NA PUTU KA DOSTIZANJU MINIMALNE VREDNOSTI TOPLOTNE PROVODLJIVOSTI TERMOIZOLACIONIH MATERIJALA

ON THE WAY TO REACHING THE MINIMAL THERMAL CONDUCTIVITY VALUE OF THERMAL INSULATION MATERIALS

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Put ka dostizanju minimalne vrednosti toplotne provodljivosti termoizolacionih materijala je od velikog značaja za probleme energetske efikasnosti. Radi poboljšanja termičkih karakteristika tradicionalnih i novih termoizolacionih materijala, sprovode se intenzivna istraživanja sa ciljem dobijanja materijala koji su ekonomski isplativi, a istovremeno poseduju minimalne vrednosti toplotne provodljivosti. Osim toga, reč je i o smanjenju štetnog uticaja na životnu sredinu i postizanju zgrada sa potrošnjom energije bliskom nuli. Rad daje pregled karakteristika sadašnjih i budućih termoizolacionih materijala, navodeći njihove prednosti i nedostatatke. Cilj je da se istraži koji termoizolacioni materijali su na dobrom putu da dostignu minimalne vrednosti toplotne provodljivosti, i eventualno njihove najniže moguće vrednosti. Međutim, i ako bi bio postignut minimum, to istovremeno ne bi značilo da su ovi materijali ispunili sve zahteve potrebne za postizanje održive i zelene gradnje, pa je od velikog značaja poznavanje svih njihovih ograničenja.

Ključne reči: *tradicionalni i budući termoizolacioni materijali; toplotna provodljivost; nanotehnologija; energetska efikanost; prenošenje toplote*

The way to reaching the lowest value of thermal conductivity of thermal insulation materials is highly relevant for issues of energy efficiency. In order to improve thermal characteristics of traditional and new thermal insulation materials, intense research has been conducted with the goal of creating materials that are economically cost effective, and at the same time have the lowest value of thermal conductivity. Furthermore, it is also about reducing harmful effects on the environment and designing buildings with close to zero energy consumption. The paper provides an overview of characteristics of available and future thermal insulation materials, citing their advantages and disadvantages. The goal is to research which thermal insulation materials are on the way to reaching the lowest values of thermal conductivity, and their lowest possible values. Nevertheless, even though the lowest value is reached, that does not mean that these materials fulfill all requirements of sustainable and green buildings, so it is crucial to be knowledgeable about their limitations.

Key words: *traditional and future thermal insulation materials; thermal conductivity; nanotechnology;energy efficiency; heat transfer*

1 Introduction

Efforts to increase energy efficiency, primarily in buildings, are increasing due to increased energy consumption in the construction sector, which contributes a significant share of total global energy consumption (approximately 40%). Besides, buildings are the biggest source of greenhouse gas emissions. These are the reasons for which the buildings in near future will have to reduce to minimal energy consumption (tendency to "zero energy consumption") neaded to provide heating, cooling, air conditioning, lighting etc. Energy consumption in buidlings is determined mostly by building envelope characteristics. Adequate heat insolation is (besides increased energy performance of the HVAC system, lighting system and other appliances) without doubt one of the best and the most cost effective ways for energy saving. Research has shown that improving heat insolation can decrease energy consumption up to 40% [1].

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As it has been established, thermal properties of material are largely determined by thermal conductivity λ [W/mK]. Insight into the fact that different materials have different heat transfer rates existed since the earliest times. When one touches different materials at the same temperature, one would feel different levels of “coldness”, which could not be explained by the existing knowledge.

Figure 1 depicts an experiment from 1789. [1], which showed how some materials conduct heat differently. The apparatus consists of rods made of different metals (i.e. aluminum, brass, copper, zink and iron), but the same size and shape, set along outer wall of a metal box containing boiling water. The rods, penetrating the metal box for a few centimeters, are covered in a thin layer of wax with melting point around 60°C. It was noted that different thermal conductivity of a metal followed by different speed of melting the thin wax layer. This is one the first apparatus for measuring thermal conductivity and it was designed by Dutch J. Inhenhousz (1730-1799). With the technological development that ensued, there was a need to provide numerical definition of λ value.

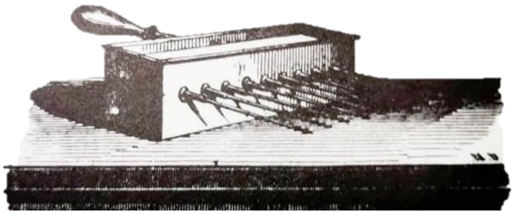


Figure 1. One of the first apparatus for measuring thermal conductivity of materials [2].

To determine thermal conductivity of solid materials experimentally, different methods are used, which include various mathemathical and physical principles, whose application depends on the type of material, the accuracy required and the speed of obtaining results [3]. With stationary method, a material’s thermal conductivity is computed by measuring thermal flux and temperature gradient directly, after achieveing stationary state, i.e. by directly applying Fourier’s Law. Some of these methods are: methods with axial or radial heat flow, the comparative method with axial heat flow, direct electrical heating method, the guarded hot plate method, the fluxmeter method. With non-stationary methods one needs to measure speed of temperature change, which defines thermal diffusivity of a material. Thermal conductivity is them computed based on thermal diffusivity, which requires data on the material’s density and specific heat capacity. This group of methods include: the linear heat source method, the transient plane source method, the 3*w* method, the laser pulse method and the transient impulse method.

Many studies have shown that λ cannot be taken as a scalar quantity, because many materials are not isotropic. In technical practice, the λ is present in the Fourier’s Law as:

$$q_i = -\lambda_{ij} \nabla T_j \tag{1}$$

where ∇T_j is temperature gradient in direction j ($i=j$ for isotropic materials).

In the strcitest mathematical sense λ_{ij} for solid materials is a second order tensor, which in relation to Decartes’ coordinate system (x,y,z), can be presented as:

$$\lambda_{ij} = \begin{bmatrix} \lambda_{xx} & \lambda_{xy} & \lambda_{xz} \\ \lambda_{yx} & \lambda_{yy} & \lambda_{yz} \\ \lambda_{zx} & \lambda_{zy} & \lambda_{zz} \end{bmatrix} \tag{2}$$

Nevertheless, in engineer practice materials are considered isotropic so $\lambda_{ij} \equiv \lambda$, so the thermal conductivity mainly depends only on the temperature. In this case, heat flux (q_i) in direction i is defined only by temperature gradient in the direction. Although the Fourier’s Law provides basis for analysis of thermal conductivity, it does not define physical sense of this value. In solid homogenous materials, it depends on mechanism of heat transfer, which primarily depends on the type of materials and the temperature level where the conductivity is being done.

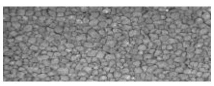
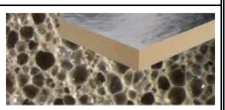
Materials with thermal conducitivity values lower than 0.1 W/mK can be classified as thermal insulation materials (according to standard DIN 4108). Intense research of use of new and high performance thermal insulation materials with lowest values of thermal conductivity contribute to minimal energy consumption in building, but also reduce use of natural resources, contributing to sustainable development. During winter when stationary conditions can be acquired, thermal conductivity may be the only parameter which affects thermal insolation of a building. However, during summer, apart λ , when assessing the thermal insulation properties, the dynamic conditions must be taken into account, that is material density and specific heat capacity (thermal diffusivity term *a*).

2 Conventional Thermal Insulation Materials

Conventional thermal insulation materials are most commonly classified to non-organic and organic, based on the origin of raw material they are made of. Thermal insulation materials of non-organic (mineral) raw materials make up 60% of the market, including glass and rock wool which are known as mineral wool. Their main down side is their negative effect on people's health, usually manifested with skin or lung irritation. Unlike the non-organic ones, organic thermal insulation materials like polyurethane (PUR), polyisocyanurate (PIR), extruded polystyrene (XPS), expanded polystyrene (EPS) make up 27% of the market, they are convenient becuase of their low thermal conductivity, ecologically acceptable, recyclability and low price tag. In recent years, apart from the commercial ones, there is a variety of ecologically acceptable alternative materials such as: cellulose, expanded clay, cork, sheep wool etc. Thermal conductivity values of these thermal insulation materials do not differ significantly from the aforementioned conventional materials. Tipical values of thermal conductivity of conventional thermal insulation materials most commonly used are presented in Table 1.

Out of all commercial thermal insulation materials, the lowest values of thermal conductivity have synthetic materials. Among these, polyurethane (PUR) can have a value of 0.020 W/mK compared to the other materials whose values are usually between 0.030 and 0.040 W/mK [4]. Values λ of thermal insulation materials provided by producers are examined in laboratory conditions with standard temperature and relative air humidity (T_{amb}=25 °C; φ=50 ± 10%). However, in reality thermal conductivity of thermal insulation materials can differ significantly depending on different climate conditions (material equilibrium moisture content). It shows that λ on macroscopic level depends mostly on working temperature, humidity content and material density. Material thickness, pressure, material aging and suface wind speed also significantly affect thermal conductivity [5]. It is also important to be knowledgeable about combined effects of all aforementioned factors.

Table 1. Properties of most commonly used conventional thermal insulation materials for the building sector

Material	Density [kg/m^3]	Thermal conductivity [W/mK]	Specific heat capacity [kJ/kgK]	Illustration
Stone wool	40-200	0.033-0.040	0.8-1.0	
Glass wool	15-75	0.031-0.037	0.9-1.0	
Expanded Polystyrene (EPS)	15-35	0.031-0.038	1.25	
Extruded Polystyrene (XEPS)	32-40	0.032-0.037	1.45-1.7	
Polyurethane (PUR)	15-45	0.022-0.040	1.3-1.45	

3 Advanced Thermal Insulation Materials

In order to achieve energy efficiency goals, traditional thermal insulation materials due to their relativelly high thermal conductivity require too thick building envelope (up to 50 cm). This option can be unatteinable in existing and new buildings due to spatial and techno-economical constraints. Development of advanced nanoporous and nanostructured thermal insulation materials of high thermal performances, with exceptionally low values of λ, is achieved primarily by understanding the mechanisms of heat transfer of porous insulation materials. Heat transfer mechanisms on a microscopic level which provide lowst values of thermal conductivity mainly depend on components of the material microstructure (shape, size and layout of pores and particles), but also on the gas pressure in the pores. Resulting thermal conductivity of the material of porous structure can be defined with effective thermal conductivity (λ_{eff}) which consists of heat transfer through solid phase (λ^{s}_{cond}), heat transfer through gas phase within the pores (λ^{g}_{cond}), convective heat transfer within the pores (λ_{conv}) and radiation between solid particles (λ_{rad}) [6].

$$\lambda_{eff} = \lambda^{s}_{cond} + \lambda^{g}_{cond} + \lambda_{conv} + \lambda_{rad} \tag{3}$$

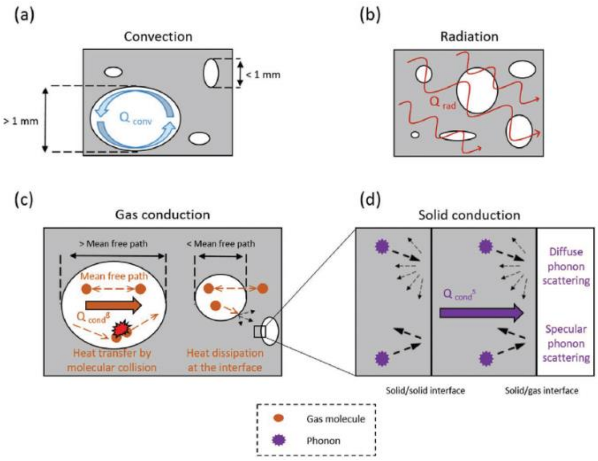


Figure 2. Schematic diagram of mechanisms of heat transfer through porous microstructure of construction materials [6] .

Convective heat transfer within pores, conditioned by movement of gas molecules – as a reaction to differences in temperatures, can be neglected bacuse of its low value, especially within pores smaller than 1 mm (Figure 2a). Heat transfer by radiation can also be neglected for pore's diameters smaller than 5 mm, except in cases of low density of porous material and high temperature, and when a significantly high vacuum can be obtained (Figure 2b).

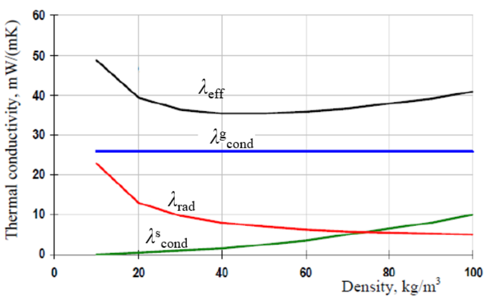


Figure 3. Influence of material density on mechanisms of heat transfer through porous microstructure [7].

When it comes to thermal conductivity through solid phase, in nanoporous materils with particles of nanostructure size diffuse, phonon scattering is increased (quantized vibrational of crystal lattice) on border surface of solid phases as well as on border surface between solid and gas phases, which leads to λ^{s}_{cond} to decrease (Figure 2c).

Heat transfer by radiation and thermal conductivity through solid phase depend on material density (Figure 3) [7]. It can be noticed that heat transfer through gas phase does not depend on material density, so lowering gas thermal conductivity can contribute to development of highly efficient thermal insulation materials. Although it depends on the type of gas, λ^{g}_{cond} can be significantly decreased using Knudsen effect which is achieved when the pore diameter of the material becomes less than the average free length of the path of gas molecules between two interactions [8]. In that case a gas molecul will collide with nanopores' walls more frequently than it collides with other gas molecules. Decreasing pore diameter below 50 mm leads to eliminating intermolecular collision, which leads to lower gas thermal conductivity.

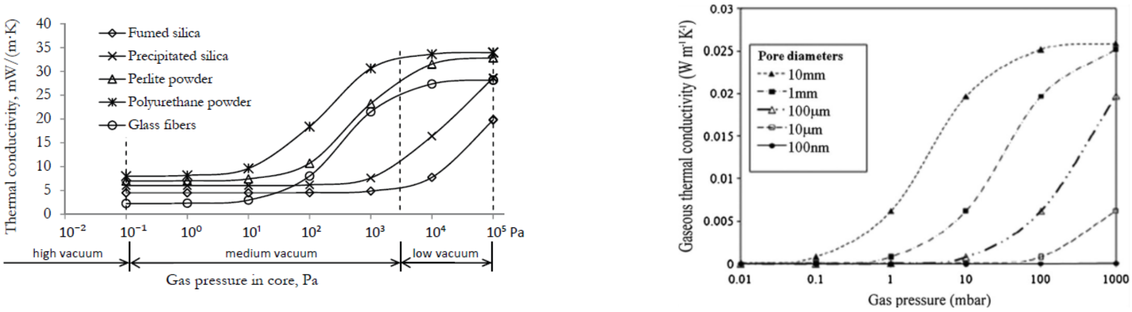
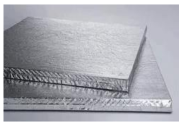
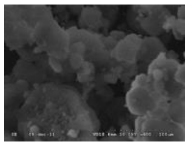
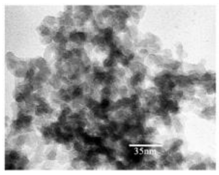
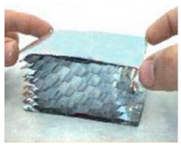
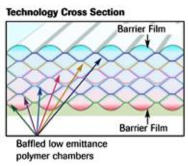


Figure 4. Change of gas thermal conductivity as a function of 1. achieved pressure within proes for different cores of material [9]*; 2. achieved gas pressure and pores diameter* [10].

Lowering gas thermal conductivity can be achieved also through obtaining vacuum within materials with open pore structure (i.e. vacuum isolation planes). By extracting gas molecules from the core of the material, λ^{g}_{cond} and λ_{conv} are eliminated. Fifure 4.1, shows relation between vacuum size and resulting thermal conductivity for different insulation materials [9]. It can be noticed, for example, that thermal conductivity of a fumed silica core is the same as that of a glass fiber core, but at a much lower obtained vacuum. Thermal conductivity of glass fibers, polyurethane (PUR) and poystyrene (PS) foam is multiply increased when their internal pressure reaches 1 mbar, which is a consequence of bigger pores comapred to fumed silica. Effect of pores diameter on internal pressure within core, and consequently on resulting thermal conductivity, is depicted in Figure 4.2 [10].

Table 2. Properties of new thermal insulation materials for the building sector.

Material	Density [kg/m^3]	Thermal conductivity [W/mK]	Specific heat capacity [kJ/kgK]	Illustration	Pore Structure
Vacuum insulation panel (VIP)	160-230	0.002-0.008	0.8		
Aerogel (rolls, panels)	70-150	0.013-0.015	1.0		
Aerogel (granular)	120-180	0.022	N.A.		
Gas-filled panel (GFP)	N.A.	0.010 (Krypton) 0.021 (Argon) 0.035 (Air)	N.A.		

In Table 2 most contemporary insulation materials properties are presented, which will be discussed in further text.

3.1 Vacuum Insulation Panels (VIP)

Vacuum insulation panels (VIP) are non-homogenous insulation materils which consist of multilayer envelope which is air/humidity resistant, and a core which must have an open structure of nanopores, in order to make sure that high vacuum can be reached. Aforementioned envelope consists of basic (inner) layer, guarded (outter) layer made of plastic sheet and middle (barrier) layer made of alluminum sheets. Different configurations of core envelope layers are depicted in Figure 5.1 [9]. Configuration and size of panels also affect on thermal conductivity value of VIP materials over time (Figure 5.2) [4].

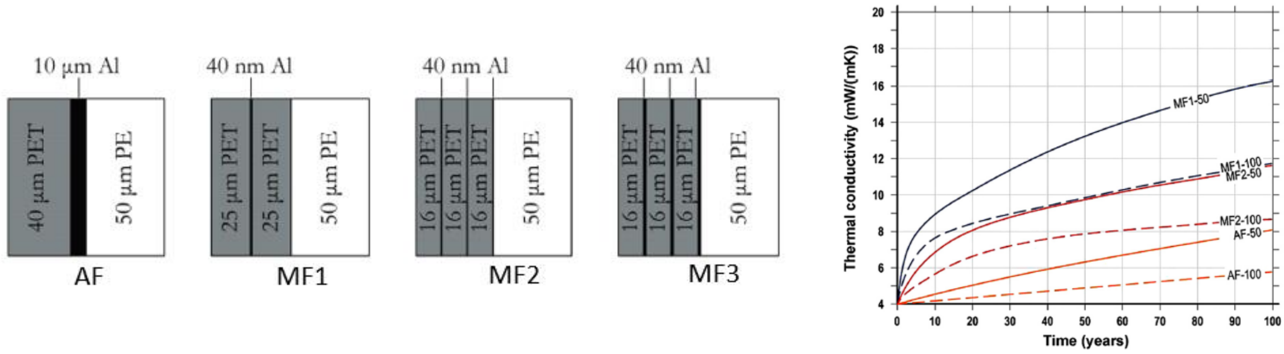


Figure 5. 1) Cross section of different configurations of vacuum insulation panels with barrier films made of alluminum films (AF) or metalized polymer films (MF) [9]*; 2) Effect of panel size (50 cm* x *50 cm* x *1cm i 100 cm* x *100 cm* x *2cm) with different configurations of envelope (AF, MF1, MF2) on effective themrnal conductivity of VIP over time* [4].

As the most contemporary, and probaby the most competitive VIP thermal isolation has thermal conductivity which, depending on material of the core and achieved vacuum, can reach values as low as 0.002 W/mK – which makes it a material with the lowest current value of thermal conductivity. As stated in the previous chapter, in order to reach a low thermal conductivity of a gas in a core with wider pore diameter, the pressure within the core must be very low (a high vacuum must be obtained) – which is likely unfeasible (Figure 4). This is the reason why it is common to use a core of nanoporous material because the low gas thermal conductivity can be achieved even with a higher pressure within the core. A VIP with a core of fumed silica (although relatively more costly than other core materials) is the most commonly used nowadays for its low thermal conductivity even with lower achieved vacuum (Figure 4.1), and additionally for being more resistant to higher temperatures. At the same time it is non-toxic and inflamable porous material which can be recycled. It must be noted that in case the envelope is not entirely impermeable, bigger temperature and humidity changes can lead to increase of pressure within the core – which will lead to loosing vacuum within the core and increase of thermal conductivity value (from 0.008 W/mK after 25 years) [11]. Due to the vacuum in the core, VIP is highly sensitive, so it must be transported, stored and placed carefully (in standardized sizes), as to avoid mechanical damages, vacuum loss and increase of thermal conductivity values – all of which lowers a VIP's flexibility. One of the good solutions for prevention of a VIP harm due to any mechanical damage is using VIP sandwich panels coated in other materials such as expanded polystyrene. Life span of 50 years for a VIP with a fumed silica core can be obtained through increasing the pressure within the VIP for 2 mbar per year [10]. Yearly increase of pressure within VIP should not exceed this value. Although very expensive (around 220 €/m^2 for thickness of 6 cm), they can be more cost effective compared to traditional thermal insulation materials. For instance, by replacing mineral wool thick 35 cm with a VIP thick 6cm, due to increase of useable living space, there is a profit to be made if market value of the property is 3000 €/m^2 [4]. Current research are intensily focused on development of a new generation of VIP materials due to high costs of production of a microporous core made of fumed silica, which limits their wider usage in construction sector.

3.2 Aerogels

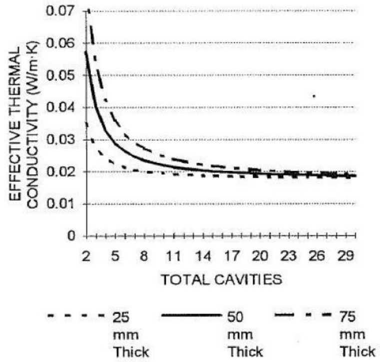
It has been known that aerogels, due to its high production costs compared to conventional insulation materials, are not as common in application in practice, yet they are considered one of the most promising advanced thermal insulation materials whose performances are constantly perfected. These ultralight thermal insulation materials, filled with air, with highly porous structure and nanodiametres of pores (2-50 mm) have all the necessary qualities for contemporary construction. Aerogel's density due to its high porosity can be as low as 3 kg/m^3 (for construciton application range from 70 to 150 kg/m^3) which makes it the lightest solid material [12]. Silica aerogels which is the most commonly used one in construction consists of nanostructured network of SiO_2, with porosity of 85% up to 99,8% [9]. Silica aerogels are usually transparent, and their bluish shade in daily light is a result of Raileigh scattering (scattering of electromagnetic radiation which, while passing through transparent materials, manifests on particles of much smaller dimensions than that of radiation wave length). Commercially available monolithic aerogels can reach thermal conductivity values of up to 0.013 W/mK at atmospheric pressure, which make it approximately 2 or 3 times more efficient material compared to the traditional ones [8]. Thermal conductivity value of 0.004 W/mK can be achieved at a pressure of 50 mbar. Besides their good thermal conductivity, aerogels have good sound insulation properties. Pores of aerogels are filled with air so unlike the VIP there is no risk of vacuum loss, and thermal conductivity does not oncrease over time. They are also flexible because they can be cut and adjusted in the construction site without decrease of their thermal properties. Beside that, aerogel granules can be used in combination with plaster to achieve satisfactory value of thermal conductivity. In comparison, thermal conductivity of plaster is around 0.50 W/mK, while combined with aerogel granules the thermal conductivity can reach values as low as 0.013 to 0.022 W/mK, depending on the share of aerogel granules in the plaster [13]. Porous aerogels have light conductivity of around 80%, which makes them suitable, besides application as thermal insulation materials, to be used in hollows of double glazed windows in order to decrese values of heat transfer coefficient of the window (k). Although the thermal conductivity of a granular aerogel is higher than that of a monolithic one, λ can be reduced by a compression operation of aerogel where the thermal conductivity decreases from 0.024 W/m^3 at a density of 88 kg/m^3 to 0.013 W/m^3 at a density of 150 kg/m^3 [4].

3.3 Gas Filled Panels (GFP)

Another type of innovative thermal insulation materials are panels filled with air or inert gas of lower thermal conductivity than air (i.e. argon, krypton or xenon). The choice of gas is made with taking into consideration the price, effect on the environment, toxicity, fire resistance and dew point temperature. GFP are made of reflecting (low emitting) multilayer buffles which are hermetically sealed with a low emitting barriere envelope. Thermal conductivity of GFP as well as its production costs depends on the number and thickness of the buffles, type of gas and thermal conductivity of barriere envelope material. Theoretical values of thermal conductivity of panels filled with air, argon and krypton are 0.035 W/mK 0.021 w/mK i 0.010 W/mK, respectively [11]. Nevertheless, in practical construction application the value of thermal conductivity of GFP is higher and, for example, for a panel filled with argon and krypton is approximately 0.04 W/mK, and for a one filled with air 0.046 W/mK [9]. Figure 6 shows how thermal conductivity values depend on type of gas and panel thickness [14]. A GFP panel of bigger thickness due to higher content of gas also has a higher price, and lower thermal conductivity. Given that vacuum is a better thermal insulator than the aforementioned gasses, vacuum insulation panels are a more applicable solution compared to GFP. An advantage of these materials is that there is no need to maintain inner vacuum as with VIP materials.

4 Future Thermal Insulation Materials

Thermal insulation materials that will be developed in the future must fulfill certain requirements in order to eliminate shortcomings of previously described developed materials. Apart from them needing to have as low thermal conductivity as possible (it is suggested a boundary value of thermal conductivity of 0.004 W/mK [15]), after certain time period this valuse should not increase significantly (λ <0.005 W/mK) [16]. Also, low thermal conductivity of material should be maintained after redrawing and cut of material for installation. The materials need to be competitive in the market, to have good mechanical strength and not to emmit toxic gasses. At the moment these materials are still at a conceptual phase and are only being discussed theoretically, i.e. results of laboratory texting have not been published yet. A short review of performances of future thermal insulation materials improved compared to the previous ones, is given in further text. The concept of nanotechnology, that is the use of nanopores between 0,1 and 100 nm is needed to achieve their high performances [8].



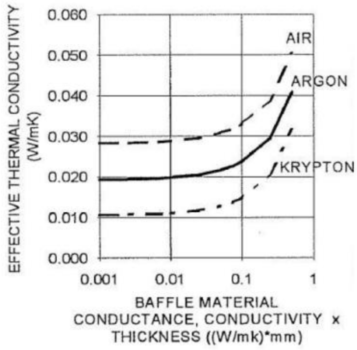


Figure 6: Effect of 1. number and thickness of buffles within GFP materials filled with argon; 2. different gasses within buffles on effective thermal conductivity [14].

4.1 Vacuum Insulation Material (VIM) and Gas Insulation Material (GIM)

The vacuum (VIM) and gas (GIM) insulation materials, with closed nanoporous structures, are basically the same but unlike VIM whose pores are filled with vacuum, the pores of gas insulation materials (GIM) are filled with a gas of low thermal conductivity. Thermal conductivity of these materials should, as stated previously, be around λ = 0.004 WmK [8]. Nanopores' structure created during the production process must be strong enough in order for thermal conductivity not to be decreased due to diffusion of water vapour and air during exploitation.

Even though it is easier to produce a closed structure of nanopores filled with gas than achieve vacuum, VIM are still considered more promising future thermal insulation material than GIM, because a lower thermal conductivity can be obtained with a vacuum. Yet, for now, achieving vacuum within a closed structure of pores is only a hypothetical possibility, VIM materials would provide in that case: low thermal conductivity and eliminating the need for sealing an envelope. Additionally, vacuum would not be lost by redrawing dimensions of VIM, and consequently thermal conducitivity would not be decreased as it is the case with VIP. Figure 7 shows a possible evolution of VIM and GIM, which could be achieved with VIP materials [16]. Potential shortcoming of these future thermal insulation materials would be complex and expensive production, and creating conditions which would not allow for water vapour and air to penetrate after a certain period of time – all of which would require significant innovations.

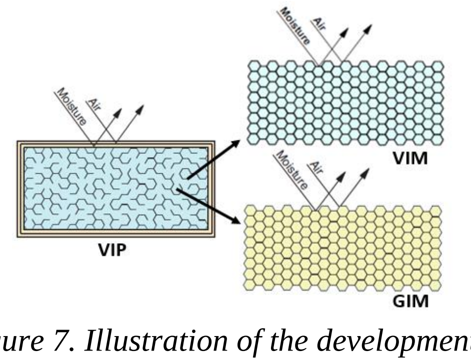


Figure 7. Illustration of the development of vacuum insulation (VIM) and gas insulation (GIM) material using a vacuum insulation panel (VIP) [16].

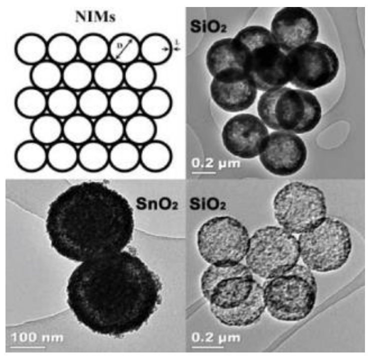


Figure 8. Conceptual model of silicon dioxide with holllow nanospheres [17].

4.2 Nano Insulation Materials (NIM)

Nano insulation materials are potential future homogenous materials with a closed or open structure of nanopores (0,1 nm-100 nm), which at this moment are far form commerical use (Ficture 8) [8]. At the moment one of the most commonly researched approches for creating these materials is based on production of silicium dioxide with hollow nanospheres [17]. To get significantly small values of thermal conductivity (below 0.004 W/mK) it is needed to lower gas thermal conductivity within pores, which is achieved through decreasing nanopores diameter below value of 40 nm. This would be achieved based on aforementioned Knudsen effect, which defines how thermal conductivity of a gas depends on pores diameter and gas pressure within pores. In this way air and water vapour penetration into pores is eliminated, which would lead to maintaining low thermal conductivity over time.

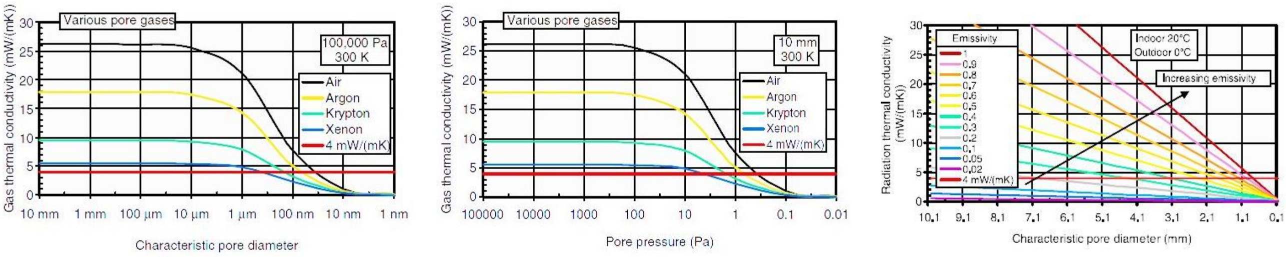


Figure 9. Influence of 1. characteristic pores diameter; 2. gas pressure within pores 3. characteristic pores diameter and pore surface emissivity on gas thermal conductivity [15].

Figure 9.1 shows that in closed structure pores filled with gasses (argon, krypton or air), at atmospheric pressure, when pores' diameter is reduced from 1µm to 10 nm, a drop of the gas thermal conductivity occurs to values below 0.004 W/mK [15]. Also, it has been established that in pores of diameter of 10 nm, with lowering pressure from 10 Pa to 0,1 Pa, there is a reduction of thermal conductivity of the gas (Figure 9.2) [15]. Furthermore, when xenon is used as gas, gas thermal conductivity is low – even at atmospheric pressure and pores' diameter of 10 nm. Heat transfer by radiation within the pores, which also affects material's thermal conductivity, reduces linearly with reduction of pores' diameter and reduction of emissions on pores' surface (Figure 11) [15]. The use of NIM in the future can be achieved in combination with carrying case of building envelope (i.e. concrete) (Figure 10) [8]. In this way, thermal conductivity of the building construction is reduced, while maintaining its mechanical strength and load capacity.

5 Conclusion

The article analysis thermal properties of conventional, advanced and future thermal insulatin materials, and also analysis the advantages and disadvantages of these materials. Thermal conductivity mostly affects efficiency and thermal performances of insulation materials, so its value should be as low as possible, in order to fulfill requirements for increased energy efficiency in buildings. Values of thermal conductivity can be reduced to minimal, by introducing certain measures that arise from the analyzing mechanisms of heat transfer and structures of porous materials. It has been shown that currently the lowest value of thermal conductivity is achieved with vaccum insulation panels (VIPs) (λ =0.002 W/mK), followed by GFP filled with gas krypton (λ =0.10 W/mK), and aerogels (λ =0.013 W/mK at pressure of 1 bar). These values are significantly lower than the lowest value achieved by all commercial materials, that is polyurethane (λ=0.022 W/mK), and especially those that are the most commonly found in the market, like mineral wool and polystyrene (which all have approximate value of $\lambda \approx$0.035 W/mK). It has been stated that thermal insulation materials with the lowest value of thermal conductivity may not be the most convenient ones, because there are limits and challenges which need to be overcome, stemming from significant increase of the thermal conductivity value due to water vapour and air diffusion, lack of flexibility, risk of perforation, adjustments in the construction, etc. Besides, factors such as cost, effect on the environment, recyclability, availability, etc. must also be taken into account. It can be

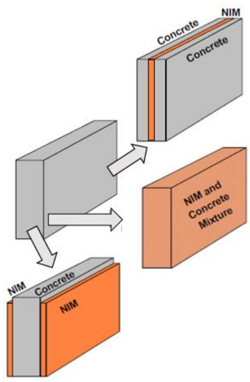


Figure 10. Different configurations of nano insulation materials and combinations with concrete [8].

concluded that at the moment there are no thermal insulation materials which can fulfill all of the requirements regarding the most important properties. Besides improvement of properties of materials that are already available in commercial use, there has been development of theoretical exploration of new concepts of future thermal insulation materials (GIM, VIM, NIM) of high performances with minimal values of thermal conductivity. Based on described properties of future thermal insulation materials, it can be concluded that NIM is the most likely to have the best required performances and achieve the lowest value of thermal conductivity.

In consideration of thermal insolation, it is needed to have a systemic approach. Insulation materials of the future that have been analyzed so far have high static value of thermal resistance (*R*), with low value of thermal conductivity. This approach is efficient from the perspective of reducing heat transfer through building envelope. However, very high value of thermal resistance of an optimally insulated building is not always useful, because in case of prolonged periods of high temperatures, energy consumption for cooling of the building increases.

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