Durable and Robust Vacuum Insulation Technology for Buildings

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ABSTRACT

Vacuum insulation panels (VIPs) provide unprecedented opportunities for obtaining excellent thermal insulation with light and slender constructions. This article discusses the performance over time of VIPs, and the possibilities to overcome the current problems related to fragility and limited durability.

Aerogels are together with fumed silica among the most competitive core materials for VIP’s. The use of classical aerogels, as produced in autoclaves is, however, limited due to the high production costs. The fumed silica on the other hand requires vacuum levels that are difficult to maintain with the currently available vacuum envelopes. A material with comparatively smaller pores will on the other hand allow obtaining low thermal conductivity at higher pressure (less vacuum) and will therefore reduce the pressure difference over the envelope. There is therefore much to be gained by reducing the pore size. New cost and performance efficient silica aerogels offers opportunities to enhance the properties of the panels by customizing the pore structure and pore size distribution. Building technologies and how the panels are applied in a manner that improves the structural, thermal and hygroscopic performances of vacuum insulated constructions have been studied and are discussed.

KEYWORDS

Vacuum insulation technologies, Performance over time, Building technology, Aerogel, Core materials.

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1 INTRODUCTION

1.1 Energy and the Climatic Envelope

Space heating constitutes a large part of the energy used in Sweden and the European Union (about 40%). About half of that can be related to the thermal losses through the climatic envelopes of buildings. This presents an economical problem as well as a threat to our local and global environment. The technical solution of the problem is complex, but will essentially involve severe reduction of heat losses through the walls, floors and roofs of the buildings. With traditional insulation materials this will lead to a significant increase in the thickness of the climatic envelope. A house in Sweden that is to meet the passive house standards would thus have an insulation thickness of some 335 mm in the wall and 500 mm in the roof in order to meet a U-value of 0.10 and 0.066 W/(m².K), respectively.

1.2 New Opportunities with VIPs

Today’s requirements on energy savings demand vast insulation thicknesses if traditional insulation materials are to be used in the construction of residential buildings. As a result, significant living space area may be lost and restrictions are put on architectural expression. Regarding the refurbishment of the existing building stock there is often too little space available for adequate additional insulation on the inside of the building and the application of external insulation may endanger the architectural values of the facades. The excellent insulations properties of VIPs may however provide a solution since only a fraction of the insulation thickness is required.

A conventional vacuum insulation panel consists of a gas-tight envelope surrounding a porous core from which the air has been evacuated. The combination of pore size and low pressure prevents thermal transport through convection of the gases within the core. Conduction through the collision of gas molecules is eliminated by using core material with pore size less than the mean free path of the gas molecules, which in turn depends on the extent of evacuation. Consequently the gas pressure that has to be obtained within the envelope in order to reach a certain value of thermal conductivity in the VIPs depends on the pore structure of the material applied in the core. Fumed silica, for instance, maintains a constant thermal conductivity of about 0.004 Wm⁻¹K⁻¹ up to a gas pressure of about 10 mbar, the value being the double for a tenfold pressure of 100 mbar. Material with coarser pores, however, such as polyurethane, polystyrene or fiber glass will only maintain a comparable constant level up to a pressure just above 0.1mbar with a fourfold thermal conductivity at a pressure of 10 mbar (Fricke et al, 2006; vip-bau.de, 2009). The relationship between core pressure and the thermal conductivity of several different core materials is shown in figure 1.

![Figure 1. Core pressure and thermal conductivity of different core materials(IEA, Annex 39, 2005a).](image-url)
Consequently a core material with coarser pores will require a greater degree of vacuum in order to obtain the same thermal insulation, other things being equal.

Conduction through the solid matrix of the core is limited by using materials with geometric structures that minimize the area of contact between the particles while the radiative heat exchange between the interior surfaces of the core material is determined by the temperatures as well as the geometries and surface properties, the latter which can be improved by the use of additives.

A regular VIP panel consists of a metalized polyester film with a core of fumed silica a picture of which is shown in figure 2. There are, however, vast possibilities of combining different core materials and envelopes in different typologies as described in the literature (Cremers, 2005).

![Figure 2. A regular VIP panel with a fumed silica core (IEA, Annex 39, 2005a).](image)

The application of VIPs has been limited to a small number of buildings. An account of their applications is to be found in the report of the International Energy Agency (2005b) as well as in Ghazi Wakili et al. (2005), Schwab et al. (2005) and Binz and Steinke (2005). Batens et al. (2010) have done a review of VIPs in building applications.

1.3 Durability and Service Life of VIPs

The service life time of a VIP can be defined as the time at which the required thermal conductivity has been surpassed. A further account is given in ISO 15686-2 (2001).

The most important aging mechanism of VIPs with fumed silica cores and a metalized polymer film envelope is the permeation of gas through the envelope. This effect may be enhanced at higher temperatures and humidity and is further increased at the edges due to a higher defect density of wrinkles and at the seal of the foil (Simmler and Brunner, 2005). The edge effect will get greater with the ratio of edge length over area of the panel (Schwab et. al, 2005) As can been seen in figure 1, the thermal conductivity of the fumed silica core will increase by a factor of about 5, when going from a pressure of 1 mbar to standard atmospheric pressure.

Short term measurements of Vacuum insulation panels can be used to predict the service life of vacuum insulation panels. Based on the measured gas transmission rates or measurements of pressure increase (Caps et. al., 2008) and water vapor transmission rates of the VIPs, the service life can be predicted through an analytical model that relates the gas pressure, vapour pressure and water content to the thermal conductivity of the panel (Simmler and Brunner, 2005; Annex 39, 2005a).

A commonly used method for securing or prolonging the service life of panels is to put getters or desiccants in the core material in order to adsorb or entrap residual gas or moisture (Thorsell, 2006).
With current technology the gas pressure increase of a 20mm thick VIP with metallized high barrier envelope is around 1 mbar a year giving a lifetime of 10-25 years depending on the required performance of the panel (Caps et al. 2008) and initial pressure that can assumed to be in the range of 1-5 mbar at delivery (Microtherm, 2010).

While the problem of gas diffusion through the envelope may be solved by using virtually impermeable metal films with a thickness of 10 µm or more it has been shown that this may give lead to thermal losses that are of the same magnitude as the heat flow through the panel (Ghazi et al, 2004). One must bear in mind, however, that a VIP panel might even fail due to failures caused by imperfect production or through mechanical damages during installation.

2 VIP OPPORTUNITIES

The in situ performance of VIP panels depends of the properties of the panels and the manner in which they are applied. Our work is concerned with studies of how the prestanda of the panels may be improved by changing the material of the core and the possibilities of enhancing the robustness, performance and durability of the panels through an appropriate building technology. The relevance of these measures can be measured in terms of economical and environmental benefits.

2.1 Robust Building Technology

The superior thermal properties of the panels are somewhat diminished by the thermal bridges at the edges. Tenpierik and Cauberg have presented analytical models for calculating this thermal edge effect for thin high barrier laminates around VIPs (Tenpierik and Cauberg, 2007) while Thorsell and Källebrink studied the effects of applying a serpentine edge on a metal panel (Thorsell and Källebrink, 2005). Other researchers have investigated the different thermal bridges that arise when VIPs are applied in different constructions and various building details (Schwab et al., 2005; Ghazi Wakili et al, 2005; Nussbaumer et al, 2006, Platzer, 2007).

Our work is concerned with building technology that adresses the issue of thermal bridges while at the same time overcoming the fragility and limited durability of the VIPs. Previous and ongoing parametric studies show that the thermal edge loss can be compensated with an adjacent layer of thermal conductivity in the range of traditional insulation materials (Gudmundsson, 2009).

The left side of figure 3 shows a section where two VIPs meet with a gap of 2 mm at the joint. The VIP panel is assumed to have a $\lambda$-value of 0.005 Wm$^{-1}$K$^{-1}$ while that of the sealant in the gap is 0.02 Wm$^{-1}$K$^{-1}$. The figure on the right shows the thermal loss at the joint for different thermal conductivities of the adjacent insulation as compared the heat flow through an unbroken VIP. The results were obtained with COMSOL Multiphysics®.

Figure 3. A section where two VIPs meet and a diagram that shows the additional linear thermal loss at the joint for different thermal conductivities of the adjacent insulation.
Based on our findings we therefore propose a solution where the panels and their edges of the panels are covered with an adjacent insulation material that breaks the thermal bridges while protecting the panels and providing a carrier for the rendering of the façade.

The effect of using an exterior insulation with low thermal conductivity is positive in terms of reducing the thermal bridge while much is to be gained by increasing the size of the panels and thus the length of the joints per square meter of VIP. The exterior application of VIPs is also favourable in terms of the risk of condensation and high relative humidities.

2.2 Improving the Core Material

Aerogels are together with fumed silica among the most competitive core materials for VIP’s. The use of classical aerogels as produced in autoclaves is, however, limited due to the high production costs. The fumed silica on the other hand requires vacuum levels that are difficult to maintain with the currently available vacuum envelopes. A material with comparatively smaller pores will on the other hand allow us to obtain low thermal conductivity at higher pressure (less vacuum) and will therefore reduce the pressure difference over the envelope. Consequently there is much to be gained by reducing the pore size of the core material. It will be of particular interest to investigate the margin of improvement in terms of the environmental impact when substituting fumed silica with aerogel and to compare it with the results for traditional insulation materials. A study by Mukhopadhyaya et al. (2009) shows that fiber-powder composites have promising potential to be used as core materials for the construction of high-performance VIPs.

2.3 Economics and Durability

The use of VIPs can in some instances be motivated by the gain of living space area. The economic effect of increasing the service life of VIP panels in can be illustrated within that context. Assuming a VIP panel with a given thickness, thermal conductivity and price per sqm we can calculate the net cost of using vacuum insulation instead of EPS with the same thermal performance, given a certain rate of interest rate and inflation (Gudmundsson, 2009). The figure below illustrates the net cost as a function of net income per sqm and shows what is to be gained with an increased lifetime of the panels, through which the panels are assumed to have a constant thermal resistance.

![Figure 4](image-url)  
**Figure 4.** The net cost and net income per sqm. Assuming 30 mm thick VIP panel with a thermal conductivity of 0.004 Wm⁻¹K⁻¹ and a price of 1800 SEK/m². The real interest rate is assumed to be 5%.
Another way of approaching the problem is to look at the break even price for a given net income and a durability of a given period of time. The results are that for a lifetime of 25 years and an annual income corresponding to the average rental income in Sweden there will be a break even for an investment cost for VIPs of about 1250 SEK per sqm wall area. This price is beneath the current price levels which means that with current lifetime the prices have to go down if VIPs are to be able to be fully economically competitive.

![Figure 5. Price of VIP vs net cost for an average annual rental income of 1000 SEK/m². A lifetime of 25 years is assumed.](image)

**2.4 Life Cycle Impact of VIPs and Potential for Improvement**

There are reasons and possibilities for improving the technical and economic aspects of VIPs. Together with the aspects of building technology and durability it is plausible to assume some advantages in terms of sustainability, that need to be analysed and verified in accordance to the relevant ISO standards.

Besides the discussion of the technical and economic possibilities, the quantification of environmental impacts, through the life cycle of a VIP panel is a necessity when evaluating the potential effects of altering their design. A Type III environmental product declaration (EPD) according to ISO 14025 and in line with the forthcoming European Standard prEN 15804 has to be carried out. The manufacturing processes have to be monitored in order to provide the necessary data. Complementary to the production process, the environmental declaration will include the “cradle to gate” stages in terms of environmental LCA (ISO 14040 and 14044), as well as the end-of-life stage. Aspects related to the use-stage of construction products can usually not be ascribed to the product itself, hence this stage is not a part of the declaration. Instead, key technical properties of the product will be presented, enabling the reader to put the presented data into the overall performance context of a building.

Ultimately, the forthcoming life cycle assessment will generate a strictly product related EPD presenting the quantified environmental impact according to the relevant standards, and in line with the detailed product category rules applicable to the VIP panels. The discussion of the environmental pro’s and con’s will include the application of the material in a building, focusing on the contribution of the material to the overall building performance. For such an assessment, either a reference-comparison with a building with the same technical properties but different materials must be set up, or the effect of changing from a given design to a design incorporating the presented materials must be set up. A direct raw comparison of the EPD data of this product with competing products is of limited use. Mainly the weaknesses and improvement potentials may be determined, but a fair comparison will necessarily need to be conducted in the application context of the products.
Previous work indicates that the greatest potential of improvement is replacing the fumed silica in the core since it is currently a by-product of the production for electronic chips. The common precursor silicon tetrachloride is highly energy intensive and dominates the results of the ecobalance to over 60% (IEA, Annex 39, 2005b).

3 CONCLUSIONS AND DISCUSSION

While vacuum insulation panels have superior thermal properties the fragility and limited durability pose a threat to the lifetime of the panels and hence the economy of their application.

The economical benefits of prolonging the lifetime of the panels are clear and the issue of fragility may be overcome by applying an appropriate building technology such as panels with a protective layer that may also be used to reduce the thermal bridge at the joints of the panels.

Further improvements of the panels may be reached by replacing the fumed silica core with a material with comparatively smaller pores, thus reducing the pressure difference over the envelope and extending the service life of the panels.

We are currently working on a solution with an aerogel as a core material. Previous work indicates a potential for environmental benefits due to the prolonged lifetime and ultimately due to the production process of the core. A quantification of environmental impacts will be necessary in order to quantify any advantages in terms of sustainability, however. This can be done according to the previously mentioned ISO standards and European Norms. Such work will demand the manufacturing process to be monitored in order to provide the necessary data.

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REFERENCES


