

Article

Super Insulation Materials—An Application to Historical Buildings

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Abstract: The main purpose of this paper is to present the use of super thermal insulation materials for a historical building through a calculation-based case study. The development of the insulation materials is based on the objective of making buildings as energy efficient as possible, and the energy loss should be kept to a minimum, for both new and existing buildings. For this purpose, the thermal insulation materials used so far have not always achieved maximum effectiveness. In the case of historical buildings, it is particularly difficult to solve insulation issues, as the building cannot lose its former appearance. However, aerogel and vacuum insulation panels can also be used as thin thermal protective layers. In this paper, we will specifically deal with the presentation of the possible application of super thermal insulation materials, such as vacuum insulation panels and aerogels. We will present thermal conductivity measurement results as well as their application through building energetic calculations applied to a historical building as a case study. We will also present certain calculations regarding the costs. The paper highlights that savings of energy costs of approximately 30% can be reached using vacuum insulation sandwich panels. Furthermore, the overall thermal transmittance of the building also decreases by about 35% if vacuum insulation sandwich panels are used for the refurbishment.



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1. Introduction

Energy is used in buildings to maintain an acceptable level of comfort. The main aim is to keep the energy consumption as low as possible without diminishing comfort. In order to ensure and maintain the appropriate values, certain regulations should be applied [1,2]. The directive issued by the European Union is only a framework regulation, so the detailed descriptions must be determined by each Member State. However, there must be consistency between the regulations laid out by the Member States. A key action to reduce the energy use of buildings is the application of thermal insulation materials. Thermal insulation has been understood as a separate building structure layer since the XIX. century, but this does not mean that humanity did not previously use different materials for thermal insulation. However, with the development of the industry, the development of thermal insulation materials has arisen [3,4]. With the development of I4.0, the development of thermal insulation materials has also become an important point. Nowadays, one needs thinner and thinner insulation with high thermal resistance. In order to achieve these objectives, so-called super thermal insulation materials were created, which refer to vacuum insulation panels and advanced nano-porous materials such as aerogel. They appeared on the market around 2013 after the launch of the IEA-EBC Annex 65 (EBC = Energy in Buildings and Community) program [5]. Super insulation materials have garnered special attention in the construction sector in the last decade [6,7]. Although their market price is much higher than the price of conventional insulation materials, such as expanded polystyrene, their most important advantage is that they can be used in thinner

layers (approximately 2–3 cm) [8–11]. Earlier, it had been well documented that both vacuum insulation panels and aerogel-type blankets could be used effectively in buildings where the available space for the insulation is smaller, or they could be applied as internal insulation [12]. Another case where they can be utilized is in historical buildings [13–17]. This paper focuses on the possible use of super insulation materials, namely an aerogel and a vacuum insulation panel. Their thermal conductivities were measured by Holometrix-type lambda 2000 equipment and the results were used for energetic calculations. For the calculations, an encapsulated (sandwich) vacuum thermal insulation panel and Slentex-type aerogel were used. As a result, the paper will show the possible use of these insulation materials as an energetic refurbishment in a historical building. The paper also presents cost calculations and the calculated energy performance certificate categories.

2. Materials and Methods

2.1. Tested Materials

2.1.1. Vacuum Insulation Panel

The production of vacuum thermal insulation panels (VIP) is based on simple manufacturing tests one after the other. Firstly, the core panel is compacted into a specific mold, to remove all ambient gases. Often, panels are produced in a vacuum chamber as the pressure in the chamber should be low. They are then packed in a cover film designed to protect them from dust, dirt, and impacts of the external environment. Then they are dried slowly, as far as possible, and covered with an airtight aluminum foil, the edges of which are glued together [18,19]. In addition to these materials, a so-called “getter” material is added inside the core, which is responsible for binding the disturbed gas molecules. The use of vacuum panel thermal insulation has many advantages that set it apart from other thermal insulation materials [20]. With the rise of energy-conscious architecture, it has become important to use thermal insulators that are as efficient as possible, but for many materials, this has only been achieved by thickening the layers. In terms of construction and material costs, this is not always an option. Vacuum panels, on the other hand, are made to a maximum thickness of 5–6 cm, while they are also made to a thickness as small as 1 cm [21]. Due to these properties, their use is widespread in places with a high price per square meter, or when it is necessary to save on useful areas. Vacuum panels are thermal insulation elements with a center-of-panel thermal conductivity of 0.0035–0.008 W/mK. Beside the advantages, unfortunately, it is also important to mention their disadvantages. One of the most important properties to highlight in this respect is the sensitivity of the outer layer to mechanical effects. Even the slightest damage can destroy the panel [22]. This means that during construction, builders must be careful to exercise due care in the installation. After describing the properties of vacuum panel thermal insulation materials, the article also has to briefly establish in which parts of the buildings the vacuum insulation panels can be used. It follows from their unusual thermal properties that they can serve as excellent thermal insulation systems for flat roofs, facades, terraces, floor structures, parapet glazing of curtain walls, and interior insulation.

2.1.2. Aerogel Insulations

Another super thermal insulation material is aerogel, which belongs to the advanced porous materials (APM) group [5,15,23]. These materials contain nano-sized open pores. Their porosity is high. Aerogel materials have a special appearance as well as structure. They are considered to be one of the lowest density, and at the same time, most effective thermal insulation materials. Aerogels can be grouped into two major categories: Organic and inorganic aerogels. The definition depends on the nature of the materials used to produce them. Organic aerogels are generally less brittle and less sensitive to compression than inorganic aerogels. The group of organic aerogels consists primarily of oxide, metal, fluoride, chalcogen, and silica aerogels. Silica aerogels are usually used as the raw material for aerogel-based thermal insulation. They are among the best-known and most applied types of aerogels. In general, they are very porous and light, but structurally very rigid.

They consist of silicon bonds in which the particle size is approximately 0.5–4.0 nm with a pore diameter of 10–100 nm. They are extremely low-density materials with a value of approximately 0.03–0.6 g/cm³. Their volume contains approximately 95–98% air, so they are an extremely light material. The longitudinal propagation speed of sound in the materials is 100–120 m/s, which means that they are also excellent sound insulators. Silica aerogels can be prepared in monolithic, powder, granular, and quilt forms. The present study deals with fibrous silica aerogel-based thermal insulation. Aerogel insulation blankets are one of the most common types of super thermal insulation materials in the construction industry. These super-thermal insulators are flexible composite materials embedded in their cross-linked aerogels. The quilts are mechanically flexible and have a very low thermal conductivity of up to 15 mW/(mK). They are compressible materials to some extent, so they can be used in different places without losing their tensile strength and flexibility. Regardless of the manufacturer, thermal insulation blankets are available in different material compositions in order to suit both temperature ranges and fires [24,25]. They are mainly used as post-insulation for thermal bridge interruptions, as well as in the case of historical buildings, where it is necessary to maintain the characteristics of the original building. In addition, they are ideal for areas where there is small space to implement insulation, for example in for thermal bridges and window sills behind blinds. They can be used in buildings of special structure and shape, as well as to improve thermal problems in critical junctions such as plinths, pillars, and pipes [26,27].

2.1.3. Thermal Conductivity Measurements

The experimental tests were performed in the Building Physics Laboratory of the University of Debrecen as Refs. [23,26,27]. In the study, the main goal was primarily to determine the thermal conductivity (λ) of the two selected super thermal insulation materials by Holometrix Lambda 2000 equipment (Bedford, MA, USA, HFM) presented in Figure 1a. Here, the authors will describe the composition of the equipment used during the measurements, as well as the measurement process and the measurement results of the examined thermal insulation. The measurements were based on two thermal insulation materials, namely a Slentex aerogel thermal insulation blanket and an encapsulated VIP SP-2 vacuum panel. At first, the samples were placed one after the other in the Venticell 111 type oven (MMM Medcenter Facilities GmbH, München, Germany) (see Figure 1b). The device can provide even heating in a short time, which makes the internal space heat distribution extremely unique. Thanks to its ventilation system, it can reach temperatures of up to 300 °C. During the measurement, the drying temperature was set to 50 °C. The drying time lasted for 1 day. During the process, the equipment dried the thermal insulation materials until they reached mass equilibrium, and after removing them from the dryer, their thermal conductivity was characterized with a Holometrix Lambda 2000 heat flow meter. During the measurement, the temperature of the plates was set to 40 °C and 20 °C, thus creating an average temperature of 30 °C. After the heat balance was established, the temperature of the heating plate, the temperature difference, and the heat flow in the sample were constant. The equipment can determine the thermal conductivity of thermal insulation materials from these constant values. Despite having an excellent insulation performance, these materials are relatively expensive and little is known about their durability, long-term performance, and basic thermal properties. In Table 1 the most important thermal parameters and information are collected regarding the tested materials.

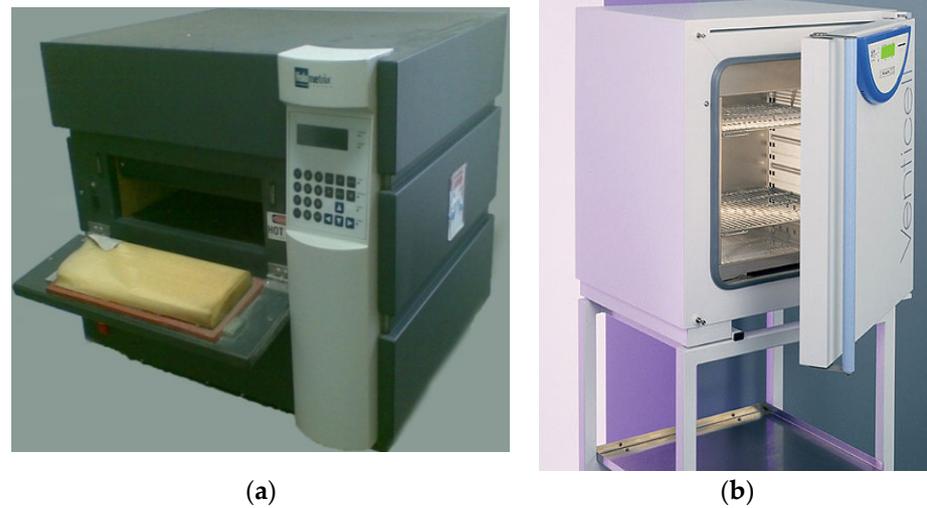


Figure 1. (a) Holometrix lambda 2000 equipment; (b) Venticell 111 drying apparatus.

Table 1. Technical parameters of tested materials.

Slentex	Protected Vacuum Panel
Class A2-s1, d0	Polystyrene and Fume Silica
Entirely mineral-based product	Sandwich panel 3 = core + foil covering (VIP) with aluminium/aluminium and circumferential EPS insert edge band
Thermal conductivity declared by the manufacturer: 0.019 W/mK	Thermal conductivity declared by the manufacturer VIP _{cop} : 0.007 W/mK, PS: 0.035 W/mK
Open to diffusion	Polystyrene closed cell
Sold in rolls	Slabs
Non-combustible	Polystyrene is combustible, fume silica non-combustible

3. Results

3.1. Measurement Results

3.1.1. Slentex Insulation Results

The first thermal insulation tested was the Slentex aerogel thermal insulation blanket (see Figure 2). Slentex thermal insulation is also known as Spaceloft A2. From its name, one can conclude that it is a Spaceloft thermal insulation blanket, which is classified as fire protection class A2, i.e., non-combustible [28]. Due to this property, it is mainly used on surfaces where increased fire safety is expected. It has extremely low thermal conductivity as well as outstanding flexibility, pressure resistance, and hydrophobicity. Of course, the properties and areas of application highlighted in the previous chapter for thermal insulation blankets are also applicable to this material. Table 2 represents the thermal conductivity measurement results executed on the aerogel. It was notable that after the measurements, according to standard ISO 10456 [29], the average thermal conductivity value was approximately 0.022 W/mK.



Figure 2. Tested Slentex aerogel insulation.

Table 2. Thermal conductivity test results of the Slentex aerogel.

Measurement Row	Thermal Conductivity (W/mK)	Average Deviance (W/mK)
1	0.021781	0.000197
2	0.021945	0.000033
3	0.022027	0.000049
4	0.0221	0.000132
5	0.022027	0.000049
Average	0.021978~0.022	0.000046

3.1.2. Vacuum Panel Results

Figure 3a–c presents the tested encapsulated vacuum insulation panels. The special feature of this vacuum panel thermal insulation (and at the same time, a huge advantage) is that it is protected from all sides, with expanded polystyrene foam boards as a protective cover [21,22]. It is surrounded on both sides by a 10 mm polystyrene panel and on four sides by a 25 mm thick polystyrene. So, the total thickness of the material is 3 cm, of which the VIP is 1 cm. The insulating core consists of pressed powder, the main component of which is microporous silica. The core of the panel is non-flammable, i.e., it is classified as fire protection class A1. The density of the vacuum panel together with the polystyrene boards is 106.29 kg/m³. Table 3 represents the thermal conductivity measurement results executed on the VIP board covered with the Expanded Polystyrene (EPS). We noticed that after the measurements, according to standard ISO 10456, the average thermal conductivity value was about 0.021 W/mK. As mentioned above, these values were measured at 30 °C mean temperature, within the value range of the standard ISO 10456.

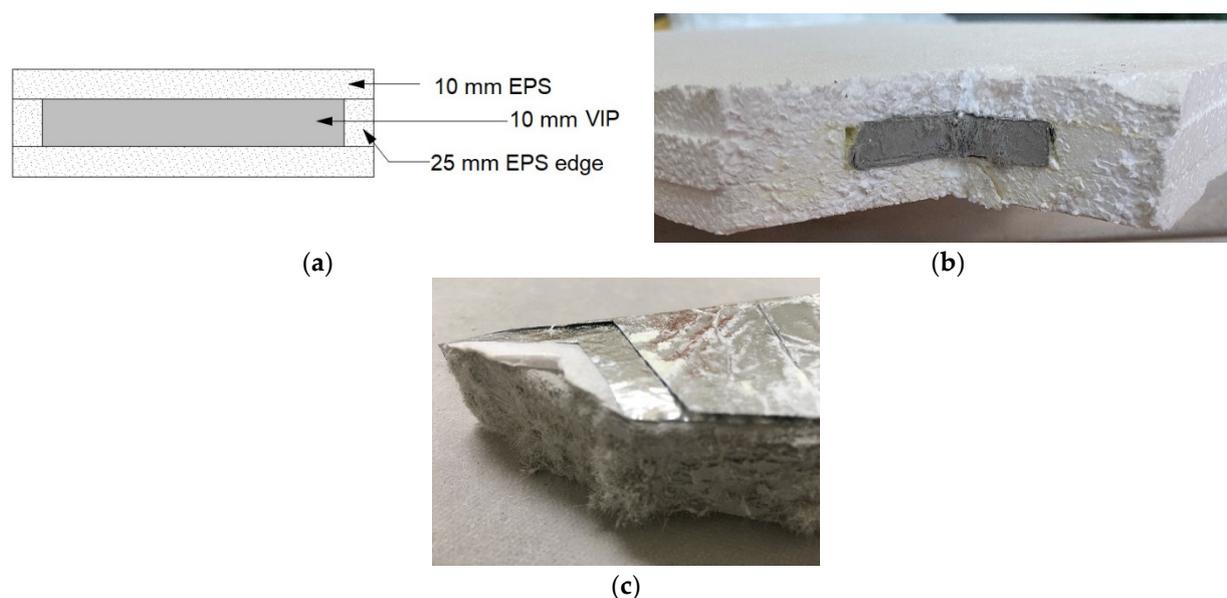


Figure 3. Tested encapsulated vacuum insulation Panel (a) sketch; (b) cross-section; (c) core material with the foil.

Table 3. Thermal conductivity test results of the vacuum panel.

Measurement Row	Thermal Conductivity (W/mK)	Average Deviance (W/mK)
1	0.0206	0.0003
2	0.0207	0.0002
3	0.0211	0.0001
4	0.0210	0.0002
5	0.0211	0.0001
Average	0.0209~0.021	0.0001

It is worth recalling that the measurement results are for the aerogel with 1 cm thickness and the VIP, in total (3 cm). For the calculations below, 3 cm was used for the VIP–EPS sandwich panel, and 1 cm for the Slentex.

3.2. The Model Building

In order to determine the possible applicability of the tested materials, a historical building was chosen to be hypothetically renovated from an energetic point of view. This building is a secondary school in Hungary, in Karcag, and was built in the 19th century (see Figure 4).



Figure 4. Historical building—secondary school in Karcag.

3.2.1. BIM (Building Information Modeling) of the Building

Building information modeling, i.e., BIM, is a method that allows the design, implementation, and optimization of individual industry processes using a 3D model [30,31]. This type of modeling ensures that all information about a given building becomes available in one place, covering all disciplines. The BIM model includes an architectural model, a structural model, an MEP model, and linked databases. The great advantage of this method is that it shortens each workflow by making relevant information available even at the design stage. After a brief introduction, the paper will now focus on the presentation of the created BIM model, as well as the presentation of the energy analyses performed on the building. The building was modelled using software called Revit, an Autodesk product (see Figure 5). As the first step in modeling, we determined exactly what “workset” settings were necessary during modeling. The use of a “workset” is important because it helps to systematize and increase the transparency of the model.

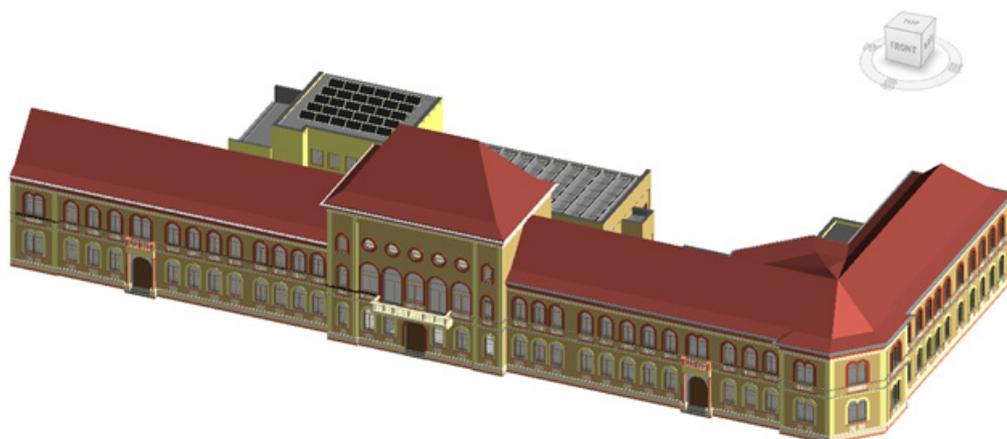


Figure 5. The BIM model of the building.

3.2.2. Calculation Results on the U-Values of the Building

To determine the positive effects of the thermal insulation applied to the wall, the overall heat transfer coefficients (U-value, W/m^2K) were calculated with the following equation:

$$U = 1/((1/\alpha_i) + \Sigma(d/\lambda) + (1/\alpha_e)) \quad (1)$$

where d (m) is the thickness of the layer, λ (W/mK), and α_i and α_e (W/m^2K) are the internal and external surface heat transfer coefficients, respectively. The base wall was a 50 cm-thick small solid brick, covered with 1.5 cm-thick plaster at both sides. For the calculations, the measured thermal conductivities of the insulations were used. The results can be found in Table 4. It can be concluded that the application of the 3 cm-thick EPS/VIP sandwich panel results in a 70% reduction of the U-value while the 1 cm-thick Slentex decreases it from 1.296 to 0.741 W/m^2K .

Table 4. The overall heat transfer coefficients.

Case	U-Value (W/m^2K)
U-value before renovation	1.296
U-value with the Slentex insulation	0.741
U-value with VIP	0.429

3.2.3. Cost Calculations—Use of Natural Gas

We assessed the energy condition of the building through the energy certificate and the yearly energy use. From these, one can estimate that with the use of the vacuum insulation panel, approximately 30% energy savings can be expected (see Table 5). In Table 5, the calculation results of the energetic performance of the three cases are also presented. The calculations regarding the energetic performance were executed by the 7/2006 decree issued by the minister without portfolio. For the calculations, the measured thermal conductivities were used. In Appendix A, Table A1, we present the most important constructional and building services system parameters of the building. After the refurbishment of the external wall with VIP, we reached a 66% reduction in the primary energy consumption of the building.

Table 5. Results of energetic calculations.

State of the Building	E_p Specific Primary Energy Consumption ($kWh/m^2/year$)	Energetic Category According to 7/2006 Decree in Hungary	Yearly Use of Natural Gas (MWh/year)	Savings Compared to the Current State (%)
Current	112.87	DD (up-to-date)	391.15	-
With Slentex	93.33	CC (modern)	328.48	16
With VIP	75.46	CC (modern)	273.44	30

3.2.4. Cost of Renovation—Thermal Insulation

A rough cost calculation was executed depending on the market price of the insulation and the function of the total free surface to be insulated. The total surface to be insulated is 2197.3 m^2 . By using the actual market price of the Slentex of approximately 95 Euro/ m^2 and the VIP (about 100 Euro/ m^2), the total costs were also estimated and were found to be approximately 207,000 and 220,000 Euros as full insulation costs. It must be mentioned that the cost of the VIP is greater, but the potential energy saving is twice as much as in the case of Slentex. The calculations for the savings were executed using the yearly gas usage, between the values of the original building and the modelled building. It should be concluded that the costs for the insulation with VIP and the aerogel seem too

high compared to the value of other conventional methods of insulation (e.g., expanded polystyrene). However, from a sustainability point of view and in terms of conservation, the use of super insulation materials would be beneficial with respect to space, as it is also mentioned in Refs. [14–17] and Refs. [32,33]. In contrast to those papers [15,17,32], where the implementation of the aerogel-based refurbishment was presented, the novelty of our paper is the use of measured thermal conductivities for energy calculations for buildings and the possible application in Hungary. Nowadays, in the western countries of the EU, the use of super insulation materials may not be a problem, while in other countries, the possible application of SIMs has only reached a theoretical level. Moreover, our goal was to present the early design phase of refurbishment.

4. Conclusions

In Europe, the use of super thermal insulation materials in historical buildings is receiving increasing attention. This is mainly due to the innovations and regulations that have taken place in certain Western European countries. Highlights include Switzerland, for example, where the use of super-thermal insulation materials for insulation is highly recommended when refurbishing historical buildings. Due to these notions, their domestic spread and regulation may be expected soon. We performed measurements and made calculations based on experiments from an energy point of view. The thermal conductivity values of the abovementioned super insulation materials were measured, such as the Slentex aerogel and encapsulated vacuum insulation panels, and the values reached approximately 0.022 and 0.021 W/mK for the 1 cm-thick Slentex and the 3 cm-thick VIP, respectively. Based on the results, one can conclude that the examined vacuum insulation panel has more benefits from an energetic point of view; however, its costs are greater. It must be mentioned here that this advantage comes from the nature of this insulation, because the thickness of this insulation is 3 cm in its entirety. It must be also concluded that the use of the tested materials is promising from an energetic refurbishment point of view for historical buildings. It was also shown that by using super insulation materials in such a thin layer, energy savings of approximately 15–30% can be reached in historical buildings, thus increasing their energetic category. Another interesting result to be highlighted is the reduction of the natural gas usage of the building to about 70%–85% compared to the initial state. Furthermore, the yearly primary energy consumption can also be reduced.

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Appendix A

Table A1. Model building parameters—original state.

Building Element	Information
External wall:	50 cm thick solid brick with 1.5 cm thick plaster at both sides.
Internal walls between internal heated spaces:	brick walls with 10 to 20 cm thicknesses
Windows:	$U_w = 1.15 \text{ W/m}^2\text{K}$, glazing ratio 80%, g-value of glazing: 0.87.
Doors:	$U_d = 1.15/1.45 \text{ W/m}^2\text{K}$.
Attic floor:	0.55/0.876 $\text{W/m}^2\text{K}$
Floor:	0.554 $\text{W/m}^2\text{K}$
Heating and hot water system:	Condensing gas boilers (VIESSMANN Vitodens 200-W—3 pieces) with two round radiators (60/40 °C).
Electricity:	120 db KYOCERA KD 245GH-2PB 245Wp solar panel, produces 32,340 kWh/year electric energy

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