CHALMERS

Retrofitting of old Exterior Wall with Vacuum Insulation Panels

Measurements of Thermal Properties, Moisture Performance and Practical Considerations

Thesis for the Degree of Licentiate of Engineering

PÄR JOHANSSON

Department of Civil and Environmental Engineering
Division of Building Technology, Building Physics
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2012
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Cover:
A vacuum insulation panel (VIP) is mounted on the exterior wall of an old protected multi-family building from the 1930s in Gothenburg. Strips of mineral wool are placed between the VIP to allow attachment of the exterior wooden cover boarding (Photo: Pär Johansson).

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ABSTRACT

The building industry is facing one of its most challenging tasks ever. Until 2050 the energy use for heating of buildings should be decreased by 50% which means a large part of the building stock have to be retrofitted to become more energy efficient. One of the possible solutions is to add thermal insulation to the exterior wall of the buildings. The insulation can be placed on the interior or exterior of the existing structure. Adding insulation on the exterior of the façade means that the architectural, historical, environmental and artistic features of the building may be lost. Vacuum insulation panels (VIP) is a novel thermal insulation component used in refrigerators and cold shipping containers which, during the last decade, also have been introduced in the building industry. The VIP is a composite which has a thin metalized multi-layered polymer film wrapped around a porous core material from which the air has been removed.

A problem associated with the use of VIP is the fragility of the product. A punctured VIP has a loose film which is easily detectable by visual inspection. However, a VIP can be damaged without having a loose film. This requires a measurement procedure that can determine the thermal conductivity of a VIP in situ, before integrated in the construction. Such a method is lacking today but in the scope of this project the transient plane source (TPS) method has been evaluated. Initial investigations show that the TPS method possibly can be used, with some modifications, to determine the thermal properties of VIP.

The main purpose of this study is to investigate the applicability of VIP when retrofitting the exterior wall of old listed buildings. The applicability has been evaluated in a field study and by theoretical assessments. The VIP cannot be cut on site which requires design with high precision. In places where VIP could not be used due to lack of space, glass wool was used instead. Hygrothermal sensors were installed in the field study building which monitors the temperature and relative humidity at various locations in the façade and in a neighboring reference façade. Initial results from the hygrothermal sensors showed that the relative humidity in the retrofitted wall was lower than the reference wall. The lowest and highest relative humidity was found behind the center of a VIP and at the window frame respectively. The hygrothermal monitoring of the wall will continue in the next phase of this project.

A theoretical assessment of the moisture performance of the wall before and after retrofitting was carried out using hygrothermal simulation software. The hygrothermal simulations showed that the relative humidity in the wall decreases with time after the retrofitting. The results of the simulations showed that the indoor climate was an important parameter for the moisture performance of the wall. Therefore a stochastic simulation model was developed of the indoor moisture supply which could be used in future hygrothermal simulations.

Key words: listed building, retrofitting, exterior wall, vacuum insulation panel, transient plane source, hygrothermal sensor, hygrothermal simulation, indoor moisture supply

Tilläggsisolering med vakuumisoleringspaneler av äldre yttervägg
Mätning av termiska egenskaper, fuktprestanda och praktiska frågeställningar
Uppsats för licentiatexamen

PÄR JOHANSSON
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SAMMANFATTNING

Byggindustrin står inför en av sina största utmaningar någonsin. Energianvändningen för uppvärmning av byggnader ska reduceras med 50 % till 2050 vilket innebär att en stor del av det befintliga byggnadsbeståndet måste renoveras för att bli mer energieffektivt. En möjlig lösning är att montera tilläggsisolering på byggnaders ytterväggar. Isoleringen kan antingen monteras på den existerande ytterväggens in- eller utsida. Monteras isoleringen på utsidan av den befintliga väggen riskerar arkitektoniska, historiska, miljömässiga och konstnärliga värden att gå förlorade. Vakuumisoleringspaneler (VIP) är en ny isoleringskomponent som använts inom kylskåpsindustrin och i kylda transportbehållare under ett antal år och nu även i byggindustrin. Komponenten består av en tunn metalliserad plastfilm i flera lager som är omslagen kring en porös kärna som evakuerats.

Ett av problemen vid användandet av VIP är att den är mycket känslig för skador. En punkterad VIP kan lätt upptäckas eftersom filmen då sitter löst kring kärnan. Tyvärr kan en VIP vara skadad utan att vara helt luftfylld och därmed ha en fast film. En mätmetod som kan användas i fält för att undersöka de termiska egenskaperna innan VIP byggs in i konstruktionen existerar inte i dagsläget. Inom detta projekt har TPS-metoden undersökts för att utreda huruvida den skulle kunna var en lämplig mätmetod. Initiala resultat visar att en modifierad TPS-metod skulle kunna vara användbar för att mäta VIP:s termiska egenskaper.

Huvudsyftet med denna studie är att undersöka användandet av VIP vid renovering av äldre skyddade byggnader. Undersökningen är baserad på fältförsök och teoretiska utvärderingar. VIP kan inte geometriskt anpassas på plats vilket kräver en noggrann projektering av vilken panel med vilka mått som ska placeras var. En mineralullsskiva med hög densitet har använts på platser där det inte gått att använda VIP. I fältförsöket har sensorer som loggar temperatur och relativ fuktighet varje timme byggts in på flera olika platser i den renoverade väggen vilka jämförs med resultat av mätningar i en närliggande referensvägg. Initiala resultat från mätstudien har visat att den relativa fuktigheten i den renoverade väggen var lägre än i referensväggen. Den lägsta och högsta relativa fuktigheten uppmättes bakom mitten av en VIP respektive vid fönsterramen där isoleringsgraden är lägst. Utvärderingen av mätningarna i den renoverade väggen kommer att försätta i nästa skede av projektet.

En teoretisk utvärdering av fuktförhållandet i väggen före och efter renoveringen har genomförts med hjälp av ett hygrotermiskt beräkningsprogram. De hygrotermiska simuleringarna visade att den relativa fuktigheten i väggen minskar med tiden efter renoveringen. Simuleringsresultaten visade att inomhusklimatet är en viktig parameter för väggens fuktprestanda vilket ledde till utvecklandet av en stokastisk simuleringsmodell för fukttillskottet i en lägenhet. Modellen kan användas i framtida hygrotermiska simuleringar.

Nyckelord: riksintresse, renovering, yttervägg, vakuumisoleringspanel, transient plane source, hygrotermisk sensor, hygrotermisk simulering, fukttillskott

CONTENTS

PREFACE

This thesis is the result of two years of research studies at the Division of Building Technology, Building Physics Research group at Chalmers University of Technology in Gothenburg, Sweden. The project is financed by FORMAS, the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning through the project: Retrofit applications on old buildings using highly efficient novel thermal insulation materials. The public housing corporation Familjebostäder i Göteborg AB contributed with a field study building and financed all material, measurement equipment and construction work. Without the fruitful cooperation and financial support from Familjebostäder this project could not have been realized to this extent. Also the financial support for travel expenses from the Adlerbert Research Foundation, Chalmersska forskningsfonden and Friends of Chalmers – Young Researchers are greatly acknowledged.

I would like to thank all my colleagues at the Division of Building Technology for the encouraging and collaborative spirit which create an excellent working environment. A special thanks to my supervisors Professor Carl-Eric Hagentoft and Associate Professor Angela Sasic Kalagasidis who have inspired me with their cheerfulness and curiosity. I am also grateful to Doctoral student Simon Pallin and Senior Lecturer Bijan Adl-Zarrabi for our positive and productive collaborations.

At last I would like to thank my family and friends for all support during this time.

Pär Johansson

Gothenburg, February, 2012

NOTATIONS

Roman letters

a	(m^2/s)	Thermal diffusivity
c_p	(J/(kg·K))	Specific heat capacity at constant pressure
d	(m)	Diameter
d_t	(m)	Time dependent penetration depth
k_B	(J/K)	Boltzmann constant
l_{mean}	(m)	Mean free path
n	(-)	Refraction index
q	(W/m^2)	Heat flux
s_d	(m)	Vapor diffusion thickness
t	(s)	Time
v	(kg/m^3)	Vapor content
A	(m^2)	Surface area
G	(kg/s)	Moisture production rate
K	(-)	Extinction coefficient
K_n	(-)	Knudsen number
P_g	(Pa) or (bar)	Gas pressure
R	(m^2K/W)	Thermal resistance
R_a	(m^3/s)	Air flow
T	(°C) or (K)	Temperature
U	(W/(m^2K))	Thermal transmittance
Z	(s/m)	Vapor resistance

Greek letters

α	(-)	Solar absorptivity of a surface
β	(-)	Heat transfer efficiency between gas molecule and pore wall
δ	(m)	Characteristic size of a system
δ_v	(m^2/s)	Vapor diffusion coefficient
ε	(-)	Emissivity
λ	(W/(m·K))	Thermal conductivity
μ	(-)	Vapor diffusion resistance factor
ρ	(kg/m^3)	Density
σ	(J/(K^4m^2s))	Stefan-Bolzmann constant
ξ	(kg/m^3)	Moisture capacity
Δ	(-)	Difference

LIST OF PUBLICATIONS

The thesis is based on the following appended papers:

I. Johansson, P. (2011). Assessment of the Risk for Mold Growth in a Wall Retrofitted with Vacuum Insulation Panels. *Proceedings of the 9th Nordic Symposium on Building Physics*. May 29-June 2, 2011, Tampere, Finland, pp. 349-356.

II. Johansson, P. (2011). In situ Measurements of Façade Retrofitted with Vacuum Insulation Panels. *Proceedings of the 10th International Vacuum Insulation Symposium*. September 15-16, 2011, Ottawa, Canada, pp. 107-111.

III. Johansson, P., Adl-Zarrabi, B., and Hagentoft, C.-E. (2011). Measurements of Thermal Properties of Vacuum Insulation Panels by using Transient Plane Source Sensor. *Proceedings of the 10th International Vacuum Insulation Symposium*, September 15-16, 2011, Ottawa, Canada, pp. 18-21.

IV. Johansson, P., Adl-Zarrabi, B., and Hagentoft, C.-E. (2012). Using Transient Plane Source Sensor for Determination of Thermal Properties of Vacuum Insulation Panels. *To be published in Proceedings of the 5th International Building Physics Conference*, May 28-31, 2012, Kyoto, Japan.

Papers I-II are written by me. Angela Sasic Kalagasidis provided input for which cases to simulate. Carl-Eric Hagentoft and Angela Sasic Kalagasidis were involved in the final editing of both papers.

Papers III-IV are written in cooperation with Bijan Adl-Zarrabi and Carl-Eric Hagentoft. I have done the numerical simulations and compared them to analytical solutions and measured data by Bijan Adl-Zarrabi and myself.

Two reports with literature studies are important to the conclusions of this study but are not appended with the thesis:

i. Johansson, P. (2012). *Vacuum Insulation Panels in Buildings: Literature Review*. Report 2012:1. Gothenburg, Sweden: Chalmers University of Technology, Department of Civil and Environmental Engineering.

ii. Berge, A. and Johansson, P. (2012). *Literature Review of Novel Thermal Insulation Materials and Components*. Report 2012:2. Gothenburg, Sweden: Chalmers University of Technology, Department of Civil and Environmental Engineering.

Other publications by the author are:

A. Pallin, S., Johansson, P., and Hagentoft, C.-E. (2011). Stochastic Modeling of Moisture Supply in Dwellings based on Moisture Production and Moisture Buffering Capacity. *Proceedings of the 12th Conference of the International Building Performance Simulation Association*. November 14-16, 2011, Sydney, Australia, pp. 366-373.

B. Johansson, P., Pallin, S., and Shahriari, M. (2011). Development of a Risk Assessment Procedure Applied on Building Physics: Part One; Model Development. *Proceedings of the 12th International Conference on Building Materials and Components*. April 12-15, 2011, Porto, Portugal, pp. 109-116.

C. Pallin, S., Johansson, P., and Shahriari, M. (2011). Development of a Risk Assessment Procedure Applied on Building Physics: Part Two; an Applicability Study. *Proceedings of the 12th International Conference on Building Materials and Components*. April 12-15, 2011, Porto, Portugal, pp. 479-486.

D. Johansson, P. (2010). Hygrothermal Conditions in Ventilated Cathedral Ceilings: Influences on Roof Ventilation and Emissivity; Field Study and Analysis. *Proceedings of the 11th International Conference on Thermal Performance of the Exterior Envelopes of Whole Buildings*, December 5-9, 2010, Clearwater Beach, Florida, USA.

Within the framework of IEA/ECBCS Annex 55 Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance and Cost (RAP-RETRO), the following reports have been presented by the author:

a. Johansson, P. (2011). Solution on IEA/ECBCS Annex 55 RAP-RETRO, Subtask 2, Common Exercise 3: Sensitivity Analysis on Hygrothermal Performance of Cold Attics. *Prepared for the fourth IEA/ECBCS Annex 55 meeting*, October 25-27, 2011, San Antonio, Texas, USA.

b. Johansson, P. (2011). Solution on IEA/ECBCS Annex 55 RAP-RETRO, Subtask 2, Common Exercise 2: Hygrothermal Analysis of Massive Wall with Interior Insulation. *Prepared for the third IEA/ECBCS Annex 55 meeting*, April 18-20, 2011, Porto, Portugal.

c. Stein, J., Hagentoft, C.-E., Arfvidsson, J., Harderup, L.-E., Johansson, P., Mjörnell, K., Pallin, S., Pietrzyk, K., Kalagasidis, A. S., Ståhl, F., and Svennberg, K. (2011). Energieffektiviseringar – vilka risker finns och hur ska de hanteras? *Bygg och teknik, 2/2011*, pp. 30-33.

d. Johansson, P., Pallin, S., and Shahriari, M. (2010). Risk Assessment Model Applied on Building Physics: Statistical Data Acquisition and Stochastic Modeling of Indoor Moisture Supply in Swedish Multi-family Dwellings. Unpublished Report. *Prepared for the second IEA/ECBCS Annex 55 meeting*, October 25-27, 2010, Copenhagen, Denmark.

1 Introduction

1.1 Background

The energy use in the European Union should decrease with 20% in 2020 and with 50% in 2050 compared to the energy use in 1990 (European Commission, 2008). A large part of the energy use is related to heating of buildings and production of domestic hot water. In Sweden this part is just below 30% of the total end energy use which corresponds to around 10% of the Swedish greenhouse gas emissions. The data on energy use is uncertain, but according to the Swedish National Board of Housing, Building and Planning (Boverket) which is responsible for the Swedish energy use targets in buildings, the energy use for heating and domestic hot water has been reduced by 8%[1] between 1995 and 2008. To reach the Swedish energy use targets of a 20% reduction in 2020 and a 50% reduction to 2050 compared to 1995, further decisive actions are needed (Boverket, 2010).

There are approximately 2.1 million buildings in Sweden distributed on 1.9 million single family houses, 165 000 multi-family buildings and 46 000 commercial buildings (Boverket, 2009). These buildings are from different time periods which mean they were built with different building techniques and technical solutions. The number of multi-family buildings, based on year of construction and average thermal transmittance of the exterior wall, are presented in Table 1.1.

Table 1.1. Number of multi-family buildings in Sweden characterized by the year of construction and average U-value of the exterior wall. There are in total 165 000 multi-family buildings with an average U-value of the exterior wall of 0.44 W/(m^{2}K) (Boverket, 2010).

Year of construction	1 000 buildings	% buildings	Average U-value of wall (W/(m^{2}K))
-1960	77	47	0.58
1961-1975	32	19	0.42
1976-1985	12	7	0.33
1986-1995	31	19	0.22
1996-2005	12	7	0.19

Almost half of the buildings are from the time before 1960. These buildings are also the buildings with the highest average U-value of the exterior walls. As mentioned earlier, the energy use in the Swedish housing stock should be decreased by 50% in 2050 compared to in 1995. The average energy use in the Swedish housing stock in 2005 was 171.8 kWh/m^2 which has to be decreased to between 89.2 and 95.1 kWh/m^2 in 2050. If the existing building stock is 30% more energy efficient in 2050 than today, all new buildings built from today and forward need a maximum energy use of 35-40 kWh/m^2 for heating and domestic hot water to reach the target. Clearly it is impossible to reach the energy target only by building new energy efficient buildings. Therefore the existing building stock is in need of extensive energy retrofitting measures (Boverket, 2010).

[1] Temperature corrected; the reduction is 15% in absolute figures.

A step to reduce the energy use in buildings was taken in January, 2012 when the new Swedish building regulations were enforced which equalizes the demands on energy efficiency when retrofitting old buildings with the demands on new buildings. For residential buildings the demands are reduced with 20% to a maximum energy use of 90 kWh/m^2 and year for heating and domestic hot water in the south of Sweden. The maximum average thermal transmittance, U (W/m^{2}K), of the building envelope is lowered from 0.5 to 0.4 W/m^{2}K. The energy demands for retrofitted buildings are the same as for new buildings, unless they are unreasonable with regard to the magnitude of the retrofitting measure or the prerequisites of the building. Also, the architectural, historical, environmental and artistic features of the building have to be considered since they should be preserved after the retrofit. If the demand on the maximum average thermal transmittance of 0.4 W/m^{2}K cannot be reached, the energy use should at least not increase after a retrofitting, unless under very special circumstances. These very special circumstances could be that another demand, e.g. on indoor air quality, cannot be met without increasing the energy demand (Boverket, 2011).

According to Boverket (2010), approximately 31% of the multi-family buildings are suitable for a façade retrofitting, 41% of the buildings are not considered reasonable and 28% are dubious. However, there is a discussion on when the value of the energy efficiency obtained by retrofitting the façade is larger than the societal value of preserving the features of the building. In the past, retrofitting measures have ruined the aesthetic values of some buildings, possibly leading to a bad image of energy efficiency measures among the public.

The first wave of energy efficiency retrofitting measures followed the energy crisis in the 1970s. At that time the Swedish government proposed a program aiming at reducing the heating energy use in the building stock with 25-30% (Boverket, 2010). Some of the buildings that were left after the large demolition and urban remediation projects in the 1960s and 1970s were retrofitted and many buildings got additional insulation in the exterior wall. Figure 1.1 shows the façade and the wall materials of a building that was retrofitted in the late 1970s.

Peterson *et al.* (1982) studied three different solutions for adding insulation to the exterior walls of the building. Both solutions with exterior and interior insulation were considered but were too expensive, changed the aesthetics of the building or reduced the room areas to much to be possible in this building. A solution used in buildings that were retrofitted by adding insulation to the exterior walls was to remove the existing wooden cover boarding and replace it with 95 mm mineral wool covered by a corrugated steel sheet façade, see Figure 1.2.

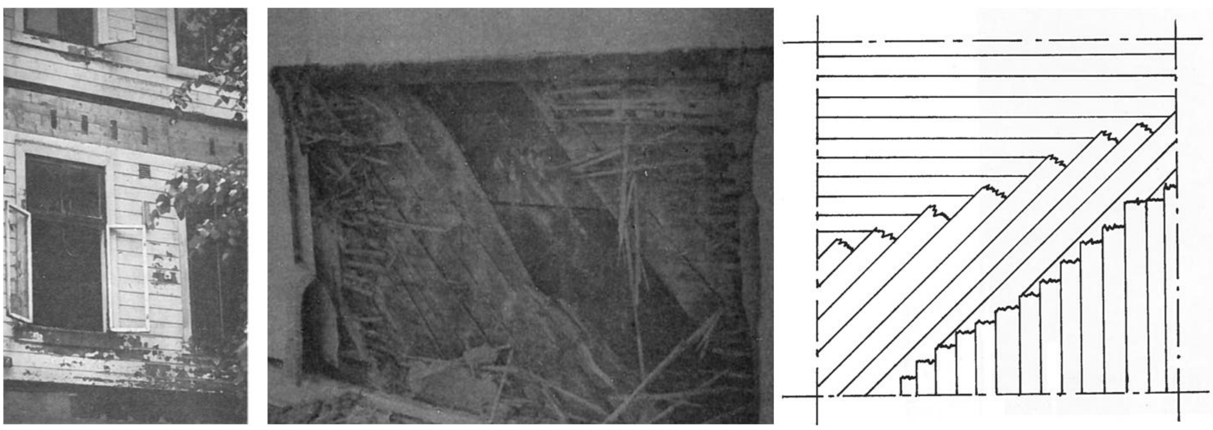

Figure 1.1. Exterior wall of a building retrofitted in the 1970s to the left. The photo in the middle and the figure to the right show the wooden materials of the exterior wall which is composed of three layers of wooden planks covered with straw and plaster on the interior. The exterior of the wall was covered by a tar paper and wooden cover boarding (Peterson et al., 1982).

Figure 1.2. Original façade of a county governor's house in 1930 (left) and in 2005 (right). The wall was retrofitted in the 1970s by adding 95 mm mineral wool and a corrugated steel sheet façade on the exterior of the wall (Photo from Sören Nilsson's collection of postcards; Melica, 2006).

A follow-up study in the 1980s of the consequences of the retrofitting measures in the 1970s showed that the aesthetics of the buildings were changed dramatically (Boverket, 2010). The owners of these buildings seek for ways to make it possible to restore the original appearance and features of the building while maintaining the energy efficiency (Melica, 2006). To reach the goals on both energy efficiency and preservation of old buildings, careful planning and design of the future retrofitting solutions are needed. Future retrofitting measures need to be more adjusted to the special features of each building than they were before. New retrofitting solutions using new materials could solve both the problem of delivering high energy efficiency and maintaining the aesthetic qualities of the buildings.

Vacuum insulation panels (VIP) is a new component that adds much insulation in a limited thickness. Therefore the façade and aesthetics of a building could be preserved while the energy use for heating could be reduced. An international research team investigated the possibilities to use VIP in buildings and concluded that VIP is feasible and an important mean to develop energy efficient buildings (Binz *et al.*, 2005).

1.2 Scope

The energy use in existing buildings can be reduced by a number of measures, such as heat recovery of the ventilation air or additional thermal insulation in the building envelope (Dalenbäck *et al.*, 2005). In this thesis the investigation is focused on the hygrothermal consequences of adding thermal insulation to the exterior of an existing exterior wall. Depending on whether the thermal insulation is placed on the interior or exterior of the existing structure, different hygrothermal conditions are yielded in the construction. The use of conventional insulation materials, such as mineral wool and expanded polystyrene (EPS), demand a thick insulation to be applied on the existing structure to reach a sufficiently high thermal resistance. With novel thermal insulation materials such as vacuum insulation panels (VIP), the required thickness of the insulation layer is reduced for the same thermal resistance.

An important parameter for the energy efficiency of the retrofitting measure is the thermal properties of the used materials. The VIP consists of a thin metalized multi-layered polymer film which has been wrapped around a porous core material from which the air has been removed. The thin film is prone to damages which can happen during manufacturing, transport, construction and inside the construction. In case the VIP is punctured the thermal conductivity increases by a factor of 5, from a center-of-panel thermal conductivity of 4 mW/(m·K) to 20 mW/(m·K) (Simmler *et al.*, 2005). Today there is no equipment that can be used for in situ measurement of the thermal conductivity before the panel is integrated in the construction (Erbenich, 2009). A fast and inexpensive method which could be used to determine the thermal conductivity of the VIP could be based on the transient plane source (TPS) method. Thermal properties, such as thermal conductivity, in materials are determined by using a sensor which supplies a constant heat pulse during a short time period. The temperature increase in the sensor is registered and used to determine the thermal properties of the material. The TPS method is not applicable to layered materials today. With development of the interpretation of the temperature increase in the sensor it might be possible to use the sensor by in situ measurements to ensure undamaged VIP is integrated in a construction.

Within this project VIP was chosen for a field study where the exterior wall of a three story residential building from 1930 was retrofitted. The insulation was mounted on the exterior of the existing wall which was made of bricks on the ground floor and wooden planks on the two upper floors. The long term moisture performance of the wall is monitored and continuously evaluated with regard to the changed thermal and moisture conditions in the wall. Durability issues such as damages to the VIP and moisture leakages in the wall and their effects on the performance of the wall are also discussed

When new materials and solutions are introduced to the building market, there is a risk of damages caused by the changed hygrothermal state in the existing building envelope. For instance the cold attics in Swedish single family houses are more prone to moisture damages today than what was the case before they were furnished with additional thermal insulation on the attic floor. To avoid a repetition of the consequences following the previous attempts to decrease energy use, investigations with sensitivity analysis and risk assessment procedures are needed before the final retrofitting solution design is determined (Day, 2003). In this study numerical simulations are used to investigate the hygrothermal consequences on the exterior wall caused by the retrofitting using VIP.

1.3 Methods

The field study is based on a case with a three story multi-family building in Gothenburg built in 1930. The owner of the building, the public housing corporation Familjebostäder i Göteborg AB, wanted to find a way to decrease the heating energy demand by retrofitting the exterior wall without changing the aesthetic qualities of the building. To find suitable solutions for the design of the retrofitted wall, the literature was reviewed and two study visits were performed in southern Germany. Two VIP producers and a building with VIP in the exterior wall were visited.

The retrofit design was developed in close collaboration with the project team which was put together by Familjebostäder. The team included a project manager and project leader from Familjebostäder, two structural engineers from WSP Byggprojektering and representatives from the building contractor Tvåtumfyra AB. Questions regarding changes to aesthetic qualities and hygrothermal conditions in the building caused by the retrofitting were discussed. The final retrofit design was based on a laser scanning of the existing wall which was imported to a CAD tool by WSP Byggprojektering.

The risk for damages to the existing wooden structure of the building was evaluated in the commercial two-dimensional heat and moisture simulation software WUFI 2D (Fraunhofer IBP, 2010). Four different wall constructions were examined. Boundary conditions and material parameters were varied to perform a sensitivity analysis of the designs. The exterior wall of the three story building was equipped with 15 hygrothermal sensors which measure the temperature and relative humidity every hour on a number of places to study the influence by the added insulation layer. Also a neighboring façade was used for reference measurements. The measurements have been monitored by SP Technical Research Institute of Sweden who also installed the sensors in the walls. Measurements of the wall before and after retrofitting using infrared thermography and blower door were also performed by SP

Three-dimensional numerical simulations were used to evaluate the TPS method and determine whether it was suitable for in situ measurements of VIP. The simulation results were compared to an analytical solution for the assumed isotropic material EPS. Transient measurements using the TPS sensor were performed on material samples of EPS, EPS covered by aluminum film and VIP film respectively, and the VIP component. EPS was used to simplify the measurements and to be able to vary the high conductive envelope material.

1.4 Limitations

There are several novel thermal insulation materials and components that have been introduced on the Swedish construction market the last years. In this study only the use of VIP in retrofitting is considered. The diversity of the Swedish building stock is large and there are many different types of buildings which have been constructed during different years. One of the most challenging type of buildings are those built during the first half of the 1900s because of their special features that have to be preserved after a retrofitting. It is also these buildings that have the largest potential reduction in heating energy use. Therefore this study only involves the use of VIP in retrofitting of one special type of building from the first half of the 1900s. In the field study only one exterior wall has been retrofitted with VIP on the exterior.

The long term durability of the VIP component itself has not been evaluated in this study. The performance of the VIP is influenced by diffusion of gases and moisture through the envelope but these matters have not been treated in the simulation study. Sufficient air tightness is an important mean to decrease the heating energy demand of a building. The influence of lack of air tightness around e.g. windows on the energy demand and hygrothermal conditions has not been studied. Measurement uncertainties of the hygrothermal sensors and TPS sensor are not included in this part of the study. There is also an economic aspect concerning the additional costs when using VIP in buildings which has been excluded from this study.

1.5 Reading guide

The thesis starts with a description of the general heat transfer mechanisms in insulation material which are used to describe the physical principles of VIP. The simulations and measurements with the TPS sensor on EPS and VIP are described in Chapter 3. In Chapter 4, the field study building is described and results from the hygrothermal measurements are presented. The hygrothermal simulations in WUFI 2D and sensitivity analysis of the retrofit design are presented in Chapter 5. Conclusions, discussions and suggestions of future research topics can be found in Chapter 6 and 7.

2 Novel thermal insulation materials

This chapter presents a summary of the literature reviews published in (Berge and Johansson, 2012) and (Johansson, 2012) of the heat transfer mechanisms in thermal insulation materials and the use of novel thermal insulation materials available on the construction market. Novel thermal insulation materials, such as aerogel and vacuum insulation panels (VIP), can reach lower thermal conductivities compared with common materials because of their smaller pores and the reduced gas pressure in the material. VIP has been used in some years in refrigerators and cold shipping boxes and has now started to be used in buildings.

2.1 Heat transfer in insulation materials

The heat flux, q (W/m^2), through a material can be divided in three parts; conduction through the solid, s, gas conduction in the pores, g, and radiation between the surfaces of the pores, r:

$$q = q_s + q_g + q_r \quad \text{(W/m}^2\text{)} \tag{2.1}$$

Heat transfer by gas convection is usually a large mean of heat transfer. In porous materials the gas convection depends on the pore size. In materials with pores smaller than around 0.1 mm, the gas convection can be neglected (Brodt, 1995).

The conduction through the solid is dependent on the characteristics of the material. In metals, the heat is transferred mainly by means of the free electrons which transfer more energy from the warm to the cold side than in the opposite direction. Imperfections in the material and atomic collisions limit the heat transfer by the electrons. On the other hand, in insulation materials the number of free electrons is much lower which means that the heat is mainly transferred by lattice vibrations (Brodt, 1995). To limit the thermal conduction through the solid structure of the materials, insulation materials are manufactured to be as porous as possible.

Gas conduction is dependent on which gas is used, the size of the pores in the material and the number of gas molecules in the pores. One way to reduce the gas conduction is to use a gas with a lower conductivity, e.g. argon and krypton instead of air in windows. Another way to decrease the gas conduction is to reduce the pore sizes of the material, leading to fewer collisions between gas molecules and an increasing number of the elastic collisions between gas molecules and pore wall. This phenomenon is called the Knudsen effect which influences the gas conduction, λ_g (W/(m·K)), according to Equation 2.2 (Baetens *et al.*, 2011):

$$\lambda_g = \frac{\lambda_{g0}}{1 + 2\beta K_n} \quad \text{(W/(m·K))} \tag{2.2}$$

where

$$K_n = \frac{l_{mean}}{\delta} \text{ (-) and } l_{mean} = \frac{k_B T}{\sqrt{2}\pi d_g^2 P_g} \quad \text{(m)} \tag{2.3}$$

where K_n (-) is the Knudsen number which is governed by l_{mean} (m), the mean free path of the gas molecules, and δ (m), the characteristic size of the system, i.e. the distance between two pore walls. k_B (J/K) is the Boltzmann constant, T (K) is the temperature, d_g (m) is the mean diameter of the gas molecules and P_g (Pa) is the gas pressure. Further on λ_{g0} (W/(m·K)) is the gas conductivity in atmospheric pressure and β (-) a constant characterizing the efficiency of heat transfer between gas molecule and pore wall, commonly between 1.5-2.0 (Baetens *et al.*, 2011). The heat transfer by gas conduction, depending on the gas pressure and pore size, is presented in Figure 2.1.

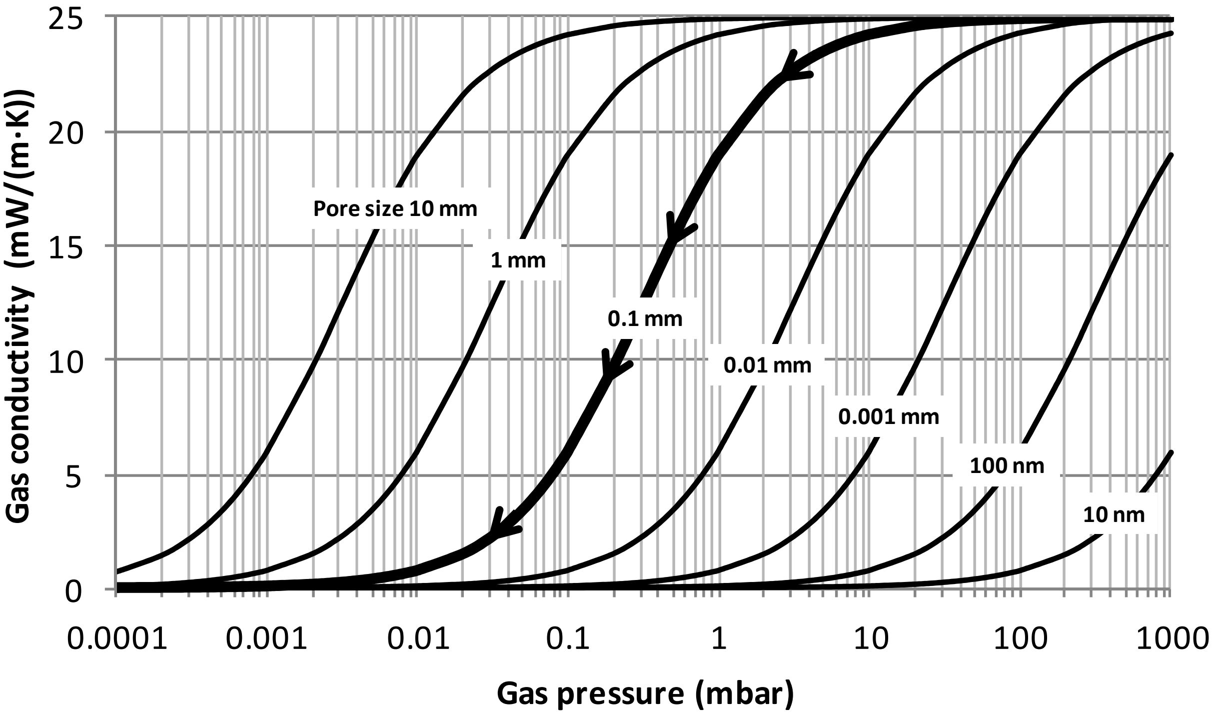

Figure 2.1. Heat transfer by gas conduction in porous materials depending on pore size and gas pressure up to atmospheric pressure at 1 000 mbar. Fumed silica, which is a material used in the VIP core, has pores in the range of 10-100 nm (Based on Simmler et al., 2005).

For a material with a pore size of e.g. 0.1 mm, there are three distinct areas as shown in Figure 2.1. The gas conductivity is constant until the gas pressure is reduced to around 20 mbar. With a decrease in gas pressure, the mean free path of the gas molecules is increased which decreases the number of collisions between gas molecules. In this area the gas conduction is strongly influenced by the gas pressure. At a sufficiently low pressure, the gas conductivity is negligible and all conductivity is caused by the conduction through the solid and radiation (Brodt, 1995).

Heat transfer by radiation is caused by the electromagnetic radiation that all surfaces emit. The net radiation is the difference between the radiation from the warm surface and the radiation from the cold surface. The rate of heat transfer by radiation is dependent on the temperature of the surface which can be described by:

$$\lambda_r = \frac{16n^2\sigma T^3}{3K} \quad \text{(W/(m·K))} \qquad (2.4)$$

where n (-) is the refraction index, σ (J/(K^4·m^2·s)) the Stefan-Blotzmann constant, T (K) the mean temperature and K (1/m) the extinction coefficient. The heat transfer by radiation can be counteracted by adding an opacifier, e.g. silicon carbide, to the material. The opacifier has a higher extinction coefficient compared with other materials which lower the heat transfer by radiation.

One of the most extreme insulation materials is aerogel which typically has a thermal conductivity down to 13 mW/(m·K) at atmospheric pressure (Lu *et al.*, 1992). The density is typically around 100 kg/m^3, but researchers have been able to produce transparent aerogels with a density as low as 3 kg/m^3 (Tillotson and Hrubesh, 1992) which is close to the density of air, 1.2 kg/m^3. The material has extremely small pores with a diameter in the range of 20-40 nm. The method of producing aerogel was invented in the 1930s but the material has until now mostly been used in special applications in space industry, chemical industry and in sport equipment. The production process demands much energy and is quite complicated with production at a critical state involving elevated temperature and pressure. Therefore the pure aerogel product is still too expensive for use in buildings. A fiber material with aerogel is available on the construction market with a thermal conductivity around 16 mW/(m·K) which could be compared to mineral wool that have a thermal conductivity of 40 mW/(m·K).

Some other novel thermal insulation materials are based on existing materials which have been improved by using some additives. The graphite EPS is such a product where graphite lowers the heat transfer by radiation in the EPS. By this measure the thermal conductivity is reduced from 36 to 31 mW/(m·K). Another way of decreasing the thermal conductivity of the material is used in the polyisocyanurate (PIR) which is an improvement of the polyurethane (PUR) by using other substances, reactants and catalysts in the production process. The thermal conductivity of PUR and PIR is around 23 mW/(m·K). In its evacuated state VIP typically has an initial center-of-panel thermal conductivity around 2-4 mW/(m·K) which increases by time due to a pressure increase in the core material due to gas diffusion. Therefore a design value of 7-8 mW/(m·K) should be used (Simmler *et al.*, 2005). Some more materials and in-depth descriptions of the materials mentioned here can be found in (Berge and Johansson, 2012).

2.2 Vacuum insulation panels (VIP)

Vacuum insulation panels (VIP) are used in refrigerators, freezers and cold shipping boxes where the space for insulation is limited. The product was introduced in the mid 1980s following the search for materials that could replace insulation materials which contained CFCs, harmful to the ozone layer. The potential of using VIP in buildings is large but VIP cannot be integrated in buildings without considering the ageing of the material. The technical life time of a refrigerator is around 10-20 years, which is much shorter than what can be expected from a building. Buildings should typically last for 80-100 years without too much maintenance while VIP available today typically has a service life of around 25-40 years.

VIP is a composite material which can be divided in two parts; the core material and the envelope as shown in Figure 2.2. The core material is a fine powder or fiber which is evacuated to pressures of 0.2-3 mbar and therefore should be able to resist the atmospheric pressure on the envelope, i.e. 0.1 MPa.

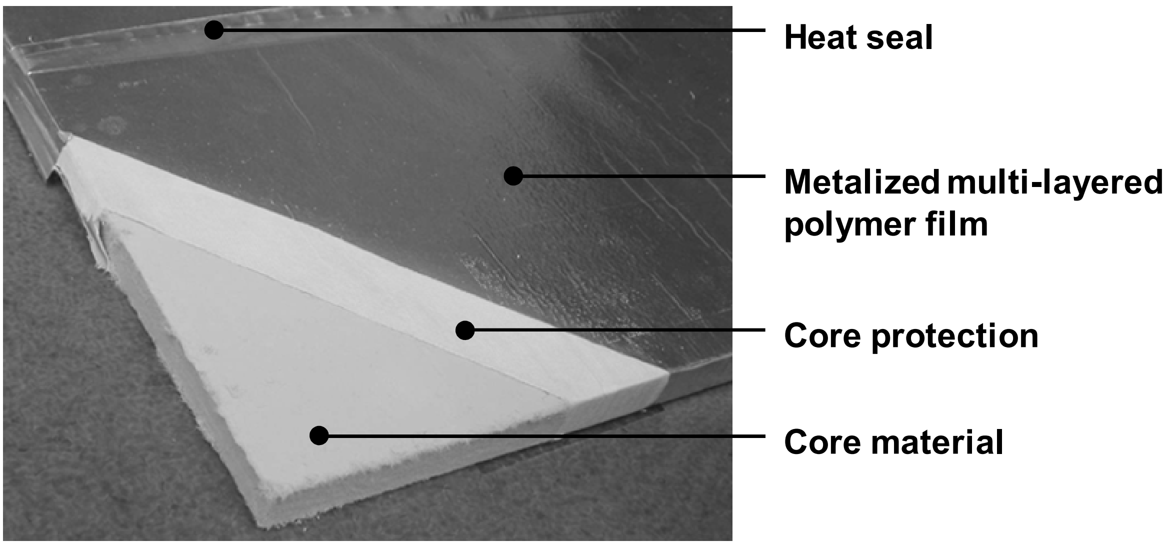

Figure 2.2. VIP is a composite material with a fine powder core wrapped in a heat sealed metalized multi-layered polymer film (Photo: va-Q-tec AG).

The most common core material in Europe is fumed silica while also glass fiber and open cell polyurethane are common in Asia. Fumed silica is a material used in semiconductor industry and in the production of photovoltaic cells. It is produced by pyrolysis of silicon tetrachloride, $SiCl_4$, which is vaporized and reacts with oxygen to form silicon dioxide, SiO_2. To reduce the heat transfer by radiation silicon carbide, SiC, is added to the silica and a fiber material is used to increase the stability of the mixture.

Typically metalized multi-layered polymer films with thin aluminum layers, 30-100 nm, are used as envelope around the core. The film is not perfectly gas tight which makes it possible for gas molecules to diffuse through the envelope which leads to an irreversible pressure increase. After 25 years, the thermal conductivity of a panel with fumed silica is around 8 mW/(m·K) and if the film is punctured, the thermal conductivity increases to 20 mW/(m·K) which is still lower than e.g. mineral wool which has a thermal conductivity around 40 mW/(m·K) (Simmler *et al.*, 2005).

It is not only the thermal conductivity which is important when evaluating the energy efficiency of a material. Also the energy use during production and recycling of the material has to be considered. Schonhardt *et al.* (2003) used three Swiss life cycle assessment (LCA) methods which showed that VIP is competitive with EPS but worse than glass wool in regard of environmental impact. The embodied energy of VIP was 999 MJ/m^2 which was compared to glass wool, 455 MJ/m^2, and EPS, 890 MJ/m^2. The analysis also showed that 90% of the energy used during the VIP production derived from the core material while only 4% was used for the film production. With an alternative core material or a more energy efficient production process, the environmental impact of VIP could be lowered by 45%. More information on long time performance of VIP and other material properties are presented in (Berge and Johansson, 2012). Next section is dedicated to the use of VIP in buildings.

2.3 Experiences of use of VIP in buildings from practice

In 1999 the US Department of Housing commenced an investigated of how and in which constructions VIP could be possible to use. In total 27 constructions were evaluated based on the cost of manufacturing, impact of VIP on the energy performance of the building, risk of damage on the construction site and additional installation costs. Five constructions were identified to be promising for use of VIP: floor panels, exterior doors, garage doors, ceiling panels and attic access panels and stairway insulation. Of these constructions the prefabricated attic access panels and insulated attic stairways was chosen for an in-depth study. The products were developed together with VIP producers DOW and Wacker. The pay-back time for the increased investment of the product compared to a product using conventional materials was approximately 5 to 30 years which limited the interest from industry to investigate the prefabricated solutions further (NAHB Research Center, 2002).

Prefabricated constructions are interesting for VIP applications since the VIP cannot be adapted on the construction site. The design process has to be very detailed since the layout of each VIP is determined before the material can be delivered from the producer. In the literature there are a number of research papers and reports describing different cases where VIP has been used in different constructions. A large part of the projects was built during the period 2002-2005 when the international efforts in VIP research were assembled in the IEA/ECBCS Annex 39 High Performance Thermal Insulation (HiPTI). An evaluation of 20 projects with VIP in floors, roofs, walls, dormer windows and other constructions showed good results on the reduced energy use for heating. An extensive summary of the experiences from those and other projects is presented in (Johansson, 2012).

Figure 2.3. VIP used in the retrofitting of a multi-family building in Germany. The 40 mm thick VIP is attached to the façade in a rail system and covered on the exterior by 50 mm EPS. The design of the wall has aimed to maximize the surface covered by VIP (Photo: Schöck Balkonsysteme GmbH, Brillux GmbH & Co. KG).

The number of projects where façades have been retrofitted with VIP is limited. However, both interior and exterior use of VIP in façades have been tested and evaluated by temperature measurements and infrared thermography. Some practical issues when retrofitting with VIP on the exterior is discussed by Zwerger and Klein (2005) who investigated the use of VIP in wall insulation systems such as the one presented in Figure 2.3.

Heinemann and Kastner (2010) investigated 19 objects with in total 3 224 m^2 VIP a few years after the construction finished. Some objects had more punctured panels than others and with three objects removed from the study, the failure rate decreased from 12.8 to 4.9%. The study was based on infrared thermography which is only possible to use when the VIP is not covered by a high conductive material or a ventilated air space. This is an important limitation when evaluating the thermal performance of the finished VIP wall.

The difficulty when retrofitting old buildings is that the old materials are uneven and it is hard to use a material as static as VIP. Between details such as balcony attachment and windows, other materials have to be used to bridge the gap between the VIP. In this study the problem with the old versus new materials has been solved by using mineral wool at such places. Figure 2.4 shows the retrofit solution and the different materials used in this study which are described more thoroughly in Papers I, II and Section 4.1.

During the construction VIP could be damaged in a number of different ways. Today only visual inspection can be used to ensure VIP with a failed vacuum is not integrated in the construction. The next chapter introduces an investigation of a measurement method based on the transient plane source (TPS) method which could be used to measure the thermal conductivity of VIP in situ.

Figure 2.4. The multi-family building in Gothenburg was retrofitted with VIP. Mineral wool covered the VIP and was used at places where VIP could not be used (Photo: Pär Johansson).

3 Measuring thermal properties of VIP

This chapter is based on the studies described in Paper III and IV. Since the thermal conductivity of the VIP is very different between the evacuated and punctured state it is important to make sure that the VIP is undamaged when integrated in the construction. The lack of fast and reliable in situ measurement methods is one of the factors that limit the applicability of VIP on broad scale. The first section of this chapter introduces the basic properties of the tested materials and the transient plane source (TPS) method. The method is tested and the results compared to numerical simulations to evaluate the applicability of the measurement method based on these initial experiments.

3.1 Thermal properties of VIP

A material is characterized by its thermal properties which can be measured by a number of different methods. The steady-state guarded hot plate method is a common mean to determine the thermal conductivity, λ (W/(m·K)), of a material. The method takes some time, typically several hours, since the specimen has to be in steady-state with the hot and cold plates over which the heat flow is measured.

The specific heat capacity, c_p (J/(kg·K)), of a material tells how much heat is needed to increase the temperature. It can be measured by e.g. the calorimetric method where heat is added to a specimen and the corresponding change in temperature measured. Another parameter which is important is the density, ρ (kg/m^3), of the material. The product of the specific heat capacity and density gives the volumetric heat capacity (J/(m^{3}K)). These parameters together with the conductivity defines the thermal diffusivity, a (m^2/s), by

$$a = \frac{\lambda}{\rho \cdot c_p} \quad (\text{m}^2/\text{s}) \tag{3.1}$$

The thermal diffusivity is a measure of how fast heat is transferred through a material. A high thermal diffusivity means that the material reacts quickly to changes in the surrounding temperature compared to a material with a low thermal diffusivity. This material property can be used to calculate the time dependent penetration depth, d_t (m), by

$$d_t = \sqrt{a \cdot t} \quad (\text{m}) \tag{3.2}$$

where t (s) is the time after a step change in heat flow is introduced. In Table 3.1 the tabulated thermal properties of polystyrene, aluminum, fumed silica and a metalized multi-layered polymer film (VIP film) are presented. The penetration depths have been calculated after 40 s.

Table 3.1. Tabulated material properties and the penetration depth after t = 40 s.

Material	λ (W/(m·K))	ρ (kg/m^3)	c_p (J/(kg·K))	a (mm^2/s)	d_t (mm)
Polystyrene	0.032	29	1 760	0.627	5
Aluminum	226	2 700	920	91.1	60
Fumed silica	0.004	175	850	0.027	1
VIP film (⊥/‖)	0.275/0.489	1 100	1 800	0.14/0.24	2.3/3.1

Since the core and film of the VIP have very different properties with a ten times higher thermal diffusivity in the VIP film compared to the fumed silica, direct measurements of the combined thermal properties is complicated. There exist indirect methods that measure the internal pressure of the panel, e.g. the foil lift-off method or integration of a pressure sensor in the VIP. The methods rely on the empiric relation between internal pressure and thermal conductivity that is used to evaluate the properties of the VIP. Erbenich (2009) described the available methods and concluded that it does not exist a method that can be used on the construction site to measure the thermal properties of VIP. By measuring in situ before the VIP is integrated in the construction the constructor can make sure the VIP has not been damaged after it left the production plant.

A measurement method that exists today which can be used in the production facility in the quality assurance process was developed by Caps (2004). The measurement method is based on a transient measurement where a heat sink is integrated in the core material. Between the core material and the film, a fiber material with a defined pressure dependent thermal conductivity is inserted. A warm sensor is placed on the surface of the panel, close to the heat sink, which during a specified time period registers the temperature decrease of the sensor. With the relation between the temperature decrease and thermal conductivity of the fiber material, the interior pressure of the VIP can be determined. Another transient measurement method available for a wide range of materials is the TPS method which is described in next section.

3.2 Transient plane source (TPS) method

The transient plane source (TPS) method uses a sensor produced of a 10 μm thick double nickel spiral, sandwiched between two layers of 25 μm thick kapton (polyimide film). The spiral serves both as heat source and as electric resistance thermometer. The sensor is clamped between two samples of the material as shown in Figure 3.1.

A constant electric power is supplied through the spiral which develops heat by the electric resistance of the nickel raising the temperature of the sample. The rate of the temperature increase depends on how quickly the heat developed in the spiral is conducted away through the surrounding materials. Heating is continued for a period of time, with the voltage across the spiral being registered. As the current is held constant, the voltage changes in proportion to changes in the resistance of the spiral. With knowledge of the temperature variation with time, i.e. variation of voltage, and the supplied heat flow, it is possible to calculate the thermal conductivity and volumetric heat capacity of the material.

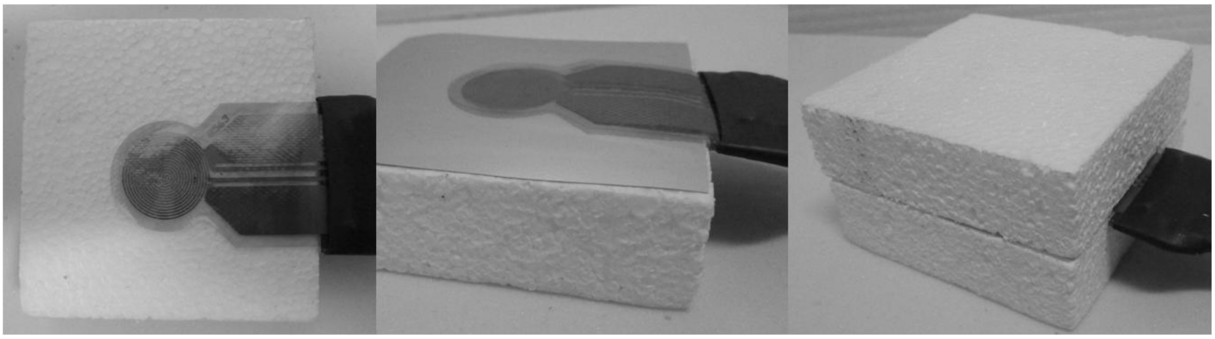

Figure 3.1. The kapton insulated nickel sensor is clamped between two material samples and a heat flow is produced in the sensor. The registered temperature increase makes it possible to calculate the thermal properties of the samples (Photo from Paper III).

Measurements on only the VIP setup is limiting the evaluation of the TPS method since it is limited to only two basic cases; one evacuated and one punctured case. Therefore EPS, EPS covered by aluminum film and EPS covered by VIP film are measured with the TPS sensor. The average dimensions of the polystyrene were about 70x70x20 mm (length, width and thickness) and the measured thickness of the aluminum film and metalized multi-layered polymer film were 0.01 mm and 0.1 mm respectively. The samples are pressed together by applying a weight on top of the upper sample creating a pressure of 4.7 kPa. The pressure was varied for the VIP setup to investigate the influence of the contact resistance. The measurements were performed with a pressure of first 1.8 kPa, continuing with 2.5 kPa and ending at 4.7 kPa. Each setup was tested 10 consecutive times with a break of 60 minutes between each measurement to make sure it was cooled down to the surrounding air temperature of 20.5°C. The heat supply in these initial experiments was limited to 0.02 W through a 6.4 mm radius sensor. The initial measurement results are presented in Figure 3.2.

The measured temperature increase after 80 s was on average 1.4, 5.2, and 7.6°C for the setups with EPS covered by aluminum film, VIP film and pure EPS respectively. The different VIP setups had a temperature increase of 5.8, 6.1 and 6.8 after 80 s. The highest applied pressure on the VIP gave the lowest temperature increase.

After 160 s the average temperature increase was 1.6 and 6.1°C respectively for the EPS covered by aluminum and VIP film. There has not yet been performed a measurement on the pure EPS samples during 160 s. For the three evacuated VIP setups the temperature increase after 160 s was 7.59, 7.81 and 8.58°C on average.

The measurements of the pure EPS setup had a coefficient of variation (CV), i.e. standard deviation divided with mean value, of 0.14% after 80 s. After 160 s the CV for the EPS covered by aluminum and VIP film was 0.79 and 0.21% respectively. For the three VIP setups the CV was 0.35, 0.27 and 0.37%. The low CVs show the possibility of repeating the TPS measurements with small relative deviations between the results.

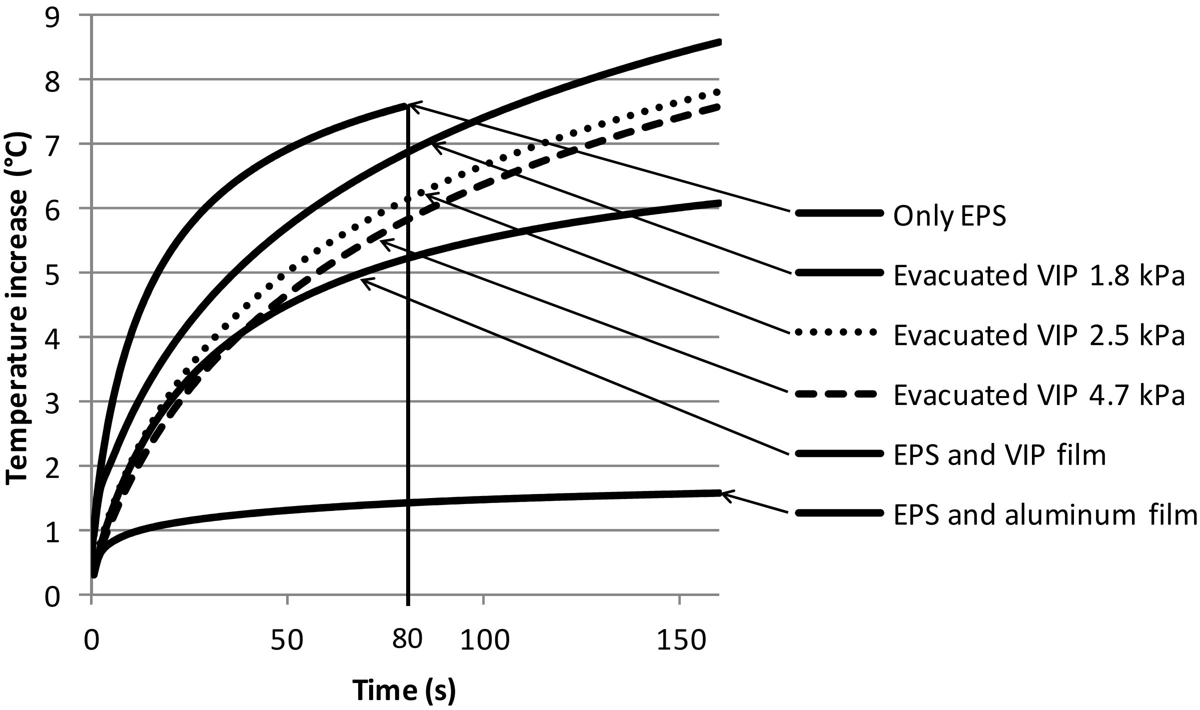

Figure 3.2. Measured temperature increase during 80 and 160 s when 0.02 W was supplied in the TPS sensor. All materials were measured with 4.7 kPa applied on the upper sample except for the evacuated VIP which was measured in three steps.

In Paper III and IV, measurements during 40 s have been used, but that has now been shown to be a too short measurement period to separate the different materials behind the VIP film. In future evaluations a measurement period of at least 160 s will be used.

There was a small difference in the composition of the VIP film used in the samples. The film in the VIP setups is coated with a 6 µm brominated acrylic copolymer on the surface of the film which acts as a flame retardant layer. The thermal properties of this layer and its influence on the temperature increase are unknown. Therefore conclusions based on the differences between the measurements on the VIP setups and the setup with EPS covered by VIP film are uncertain.

The measurement results show that there is a problem measuring on the surface of the VIP since the results deviate when a changed pressure is applied. This is caused by the vacuum in the panel which makes the film uneven and reduces the contact surface between the material and sensor. In the case with the setup with EPS and VIP film the film is lying flat on the EPS and the contact surface is maximized by applying the 4.7 kPa. However, Madhusudana (1996) states that the microscopic and macroscopic irregularities of a metal surface heavily reduces the contact surface between two metals. The actual contact surface is only about 1-2% of the available surface at pressures around 10 MPa which is more than 2 000 times the maximum pressures used in these investigations. The impact of the surface resistances and air layers between the surface of the sensor and film as shown in Figure 3.3 needs to be further investigated.

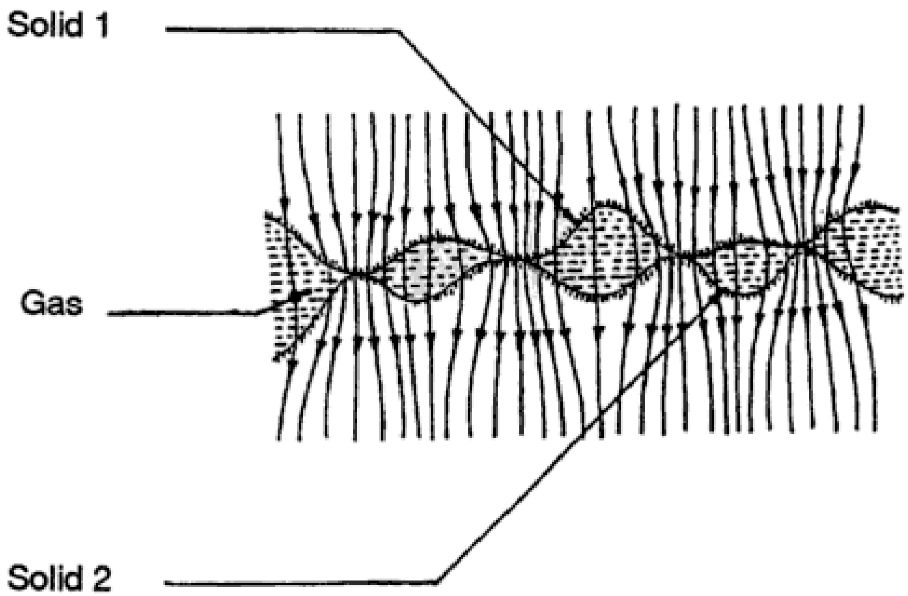

Figure 3.3. The heat flow between two surfaces in contact to each other is dependent on the actual contact surface and the air layers in the cavities between the surfaces (Madhusudana, 1996).

The surface contact resistance is dependent on the three modes of heat transfer described in Section 2.1. The gas convection in the cavities can be neglected since the cavities are relatively small and the temperature differences between the surfaces are low. On the other hand, heat transfer by radiation between the surfaces is virtually unaffected by changes to the cavities. There is a limited heat conduction through the gas corresponding to a surface contact resistance between the materials. A way to decrease the surface contact resistance is to reduce the size and number of cavities which could be done by applying a substance with high thermal conductivity on the sensor.

If the TPS method should be used on the construction site, a standardized methodology has to be developed so repetitive measurements show the same results. As was shown in Table 1 in Paper III, the results from the TPS method did not correspond to the values found in the literature. The method showed a 3-6 times higher thermal conductivity than what was expected. A first investigation on which parameters are influential to the temperature increase in the samples was performed by numerical simulations of the different setups and materials. The results were compared to the measured temperature increase by the TPS sensor. The numerical simulation model is described in next section.

3.3 Numerical models of isotropic and layered materials

To investigate whether the TPS method is suitable to be used for measurements of the thermal properties of VIP a numerical model was developed. In the literature, different examples of how numerical methods have been used to study material properties using transient methods can be found. Model and Hammerschmidt (2000) developed a numerical model to simulate the influence of different boundary conditions when measuring with transient methods. Miller *et al.* (2006) tested carbon-filled nylon 6,6 composites with the TPS method and compared to numerical finite element analysis. The results from the simulations compared with measured data showed very good agreements in both studies.

The numerical model developed in this study was based on a three-dimensional model where the sensor is placed in the center of the specimen. The setup could be treated axis symmetrical which means the three-dimensional model can be transformed into cylindrical coordinates, as shown in Figure 3.4.

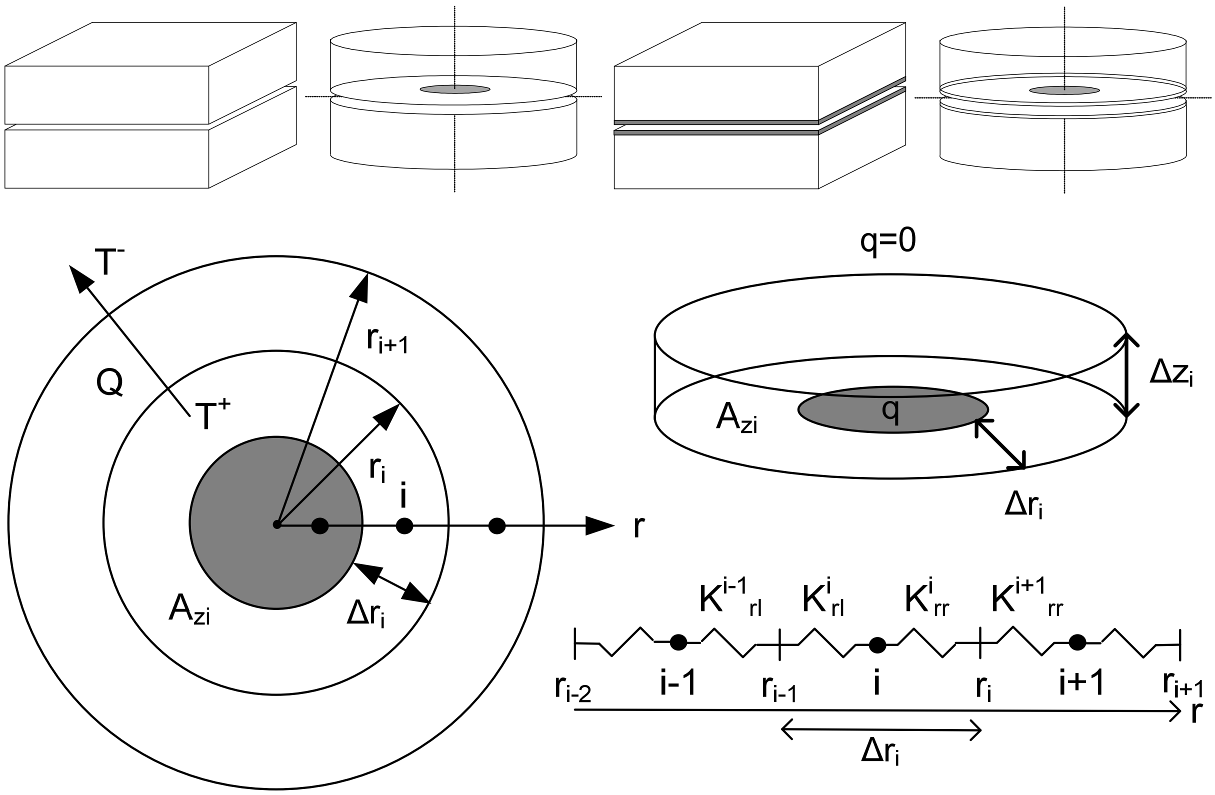

Figure 3.4. The numerical simulation model was based on the isotropic and layered materials which were transformed to cylindrical coordinates. The sensor was placed in the center of the model where a constant heat flow q (W/m^2) is supplied. The finite difference calculation procedure is based on nodes located in the center of each cell. The cells are connected with a thermal conductance dependent on the thermal conductivity in the materials between them. All other boundaries are adiabatic thus has zero heat flow through the boundary (From Paper IV).

The numerical simulations were performed in Matlab (MathWorks, 2009) where the isotropic material of 20 mm thickness and 20 mm radius was divided into 200 cells respectively in the vertical and radial direction. The 20 mm thick layered materials of 60 mm radius were divided into 200 cells in the vertical direction and 600 cells in the radial direction as described in Paper IV.

The numerical model for the isotropic case was validated by comparing the temperature increase in the sensor with an analytical solution which is described in Paper IV. The numerical model and analytical solution for the isotropic case with EPS gave very consistent results. The deviation was largest during the first time steps, but was then stabilized around 0.037% for the temperature increase in the center of the sensor and 0.056% for the average temperature increase in the sensor area.

No analytical solution for the case with a cylindrical highly conductive thin layer covering a isotropic low conductive material have been found which make it impossible to validate the numerical simulations of those cases. However, the numerical model is based on the model for the isotropic case with some modifications which implies that the model should give accurate results compared to measurements. The comparisons between measured and numerically simulated temperature increases are presented in the next section.

3.4 Comparison of measurements and numerical simulations

The temperature increase in the specimen has been simulated numerically with the model described above using data specified in Table 3.1. The simulation has been based on the case of supplying 0.02 W in a 6.4 mm radius TPS sensor during 80 and 160 s. The results of the numerical simulations are presented in Figure 3.5 and a comparison between the measured and numerically simulated temperature increases are presented in Figure 3.6.

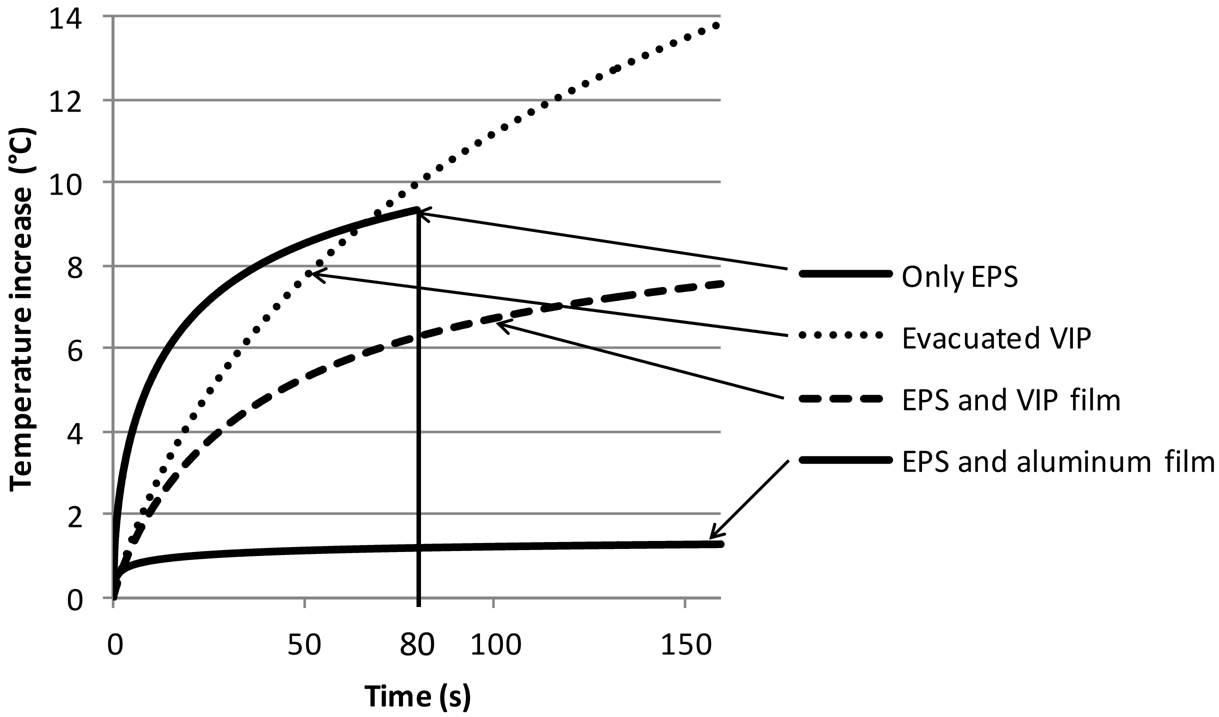

Figure 3.5. Numerically simulated temperature increase using the data in Table 3.1. The numerical simulations of the temperature increase are based on the case with 0.02 W supplied during 80 s in the EPS setup and 160 s in the three remaining setups.

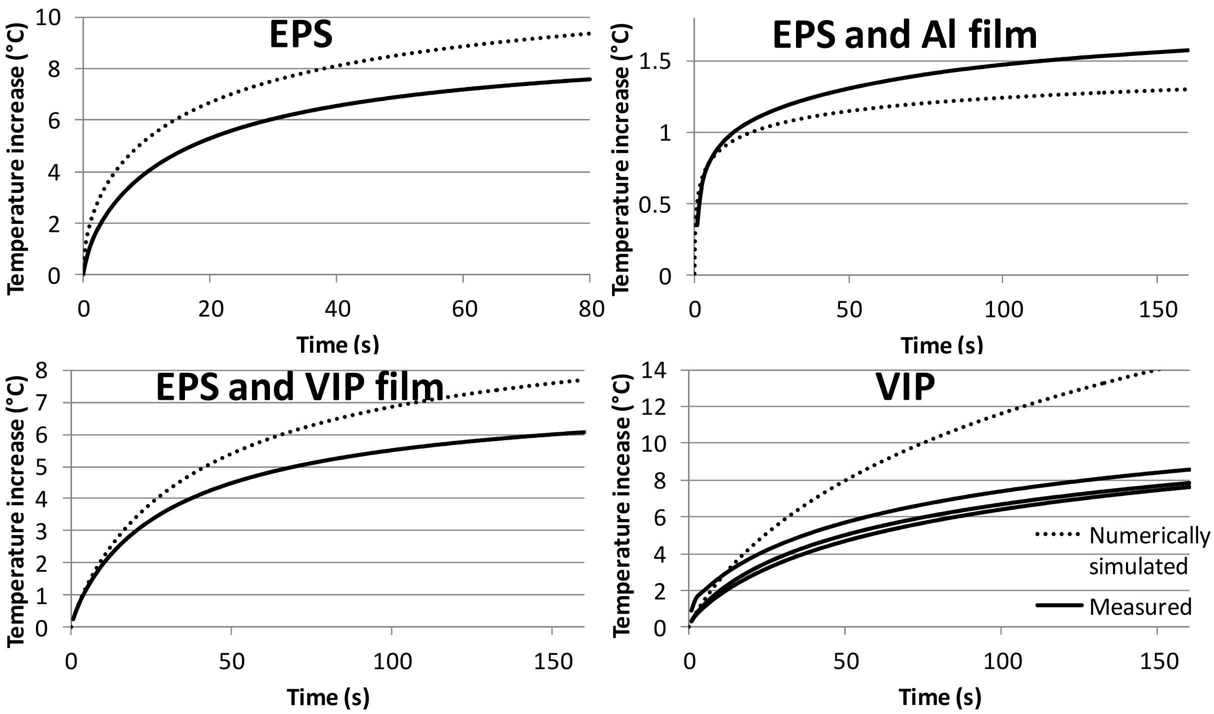

Figure 3.6. Comparison between simulated (dotted line) and measured (continuous line) temperature increase for the four setups. The numerical simulations of the temperature increase are based on the case with 0.02 W supplied during 80 and 160 s in the TPS sensor using data in Table 3.1.

The simulated temperature increase for the EPS setup after 80 s was 9.4°C which should be compared to the measured temperature increase of 7.6°C which means a deviation of 23% between the numerical simulations and measurements. For the setups with EPS covered by the 10 µm thick aluminum film and 100 µm thick VIP film, using the material data in Table 3.1, the simulated temperature increase was 1.3 and 7.5°C respectively. Compared to the measurements the deviation was 21 and 27% respectively. The simulated temperature increase for the VIP samples was 13.84°C which was between 68-90% higher than the measurements, depending on the pressure applied on the upper specimen of the VIP.

The cause of the deviations between the simulated and measured temperature increase could be caused by a large number of uncertainties. First of all the thermal properties have to be investigated more in detail to get the correct properties for the specimens used in this investigation. Only the EPS and VIP have been measured in guarded hot plate apparatus to get the thermal conductivity. The volumetric heat capacity of the EPS was measured in lab at SP Technical Research Institute of Sweden but is unknown for the other specimens.

The effective thermal conductivity of the VIP film is under debate in the literature where different values are argued for. This far in the study the arithmetic mean value of all material layers in the VIP film has been used, but Ghazi Wakili *et al.* (2011) showed that a value around 10 W/(m·K) give more corresponding results between measurement and simulations based on measurements of the thermal bridges between panels. The changed thermal properties of the VIP film due to the brominated acrylic copolymer on the surface of the film are unknown. What could further influence the deviations is the surface contact resistance between the sensor and film. All these parameters have to be studied in detail to investigate their respective influence on the temperature increase.

The effective thermal conductivity of the VIP film was varied in the simulations of the EPS covered by VIP film and the VIP setup. Preliminary results showed that the agreements between numerical simulations and measurements were improved when a thermal conductivity of 1.6-2 W/(m·K) was used in the model of the EPS covered by VIP film. The thermal conductivity had to be changed to 1-1.3 W/(m·K) to improve the agreements in the VIP setup. These simulations show that the surface resistance could be a very important factor which decreases the heat transfer from the sensor more in the case with evacuated VIP than in the case with EPS where the latter should have a lower surface contact resistance.

With further investigations the TPS method could be developed to measure thermal properties of VIP before they are integrated in the construction. In the next chapter the field study building retrofitted with VIP is described and measurements of the hygrothermal state in the construction are presented.

4 Retrofitting of façade with vacuum insulation panels

This thesis is focused on the use of VIP in buildings in general and more specifically on the use in an exterior wall of an old building in Gothenburg. In this chapter the field study building and the design of the retrofitting measure are described based on Papers I and II. Measurements from the first winter are presented to give a basis for a first evaluation of the impact by the retrofitting on the existing old wall.

4.1 Field study building and retrofit design

The building chosen for the field study is a county governor's house (landshövdingehus) from 1930, see Figure 4.1. This is a typical historical building for the city of Gothenburg on the Swedish west coast. Most of them were constructed during 1876-1936 following an approval by the county administrative board to build two wooden floors on top of a brick or stone masonry ground floor in order to circumvent the fire regulations that limited the height of wooden buildings to two floors. At that time Gothenburg experienced severe lack of housing due to the massive migration of people from the rural areas surrounding the city. During the period 1880-1940 the population of Gothenburg more than tripled from around 100 000 to 300 000 inhabitants, creating a high demand on affordable housing. Today there are approximately 1 400 buildings left of this type around the city. However, the original stock was larger but due to the very low technical standards of the apartments in the buildings many of them were demolished in the 1960s and 1970s (Larsson, 1973).

Figure 4.1. The three story county governor's house from 1930 chosen for the field study. The right part was retrofitted with vacuum insulation panels while the left part of the façade was left untouched as a reference case (Photo from Paper I).

The field study building was built in 1930 when it was common that the ground floor was built in 1.5 stone brick masonry in the wall which gave a thickness of approximately 340 mm. The two wooden floors have walls of 80 mm standing wooden planks in three layers with flax between the boards to increase the air tightness. On the exterior a 22 mm thick vertical wooden cover boarding with rib flanges was mounted on top of a wind and waterproof tar paper. The interior side of the walls were originally covered with plaster on reed and wooden battens (Larsson and Lönnroth, 1972).

The moisture content in the wall was measured in June, 2010 when holes in the wooden cover boarding were drilled and the moisture quotient measured with a two-pin sensor. The moisture quotient was approximately 9% close to the surface of the wooden planks while it was around 8% a few cm into the construction. In the brick grout, wooden laths were found which had a moisture quotient of 12% at the surface and 9.5% further in. The critical moisture quotient for mold growth on a wooden surface is around 20%. Figure 4.2 shows the condition of one of the window frames and the materials behind the wooden cover boarding.

Figure 4.2. At a visit to the buildings, holes were drilled through the wooden cover boarding to investigate the condition of the materials behind. The worst places were around windows (left) and in the wooden laths found in the grout between the bricks (middle). The wooden planks had flax between the planks (right) to increase the air tightness of the wall (Photo: Pär Johansson).

The two different structural materials, brick on the ground floor and wooden planks on the two upper floors, have different critical moisture levels. Wood is susceptible to moisture and a relative humidity above 75-80% together with a temperature above 0°C during a consecutive time period could initiate mold growth at the surface. Brick, on the other hand, is vulnerable to freeze and thaw action on the exterior surface which may cause cracks in the brick. These problems would increase with a retrofit solution where the insulation is mounted on the interior side of the wall. With a solution of insulation on the exterior, the materials get a better protection from the surrounding weather such as driving rain. The old structure is exposed to higher temperatures and with an unchanged moisture condition in the wall the relative humidity should decrease.

Depending on which U-value is targeted after retrofitting, the thickness of the VIP can be varied. The original wall has a U-value of around 1.1 W/(m^{2}K) both in the brick and wooden parts. Since the building is listed the walls cannot be changed too much and the thickness of the wall is limited by the connection to the roof and fire wall that separates it from the next building. Discussions in the design team and with the owner Familjebostäder resulted in an allowed additional thickness of 80 mm without risking the original features of the façade. The solution demanded that the windows were moved 80 mm to be in line with the new façade.

Before the construction started SP Technical Research Institute of Sweden performed measurements in the building to detect thermal bridges and air leakage paths. Two rooms in the building were measured with the blower door method where each room was sealed off from the rest of the apartment by a plastic tarp in the doorway. The results showed that the airtightness at 50 Pa was 2.6 l/(s·m^2) (5.7 1/h) for a room on the ground floor and 4.3 l/(s·m^2) (3.4 1/h) for a room on the third floor. The difference could be explained by a large leakage path between the ground floor apartments to the basement. With infrared thermography the temperature difference between the indoor air and surface temperature of the exterior walls was on average 2°C which indicated a U-value around 1 W/(m^{2}K) of the wall.

A risk assessment and sensitivity analysis of the hygrothermal conditions in the wall before and after retrofitting was performed. The methodology and results are discussed in Paper I and Section 5.1 of this thesis. The final solution of the retrofitted wall is shown in Figure 4.3.

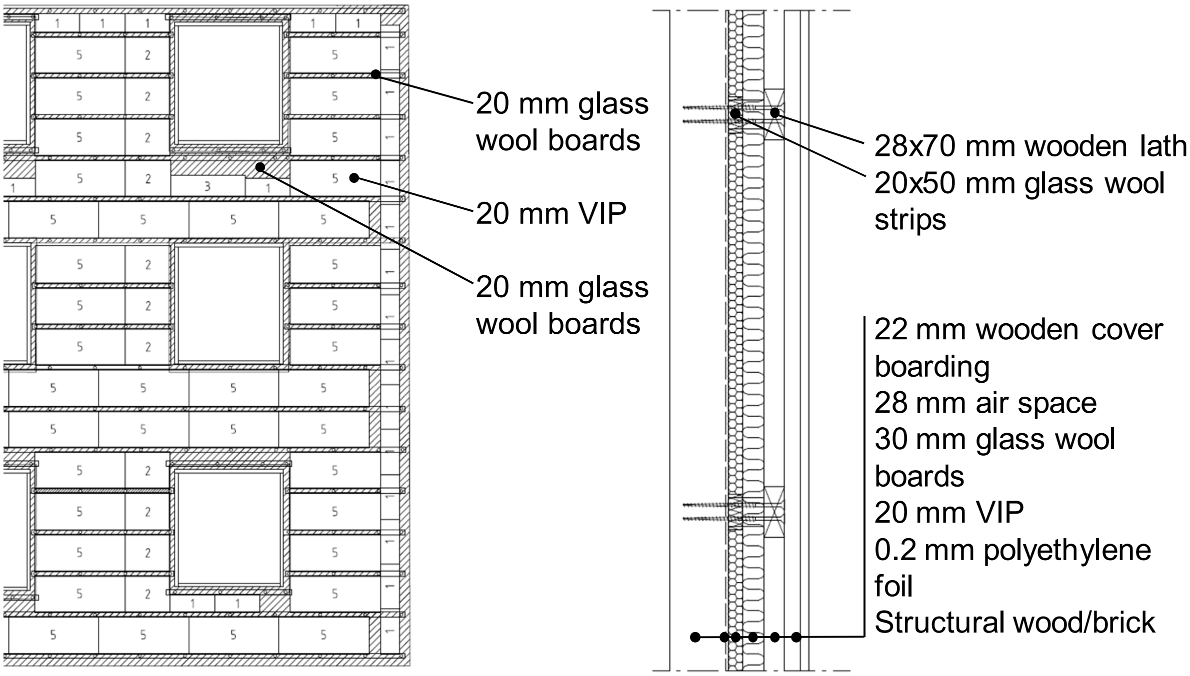

Figure 4.3. Final solution of the retrofitted wall with 20 mm VIP covered by 30 mm glass wool boards. Between the VIP 20x50 mm strips of high density glass wool are attached to allow attachment of the wooden cover boarding (From Paper II).

During the reconstruction phase of the façade it showed to be difficult to follow the new technical drawings of the façade. Although great concern had been given to the design of the wall to follow the original measurements of the façade, the laser scanning had been based on a point in the lower left corner of the façade which was removed when the old wooden cover boarding was torn down. This meant that the required number of VIP of specified sizes did not match the drawings. The problem was solved by ordering additional panels, 10% of each size, so at the end only minor changes had to be done to the original design.

Of the 180 panels mounted on the façade three panels had a loose film which meant they had been punctured or damaged before they reached the construction site or during construction. These VIP were exchanged to panels without visibly detectable damages. As described in Chapter 3 there are no available measurement techniques which could be used for in situ measurements of VIP before integrated in the façade. Therefore only visual inspection of the façade was possible before the wall was finalized. Sensors were mounted in the existing wall to evaluate the hygrothermal performance of the retrofit solution. The measurements are described in next section.

4.2 Hygrothermal monitoring

The field study building is exposed to the humid climate of Gothenburg on the Swedish west coast. The chosen façade faces the southwest which is the dominant wind direction for driving rain. Therefore it is interesting to study the hygrothermal conditions in the façade compared to the reference façade adjacent to the file study building. A number of 15 wireless hygrothermal sensors were mounted on different locations in the wall as shown in Figure 4.4.

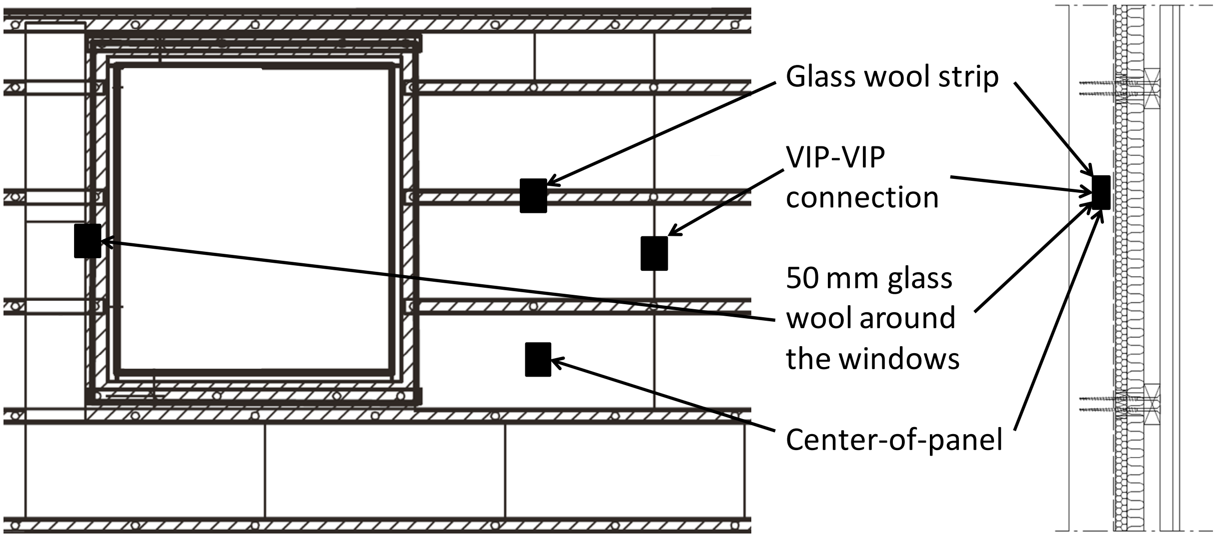

Figure 4.4. Location of the hygrothermal sensors that were integrated in the walls (From Paper II).

The sensors are integrated in the wall and report the temperature and relative humidity every hour until the battery runs out of power after approximately 15 years. A wireless connection makes it possible to gather the data every hour with real-time monitoring. The sensors are 60x40x28 mm (length, width and thickness) and located behind the VIP in the wood and brick respectively. The measurement accuracy of the sensors is ±2.5% for relative humidity in the range of 10 to 90% and ±0.5°C at 25°C. The temperature can be measured between -40 to 85°C (GE Sensing, 2007).

In the brick and wood wall four sensors are located behind the center-of-panel, VIP to VIP connection, glass wool strip and at the window frame. Two sensors are located behind the wooden cover boards in the reference façade, one in the brick and wood parts respectively. Four sensors are located in the kitchen of four of the apartments in the building to obtain indoor climate conditions based on the individuals living in the apartments. The final sensor monitors the outdoor temperature and relative humidity at the building site.

The measurement equipment suffered from problems in the beginning of the period after the wall was finished. According to the producer of the system the distance between the sensors and data acquisition gateway could be up to 46 m. However, signals from some of the sensors were blocked and the sensors were not detected by the gateway. It could be the thick brick fire wall or the aluminum layers around the VIP which created disturbances for the signals. The problems were solved when an additional data acquisition gateway was installed, thou data from October, 2010 to early January, 2011 were sent very sporadically. Parts of the data from the period January 5 to March 22, 2011 are included in this thesis based on the information given in Paper II. The brick wall was chosen for the analysis which is based on 24 hours moving averaged data.

The temperature and relative humidity can be used to derive the vapor content of the air which is the driving force for vapor transfer through a construction. Figure 4.5 shows the temperature in the retrofitted wall behind the center of the VIP compared to the reference wall and the temperature in two apartments are compared to the outdoor climate.

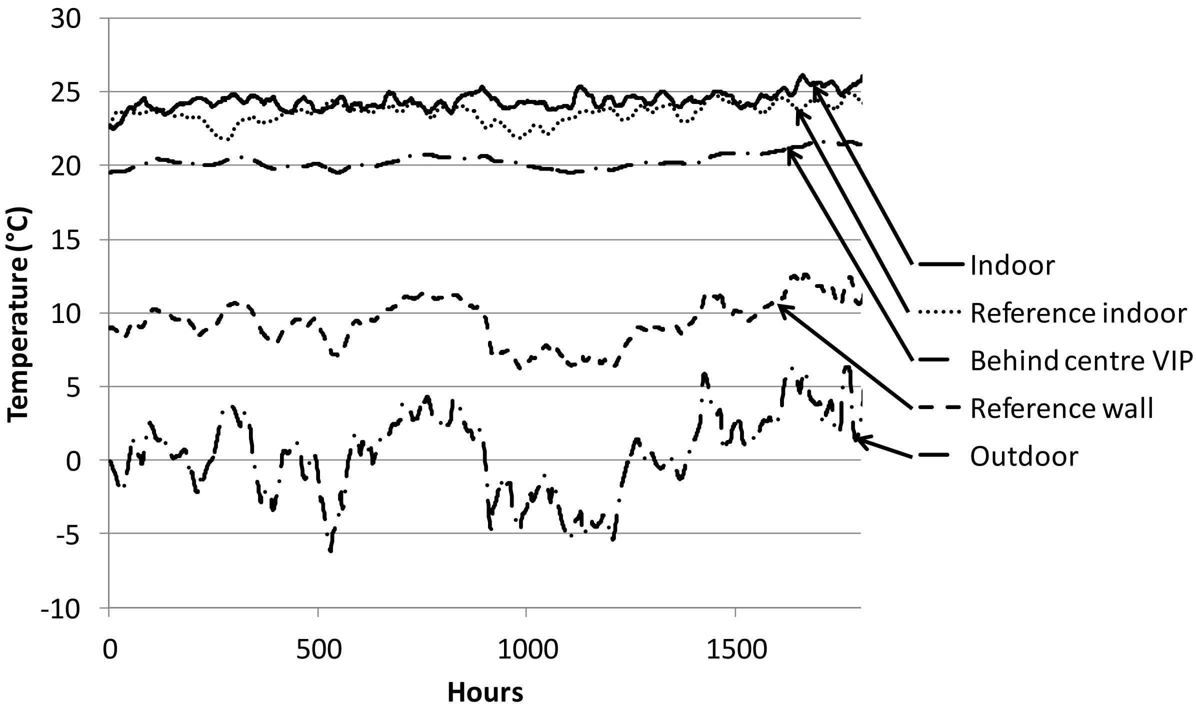

Figure 4.5. Measured daily averaged temperature behind the center of a VIP in the retrofitted brick wall compared to the reference wall and the temperature in two apartments compared to outdoor climate during January 5 to March 22, 2011.

The average temperature was 10°C higher in the retrofitted wall compared to the reference wall. The indoor temperature was around 24°C in both apartments, reaching maximum 26 and 25°C respectively, while the outdoor temperature varied between -6 and 6°C with 0.5°C on average. The unbalanced heating system of the building is probably the main cause of the high indoor temperature. The corresponding vapor contents are presented in Figure 4.6.

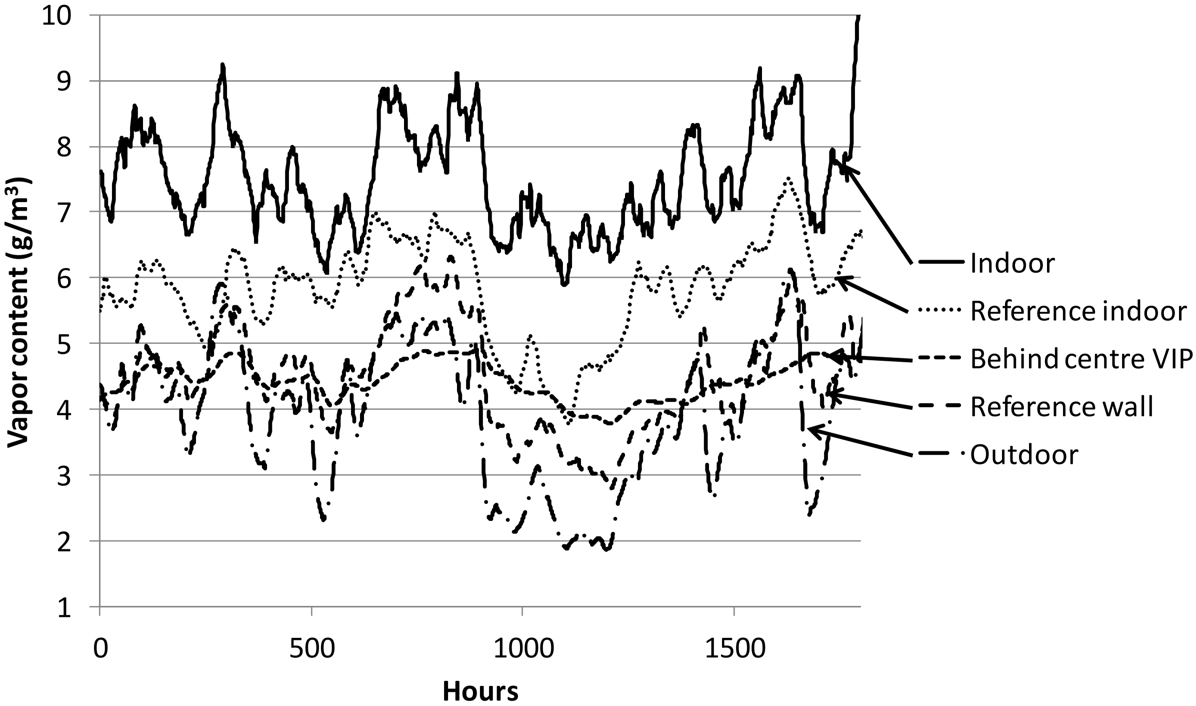

Figure 4.6. Measured daily averaged vapor content behind the center of a VIP in the retrofitted brick wall compared to the reference wall and the vapor content in two apartments compared to outdoor climate during January 5 to March 22, 2011.

The vapor content in the retrofitted wall is measured on the warm side of the vapor tight VIP which should give higher vapor content in that wall compared to the reference wall if the interior moisture supply is the same. The moisture supply is defined as the difference between the indoor and outdoor vapor content. In this case the indoor moisture supply is almost twice as high in the retrofitted part as in the reference, 3.6 compared to 1.9 g/m^3. This could be caused by different airing behavior of the occupants, but since the average indoor temperature difference is only 0.8°C higher in the apartment in the retrofitted part than in the reference, this is probably caused by a higher moisture load in the first apartment.

What can be clearly seen by studying the vapor contents in the two walls is that it is much more stable in the retrofitted wall than in the reference wall. In the retrofitted wall, the vapor content varied between 3.8 and 4.9 g/m^3, while in the reference wall between 2.8 and 6.3 g/m^3. The outdoor vapor content was varying between 1.9 and 6.1 g/m^3 and was on average 3.9 g/m^3. The corresponding relative humidity is shown in Figure 4.7.

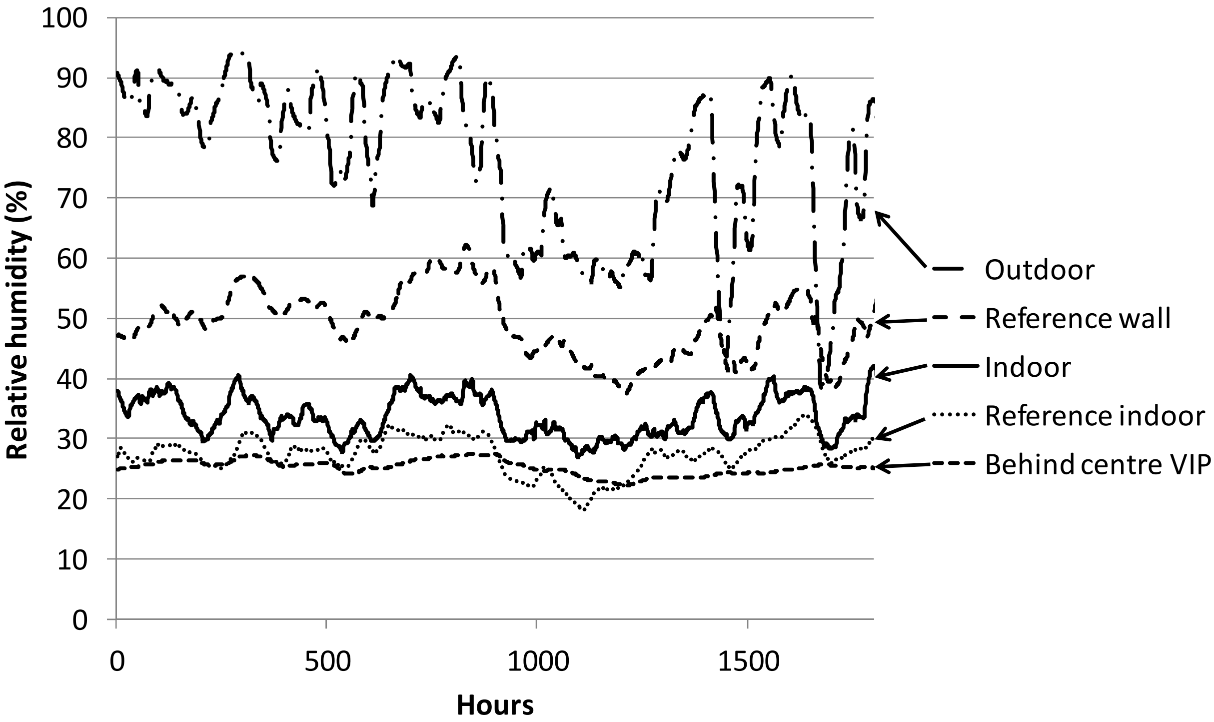

Figure 4.7. Measured daily averaged relative humidity behind the center of a VIP in the retrofitted brick wall compared to the reference wall and the relative humidity in two apartments compared to outdoor climate during January 5 to March 22, 2011.

The relative humidity of the air in the two apartments and in the reference wall followed the changes in the outdoor air. Behind the VIP, the relative humidity was more stable with a slower response to the changes. The average relative humidity behind the center of the VIP in the retrofitted wall varied between 22 and 27% with an average of 25%. In the reference wall it varied between 37 and 62% with an average of 50% relative humidity.

The hygrothermal conditions are measured on different locations in the retrofitted wall as shown in Figure 4.4. One sensor in the brick wall was mounted in an incorrect location, which means that two sensors were located behind the glass wool strips and none behind the VIP to VIP connection. The temperatures at the different locations are presented in Figure 4.8.

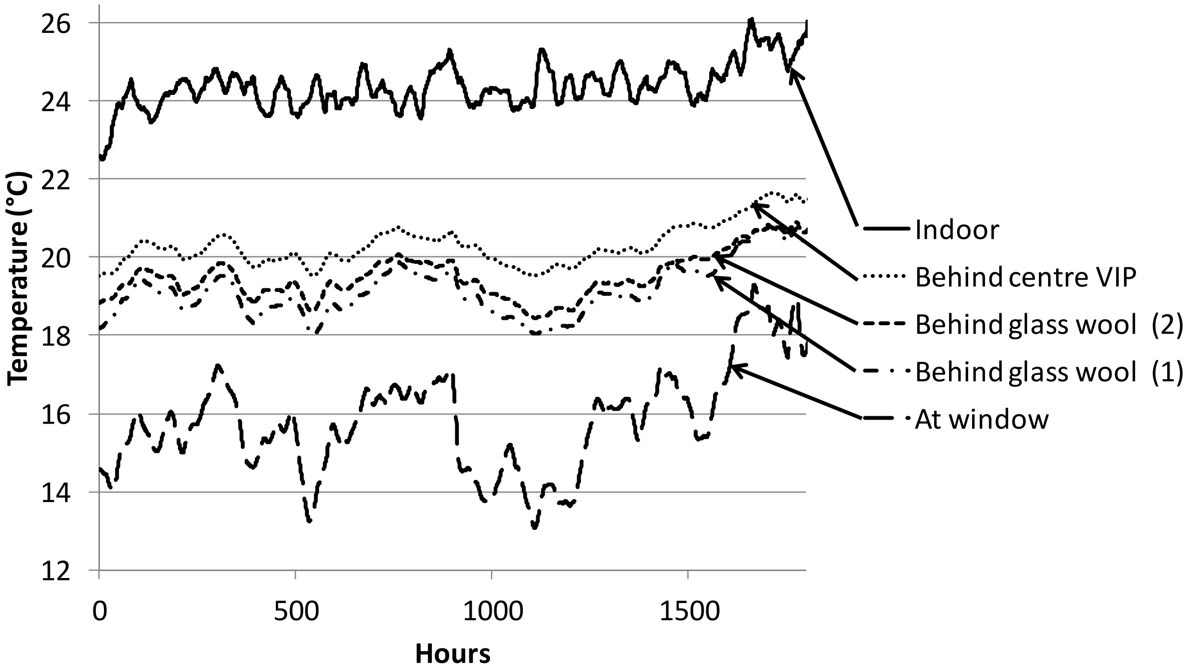

Figure 4.8. Measured daily averaged temperature at different locations in the retrofitted brick wall during January 5 to March 22, 2011.

The temperature next to the window varied between 13.1 and 19.3°C with an average value of 15.8°C. Out of the measured locations this was the one with the lowest temperature which was expected since this was the location with the smallest amount of insulation. The influence of the glass wool strips on the temperature was measured on two locations which had a lower average temperature of 0.8 and 1.2°C compared to behind the center of the VIP where the temperature varied between 19.5 and 21.7°C. The vapor content at the different locations in the part with brick is presented in Figure 4.9.

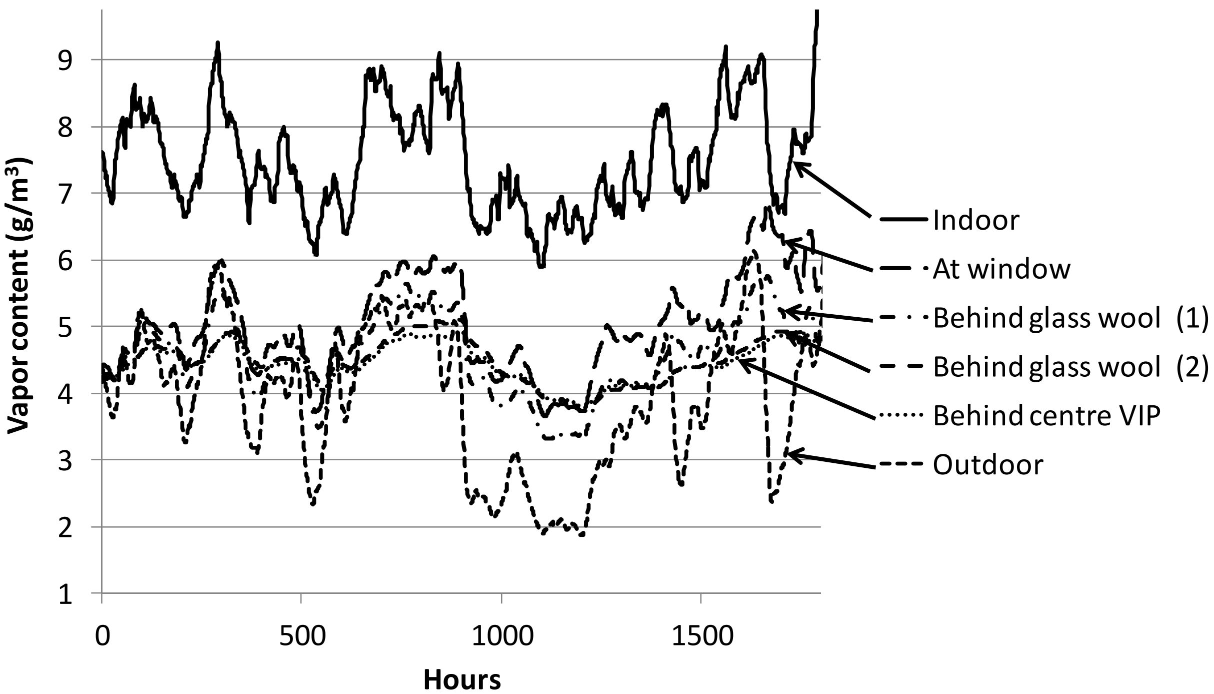

Figure 4.9. Measured daily averaged vapor content at different locations in the retrofitted brick wall during January 5 to March 22, 2011.

The vapor content at the different locations of the wall was higher than outdoors during the period. Indoors, at the window and behind one of the glass wool strips, the vapor content was following the changes in the outdoor vapor content faster than behind the second glass wool strip and center of the VIP. There could be a crack in the wall where an air flow is induced from the exterior which could explain the difference. The average vapor content was highest behind the window where it varied between 3.6 and 6.9 g/m^3. On average the vapor content was 5.0 g/m^3 which was 1.1 g/m^3 higher than outdoors. The location behind the glass wool strips and the center of the VIP had an average vapor content that was between 0.5 and 0.6 g/m^3 higher than the average outdoor vapor content. The indoor moisture supply was on average 3.6 g/m^3. Figure 4.10 shows the relative humidity at the different locations of the retrofitted wall in the part with brick.

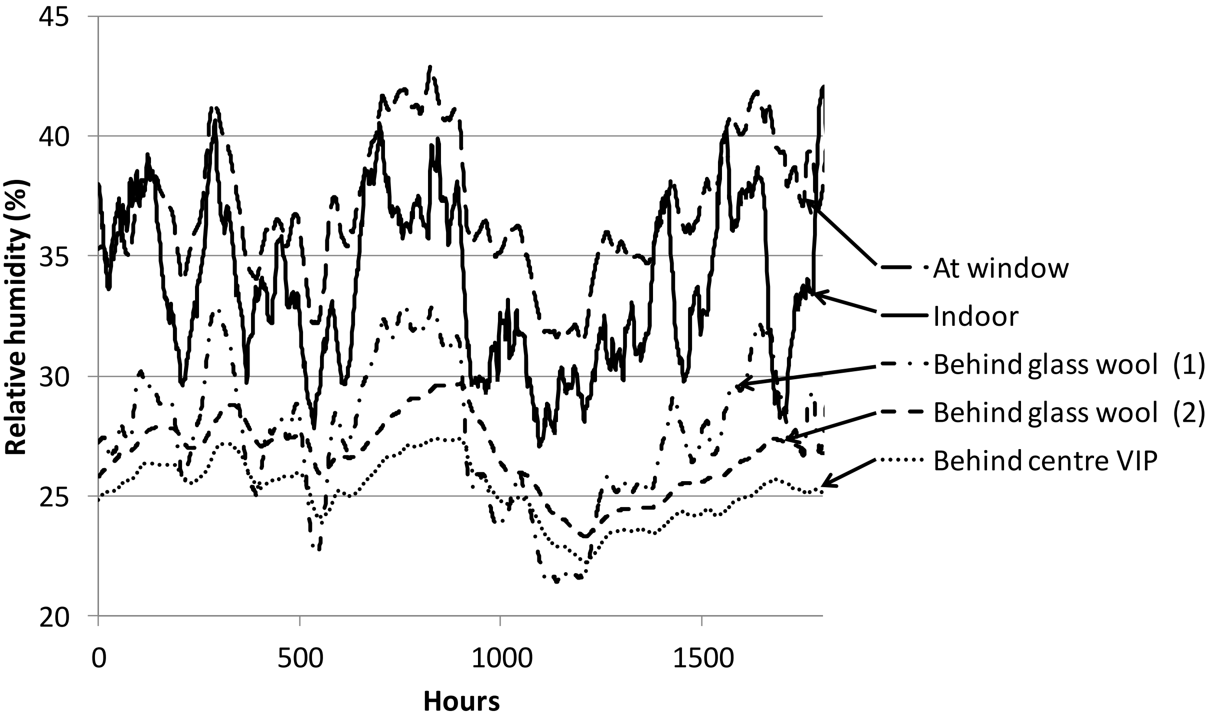

Figure 4.10. Measured daily averaged relative humidity at different locations in the retrofitted brick wall during January 5 to March 22, 2011.

The outdoor relative humidity was between 37 and 95% with an average of 78% during the period. The relative humidity was lower than the critical relative humidity at all measured locations of the wall. The highest relative humidity was at the window, varying between 32 and 43% with an average of 37%. As was seen with the vapor content, there was a difference between the measurements behind the two glass wool strips. The first location varied between 21 and 33% while the other case varied between 23 and 27%. On the other hand, the average relative humidity only differed by 1 percentage point between the two glass wool strips during the measurement period. The lowest relative humidity was behind the center of the VIP where the temperature was the highest.

Measurements of the air tightness and thermal bridges were performed by SP Technical Research Institute of Sweden after the construction finished. Only small improvements in the air tightness could be found after retrofitting. On the other hand, the thermal performance of the wall was heavily improved with 1-1.5°C higher interior surface temperatures than before the retrofitting. To assess the risk of moisture damages in the wall hygrothermal simulations can be performed. In next chapter the hygrothermal performance of the original wall is compared with the performance of the retrofit solution during five years of simulations.

5 Moisture performance of the exterior wall

The measurements in the retrofitted wall showed that the moisture performance of the wall had been improved compared to the reference wall. Hygrothermal simulations have been used to evaluate the influence by different retrofit designs on the moisture performance of the wall which are presented in Paper I. The boundary conditions, especially the indoor climate, are found to be important for the moisture performance of the wall. Therefore simulations of the stochastic indoor moisture supply have been performed (Johansson *et al.*, 2010; Johansson *et al.*, 2011; Pallin *et al.*, 2011a; Pallin *et al.*, 2011b). The simulation results could be used as input data in future stochastic hygrothermal simulations.

5.1 Input data for the hygrothermal simulations

By adding insulation to an existing wall the temperature field in the wall changes which, with an unchanged moisture load, leads to a changed moisture performance. The risk of damages to the existing wall by the retrofit measure has to be assessed to make sure the hygrothermal conditions in the wall are on the safe side. The steady-state Glaser method can be used to identify possible problems with condensation and high moisture content in materials by one dimensional heat and vapor flows. More advanced methods involving dynamic boundary conditions, capillary suction and vapor diffusion can be used to incorporate the wetting and drying of surfaces to take the buffering capacities of the different materials into account.

The vapor diffusion resistance of a surface can be defined as the thickness of a stagnant air layer with the same vapor resistance. This vapor diffusion thickness is referred to as the s_d-value (m). For instance, the s_d-value for a vapor barrier is 1 000 m and for a plaster board it is around 0.1 m. A way of describing the vapor resistance of a material is by the water vapor diffusion resistance factor, μ (-), which is defined as the ratio between the water vapor diffusion coefficient, δ_v (m^2/s), in stagnant air and in a material. The value is constant for every material and increases with a decreasing vapor diffusion coefficient, i.e. vapor permeable materials (e.g. glass wool) have a lower water vapor diffusion resistance factor compared to less permeable materials (e.g. spruce).

Surfaces are also exposed to short and long wave radiation where the short wave radiation is connected to the solar radiation and the long wave radiation (infrared spectrum) is dependent on the temperature of the surrounding surfaces. The short wave absorptivity, α (-), is defined by the fraction of solar radiation absorbed by the surface, i.e. the reflected and transmitted parts are subtracted from the total solar radiation hitting the surface. Long wave radiation exchange is dependent on the emissivity, ε (-), of the surface which is defined as the fraction of heat radiated from the surface compared to a black body. Materials with a high emissivity are e.g. brick and concrete while metals and galvanized materials have a low emissivity.

The heat transfer resistance, R (m^2K/W), of a surface is due to the combined effect of heat transfer by convection and radiation to and from the surface. Normally the standard values used for the surface heat transfer resistance is 0.13 and 0.04 m^2K/W respectively for interior and exterior surfaces. There is also a surface vapor resistance, Z (s/m), dependent on the air layer and convection at the surface. These standard values are 360 and 60 s/m respectively for interior and exterior surfaces.

Four different designs of the retrofit solution have been modeled in the commercial hygrothermal analysis software WUFI 2D (Fraunhofer IBP, 2010). The original wall is analyzed and compared to the changes by the additional layers of insulation placed on the exterior of the wall. The different designs that were modeled are described in Paper I and presented in Figure 5.1.

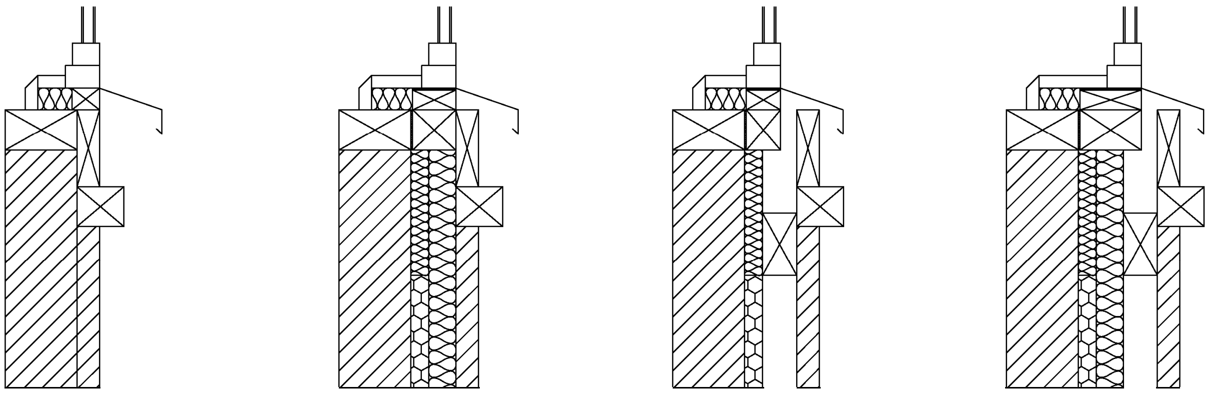

Figure 5.1. The hygrothermal analysis was performed on the four different retrofitting designs which were based on the original wall of 80 mm wooden planks, 1 mm tar paper and 22 mm wooden cover boarding. 20 mm thick VIP was added to the wall which was covered by a 0.2 mm polyethylene foil followed by 30 mm glass wool and 28 mm air space before the 22 mm wooden cover boarding were attached (From Paper I).

On the interior of the wall, a plaster board covered by wallpapers of unknown thickness is mounted. An interior s_d-value of 0.1 m was added to the standard surface vapor resistance and the interior surface heat transfer resistance was 0.13 m^2K/W. There is a layer of paint on the exterior façade which has unknown vapor properties; therefore the standard value for the surface vapor resistance was added with an s_d-value of 0.3 m. The heat transfer resistance of the exterior surface was considered to be dependent on the wind speed. The absorptivity of the exterior surface was 0.3 and emissivity was 0.94.

Because the façade is exposed to the surrounding climate and located in the dominant wind direction, in this case south west, driving rain hits the surface which is virtually unsheltered. The air space between the wooden cover boarding and glass wool boards effectively stop all penetrating water in the simulation model. Although the exposure of the façade means that also wind will have an influence on the hygrothermal performance, the air leakage through the façade is neglected in the simulations. The ventilated air space is treated as a non-ventilated air space, but with a somewhat higher thermal conductivity than stagnant air. This could be modeled as a real ventilated air space in later versions of WUFI 2D, but was not available in the version used in these simulations.

The outdoor climate used in the simulations was the Gothenburg climate supplied with WUFI 2D. The indoor climate was modeled using EN 15026 with a normal indoor moisture load as shown in Figure 5.2 (CEN, 2007).

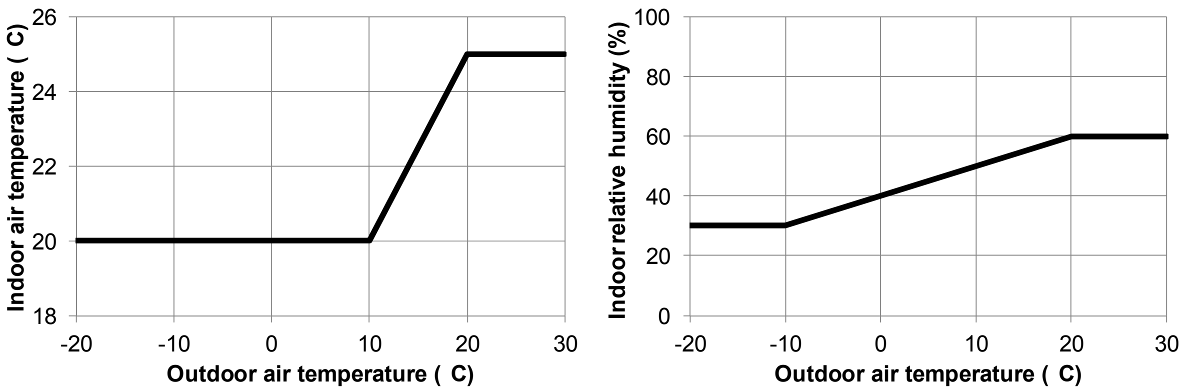

Figure 5.2. Indoor air temperature and relative humidity based on outdoor temperature according to EN 15026 (CEN, 2007).

The outdoor temperature ranged between -12.2 and 27.8°C with an average of 8.8°C. The outdoor relative humidity was on average 74.5% and ranged between 19 and 100%. The indoor temperature based on the outdoor temperature was on average 21.1°C and the indoor relative humidity was on average 48.8% which give an average moisture supply of 2.3 g/m^3. The simulated indoor climate could be compared to measurements in one of the apartments during June to August, 2010 which showed that the indoor temperature ranged between 23.7 and 28.1°C with an average of 26°C. The measured indoor relative humidity ranged between 41.9 and 62.7% with an average of 52.8%. The measurements presented in Section 4.2 of the indoor climate showed that the moisture supply was 3.6 g/m^3 in one of the apartments. Therefore an alternative indoor climate was modeled with a higher indoor moisture supply. This case had an average indoor temperature of 22.2°C and an average relative humidity of 53.3% leading to a moisture supply of 3.9 g/m^3 on average.

Almost all the material data used in the simulations are derived directly from the WUFI 2D database. However, the hygrothermal properties of the VIP were gathered from other sources and added to the simulation as two different materials where the core is modeled as an 18 mm thick sheet of fumed silica and the film as a 1 mm thick layer. The thermal conductivity of the film layer was based on the weighted arithmetic mean value of the different layers in the film perpendicular to the direction of the layers and as pure aluminum in the direction parallel with the film. The properties of the different materials are presented in Table 5.1.

Table 5.1. Material data used in the simulations based on data from WUFI 2D material database (Fraunhofer IBP, 2010) and the values for VIP used by Tenpierik and Cauberg (2007).

Material	*d (mm)*	λ (W/(m·K))	ρ (kg/m^3)	c_p (J/(kg·K))	μ (-)
Gypsum board	20	0.2	625	850	8.33
Spruce, tangential	80	0.12	430	1600	83.3
Spruce, radial	80	0.09	455	1500	130
Tar paper	1	10	909	1500	$2.1 \cdot 10^3$
PE membrane	0.2	1.65	130	2200	$8.7 \cdot 10^4$
Mineral wool	-	0.04	60	850	1.3
Mineral wool board	20/30	0.043	115	850	3.4
Air layer	30	0.18	1.3	1000	0.46
Evacuated VIP core	18	0.005	200	850	1.3
Punctured VIP core	18	20	200	850	1.3
VIP film, tangential	1	0.54	189	134	Inf.
VIP film, radial	1	200	189	134	Inf.

During the work with this thesis it has become clear that the model could be refined. For instance, the VIP film is only 0.1 mm but modeled 10 times thicker since the software did not allow thinner layers. Furthermore, the thermal conductivity of the VIP film was modeled by using values which Tenpierik and Cauberg (2007) used in their model of thermal bridges around the VIP perimeter. However, Ghazi Wakili *et al.* (2011) have shown that the apparent thermal conductivity of the film in fact is much higher, up to 10 W/(m·K), which coincides with own modeling and measurement efforts described in Chapter 3.

5.2 Results of the hygrothermal simulations

With the boundary conditions and material data described above, a parametric study was performed in WUFI 2D of the different retrofitting designs in Figure 5.1. Five years were simulated, each year starting in October. The in situ measurements of the materials in the old wall showed that the moisture quotient in the materials was around 8-9% which is approximately equal to a relative humidity of 70%. Therefore the initial relative humidity in the materials was chosen to 70% and the initial temperature 15°C. The results of simulations of the four designs with the low indoor moisture supply are presented in Figure 5.3.

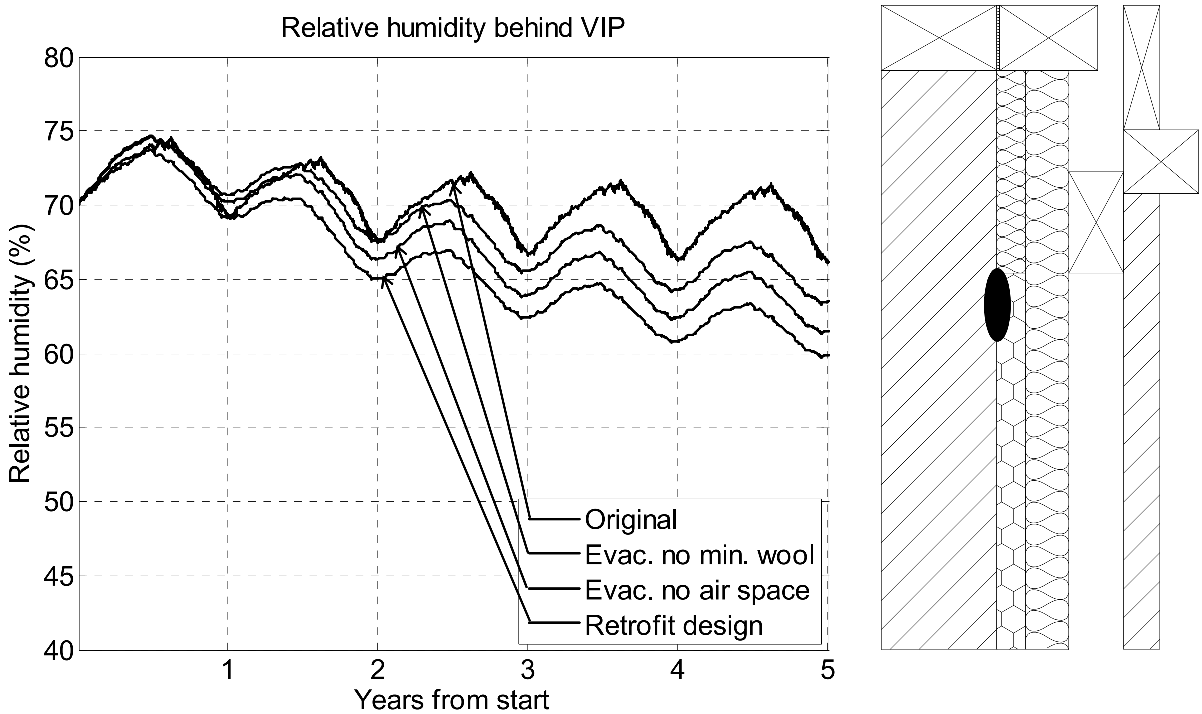

Figure 5.3. Simulated relative humidity in the wood behind the wooden cover boards in the original wall compared to the state behind the VIP (marked by the dot) in the wall with evacuated VIP and a 30 mm air space, evacuated VIP and 30 mm mineral wool and with evacuated VIP with both mineral wool and an air space.

The original wall had the highest relative humidity compared to all the retrofit designs. The wall is accumulating moisture during winter and spring which is dried out during summer and autumn with a minimum relative humidity in October each year. The case with only 28 mm air space had a slightly higher relative humidity compared to the case with mineral wool without air space. As could be expected the solution with the lowest relative humidity was the case with both an air space and mineral wool insulation. It should be noted that the air space is modeled without considering natural and forced convection which could increase the heat flow through the wall. A comparison between the five year simulations using the higher and lower indoor moisture supply for the final retrofit design are shown in Figure 5.4.

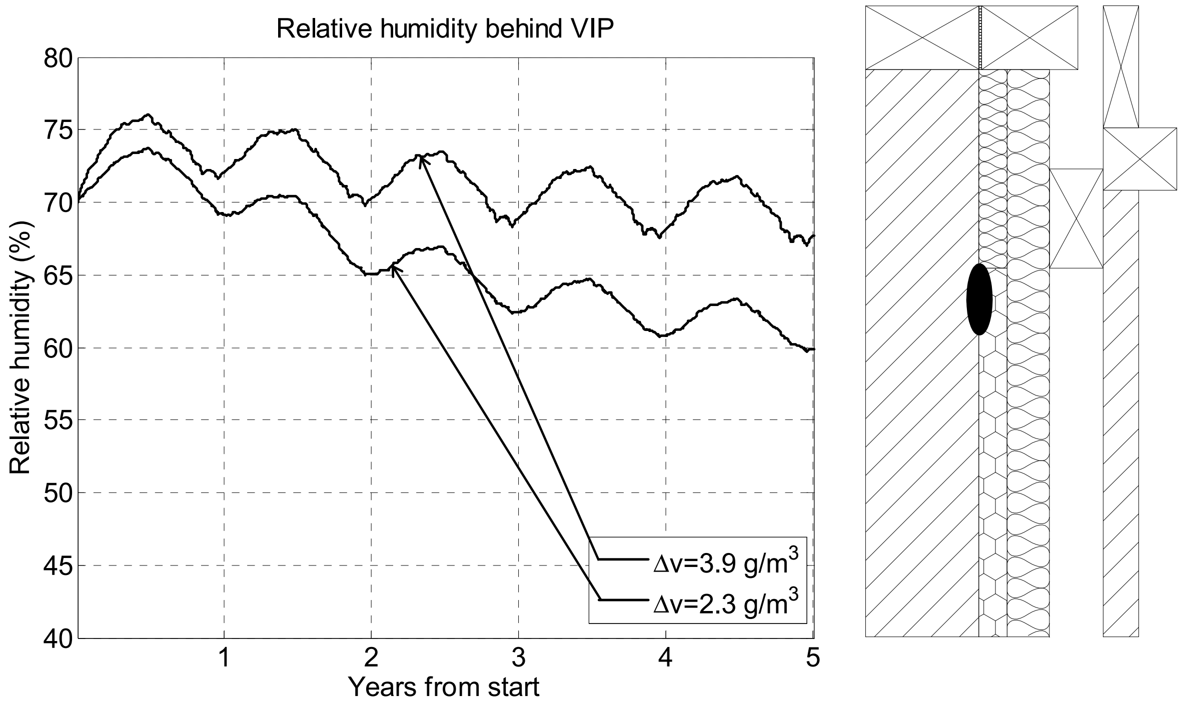

Figure 5.4. Simulated relative humidity in the wood behind the VIP (marked by the dot) for the final retrofit design using an indoor moisture supply of 2.3 g/m³ compared to 3.9 g/m³.

The case with a higher indoor moisture supply raised the relative humidity in the wall. However, the risk of moisture damage in the wall is still low using the higher indoor moisture supply. The relative humidity is well below the critical level of mold growth in wood which is around 75-80% relative humidity with a temperature above 0°C during certain time duration.

As described earlier in the thesis, VIP is vulnerable to damages which could increase the heat flow through the panel fivefold. Figure 5.5 shows the relative humidity with punctured VIP compared to evacuated VIP for the two different indoor moisture supplies.

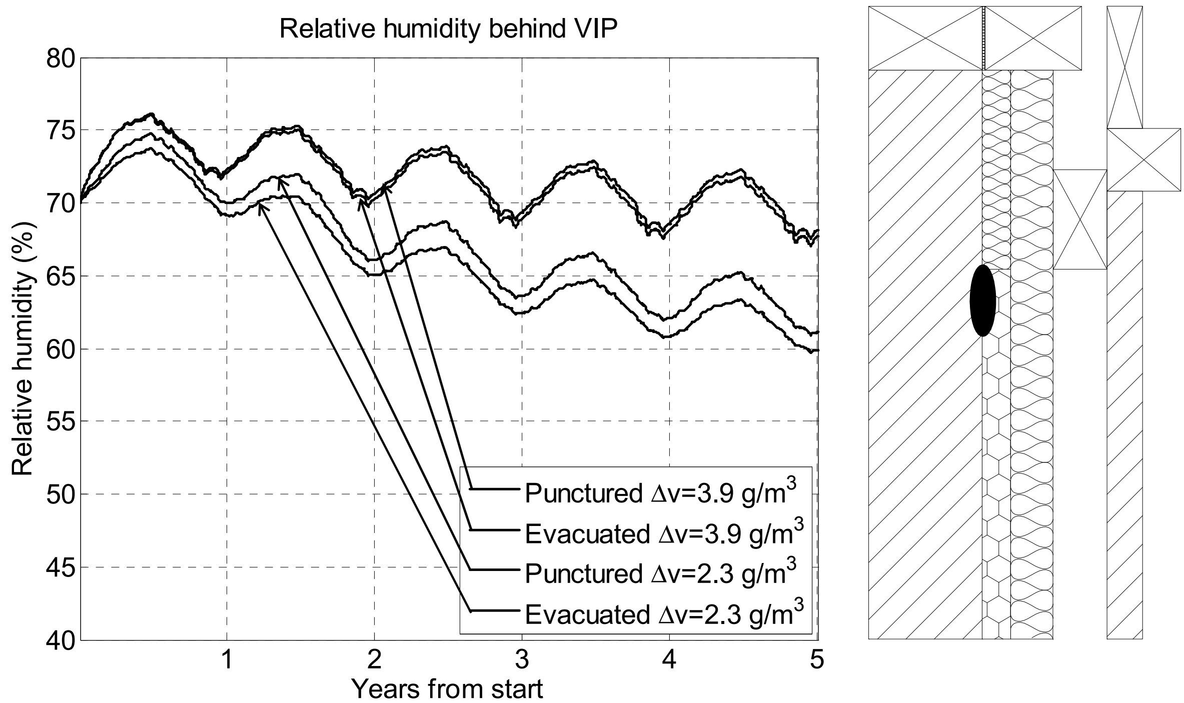

Figure 5.5. Simulated relative humidity in the wood behind the VIP (marked by the dot) for the final design with punctured and evacuated VIP using an indoor moisture supply of 2.3 g/m³ and 3.9 g/m³.

The effect by a punctured VIP is that the relative humidity in the wall is slightly higher than in the case with evacuated VIP. The difference is only marginal for the case with higher indoor moisture supply while the difference after 5 years of simulation is 1.25 percentage points with the lower indoor moisture supply.

5.3 Influence of indoor moisture supply

As was seen in the measurements presented in Section 4.2 the indoor moisture supply varied with a factor of two between the two apartments. Also the simulations in Section 5.2 showed the importance of considering the correct indoor moisture supply. The relative humidity in the wall was around 8 percent points higher in the case with a higher indoor moisture supply compared to the lower. In the IEA/ECBCS Annex 55 Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance and Cost (RAP-RETRO), the influence by stochastic parameters on the hygrothermal performance of buildings are investigated. Within this framework a method to simulate the indoor moisture production based on stochastic input data was developed (Johansson *et al.*, 2010; Johansson *et al.*, 2011; Pallin *et al.*, 2011b). The results of the simulations were used in a case study where the moisture supply, i.e. the difference between the indoor and outdoor vapor content, of a typical apartment in a Swedish multi-family building was simulated. The results were compared with measured data of the moisture supply in the Swedish building stock. In (Pallin *et al.*, 2011a) the analysis is taken one step further by adding the effects of stochastic ventilation and moisture buffering of interior surfaces.

Moisture buffering of a material is dependent on several material parameters of which the vapor diffusion coefficient, δ_v (m^2/s), the moisture capacity, ξ (kg/m^3), and the surface properties are the most important. In the study by Pallin *et al.* (2011a), only the first two properties are used in the model, i.e. the surfaces are considered to be completely vapor permeable and the thickness of the materials larger or equal to the daily moisture penetration depth. This is typically a few mm for the materials in this study which make this approximation valid here.

The effective moisture buffering area, A_{buff} (m^2), is determined by the relation between the surface of the buffering materials and the floor area, A_{floor} (m^2). This relation is assumed to be 2.6 m^2/m^2 which is multiplied with the stochastic floor area based on statistical data. The percentage of surfaces with wood, plaster board and textiles are then multiplied with the effective moisture buffering area. The influence by moisture buffering on the moisture supply, Δv (kg/m^3), is treated with the superposition principle where the moisture production rate, G (kg/s), is changed every hour.

The ventilation rate, R_a (m^3/s) is based on measured data which has been fitted to a normal distribution of the yearly average ventilation rate. The outdoor vapor content, v_e (kg/m^3), also influences the vapor content in the dwelling since the indoor vapor content is dependent on which vapor content the ventilation air has. With the indoor moisture supply, indoor temperature and outdoor climate, the indoor relative humidity can be simulated. The simulated relative humidity in 1 000 random apartments in Gothenburg, Sweden is presented in Figure 5.6.

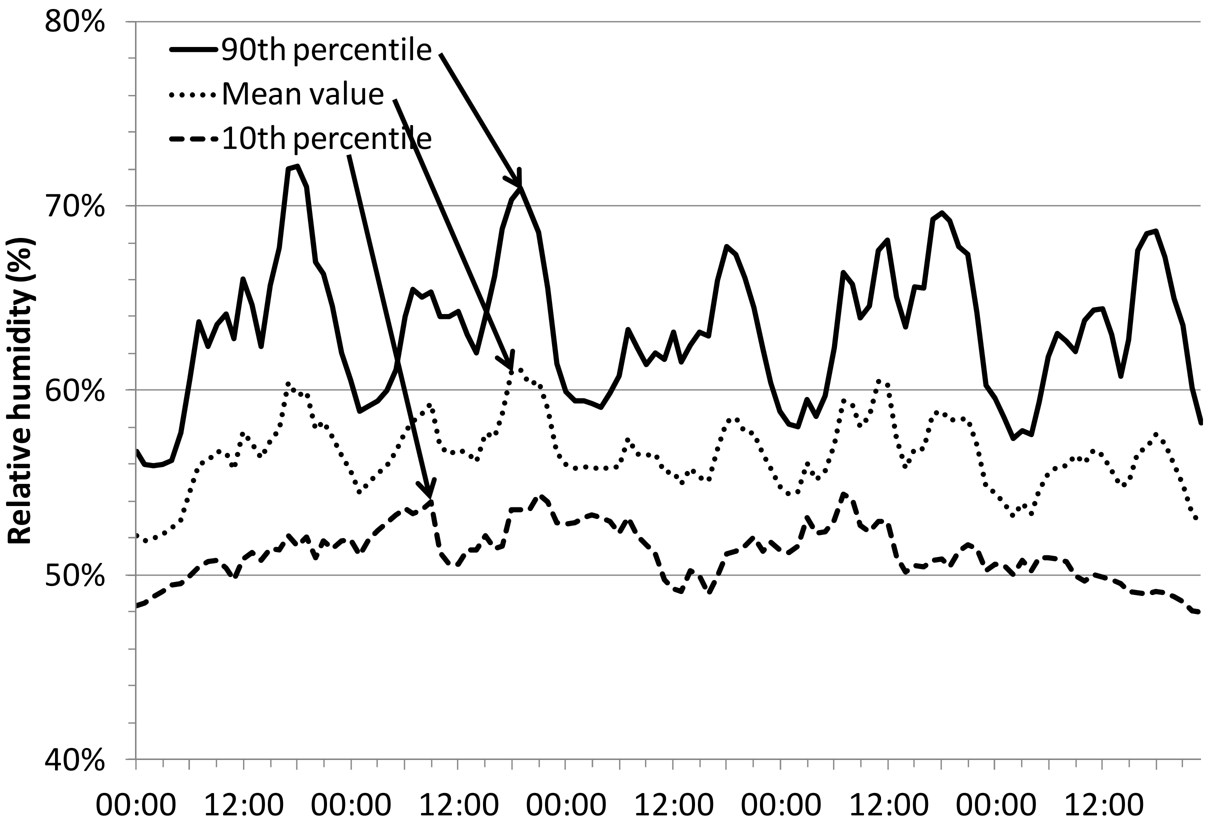

Figure 5.6. The simulated relative humidity in 1 000 apartments in Gothenburg, Sweden during five days in February. The 10th percentile and 90th percentile show the distribution around the mean relative humidity.

The average simulated relative humidity varies between 50-60%, while the maximum of the 90th percentile is 72% and the minimum of the 10th percentile is 48%. The indoor relative humidity by using the method in EN 15026 (CEN, 2007) with a normal moisture load was on average 48.8% which is lower than the simulated indoor relative humidity. These results can be compared with the measurements which were briefly discussed in Section 5.1 which showed that the relative humidity varied between 42.9 and 62.7% in one apartment and between 36.5 and 68.6% in another apartment in the same building. Thus, in future simulations the stochastic indoor moisture supply should be used to get the range of indoor climates which the construction should be able to be exposed to without suffering from moisture damages.

6 Conclusions

In case a VIP is punctured the thermal conductivity increases fivefold which make it important to determine the thermal conductivity of the component before integrated in the construction. There is a lack of measurement methods that could be used to measure the thermal conductivity of VIP in situ. To evaluate the feasibility of the TPS method a numerical model was developed. Two analytical solutions were used to validate the numerical model. The analytical temperature increase agreed well with the numerically modeled temperature increase. Four different setups were measured with the TPS sensor and compared to the numerical simulations. The numerically simulated temperature increase deviated quite much from the TPS measurements in all setups. The effective thermal conductivity of the VIP film was found to be significantly higher than the arithmetic mean value of the layers in the VIP film. Uncertainties such as material parameters, surface heat resistances, the influence of the sensor and the losses in the wire between the TPS sensor and TPS unit contributed to the deviation between measurements and simulations. With some modifications the TPS method could be used to measure the thermal conductivity of VIP in situ.

The wall of a listed multi-family building from the 1930s in Gothenburg, Sweden was retrofitted with 20 mm VIP on the exterior. The calculated U-value of the wall was reduced from 1.11 to 0.23 W/(m^{2}K) without considering the thermal bridges between panels and the areas where mineral wool had to be used. The average U-value with these factors taken into consideration was 0.40 W/(m^{2}K). It is estimated that the U-value increases to 0.54 W/(m^{2}K) in case the VIP are punctured.

To evaluate the changed hygrothermal performance of the wall after retrofitting, temperature and relative humidity sensors were installed in the wall at 15 different locations. The moisture content was lower in the retrofitted wall compared to the reference wall which is beneficial from a building physics point of view. Different locations around the VIP were monitored by the sensors. After the first cold season it was concluded that the different locations had different hygrothermal conditions. As expected, the temperature was lowest at the window attachment and at the thermal bridges, compared to behind the centre of the VIP.

The retrofitted wall was studied in a hygrothermal simulation tool to simulate the transient hygrothermal conditions in the existing load-bearing wooden construction after retrofitting. The moisture content in the wall was lower with time after the retrofitting. This is an improvement in the hygrothermal performance since the risk of damage is decreased. In case a moisture leakage occurs in the wall drying is only allowed inwards since the VIP is vapor tight. The result of the simulations showed that the retrofitted wall will be able to dry out. However, if a moisture leakage on the interior of the polyethylene foil would occur in the wall, the time it takes for the wall to dry out increase when insulated with VIP. Nevertheless, the simulations showed that there are no major consequences to the moisture performance of the wall in case a VIP is damaged. It was also found that the indoor moisture supply is an important factor for the moisture performance of the wall. By using stochastically produced input data, the risk for damages by high internal moisture loads can be determined and accounted for in the design process.

Despite the obstacles which have to be overcome to use VIP in building applications, it is an interesting component that may play an important role on the path to reduce the energy use for heating of buildings. In the literature it is recommended to integrate the VIP in a way that they are easy to exchange after their service life has expired. By doing so and by educating the builder and designer in the special considerations when working with VIP the energy use for heating in the existing building stock could be reduced.

7 Future research

Numerical simulations of the retrofitting solution showed that the conditions on the interior of the dwelling are important for the hygrothermal condition of the wall assembly. VIP has a high vapor resistance and therefore only drying towards the interior side of the wall is possible. The vapor content in the indoor air varies much between different dwellings which was found in a recent measurement study (Boverket, 2009). There is no way to predict which family will move into the dwelling and therefore simulations using stochastic data with different behavior profiles could be used in future simulations to find the probable distribution of the indoor vapor content. Depending on which risk level that the owner of the house is willing to take in concern of damages to the construction, simulations based on stochastic data can give an approximation on how the retrofitting solution should be designed to work in the most efficient way.

Future studies involve continued monitoring of the retrofitted wall, together with deepened analysis of the hygrothermal performance of the wall, such as calculations using the mold growth index. Also numerical simulations are needed in order to evaluate the causes of the differing results at the measured locations. The increased temperature in the existing wall might lead to less moist conditions that are drier than what the old structural wood can manage. Moisture induced movements and cracking in the wall due to drying might have an effect on the service life of the VIP. An analysis of the measurement uncertainties will be performed in the analysis of the hygrothermal data.

Future cases that could be investigated is interior insulation with VIP which could be interesting in case the façade of a building is even more protected than was the case here. There are a large number of brick masonry buildings without any thermal insulation which could be retrofitted on the interior.

For the further evaluation of the TPS method an analytical solution will be developed of the case with a low conductive material covered by a layer of a high conductive film. This solution will make it possible to derive material parameters from a measured temperature increase. Before this step can be taken all the causes of the deviations between numerical simulations and measurements need to be investigated. Variations and the effects of material data, boundary conditions and surface heat transfer conditions on the temperature increase have to be investigated.

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