Field Testing of Interior Super Insulation Materials on a Brick Wall in an Industrial Building

(article starts on next page)

Field Testing of Interior Super Insulation Materials on a Brick Wall in an Industrial Building

Pär Johansson, PhD **Paula Wahlgren, PhD** **Petra Eriksson**

ABSTRACT

Conventional thermal insulation materials, such as fiber glass and EPS, demand a thick layer of insulation to reach the energy targets. Super insulation materials (SIM) are thermal insulation components with a 3-10 times higher thermal resistance than conventional insulation materials, such as vacuum insulation panels (VIP) and aerogel blankets (AB). They are efficient in increasing the thermal performance of walls when retrofitting, without significantly tampering with the wall thickness. Usually other measures such as changing windows or heating system are preferred before adding insulation to the walls, but to improve the thermal comfort and energy performance further, interior insulation is a possible alternative. In this study, an industrial building from 1896 with a 470 mm (1.5 ft) homogenous brick masonry wall is investigated regarding the hygrothermal performance and thermal inertia of the wall with interior insulation. Earlier research has shown that interior insulation decreases the drying-out capacity of the exterior wall and increases the risk for freeze-thaw damages in brick walls. In this study measurements from field investigations and simulations of a homogenous brick wall with 20 mm (0.8 in) interior VIP and 20 mm (0.8 in) aerogel blankets are compared to a non-insulated reference wall. The measurements showed that the wall was wet throughout the measurement period while the measured U-value was reduced with 82-83% for the AB and 81-84% for the VIP layers.

INTRODUCTION

Buildings from before 1941 account for 25 percent of the energy use for heating in the Swedish building sector (Swedish Energy Agency 2014). The challenge is to reduce their energy use while preserving their cultural values. To improve the thermal comfort and energy performance further, interior insulation is a possible alternative. However, earlier research has shown that interior insulation decreases the drying-out capacity in the outer wall and increases the risk for freeze-thaw damages in brick walls (Johansson et al. 2014). Interior insulation will also negatively affect the heat storage capacity, thermal inertia of the building and change the appearance of the wall, which is particularly important to consider for historical and/or listed buildings.

New materials and solutions are being developed that could contribute to improving the energy performance of historic buildings, without altering their character defining elements. Super insulation materials (SIM), such as vacuum insulation panels (VIP) and aerogel blankets (AB), are thermal insulation components with a 3-10 times higher thermal resistance than conventional insulation materials, and thus thinner layers can be used. As a part of this study, a workshop with representatives from different disciplines, such as architecture, cultural heritage, building physics, project management, indoor air quality, property developer, pointed out several areas where SIM applied to the interior of buildings would be the preferred choice of insulation. Interior decorations might also be preserved with

Pär Johansson is an associate professor at the Department of Architecture and Civil Engineering, Chalmers University of Technology, Gothenburg, Sweden.
Paula Wahlgren is an associate professor at the Department of Architecture and Civil Engineering, Chalmers University of Technology, Gothenburg, Sweden.
Petra Eriksson is a lecturer at the Department of Art History, Uppsala University, Visby, Sweden.

SIM, and if U-values are substantially improved, even the heating systems (radiators) that affect furnishing of a room can be re-designed, which could create increased value for the user of the building.

As mentioned above, two examples of SIM are VIP and AB, see Figure 1. VIP are rigid panels which cannot be cut on site and are sensitive to puncturing. Therefore, attention must be paid in the design of details and envelope components. AB are more like conventional fiber-based insulation materials. They can be cut at the construction site and adapted to the specific measurements. VIP were first tested in buildings in the early 1990s which was later followed by several case studies both in laboratory and in the field while AB have been installed in various building assemblies since the early 2000s (Adl-Zarrabi and Johansson 2018).

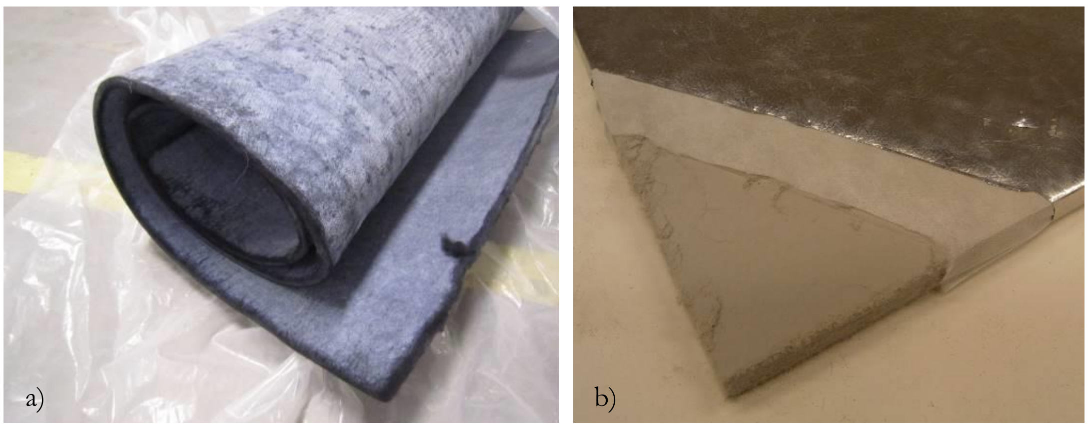

Figure 1: Super insulation materials; (a) aerogel blanket (AB), (b) vacuum insulation panel (VIP).

VIPs have different core materials (fumed silica, glass fibre, polyurethane, expanded polystyrene and others) and different envelopes (metalized film, aluminium laminate, stainless steel, glass, or combinations). The hygrothermal properties for AB and VIP differ subtantially. The VIP envelope allows vapour and liquid water transfer only at the edges between the VIPs (Johansson et al. 2014), while the vapor diffusion resistance of AB is around μ=5 (-) which is a factor five higher than mineral wool. The blankets are coated with a water-repellent substance which reduce the liquid water transfer. The thermal conductivity is 0.014-0.020 W/(m·K), 0.008-0.012 BTU/(h·ft·°F), for AB and 0.002-0.008 W/(m·K), 0.001-0.005 BTU/(h·ft·°F), for VIP (Heinemann 2018).

Previous laboratory studies showed that the properties of the interior insulation material have a lesser influence on the moisture accumulation rate than the exterior rain tightness (Johansson and Wahlgren 2018). The rain load was the dominating factor determining the vapor and water transport in the wall. By combining interior insulation with water repellent surface treatment, the amount of rain that enter the façade can be reduced. However, there are several drawbacks with these treatments, such as the limited service life and the adverse effects on the performance of the façade if it is not free from cracks and other defects.

This study presents results from a field investigation in an old industrial brick building, see Figure 2, located in a cold and moist climate in Sweden. A homogenous brick wall with 20 mm (0.8 in) interior VIP insulation and 20 mm (0.8 in) AB, respectively, is investigated and compared to a non-insulated reference wall. The building has been unoccupied for a number of years without a controlled climate inside. It is exposed to the rain and wind, facing the dominant south-west direction, and regular freeze-thaw intervals. The hygrothermal aspects of the additional interior insulation have been investigated by small scale measurements of thermal conductivity, heat capacity and moisture diffusivity, by large scale measurements of heat flow, temperature and moisture conditions in the building and by numerical simulations. There were challenges to implement the internal insulation in the building. With respect to moisture, the rain load and ground water rising in the brick masonry were problematic. This made the wall very wet from the start. Calculations of the thermal inertia of the building are used to investigate the impact on the indoor climate after the renovation. The overall aim of the study is to give recommendations on how SIM can be used in historic buildings which as certain heritage significance are appointed listed buildings.

CASE STUDY BUILDING AND CULTURAL HERITAGE INVENTORY

The former industrial site, the Papyrus paper mill, situated in the municipality Mölndal, south of Gothenburg on the west coast of Sweden, is the place for the case study. The building where the tests are carried out is a long narrow brick and concrete building used as a paper machine hall originally erected in 1896, see Figure 2. The building is one of the oldest in the area. Several changes have been made during the long service time of the building, but unfortunately there has been a lack of maintenance and heating in the building during the last years, resulting in a rapid deterioration of the façades. Between 2014 and 2015 an inventory describing the building, and pointing out the most characteristic elements of the building, was conducted by a heritage consultant firm. This inventory points at the following important character defining elements of the building; 1) the expression of the façades, and especially the red brick masonry, 2) the construction of the basement in stone, 3) the volume of the building, 4) the decoration of yellow bricks in the otherwise red brickwork, 5) the windows and the window frames.

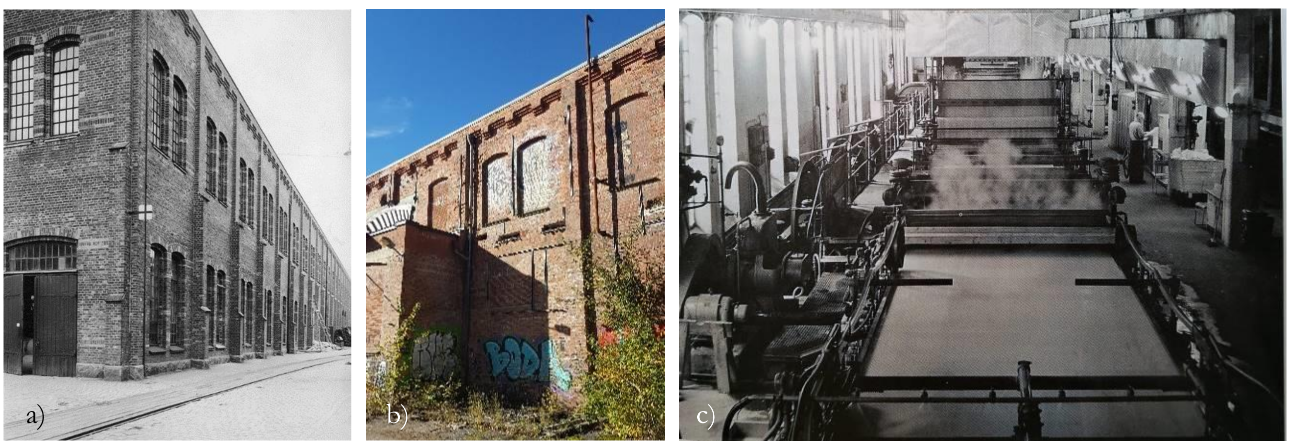

Figure 2: (a) The industrial building from 1896, photo from 1918, (b) The exterior of the tested external wall, (c) Interior of the building when it was in operation as a paper mill.

The conflict between energy efficiency and heritage values in buildings have been touched upon on in several research projects and are common in everyday practice when renovating buildings for improving energy performances. The conflict is usually about the impact on the exterior of a building which has led to research that investigates how interior insulation affects historical buildings (de Place Hansen and Wittchen 2018; Marincioni and Altamirano-Medina 2018). How energy improving measures affects heritage values is also the focus in the newly accepted European standard suggesting a procedural approach when planning for improving energy performance in historic buildings, SS-EN 16833:2017. The standard suggests an iterative process run by a multidisciplinary group of professionals. Each step needs to be assessed according to specific assessment categories. For example, technical compatibility and heritage significance are two main categories that are assessed through risk criteria. Risk criteria for heritage signigificance are assessed by the impact different interventions has on visual, material and spatial appearance affecting the character defining elements.

For this case study the conservation officer at the city museum has a role to follow up on development of built heritage and monitor that appointed values are being respected in transformation situations. Based on long experience, a working method has been developed that is based on dialogue with the parties in the early stages of development. This approach is verified by the developer who refers to the dialogue that has been held. The dialogue is informal and ongoing during the time of the project and documentation is not kept. This informal negotiation has resulted in decisions to save windows and facades while improving the energy performance through interior insulation could be a possible measure together with implementing solar panels on the roof.

MEASUREMENTS OF BRICK PROPERTIES

To have correct material properties for the building and thermal performance analyses, the original brick was investigated. Samples of the actual brick from the field study building was removed and brought to the laboratory for testing. The size of the bricks is 225 x 110 x 60 mm (8.9 x 4.3 x 2.4 in) (length x depth x height) which were constructed in two wythe-masonry with 10 mm (0.4 in) hydraulic lime mortar in between the bricks and facing the internal surface. This gives a total wall thickness of 470 mm (1.5 ft). Measurements of density, porosity, capillary suction, vapor permability and thermal conductivity were performed in the laboratory (Johansson et al. 2018). The results showed that the bricks have a density of 1,822 kg/m^3 (114 lb/ft^3) and a porosity of 29%.

The capillary suction was tested on three dry samles that were partially immersed in water while the mass was recorded, following SS-EN ISO 15148:2002. The short-term liquid water absorption coefficient A_w was calculated to 0.18 $kg/m^2s^{0.5}$ which can be compared new bricks which has 0.16 $kg/m^2s^{0.5}$ and 0.19 $kg/m^2s^{0.5}$ for new bricks with properties matching old production techniques (Johansson et al. 2014). The water vapor permeability was measured by the dry cup method. The samples were placed as a lid in a cup with water and an air layer of 100% RH which were placed in a room with constant climate conditions of 20°C (68°F) and 50% RH according to SS-EN 12086:2013. Three brick samples were measured using this method. The water vapor permeability was $2.6 \cdot 10^{-6}$ m^2/s which is equivalent to a water vapor diffusion resistance factor (μ-value) of 9.6. This can be compared to other bricks which have a μ-value of 9.5-17, depending on the production method, age, porosity and density (Johansson et al. 2014).

The thermal conducitivity was measured using the transient plane source (TPS) method on a Hot Disk device, SS-EN 22007-2:2008. The TPS sensor used in the setup had a radius of 6.4 mm (0.25 in) and was placed between two samples of the material. A constant electric power was conducted through the spiral with the electric resistance registered and transformed into a temperature increase. The thermal conductivity of the dry brick was 0.61 W/(m·K) (0.35 BTU/(h·ft·°F)) and the specific heat capacity was 725 J/(kg·K) (0.17 BTU/(lb·°F)).

FIELD MEASUREMENTS OF HEAT FLOW, TEMPERATURES AND MOISTURE CONDITIONS

To evaluate the large-scale hygrothermal performance of brick walls with additional interior superinsulation, a small room (2.1 x 2.6 x 4.0 m, 6.9 x 8.5 x 13.1 ft) was constructed inside a part of the building, which consist of floor, walls and roof insulated with 170 mm (6.7 in) mineral wool, and the exposed brick wall, see Figure 3. The room is heated to around 23°C and ventilated by natural ventilation with 0.5 h^{-1} air exchange rate. The air in the room is circulated by a fan to create homogenous temperature and moisture conditions in the entire room. The exterior wall is divided in three parts where AB and VIP are installed in 500 x 1,200 mm^2 (1.6 x 4 ft) panels, see Figure 3, and compared to a non-insulated reference.

The wall was equipped with hygrothermal sensors that every hour registers the temperature and relative humidity in the middle of the wall and at the interior surface. The sensors are wireless Sahlén sensors (wood moisture sensors) which measure the weight percentage moisture in a piece of birch around the sensor. The measurement range corresponds to 60% to 100% RH. The size of the sensors is 40 x 13 mm (1.6 x 0.5 in) (height x diameter), inserted in a 15 mm (0.6 in) wide hole in the wall. The temperature and relative humidity of the air is measured by three sensors. The measurement accuracy is ±2.5% for relative humidity in the range of 10 to 90% and ±0.5°C (±1°F) for temperature at 25°C (77°F). The temperature can be measured between -40 to 85°C (104 to 185°F).

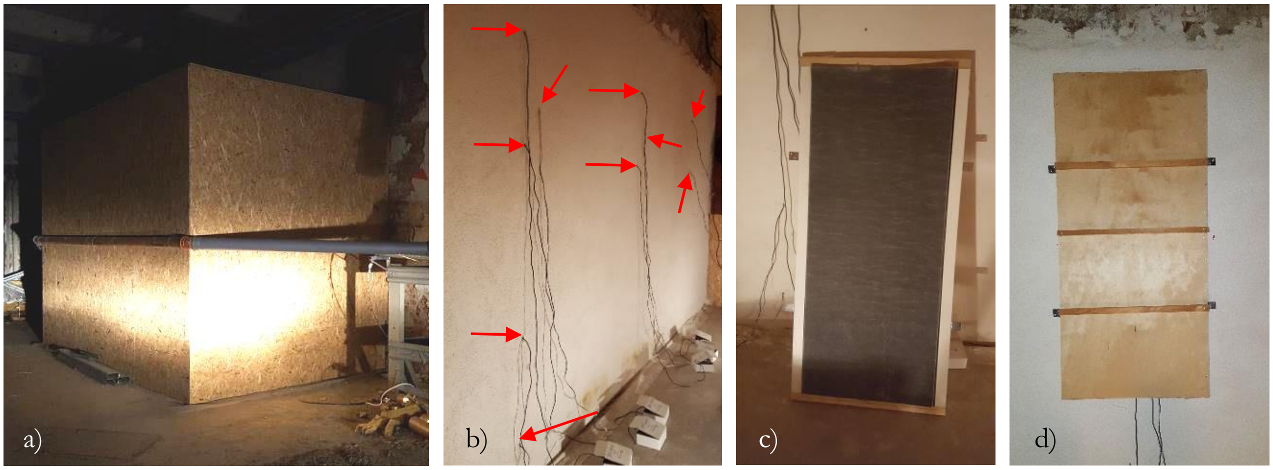

Figure 3: (a) Small test room inside the building, (b) Hygrothermal sensors (marked with arrows) in the brick in the plastered brick wall, (c) AB insulated panel (removable for inspection of the wall), (d) Installed AB and VIP panel.

The heat flux sensor Hukseflux HFP01 (thickness 5.4 mm (0.2 in), diameter 80 mm (3.1 in)) was used to evaluate the thermal resistance of the wall with and without insulation. The sensor is a thermopile sensor which measures the temperature difference across the ceramic plastic composite body. The heat flux in W/m² (BTU/(ft²·s)) is calculated by dividing the voltage output by the sensor's sensitivity. The sensors were calibrated by the producer and delivered with a calibrated sensitivity and calibration uncertainty of 3% for each sensor. Air gaps between the sensor and surface of the wall, and between the sensor and the surrounding environment could add additional resistances to the sensor thermal resistance. The sensor was placed in the mortar between the insulation and brick masonry in the wall panels with insulation, while the sensor was facing the indoor environment for the wall without insulation, see Figure 4.

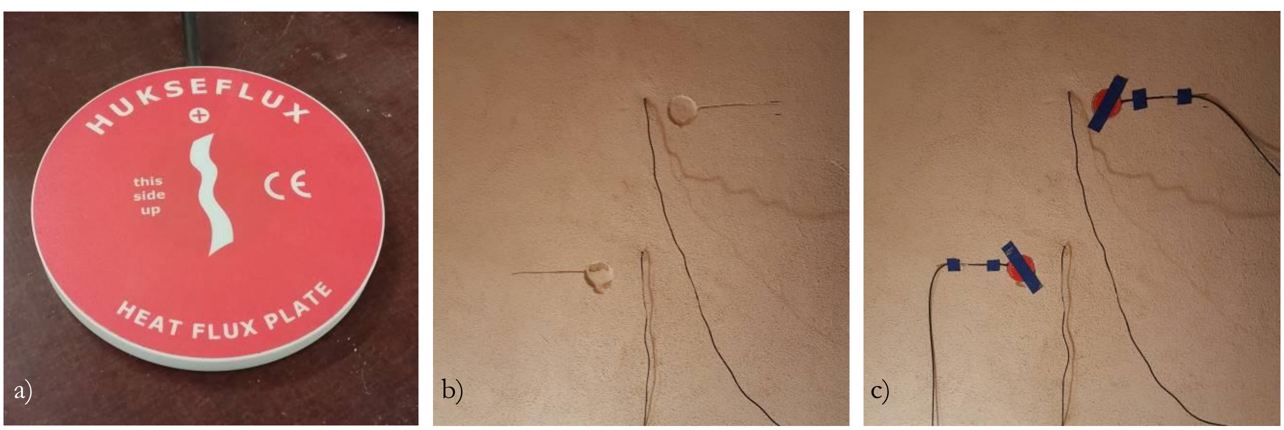

Figure 4: (a) Heat flux sensor used in the field tests, (b) before installation of two heat flux sensors inside the mortar layer in the reference wall and (c) after installation of two heat flux sensors in the reference wall.

Each wall set-up (reference, AB, VIP) has two sensors, top and bottom and the heat flux was measured at two occations (early March and mid April) at all six locations. The measured temperature difference between the indoor and outdoor air was averaged over the 3 preceeding days. The measurements were performed early in the morning before sunrise, after a cloudy night with stable outdoor temperature. The momentary U-value based on the measurements and calculations (following SS-EN ISO 6946:2017) are presented in Table 1.

Table 1. U-value (R-value) based on Heat Flux Calculations and Measurements

Location	Calculation				Measurement			
	Dry brick		Wet brick		March		April	
	[W/ (m^{2}K)]	[BTU/ (h·ft^2·°F)]	[W/ (m^{2}K)]	[BTU/ (h·ft^2·°F)]	[W/ (m^{2}K)]	[BTU/ (h·ft^2·°F)]	[W/ (m^{2}K)]	[BTU/ (h·ft^2·°F)]
Aerogel top	0.394	14.4	0.452	12.6	0.310	18.3	0.296	19.2
Aerogel bottom	0.394	14.4	0.452	12.6	0.292	19.5	0.264	21.5
VIP top	0.264	21.5	0.289	19.7	0.308	18.4	0.254	22.3
VIP bottom	0.264	21.5	0.289	19.7	0.323	17.6	0.277	20.5
Reference top	0.997	5.7	1.476	3.8	1.331	4.3	1.549	3.7
Reference bottom	0.997	5.7	1.476	3.8	1.957	2.9	1.817	3.1

The heat flux is substantially reduced in the wall with interior insulation. There is a difference between the top and bottom locations, where the top location has a lower heat flux for the reference wall and the wall panel with VIP compared to the bottom location. For the wall panel with AB it is higher at the top location compared to the bottom location. The higher heat flux closer to the bottom of the wall could be caused by the higher moisture content in the wall closer to the foundation and ground water. To validate the cause of this deviation, measurements of the heat flux and surface temperature of the external wall are planned. The thermal conductivity of dry bricks was 0.61 W/(m·K) (0.35 BTU/(h·ft·°F)) and for the wet it was 1.0 W/(m·K) (0.58 BTU/(h·ft·°F)), the average of dry and wet brick.

The deviation between the different parts of the wall could be explained by the difference in solar radiation between them, where the reference wall is less exposed to solar radiation than the parts with interior insulation. This part of the wall therefore has a higher temperature difference and consequently a higher measured heat flux which results in a lower U-value. Other factors that could influence the meaurements is the evaporation of water from the wall. This could increase the heat flux by around 5% which decreases the measured U-value for the reference wall, but not the parts of the wall with interior insulation.

Moreover, the measured difference in heat flux between the AB and VIP insulation layer is smaller than expected from the calculations. Assuming wet bricks, the average calculated U-value was reduced by 69% for the AB and 80% for the VIP layer, while the measurements gave a reduction of 82-83% for the AB and 81-84% for the VIP layer, i.e. the same order of magnitude. The reason for this could be that the VIP (only one in the façade) had been damaged and therefore had a thermal conductivity of 0.02 W/(m·K) (0.012 BTU/(h·ft·°F)), close to the thermal conductivity of the AB, 0.016 (W/m·K) (0.009 BTU/(h·ft·°F)). However, this does not explain why the calculated U-value for the AB is up to 70 percent higher than the measured U-value. Cuce and Cuce (2016) experienced similar deviations. They developed a numerical statistical method to account for all effects by other factors. In this case the wall panel with AB is most exposed to solar radiation which may have influenced the measurements more than the other parts of the wall with a lower heat flux than expected. The heat storage in the wall can also have an impact on the measured U-values, which is described in the following.

NUMERICAL INVESTIGATION OF THE THERMAL INERTIA OF THE BUILDING

The thermal inertia of the building and the respons to temperature variations is important for two reasons in this project; the general thermal performance of the buildings is affected, and the heat flux measurement results need to be discussed with thermal inertia in mind. Since field measurements are performed, there are no steady-state conditions. The outdoor temperature varies over the day but since the heat capacity of the wall is large, this will have very little effect on the heat flux measurements on the inside. Consequently, the average temperatures should be used. The thermal distance between the outside and the location of the heat flux meter can be described using a periodic penetration depth, d_p (m).

$$d_p=(a\cdot t_p/\pi)^{0.5} \tag{1}$$

Here, a (m/s) is the thermal diffusivity (for the current brick a=4.618·10^-7 m/s) and t_p is the time period (24·3600 s). If the thickness of the wall is much larger than the penetration depth, the effect of the temperature variations on one side does not affect the temperatures or heat flux on the other side. For the current brick wall, d_p=110 mm (4.3 in) and the wall thickness is 470 mm (1.5 ft), which means that the impact of temperature variations on the exterior of the building on the heat flux meter on the inside, can be neglected. The indoor air temperature is constantly measured and very stable. An estimation of the time required for a step change at the outside to reach the inside of the wall is made according to Hagentoft (2001) using following approximation for heat flow, q (W/m²), for times up to 1.5 days.

$$q(L,t) = \lambda \cdot \frac{(T_1 - T_0)}{\sqrt{\pi \cdot a \cdot t}} \cdot 2 \cdot e^{\frac{-L^2}{(4 \cdot a \cdot t)}} \tag{2}$$

Using a temperature step of 10°C at the exterior surface (due to for example increased outdoor air temperature and solar exposure in the morning), the resulting increase in heat flow after 5 hours is 0.1 W/m² on the inside for the current brick wall (dry brick). After 48 hours, the heat flow is 5% from steady state, while the corresponding percentage for 36 hours is 15%. (Times are shorter for wet brick.) Therefore, an outdoor air temperature measured for 3 days is enough for the estimation of the U-value from the heat flux measurements.

Secondly, the thermal inertia of the inside of the building is important for the thermal comfort in the building. The old brick buildings that are being renovated and insulated now benefited from having a large thermal storage. The studied building was an industrial building with periods of high internal heat loads during the day. The thermal inertia of the building helped preventing overheating in summertime but was also preventing extreme low temperatures in wintertime. However, the resulting thermal climate indoor was far from what we accept today. Today, the thermal inertia of the building can still be benificial to the indoor climate and dampen temperature variations. Some of the older industrial buildings have large windows and skylights since they depended on daylight. The windows preferably faced north (in Sweden) to prevent overheating. If there are large internal loads in renovated old brick buildings from, for example, solar radiation or people and activities (industrial buildings are often remodelled into public buildings or offices) the thermal inertia of the walls can still be benificial, which need to be considered when insulating on the inside. Insulation will substantially decrease the heat storage capacity. In Figure 5, a temperature variation of ±1°C (±2°F) is modelled, and the amount of heat that is stored and released into 1 m² (11 ft²) of surface is estimated. As an example, the heat capacity of the unisulated wall (Figure 5a) is compared to the heat capacity of a wall with 20 mm (0.8 in) AB (Figure 5b) as interior insulation (rendering on the AB is neglected).

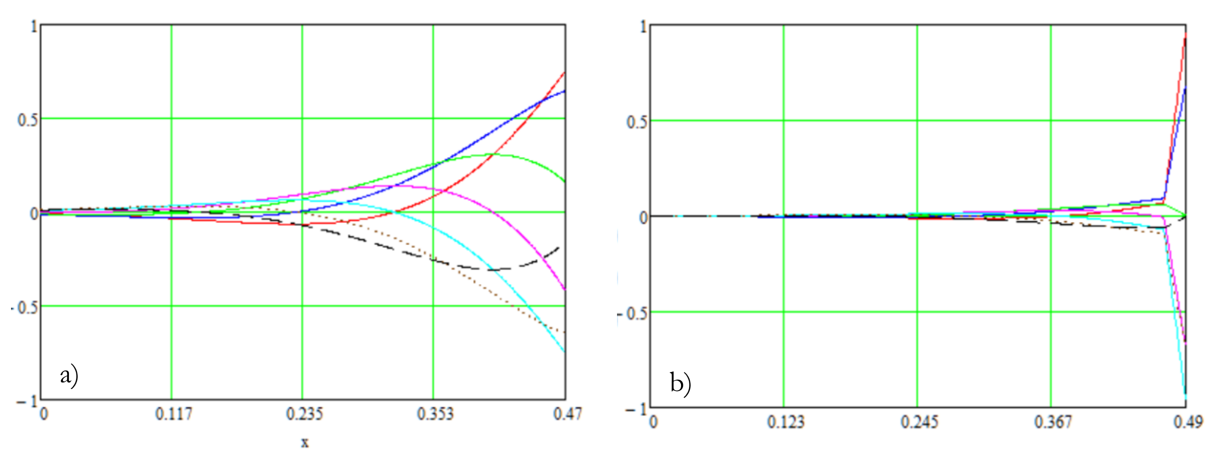

Figure 5: (a) Temperature variations in the brick wall without interior insulation and (b) with interior insulation (20 mm (0.8 in) AB). In both cases, the standard thermal surface resistance is 0.04 m²K/W (R 0.2) on the outside (left

side of the wall) and 0.13 m^2K/W (R 0.7) on the inside, and temperature variation in the inside air is ±1°C (±2°F). The temperature profile is shown for every three hours during a day.

As seen in Figure 5, the aerogel effectively reduces the temperature variations in the brick wall, and thus the thermal storage. The heat flow into (and out from) the wall in the uninsulated wall is 5.9 W/m^2 (5.2 $BTU/(ft^2\cdot s)$) and in the insulated wall 0.72 W/m^2 (0.6 $BTU/(ft^2\cdot s)$) for a temperature variation of ±1°C (±2°F). If the wall surface roughly constitutes 25% of the total heat storage area (excluding inner walls), the thermal storage capacity (heat flows) for a building with insulated walls will be 20% lower than the thermal storage capacity of the unisulated building. For simplicity, the floor and roof are assumed to have the same thermal properties as the uninsulated wall and the windows (10% of wall area) have no thermal storage.

CONCLUSION

Many heritage buildings make a significant contribution by the character defining elements of the building. In the case of the industrial buildings at the paper mill area, only few character defining elements has been identified that are connected to the interior design of the buildings. Instead focus is to preserve the expression of the façades, and especially the red brick masonry. Therefore, interior insulation was proposed as a measure for combining energy efficiency and heritage preservation. The process of balancing between energy saving objectives and heritage preservation objectives is in this case a mix between formal and informal working methods to reach decisions regarding possible energy improving measures. The decisions are not necessarily less relevant than in a transparent process. However, the process is vulnerable from a knowledge building perspective if the human resources in the project would be changed. Most likely, the decision-making process in this kind of projects would benefit from following a clear procedure where the decision process as well as the working process is documented.

An industrial building from 1896 with a 470 mm (1.5 ft) homogenous brick masonry wall was investigated regarding the hygrothermal performance and thermal inertia of the wall with interior insulation. Earlier research has shown that interior insulation decreases the drying-out capacity of the exterior wall and increases the risk for freeze-thaw damages in brick walls. In this study the hygrothermal performance was measured inside the wall with very high moisture contents throughout the measurement period. The building was exposed to both heavy rain and rising ground water. No significant drying took place and water was added to the wall from the outside and through the foundation. Therefore, the owner has now planned to cover the building in an external rain protective envelope Measurements and numerical simulations show that additional superinsulation substantially decreases the U-value of the wall. Assuming wet bricks, the average calculated U-value was reduced by 69% for the AB and 80% for the VIP layers, while the measurements gave a reduction of 82-83% for the AB and 81-84% for the VIP layers, i.e. the same order of magnitude. With planned measures to make the wall dryer, the interior insulation will be monitored continuously and conclusions on the performance will contribute to develop recommendations on how SIM can be used in historic buildings

ACKNOWLEDGMENTS

This study is supported by the Swedish Energy Agency through the project 42856-1. We would also like to thank MölnDala Fastighets AB and Pontus Johansson, Gabriella Josefsson and Maria Daoud Rajha for performing the laboratory investigations.

REFERENCES

Adl-Zarrabi, B., and Johansson, P. 2018. *Annex 65 Long-Term Performance of Super-Insulating Materials in Building Components and Systems. Report of Subtask 3: Practical Applications – Retrofitting at the Building Scale – Field scale (Report to be published).*

Cuce, E., and Cuce, P.M. 2016. The impact of internal aerogel retrofitting on the thermal bridges of residential buildings: An experimental and statistical research. *Energy and Buildings*, 116:449-454.

de Place Hansen, E.J., and Wittchen, K.B. 2018. Energy savings due to internal façade insulation in historic buildings. *Proceedings of the 3rd International Conference on Energy Efficiency in Historic Buildings 2018*, Visby, Sweden, September 26-27, 2018.

Hagentoft, C-E. 2001. *Introduction to building physics,* Studentlitteratur, 2001, ISBN 91-44-01896-7.

Heinemann, U. 2018. *Annex 65 Long-Term Performance of Super-Insulating Materials in Building Components and Systems. Report of Subtask 1: State of the Art on Materials & Components - Case Studies (Report to be published).*

Johansson, P., Geving, S., Hagentoft, C.-E., Jelle, B.P., Rognvik, E., Kalagasidis, A.S., and Time, B. 2014. Interior insulation retrofit of a historical brick wall using vacuum insulation panels: Hygrothermal numerical simulations and laboratory investigations. *Building and Environment*, 79 (September 2014):31-45.

Johansson, P., Josefsson, G., and Rajha, M.D. 2018. *Energieffektivisering av tegelfasad med kulturhistoriskt värde (Energy efficiency of brick façade with cultural historical value). [In Swedish]*. Bachelor's thesis ACEX-10-18-14, Chalmers University of Technology, Gothenburg, Sweden.

Johansson, P., and Wahlgren, P. 2018. Interior insulation retrofit of a brick wall using super insulation materials: design of a field testing in an industrial brick building. *Proceedings of the 7th International Building Physics Conference, IBPC 2018*, Syracuse, NY, USA, September 23-26, 2018.

Marincioni, V., and Altamirano-Medina, H. 2018. Can probabilistic risk assessment support decision-making for the internal insulation of traditional solid brick walls? *Proceedings of the 3rd International Conference on Energy Efficiency in Historic Buildings 2018*, Visby, Sweden, September 26-27, 2018.

Swedish Energy Agency. 2014. *Programbeskrivning för programmet Spara och bevara etapp 3, 2015-01-01 – 2018-12-31 (Programme Description for Save and Preserve Stage 3). [In Swedish]*. Eskilstuna, Sweden: Swedish Energy Agency.

Swedish Standards Institute. 2002. SS-EN ISO 15148:2002. Hygrothermal performance of building materials and products - Determination of water absorption coefficient by partial immersion. Geneva, Switzerland: International Organization for Standardization (ISO).

Swedish Standards Institute. 2008. SS-EN ISO 22007-2:2008. Plastics - Determination of thermal conductivity and thermal diffusivity - Part 2: Transient plane heat source (hot disc) method. Geneva, Switzerland: International Organization for Standardization (ISO).

Swedish Standards Institute. 2013. SS-EN 12086:2013. Thermal insulating products for building applications - Determination of water vapour transmission properties. Brussels, Belgium: European Committee for Standardization (CEN).

Swedish Standards Institute. 2017. SS-EN ISO 6946:2017. Building components and building elements – Thermal resistance and thermal transmittance – Calculation methods. Geneva, Switzerland: International Organization for Standardization (ISO).

Swedish Standards Institute. 2017. SS-EN 16883:2017. Conservation of cultural heritage - Guidelines for improving the energy performance of historic buildings. Brussels, Belgium: European Committee for Standardization (CEN).