that the vapour barrier and the hydrophobic impregnation were still efficient so the hygrothermal conditions have not changed.

To get an idea of what changes could be expected, an extreme case model has been carried out. All the panels of the models are now considered as punctured. Therefore, the U value of the wall rises to 0.25 $W.m^{-2}.K^{-1}$ instead of 0.16 $W.m^{-2}.K^{-1}$ without punctured panels. The influence of the failed panels is very small. The surface temperatures are a little bit colder so the changes would be hardly perceptible by the future users. In the façade materials, bricks, mineral wool and wood wool, the thermal and hygrothermal conditions are almost the same.

Since the rate of failure of the panels is low (Simmel et al. 2005) early failure should not jeopardize the overall efficiency of the insulation system and the durability of the façade.

5.3.5 Influence of the air gaps between the panels

The edges of the panels are not perfectly flat so there are tiny air gaps between them. The tolerances related to the panel size are given by the VIP's producers. The length and width tolerances are usually up to 5 millimeters. The influence of the air gap size is evaluated in this section.

For the following models, the vapour barrier has been suppressed in order to better underline the changes. Four different air gap thicknesses have been studied (see Table 5.6)

Table 5.6 Different alternatives studied

Alternative Name	Alt.0	Alt.1	Alt.2	Alt.5
Air Gap Thickness [mm]	0	1	2	5

The temperatures and the relative humidity differences due to the air gaps in the different materials are not significant and vary according to the thickness of the air gaps (see Figure 5.17).

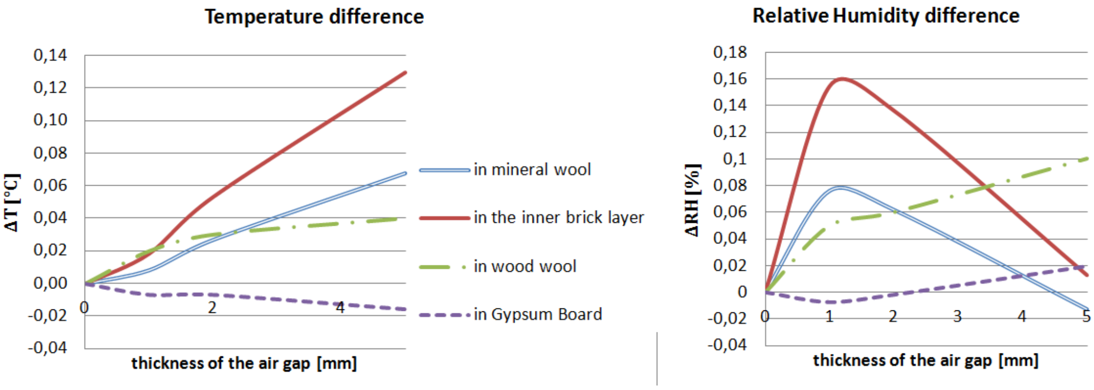


Figure 5.17 Influence of the air gap on the temperature and relative humidity

The air gaps induce more air transfer between the indoor and the outdoor which explains why the materials of the façade: the inner brick layer, the mineral wool and the wood wool are a little warmer and the indoor materials such as the gypsum board are colder. The thickness of the air gap influence the temperature difference but in all cases the differences is not significant, only up to 1.14% (see Figure 5.18).

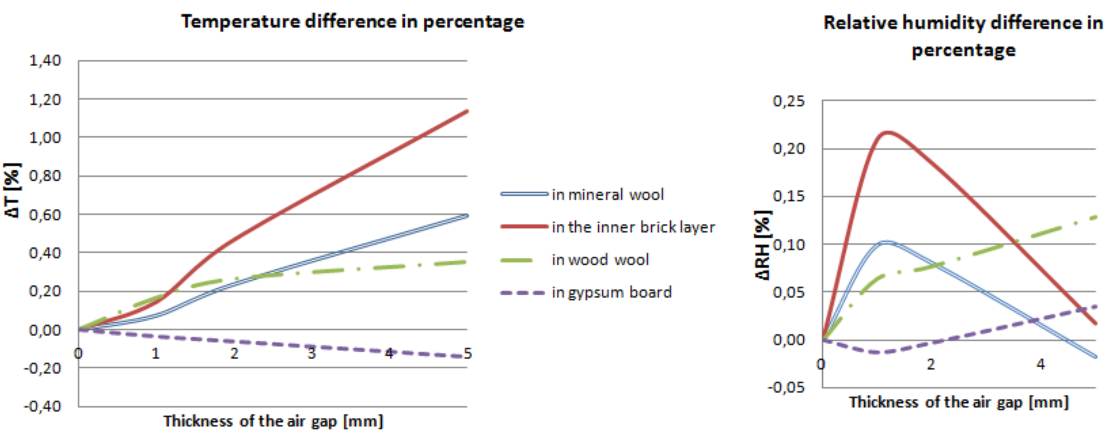


Figure 5.18 Influence of the air gap on the temperature and relative humidity in percentage

The general influence on the relative humidity is harder to explain. Two different behaviors can be underlined. One in the upper part of the façade where there are the concrete element and on in the lower part of the façade where there is an inner layer of bricks. In the lower part, it seems that when the air gap thickness oversteps a limit value, the material of the outer parts façade dries out whereas the inside materials fill with water. There, the two types of materials are separated only with VIPs. In the upper part of the façade, the behavior of the relative humidity in the wood wool is different (see Figure 5.17). The wood wool continuously charges itself with water. It might be due to the thick concrete block set up between the wood wool and the VIP.

6 Discussion

The method implemented in this thesis is quite similar to the one used by companies having to design technical solutions. Indeed, in most of the cases the first steps are a well understanding of the general requirements before realising a pre-study to select one or various promising solutions. The economic aspects are considered from the pre-study because companies want to be sure that the time and money they will later invest in developing their solutions will be profitable. Eventually, once the cost efficiency of the solution checked, detailed technical verifications are carried on to validate the solution that will be implemented. These are the steps followed in this work.

This section analyses and evaluates the results obtained. It is divided in two parts: a first discussion regarding the thermal improvements carried out by the new insulation and the WUFI 2D models and a second discussion concerning the LCC analysis.

6.1 Thermal efficiency of the retrofitting

Previous works have reported that the old façade of Kajskjul 113 has been damaged by the action of time, temperatures changes and the driving rain. As a result, some rust and corrosion can be observed on the façade and the building is not air and water tight anymore (Anderson and Olin 2008). The diverse studies realised in this thesis point out the different defects of the older facade. Indeed, the insulation is not sufficient enough to reach the current thermal regulation set by the Swedish Building Regulations (BBR). The computer model underlines that the bad hygrothermal conditions lead to an accumulation of water in the insulating materials, the development of mould growth, the mechanical damage of the bricks, the deterioration of the thermal properties and as a consequence the jeopardize of the historical yellow brick façade.

For this reason, a thermal retrofitting of the façade is necessary. The new insulation will be internal due to the preservation of the historical façade. After the pre-study, it has been established that 3 centimeter VIPs encapsulated in 1 centimeter polystyrene on both side should be sufficient to reach the thermal regulation imposed by the BBR. The parts of the wall that could not be covered by VIPs will be covered with cork, an insulating material with good capillary properties A gypsum board will be added on top to better mechanically protect the VIPs. Thus, the opaque parts of the façade reach a U-value of 0.16 $W.m^{-1}.K^{-1}$ whereas the BBR imposed a value of 0.20 $W.m^{-1}.K^{-1}$. By comparison, previously, the opaque parts of the older façade had a U-value of 0,58 $W.m^{-1}.K^{-1}$. Moreover, since Kajskjul 113 façade present a large surface of windows, the replacement of the old damaged windows for new ones is necessary to successfully complete the retrofitting.

The efficiency of this insulating system has been controlled with computer models and a particular attention has been carried on the hygrothermal conditions in the external part of the façade since it is the coldest one and so the more sensitive. The computer models prove that hydrophobic impregnation is required to protect the façade from an accumulation of water. As a consequence, with the VIPs insulation system and the hydrophobic impregnation, the relative humidity is 14% inferior and do not lead to any conditions which threaten the durability of the façade. The thermal bridges which used not to be too dominating are now suppressed. Therefore, this solution is durable, thermally and hygrothermally efficient and will contribute to a healthy indoor conditions for the future users of Kajskjul 113.

6.1.1 Possible improvements of the models with WUFI 2D

However, the results given by the software WUFI 2D might lack of accuracy for a very detailed analysis and some approximations done might be improved.

The first approximations were due to the input data concerning the boundary and initial conditions. The usual indoor conditions in Kajskjul 113 when used as a warehouse were not known. In the same way, the indoor conditions after the retrofitting could only be estimated. In particular, the indoor relative humidity and water vapour content greatly influence the thermal behavior of the wall (Johansson 2012). Johansson (2012) presents a study carried out to evaluate the average relative humidity in 1000 dwellings in Gothenburg during 5 days in February. This study points out that the relative humidity is very dependent on the season, the type of the dwelling and on the occupants' behavior. It usually ranges from 48% and 92%. Although in office buildings, the relative humidity levels are usually lower than in dwellings, the relative humidity is very variable and its evolution is still hard to predict. Moreover, sine curves were used to simulate the interior condition based on reasonable estimations. The EN 15026 indoor conditions could also have been used. They give the indoor temperature and relative humidity as a function of the outdoor conditions of the warehouse which is a little more precise than sine curve. However, the more interesting would have to investigate the real indoor conditions to create an accurate file with the daily variations of the temperature and relative humidity. In the same way, the initial conditions in the older materials have been estimated with the results of the first model. In a real case, measures in situ could have been done to determine the exact values.

The choice of the materials was also tricky. No information was available concerning the characteristics of the façade materials so the materials have been selected from WUFI 2D database according to reasonable estimations. These estimations might have led to some variations in the results that would have been interesting to study. For instance, each bricks model presents very different hygrometric properties that might influence the hydrothermal behavior of the façades. Furthermore, the modeling of the VIPs was a real challenge. It has been decided that only the core material be modeled with the value of diffusion resistance of the envelope. Moreover, no information was given to the software about the evolution of the thermal conductivity with the water content or the moisture storage function. It would be interesting to develop a precise model to use with WUFI 2D. Thus, models for the moisture storage function, the dependency between the thermal conductivity and the moisture or the dependency between the thermal conductivity and the temperature could be established for different type of panels depending on their envelope, the composition of their filling materials, their thickness, their encapsulating materials ... With these accurate data sheets, the simulation should be more precise.

Another important factor is the grid chosen. The number of elements in the x-direction as well as in the y-direction can be specified. The finer the grid is, the more reliable the results will be because neighboring materials will get elements with a size of the same order of magnitude. However, heightening the number of elements prolongs the time of calculation which can be really extended with only few additional elements. To optimize the grid, a preliminary work could have been done for each model in order to estimate the optimal number of elements. Usually, after a certain number of elements is overstepped, the results converge while the time of calculation increase (see Figure 6.1). This optimal number of elements of the grid should be calculated for the water vapour transfer since it is longer to reach the steady state than the heat transfer. This preliminary step is time consuming, that is the reason why, it has not be done in this thesis.

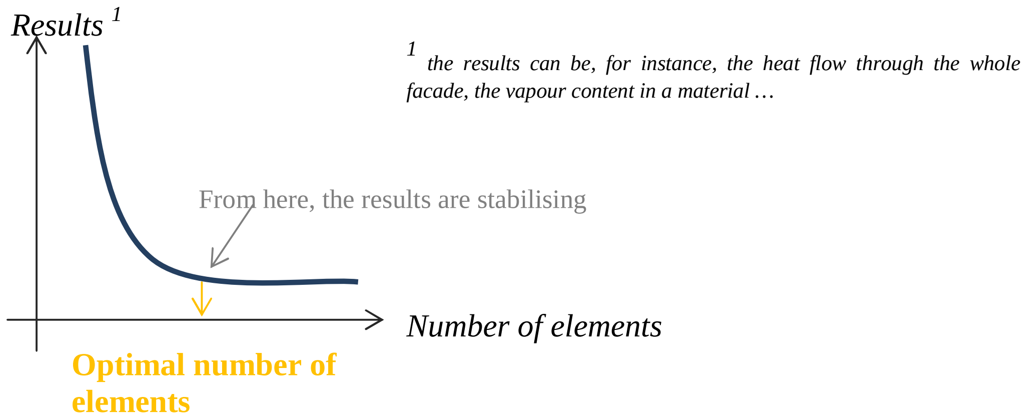


Figure 6.1 Proposition to find the optimal number of elements for the grid in WUFI 2D.

As a result, almost all the limiting factors and approximations can be improved to get more accurate results. However, the limiting time allowed to realise this master's thesis has not made it possible to correct the approximations. In particular, the time of modeling was rather long, up to half a day, so the number of simulation was limited.

6.1.2 Other ways to do the models

Some elements have been neglected in our models due to the software WUFI 2D. First, it was not possible to model windows although, as underlined in Chapter 4, the windows represent a large part of the facade and therefore play a prominent part in the thermal behavior of the building envelope. Furthermore, since the model can only be done in two dimensions, some elements have not been modeled such as the attachments between the bricks. The attachments, usually made of wood or steel are likely to be subjected to mould growth or rot.

To complete the study, it would be interested to implement the new insulation system on a part of the façade to measure in situ the changes produced. Indeed, Brandt et al (2012) have underlined the fact that the appearance of mould growth is difficult to foresee in brick facade. It is a seldom phenomenon. With a real installation, the measures obtained might differ from the ones obtained with the computer models for all the reason explained previously.

6.2 The LCC model

On the whole, retrofitting the insulation system of a façade is a cost effective measure. Indeed, the LCC illustrates that with a well-insulated façade, the cost of heating gets much lower. With new double glazed windows and a retrofitted façade that reaches the thermal levels established by the BBR, the annual cost for heating Kajskjul 113 would be approximately 62 000 € whereas it would have been 182 000 € without any retrofitted measures. The retrofitting enables to cut the expenditures of heating by three. However, the cost of the insulation materials is very variable.

The two LCC realised underline that the proposed insulation system with VIPs is around 25% more expensive than a conventional insulation with mineral wool and for the same level of thermal efficiency. For a life span of 50 years, the solution with VIPs will cost 10.9 €.$yr^{-1}.m^{-2}$ whereas insulating with mineral wool costs 8.8 €.$yr^{-1}.m^{-2}$. These expenditures include the purchasing, the installation, the maintenance and the cost of energy to heat and cool Kajskjul 113. As a consequence, the solution with VIPs is not economically interesting for the building owner, Älvstranden utveckling AB, who wants to retrofit the former warehouse for its own usage so no payback period can be expected from a rental income.

The extra cost of the VIPs system is mainly due to the high purchasing price of the panels which is still far more expensive than conventional insulation materials. As a consequence, the investment costs are doubled compared with the ones of an insulation with mineral wool. Nevertheless, even if the VIPs purchasing price was divided by three, the VIPs solution would have remained more expensive than the use of mineral wool. In 2005, Binz et al. announced a decrease of the VIPs price. However, between 2005 and 2013, it can be noticed that the price of the panels has not decreased: in 2005, it was 129 €.m^{-2} (Simmer et al. 2005) and in 2013, Porextherm, for the same product, gives a price that ranges between 120 and 130 €.m^{-2}. The purchasing price of the panels is still a serious disincentive so it could be interested to study how to decrease it. Until now, it has been pointed out that the high purchasing price is mainly due the expensive filling materials and to the production process which is not optimized yet (Simmler et al. 2005). It seems that there are a lot of potential improvements in this area.

Nevertheless, the calculation of the minimum rental cost shows that an insulation with VIPs is more profitable than one with conventional materials for buildings earmarked for renting in urban areas where the real estate is high. In this case, the living space saved by the use of VIPs leads to a higher renting income which will pay back the extra cost of the insulation before 5 to 8 years. Considering that the life span of VIPs is now up to 60 years, the payback period is rather short.

6.2.1 Imprecision of the LCC

The LCC implemented in this thesis is a rather simplified model. However, it highlights the main indicators of costs such as the purchase price, the maintenance or the cost of energy. It represents a broader global outlook for a justified decision by building owners.

The main approximations of the LCC are difficult to correct. The LCC is based on an estimation of the future operational costs whose prices in the future are unknown. Indeed, the prices are subjected to various variations due to the real cost of capital, the inflation and interest rates and the value of this rates over the period of calculation can only be estimated. Moreover, the considered rates are constant over the period of calculation which will never be the case in reality. Over a long period of the LCC calculation such as in this thesis, 50 years, the estimations can easily be too rough. For instance, in our model, by changing the inflation rate and the interest of more or less one percent, the over whole price obtained varies from 9.9 to 12.3 €.yr^{-1}.m^{-2} which leads to a range of variation of the total cost of the insulation with VIPs of 313 000 €.

The maintenance costs are also hardly predictable. The early failure of the panels occurs randomly and the cost of their replacement varies with many parameters such as the spatial location of the panels. The science of decision support has established various schemes based on the statistics and probability mathematics to evaluate the occurrence and cost of failure during the life span of a product.

6.2.2 Propositions for different LCC models

A LCC is often implemented to compare different solutions to determine the less costly one. If different insulation materials were compared, it would have been interested to integrate in the LCC some operational gains due to the rental of the building. Indeed, the implementation of VIPs is particularly attractive for internal insulation because living space is saved. In this case, since the VIPs are thinner than the commonly used insulation materials, more living area is saved so more surface can be dedicated to hire. Therefore, the building owner will earn more money from the rent. Owing to this, when comparing insulating system with different materials, it seems wise to take in consideration the rental incomes.

A LCC can also be used to establish the optimal insulation thickness (Ozel 2012), that is to say the best thermal efficiency at the lowest prices. In order to do so, the total price of the insulation system is calculated as a function of the insulation thickness and energy consumption cost. As it can been seen in the Figure 6.2, the insulation cost increases when its thickness rises whereas the energy cost decrease because the building gets better insulated. Therefore, the optimal insulation thickness corresponds to the lowest total cost.

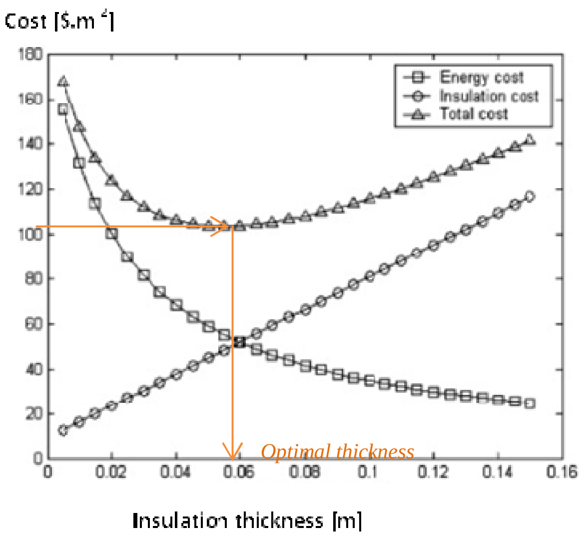


Figure 6.2 Variation of cost with insulation thickness (Ozel 2012)

The LCC emphasizes the importance of the choice of the heating and cooling systems. Indeed, the type of energy used and their efficiency greatly influence the total cost. To reduce, the overall use of energy in buildings, an efficient building envelope is considered as the first step to be realised and only then, the heating system should be optimized (Gross 2010). The combination of these two measures undoubtedly largely reduces the energy consumption of the building and the contribution to the global warming. A step further would have been the production of energy by Kajskul 11, for instance with the use of solar panels that would have been set up on the large flat roof.

7 Conclusion

The aim of this thesis was to evaluate the insulation retrofitting of the old façade of the former warehouse Kajskjul 113 with vacuum insulation panels. Three criteria were considered: the compliance with the current thermal regulations, the hygrothermal behaviour of the wall and the cost efficiency of the solution. A new insulation system has been designed after pre-calculations and pre-studies so the building envelope complies with the new thermal requirements. Then, computer models were realised to accurately control the hygrothermal conditions in the retrofitted façade. The cost efficiency has been estimated with a Life Cycle Cost in order to take into account all the expenditures induced by the retrofitting measures from the purchase price to the operational costs.

This master´s thesis concludes that today, the VIPs are an effective insulation system for building applications. The VIPs producers have been improving the main drawbacks of the panels. They now offer panels whose life expectancy is around 60 years and provide a lot of technical documentation, instructions and recommendations to successfully set up the panels.

The internal insulation system proposed for Kajskjul 113 uses VIPs encapsulated in polystyrene and cork to complete the parts of the walls not covered by the panels, a gypsum board is added on top as a mechanical protection. Thus, Kajskjul 113 façade reaches the current thermal levels imposed by the BBR: its U value is around 0.53 $W.m^{-1}.K^{-1}$ and for the opaque parts it is 0.16 $W.m^{-1}.K^{-1}$. To complete the system, it is necessary to set a vapour barrier between the panels and the gypsum board and to spray an hydrophobic impregnation on the façade. The vapour barrier is required since the air gap between the panels enable part of the inside air to move inside the façade materials and leads to an increase of the relative humidity in the insulation materials. Thus, the hydrophobation of the façade is necessary to prevent the rain water to enter the materials. Indeed, once inside the façade, the water will hardly evacuate because of the vapour barrier. Therefore with the new insulation system, the hydrothermal conditions are improved and do not enable the appearance of condensation or mould growth. Healthy indoor conditions can be maintained.

However, the LCC has underlined the higher cost of this insulation system compared with conventional insulation. Insulating Kajskjul 113 façade with VIPs would be 25% more expensive than with mineral wool, that would result of a extra cost of 275 000 €. The expenditures difference is mainly due to the high purchasing price of the panels, still more costly than conventional materials. Certainly, the purchasing price of VIPs is expected to decrease, nevertheless, during the last eight years, no important reduction has been noticed. In order to pay-back, this extra cost, it would be interesting for Älvstranden utveckling AB to rent a part of its building. Indeed, by renting half of its surface, the building company could pay back the extra cost pointed out by the LCC within 20 years.

To conclude, this master´s thesis should be read as a decision support document for building constructors and designers willing to implement VIPs to insulate their buildings. Until now, most of the reports have focused on the thermal properties of the panels, their ageing effects, their thermal bridges effects and have summarized much feedback from research projects. Thus, this work which stands from the point of view of a building company offers a new vision of the potentials of VIPs.

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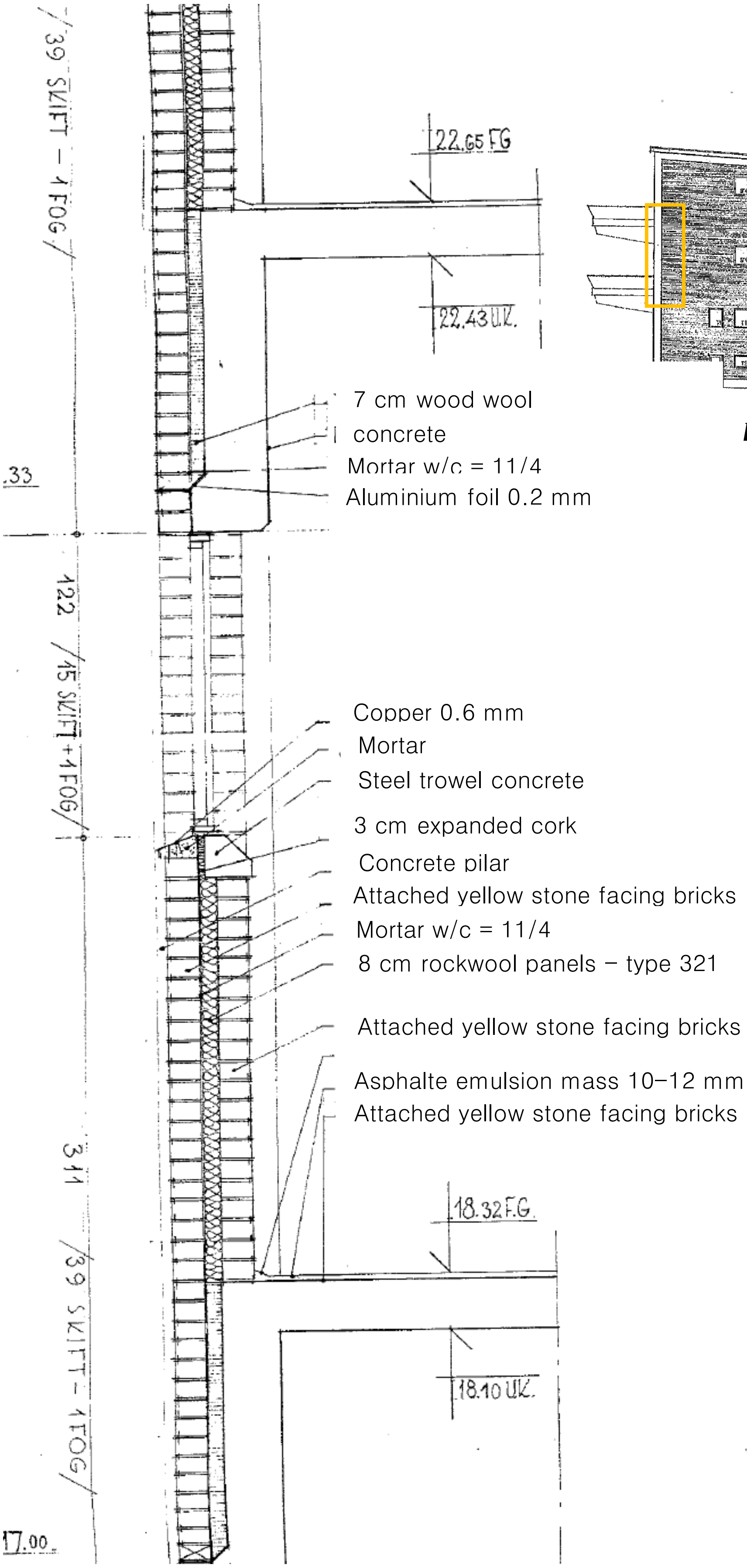
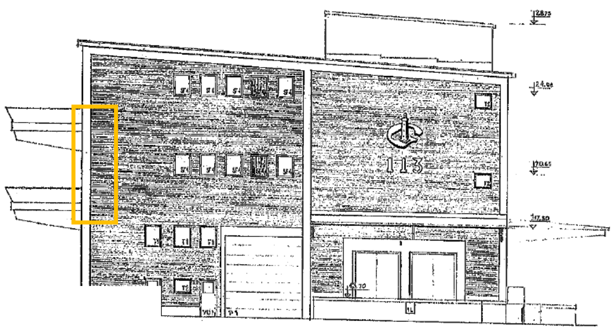
Appendix 1 - Cross Section of the external walls of Kajskjul 113 from Älvstranden utveckling AB





location of the cross section

Appendix 2: Vacupor ® PS-B2-S, data from the producer Porextherm

Characteristics

Vacupor® PS-B2-S is a microporous insulation material with an extremely low coefficient of thermal conductivity, i.e. with very good insulating properties.
Vacupor® PS-B2-S consists of inorganic oxides. The main constituent is fumed silica. The other components are opacifiers for minimizing infrared radiation, and fiber filaments as reinforcing fillers.

Under the certification number Z-23.11-1662 the German Institut for civil engineering (DIBT) granted the approval by the building authorities for Vacupor® PS-B2-S. The approval is valid for construction applications DAD, DZ, DI, DEO, WAB, WAA, WH, WTR and WI according to standard DIN 4108-10, table 1 and for prefabricated façade panels with insulated glass character.

Vacupor® PS-B2-S conforms to Baustoffklasse B2.
The test of behaviour in case of fire according DIN 4102-1, May 1998, Baustoffklasse B2; Testcertificate No. H.3-145/07 and H.3-146/07, was issued by the Forschungsinstitut für Wärmeschutz e.V. München.

The core material of Vacupor® PS-B2-S is not flammable and is classified A1 according to DIN ISO EN 13501-1.

Vacupor® PS-B2-S is heat sealed in a barrier film under vacuum. The very low internal pressure and the microporous panel core is responsible for the extremely low thermal conductivity values.

Application

Vacupor® PS-B2-S was specially developed for applications in the building and construction industry where an approval by the building authorities is required.

The low density and IR opacifiers contained in these grades greatly reduce the thermal conductivity of Vacupor® PS-B2-S Systems.

Due to the single- or double-sided coverage with polystyrene sheets, Vacupor® PS-B2-S is excellently suitable for all kinds of wall and floor layings.
The fixing of the insulation is substantially facilitated, through the possibility of bonding with commercial polystyrene adhesives.

Vacupor® PS-B2-S is offered in two versions:

- Vacupor® PS-B2-S 10/10, 10mm thick coating on both sides
- Vacupor® PS-B2-S 10/20 with 10 mm and 20 mm coating for the use as an EWIS.

Vacupor® PS-B2-S offers different advantages, like e.g.:

- Increase of the heat support ability
- Decrease of weight and insulation volume
- Decrease of the land consumption

Vacupor® PS-B2-S is sucessfully used as insulation material in the following areas:

- External Wall Insulation Systems (EWIS)
- Reveal insulation
- Insulation of basement ceilings

Form of delivery

1. **Standard sizes:**
   - 1000 mm x 500 mm
   - 500 mm x 500 mm
   - 500 mm x 250 mm

2. **Standard thicknesses (without protection):**
   - 10, 15, 20, 25, 30, 35, 40, 45 and 50 mm
   - Further thicknesses on request

3. **Special formats available on request**

Restrictions on Applications

The laminated aluminum foil of the Vacupor® PS-B2-S must not be damaged by drilling, cutting, milling, nailing or the like, since the interior pressure of the panel will rise and the special properties of the panel, in particular its excellent insulation characteristics, will be lost.

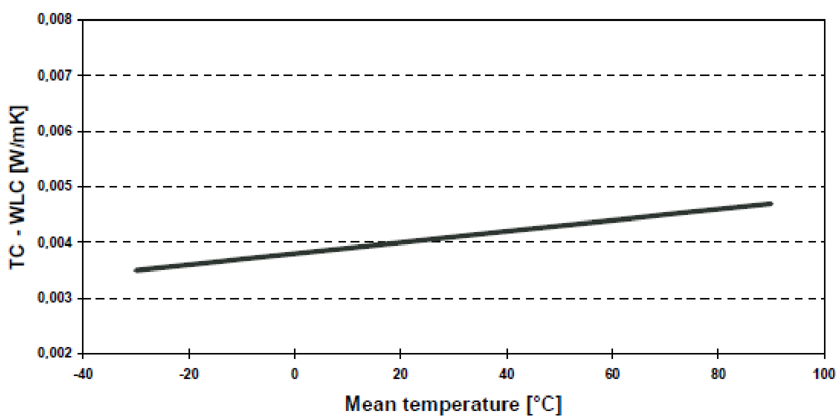
Shelf life

Vacupor® PS-B2-S has a very long shelf life. Please also observe our pressure rise table: Thermal conductivity as a function of interior pressure.

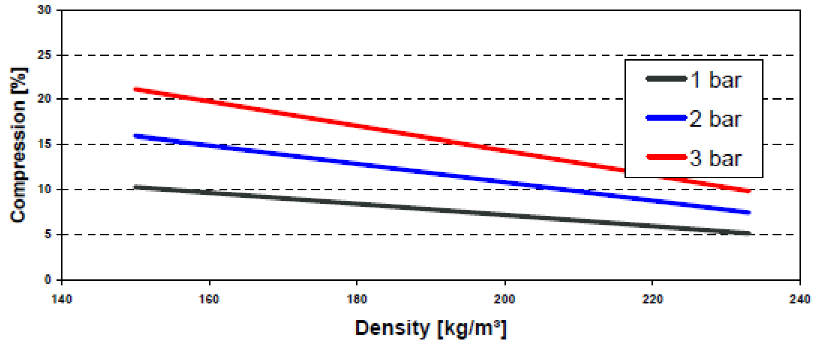
Product data

Properties (applicable to standard format)	Comments	Standards	Units	Values
Color	Caused by film / coverage			Silver / White
Density [1]			kg / m^3	150-300
Thermal conductivity [2] @ 1 mbar [3]	Measured at 22,5 °C (72.5 °F) mean temperature	DIN 52612	W / (m×K)	≤ 0,005
@ ambient pressure			W / (m×K)	≤ 0,019
U-Value			W / (m^2K)	
		Thickness VIP [mm]		
		10	20	30
	Vacupor PS-B2-S 10/10	0,52	0,30	0,21
	Vacupor PS-B2-S 10/20	0,46	0,28	0,20
Rated value	According to DIBT approval number Z-23.11-1662		W / (m×K)	0,007
Heat resistance [4]	Caused by film weld seam		°C	-50 <T< 120
Maximum film projection			mm	0
Interior pressure [3]	As delivered		mbar	≤ 5
Theoretical pressure rise	Under standard conditions		mbar / a	0,5
Maximum panel dimensions	Length Breadth Thickness		mm mm mm	150 - 1500 150 - 1000 10 - 50
Length and width tolerances	0 bis 500 mm 501 bis 1000 mm > 1000		mm mm mm	+ 1,0 / - 2,0 + 1,0 / - 4,0 + 1,0 / - 6,0
Thickness tolerances	< 20 mm 20 mm bis 30 mm > 30 mm		mm mm mm	± 1,0 + 1,0 / - 2,0 + 1,0 / - 3,0
Thermal shock resistance	The core material of Vacupor® PS-B2-S is insensitive to high and low temperature thermal shocks			

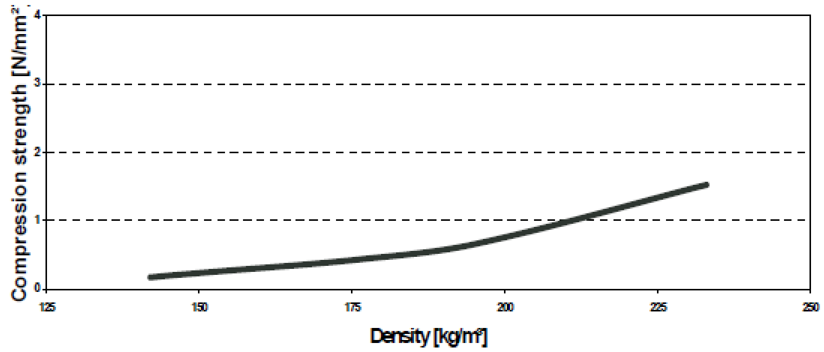
Thermal conductivity (panel core) DIN 52612



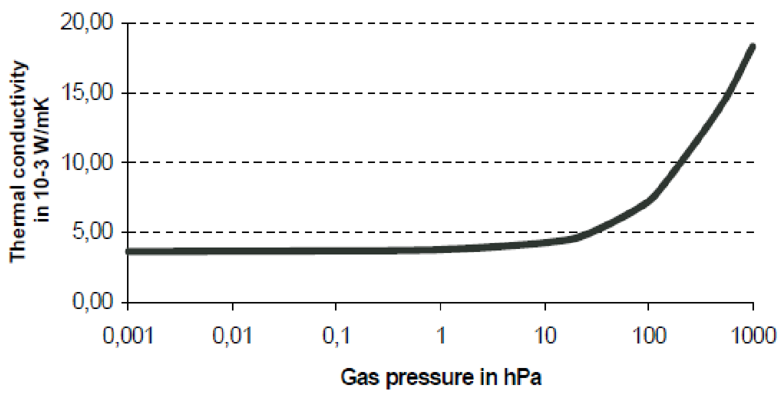
Compression behavior (panel core)



Low-temp. Compression strength (panel core)



Thermal conductivity as a function of internal pressure (DIN 52612)



gas pressure p_{gas} [hPa]	U- Value [W/(m²K)]	λ [10^{-3} W/(mK)]
< 10^{-3}	0.187	3.63
0.1	0.188	3.66
1.0	0.193	3.75
10	0.219	4.25
150	0.448	8.70
1000	0.943	18.30

Appendix 3: Life Cycle Cost Analysis

Data from: Anderson and Olin D (2008), Bizee Degree Days (2013), Boursorama (nd), Eriksson Andin, M. (2011)

Insulation with VIPs

$C_{investment}$

C_{VIP}	150 [€.m^{-2}]	L_{VIP}	0,05 [m]
$C_{gypsum\ board}$	5 [€.m^{-2}]	$L_{gypsum\ board}$	0,02 [m]
C_{cork}	303,6 [€.m^{-3}]	L_{cork}	0,05 [m]
Price of an hour of work	38,3 [€.hour^{-1}]	Hours of work	4 [hour]
Total $C_{investment}$	**4,1** [€.year^{-1}.m^{-2}]		

$C_{maintenance}$

Cost of the new VIP	0,00 [€.year^{-1}]	Rate of early failure	1 [%]
Cost of the new gypsum board - 3m²	0,3 [€.year^{-1}]		
Price of an hour of work	38,3 [€.hour^{-1}]	Hours of work	3,5 [hour]
$Ca_{maintenance}$	134,3 [€.year^{-1}]		
Total $C_{maintenance}$	**0,09** [€.year^{-1}m^{-2}]		

C_{energy}

HDD	4174 [-]	CDD	82 [-]
$c_{e\ -\ district\ heating}$	0,059 [€.kWh^{-1}]	$c_{e\ -\ electricity}$	0,106 [€.kWh^{-1}]
COP	3,15 [-]	*COP*	3 [-]
$C_{heating}$	0,6 [€.year^{-1}]	**$C_{cooling}$**	0,024 [€.year^{-1}]
PWF	21,8 [-]	r	0,039 [-]
Total C_{energy}	**6,76** [€.year^{-1}.m^{-2}]		

TOTAL COST : 10,9 [€.year^{-1}.m^{-2}]

Insulation with mineral wool

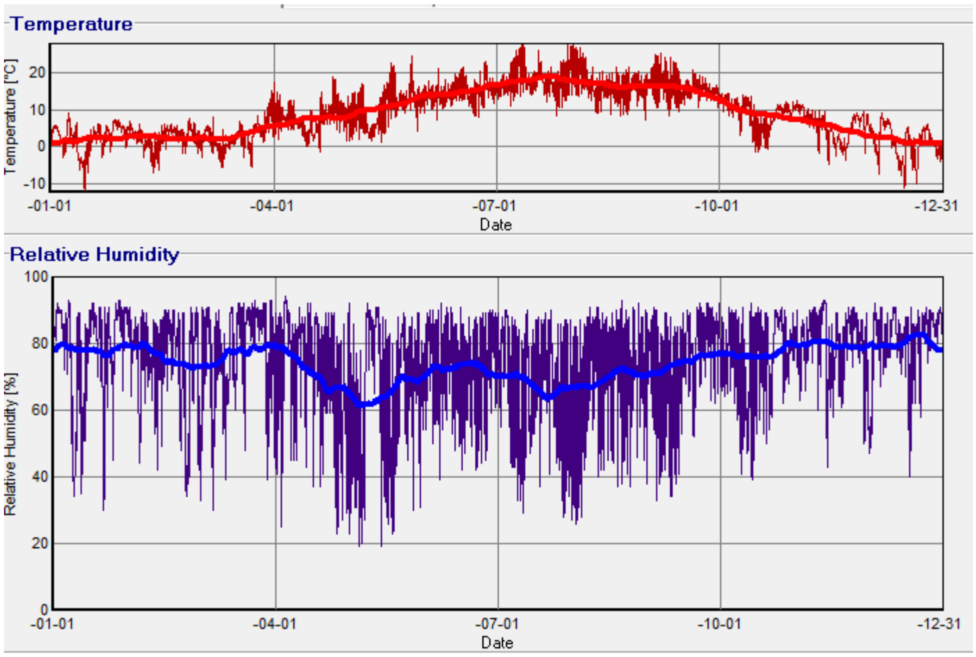
$C_{investment}$			
C_{mw}	174 [€.m^{-3}]	L_{mw}	0,17 [m]
$C_{gypsum\ board}$	5 [€.m^{-2}]	$L_{gypsum\ board}$	0,02 [m]
Price of an hour of work	33,3 [€.hour^{-1}]	Hours of work	4 [hour]
Total $C_{investment}$	**1,9** [€.year^{-1}m^{-2}]		

$C_{maintenance}$			
Cost of the new MW	0,03 [€.year^{-1}]	Rate of early failure	5 [%]
Cost of the new gypsum board - 5m²	0,5 [€.year^{-1}]		
Price of an hour of work	33,3 [€.hour^{-1}]	Hours of work	3,5 [hour]
$Ca_{maintenance}$	117,1 [€.year^{-1}]		
Total $C_{maintenance}$	**0,07** [€.year^{-1}m^{-2}]		

C_{energy}			
HDD	4174 [-]	CDD	82 [-]
$C_{e\ -\ district\ heating}$	0,059 [€.kWh^{-1}]	$C_{e\ -\ electricity}$	0,106 [€.kWh^{-1}]
COP	3,15 [-]	*COP*	3 [-]
$C_{heating}$	0,648 [€.year^{-1}]	$C_{cooling}$	0,024 [€.year^{-1}]
PWF	21,8 [-]	r	0,039 [-]
Total C_{energy}	**6,76** [€.year^{-1}m^{-2}]		

TOTAL COST : 8,8 [€.year^{-1}.m^{-2}]

Appendix 4: Gothenburg Climate Data from WUFI 2D



Mean Temperature	8.8 ^{0}C	Mean Relative Humidity	74 %
Max. Temperature	27.8 ^{0}C	Max Relative Humidity	94 %
Min. Temperature	-12.2^{0}C	Min Relative Humidity	19 %

Normal Rain Sum 1074 mm/a