

Thermal analysis of aerogels and their vacuum-formed forms, their potential uses, and their effects on the environment

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ABSTRACT

The main topic of the paper is to investigate the thermal examination of aerogels and their vacuum-formed forms, application possibilities, and environmental impact. In the paper, the thermal conductivity of homemade vacuum insulation panels was tested with different silica-based core materials. Three types of fibrous aerogel materials were used as core materials; another silica-based microporous insulation was used as a filling material. Microscopic images were taken from the core materials; furthermore, the thermal conductivities of both base materials and their vacuum-formed form were also tested at different mean temperatures (0, 10 and 20 °C). The results regarding the applicability of these materials as filling-core materials for vacuum insulation panels are interesting. The results showed that for microtherm and pyrogel, the thermal conductivities decreased more than 15%, while for the spaceloft and slentex it was about 8 and 2%, respectively, after evacuating the air. The paper also presents compressibility changes of the samples after vacuumization. The results were used as a basis for building energetic calculations; furthermore, the comparison of different materials from their carbon footprint point of view was also presented. These calculations depicted aerogel's very long payback time with a current market price.

1. Introduction

To meet the Net Zero Emission Scenario and address energy poverty and efficiency, thermal insulation should be installed in existing structures [1]. Thermal insulation materials have been known and used since the beginning of humanity [2]. The development of these materials is closely related to the recoverable amount and affordability of energy carriers [3]. Nowadays, the nature-damaging effects of specific industries are becoming increasingly problematic. It is no different in the construction industry. Creating currently used insulation materials requires a lot of hydrocarbons (fossil energy). Using insulation materials for other purposes is challenging, but their destruction also often damages our environment.

Starting from the middle of the 19th century, materials of animal and vegetable origin were replaced by the preparation of different materials still connected to nature (bricks filled with ash), which further improved the thermal insulation ability [2]. From the second half of the century until the first decades of the 20th century, many experiments were related to creating artificial insulating materials [4]. Many such materials have not entered the public consciousness due to their short lifespan and unfavourable properties. The well-known stone wool also appeared in these years, and it became more widespread years later. The start of mass production of plastics in the middle of the 20th century brought a new perspective to the construction industry. Plastics such as polystyrene foam and artificially improved insulation materials (mineral wool, glass wool) became the most popular insulation materials of the era [5]. With the spread of artificial insulation, the use of natural materials declined. The development of insulation materials accelerated in

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the 1970s due to external economic factors (oil crisis) [6]. Then, people became widely aware that the Earth's supply of energy carriers is finite.

For this reason, it has become important not to use as many energy carriers as possible. During this period, polystyrene foam (EPS) and polyurethane foam (XPS) products continued to develop [7]. At the beginning of the 21st century, new insulating material alternatives appeared continuously with the development of technology [8,9]. Aerogels and vacuum panels can be classified as super thermal insulations [10–14]. The paper particularly emphasises the measurement of the thermal conductivity coefficient with a heat flow meter, which is the most crucial component of classifying an insulating material. In the second stage, thermal insulation materials will be presented. Then, the paper will show the measurement methods used, where the measurement of the thermal conductivity factor will be written in greater detail. After these, the paper presents an uninsulated model building in which heat demand will be determined before and after insulating. After selecting the heat requirement of the insulated house, the calculation of the financial return for the unit of aerogel insulation and the currently most widely used thermal insulation materials of equivalent thickness is presented. In the next unit, the paper will present the harmful emissions caused by the production and transport of individual insulating materials. Then, it will be examined how long it took for a gas boiler to emit as many harmful substances during the heating period as are generated from the production of each insulating material to its use.

1.1. Thermal insulation materials

One could almost call a material a heat-insulating material since the material prevents the spread of heat through a surface [2]. This is because the properties of materials include the ability to conduct heat. Insulation materials can be natural, artificial, fibrous, hollow, or porous [7]. The cavities are filled with air or some gas, so the density of these insulating materials is relatively low [15].

Fibre heat insulators: Fibrous materials comprise thin (micro-sized) fibres, and among them, the air layer is trapped, thus ensuring sufficient insulation [16].

Porous heat insulators: Porous thermal insulation materials include thermal insulation foams; a significant part of the insulation capacity is due to the formation of bubbles in the insulation material during their preparation [17]. Porous thermal insulation materials are primarily found in VIP panels. In this case, tiny pores are formed during preparation due to the bulking. Modern thermal insulation panels have nanopores close to an air molecule's size [18–25]. Several essential aspects must be examined to choose the suitable thermal insulation material for a specific system. Typically, as in all fields of mechanical engineering, standards apply to these materials, and there are expected demands.

The study's originality and novelty lie in its thorough introduction to thermal insulation materials; moreover, it will be easier for scientists, researchers, designers, developers, and practitioners to understand the thermal properties of aerogels. The paper will show the possible degree of reducing the thermal conductivity of silica-based materials after vacuuming them and creating silica-based pilot vacuum insulation panels. These results open new possibilities and raise future research opportunities. The article also gives new and vital results by comparing the carbon footprint of different insulation materials.

2. Materials and methods

2.1. Aerogels

The history of aerogels can be traced back to the early 1930s. The basis of its production is that the liquid components of the gels are replaced with a gaseous substance. The first aerogels were silica aerogels, produced from silicon dioxide, which is still the most widely studied and used aerogel [26]. Its two main groups are organic and inorganic aerogels. The classification of an aerogel depends on the nature of the material used. The distinguishing feature of organic aerogels is that they are more resistant to mechanical pressure (which is also why they are less fragile) than inorganic aerogels. Among the aerogels, the most researched are silica-based aerogels. It has many favourable physical properties, the most outstanding of which is its thermal conductivity and extremely low density. It is also a sought-after material due to its large internal surface. Its advantages are its soundproofing ability and the fact that the dielectric constant is also deficient. It can be said that silica aerogels have favourable properties that apply to all disciplines. For promotion: aeronautics, medicine, pharmacy. Their practical use could be even more comprehensive, but these materials, like silicates, are pretty brittle so that they can be damaged even by hand. Therefore, much research is being done to increase the mechanical toughness of silica aerogels. Its properties (both chemical and physical) can be significantly improved if organic groups are introduced into the inorganic framework. This is called organic-inorganic hybridisation. With this activity, one can preserve the favourable properties of inorganic aerogels. They are sensitive to moisture, and their extensive specific surface area binds water vapour, which damages their macroscopic structure. It loses its dimensional stability at high temperatures, and its mechanical strength will be meagre [27–37]. It is written in Ref. [38] that aerogels and vacuum insulation panels can be used for building refurbishment because they can be used either inside or outside the wall due to their high thermal performance. They can also be used in thinner thicknesses compared to other conventional insulations. It is well presented in Ref. [39] aerogels can also be used as insulation after blowing them. Cuce et al. further states that aerogels provide excellent comfort rates in indoor environments [40]. They also state that the price of this material is much higher than that of conventional insulations. Lucchi presents in Ref. [41] historic buildings can also use that aerogel.

2.1.1. Spaceloft aerogel

Spaceloft thermal insulation material is a nanoporous aerogel quilt insulation easily applied to floors and exterior and interior walls. Silica aerogel was reinforced with glass fibre to create an insulating material with more comprehensive industrial applications. As it is air and vapour-permeable, it leaves the walls ventilated. Due to its flexibility and easy deformability, it can also be used for

monumental buildings, as it quickly absorbs any unevenness of the wall. Compared to the other thermal insulation materials presented so far, this has a much better thermal conductivity because at 10 °C, this value is 0.013 W/mK. Its density is 150 kg/m³. The manufacturer maximises its application at 200 °C and is rated “C” regarding its fire protection class. This aerogel thermal insulation quilt is available in the construction industry and has a thickness of 5 and 10 mm [42].

2.1.2. Slentex aerogel

The Slentex aerogel thermal insulation quilt (Spaceloft A2) is an improved version of Spaceloft. What differs the most from its predecessor is that it is not flammable. It is flammable. Because of these two properties, it can be used in places with no other option for fire protection. It has retained its flexibility, vapour and air permeability, so this type can also be used in historic buildings. It is commercially available with a thickness of 10 mm [43].

2.1.3. Pyrogel aerogel

Pyrogel is a silica aerogel that can function well at very high temperatures. One talks about a very flexible material, the property of which is that it was mainly designed to insulate pipes. Its thermal conductivity, even at 50 °C is 0.0163 W/mK, which is relatively high compared to other thermal insulation materials [44].

2.1.4. Microtherm

What differs from the thermal insulation presented so far is that the lambda value remains low even at extremely high and low temperatures. At 800 °C it is 0.034 W/mK, and at −170 °C. this value decreases to 0.015 W/mK. It is non-combustible, and to avoid thermal bridges, larger and unique pieces can be made from it [45].

2.1.5. Vacuum insulation panels

The fact that a vacuum can provide good insulation has been known for more than a century. According to scientific facts, no better thermal insulator exists than a vacuum. In 1930, the first rubber vacuum panel, which contained a porous material, appeared. Significant breakthroughs came after the appearance of aerogels, as the thermal conductivity of nanostructured materials was much better than those previously known. The first vacuum panel was made in 1963 [19–21]. The construction of vacuum panels is as follows: it consists of a core material and the material covering it. The core material can be fibrous, diatomaceous earth, nano-silica powder and plastic foam. The coating material can only be steel foil, but according to the newer method, this coating material must consist of two different materials: steel foil and PE foil. This way, a longer service life is achieved, as the mechanical protection is more outstanding. To keep the vacuum rate inside for as long as possible, getter material must be placed inside the panel in addition to the core material because it will bind the molecules that have infiltrated during its lifetime [21–24]. Its advantage is its excellent thermal conductivity, with a 0.0045–0.008 W/mK value.

Furthermore, the panel is completely waterproof and does not absorb or let any moisture through. Therefore, it can be used to insulate flat roofs and terraces. The latest vacuum panels are also entirely fireproof, thanks to the outer skin of a very thin brominated acrylic copolymer. Among its disadvantages is that it is easy to damage, and even slight damage can destroy the vacuum panel.

For example, the vacuum panels used to insulate the house must be considered as if all the panels are damaged. Among the harmful properties of the vacuum panel, it should also be mentioned that you already know when these vacuum panels will have to be replaced. Therefore, these should not be incorporated into the wall structure, so their replacement requires too much material and time [46].

2.2. Thermal conductivity measurements

Four materials were tested. Three were aerogels (Spaceloft, Slentex, Pyrogel), and the last was a Microtherm microporous silica-based material. As a first step, all four types of thermal insulation materials were placed in a drying chamber (Venticell 111) at 70 °C till no mass changes. Before the thermal conductivity measurements, they were conditioned at about 25 °C. After the suitable samples became ready, their weight and the length and width of their sides were measured; parallel to this, their mass was also registered. After that, the equipment determined the value of each sample's thermal conductivity, a Netzsch Lambda HFM 446 measuring instrument, at 0, 10 and 20 °C degrees temperature with 20 °C temperature difference at our disposal in the laboratory. The Netzsch Lambda HFM 446 measuring instrument can measure the thermal conductivity of insulating materials, polymers, aerogels, and non-woven materials. The measuring device was developed based on the following standards: ASTM C518, ISO 8301, JIS A1412, DIN EN 12664 and DIN EN 12667. The manufacturer offers two ways to view the measurement results. The more straightforward way is to look at the paper printed by the printer integrated into the device and connect it to a desktop computer to view the measured results outside the lab. The two sheets of the instrument are uniformly 20 cm × 20 cm in size. Depending on the setting, the instrument can load the measured material. Using this opportunity, the compressibilities (thickness changes) were also registered before and after evacuating the air. You can also produce the appropriate temperature difference by heating these sheets. The precise heat current meters on the two sheets are responsible for the final result. Next, the air was evacuated from the samples with a commercially available vacuum laminating machine. Then, the thermal conductivity value of the vacuumed samples was reached. After this, the obtained values were compared. Then, the samples were measured with the instrument after trying to cut out a 17 cm × 17 cm area of material from the individual aerogels, since the size of the vacuum bags did not allow the samples to be larger than this.

2.3. Vacuumization

The vacuumization was executed with a SilverCrest vacuum lamination equipment. The type of vacuum laminator is SV 125 C6, capable of 125 W. Its maximum working length is 300 mm, and it can solder plastic after vacuuming. A 0.75 bar vacuum pump extracts the air. In Fig. 1, one can see the vacuumed samples in the plastic bag.

Microscopic images were taken from the surface with about $20\text{--}30\times$ magnification with an optical microscope (see Fig. 2). The photo-images show that all samples have a fibre reinforcement (usually glass) and a porous silica structure.

3. Results and discussion

3.1. Thermal conductivity measurement results

In Table 1, one can see the base data of the tested materials. For the thermal conductivity measurements, it is required to know the length of the sides of the samples, their dry mass and the thicknesses, which was measured with the in-built calliper of the Netzsch equipment. From these, the equipment calculates the density of the samples, which is used to determine the thermal conductivities.

Tables 2–5 present the measured thermal conductivities of the microtherm, pyrogel, spaceloft and slentex samples before vacuumization. The thermal conductivities for the microtherm are among 0.024 W/mK and 0.025 W/mK , for the pyrogel $0.02\text{--}0.0212$, for the spaceloft $0.018\text{--}0.0192$, while for the slentex $0.018\text{--}0.0186\text{ W/mK}$. It must be emphasized that these thermal conductivities are much better (=less) than the conventional polystyrene or mineral wool samples.

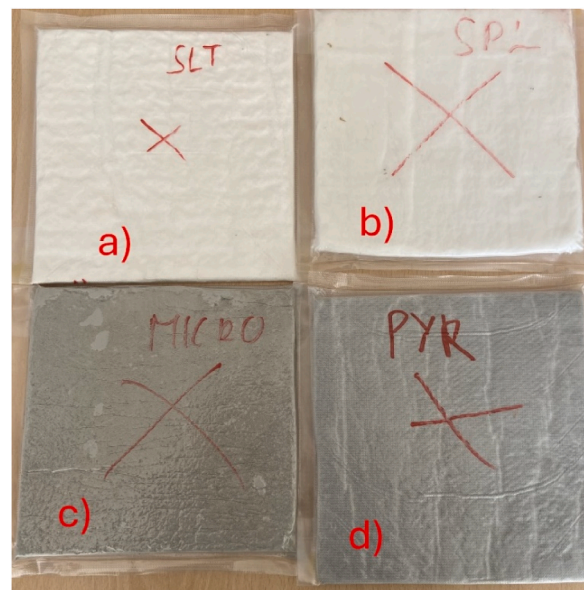


Fig. 1. The vacuumed samples: a) Slentex, b) Spaceloft, c) Microtherm, d) Pyrogel.

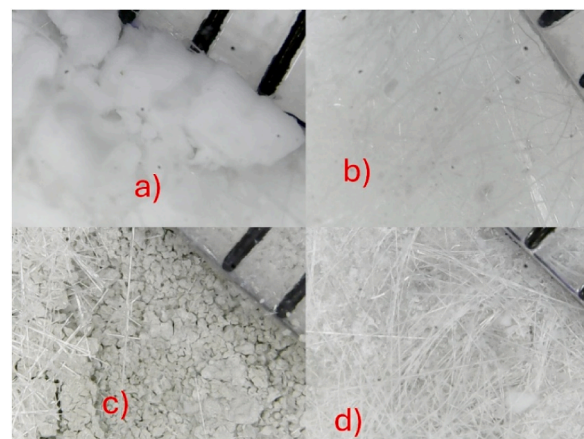


Fig. 2. The microscopic image of the samples a) Slentex, b) Spaceloft, c) Microtherm, b) Pyrogel.

Table 1

The Tested material's data.

Material	Length: [cm]	Width: [cm]	Mass: [g]	Thickness: [cm]
Microtherm	16.9	17.05	90.95	1.00
Pyrogel	17	17.25	59.85	0.95
Spaceloft	17.3	17.2	43.1	1.02
Slentex	17	17.15	48.9	0.99

Table 2

Thermal conductivity of Microtherm.

Microtherm	Temperature		Thermal conductivity	Rel. err.
	Mean	Delta		
	[°C]	[K]		
1	0	20	0.024	2.2
2	10	20	0.0247	2.22
3	20	20	0.025	2.22

Table 3

Thermal conductivity of Pyrogel aerogel.

Pyrogél	Temperature		Thermal conductivity	Rel. err.
	Mean	Delta		
	[°C]	[K]		
1	0	20	0.0205	2.4
2	10	20	0.0209	2.34
3	20	20	0.0212	2.34

Table 4

Thermal conductivity of Spaceloft aerogel.

Spaceloft	Temperature		Thermal conductivity	Rel. err.
	Mean	Delta		
	[°C]	[K]		
1	0	20	0.0184	2.2
2	10	20	0.0188	2.19
3	20	20	0.0192	2.189

Table 5

Thermal conductivity of Slentex aerogel.

Slentex	Temperature		Thermal conductivity	Rel. err.
	Mean	Delta		
	[°C]	[K]		
1	0	20	0.018	2.3
2	10	20	0.0183	2.26
3	20	20	0.0186	2.258

It can be seen from the rows of tables (2–5) that the Slentex aerogel has the lowest thermal conductivity, while the worst (highest lambda value) among them belongs to the Microtherm thermal insulation material with a thermal conductivity of 0.025 W/m*K at an average temperature of 10 °C.

The next step in the measurement was placing the previous materials in vacuum (polymer) foil and vacuuming them. As a result, its external parameters (mass and thickness) also changed, which are collected in [Table 6](#).

The soldered side of the evacuated thermal insulation materials was folded back in the film and glued down. After the glue had dried, the thermal conductivities using the Netzsch heat flow meter equipment were re-measured. The results are presented in [Tables 7–10](#). All the thermal conductivities decreased due to the vacuumization. The percental changes of the thermal conductivities are presented in [Fig. 3](#).

Table 6

Material data of vacuumed samples.

Material	Length: [cm]	Width: [cm]	Mass: [g]	Thickness: [cm]
Microtherm	16.9	17.05	97.9	1.01
Pyrogel	17	17.25	68.3	0.882
Spaceloft	17.3	17.2	50.55	0.95
Slentex	17	17.15	52.55	1.01

Table 7

Thermal conductivity results of vacuumed Microtherm.

Microtherm	Temperature		Thermal conductivity	Rel. err.
	Mean	Delta		
	[°C]	[K]		
1	0	20	0.0198	2.2
2	10	20	0.0203	2.21
3	20	20	0.021	2.2

Table 8

Thermal conductivity results of vacuumed Pyrogel insulation.

Pyrogel	Temperature		Thermal conductivity	Rel. err.
	Mean	Delta		
	[°C]	[K]		
1	0	20	0.0172	2.5
2	10	20	0.0177	2.49
3	20	20	0.0182	2.486

Table 9

Thermal conductivity results of vacuumized Spaceloft aerogel.

Spaceloft	Temperature		Thermal conductivity	Rel. err.
	Mean	Delta		
	[°C]	[K]		
1	0	20	0.0167	2.2
2	10	20	0.0172	2.45
3	20	20	0.0178	2.45

Table 10

Thermal conductivity results of vacuumized Slentex aerogel.

Slentex	Temperature		Thermal conductivity	Rel. err.
	Mean	Delta		
	[°C]	[K]		
1	0	20	0.0174	2.2
2	10	20	0.0178	2.21
3	20	20	0.0184	2.21

Fig. 3 shows that after vacuumization, the thermal conductivity value decreased in all cases. By comparing the original thermal conductivities with those after vacuuming, one can obtain the percental reduction of the thermal conductivities shown in the figure below (see Fig. 4).

Fig. 4 shows that the highest percental decrease in thermal conductivity belongs to microtherm (approx. 18%), followed by pyrogels, with a more than 15% change. The thermal conductivity of the spaceloft reduction is about 8%, while the change in thermal conductivity of the slentex is about 2–3%.

The reason for the decrease in thermal conductivity is clearly presented in Ref. [13], It is the latest paper by one of the authors. Now, the paper will give a brief overview of this. Aerogels have nanopores, where the gas particles are trapped since both the heat conduction and convection inside the pores are reduced. But, fibrous aerogel thermal insulation can contain more air among the fi-

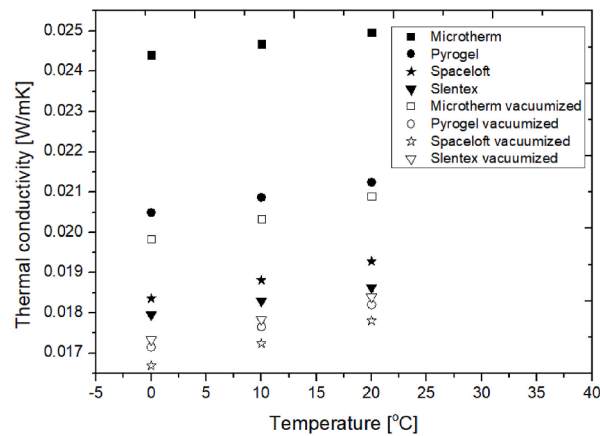


Fig. 3. The measured thermal conductivity values of all samples before and after vacuumization.

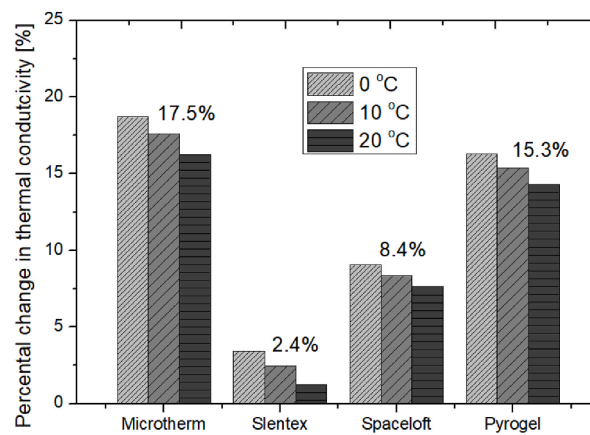


Fig. 4. The percent decrease in the thermal conductivity values after vacuumization.

bres than a monolith. However, after the vacuumization process (evacuation of the air), the thermal conductivity can be reduced by decreasing the conduction and convection of air molecules.

3.2. Load vs compressibility

Netzsch HFM 446 lambda equipment contains an in-built part that measures thermal conductivities under load from 0.5 to 15 kPa. In Fig. 5 and b, the paper presented the results of the relative change in the thickness of the samples after applying load on them. A

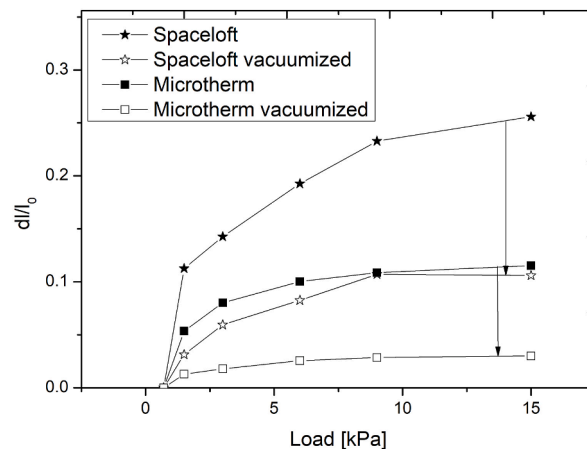


Fig. 5. a. Load versus compressibility test results (spaceloft and microtherm).

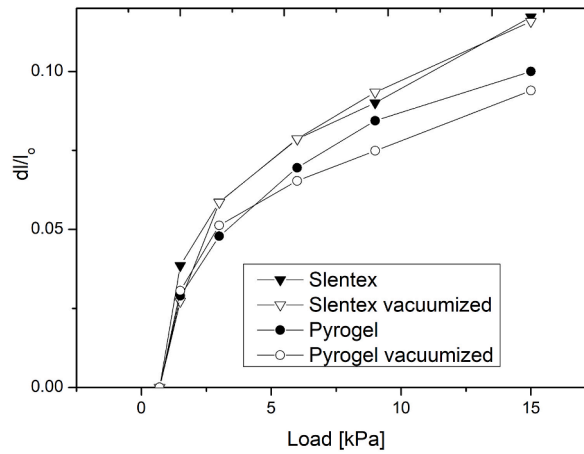


Fig. 5. b. Load versus compressibility test results (slentex and pyrogel).

significant change was observed for the spaceloft and the microtherm, while the slentex and pyrogel change was insignificant before and after vacuumization. This equipment unit can also be used for compressibility tests without measuring the thermal conductivity.

3.3. Building energetic calculations

3.3.1. Heat demand calculations

As a basis for measuring thermal conductivity, building energetic calculations were executed on a model house to assess the samples' applicability. Firstly, the overall heat transfer coefficient (U-value, W/m^2K) of the wall structure was calculated by using the following equation:

$$U = 1/((1/h_i) + (\Sigma(d/\lambda)) + (1/h_e)) \quad (1)$$

where d is the thickness (in m), λ (W/mK) is the thermal conductivity, and h_i and h_e is the internal and external heat transfer coefficients (in W/m^2K), respectively.

The heat demand of the house was calculated as follows:

$$Q = Q_k + Q_f \quad (2)$$

Where Q_k is the transmission, while Q_f is the filtration energy flow, for the external design, temperature $t_e = -15^\circ C$ was chosen for the localisation in Debrecen, Hungary.

$$Q_k = \Sigma UA(t_i - t_e) \quad (3)$$

where U is the overall heat transfer coefficient, calculated by using Eq. (1), A is the internal surface of the wall structure in contact with the external environment (m^2) – For internal transmission heat flow, the internal wall structure's surface – and t_i is the internal room temperature.

$$Q_f = c_p V n (t_i - t_e)$$

where n is the air change rate (1/h), V (m^3) is the volume of the room, ρ (kg/m^3) is the density of the fresh air, and c is the specific heat capacity of the air (J/kgK).

Then, Table 11 presents the available data and properties of the buildings.

After this, the overall heat transfer coefficient of the external wall covered with the spaceloft insulation with a thickness of 1 cm was calculated. For the calculations, a thermal conductivity of 0.0135 W/mK and 1 cm for the thickness taken from the datasheet of this material [42] were used. This value reduced the above U-value to 0.63 W/m^2K . For comparison, two conventional thermal insulations, mineral wool and expanded polystyrene, with 30 mm thicknesses and 0.039 and 0.0393 W/mK thermal conductivities, were chosen, respectively. Using these, the U-value can be reduced to $U = 0.62 W/m^2K$, comparable to the abovementioned $U = 0.63 W/m^2K$. In the calculations, these were the same values as the aerogel.

Table 12 presents the heat demands of the rooms of the model building.

The building was supposed to be heated only with gas to meet the winter heat needs. It was found that the building's gas use to be 1497 m^3 annually. For this, the yearly cost of the building for gas is about 400 euros.

3.3.2. Payback calculations

If one insulates this building with the materials tested so far, the initial heat demand is reduced to 80%. This 20% reduction means that the gas consumption will decrease by 20%, so the recent consumption will be 1198 m^3 . This difference, which is 299 m^3 , means

Table 11

The data of the model building.

Base area (m ²)	67.12
Net base area (m ²)	51.32
Internal height (m)	2.8
External wall [cm]	adobe
U-value of the external wall [W/m ² K]	1.181
Windows U-value (W/m ² K)	1.2
Wall areas (m ²)	
North	18.424
South	21.664
West	22.068
East	19.898
Sum	82.054
Window ledge	2.06
Sum	84.114
Applied area to be insulated	90

Table 12

The heat demand.

Room	Heat demand (W)	
	Without insulation	With insulation
Hall	1030	810
Kitchen	844	715
Room	2112	1680
Living room	1631	1294
Bathroom	1281	1017
Sum	6898	5516

that the annual saving is less than 100 euros. From the market price and the saved money, one can calculate the payback cost of each material (see Table 13) (see Table 14).

Since 100 Euros can be saved annually for the model building, the payback of the cost of the insulation material at the current discount price of natural gas and insulation material is 2.12, 6.89, and 69.27 years.

The last value is relatively high, as the production cost of aerogels is currently expensive. According to some specialised literature [47], this current price may drop by as much as 70–90% in the coming years. Converted to Eur, a square meter of aerogel insulating material can be reduced to 5 Euro. As a positive feature, I would like to mention that a significant part of these aerogels are available in running meters, which will reduce the thermal bridge. They can also produce unique aerogels, which are not cheaper but can reduce the number of thermal bridges to a minimum.

In the cities, you can find smaller and smaller plots of land and house sites, so houses with smaller and smaller net floor areas can be built due to the imposed construction laws, which maximise the height and floor area of the house to be made. It can also be a problem in cases where the facade of a building to be renovated falls on the plot boundary from the street since the minimum distance between the houses on both sides of the street is defined, so they may not be able to insulate that facade sufficiently because of this. This affects insulations because they are trying to create materials with ever smaller thicknesses but with super low lambda values. This aerogel is a perfect example of this. Thus, it should not be overlooked that the aerogel, in this case, also has a thickness three or four times smaller than the thickness of the other two traditional insulating materials.

Table 13

Return and cost.

	Market price (Eur/m ²)	Cost (Eur)	Return (years)
EPS	2	160	2.12
Mineral wool	6	526	6.89
Spaceloft	60	5300	69.27

Table 14

GWP and CO2eq with return.

	Volume (m ³ /m ²)	GWP (kgCO2eq/m ²)	CO2 equivalent (kgCO2eq)	Return (years)
EPS	0.0393	3.69	249.813	0.433
Mineral wool	0.0393	3.78	340.2	0.59
Aerogel	0.0131	12.5	1125	1.95

3.4. 3.4.CO2 carbon footprints of the tested insulation materials

This section will show how much carbon dioxide is equivalent to the harmful substances produced by the production, manufacture, and transportation of the raw materials belonging to each thermal insulation material. After that, it will be discussed how long it is possible to heat the house without insulation with the current heat generator. One supposes that its harmful emissions are equal to the carbon dioxide equivalent of the harmful emissions of the insulation material used. The life cycle analysis of individual materials (LCA-Life Cycle Assessment) was considered during the calculations. Here, it is used as predefined GWP (Global Warming Potential) values to quantify the greenhouse effect of gases. The amount of materials required to insulate the outer surface of the house (external wall area 90 m^2), thus, the volume of the insulating material placed on the house in the case of EPS and rock wool is 2.7 m^3 , while in the case of aerogel it is 0.9 m^3 .

3.4.1. The carbon footprint of EPS

Most of the EPS produced today are almost entirely recyclable. The only problem is that the storage takes up much space, so you need proper storage places to collect them. The EPS's GWP value was obtained by averaging several data, approximately $3.69 \text{ kg-CO}_2\text{eq}$. This means that the environmental impact of 3.69 kg of carbon dioxide emissions is equal to the amount of harmful substances is released into the environment during the production of EPS with heat transfer resistance of 1 m^2 and $R = 1 (\text{m}^2 \text{ K})/\text{W}$ [48–56]. The largest share of this, 70%, is generated during raw material production. To meet the heat transfer resistance of $R = 1 (\text{m}^2 \text{ K})/\text{W}$, one has to choose a thickness of 39.3 mm . This will result in one square meter of this material being 0.0393 m^3 . If one divides the required volume of the thermal insulation material by this value, one gets that $2.7/0.0393 = 68.7$ units are needed for the outer wall. This number is multiplied by the GWP value to obtain the emissions of the insulating material used to insulate the house, which is $68.7 * 3.69 = 249.813 \text{ kgCO}_2\text{eq}$.

3.4.2. The carbon footprint of mineral wool

This insulation material can also be reused several times, which can be used to reduce the burden on the environment in the long term. The density of the material that was chosen was 140 kg/m^3 . The value of GWP per kilogram is $0.9 \text{ kgCO}_2\text{eq}$. In our case, to meet the heat transfer resistance of $R = 1 (\text{m}^2 \text{ K})/\text{W}$, a thickness of 39 mm must be chosen. Since the quantity to be insulated is 2.7 m^3 , the weight of the insulating material used for the wall is $140 * 2.7 = 378 \text{ kg}$. Thus, the mass per square meter is $378/90 = 4.2$. Since the GWP value per kilogram is $0.9 \text{ kgCO}_2\text{eq}$, the GWP value per square meter is $4.2 * 0.9 = 3.78 \text{ kgCO}_2\text{eq}$. Therefore, the insulated surface's value is $340.2 \text{ kgCO}_2\text{eq}$ [48].

3.4.3. The carbon footprint of aerogel

Aerogels with the best properties can be prepared by drying them with carbon dioxide in a supercritical state [57–59]. This results in high carbon dioxide emissions, but it is also connected to another high-emission process: silica extraction from quartz. This can only be cleaned of impurities at high temperatures. Moreover, Ref. [56] presents results on the environmental impact of a silica aerogel-based fibre reinforced renders environmental impact. They found that raw materials significantly contribute to the aerogel-based thermal render's environmental performance, accounting for over 95% of its environmental impacts. The silica aerogel synthesis emerged as the primary contributor (+90%) to the environmental effects due to the use of isopropanol and electricity for drying.

To some extent, carbon dioxide can be recovered with the help of a suitable machine, so both the cost of production and emissions are reduced. Averaged from several sources, the GWP value projected per unit surface is $12.5 \text{ kgCO}_2\text{eq}$. It is noticeable that this has the highest value among the three insulating materials investigated. It is calculated for 90 square meters as $1125 \text{ kgCO}_2\text{eq}$ [48,50,60]. Furthermore, it is interesting that Cuce, in Ref. [51], if coal is used as an energy source, aerogel-based thermal superinsulation reduces CO_2 emissions for non-insulated cavity walls by 86.4% and for insulated cavity walls by 55.2%. Thus, with noticeably thinner insulation thicknesses, aerogel insulation produces more significant greenhouse gas emission mitigation [51]. In Ref. [61] It was presented that aerogel's environmental impact data relates to its laboratory production; it is predicted that these values will drop as the production scales up in the industry, albeit it is impossible to pinpoint the precise amount of that reduction. It was presented in Ref. [62] that aerogel glazing systems (windows) have a higher potential to save carbon compared to double and triple-glazing systems. Ref. [63] presents the LCA analysis of thermal insulation materials through a review article. They depicted that stone wool is marginally more frequently positive than PUR and slightly more frequently negative than glass wool and EPS. Only 47% of the time is stone wool superior, especially when combined with EPS.

3.4.4. Carbon footprint payback for the discussed insulation materials

The model building emits greenhouse gases when burning natural gas. This equates to approximately 0.20 kg of CO_2 per kWh. The heating value of gas is 34.71 MJ/m^3 , so one m^3 of gas stores 9.64 kWh of energy. Thus, by burning one m^3 of natural gas, man burdens the environment with $1.928 \text{ kgCO}_2\text{eq}$. Looking back, one can see that after the insulation, 299 m^3 less natural gas needs to be used annually, which means $299 * 1.928 = 576.5 \text{ kgCO}_2\text{eq}$ [59].

Since it would emit $576.5 \text{ kgCO}_2\text{eq}$ more in a year if the building were not insulated, one divided this value by the value to find when the preliminary emission will equal the saved emission.

These data show that the carbon footprint of traditional insulating materials is currently 70–75% lower than that of aerogels. Thus, besides the financial differences, it is not worth using aerogels for residential purposes, as opposed to the current insulation materials, from an environmental protection point of view. On the other hand, its positive side is that its thickness makes it more space-saving during transport, so the harmful substances emitted are better distributed over a unit of insulating material. In the future, if one manages to create a cost-effective procedure, one will get different results from both aspects examined.

4. Conclusions

Optimising energy usage and mitigating climate-related concerns need the use of thermal insulation. This element pertains to several applications throughout diverse industries: construction, transportation, automotive, and industrial facilities. In this case, creating these objects requires a precise understanding of the thermal characteristics of the insulation materials. Nominal values given by manufacturers frequently rely on particular measuring settings and tools. This paper presented results in three sections. Firstly, the measured thermal conductivities of different silica-based insulations (three aerogels and microporous silica) at various temperatures (0, 10 and 20 °C) are highlighted. Then, pilot vacuum insulation panels were created after the air was evacuated from the samples. The paper presented percental reductions in thermal conductivity. Also, in this section, the article showed, through compressibility tests, that spaceloft and microtherm become more rigid after vacuuming them. At the same time, slentex and pyrogel did not suffer significant changes in the thickness after vacuumization. In section 2, through a model building, the possible application of aerogels, expanded polystyrene and mineral wool for reducing the heat demand of the building was shown. Payback calculations were also represented. Finally, the result of comparing the CO2 footprint of these materials (section 3) was also highlighted.

The point-to-point findings of section 1 are as follows:

The percentage reduction calculated for the thermal conductivity of the Microtherm insulation material.

- 0 °C - 18.7 %
- 10 °C - 17.6 %
- 20 °C - 16.2 %

The calculated percentage reduction in the thermal conductivity of the Slentex thermal insulation material.

- 0 °C - 3.4 %
- 10 °C - 2.5 %
- 20 °C - 1.25 %

Percentage reduction of the thermal conductivity coefficient of the Spaceloft thermal insulation material.

- 0 °C - 9.1 %
- 10 °C - 8.4 %
- 20 °C - 7.6 %

The calculated percentage reduction of the thermal conductivity of the Pyrogel thermal insulation material.

- 0 °C - 16.3 %
- 10 °C - 15.4 %
- 20 °C - 14.3 %

It is very clear from the values offered by the thermal insulation materials that their thermal conductivity can be intensely reduced by vacuumization.

Key findings in section 2:

The research examined how much it costs to insulate a typical building in Hungary with one unit of the selected materials. Knowing the building's heat demand and gas bills, it was given to determine what kind of gas savings could be achieved annually. Return of the price of insulating materials needed to insulate the house.

- For EPS material: 2.12 years
- For stone wool material: 6.89 years
- For Spaceloft aerogel: 69.27 years

In the case of the Spaceloft material, it was found that even a smaller amount is enough to reach the heat transfer resistance and get a much larger net floor area. If one changes it to EUR, the payback of the insulating material for insulation drops to 47.78 years. It is also considered for a future case when aerogels will be available at a 70–90% lower cost for their production. In this case, if the area is saved, the price of the insulating material will pay off immediately if the insulation is applied.

In section 3 the environmental impact of the materials was compared. Therefore, the return (payback) of the carbon footprint of each thermal insulation material was calculated. The basis of the calculation was the equivalent amount of non-emitted carbon dioxide calculated from the amount of recovered natural gas, the value of which is 576.5 kgCO₂eq.

- EPS: 0.433 years
- Rockwool: 0.59 years
- Spaceloft: 1.95 years

Payback of the Spaceloft aerogel material takes the most time, which can be reduced with technology development. All the presented results are new, original and essential, it can be significant and exciting to the readers. These results open new possibilities and raise future research opportunities. Based on this, it can be stated that the paper has practical applications for designers and government institutions in renovating buildings.

CRediT authorship contribution statement

Ákos Szabó: Writing – review & editing, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ákos Lakatos:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The 2nd author, Ákos Lakatos is a member of the Editorial Board of the journal. Therefore, the submission was handled by a different member of the editorial team.

Data availability

Data will be made available on request.

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