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AEROGEL – MATERIAL OF THE FUTURE FOR CIVIL ENGINEERING

AEROGEL – MATERIÁL BUDOUCNOSTI PRO STAVEBNÍ INŽENÝRSTVÍ

Abstract

Aero gel is a solid with the lowest known density. It stands up to 2000 time's greater load than its own weight. It has extremely low thermal conductivity; the material is very suitable to limit the heat losses of buildings. Its melting temperature is 1200 °C. Well dampens vibration and sound. Aero gel is the only compound with significant thermal insulation capabilities, which is currently well clear. Thanks to these properties have fifteen records in the Guinness Book of Records. For these reasons, it is possible to consider aero gel as a material of the future not only in construction, and therefore it is necessary to deal with this interesting material now. The future use of aerogels as filler in thermall insulating glazing will cause a significant reduction of heat transfer coefficient in lightweight claddings, this follows from the results of our calculations. The bluish color of aerogels is not always a bad thing.

Keywords

Aerogel, Nanogel, thermal conductivity, density, weight.

Abstrakt

Aerogel je pevná látka s nejnižší známou hustotou. Snese až 2000x větší zatížení než je jeho vlastní hmotnost. Má extrémně nízkou tepelnou vodivost, materiál je tedy velmi vhodný pro omezení tepelných ztrát budov. Jeho teplota tání je cca 1200 °C. Dobře tlumí vibrace a zvuk. Aerogel je jediná hmota s výraznými tepelně izolačními schopnostmi, která je současně také čirá. Díky těmto vlastnostem má patnáct záznamů v Guinnessově knize rekordů. Z těchto důvodů je možno aerogel považovat za materiál budoucnosti nejen v oblasti stavebnictví, a proto je nutné se tímto zajímavým materiálem zabývat již nyní. Jak vyplývá z výsledků našich výpočtů, při budoucím využití aerogelu jako náplně do tepelně izolačního zasklení dojde u lehkých obvodových plášťů k výraznému snížení součinitele prostupu tepla, přičemž namodralé zabarvení aerogelu není vždy na škodu.

Klíčová slova

Aerogel, Nanogel, tepelná vodivost, hustota, hmotnost.

1 INTRODUCTION

Aerogel was first created by Samuel Stephens Kistler in 1931 from ordinary gelatin [6]. At that time the processes were too costly and the market not receptive to expensive materials.

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Using it in its current form with silicon started in the 1990s as a result of work done by NASA (National Aeronautics and Space Administration). Currently, there are aerogels based on oxide - silica, carbon, oxide - aluminum, etc. The cost of energy is growing and Aerogel, which is harmless and inert, looks like an interesting alternative for the future with its ability to reduce the thickness of thermal insulation to a third. All calculations in this paper are related to oxido - silica aerogels.

2 SPECIFICATIONS OF AEROGEL

The internal structure of Aerogel consists of siliceous hollow balls of approximately several nanometers in size.

Tab. 1: Specifications of Aerogel and a comparison with expanded polystyrene EPS

	Aerogel	**Expanded polystyrene**
Density	cca 3-350 kg.m^{-3}	cca 16 kg.m^{-3}
Proportion of solids	0,13 – 0,15 %	-
Compressive strength	16 kPa	> 70 kPa
Speed of sound	100 m.s^{-1}	2 320 m.s^{-1}
Size of micropores	2-50 nm	-
Thermal tolerance	do 500 °C	do 80 °C
Melting point	1200 °C	-
Coefficient of thermal expansion	2 – 4.10^{-6} m.K^{-1}	5 - 7.10^{-5} m.K^{-1}
Coefficient of hermal conductivity	0,004–0,030 W.m^{-1}.K^{-1}	0,033-0,044 W.m^{-1}.K^{-1}

***U* = 0.15 W/m^{2}K – recommended heat transfer coefficient for passive shell construction**

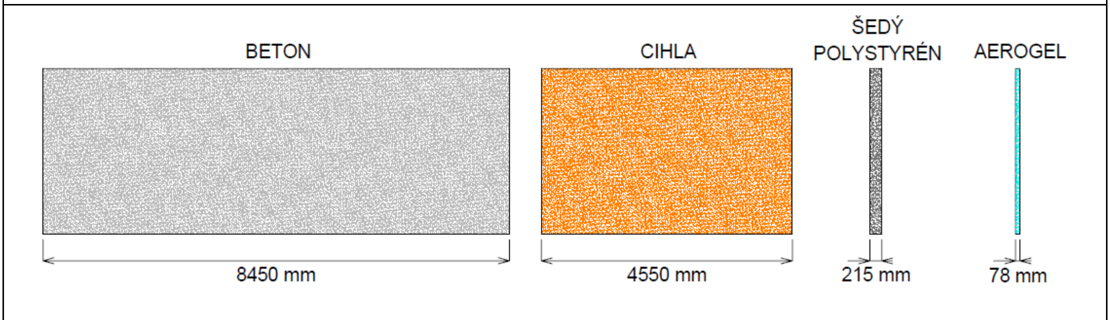

Fig. 1: A comparison of the thickness of various materials at $U = 0.15$ W/m^{2}K
(CONCRETE BRICK GREY POLYSTYRENE AERO GEL)

3 PHYSICOCHEMICAL PROPERTIES OF AEROGEL

Aerogel is a substance based on silicon, often referred to as frozen smoke or blue smoke. But it is a solid substance, similar in touch to foam polystyrene. Aerogel is a solid substance with the lowest known density. It contains more than 95% air, the rest is SiO_2 (quartz), which is a common mineral on Earth. Aerogel can be made from carbon, aluminum, chromium, zinc and tin. It is produced through a process of drying gel, which consists of a mixture of silicon dioxide, liquid carbon dioxide and ethanol under extreme conditions. All liquid components are removed from this mixture under high pressure. Only this way is the silica gel not deformed and the silicon cells remain intact. Its porosity exceeds 95% and it has a very broad distribution of pores from 10^{-10} to 10^{-6} m [6]. Since Aerogel has open pores, gases and liquids can pass through it with minimal restrictions. At normal temperatures Aerogel is nonflammable, nor does it significantly change in shape or volume up to 500°C; at higher temperatures it shrinks. Temperatures for common usage are from -200°C to 250°C. Loose particles ignite at about 400°C and the melting temperature is 1200°C. It is also used for glazing shuttles and space stations, windows in industrial furnaces and reactors with temperatures up to 800°C. Aerogels impede the flow of electrical energy very well and dampen vibrations and sound. Aerogels absorb low frequency sound from 50 to 1000 Hz. Windows and panels with a 16 mm layer of Aerogel absorb up to 25% of sound energy. The first experience with dampening noise around airports and highways has been definitely positive. The most characteristic optical property of Aerogels is their transparency. They are not, however, fully transparent due to their heterogeneity. The permeability of solar radiation through Aerogels ranges τ = 0.85 to 0.95 depending on the thickness of the Aerogel layer.

The typically excellent thermal conductivity of silicon Aerogels is about λ = 0.017 W.m^{-1}.K^{-1} (λ = 0.015 – 0.020 W.m^{-1}.K^{-1}, a value much lower than that of fiberglass. For comparison, air has a thermal conductivity of 0.026 W.m^{-1}.K^{-1}) The thermal conductivity for nanogel is, according to design, λ = 0.009 – 0.022 W.m^{-1}.K^{-1}. Compared with polystyrene foam (λ = 0.036 W.m^{-1}.K$^{-1)}$ and the newer Neopor (λ = 0.033 W.m^{-1}.K$^{-1)}$, stabilized against the loss of heat radiation through graphite micro-particles, it is at most half to a quarter.

4 DIFFICULTIES WITH USING AEROGELS

What prevents it from being used on an industrial scale is the fact that contact with water turns it back into a gel. It should also be said that at present Aerogel is not perfectly clear, but occurs with a blue tinge, which currently limits the use of it in transparent plastics. However, it has found application in construction work, where the bluish color is not an inhibiting factor; it may even be desirable, for example, in indoor swimming pools.

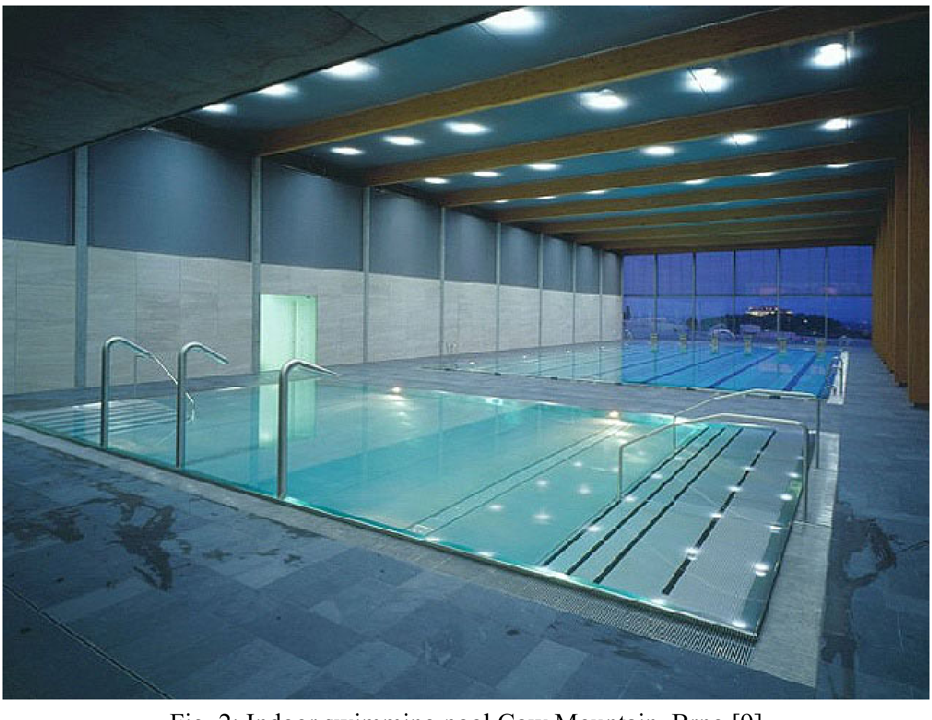

Fig. 2: Indoor swimming pool Cow Mountain, Brno [9]

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Despite theoretical expectations, Aerogel with precisely defined properties has never been successfully produced in a space with gravity. As a result, it seemed almost impossible to set up the mass production of Aerogel for engineering use. One special difficulty was maintaining the size of the pores in the material, as well as the dimensions and proportions of the solid parts. Research has found that this problem can be solved by manufacturing it in a state of weightlessness. The aim of the research is not to produce a unique material in a state of weightlessness because in the current state of astronautics, production would not be cost effective. Space travel, however, should provide knowledge about which factors and means will affect the particle size of Aerogel, its internal structure and visual properties. Once it succeeds, the world will have a completely new product that opens up unheard of possibilities. That is why the attempt is being made here to find other options through research in space and bring knowledge to industry that would enable an economical means for producing it here on Earth. The first experiments in zero gravity were conducted in 1996, using Starfire rockets on short, suborbital flights. It showed that the material has a four to five-time better parameters than when producing it on the ground.

5 PROSPECTS FOR USE IN CIVIL ENGINEERING

Since Aerogel has excellent thermal insulating properties (minimal heat loss), no critical surface temperature is reached, nor does any condensation of water vapor occur, at standard borderline conditions. For these reasons, no misting or fogging of window components occurs.

Unlike gas-filled or vacuum-sealed windows, windows filled with Aerogel do not lose their thermal resistance over time. For gas-filled windows, there is a gradual reduction in thermal resistance due to the long-term leakage of inert gas. The performance of double glazing with inert gas has reached the limit of its ability today, while Aerogel has the potential to achieve even better properties in the future. With the gradual development of manufacturing processes, the price of Aerogel is becoming acceptable. We can recall a time when silicone sealants started off as an extremely expensive and rare material.

"A more serious problem in the future will be its weight. Some designs will have half the weight of today's. The production volume of material used will definitely have an effect on the environment." *Jan Kaplický (2005)*

So far, the most promising use of Aerogel appears to be as thermal insulation. The material has significantly better insulating properties than glass, yet weighs only a thousandth of the mass. This opens up possibilities of using it for extra light shells, which will significantly reduce the static load on the loadbearing system of the building.

Aerogel is the only material that, in addition to significant thermal insulation capability, ranges from translucent to clear. The use of Aerogel is mainly for the transparent shells of buildings and, with improvement in the transparency of the material, in future glazing. Transparent silicone Aerogel would be very good as thermal insulation for windows, where it would significantly limit heat loss from buildings. The Swedish company Airglass is developing new material for glazing windows, made out of a layer of Aerogel vacuum-sealed between two glass panes. Production is still in the pilot plant phase, with a monthly production of 3 – 6 m^2, which is now used only for testing. The road, however, looks very promising [4]. Commercially, Aerogel was used in granular form to improve the insulation properties of roof windows. The first test use of Aerogel as an insulator is in the Georgia Institute of Technology's Solar Decathlon House (see Figure 3), where it is used as a semi-transparent roof [6].

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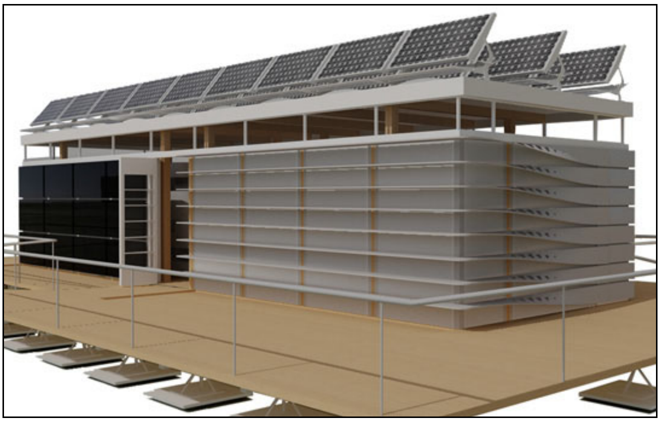

Fig. 3: Solar Decathlon House [10]

Unique is the ability of the translucent layers of Aerogel to capture daylight in poor light conditions and disperse it in the space where it does not directly impact. It is an ideal solution for illuminating museums, galleries, libraries and sports halls. This knowledge is already being used by several manufacturers of flat or celled lighting panels made of polycarbonate filled with Aerogel. In addition, the glass absorbs heat radiation. It absorbs up to 27% of thermal radiation for a 13 mm thick layer of Aerogel [7].

The company Aspen Systems is trying Spaceloft blankets and Aerotex fabrics in a development program with the Kennedy Space Center in Florida. The materials are not subject to degradation during long-term usage, in contact with air or the effects of light; they repel water, are not subject to corrosion and are not toxic [7]. It almost floats in the air thanks to its low density. It is ecological and, as a material based on SiO_2, easily recyclable. It is being manufactured on an industrial scale only in a few places around the world. According to early feedback, it seems that Nanogel can expect a future similar to what awaited the Gore-Tex membrane did years ago [7].

The insulating and mechanical properties of the new material will be applied in all kinds of vehicles from cars to planes and rockets. The large internal surface of the pores is again an advantage for manufacturing filters and catalytic converters. NASA experts believe in the great possibilities of Aerogel in the construction of spacecrafts, orbital stations and planetary bases.

6 THE PROSPECTS OF AEROGEL FOR USE IN TRANSPARENT SHELLS

The thermal protection of buildings is nowadays an integral part of all designs. The need for energy savings in heating costs requires adequate insulation in all building façades. The installation of high-quality windows with appropriate heat insulating glass is a necessity nowadays. The reduction of the thermal insulation properties of windows due to the leakage of gas infill is therefore undesirable and leads to increased demands for heating and thus economic losses for the building owner.

Currently, use of insulating double glazing are the most common, which in the combination with inert gases can achieve heat transfer coefficient up to $U_g = 0.5$ W.m^{-2}.K^{-1}. This value is achieved by coating glass with metal from the interior and using a gas infill, usually argon. The heat transfer coefficient of the same air-filled double glazing is approximately $U = 1.4$ W.m^{-2}.K^{-1}. If the insulating gas infill escapes from the space between the glass panes, this would significantly reduce the heat-insulating properties of double glazing. The gas infill of insulated glass provides, together with specially modified panes, sufficient thermal insulation and prevents undesirable heat loss. As windows age, the gas insulation infill may leak out of the space between the panes. The amount of gas that can escape from the window is given in ČSN EN 1279-3 [1]. This sets the maximum allowable leakage at 1% of the gas infill per year. The reduction in the value of “U_g” during the lifetime can be demonstrated by measurement or theoretical calculation.

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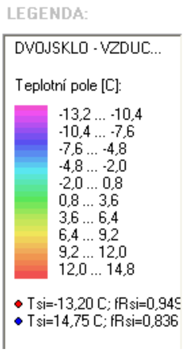
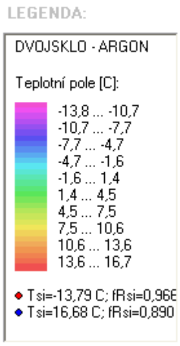
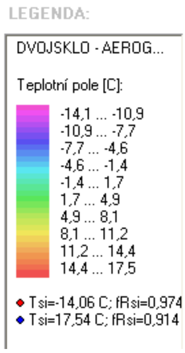
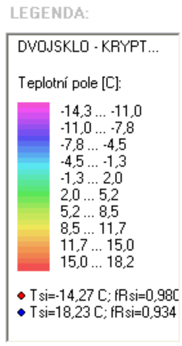
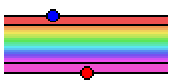
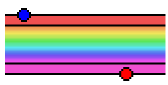
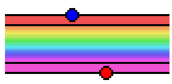
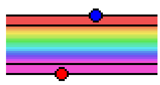
Tab. 2: A comparison of double glazing 4-16-4 under the same borderline conditions with different infills [11, 12]

Air	Argon	Aerogel	Krypton
λ = 0,0262 W.m^{-1}.K^{-1}	λ = 0,016 W.m^{-1}.K^{-1}	λ = 0,012 W.m^{-1}.K^{-1}	λ = 0,009 W.m^{-1}.K^{-1}
Air infill	Argon infill	Aerogel infill	Krypton infill
U=1,26 W.m^{-2}.K^{-1}	U=0,85 W.m^{-2}.K^{-1}	U=0,66 W.m^{-2}.K^{-1}	U=0,51 W.m^{-2}.K^{-1}
			
			

The price for modern windows is considerable and therefore their performance should be assured by the manufacturer over their lifetime. Unfortunately, it is very difficult to determine how much gas is contained in the intermediate space and we are no longer talking about any timeframe for finding out. Glass panes are usually filled from 90 to 95% with inert gas under normal atmospheric pressure. Manufacturers indicate that the maximum gas leakage is no more than 0.5% per year. The lifetime of glazing is reckoned to be about 20 – 25 years. The fundamental importance of using inert gas in the intermediate space of insulating glass is its lower thermal conductivity compared to air, and so the greater resistance of gas to heat transfer. This property of inert gases can be easily explained by the fact that the molecules of gases of this type basically do not form any molecular structure among themselves or with particles of other gases and so appears strictly in single molecular arrangements [8]. The speed of diffusion, or the leakage of inert gas and its replacement by surrounding air, thereby reducing the concentration of inert gas in the space between the glass panes, has a significant effect on the thermal-technical and acoustic characteristics of insulating glass.

It has been shown through computations that the deterioration of the coefficient of heat transfer U_g during a change in concentration from 90/10 to 60/40 is 7.3% for argon and 13.5% for krypton. The optimum width of the frame is not the same for both gases (argon and krypton). The best for argon is a width of 16 mm and 12 mm for krypton. For illustration, we can offer the differentiation of U_g double glazing insulation with the performance of various inert gases in different concentrations [8].

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Tab. 3: The dependence of U_g on the concentration of gas in the intermediate space

Insulated double glazing Low-E 4mm – 12 mm – Float 4 mm					
	***Ug* [W.m^{-2}.K^{-1}]**				
	100%	**90%**	**75%**	**50%**	**25%**
Air	1.63				
Argon	1.27	1.31	1.36	1.45	1.54
Krypton	1.00	1.04	1.10	1.24	1.42

The heat transfer coefficient is the basic quantity characterizing the thermal insulation properties of building structures. The procedure for calculating the heat transfer coefficient of thermal lightweight shells (hereinafter TLWS) is given in ČSN EN ISO 13947 [2]. The two basic methods of calculation are defined. The method of the overall evaluation, which works with the equivalent heat transfer coefficients of thermal bonds, and the method of evaluation by parts, which is analogous to the calculation of the heat transfer coefficient of window constructions.

In view of the limited scope of the paper, we shall take a closer look at only the method of overall evaluation, which is simpler, usually the more convenient option for practical usage, and still has the widest range of applications. The heat transfer coefficient of TLWS will be determined for the characteristics of a TLWS section (see Fig. 5). The numerical relationship is again the weighted average of heat transfer coefficients conducted through the partial surface of TLWS.

The method of overall evaluation uses this relationship:

$$U_{LTWS,vz} = \frac{\sum A_g \cdot U_g + \sum A_p \cdot U_p + \sum A_{TJ} \cdot U_{TJ}}{\sum A_g + \sum A_p + \sum A_{TJ}} \quad \left[W/m^2K\right] \qquad (1)$$

Where:

A_g, A_p a A_{TJ} - are the exposed surfaces of the glazing, with complete infill and thermal bonds in a characteristic section of TLWS in m^2 (Fig. 4)

U_g, U_p a U_{TJ} - are the applicable heat transfer coefficients of the glazing, with complete infill and thermal bonds in W.m^{-2}.K^{-1}

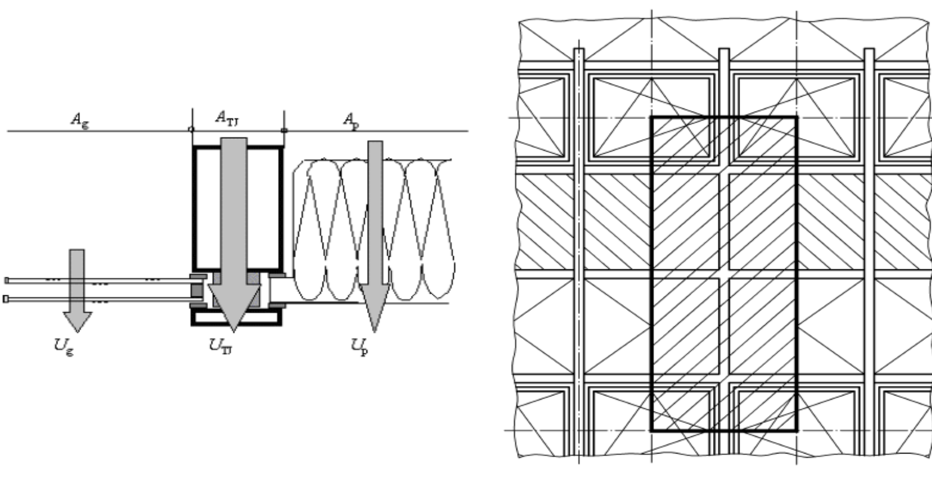

Fig. 4: Definitions of partial surfaces and heat transfer coefficients of TLWS in a characteristic section of TLWS

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The numerical relationship is again the weighted average of heat transfer coefficients conducted through the partial surface of TLWS. The effect of thermal bonds in the location of the glazing, with complete infill or column/beam windows is reflected in the value of the heat transfer coefficient of the thermal bonds for U_{TJ}. This quantity thus reflects both the thermal properties of the individual TLWS profile (column/beam) and the placement method of the glazing/complete infill/windows and other effects (e.g. the influence of a spacer bar in the glazing).

A normal raster façade design has a coefficient of thermal conductivity of the frame $U_f \approx 2.2$ W.m^{-2}.K^{-1}. Façade system designs also include profiles with thermal breaks. The thermal break makes it possible to achieve heat transfer coefficient values for the frame U_f = 1.00 – 1.40 W.m^{-2}.K^{-1}. It is a general rule that beam and column have different thermal specifications. These values with big margins also meet the requirements of standard ČSN 73 0540-2 [3], which gives the value of U_f = 2.0 W.m^{-2}.K^{-1} as the maximum allowable. The quality of the frame should be supplemented with high-quality glazing. For glazing with low-emissions and metal-coated glass, including the use of inert gases with low thermal conductivity (Argon, Krypton), special values of the coefficient of the permeability of the transparent portion can be achieved up to 0.5 W.m^{-2}.K^{-1}.

In order to demonstrate the beneficial impact of a transparent façade with glazing panels in the form of Aerogel, a light façade with concrete specifications was prepared. The model of the raster façade was used as the example for the calculation, see fig. 5.

U_f=1.40 W/m^{2}K

$U_{g,vz}$=1.20 W/m^{2}K

$U_{g,ag}$=0.70 W/m^{2}K

A_f=0.576 m^2 …7% TLWS – see fig. 5.

A_g=7.788 m^2 …93% TLWS – see fig. 5.

$$U_{TLWS,vz} = \frac{\sum A_{g,vz} \cdot U_{g,vz} + \sum A_f \cdot U_f}{\sum A_{g,vz} + \sum A_f}$$

$$U_{TLWS,vz} = 1{,}20 W/m^2K$$

$$U_{TLWS,ag} = \frac{\sum A_{g,ag} \cdot U_{g,ag} + \sum A_f \cdot U_f}{\sum A_{ag} + \sum A_f}$$

$$U_{TLWS,ag} = 0{,}75 W/m^2K$$

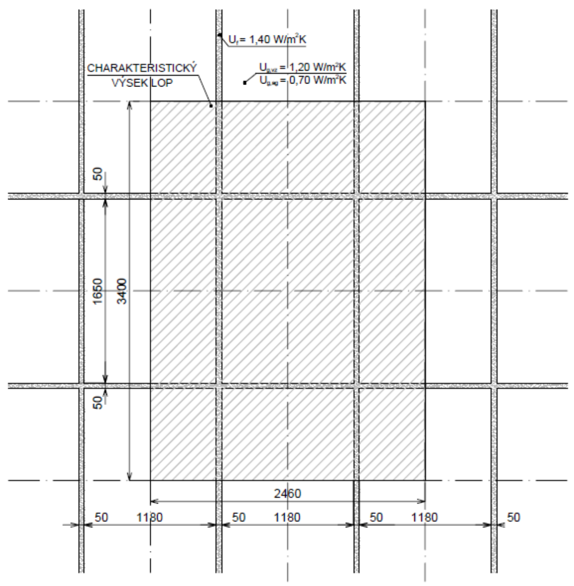

Fig. 5: A characteristic section of a transparent façade with real specifications

The difference between $U_{LOP,vz}$ = 1.20 W.m^{-2}.K^{-1} and $U_{LOP,ag}$ = 0. W.m^{-2}.K^{-1} is a full 37%. This means that a transparent façade made of double glazing filled with Aerogel has 37% better thermal-technical specifications than standard double-glazed windows filled with air.

Our calculations were considered with the spread of heat conduction only, other forms cannot be taken into account due to applied software. All glazing models are without metallized layers and these are not absolutely taken into account.

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7 CONCLUSION

There are not too many similar multi-application materials like Aerogels. But their time is probably only just now coming and will depend on how quickly and with what means the technology for their manufacture will be developed. One NASA scientist even predicted that Aerogel will soon be an ordinary material in our surroundings and will be used like plastics are today [5]. Aerogel will certainly become a part of our homes just as Goretex is a part of our clothing or vapor permeable and diffusion-open foil is. The price of some components of Aerogels is now approaching affordable levels mainly due to the price/performance ratio. So it seems that the main advantage of Aerogels is their thermal insulating properties. Spreading the use of Aerogels as thermal insulation will reduce energy consumption, thereby reducing greenhouse gas emissions and the pollution of the earth [4]. Thanks to its excellent properties and environmental harmlessness, Aerogels will likely find a place in the market in the foreseeable future.

In conclusion, it can be said that Aerogels have certainly surprised us in many aspects and it has gradually begun to fulfill a number of expectations, certainly for a material that is destined to become one of the most important materials of the 21st century.

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[11] HEAT 2010

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