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Aerogel glazing systems for the energy efficiency of buildings: A review

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Abstract: To maintain indoor comfort, buildings and the construction sector in general consume 30-40% of the World's total energy. This is mainly due to air conditioning, ventilation, and heating. The least effective and weakest elements of the building envelope are windows and glazed surfaces. So far, several technological solutions have been designed to reduce heat losses and eliminate excessive heat gains through transparent surfaces. In recent decades, aerogel has attracted attention, mainly known for its excellent thermotechnical properties and transparent structure. As a result, it is considered one of the most promising thermal insulation materials for building applications. This paper provides a comprehensive review of aerogel glazing systems, their properties and future potential in the construction industry (especially in the energy efficiency of buildings).

Keywords: aerogel, aerogel glazing systems, energy efficiency

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Introduction

Stricter requirements for the internal comfort of buildings, increased energy consumption in buildings and together with increasing CO_2 emissions has aroused interest in the research of energy efficiency in buildings. Each component of the envelope structure plays an equally important role in the energy efficiency of the building (Buratti et al., 2019). The weakest part of the building's envelope is the glazed surfaces, which have become a prominent element of modern architecture

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today. Sufficient daylight and an optical connection with the exterior increase the internal comfort for the building's users. Solar gains through windows contribute to energy savings for heating and artificial lighting. On the other hand, during warm seasons, the sun's rays cause unpleasant excessive glare and overheating of the interior space. It can have a dangerous effect on the health of users.

Glazed surfaces make up 37% of the total energy consumption for cooling and 40% of the building's heat losses during the heating season (Fiorini et al., 2023). As a result, scientific research on the topic of energy savings focuses mainly on the implementation of new innovative materials. Due to remarkable properties such as high light transmittance and low thermal conductivity, aerogel is a promising material, which has recently received more and more attention. It is used in both new and existing buildings for solutions, such as, retrofitting glazing systems (Berardi, 2015).

1. Aerogel

Aerogel is a material that has been around for over 80 years. More precisely, it was invented in 1931 and named in 1932 by the American scientist Samuel Kistler (Klassen, 2023). It is a light silica derived from a gel in which the liquid component has been replaced by a gas. After liquid extraction, the result of the gel is an extremely low-density, highly porous solid with remarkable properties, particularly known as an effective thermal insulator. These properties are responsible for a wide range of technological applications. Due to the way the light scatters in the material and its transparent nature, it is also called a "frozen, solid, or blue smoke" (Azum et al., 2021). This material has a wide range of uses and has been used in various fields since its discovery. For instance, in the space industry, where aerogel filters are used as space dust collectors (Burchell et al., 2006). Other areas where we can find its use are in medicine, aircraft construction, electronics, oil purification, nanotechnology and in many others, not least construction (Hrubesh, 1998).

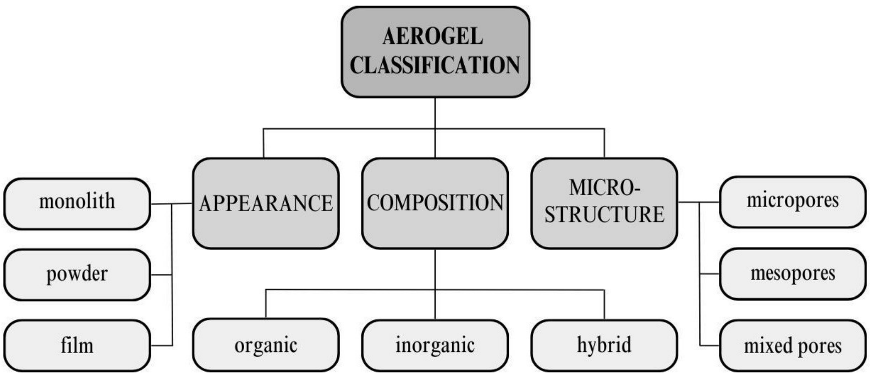

Fig. 1. Classification of aerogels (according to Akhter et al., 2021)

1.1. Classification of aerogels

Due to the widespread use of aerogel, its categorization is individual and specific for each industry. The best-known is silica aerogel, which has been studied and used the most extensively so far. Another known type is carbon aerogel, made of aluminium oxide or agar (Du et al., 2013). Aerogel material is classified, for example, according to its preparation methods. These classifications are Aerogel, Xerogel, Cryogel and other aerogel-related materials. Based on the chemical structure, it is classified as oxide, polymer, mixed, hybrid, or composite aerogels (Thapliyal & Singh, 2014). In the field of construction, it is generally classified according to appearance, composition, and microstructure (Fig. 1) (Akhter et al., 2021).

1.2. Properties and use of aerogel in the construction industry

Aerogel is currently considered to be the most versatile available material for various technical uses. In construction practice, the use of aerogel is based on a combination of its favourable properties. The greatest benefit is its high thermal insulation. Compared to traditional thermal insulation materials, it shows remarkable results due to its low thermal conductivity (up to 0.010 W/(m·K)). For a better understanding, a 10 mm thick aerogel panel achieves the same level of insulation as 25 mm thickness expanded polystyrene (Guinoa et al., 2017). It also reaches a high permeability of daylight and solar energy. Another benefit is its good acoustics (Rw index 3dB higher) (Buratti & Moretti, 2012). In addition to glazing systems, it is mainly used as thermal insulation. In general, it is used wherever there is a need to effectively reduce the building's energy losses (Berardi, 2017). The basic features and benefits are provided in Table 1.

Table 1. Properties of aerogel and their advantages for construction applications (according to Riffat & Qiu, 2013)

Property	Benefits	Values
thermal conductivity	best insulating solid	0.01-0.02 W/(m·K)
density/porosity	lightest synthetic solid	3-350 kg/m^3
	homogeneous	
	high specific surface area	600-1000 m^2/g
optical	low refractive index	1.0-1.05
	transparent	
acoustic	lowest speed of sound	100-300 m/s
mechanical	elastic	
	tensile strength	16 kPa

In addition to many positive aspects, these glazings also have their disadvantages. First is the translucency of the material. It is not completely transparent but it does allow the passage of daylight into the interior. Light transmission varies with particle size and material thickness. Another limitation is its fragility and mechanical resistance (Baiz & Atakara, 2022). However, the main imperfection is its high price compared to other insulating materials. During its production process, hard-to-remove dust is created, which represents another disadvantage. For this reason, it is necessary to continue research on aerogel to eliminate these shortcomings (Melițǎ & Croitoru, 2019).

2. Aerogel glazing systems

From the point of view of the thermal balance of buildings, windows make the most significant contribution. In terms of thermal insulation, they are the most vulnerable. Therefore, glazing systems are constantly evolving to improve their effectiveness. For decades, researchers have been dealing with the usage of aerogel in glazing systems. It is similar to double glazing, where the inner space between the panes of glass is filled with aerogel (Ghoshal & Neogi, 2014). In studies by Pajonk et al. (1997) the authors focused on the transparency of aerogel compared to simple glass. The results showed a relatively identical transparency ratio with single window glazing at almost the same aerogel thickness. Of course, when analysing the effectiveness of these systems, factors such as climate zone, location and orientation to the cardinal points play a significant role. Researchers Buratti et al. (2021) monitored the effects of aerogel glazing in different climates in the context of solar heat gain. They studied elementary school buildings in Iran, comparing an aerogel double-glazing system with a single-glazing system. In dry and hot climates, solar gain is reduced by 73% and cooling load by 33% compared to single glazing. Compared to standard double-glazing, the reduction was 56% and 16%, respectively. However, when it comes to solar gains, another essential factor is the percentage of glazed area of the building (Buratti et al., 2021).

In another study from Italy, researchers found that aerogel can reduce heating energy in the cold season by up to 50%. It can also maintain internal thermal comfort for several days after the heating system is switched off. On the other hand, the aerogel effect reduced room illuminance by only 10% on sunny days (Cotana et al., 2014). In Hong Kong, they evaluated the potential for reducing the cooling costs of a 40-story office building. The results of the study showed that aerogel glazing, compared to double-glazing, can reduce the heat gain of the window by up to 57% and the total cooling energy by 8.5% (Leung et al., 2020). On the other hand, it eliminates heat loss in cold climates. It reduces energy consumption for heating by up to 21% (Gao et al., 2016). In another contribution, the authors devoted themselves to simulations, the result of which was a reduction in energy losses through the windows of a family house by 39.1% using aerogel in the glazing (Thie et al., 2023). In the UK, researchers compared monolithic and granular aerogel with single-glazing. The results showed in favour of the monolithic material in terms of energy efficiency but also daylight permeability. The building's total annual energy consumption decreased by 12.2%. The authors also addressed the issue of CO_2

emissions. Compared to standard double-glazing, emissions are reduced by up to 63% (Mohammad & Ghosh, 2023).

Well-known researchers in this field are Zhou and Zheng. Using a multi-level optimization process, they found that the heat flux can be reduced by 31.5% with aerogel structures and the total heat gain by 28.3% (Zhou & Zheng, 2020b). Again, it is different in cold regions, where heat gains can be diminished by 62.5%. On the contrary, in subtropical zones, it can be about 5.9% (Zhou & Zheng, 2020a). Zhou in his overview of aerogel systems mentioned another type of aerogel glazing. The study deals with the integrated PCM material in the aerogel system. The principle consists of the outer layer of aerogel, which provides thermal insulation, and the inner layer of PCM material (Fig. 2). The material, with a phase change, can accumulate solar radiation during the day and transmit it back over the night to maintain internal comfort. However, this system is especially suitable during the prevailing heating season. It is then possible to keep the temperature of the interior air 9°C higher than the external air (Zhou, 2021).

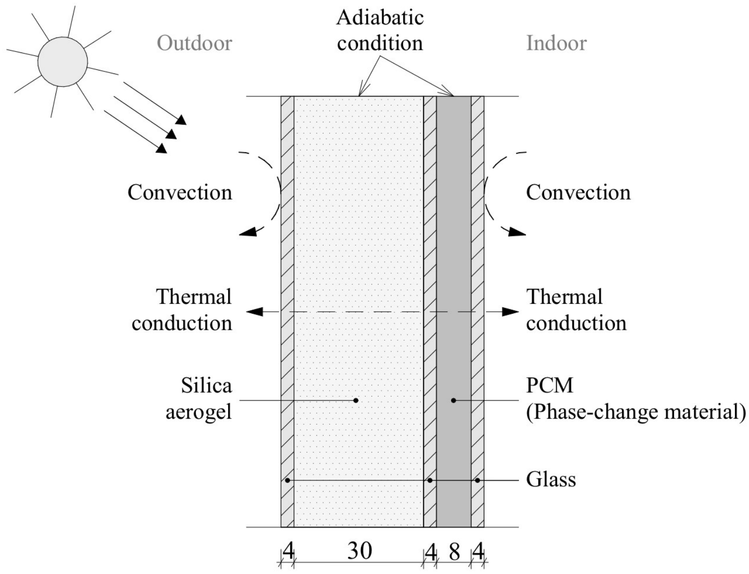

Fig. 2. A PCM and aerogel integrated window glazing system’s structural configuration (according to Zhou, 2021)

In Egypt, they devoted themselves to simulations and measurements of the energy efficiency of various types of glazing in combination with shading elements on a school building. At the same time, they took into account different orientations to the cardinal points. The best results were demonstrated by south-facing glazing, where the annual energy consumption was reduced by 26.3% compared to standard glazing (Mohamed et al., 2023). Further research in this climate zone took place in an administrative building. The simulation results showed that the usage of aerogel instead of simple glazing can save up to 19% of the building’s total annual energy. At the same, the heat flow decreased by more than 40% (Hegazy, 2019).

Conclusion

Windows and generally transparent surfaces are an integral part of the building envelope. They significantly affect the internal thermal comfort of the building. That is why their constant development and improvement of insulating properties is essential (Valachova et al., 2018). According to the latest research, aerogels represent a promising future for thermal insulation. At the same time, they ensure a high quality of diffused light while maintaining their thermal insulation properties. In a transparent form, glazing systems provide remarkable energy savings for buildings (Baetens et al., 2011). It is important to remember that the climate has the biggest influence on the effectiveness of these systems. However, compared to standard double-glazing, their efficiency is favourable in all climates (Chen et al., 2018). In cold climate areas, they can reduce the total need for heating energy by 50%. On the contrary, in a hot climate, they can eliminate excessive solar heat gain by up to 73% and thus reduce the cooling load by 33%. Another favourable feature of aerogel glazing is the reduction of emissions by 63% compared to classic double glazing (Mohammad & Ghosh, 2023).

Future development of monolithic silica aerogels could significantly increase solar transmittance and improve their thermal insulation properties better than granular aerogel (Wang et al., 2015). Through this review, it is possible to conclude that aerogel glazing systems represent a promising solution for increasing the energy efficiency of buildings. These innovative systems not only provide effective insulation but also significantly contribute to the overall reduction of carbon dioxide emissions in the construction industry. By exploiting the impressive thermal properties of aerogels, these glazing systems have demonstrated their potential to mitigate heat losses and gains, thereby optimizing the overall energy performance of structures. However, it is important to note that aerogel material is still in the research stage and its future use in construction practice depends mainly on economic sustainability. During the development and implementation of this material, it is necessary to pay attention to the potential disadvantages and negative effects associated with its use.

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