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Interior insulation using super insulation materials: saving energy and space

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Abstract. Interior insulation can be used in buildings where the exterior characteristics may not be altered due to cultural heritage protection. This is common for many buildings in Sweden from the period before 1941. Energy efficiency, thermal comfort and building performance are all affected by an interior insulation. Super insulation materials present novel opportunities to save both energy and space. The aim of this study is to investigate the benefits and drawbacks of using super insulation materials as interior insulation. A field study building was investigated for feasibility, which, together with interviews with professionals in the field of architecture, cultural heritage and building consultants, give a general overview. In conclusion, there are both benefits and drawbacks with interior insulation. Super insulation provides increased flexibility in terms of interior detailing and possibility to preserve characteristic elements. On building level interior super insulation could reduce the energy use by up to 20%. This gives energy savings of 0.5 TWh on national level and a reduction of 0.7% of the total CO_2 emissions for heating the Swedish building stock. A drawback is that there are few examples and little experience from building with super insulation materials among both architects and other decision makers.

1. Introduction

Around 78% of the energy use in the Swedish construction sector is accounted to heating and cooling of buildings. The remaining part is associated to construction, renovation and demolition activities. During the last years, the amount of energy use for heating and cooling has increased. In 2016 the energy use was 7% higher than the average energy use in the preceding 10-year period and 8% higher than the previous year [1]. Around 25% of the energy for heating is used in the part of the building stock from before 1941 [2]. According to EU Building Stock Observatory (BSO) [3], more than 20% of the European building stock is built before 1945 and a large part of the building stock has very low energy performance. The share of residential buildings within a country, with a very poor energy rating (D) in the EPC was on average more than 50% (16 European countries were included in this study). The thermal transmission, U-value, of the wall in the current study is approximately 1-1.4 W/m^{2}K. According to EU Building Stock Observatory (BSO) [3], 75% of the building stock has an average U-value higher than 1.44 W/m^{2}K. The energy impact of such high U-values is of course dependent on climate conditions. Nevertheless, one conclusion from the analysis of data for 16 European countries/regions, covering 66% of the European total floor area, is that over 87% of the building stock must be upgraded to comply with the 2050 decarbonization vision [3]. Consequently, the current intention is to enforce national renovation strategies of buildings to reach low or zero carbon dioxide emissions from the building industry by 2050. This means many existing buildings need to be adapted to the modern energy standards soon. The renovation of buildings would contribute to SDG 3, 9 and 11 by reducing use of energy, increased thermal comfort for the occupants and developing means to maintain cultural heritage values in cities. The main issues hindering the renovations is lack of knowledge, issues with increased rents and other financial barriers.

The aim of this study is to investigate the benefits and drawbacks of using super insulation materials, such as aerogel blankets (AB) and vacuum insulation panels (VIP), for interior insulation. A former industrial building from the late 1800s in homogenous brick is used as a case study. The building outside of Gothenburg, Sweden, has been studied with regard to the impact of interior insulation with super insulation materials using measurements of heat and moisture conditions. A workshop was held with professionals in the field of architecture, cultural heritage and building physics to give a general view of benefits and drawbacks of super insulation materials as interior insulation. The results from the workshop and case study are complemented with data from a previous inventory [4; 5] of the building stock in Gothenburg to scale the results to potential national impact.

2. Retrofitting with respect to decreased energy use

There are several different approaches to decrease energy use and improve the indoor environment (both thermal and air quality). In a previous study, Johansson and Wahlgren [5] investigated common renovation measures. Examples are; additional insulation (wall, attic, foundation, including decrease of thermal bridges), change of windows or adding windowpanes, change or upgrading of building services, increased airtightness and decreased water penetration. The latter can seriously damage the durability of the structure, indoor air quality and energy use. It can occur through façades, roofs, foundation (rainwater and ground water), joints and the areas around penetrations are in particularly vulnerable. When estimating the most suitable renovation strategies, there are many building physics functional requirements (e.g. rain or wind barrier) that need to be considered and fulfilled in a building. These functional requirements have been structured in Table 1. The different categories are labelled E (energy) or I (indoor air quality) for the reason to renovate. For decision making, other aspects also need to be included; such as building heritage aspects, daylight, regulations, social and economic aspects.

Table 1. Building physics aspects of the thermal envelope and building components they affect. The different categories are labelled E (energy) or I (indoor air quality) for the reason to renovate [5].

Building component Function	Wall	Roof	Foundation	Windows	Building services incl. penetrations
Rain barrier	E, I	E, I	E, I	E, I	(E), I
Wind barrier	E, I	E, I	E, I	E, I	(E), I
Air barrier	E, I	E, I	E, I	E, I	E, I
Interior moisture protection	(E), I	(E), I	(E), I	(E), I	E, I
Heat/cold protection (insulation, thermal bridges)	E, (I)	E, (I)	E, (I)	E, (I)	E, I

Apart from the different functional requirements above, there are several challenges associated with decreasing the energy use in existing buildings, especially in buildings located in areas of national interest for cultural heritage or listed buildings. Here, one of the challenges is to reduce the energy use while not tampering with the character defining elements of a building, such as the expression of the façade, the foundation, the volume of the building, the decoration of the façade, the windows and the window frames.

Specific to older brick structures is the risk of freeze-thaw damage when exposed to rain and varying temperature conditions. Interior insulation may worsen the risk of these structural damage [6]. Often the structural integrity in older brick buildings is supported by wooden beams that lay in the brick. In the United States, studies on how these wooden beams are affected by an internal insulation have shown that rain and water leakages must be handled correctly in order to avoid damage [7]. So-called capillary-active materials have been proposed as a solution to the problem [8], while other studies have shown that on the contrary, they absorb even more moisture [9].

Generally, façades can be insulated either on the interior or exterior side, see Figure 1. Interior insulation can be used in buildings where the exterior characteristics of buildings may not be altered due to cultural heritage protection. This is common for many buildings in Sweden from the period before 1940. Energy efficiency, thermal comfort and building performance are all affected by an interior insulation. 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 [10]. Interior insulation will also negatively affect the thermal storage capacity of the building and change the interior appearance of the walls. This is particularly important to consider for historical and/or listed buildings [11].

Figure 1. Installation of insulation on the interior or exterior of listed buildings. a) Multi-family building from 1930s in Gothenburg [12], b) Installation of VIPs on the exterior, c) Industrial building from 1896 in the south of Gothenburg, d) Sensors inside the case study building.

Super insulation materials present novel opportunities to save both energy and space by requiring a thinner insulation layer than conventional insulation materials. These thermal insulation components have a 3-10 times higher thermal resistance than conventional insulation materials, and thus thinner layers can be used. The thermal conductivity of AB is 0.015-0.020 W/(m·K) and 0.002-0.008 W/(m·K) for VIP. In the IEA Annex 65 'Long-Term Performance of Super-Insulating Materials in Building Components & Systems' several super insulation materials were investigated, and case studies were collected from all over the world. Several questions regarding the long-term performance of SIMs on the building scale were identified and discussed. Four main challenges were identified [13];

- Knowledge and awareness among designers concerning using SIM,
- Conservative construction market,
- Cost versus performance,
- Long-term performance of SIMs.

3. Results from workshop on suitable application of interior super insulation

A part of this study consisted of workshops and interviews with practitioners in the field of energy efficiency and cultural preservation. One of the topics covered by this team of experts is investigations of the benefits, drawbacks, possibilities and limitations of interior super insulation. The team formed a reference group to the project and consisted of seven professionals with different competences; indoor environment expert (focus moisture), experienced senior structural engineer and building physics expert (consultant), professor with focus on conservation, building antiquarian (consultant), senior architect (focus transformation), project manager and facilities manager.

Since SIM can be thinner than conventional insulation, for the same energy performance, details in the façade can be preserved to a higher extent. It is important to initially determine to which extent the façade can be changed. The first step is to identify the significant character defining details and elements of the building. This is valid both for the exterior façade (for exterior insulation) and for the inside of the external walls (interior insulation). Using SIM provide several opportunities to reduce the intervention on important character defining elements. However, the necessary detailed design of the façade is time consuming, and the measuring of the original façade needs to be thorough. Consequently, there is a necessity to have the required time and funding for this work to be able to motivate the work and the non-standardized solutions, and to include them in the procurement process from the beginning.

In the construction industry today, there is a certain reluctance to use non-standardized solutions. Designers and craftsmen need to be skilled with enough knowledge to develop the required solutions. The compatibility of SIM with other materials and constructions is not always well known or understood, and the long-term performance of the solutions needs in some cases to be further evaluated, as also described in IEA Annex 65 [13].

Using interior insulation, whether it is SIM or not, will lead to a colder original structure. This, in turn, can lead to high moisture levels in the original structure, with following durability problems, such as mold growth in wooden parts or frost wedging of bricks. The drying out capacity of brick walls will also decrease when insulation is applied. Due to the problems connected to interior insulation of exterior walls, it is very important to first determine if the conditions of the wall allow interior insulation. Otherwise, other solutions to increase energy efficiency and indoor thermal comfort should be used when the exterior façade needs to be preserved. Such solutions include insulation of the roof construction, changing of windows, excavation and insulation of the foundation and floor construction, and improved heating and ventilation systems. In many cases, when renovating older buildings, the ground conditions need to be improved in any case. This was also the case with the case study building, where the exterior walls were very wet, and water was constantly absorbed from the ground and from rainwater.

The benefits of SIM, in particular for flexible materials like aerogel blankets, become evident when details are to be preserved. These can be round staircases, window settings, roof eaves, connection between foundation and façade. In fact, SIM is very efficient for reducing the impact of thermal bridges. One example is to use a combination of insulating insertion windows and SIM at thermal bridges around the insertion window, instead of changing the whole window and frame. This is also advantageous in order to minimize air leakage around windows [14]. Another example is to use SIM and wooden beam ends (inside the wall) to keep the beam from becoming too cold and moist.

Since walls with SIM will require less heating than non-insulated walls, it might be possible to decrease the number of radiators, which will increase usability and flexibility. Internal SIM will also decrease floor area to a lesser degree than conventional insulation, due to its smaller thickness.

4. Results from case study

An old industrial brick building outside of Gothenburg on the Swedish west-coast is under initial testing for evaluation of AB and VIP on the interior of the wall, Figure 1. In a previous study, hygrothermal numerical simulations and laboratory measurements of a brick wall showed that it is important to investigate the amount of moisture from driving rain [15]. The properties of the interior insulation material showed to have a lesser influence on the moisture accumulation rate than the exterior rain tightness. The rain load was the dominating factor determining the vapor and water transport in the wall. Having the possibility of inward drying lowered the moisture accumulation rate slightly.

A small room was constructed inside the building with insulated, using 170 mm mineral wool in the floor, inner walls and roof, and super insulation on the exposed brick wall. Prior to the installation of the interior insulation, the existing plaster was removed from the internal brick surface. There was substantial capillary suction from the ground. The brick wall is divided into three parts (500 x 1,200 mm) where 20 mm AB and VIP, respectively, are tested on the interior of a 470 mm thick homogenous brick masonry wall and compared to a non-insulated wall as reference. The wall is equipped with 10 hygrothermal sensors that every hour registers the temperature and relative humidity in the wall.

The heat flux sensor Hukseflux HFP01 (thickness 5.4 mm, diameter 80 mm) 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/m^2 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. Each wall set-up (reference, AB, VIP) has two sensors, top and bottom and the heat flux was measured at three occasions (March, April and November). The averaged results show that the heat flux is substantially reduced with interior super insulation, see Figure 2.

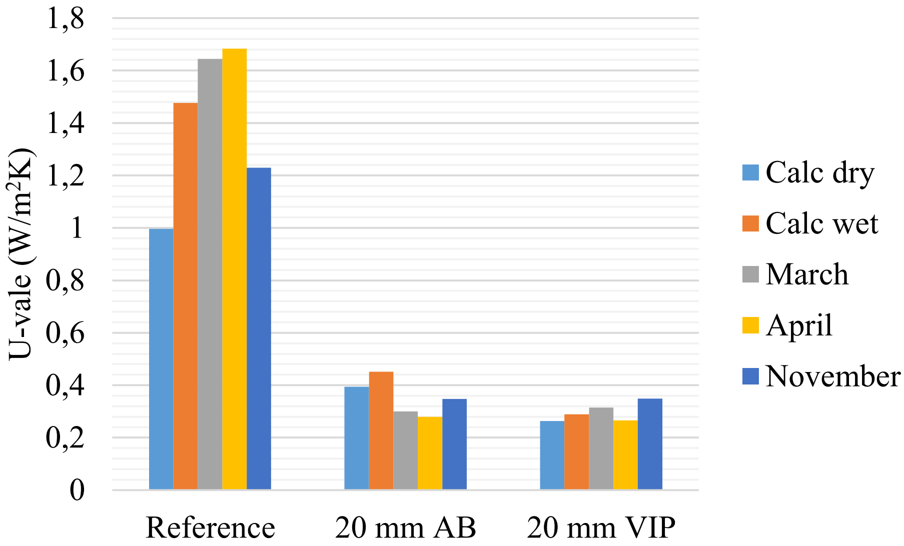

Figure 2. U-value of the 470 mm homogenous brick masonry wall without insulation compared to the wall with 20 mm AB and 20 mm VIP and no insulation, based on heat flux calculations and measurements [11].

The measured difference in heat flux between the 20 mm AB and VIP insulation layers is smaller than expected from the calculations. The thermal conductivity of dry bricks was 0.61 W/(m·K) and for the wet case it was 1.0 W/(m·K), which is the average of dry and wet brick 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 [11]. On a building level this would mean that the energy use could be reduced by up to 20%, assuming that 25% of the energy use in buildings from this time period is caused by transmission losses through the façade [16] and with 80% reduction in U-value of the façade.

5. Potential for interior insulation in Sweden

To estimate the potential energy use and carbon dioxide reductions by interior super insulation of brick buildings, a previously presented inventory and database of the Gothenburg building stock is used [5]. Gothenburg is the second largest city of Sweden with around 570,000 inhabitants (2018) and in total 150,804 buildings in the property register. There are 2,217 residential multi-family buildings built before 1945 in Gothenburg whereof 2,124 buildings have a valid energy performance certificate (EPC). The inventory includes 640 buildings out of these 2,124 buildings, on 602 properties, which means that almost 30% of the buildings of interest were investigated in the inventory [4].

Before 1950 brick was a common load-bearing material, but after this period brick is mostly used for cladding on the façade. The inventory showed that a majority of the investigated buildings have already been renovated when looking into the official statistics, where the so-called value year is used. This is a term based on the economic extent of the renovation or improvement of standard, related to the expected remaining service life of the building. Only costs for renovation measures or extensions larger than 20% of the cost of a new building is registered. However, the inventory showed that a majority of the buildings did not have any visible additional wall insulation. Furthermore, many building walls were only partly insulated. This means that not all external walls of the building were insulated or that the walls are not insulated over the whole building height. In many cases, the ground floor has another type of construction and materials than the ones above and is therefore left without additional insulation [4].

The inventory contains 147 buildings which have a façade of brick both on the ground floor and upper floors. This is a good indication that the construction is also made of bricks. Out of these buildings, 26 had added insulation on the exterior of the façade, i.e. less than 18%. Many of the remaining buildings have a protected or listed façade which makes interior insulation the remaining option to reduce the U-value of the façade. The (final) measured energy use for heating, domestic hot water and facility electricity is reported for 107 of the buildings, i.e. 14 buildings lack an EPC. The energy use in the buildings with an EPC varies between 89 kWh/m^2 and 181 kWh/m^2 with an average energy use of 133 kWh/m^2. This can be compared to the maximum energy use in the building regulations for new multi-family buildings which until July 2017 was 75 kWh/m^2 in Gothenburg. Nowadays, Sweden uses primary energy in its energy performance legislation which creates problems when comparing existing buildings with new ones. The energy use for the 107 buildings is presented in Figure 3.

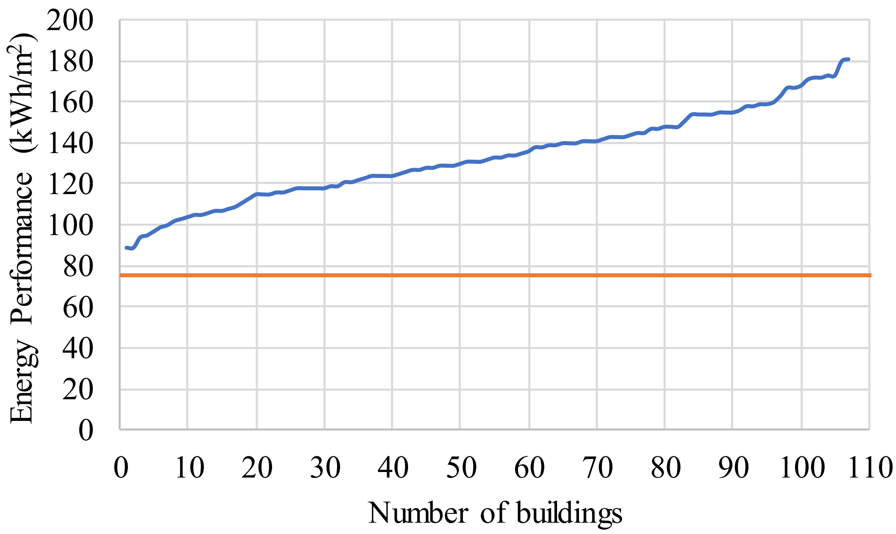

Figure 3. Energy use in 107 brick buildings in Gothenburg from before 1945, compared to the maximum energy use in the building regulations.

According to the case study in this paper, around 20% of the energy use could be saved by using 20 mm interior super insulation an older brick building. Since 82% of the buildings did not have any added insulation on the façade before, we can assume many are suitable for interior insulation. The average heated floor area of the buildings in the inventory is 2,300 m^2. Assuming the same share of non-insulated multi-family brick buildings from this time period on national level as in the inventory of buildings in Gothenburg, the total number of suitable buildings is 8,900. The total potential energy savings is then 0.5 TWh, which can be compared to the total energy use for heating and cooling in Sweden which was 80 TWh in 2016 [1]. The heating of buildings in Sweden on average emits 68 gCO_2/kWh. This gives a reduction in CO_2-emissions of 37 thousand ton CO_2-equivalents which is 0.7% of the total CO_2 emissions for heating the Swedish building stock.

6. Conclusions

There are both benefits and drawbacks of interior insulation. Optimized thickness (from heat and moisture perspective) for a specific building needs to be calculated to reach the best performance from the building owner's and user's perspectives. Super insulation provides increased flexibility in terms of interior detailing and possibility to preserve characteristic elements. A drawback is that there are few examples and little experience on buildings with super insulation materials among both architects, other decision makers and craftsmen.

The energy performance of a building is in some cases not representing one specific building but is calculated from the energy use of a whole property consisting of several buildings. In this case, a building with additional insulation can have the same energy performance as a building with less insulation. There are no databases that describe the type of renovation for buildings, which makes it difficult to separate buildings with, for example, more cosmetic or aesthetic renovations from buildings with energy efficiency measures included in the renovations.

On building level, interior super insulation could reduce the energy use by up to 20%. This gives energy savings of 0.5 TWh on national level and a reduction of 0.7% of the total CO_2 emissions for heating the Swedish building stock. This is under the assumption the 8,900 buildings in Sweden are feasible for interior super insulation. The main barriers hindering these renovations is lack of knowledge, issues with increased rents and other financial barriers.

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