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Evaluation of long-term performance of VIPs

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Abstract

Apart from the higher initial cost for using vacuum insulation panels (VIPs) in buildings there is still hesitation among architects and engineers whether these materials will withstand long-term use in buildings with a service life of 80-100 years. To evaluate the long-term performance, further investigations are needed. VIPs have been used in buildings since the 1990s and there already exists experience from using them in various applications. This paper presents the experiences from two field studies of a previously non-insulated wall with VIPs and a district heating pipe with hybrid VIP/PUR insulation. Measurements of the relative humidity in the wall showed that there is low risk of condensation in the VIP layer. Temperature measurements in the wall during the period 2010 to 2015 show no signs of deterioration of the VIPs. The same conclusion was made based on the temperature profiles in the district heating pipes during the period 2012 to 2015. The measurements are on-going to determine the long-term performance of the VIPs in different applications.

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Keywords: retrofitting; listed building; vacuum insulation panel; field study; measurement

1. Introduction

The energy use in society has to be decreased to reach the goals of less greenhouse gas emissions. The building sector stands for around 30% of the total energy use where the largest part is used for heating of buildings and for producing domestic hot water. Apart from building more thermally insulated buildings, old buildings need to be retrofitted to correspond with the modern building codes. In many cases the space for fitting additional thermal insulation in existing buildings and systems is limited. Therefore, super-insulating materials with lower thermal conductivity than seen before are being developed by the building industry. One of these materials is the vacuum

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insulation panels (VIPs) which have been used in buildings since the early 1990s. A VIP is composed of mainly two parts; the core material and the surrounding envelope. By evacuating the core material (often fumed silica) and wrapping it in a metalized multi-layered polymer laminate, the thermal conductivity at the center of the panel is less than 4 mW/(m·K). Due to air and moisture diffusion through the laminate, the thermal conductivity increases by time. Therefore the declared thermal conductivity of a VIP is 7-8 mW/(m·K). A fully air-filled VIP has a thermal conductivity of 20 mW/(m·K).

It is not only the performance of the insulation material itself that has to be considered, but also the temperature and moisture conditions in the assembly. For instance condensation inside a construction and large temperature variations over the day and night in a construction creates stress on the material structure which could cause premature failures. An issue when using VIPs is the risk of puncturing of the laminate, leading to loss of vacuum and an increased thermal conductivity. Heinemann and Kastner [1] used infrared thermography to investigate 19 buildings insulated with in total 3 224 m^2 VIPs, a few years after the construction finished. Three objects stood out in the investigation with more than 15% of the VIPs damaged. In one of these buildings it was assumed that errors were made in the design by installing unprotected panels close to an uneven plaster surface. In another project photos from the construction site showed that the VIPs had been stored and handled improperly by the construction workers. In the remaining 16 buildings with 1 999 m^2 VIPs, the total percentage of damaged VIPs was 4.9%. The conclusion of the study was that the percentage of damaged panels installed in a construction is low, as long as the recommendations by the producers are followed [1]. It should be noted that the study was based on infrared thermography which is a technique only possible to use when the VIPs are not covered by a highly conductive material or a ventilated air space. This is an important limitation when evaluating the thermal performance and durability of the VIPs in a finished wall.

In Europe, the declared thermal conductivity of insulation materials is given as the average performance over 25 years, e.g. SS-EN 13162 [2]. Since all materials are influenced by the surrounding conditions, such as temperature shifts, exposure to moisture and by ultraviolet radiation, the material has to be exposed to these conditions to give predictions of the service life. Garnier et al. [3] identified a number of factors that influence the durability of the aluminum layers in the VIP laminate. Fluoride ions, which are present in drinking water, were identified as one of the chemical compounds that could cause early degradation of the laminate. The influence by moisture and elevated temperatures was further investigated by Brunner et al. [4]. They studied a number of VIPs in different conditions in the laboratory and found that the laminate failed within a year in the most severe conditions. In a field study by Brunner and Ghazi Wakili [5], a number of VIPs were installed in a flat roof where the internal pressure and thermal conductivity were monitored. In 2013, after 8-9 years of operation, the thermal conductivity had increased to 6.6 mW/(m·K) to 7 mW/(m·K) which was higher than anticipated. Migration of water molecules inside the core material was proposed as a third ageing mechanism, apart from air and moisture diffusion. The larger contact surface between the molecules is supposed to increase the thermal conductivity. Morel et al. [6] studied this effect and concluded that fumed silica reacts with the water molecules leading to a decreased surface area and increased rigidity of the molecules. More knowledge on how VIPs will withstand long-term use in buildings with a service life of 80-100 years is crucial to foster wider acceptance among architects and engineers for the use of VIPs.

Work still remains to improve the existing aging predictions to take the moisture induced changes of the fumed silica into account. In 2013, the IEA/EBC Annex 65 Long-Term Performance of Super-Insulation in Building Components & Systems was initiated which will study several high-performance insulation materials. The long-term performance of the VIPs is one of the focus areas which will generate new knowledge and better predictions of the long-term durability of the VIPs. This paper presents the results of two field studies of a wall with VIPs and district heating pipes with hybrid VIP/PUR insulation. The VIPs are monitored by temperature and relative humidity sensors integrated in the construction. The basis for the evaluation of the wall are measurements performed during 2010 to 2015 and for the district heating pipes measurements performed during 2012 to 2015.

2. Case study building

The building chosen for the study was built in 1930 in Gothenburg, Sweden. The exterior aesthetics of the building are protected by Swedish legislation as a cultural environment of national interest. The building contain rented apartments and there are many complaints on draught and insufficient thermal comfort from the occupants. In the time when the building was constructed, thermal insulation was normally not used in the walls. This building was no exception with brick walls of 1.5 stone thickness, approximately 340 mm, in the ground floor. In the two upper floors, the walls were made of 80 mm wooden planks in three layers. Therefore the building is in great need of retrofitting measures. Due to the limited space for additional insulation in the wall, the retrofitting, presented in Fig. 1, was done with 20 mm thick VIPs placed on the exterior side of the wall. To protect the VIPs from damages, this layer was covered by 30 mm of glass wool. Between the old wall and the VIPs, a polyethylene foil was applied as an air barrier to prevent indoor air entering the wall. An air space, 28 mm thick, was added to the façade which makes the total additional thickness of the wall to be 80 mm [7].

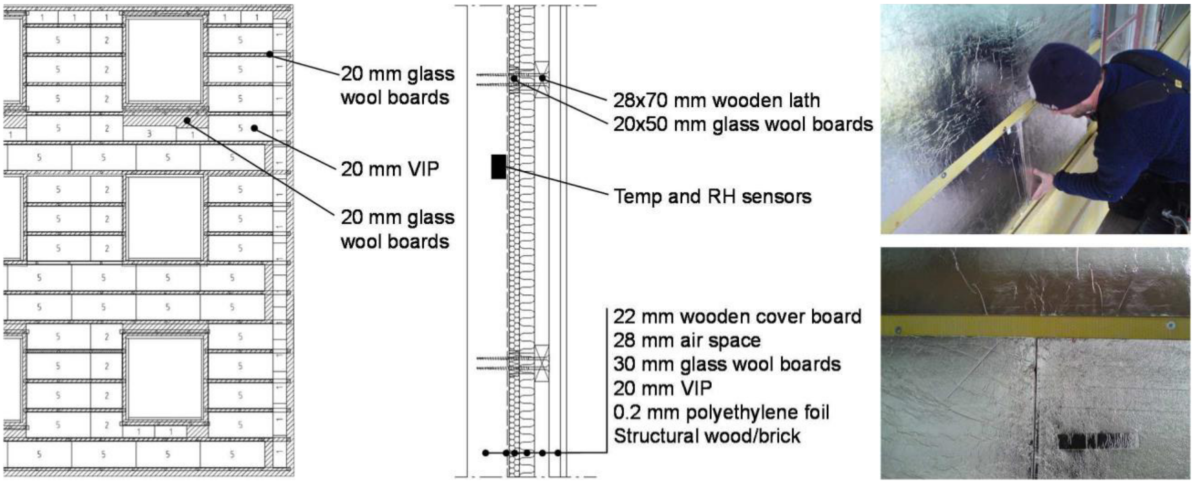

Fig. 1. Left: wall layout after retrofitting with 20 mm VIPs and 30 mm glass wool boards. Right: installation of the VIP layer with the glass wool boards between the VIPs and the taped edges between the VIPs.

The energy use for heating and domestic hot water before retrofitting was estimated to 160 kWh/m^2 (exact figures are not possible to obtain because the energy use in this building is measured together with many other buildings in the area). Calculations of the energy use show that the additional insulation of the wall will reduce the energy use by 20% (with all VIPs functioning and all thermal bridges included). As a comparison, changing the old windows to new windows with a U-value of 1 W/(m^{2}K) give an energy use reduction of 15%. The combination of changing windows and installing VIPs give an energy use reduction of 34% [7].

To evaluate the hygrothermal performance of the wall after the retrofitting, four temperature and relative humidity (RH) sensors were installed in the brick and wood walls, respectively. The sensors were located on the exterior of the existing wall, before the new polyethylene foil. The influence of the indoor climate was studied by installing sensors in the rooms closest to the monitored part of the wall. The outdoor temperature and RH at the building site was monitored by a sensor located in a perforated plastic box placed underneath the roof eave facing southwest [7].

2.1. Measurement of the temperature in the wall

The temperature at the sensor position in the reference and retrofitted walls can be expressed in a dimensionless form. In the standard SS-EN ISO 10211 [8] this is denoted the temperature factor, f (-), which is here defined as

$$f = \frac{T_{indoor} - T_{sensor}}{T_{indoor} - T_{outdoor}} \text{ (-)} \tag{1}$$

where T_{indoor} (°C) is the indoor temperature, T_{sensor} (°C) is the temperature at the sensor position and $T_{outdoor}$ (°C) is the outdoor temperature. The temperature factor is 0 on the interior side and 1 on the exterior side of the wall. The lower the temperature factor is, the higher the thermal insulation on the exterior of the sensor is. The average of the temperature factor in the reference and retrofitted walls during January 2011 to 2015 are presented in Table 1.

Table 1. The temperature factor calculated using Equation (1) for January, 2011 to 2015.

	Ground floor		2nd floor	
Year	Retrofitted	Reference	Retrofitted	Reference
2011	0.17	0.61	0.18	0.63
2012	0.18	0.65	0.16	0.63
2013	0.14	0.64	0.18	0.64
2014	0.17	0.64	0.19	0.65
2015	0.17	0.64	0.18	0.63

It is clear that the thermal resistance of the wall has been substantially improved after the retrofitting. In the reference wall about 63% of the temperature drop was over the uninsulated brick and wooden parts. After the retrofitting only about 17% of the temperature drop was over that part of the wall. The tendency is most clear during winter time since the solar radiation during summer sometimes increased the temperature in the wall above the outdoor temperature, giving a negative value for the temperature factor. The same situation was reached when the outdoor temperature exceeded the indoor temperature. The stable temperature factors during the five winters for both the reference and retrofitted walls showed that the thermal performance of the walls were roughly the same during these periods.

2.2. Calculations of the thermal performance of the wall compared to measurements

The expected temperature factors were calculated based on the standard thermal conductivity for the materials in the wall by using the resistance on the interior and exterior side of the measurement location:

$$\varepsilon = \frac{R_{interior}}{R_{interior} + R_{exterior}} \text{ (-)} \tag{2}$$

where $R_{interior}$ (m^2· K/W) is the thermal resistance of the structural wall and $R_{exterior}$ (m^2· K/W) is the thermal resistance of the materials on the exterior side of the sensor. The standard values for the thermal conductivities, λ (W/(m· K)), the thickness of each material layer, d (mm), and the resulting thermal resistance, $R = d / \lambda$ (m^2· K/W), are presented in Table 2.

Table 2. Standard values for the thermal conductivity, λ (mW/(m·K)), of the materials in the wall and corresponding thermal resistances R (m^{2}K/W) for the layers of thickness d (mm) and the heat transfer coefficient between the surface and air.

Material	d *(mm)*	λ (*mW/(m·K)*)	R (*m²·K/W*)
Wood	80	140	0.57
Cover board	22	140	0.16
Brick	340	700	0.49
VIP	20	4	5.0
Glass wool	30	40	0.75
R_{si}	-	-	0.13
R_{se}	-	-	0.04
$R_{vented\ façade}$	-	-	0.20

Using the standard values for the thermal conductivity, the temperature factor at the sensor location was 0.77 in the reference wall and 0.12 in the retrofitted wall. The measurements gave an average temperature factor of 0.63 in the reference wall and 0.17 in the retrofitted wall. The lower measured temperature factor in the reference wall could be explained by a higher surface heat transfer resistance on the exterior of the wall. The sensor was located in a perforated plastic box placed underneath the roof eave, mostly protected from wind, which leads to a higher surface heat transfer resistance than what was used in the first calculation. With an exterior surface heat transfer resistance of 0.22 $m^2 \cdot K/W$ instead of 0.04 $m^2 \cdot K/W$, the calculated temperature factor matched the measured temperature factor of 0.63. The thermal bridges created by the VIP laminate and glass wool strips were not included in the calculation. These could explain the higher measured temperature factor in the retrofitted wall compared to the calculation. In reality these thermal bridges increase the heat flow through the VIP layer. To reach the measured temperature factor of 0.17, the effective thermal conductivity of the layer with VIP and glass wool strips needed to be 9 $mW/(m \cdot K)$. Using the exterior surface heat transfer resistance of 0.22 $m^2 \cdot K/W$, the effective thermal conductivity increased to 10 $mW/(m \cdot K)$. However, other factors could contribute to increasing the heat flow through the wall. One of these factors is airflow through the wall which was not considered above.

3. District heating

District heating pipes could be insulated with VIPs to reduce the heat losses from the pipes. In a cylindrical geometry, the insulation have much larger effect closer to the center of the cylinder. This have led to a concept of hybrid pipes where the innermost part of the polyurethane (PUR) foam insulation has been exchanged with VIPs. The main issue when using VIPs in district heating pipes is the high temperature in the pipes (up to 120°C). This has two possible consequences; the temperature could destroy the laminate leading to a collapse of the VIP, and the heat speeds up the diffusion of air through the laminate. The deterioration of the VIPs have been tested in a pilot site. Hybrid insulated district heating pipes were installed at two locations in a district heating system with temperatures up to 90°C. The temperature on the surface of the VIPs and in a reference pipe with only PUR foam have been monitored every hour. The positions of the thermocouples are shown in Fig. 2. The measurements during the period 2012 to 2015 show no signs of deterioration of the VIPs and the temperature profile over the pipes is constant.

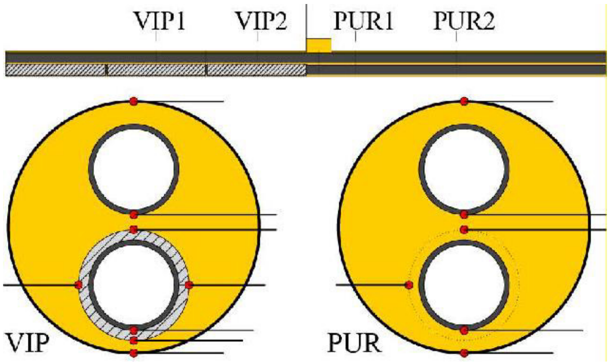

Fig. 2. Description of the thermocouple placement for one of the field measurement pipes. Left: section of the hybrid insulation part. Right: section of the reference part with conventional PUR foam insulation. Each temperature point was measured at two positions along the pipe.

4. Conclusions

It is difficult to evaluate the performance of the VIPs when installed in the wall. In the retrofitting solution presented here, the air space makes it impossible to identify the different panels by thermography. Only indirect methods, like the evaluation of the measured temperatures in the wall, can be used to follow the long-term performance of the panels. This paper shows that there is no signs of degradation of the VIPs installed in the wall during the period 2010 to 2015 and in the district heating pipe during 2012 to 2015. There was also no measured or reported condensation in the retrofitted wall. To be certain that the VIPs are not degraded, the VIPs should be transported to the laboratory where the internal pressure and thermal conductivity should be measured.

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