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State-of-the-Art and Future Building Envelopes: Application of Low Emissivity Materials, Phase Change Materials and Vacuum Insulation Panels

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Abstract:
Increasingly strict demands for the use of energy in buildings have put pressure on the construction industry to look for new ways to improve the built environment. This study has investigated three technologies, low-emissivity (low-e) materials, phase change materials (PCM) and vacuum insulation panels (VIP), and provided a state-of-the-art review of commercial products of these materials. Though the materials have different effects when applied to buildings, they all aim to increase energy efficiency and improve thermal comfort for the inhabitants.

For the mentioned materials, examples of how they are implemented in buildings have been given and research that have been conducted and research that is still being conducted have been investigated. Reflections on steps that should be taken for future research have also been investigated. Herein lies the focus on improving the current technology, possible new technologies and steps that are needed for the materials to achieve large-scale application in the construction sector.

Keywords:

1. State-of-the-art
2. Future research
3. Construction
4. Building materials

Simen Kalnæs

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Norwegian abstract

Stadig strengere krav til energibruk i bygninger har lagt press på byggenæringen til å søke etter nye måter å forbedre bygg. Denne oppgaven har undersøkt tre teknologier/materialer, lav-emissivitets (low-e) materialer, faseforandringsmaterialer (phase change materials (PCM)) og vakumisolasjonspaneler (VIP), og gitt en state-of-the-art av komersielle produkter som er tilgjengelig. Selv om disse materialene fungerer på forskjellig måte når de blir implementert i bygninger er det overordenede målet deres det samme, å øke energieffektiviteten og forbedre det termiske miljøet for brukerne.

For de nevnte materialene er det også gitt eksempler på hvordan de blir implementert i bygninger, og forskning som har blitt og fortsatt blir gjort på forskjellige bruksområder er undersøkt. Det har også blitt reflektert over hvilke steg som burde bli tatt i henhold til framtidig forskning. Her ligger fokuset på å forbedre dagens teknologi, potensielle nye teknologier og steg som trengs for at disse materialene skal bli tatt i bruk på en større skala i byggenæringen.

Preface

This master thesis is written as the finalization of the five-year Master of Science program within Civil and Environmental Engineering at the Norwegian University of Science and Technology (NTNU) during the autumn term of 2013.

The thesis contains three scientific journal articles. Two articles have been written for this master thesis and deals with low-emissivity materials and phase change materials. The third article dealing with vacuum insulation panels was delivered as my project work and has been published through a review process while writing this thesis.

The article on low-emissivity materials was written as a continuation of my summer work at SINTEF Byggforsk in the summer of 2013. The thesis should also have included a laboratory experiment on accelerated ageing of low-emissivity materials. However, due to breakdown of the temperature controller for the SOC100-HDR, which we would use to measure the emissivity of materials, and the fact that replacing it took considerably more time than expected, there was unfortunately not enough time to conduct the experiments.

The articles dealing with low-emissivity materials and phase change materials have been submitted to *Solar Energy Materials & Solar Cells* and *Energy and Buildings* respectively and will hopefully also be published.

I would like to extend special thanks to my teaching supervisor Bjørn Petter Jelle for valuable guidance and feedback that have helped me through the process of writing these scientific journal articles.

Simen Kalnæs

Simen Edsjø Kalnæs

Trondheim, Norway
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Contents

Process report

Introduction

This process report will cover the work that has been conducted when writing the master thesis as a set of three international scientific journal articles. The articles "Low-emissivity materials for building applications: A state-of-the-art review and future research perspectives" and "Phase change materials for building applications: A state-of-the-art review and future research opportunities" were written during the master thesis. The third article "Vacuum insulation panel products: A state-of-the-art review and future research pathways" was written as my project work and published through a review process while writing this thesis.

The aim of this process report is to show how the process of writing the master thesis as an international scientific journal article has been conducted based on expectations prior to the work, the working process and experiences gained after completion.

Expectations prior to the prior to the master thesis

Due to the fact that I had already written a scientific journal article as my project work in the previous semester, I had a good idea of what was expected of me for the two new articles as well. However, a part of the original work I was intended to do was a laboratory experiment on accelerated ageing of low-emissivity materials. This would be a continuation of my summer job at SINTEF Byggforsk the summer before writing this thesis. Being in the laboratory was something I had never done before, and I was looking forward to basing my article off some of my own experiments. Unfortunately, the SOC100-HDR which I would use to measure the emissivity of the materials in the experiments had a breakdown of the temperature controller at the very beginning of my thesis. Although the part should not have taken more than a couple of weeks to replace, this ended up taking over two months. Thus, not leaving enough time to complete the experiment.

The two new articles I would write were about areas which I found to be very interesting, increasing the energy efficiency and thermal comfort of buildings by using new materials or using the materials in new ways.

The master thesis

In the end, the master thesis ended up as a set of three scientific journal articles. I took part in addressing the reviewers comments on the article dealing with vacuum insulation panels and this article was published online during my thesis. The two other articles were written and finalized and have also been submitted for publication.

The layout of the two articles written for the thesis were fairly similar. An introduction where background literature and theoretical and practical principles were presented, a state-of-the-art chapter where commercial products are described, presented in tables and compared, a chapter that describes various areas where these types of materials can be used in buildings and a chapter pointing towards future research and work that can be done to improve the technology.

To write a good article the first thing I needed was background knowledge. So the first few weeks was spent doing nothing but reading up on the subject. Based on the things I read, a content list was created together with my supervisor so we knew the most important subjects would be covered. I also wrote down facts and kept the sources which I found interesting at first glance. I had learned from my project work that reading up on background knowledge without taking proper notes and immediately creating an outline of my article left me with a lot of issues when I started writing. Therefore, I started writing down my thoughts much earlier this time. Even though this is a scientific article, and the work needs to be precise and detailed but still short, it was better to write to much in the beginning than nothing at all.

I knew the time I had to my disposal and knew partly what was expected since I had written a scientific article the previous semester. I started with the article about low-emissivity materials as I had dealt with this subject on my summer job. First by creating a table of manufacturers and products. The theory chapter could then focus on the products that can be found on the market and what separates these technologies. Through briefly describing the available technologies that are available in commercial products and categorizing them in various tables, I had already gained considerably more knowledge than when I first started. From there on, the work focused on finding interesting examples from real life structures and scientific articles of experiments and simulations that tested out and described various ways of using this technology in buildings. After having described potential uses in buildings and the basic theory behind commercially available products, I could better address the final chapter about future research possibilities. Here, the weaknesses and potential improvement of the technology is discussed. This chapter is made up of issues addressed in the literature and some are part of my own reflections.

During the writing process I had several meetings with my supervisor where we discussed the themes addressed in the article so the final result would end up in the best possible way. When the first article was somewhat finished and only addressing minor details were left, I started writing the third article dealing with phase change materials. This was done basically the same way as the previous article. However, while writing this article I also addressed things pointed out to me by my supervisor on my low-emissivity article so it could be finalized and be ready for submission to a scientific journal. And by this time, we also received a minor revision from the reviewers on my project work which I took part in addressing.

Even though I had written a scientific journal the previous semester, I felt that when I read up on the subjects of low-emissivity materials and phase change materials, that these were more complex materials than vacuum insulation panels in the way they were used to increase the energy efficiency of buildings. So several times during my writing I experienced being somewhat confused about the things I wrote and had to spend some time re-reading to fully understand the systems I was describing. However, understanding the principles and gathering the most interesting articles have been a valuable learning process.

Experiences learned from the master thesis

When writing my project work, I started from scratch when it came to writing a scientific article and encountered several issues along the way. Due to that, I feel that I disposed my time better during the writing of my thesis. When I started reading background literature on my subject I started outlining my thesis and wrote down the interesting parts that I felt would be relevant later. Because of that I had a better overview of what needed to be done throughout the writing process.

Summary

During the writing of these scientific articles, not only have I gained knowledge about some very interesting materials that may be important for the built environment of tomorrow, but I also feel that my ability to write scientific texts have been improved. It has been a valuable experience and I hope I will be able to use the knowledge I have gained about these materials in the future.

Article 1:

S.E. Kalnæs, B.P. Jelle and T. Gao,
"Low-Emissivity Materials for Building Applications:
A State-of-the-Art Review and Future Research Perspectives"

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Low-Emissivity Materials for Building Applications: A State-of-the-Art Review and Future Research Perspectives

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Abstract

Low-emissivity (low-e) materials can be used in order to reduce energy usage in both opaque and transparent areas of a building. The main focus for low-e materials is to reduce the heat transfer through thermal radiation. Furthermore, low-e materials will also influence on the daylight and total solar radiation energy throughput in windows, the latter one often characterized as the solar heat gain coefficient (SHGC).

This work reviews low-e materials and products found on the market, and their possible implementations and benefits when used in buildings. Though many studies show the benefits of using low-e products, there is ongoing debate on the certainty of calculated U-values of low-e products in actual use. Low-e coated glazing has lead to improved energy efficiency of glazing. However, it is difficult for consumers to understand the improvement with many of todays labelling systems, which only takes U-values into consideration. Solar heat gain, or reduction, is left out by many countries in the energy labelling of windows. Opaque materials have demonstrated good results in warm climates where cooling loads are dominating. With opaque materials, research is still ongoing to correctly calculate the effect with regard to thermal performance when applied in buildings.

Future research perspectives on where low-e technologies may develop are explored. To the authors knowledge, there seems to be little available literature on how ageing affects low-e materials and products. This is of significance when calculating energy usage over the lifetime of a building. Especially as large glass facades have become more widespread, this should be an area for future research.

Keywords: Low-emissivity; Low-e; Building; State-of-the-art; Review; Future.

Contents

1 Introduction

Energy usage in buildings represents about 40 % of the total energy usage in Europe. The European Union has set a goal to reduce the energy usage in buildings by 20% by 2020 and 50% by 2050, compared to values from 1995 (European Union [15]). A large part of the energy usage is directly related to heating and cooling demands for buildings. Transparent surfaces, e.g. windows and skylight glazing, stands for a substantial part of this energy loss. In areas with hot climates, an increase in cooling demands, i.e. increased energy usage, due to overheating caused by high radiation conductivity is a common problem. A reduction in the heat transfer due to radiation may give positive results due to lower cooling needs in the summer and may also benefit in lower heating needs in the winter if you can keep heat from radiating to the outside. To achieve such building envelopes, with a passive reduction in energy usage, low-emissivity (low-e) materials are of interest. However, an important factor to consider with low-e materials are geographical climactic conditions. The possible effects gained are highly different between cold climate regions, hot climate regions and regions with both warm summers and cold winters (Shi and Zhang [69]).

Low-e materials and coatings can be applied in both the opaque and transparent parts of a building envelope. For transparent parts, i.e. glazing, low-e solutions consist of coatings which are added during or after the production of the glass by the manufacturers themselves, or do-it-yourself films that can be applied on the inner side of glazing even after they have been installed. It is important to consider the net energy consumption for windows as they include both transmission losses and solar energy gains (Fang et al. [17], Grynning et al. [21], Jelle [38]).

Opaque parts of a building envelope use low-emissivity solutions that consist of various low-e foil products or spray coatings. A review performed by Medina [49] showed that applying radiant barriers (i.e. low-e foils) and spray coatings can significantly reduce heat transfer across attic spaces and thereby lead to a reduction in space cooling loads.

To the authors knowledge there seems to be little available literature on how ageing affects the performance of low-e materials under building related conditions. This may be a field of interest for future research, as it is important to know both with regard to energy performance over a components lifetime and the need to plan for replacement of aged parts.

The objective of this study is twofold, i.e. (a) to present an overview of different low-e coating and material producers and products, and to evaluate the effect and durability of these products, and furthermore (b) to explore possible future research perspectives. In addition, it is of interest to see how low-e solutions are tested with respects to lifetime performance in building applications. These investigations may help for guidelines for a new testing scheme and point to future research perspectives. This work presents many tables with a lot of information, e.g. manufacturers, product names and various properties, both in the main text and in the appendices. Some of these values are crucial to the performance of low-e coatings and materials. The tables should provide the readers with valuable information regarding low-e solutions. Unfortunately, it is currently hard to obtain all the desired information from every manufacturer. In general, many of the desired property values are not available on the manufacturer's websites or other open information channels, which is hence seen as open spaces in the various tables. Hopefully, our addressing of these facts could act as an incentive for the manufacturers to state all the important properties of their products at their websites or other open information channels, and also as an incentive and reminder for consumers and users to demand these values from the manufacturers.

2 Low-emissivity concepts

2.1 General

2.1.1 Solar energy

The largest parts of energy from the sun can be found in the visible (380-780 nm) and near infrared spectrum (780-3000 nm) (Fig.1). Solar radiation onto a surface will be reflected, transmitted and absorbed. The division of solar radiation onto a surface is dependent on the wavelength (λ), incident angle and the materials optical properties. The sum of the fractions of a materials reflection (R), transmittance (T) and absorbance (A) is given by (Jelle [38]).

$$R(\lambda) + T(\lambda) + A(\lambda) = 1 \ (100\ \%) \qquad (1)$$

The solar energy which is absorbed in the material is equal to the energy emitted, i.e.

$$A(\lambda) = E(\lambda) \qquad (2)$$

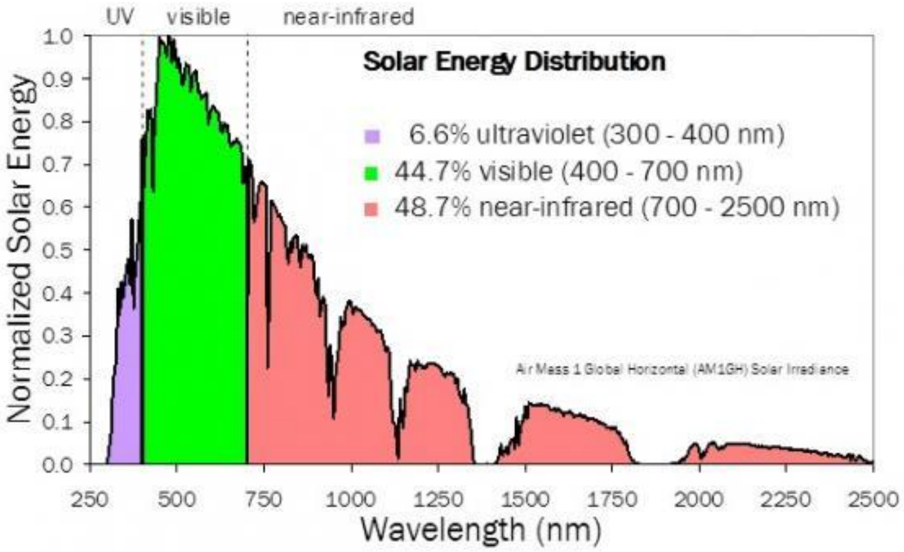


Figure 1 Solar energy distribution (Heat island group, Berkeley National Research Laboratory [25]).

However, for an opaque material there is no transmittance. Hence, Eq.1 can be written as

$$R(\lambda) + A(\lambda) = 1 \ (100\ \%) \tag{3}$$

This gives an emissivity of

$$E(\lambda) = 1 - R(\lambda) \tag{4}$$

for opaque materials (Wu and Yu [75]).

Unwanted solar radiation is a large contributor towards increased energy usage in buildings. Controlling the radiative heat given off by the sun and utilizing the solar energy when needed is the key to attain more energy-efficient buildings. The idea of low-e materials is to reduce the radiative heat conduction, either in to, or out from a building. Near-infrared radiation is reflected by the material, and long-wave infrared radiation given off at room temperature from materials inside is reflected back into the room maintaining a higher indoor temperature. Transparent materials, e.g. glazing, will allow visible parts of the solar spectrum to pass through. The climate in which the materials are intended must therefore be considered, as areas dominated heating loads or cooling loads will utilize solar energy gain in different ways. Simply installing a low-e material without sufficient planning may remove all the possible positive effects, e.g. the energy saved during summer may be neutralized by increased energy use in the winter.

Because of this difference between transparent and opaque materials, separate explanations for transparent and opaque materials will be given in the following.

2.1.2 Angle dependency

A surface whose emittance is the same regardless of direction is called a diffuse emitter. However, no real surface can be a diffuse emitter and emittance will vary with the incident angle. Figure 2 shows the directional variation of surface emittances for several nonmetals and metals (Modest [54]). It is clear that metals show lower emittance values at most angles compared to traditional construction materials such as e.g. wood, glass and clay. Hence, these materials are often used for low-emittance solutions.

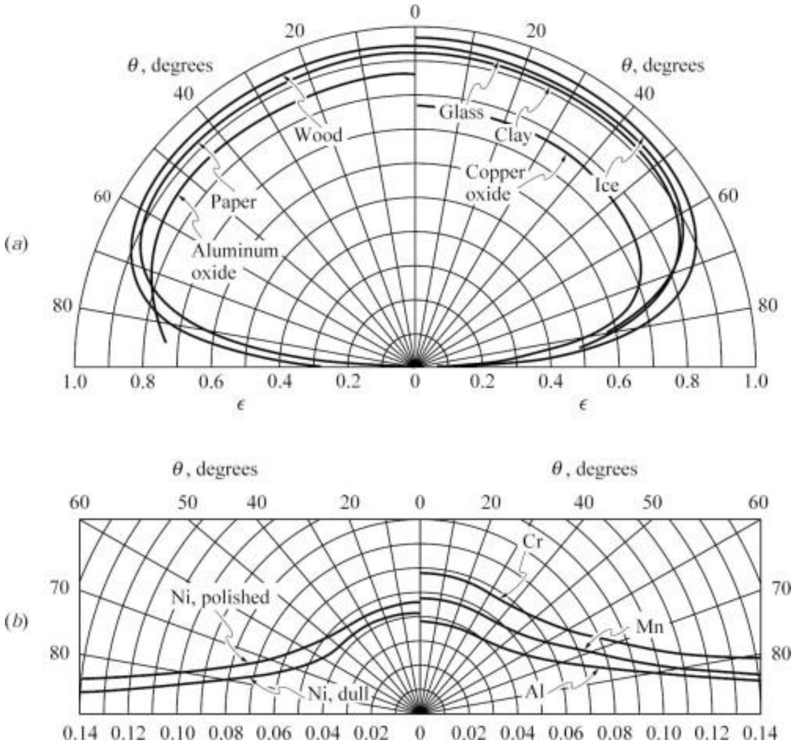


Figure 2 Directional variation of surface emittances (a) for several nonmetals and (b) for several metals (Modest [54]).

2.2 Transparent materials

2.2.1 Transparent materials in general

When low-e materials are applied to transparent areas of a building envelope there are some different requirements which need to be considered versus low-e materials that are applied to opaque areas. Glazed areas are in many cases added to be architecturally pleasing and to allow visible light inside. Hence, a low-e coating for glazing should show spectral selectivity, i.e. have a high transmittance in the visible range of the spectrum to allow visible light inside, and at the same time provide high reflectance in the near infrared part of the spectrum (Park et al. [59]). Note that because of the extra energy provided by visible light transmitting through the window, the solar heat gain will be larger through transparent areas of a facade. Controlling the solar gain so that unwanted overheating does not occur due to excessive heat through glazed parts of a facade, or so that desired heat stays inside the building during cold seasons is a challenge for optimizing transparent areas.

Desirable characteristics for a low-e coating for glazing as mentioned by Leftheriotis and Yianoulis [45] are:

1. Low-e coatings must exhibit high transmission in the visible part of the spectrum

2. The emittance must be low in order to prevent the heat from the interior to be transmitted outside.

3. The coating must have long-term stability under solar irradiation. Coatings on glazing are exposed to sunlight for large periods of time during their useful lifetime. However, no form of long term degradation should be present.

Standard clear glass has an emissivity value of about 0.84 for the long-wave part of the spectrum, i.e. 84 % of the solar energy is absorbed and emitted from the glass (Karlsson and Roos [43]). Low-e coatings greatly reduce the emissivity of a glass pane. In general, two different methods are used when coating the glass surfaces, and each method has different advantages and drawbacks, as well as various results on the emissivity value. In the following, the different methods of applying low-e coating to glazing will be explained.

2.2.2 Hard coatings

Hard coating is the result of applying a low-e coating during the production of the glass. These coatings are often also referred to as pyrolytic coatings or on-line coatings. The on-line coating process applies doped metal oxides to the glass surface while it is still heated. The common method used to apply a hard coating is by chemical vapour deposition (CVD).

Fluorine-doped tin oxide is a largely used option for low-e hard coatings. Tin oxide can be applied by atmospheric pressure CVD and has a high transparency for visible light, high reflectivity for infrared light, high mechanical hardness and good environmental stability (van Mol et al. [56]).

A hard coat becomes a part of the glass, i.e. the glass can be shaped, hardened, etc. after manufacture. Hard coatings have higher stability towards chemical and mechanical wearing than soft coatings. Thus, making it possible to use hard coated glass on exposed surfaces, e.g. single pane windows and anti-condensation glass. As these coatings can be used on exposed surfaces, it is of interest to know how they react to climate stresses with respect to their aged performance.

2.2.3 Soft coatings

Soft coatings, also referred to as metal-based multilayer coatings, are applied to the glass after it has hardened. The process usually involves high-rate magnetron sputtering with layers of at least one conductive metal layer with a thickness of about 10 nm. The most preferred option for the metallic layer is silver due to its good optical properties. Copper and gold can also be used, however they show unwanted short-wavelength absorption for wavelengths under 0.5 µm (Granqvist [20]). As the metallic layers, with the exception of gold, degrade by oxidation, they are added in between optically transparent dielectric layers (Mohelnikova [55]). The dielectric layers can consist of various oxides, such as zinc, tin, bismuth or titanium, with a thickness of below 40 nm. The metallic layers provide the thermal and solar reflectivity, the dielectric layers may provide antireflective functions in the visible spectre while at the same time protecting the metallic layers from chemical and mechanical damage (Meszaros et al. [50]).

The soft-coating process has a higher cost than the hard-coating process, and the soft coatings are not as robust. Hence, soft coatings can only be applied to multi-layered windows on the surfaces facing the cavities. In general, soft coatings do provide a lower emissivity value than hard coatings, and transmit more visible light (Commercial Windows [11]).

2.2.4 Self-applicable films

Films consist mainly of several layers of metalized polymers containing an adhesive to be applied directly on the inward facing surface of a window. These are films that are possible to apply to a window even after they are installed. Current films can only be applied to the inside of the window as they are not durable enough to handle outside climate conditions.

Even though these films cost less than industry coated glass, and are a simple solution to gain low emissivity for a glass pane, they have some considerable drawbacks. Self-applicable films gives windows a slight tint, impairing visibility and transmitted light, some films cannot be removed once applied. Films may also impair with the window manufacturer's warranty as the expansion of the glass will be altered after the film is applied due to temperature differences. Note that even though the films are self-applicable, applying them incorrectly can cause air bubbles between the film and the glass, which is aesthetically displeasing and may affect the effectiveness of the film (Home renovations [26]).

2.2.5 Suspended films

Suspended films work by implementing a film or a sheet in between two glass panes in an insulating glazing unit (Fig.3). The film is not attached or applied directly to any of the glass surfaces, but forms an additional layer inside the cavity. Installing a suspended film divides the section inside the cavity. Hence, contributing to lowering the total U-value of an insulating glazing unit. As the film is very thin it does not increase the thickness of the unit, and the increased weight is minimal compared to having a third glass pane. The films are treated to withstand UV-degradation and are protected from scratching , wear and weathering by being placed inside the cavity. (Commercial Windows [10]). A double pane window with a suspended film installed is often referred to as a triple glazed suspended film.

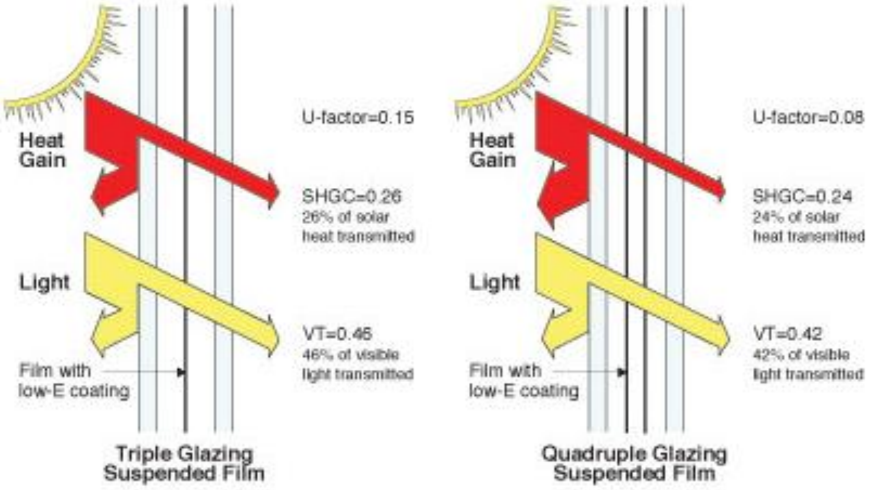


Figure 3 Illustration of suspended films in an IGU (Commercial Windows [10]).

2.3 Opaque materials

2.3.1 Opaque materials in general

Adding low emissivity opaque materials to a building envelope is most beneficial in warm climate areas. Building norms in warm climates does generally not consist of adding thick layers of insulation to the building envelope and the excess heat from the sun is unwanted for larger parts of the year. A radiant barrier will provide a more effective reduction in energy usage as it will block off more solar energy and reduce indoor temperatures, i.e. reduce the need for mechanical cooling.

There are two common solutions that consist of adding low-e properties to the building envelope. One consists of adding a foil product as an insulation layer to reflect radiant heat, the other consists of adding a layer of paint with low-e properties which fulfils the same purpose. Both are explained further in the following.

2.3.2 Reflective insulation and radiant barriers

For low-e foils used as thermal insulation the terms reflective insulation and radiant barriers are commonly used. Reflective insulations is defined as a thermal insulation consisting of one or more low emittance surfaces, bounding one or more enclosed air spaces. Reflective insulation consists of layers of aluminium, paper and/or plastic to trap air and reduce convective transfer. The aluminium part provides the reflective part of the insulation with an emittance value of 0.03. When installing reflective insulation, it is important to allow a sufficient airspaces (Fig.4). If materials are in direct contact with the aluminium on both sides, it will conduct heat straight through the material (RIMA [63]). Reflective multi-foil insulation was introduced onto the building market slightly more than a decade ago. Because of its low emissivity, radiation through the material is significantly reduced, giving low-e foils a high thermal resistance. Thermal resistance values up to 5 or 6 m^2K/W has been claimed. There has however been debates, if these claims are correct (Tenpierik and Hasselaar [72]).

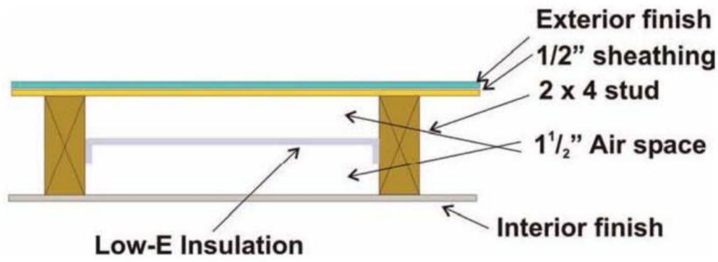


Figure 4 Illustration of installed reflective insulation with airspaces (Low-e reflective insulation [46]).

Radiant barriers are mainly metalized films or aluminium foil sheets laminated to paper, polymer films, oriented strand board or plywood (Medina [49]). These foil products also works as vapour barriers. However, they can be perforated to allow vapour to pass through.

2.3.3 Spray and brush paints

Most common paints for low-e application are paints containing aluminium, silver dust, ceramic beads or sodium borosilicate microspheres (Principi and Fioretti [61]). Spray and brush paints are used to reduce the emittance of the surface they are applied to. It can either be applied to surfaces of an already existing building surface, or be applied to components before they are installed. However, it is always required that there is an airspace of minimum ≈ 4-5 cm between the painted surface and the following material.

Spray and brush paints make for easy application of a low emissivity barrier. As of today, most spray paints are categorized as interior radiation control coating systems (IRRCS), and these have to achieve an emissivity value of less than 0.25. This value is higher than for foil products, but IRCCS can be used where the cost of a foil product would be too high or the installation of a foil would be impractical (RIMA [64]).

3 State-of-the-art low-emissivity building products

3.1 General

There are a variety of products on the market that state they have low-e properties. However, an emissivity value that quantifies something as low-e is undefined. In this chapter, tables containing information about the manufacturers and their various products will be given. Note, that in this study, products that have been categorized as low-e by the manufacturers themselves has been included in the tables.

3.2 Low-emissivity products

3.2.1 Glazing with factory applied coatings

Low-e glazing was introduced to the market in 1979, and was an improvement towards more energy-efficient glazing. Sweitzer et al. [71] concluded that low-e windows was a significant improvement, especially in cold climates. This shows that low-e windows has been of interest for well over 30 years now. Low-e windows has already been adapted as a current standard practice for most European countries when new windows are installed in buildings. Hence, there is a wide group of manufacturers that supply low-e coated windows to the market. Both soft and hard coated windows are considered as factory applied coatings, even though their area of use may vary. As there are many manufacturers of low-e glazing, it would be to extensive to include them all in this work. Hence, the manufacturers and products presented only provides examples of what can be found on the market now. Table 1 shows literature data for glazing with low-emissivity coatings.

Table 1 Literature data for manufacturers of glazing with low-e coatings

Manufacturer	Product	ε	ε_{aged}	T_{sol}	T_{vis}	T_{uv}	SHGC	Coating	Standard*
Guardian Climaguard	Climaguard 55/27				55	18	0.28		Window 6
	Climaguard 62/27				62	5	0.27	Soft coat	
	Climaguard 63/31				63	24	0.31		
	Climaguard 70/36				70	30	0.36		
	Climaguard 71/38				71	24	0.39		
	Climaguard 80/70				81	41	0.70		
Pilkington	K Glass	0.16			76		0.78	Hard coat	EN 410 and EN673
	K Glass S				81		0.75	Soft coat	
	K Glass OW				78		0.79	Hard coat	
	Optitherm S1	0.013						Soft coat	
	Optitherm S3	0.037			80			Soft coat	
	Insulight Therm								
	Spacia			62	78		0.67		
	Anti condensation			60	70		0.71	Hard coat	
PPG Industries	Sungate 400				78	32	0.68		NFRC Methodology
	Sungate 500				76	49	0.70	Hard coat	
	Sungate 600				73	45	0.70		
	Solarban 60				72	21	0.39		
	Solarban 67				55	13	0.29		
	Solarban 70XL				64	6	0.27		
Walshglass	Evantage			41	56	19	0.53		Window 5.2
	Sunergy			40	57	31	0.50		
	EnviroShield			33	61	1	0.43		
	ComfortPlus			42	66	1	0.54		
Cardinal Glass Industries	LoE-366				65	5	0.27	Soft coat	Window 6.3
	LoE-270				70	14	0.37		
	LoE-272				72	16	0.41		
	LoE-180				79	29	0.69		
	LoE-240				40	16	0.25		
	LoE-i89								

Manufacturer	Product	ε	ε_{aged}	T_{sol}	T_{vis}	T_{uv}	SHGC	Coating	Standard*
AGC GlassEurope	Planibel G				75		0.74	Hard coat	EN410. EN673 and EN12898
	Planibel TOP				78		0.61		
	Planibel LOW-E Antifog				72	17	0.63		
Saint-Gobain Glass	SGG Planitherm Total				79	35	0.63		
	SGG Planitherm Total 1.3				77	35	0.66		
	SGG Planitherm Ultra N				80	33	0.63		
	SGG Nano								
Clear Glass Solutions	Planibel G				74		0.71	Hard coat	
	Comfort E2				75		0.72	Hard coat	
	Sunergy clear				69		0.62	Hard coat	
	Planibel Energy N				79		0.64	Soft coat	
CSG Architectural Glass	Single Silver Low-E								
	Double Silver Low-E								
	Triple Silver Low-E								
Milgard corporate	Suncoat Low-E2				70	16	0.37-0.41		Window 5.2
	Suncoat MAX Low-E3				66	5	0.27		
Viridian	EnergyTech				73		0.61	Hard coat	
	PerformaTech E				58		0.32		
	Sunergy				68		0.59	Hard coat	
	EVantage				68		0.63	Hard coat	
	SolTech				73		0.61	Hard coat	
	SmartGlass			68	83	54	0.72	Hard coat	
	ComfortPlus				82		0.68		
Glaströsch	Silverstar zero E				80		0.60		EN 410 and EN 673
	Silverstar zero Eplus				74		0.53		

*Standards or calculation software used by manufacturers to validate given values

3.2.2 Transparent self-applicable films

The self-applicable films are an easy and low-cost solution when compared to replacing the windows for a higher energy-efficiency. Even though the films are self-applicable, every manufacturer recommends the use of a professional installer to avoid air-bubbles and obtain the best possible visual result. In general, most of the films available have emissivity values that are far higher than the factory applied coatings. However, the fact that they can be applied to already installed windows will allow a benefit towards lower energy usage until a window with a factory applied coating can be installed. Table 2 shows literature data for low-emissivity window films.

Table 2 Literature data for manufacturers of low-e window films

Manufacturer	Product	ε	ε_{aged}	T_{sol}	T_{vis}	T_{uv}	SHGC	Standard*
CPFilms	EnerLogic VEP35	0.07		15-19	29-33	1	0.24	NFRC
	EnerLogic VEP 70	0.09		35-46	61-70	1	0.49	
Classic window film	Solar Window film							
Saint-Gobain	SolarGard Ecolux Low-e	0.09		43	68	1	0.48	
	Silver AG 50	0.37		35	51	1	0.43	
	Silver AG 25	0.33		14	22	1	0.23	
Hanita Coatings	Silver 20 Low-E	0.39		12	17	1	0.20	NFRC
	Silver 35 Low-E	0.45		19	27	1	0.28	
3M	Amber 35 Low E Sun Control	0.34			31	1	0.31	

*Standards or calculation software used by manufacturers to validate given values

3.2.3 Opaque foils

From the information found about these products, their most common use is in attics and walls in regions dominated by cooling loads. By reflecting large parts of the incoming solar heat it reduces temperature rise inside the building. Thus, reducing the required energy to keep the indoor temperature comfortable. Most of the foils have the ability to work as a combined vapour and radiant barrier, or they may be perforated to allow vapour to pass through. Reflective insulation is more effective in climates where cooling loads are dominant (Al-Hamoud [4]).

The different terms radiant barrier and reflective insulation are often used. Both have the same ability to block incoming radiation. However, a radiant barrier refers to a fairly thin product that only aims to block radiant heat. Reflective insulation is a thicker product combined with an insulating layer, e.g. fibreglass, foam or air bubbles, to achieve higher thermal resistance. Table 3 shows literature data for low-emissivity foil insulations and radiant barriers.

Table 3 Literature data for manufacturers of low-e foil insulation/radiant barriers

Manufacturer	Product	ε	ε_{aged}	Thickness
Environmentally safe products	ESP- LOW-E	0.03		
	Econo-E	0.03		
	Attic Floor Insulation	0.03		
	LOW-E HVAC	0.03		
	SlabShield			

Manufacturer	Product	ε	ε_{aged}	Thickness
LOW-E UK	LOW-E Tab	0.03		11
	SlabShield			
Sigma Technologies	irWRAP			
Fi-Foil Company	3100 Series Radiant Barrier	0.05		
	Silver shield radiant barrier			
	FSK Shield			
	Radiant Shield			
Glidevale limited	Protect VC foil ultra			
Carolina Energy Conservation	ECO-Guard PLUS			
Energy Efficient Solutions	ARMA foil	0.05		4
	ARMA foil VB	0.05		4
Innovative Insulation	Super R Diamond	0.05		
	Super R Platinum	0.05		
	Super R Plus	0.05		
	Tempshield single bubble	0.05		1/8 inch
	Tempshield double bubble	0.05		1/8 inch
SA.M.E. S.r.l.	Isoliving	0.06		8
DuPont	Airguard	0.04		0.43
Polyair	Performa 4.0	0.03		4
	Performa 7.0	0.03		7
Reflectix	Double reflective insulation	0.06		5/16 inch
	Single reflective insulation	0.06		5/16 inch
	Concrete slab insulation			5/16 inch
	Radiant barrier	0.03		

3.2.4 Opaque paints

Paint products do not show the same low emissivity values as the foil products. However, they can be applied to areas where it is hard to use foil products. When applying low-e paints it is also important to avoid inhalation of paint which may have negative health effects. In this study, paints that have been approved as an IRCCS by RIMA, i.e. emissivity below 0.25, have been included. Table 4 shows literature data for low-emissivity paints.

Table 4 Literature data for manufacturers of low-e paints

Manufacturer	Product	ε	Binder	Solvent	VOC (g/L)
SOLEC	LO/MIT-I	0.21-0.37	Silicone	Xylene	664.41
	LO/MIT-II	0.21-0.37	Silicone emulsion	DI Water	172.73
	LO/MIT-II MAX	0.15-0.17	Silicone emulsion	DI Water	215.48
	SOLKOTE	0.20-0.49	Silicone polymer	Xylene	812
STS Coatings	HeatBloc-Ultra	0.19			< 50
Carolina Energy Conservation	ECO-Guard Coating	0.15-0.24			
BASF Corporation	Radiance e-025	0.23			212
Henry company	LiquidFoil	0.16			185

3.2.5 Comparison

The opaque and transparent products have different areas of application. Even though their purpose is generally the same, i.e. to reduce the conductive heat through radiative heat transfer, they are installed in different manners and have to fulfil some different criteria. Hence, comparing opaque and transparent materials against each other has little meaning.

Opaque materials has to be practical to install and perform well with regard to blocking out radiant heat. Opaque materials generally only have to block radiant heat from the outside, as it has been shown to be most effective in cooling dominated areas, and climates dominated by heating generally has buildings with thicker layers of conventional thermal insulation, further reducing the effect of reflective insulation solutions. Foil products performs better than paintings with respect to emissivity values. Thus, giving better results on energy savings when installed properly. However, paintings have the advantage of being more flexible and can be added to materials before installation in areas where the installation of foils can be impractical, e.g. the inside of hollow bricks and on the exterior surface of buildings.

Transparent materials must perform well with respect to decreasing radiant heat transfer, but at the same time this should not greatly affect the visible transparency. The fact that these products are also used in all various climates as well makes their use more complex. Solar heat gain coefficients in the products found in this study varies from 0.27 up to 0.79, showing that there are large differences in the possible solar heat gained through low-e windows. Hence, it is important to select the correct glazing for the correct climate to increase the overall beneficial energy usage reduction from a glazing. As insulating glazing units have become widespread due to stricter energy requirements, soft coatings can be used for most low-e glazing products. However, no manufacturer states information on how long one can expect a factory applied coating to perform. Durability and ageing of factory applied coatings is also little mentioned in the literature found in this study.

Very few manufacturers actually state the emissivity value of their factory applied coatings. From the manufacturers given values the emissivity for soft coating can be as low as 0.013 and hard coatings will generally be slightly higher. Based on these values, it is obvious that the self-applicable films have a higher emissivity value. However, comparing it to the emissivity of float glass, it is still a major improvement.

3.3 Low-emissivity related standards

It is of interest to know how the emissivity values have been tested with respects to their initial performance, life-time expectations and energy saving potential. This chapter will view some of the standards that mention testing and evaluation of energy performance of low-e materials. The standards described in this study are the standards and testing methods that have been used by the various manufacturers of low-e products mentioned in tables 1-4.

Emissivity alone cannot describe the overall energy-efficiency of a building element. Thus, the standards cover more than just emissivity and are more focused on characteristics that describe the overall energy-efficiency of glazing units and other materials. However, a low-e coating or material will always be dependent on the local climate and angle of solar radiation. Hence, when total energy usage over a whole year is to be considered climate data as to be taken into account along with the calculated values from the given standards.

"EN410 - Glass in building - Determination of luminous and solar characteristics of glazing" describes solar characteristics and provides a basis for lighting, heating and cooling calculations for glazings (European Committee for standardization [14]).

"EN 12898 - Glass in Building - Determination of the emissivity" specifies procedures for determining the emissivity at room temperature for the surfaces of glass and coated glass. The determination of the emissivity is important for evaluating the total U-value and solar transmittance of glazing according to EN 673 . This standard does however have some limitations. The procedure used is based on spectrophotometric regular reflectance measurements at near normal incidence on non-infrared transparent materials, and is not applicable to glazing with (i) rough or structured surfaces where the incident angle is diffusely reflected, (ii) curved surfaces where the incident radiation is regularly reflected at angles unsuitable to reach the detector while sing regular reflectance accessories and (iii) infrared transparent (European Committee for standardization [13]).

"EN 1096-3 - Coated glass - Part 3: Requirements and test methods for class C and D coatings" specifies requirements and test methods related to resistance to solar radiation for coated glass for use in buildings. These tests evaluate if exposure to solar radiation over an extended period of time produces appreciable changes in light transmittance, solar transmittance and reduction in IR-reflectance for low-e coatings.

The National Fenestration Rating Council (NFRC) is a non-profit organization that provides independent rating and labelling systems for windows, doors and skylights. The ratings given include U-values, visible transmittance, solar heat gain coefficients and air leakage, as well as an energy rating systems for both existing and emerging fenestration products. The NFRC is an accredited standard developer and helps develop American national standards. Most manufacturers situated in America refers to the NFRCs test methods and energy labels for their products tested values.

"ISO 10292 Glass in building - Calculation of steady-state U values (thermal transmittance) of multiple glazing" explains how to obtain the normal and corrected emissivity for coated surfaces from spectrometer measurements, and how these values are used in the total U-value calculation (International organization for standardization [27]).

"ISO 15099 - Thermal performance of windows, doors and shading devices - Detailed calculations" specifies detailed calculation procedures for thermal and optical transmission properties of window and door systems. Herein detailed calculation methods for both single and multi-layer glazing units with low-e coatings (International organization for standardization [28]).

4 Low-emissivity materials as part of an energy-efficient solution

4.1 General

Low-e materials has been shown to give a decrease in energy usage in buildings. Figure 5 shows areas where opaque materials can be implemented to help conserve energy. In addition, there is also the benefits from using low-e materials for windows.

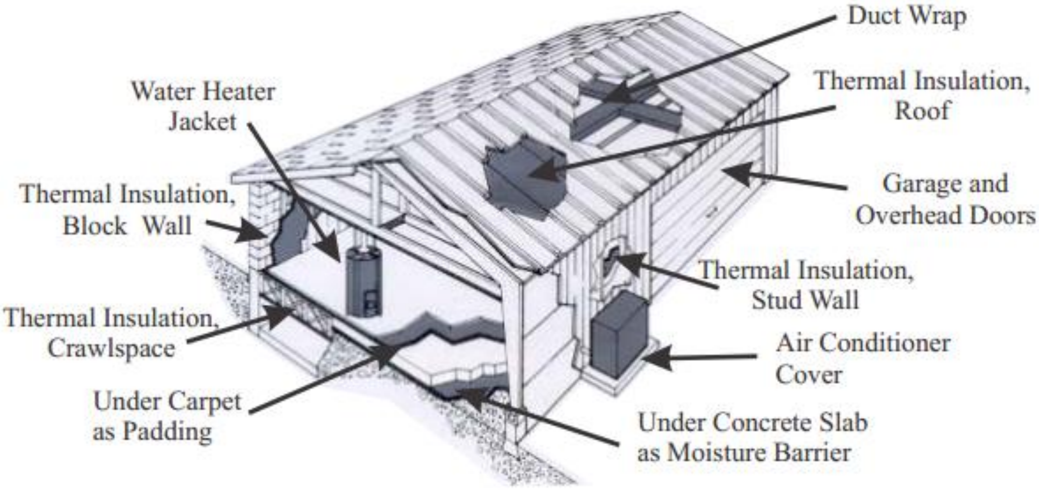


Figure 5 Areas where low-e materials can be applied for energy savings (Low-e reflective insulation [47]).

4.2 Windows

In recent years, it has become more common to design buildings with extensive glass facades. Hence, the focus on more energy-efficient glazing solutions has increased to meet the challenge of reducing heating and cooling loads. For residential buildings windows will typically account for about 30-50 % of transmission losses through the building envelope. While U-values for walls, roofs and floors can be between 0.1-0.2 W/(m^2K), the best windows may often have a U-value of 0.7-1.0 W/(m^2K) (Gustavsen et al. [23]). Windows also provides an opportunity to gain free energy from the sun, and improve both thermal and visual comfort for a buildings residents. Effectively taking advantage of free solar energy gives the potential for higher energy-efficient windows. By applying a low-e coating to a window, the thermal conductance due to radiation between glass pane surfaces can be reduced to about 0.1 W/(m^2K) (Manz [48]).

Considering a low-e window for building applications is not straight forward. Figure 6 shows that a low-e window can still have large differences in solar-gain. Hence, the energy balance between solar gain and transmission losses makes calculating window performance more complex. This means that the use of low-e windows has to be planned with consideration to the local climate of the building. Choosing a window with a low-e coating, but a solar-gain coefficient that is not suited for the climate, might neutralize the possible energy gains from the low-e coating. Thus, giving a window which saves no energy. When the correct window for a climate has been decided, the orientation of the facades will also affect the effect of a low-e window, as emissivity is also dependent on the incident angle.

Another drawback of low-e coatings is the reduction in transmission of visible light. The reduction of visible light will lead to an increased need for artificial lighting, giving a higher energy usage. This problem is still the focus of ongoing research. A solution for this includes the adding of antireflective covering, which has been shown to increase the visible transmittance (Rosencrantz et al. [65], Hammarberg and Roos [24]).

For windows to meet todays energy standards a low-e coating alone is not sufficient. The low-e coating is commonly combined with multi-layered glazing units, and can also be combined with other solutions, e.g. reflective or anti-reflective coatings, solar control films and coatings and evacuated glazing.

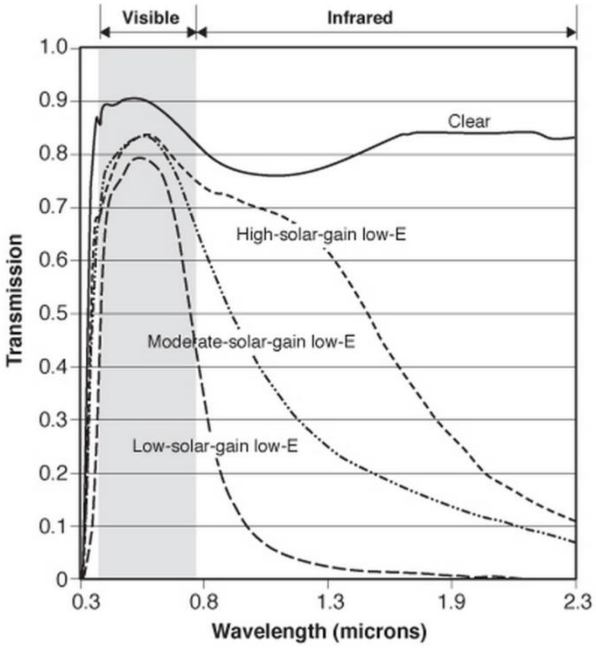


Figure 6 Transmission vs wavelength for low-e windows (Commercial Windows [11]).

Low-e coatings may provide other beneficial effects on glazing besides the increase in energy efficiency.

4.2.1 Anti-condensation windows

A common problem with new thermal insulating glass units is the formation of condensation on the outside of the window. Low-e coatings on the outward facing surface can help to prevent condensation, and allow windows to keep their desirable visual performance for longer parts of the year. Werner and Roos [74] have performed simulations on windows with external low-e coatings. Furthermore, it has been discussed how further improvements may be made to improve anti-condensation properties by applying low-e coatings.

Note that these low-coatings has to be weather resistant as it is placed in outside environmental conditions. These low-e coatings will not have the same low emissivity value as soft coatings placed inside the cavity of a multi-layered glazing unit (Gläser and Ulrich [19]).

4.2.2 Vacuum glazing

Evacuated insulating glazing units, i.e. vacuum glazing, provides high thermal resistance. Though vacuum glazing provides a significant improvement in heat loss reduction, they will still benefit greatly from the adding of a low-e coating (Eames [12], Fang et al. [16]).

4.2.3 Ageing effects

As mentioned earlier, soft coatings are not nearly as durable as hard coatings. Soft coatings needs to be placed inside the cavity of an insulating glass unit. The more durable hard coating which can be placed towards open areas, even though more robust, will face harsher climate stress. It is of interest to know if these factory applied coatings can maintain the initial emissivity over the expected lifetime of the window, and if ageing of the low-e coating impairs the visible transmittance.

Studies have been conducted on the effects of moisture on soft low-e coatings. As most soft coatings are applied with silver as the metal layer, it is important to avoid excess of air and moisture to prevent oxidation. A known problem with silver based soft coatings is white-dot defects on the coating surface due to exposure to moisture (Ando et al. [2]). Degradation usually takes place because moisture penetrates the first dielectric layer and induces silver migration, resulting in a peel off of the top oxide layer. Ando and Miyazaki [3] showed that the durability of low-e coatings in humid environments is closely correlated with the internal stresses in the oxide layers. However, this gives no results on how the coating performs under working conditions, i.e. inside a mounted insulating glazing unit with parameters matching the environment in the cavity.

4.3 Walls

The use of low-e solutions in opaque parts of walls are mainly beneficial in regions dominated by overheating. The building norms in these areas are usually distinguished by little conventional thermal insulation, i.e. thin or no layers of mineral wool, EPS etc. Temperatures in such constructions will rapidly increase in periods with high solar energy flux. Hence, adding low-e solutions to reflect this heat away will prove more effective.

Laboratory, field measurements and simulations have been conducted on the energy saving effect of opaque low-e materials in different wall structures in various climates (Joudi et al. [42], Saber et al. [66], Shi and Zhang [69]).

Foil and paint products have been described briefly in previous chapters. In the following, some of the possible areas of application to wall constructions and application to materials will be shown. Paints especially have a lot of interesting and innovative uses that can be explored to increase the overall thermal resistance of constructions without affecting the construction process.

Hollow bricks with low-e paint

Principi et al. (2012) investigated the use of low-e painting on the inner surfaces of hollow bricks (see Fig. 7). The reduction in the emissivity of the internal surfaces would lead to a reduction in thermal radiation heat transfer. For the conducted tests, a low-e painting with an emissivity value of approximately 0.5 was used. the test results showed a 20 % reduction in the thermal conductivity of the brick. It was also concluded that low-e coatings proved to be an easy and cheap technology to improve the thermal resistance of hollow bricks, as it can be applied without substantial modification in the manufacturing of the bricks.

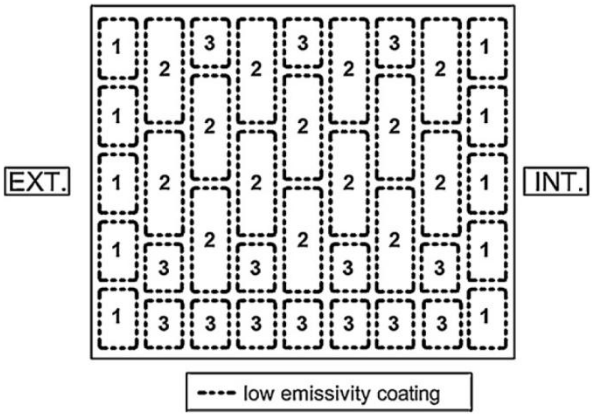


Figure 7 Hollow brick with low-e coating on the inner surfaces (Principi et al. 2012).

Coated surfaces

Studies have been conducted on the effect of adding anti-reflective coatings to the exterior cladding and the interior surfaces of walls, or at both surfaces at the same time. In a cold climate, adding reflective coatings to the interior surface was shown to give savings to the total energy usage as the required heating loads could be reduced. However, an increase in cooling loads during the summer was shown. For an exterior reflective surface coating in a cold climate, the energy usage ended up being larger than for a similar uncoated building. In warm climates the results were reversed, exterior reflective surface coating gave energy savings, while interior reflective surface coating gave an increase in energy usage (Joudi et al. [41]). Other studies also highlight the effects of coatings between different climate regions (Guo et al. [22]).

Foils

Installing foils into a building construction requires sufficient airspace on either side of the foil product (Fig. 8). If the foil product is in direct contact with materials on both sides, the heat will be transferred through solid conduction and be unable to block radiative heat. Hence, gaining no benefits from the low emissivity of the materials surface.

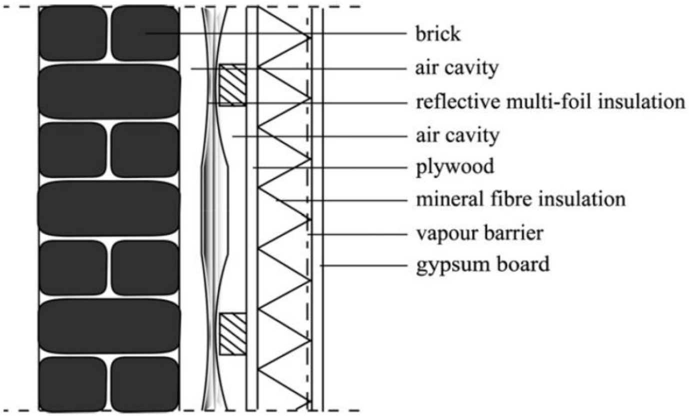


Figure 8 Reflective foil installed inside a wall cavity (Tenpierik and Hasselaar [72]).

Low-e foils as vapour barriers

It is common to use polyethylene foils as a vapour barrier in wood frame constructions. The surface emissivity of PE-foils is typically around 0.9. By exchanging the PE-foil with an aluminium-polyethylene sheet with lower surface emissivity it has been found that the thermal resistance of a wall construction can be increased. However, the overall effect of such a construction is something that should be further investigated (Pasztory et al. [60]).

4.4 Roofs

Roofs are exposed to large amounts of solar energy throughout the year, especially in warm climates. The excessive amounts of solar energy will heat up attics or top floors (Fig. 9), leading to overheating and a need for more use of air-conditioning to keep a comfortable indoor temperature. The application of radiant barriers to conserve energy in residential buildings has received considerable attention in recent years. Asadi et al. [5] developed a simplified tool for calculating the energy performance of installing a radiant barrier to an attic. This tool showed that the highest rate of energy saving with an installed radiant barrier occurs in hot and humid regions, and also where there is little else thermal insulation installed. The increased surface temperature of the radiant barrier increases its effect. In colder climates the potential for energy savings were low.

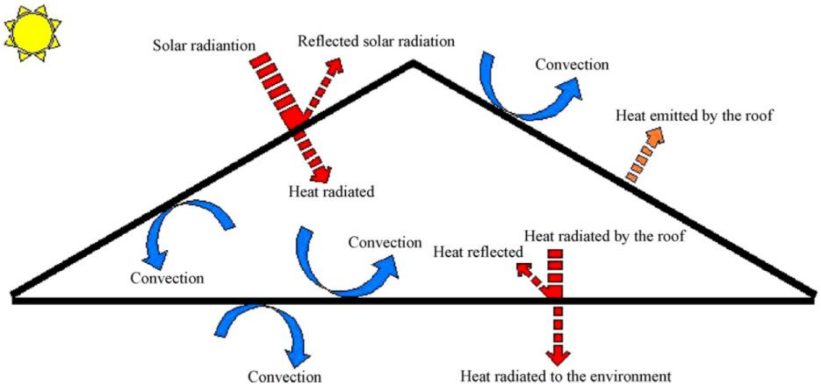


Figure 9 Heat transfer mechanisms in an attic space (Michels et al. [51]).

When installing a radiant barrier to a roof construction, as with walls, it is important to create sufficient air space on at least one side of the radiant barrier (Fig. 10). The surface of the radiant barrier must also be placed in a way which does not allow dust or dirt to form on the surface as this will reduce the effectiveness, i.e. increase the emissivity, of a radiant barrier.

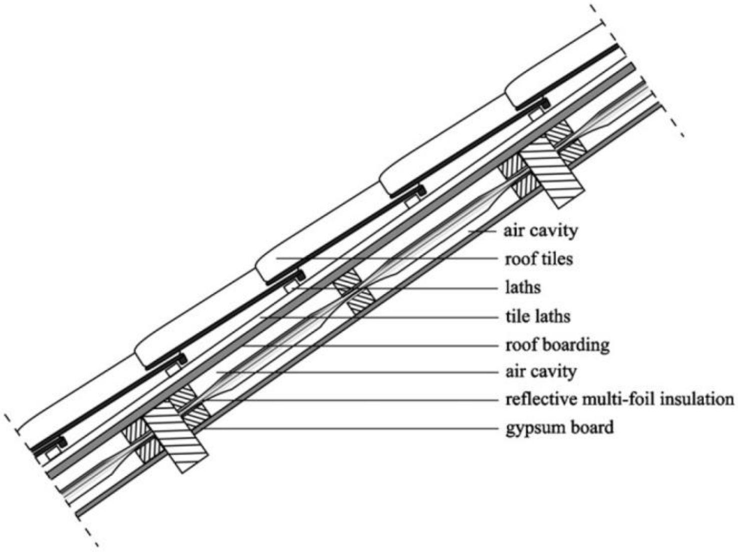


Figure 10 Reflective foil installed inside a cavity in a roof construction (Tenpierik and Hasselaar [72]).

Another approach to using low-e materials in roofs is to install them at the roof surface. This way the roof will reflect off a large amount of the heat radiating from the sun. Hence, maintaining a cooler surface temperature which will slow down the heat conduction through the roof (Akbari [1]). However, no studies have been conducted to measure how climactic conditions will affect the performance due to ageing effects of such a solution.

Measurements on various types of roof installations using reflective insulation have been conducted (Belusko et al. [7], Miranville et al. [53], Muselli [57], Saber [67], Saber [68], Suehrcke et al. [70]). Some of these studies also attempt to give an experimental evaluation of performances from field measurements.

4.5 Floors

To the authors knowledge, the use of reflective insulation in flooring has been little studied. In the previous chapter, some manufacturers who provide slab shields, e.g. low-e materials for concrete floors, were shown. These products have the extra benefit of also working as a vapour barrier if they are left un-perforated. However, there are few studies which shows the results and effects of low-e floor materials. Under floors there are in most cases little convection, i.e. still standing air. With a sufficient air gap, most of the heat will be transferred by thermal radiation (Uvsløkk and Arnesen [73]). Installing a low-e material towards such an air gap may yield benefits towards decreased energy usage.

5 Future research perspectives

5.1 Improving the current technology

5.1.1 Improving low-e coating properties

As of today, low-e coatings on commercial products give emissivities as low as 0.013. Further improvements on this may be possible by testing other combinations of dielectrics and metals, and alter the configurations with more film layers and different thicknesses (Leftheriotis and Yianoulis [45]). However, the energy saving potential of reducing the emissivity value further may be minimal and not benefit in more than a few kWh/m^2 a year (Karlsson and Roos [43]). Considerations should therefore be made towards new combinations of materials and production methods that can produce the same emissivity but with lower production costs. New combinations through various thicknesses of the layers in a low-e coating based on silver were tested out experimentally by Le et al. [44]. The aim was to identify an optimal deposition process with consideration to the thickness of the various stacks in the coating layers.

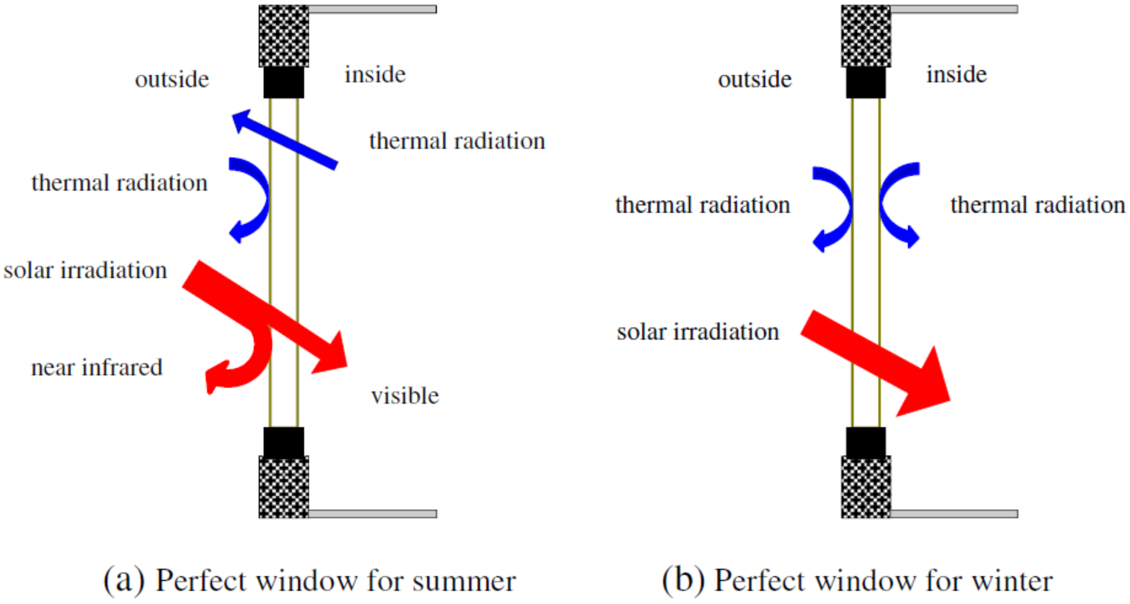
5.1.2 Increasing visible transmittance

A goal for low-e coatings used on transparent materials should be to achieve the same transparency as clear glass. As of today, the reduction in visible transmittance when applying low-e coatings is considered an undesirable characteristic, as it may increase the need for artificial lighting, i.e. increase energy usage (Jelle et al. [34]).

One option that has been tested out is to add anti-reflection treatment to low-e coatings. Hammarberg an Roos [24] showed that it was possible to increase the visible transmittance by up to 9.8 % by depositing a thin film of silicon dioxide on both sides of a commercial glazing. This study also pointed out that it is probable that an even larger increase of visible transmittance can be achieved if the sol-gels used for the antireflective layers could be optimized regarding the refractive index.

5.1.3 Angular selectivity

The use of angular selective solar control is already implemented by using prismatic glass or louver systems that block out direct sun light at specific angles while diffuse sky-light is admitted. Systems like these can be used to block certain angles in periods where the sun gives off most of its energy and overheating happens. However, these systems impair the visibility through the facade. If the same principle could be implemented with coatings, one could possibly achieve a higher visible transmittance while at the same time allowing passive use of the winter sun to reduce heating loads and blocking out summer sun to reduce cooling loads in the same glazing unit. The result would be close to the perfect window (Fig. 11) as described by Ye et al. [76]. However, this would mean that coating must be tailored to a specific building site and orientation. Thus, creating a need for more detailed planning to select a correct coating for optimization of energy savings.



(a) Perfect window for summer (b) Perfect window for winter

Figure 11 Schematic of a perfect window (Ye et al. [76]).

5.1.4 Improving film technology

Films have one major advantage compared to the factory applied coatings. That is, the film can be produced without the glass at hand. Hence, they can be manufactured separately and at the same time. However, the films of today do not perform as well as factory applied coatings. The possibilities of improving the film technology and make it achieve the same level of performance as factory applied coatings may make for a process where low-e glazing can be manufactured faster and at a lower cost. It also open up possibilities to apply low-e properties to already installed glass without coatings.

Today, films are applied to the surface toward the interior of a building. If films can achieve the same level of performance as coatings, they may become a part of the manufacturing process of multilayered glazing and be applied inside the cavities as well.

5.2 Durability and ageing

Few studies have been conducted on the effect of ageing on low-e coatings and materials over. The importance of ageing effects on the thermal performance of low-e materials is something that should be investigated with regard to the potential of energy savings over a components lifetime in a construction. Questions which needs to be answered is how a reduction in emissivity value affects energy usage and dimensioning of air conditioning and the need for room heating. None of the manufacturers in this study states an aged value for their products' emissivity values, showing that there is a need to look into ageing effects. Note also the more general accelerated climate ageing studies by Jelle [32] and Jelle et al. [33], where the former one also addresses the importance of performing accelerated climate ageing of new materials and solutions.

Soft coatings with silver as the metallic layer has been shown to be very vulnerable under atmospheric conditions when exposed to solar irradiation, but unaffected if it is kept in a moderate vacuum (Leftheriotis and Yianoulis [45]).

5.3 New low-emissivity materials and technologies

5.3.1 New materials

It has been mentioned that one of the drawbacks of low-e coatings is the decrease in visible transmittance. Currently, anti-reflection coatings are being applied to increase the visible transmittance without impairing the effect of the low-e coating. Further increasing the visible transmittance of low-e windows is still a field of interest. Gao et al. [18] discussed the anti-reflective properties of monodisperse hollow silica nanospheres and its application to windows. The spheres showed interesting optical properties and gave a decreased reflection. The anti-reflective performance of hollow silica nanospheres may still be further modified and is worth pursuing.

A possible approach to prepare new opaque low infrared emissivity materials have been investigated by Zhang et al. [77]. This approach was based on nacre biomimetic design. The structures designed in this experiment were as low as 0.206, with nacre-like PU/flaky bronze composites.

Other material choices for low-e coatings that have been investigated include coatings based on diamond like carbon (Chiba et al. [9]) and tin doped indiumoxide (Reidinger et al. [62]).

5.3.2 New glazing technologies

There are several other technologies in development that aims to control solar heat gain and at the same time have the ability to adapt to seasonal variation. One such promising technology is electrochromic windows. Together with a low-e coating this will have the benefit of low radiative conductive heat transfer along with the possibility to alter the solar heat which passes through the glazing for seasonal as well as daily variations. The efficiency of electrochromic windows has already been proven in hot climates, but more research is necessary to validate the effects in colder climates (Baetens et al. [6]). Another study performed by Fang et al. [17] have tested the thermal performance of electrochromic low-e glazing with an evacuated glazing unit, which may be the way forward to provide high-performance windows for tomorrow.

With respect to various glass surface coating technologies, the material development and studies on e.g. electrochromic materials (Baetens et al. [6], Jelle and Hagen [29-30], Jelle et al. [31] and Jelle [38]), self-cleaning glazing (Midtdal and Jelle [52]), building integrated photovoltaics (Jelle et al. [35] and Jelle and Breivik [36-37] and snow and ice related issues for e.g. solar cell panels (Jelle [39]) should be noticed. The robustness of these materials should also be addressed and evaluated (Jelle et al. [40]).

5.3.3 New manufacturing process for coated windows

The current manufacturing method, along with the cost of silver, of low-e coatings is a reason for the relative high costs of low-e coatings. A new process for coating based on solution derived nanocomposite (SDN) technology has recently been investigated. (Niitsoo et al. [58])

5.4 Future perspectives on building implementations of low-emissivity materials

5.4.1 New energy labelling for windows

State-of-the-art low-e windows utilize solar energy in different ways. Some have a high solar heat gain while others reduce the solar heat gain. However, there are many energy labels that only consider a windows total U-value, and neglects the solar heat gained or blocked. The common norm for window labelling should account for both thermal losses and solar heat gains for various climates. Grynning et al. [21] have performed a study where the effects of considering the solar heat gain is shown for windows in an office building in Oslo, Norway. Variation between summer and winter shows that choosing the optimal solar heat gain coefficient is a challenge, as high solar heat gain is beneficial in the colds part of the year, while low solar heat gain is beneficial in the warm parts of the year.

Further improvements to labelling systems could also include parameters that consider increase or decrease in the need for artificial lighting and the influence of orientation and size of windows. This will give valuable information to the consumers, and would also show the benefit of a low-e coating and other energy-efficient window solutions. Labelling based on some of these principles are already seen in the UK, Denmark, Finland Czech Republic and Slovakia (Cazes [8]). There are many other solar radiation glazing factors that can be of interest for when selecting windows for specific purposes. These have recently been mentioned and tested for various windows by Jelle [38].

5.4.2 Predicting the correct U-values for low-emissivity products in use

Saber [67] investigated the thermal performance of low-emissivity foils and how they reacted to changes in emissivity and different angles. This investigation gave a recommendation that future work should be focused on determining actual R-values of reflective insulation in combination with other insulation materials and climactic conditions. This will reduce the risk of over sizing heating or cooling equipment and help to better determine condensation risks. Several other studies also debate the actual U-values of reflective insulation and the difficulty in determining these precisely (Tenpierik and Hasselaar [72], Belusko et al. [7]).

5.4.3 Investigating the use of low-emissivity materials in floor constructions

As mentioned earlier, few studies have been found to mention the possible benefits of low-e materials in floor constructions. This subject may hold interest for further investigations.

Conclusions

This study has found that low-emissivity solutions for glazing is a widely accepted and used solution with a proven effect on energy efficiency. Positive results have been shown in most climates. These low-e coatings are a great way to passively reduce energy usage. Hence, there is a wide variety of manufacturers on the market offering a wide variety of products suited for various climates. Many countries have made low-e coated windows a part of new building norms in order to further reduce energy usage of buildings. Most likely the use of low-e coated glazing will continue to increase in other countries as well.

Opaque materials, however, are not as widely spread as transparent low-e products. Many studies have been conducted which shows the positive effects in several different climates. Where low-e glazing requires no changes in the way of constructing, opaque solutions require changes to the structure or appearance of a building. Especially so with foils mounted inside the building envelope, as they require sufficient airspace to perform adequately. As there is still ongoing debate on how to best determine the exact U-values of low-e products under building related conditions, there is still more research to be carried out. More exact U-values will be beneficial both to increase use of low-e products and to prevent over-dimensioning of heating or cooling systems.

For future research, the goal should be to evaluate how low-e products perform with regard to ageing. Change in emissivity due to ageing may change the overall energy usage of buildings, and is an important factor to know when doing life cycle energy calculations.

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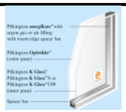
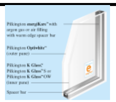
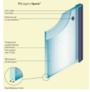
Appendix

Table A1 Glass coatings/Factory coated glazing

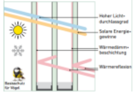
Manufacturer	Product	Illustration	ε	ε_{aged}	T_{sol}	T_{vis} (%)	T_{uv} (%)	SHGC	Coating	U_w* (W/(m^{2}K))	U_g* (W/(m^{2}K))	Additional information
Guardian Climaguard 2300 Harmon Rd. Auburn Hills, MI 48326 USA Tel: +1 855 660 5905 ClimaGuardProductInfo@Guardian.com www.climaguardglass.com	ClimaGuard 55/27					55	18	0.28		0.29 Air fill		http://www.climaguardglass.com/ProductSolutions/Energyefficientproducts/ClimaGuard5527/index.htm (Accessed 27.06.2013)
	ClimaGuard 62/27					62	5	0.27	Triple silver soft coat	0.29 Air fill		http://www.climaguardglass.com/ProductSolutions/EnergyEfficientProducts/ClimaGuard6227/index.htm (Accessed 27.06.2013)
	ClimaGuard 63/31					63	24	0.31		0.29 Air fill		http://www.climaguardglass.com/ProductSolutions/EnergyEfficientProducts/ClimaGuard6331/index.htm (Accessed 27.06.2013)
	ClimaGuard 70/36					70	30	0.36		0.29 Air fill		http://www.climaguardglass.com/ProductSolutions/EnergyEfficientProducts/ClimaGuard7036/index.htm (Accessed 27.06.2013)
	ClimaGuard 71/38					71	24	0.39		0.29 Air fill		http://www.climaguardglass.com/ProductSolutions/EnergyEfficientProducts/ClimaGuard7138/index.htm (Accessed 27.06.2013)
	ClimaGuard 80/70					81	41	0.70		0.32 Air fill		http://www.climaguardglass.com/ProductSolutions/EnergyEfficientProducts/ClimaGuard8070/index.htm (Accessed 27.06.2013)
Pilkington/ **Nippon Sheet Glass Co., Ltd.** 5-27, Mita 3-chome, Minato-ku, Tokyo 108-6321 Japan www.pilkington.com	K Glass		0.16			76		0.78	Hard coat		1.5 Argon fill	http://www.pilkington.com/europe/uk+and+ireland/english/products/bp/bybenefit/thermalinsulation/kglass/default.htm (Accessed 19.06.2013)
	K Glass S					81		0.75	Soft coat		1.2 Argon fill	Determined in accordance with EN410 and EN673 http://www.pilkington.com/europe/uk+and+ireland/english/products/bp/bybenefit/thermalinsulation/kglass/product-range/k-glass-s/default.htm (Accessed 19.06.2013)
	K Glass OW					78		0.79	Hard coat		1.5 Argon fill	http://www.pilkington.com/europe/uk+and+ireland/english/products/bp/bybenefit/thermalinsulation/kglass/product-range/k-glass-ow/default.htm (Accessed 19.06.2013)

Manufacturer	Product	Illustration	ε	ε_{aged}	T_{sol}	T_{vis} (%)	T_{uv} (%)	SHGC	Coating	U_w* (W/(m^{2}K))	U_g* (W/(m^{2}K))	Additional information
Pilkington/ **Nippon Sheet Glass Co., Ltd.** 5-27, Mita 3-chome, Minato-ku, Tokyo 108-6321 Japan www.pilkington.com	Optitherm S1		0.013						Soft coat		1.0	http://www.pilkington.com/europe/uk+and+ireland/english/products/bp/bybenefit/thermalinsulation/energikare/default.htm (Accessed 19.06.2013)
	Optitherm S3		0.037			80			Soft coat		1.1	http://www.pilkington.com/europe/uk+and+ireland/english/products/bp/bybenefit/thermalinsulation/energikare/energikare-range/triple/default.htm (Accessed 19.06.2013)
	Insulight Therm											http://www.pilkington.com/europe/uk+and+ireland/english/products/bp/bybenefit/thermalinsulation/insulighttherm/default.htm (Accessed 19.06.2013)
	Spacia				62	78		0.67			1.1	http://www.pilkington.com/europe/uk+and+ireland/english/products/bp/bybenefit/thermalinsulation/energikare/energikare-range/legacy/default.htm (Accessed 19.06.2013)
	Anti-condensation				60	70		0.71	Hard coat		1.5 Argon fill	http://www.pilkington.com/europe/uk+and+ireland/english/products/bp/bybenefit/specialapplications/anti-condensation+glass/default.htm (Accessed 05.12.2013)
PPG Industries, Inc. Glass Business & Discovery Center 400 Guys Run Road Cheswick, PA 15024 Tel: 1-888-PPG-GLAS www.ppgglass.com	Sungate 400					78	32	0.68		0.28		Given numbers based on NFRC methodology http://www.ppgresidentialglass.com/lowe_glass/low-e-windows.aspx (Accessed 04.12.2013)
	Sungate 500					76	49	0.70	Hard coat	0.31		
	Sungate 600					73	45	0.70		0.29		
	Solarban 60					72	21	0.39		0.25		
	Solarban 67					55	13	0.29		0.25		
	Solarban 70XL					64	6	0.27		0.24		

Manufacturer	Product	Illustration	ε	ε_{aged}	T_{sol}	T_{vis} (%)	T_{uv} (%)	SHGC	Coating	U_w* (W/(m^{2}K))	U_g* (W/(m^{2}K))	Additional information
Walshsglass 198 Bannister Road Canning Vale WA PO Box 1022 Canning Vale Western Australia 6155 Australia Tel: 08 9366 6666 Fax: 08 9455 2640 sales@walshsglass.com.au www.walshsglass.com.au	Evantage				41	56	19	0.53			1.7 Air fill	http://www.walshsglass.com.au/upload/pages/performance-data_20120417110627/performance-data-information---twin-seal-igu-with-energytech.pdf?1377489802 (Accessed 27.06.2013)
	Sunergy				40	57	31	0.50			1.8 Air fill	
	EnviroShield				33	61	1	0.43			1.7 Air fill	
	ComfortPlus				42	66	1	0.54			1.5 Argon fill	
Cardinal Glass Industries Eden Prairie, MN 775 Prairie Center Dr # 200, 55344 USA 952.229.2600 952.935.5538 info@cardinalcorp.com www.cardinalcorp.com	LoE-366					65	5	0.27	Soft coat	0.29[a] Air fill		http://www.cardinalcorp.com/products/coated-glass/loe3-366-glass/ (Accessed 04.12.2013)
	LoE-270					70	14	0.37		0.30[a] Air fill		http://www.cardinalcorp.com/products/coated-glass/loe2-270-glass/ (Accessed 04.12.2013)
	LoE-272					72	16	0.41		0.30[a] Air fill		http://www.cardinalcorp.com/products/coated-glass/loe2-272-glass/ (Accessed 04.12.2013)
	LoE-180					79	29	0.69		0.31[a] Air fill		http://www.cardinalcorp.com/products/coated-glass/loe-180-glass/ (Accessed 04.12.2013)
	LoE-240					40	16	0.25		0.30[a] Air fill		http://www.cardinalcorp.com/products/coated-glass/loe2-240-glass/ (Accessed 04.12.2013)
	LoE-i89											http://www.cardinalcorp.com/products/coated-glass/loe-i89-glass/# (Accessed 04.12.2013)

Manufacturer	Product	Illustration	ε	ε_{aged}	T_{sol}	T_{vis} (%)	T_{uv} (%)	SHGC	Coating	U_w* (W/(m^{2}K))	U_g* (W/(m^{2}K))	Additional information
AGC GlassEurope 166 Chaussée de La Hulpe 1170 Brussels, Belgium Tel: +32 2 674 31 11 Fax: +32 2 672 44 62 headquarters@eu.agc.com www.yourglass.com	Planibel G					75		0.73	Hard coat	1.9 Air fill		http://www.yourglass.com/agc-glass-europe/gb/en/low-emissivity_glazing/planibel_low-e/brand_summary.html (Accessed 04.12.2013)
	Planibel TOP					81		0.67		1.3 Argon Fill		
	Planibel LOW-E Antifog					72	17	0.63			1.1 Argon Fill	http://www.yourglass.com/agc-glass-europe/gb/en/lowe/antifog/brand_description.html (Accessed 21.06.2103)
Saint-Gobain Glass 66 Kornish El Nile, Zahret El Maadi Tower, Floor 38, Helwan Egypt Tel: +202 25288070/75 Fax: +202 25288072 mktg.sgge@saint-gobain.com http://eg.saint-gobain-glass.com	SGG Planitherm Total					79	35	0.63			1.7 Air fill	http://eg.saint-gobain-glass.com/b2c/default.asp?nav1=pr&nav2=single%20pane&id=2090 (Accessed 04.12.2013)
	SGG Planitherm Total 1.3					77	35	0.66			1.8 Air fill	
	SGG Planitherm Ultra N					80	33	0.63			1.6 Air fill	
	SGG Nano											http://in.saint-gobain-glass.com/b2c/default.asp?nav1=pr&nav2=single%20pane&id=18494 (Accessed 27.06.2013)
Clear Glass Solutions PO Box 26, Maryknoll Victoria 3812 Tel:03 5942 8444 Fax: 03 5942 9286 www.clearglass.com.au	Planibel G					74		0.71	Hard coat		1.9 Air fill	http://www.clearglass.com.au/glass-types/low-e-glass (Acessed 21.11.2013)
	Comfort E2					75		0.72	Hard coat		1.7 Argon fill	http://www.clearglass.com.au/glass-types/low-e-glass (Acessed 21.11.2013)
	Sunergy clear					69		0.62	Hard coat		4.3	http://www.clearglass.com.au/glass-types/low-e-glass (Acessed 21.11.2013)
	Planibel Energy N					79		0.64	Soft coat		1.6 Air fill	http://www.clearglass.com.au/glass-types/low-e-glass/planibel-energy-n-low-e-glass-2 (Acessed 21.11.2013)

Manufacturer	Product	Illustration	ε	ε_{aged}	T_{sol}	T_{vis} (%)	T_{uv} (%)	SHGC	Coating	U_w* (W/(m^{2}K))	U_g* (W/(m^{2}K))	Additional information
CSG Architectural Glass CSG Building, No.1, 6th Industrial Road, Shekou, Shenzhen, P.R.China Tel: +86-755-26860666 Fax: +86-755-26692755 www.csgglass.cn	Single Silver Low-E											http://www.csgglass.cn/en/193/2/productdetail.html (Accessed 04.12.2013)
	Double Silver Low-E											
	Triple Silver Low-E											
Viridian 39 Delhi Rd North Ryde NSW 2113 Australia Tel: 1800 810 403 www.viridianglass.com	EnergyTech					73		0.61	Hard coat		1.6 Argon fill	http://www.viridianglass.com/Products/energytech/default.aspx?ProductType=HouseHolder (Accessed 27.06.2013)
	PerformaTech E					58		0.32			1.33	http://www.viridianglass.com/Products/performatech-e/default.aspx?ProductType=HouseHolder (Accessed 27.06.2013)
	Sunergy					68		0.59	Hard coat		4.1 Single pane	http://www.viridianglass.com/Products/sunergy/default.aspx?ProductType=HouseHolder (Accessed 04.12.2013)
	EVantage					68		0.63	Hard coat		3.8 Single pane	http://www.viridianglass.com/Products/evantage/default.aspx?ProductType=HouseHolder (Accessed 04.12.2013)
	SolTech					73		0.61	Hard coat		1.6	http://www.viridianglass.com/Products/soltech/default.aspx?ProductType=HouseHolder (Accessed 04.12.2013)
	SmartGlass				68	83	54	0.72	Hard coat		3.7 Single pane	http://www.viridianglass.com/Products/smartglass/default.aspx?ProductType=HouseHolder (Accessed 04.12.2013)
	ComfortPlus					82		0.68			3.6 Single pane	http://www.viridianglass.com/Products/comfortplus/default.aspx?ProductType=HouseHolder (Accessed 04.12.2013)
Milgard Corporate 1010 54th Ave East Tacoma, WA 98424 USA Tel: +1 800 645 4273 www.milgard.com	Suncoat Low-E2 glass					70	16	0.37-0.41		0.30		http://www.milgard.com/milgard-advantages/low-e-window-coating.asp (Accessed 27.06.2013)
	SunCoatMAX Low-E3 glass					66	5	0.27		0.29		

Manufacturer	Product	Illustration	ε	ε_{aged}	T_{sol}	T_{vis} (%)	T_{uv} (%)	SHGC	Coating	U_w* (W/(m^{2}K))	U_g* (W/(m^{2}K))	Additional information
Glaströsch info@glastroesch.ch www.glastroesch.ch	Silverstar Zero E					80		0.60		1.0		http://www.glastroesch.ch/services/datentabellen-ausschreibungstexte/waermedaemmisolierglas-silverstar/silverstar-zero-e-2-fach-isolierglas.html (Accessed 27.06.2013)
	Silverstar Zero Eplus					74		0.53				http://www.glastroesch.ch/services/datentabellen-ausschreibungstexte/waermedaemmisolierglas-silverstar/silverstar-e-linie.html (Accessed 27.06.2013)

* Note that the U-value will vary depending on the thickness of the glass, thickness of the cavity, etc. The values in this table are for most cases given for 4-12-4 windows (two panes of 4 mm glass with a 12 mm cavity). However, please check the respective manufacturer sites for more detailed values.

[a] Winter U-value

Table A2 Self-applicable films for windows

Manufacturer	Product	Illustration	ε	ε_{aged}	T_{sol} (%)	T_{vis} (%)	T_{uv} (%)	SHGC	U-value (W/(m^{2}K))	Additional information
CPFilms Inc. a Subsidiary of Solutia Inc 575 Maryville Centre Drive St. Louis, MO 63141 USA Tel: 1-800-345-6088 Fax: 1-314-674-1950 Vista-films@cpfilms.com www.Vista-films.com	EnerLogic VEP35 SR CDF		0.07		15-19	29-33	1	0.24-0.30	0.34 / 0.30 Winter / summer value	http://www.enerlogicfilm.com/en/ProductPerformance.aspx Measured in accordance with NFRC standards (Accessed 27.06.2013)
	EnerLogic VEP70 SR CDF		0.09		35-46	61-70	1	0.49-0.52	0.34 / 0.31 Winter / summer value	
Classic Window Film 200 Dixon Road Toronto, ON M9P 2L8 Tel: 647-887-5647 Canada classicwindowfilm@gmail.com www.classicwindowfilm.com	Solar window film									http://www.classicwindowfilm.com/film-solar.asp (Accessed 27.06.2013)
Saint-Gobain Performance Plastics Ball Mill Top Business Park, Grimley, Worcestershire, WR2 6LS, UK Tel: +44 (0)1905-640400 Fax: +44 (0)1905 640500 solargarduk@saint-gobain.com http://solargard.com	Ecolux 70		0.09		43	68	1	0.48	0.61 Winter value	ASTM and ASHRAE standards http://solargard.com/window-films/commercial/solar-control-films/low-emissivity/ecolux (Accessed 13.11.2013)
	Silver AG 50		0.37		35	51	1	0.43	0.78 Winter value	ASTM and ASHRAE standards http://solargard.com/window-films/commercial/solar-control-films/low-emissivity/silver-ag (Accessed 13.11.2013)
	Silver AG 25		0.33		14	22	1	0.23	0.75 Winter value	

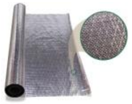
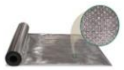
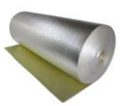
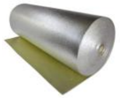
Manufacturer	Product	Illustration	ε	ε_{aged}	T_{sol} (%)	T_{vis} (%)	T_{uv} (%)	SHGC	U-value (W/(m^{2}K))	Additional information
Hanita Coatings Kibbutz Hanita 22885, Israel Tel: +972 4 985 9919 Fax: +972 4 985 9920 hanita@hanitacoatings.com www.hanitacoatings.com	Silver 20 Low-E		0.39		12	17	1	0.20		http://www.hanitaenergy.com/interior-reflective-films (Accessed 27.06.2013)
	Silver 35 Low-E		0.45		19	27	1	0.28		http://www.hanitaenergy.com/interior-reflective-films (Accessed 27.06.2013)
3M Tel: +1-866-499-8857 http://solutions.3m.com	Amber 35 Low E Sun Control Window Film		0.34		25	31	1	0.31	0.40	Film attached to a single glass pane http://solutions.3m.com/wps/portal/3M/en_US/Window_Film/Solutions/Markets-Products/Commercial/Sun_Control_Window_Films/Traditional_Series/ (Accessed 27.06.2013)

Table A3 Foils/Reflective insulation

Manufacturer	Product	Illustration	ε	ε_{aged}	Thickness (mm)	Materials	Additional information
Environmentally Safe Products, Inc. 313 W. Golden Ln. New Oxford, PA 17350 USA Tel: 717-624-3581 Fax:717-624-7089 sales@low-e.com www.low-e.com	ESP LOW-E Insulation		0.03			Polyethylene foam core with scrim reinforced double sided aluminium facings	http://www.low-e.com/products/products_view.php?Product=Low-E (Accessed 19.06.2013)
	Econo-E		0.03				http://www.low-e.com/products/products_view.php?Product=Econo-E (Accessed 19.06.2013)
	Attic Floor Insulation		0.03			Double -sided perforated aluminium laminated to polyethylene foam	http://www.low-e.com/products/products_view.php?Product=Attic%20Floor%20Insulation (Accessed 19.06.2013)
	LOW-E HVAC		0.03			Polyethylene foam faced with aluminium on both sides	http://www.low-e.com/products/products_view.php?Product=Low-E%20HVAC (Accessed 19.06.2013)
	SlabShield					Closed cell polyethylene foam applied to both sides of aluminium reflective layer	http://www.low-e.com/products/products_view.php?Product=SlabShield (Accessed 19.06.2013)
	LOW-E Tab		0.03				http://www.low-e.com/products/products_view.php?Product=Low-E%20Tab (Accessed 19.06.2013)

Manufacturer	Product	Illustration	ε	ε_{aged}	Thickness (mm)	Materials	Additional information
LOW-E UK Ltd Unit 48 Weaver Industrial Estate Blackburne Street Liverpool United Kingdom L19 8JA Tel: 0151 494 9994 Fax: 0560 310 7699 info@low-e.co.uk www.low-e.co.uk	EPS LOW-E Slab shield				11	Foam Facing/ Foil Core/Foam Facing	http://www.low-e.co.uk/low-e-reflective-products?q=Low-E_Insulation_Slab_Shield (Accessed 19.06.2013)
Sigma Technologies Int'l, LLC 10960 North Stallard Place Tucson AZ, 85737 USA Tel: +1 (520) 575-8013 Fax: +1 (520) 844-1056 info@sigmalabs.com www.sigmalabs.com	irWRAP						http://www.sigmalabs.com/permeable-membranes-const/ (Accessed 19.06.2013)
	3100 Series Radiant Barrier		0.05				http://www.sigmalabs.com/3100-series-rb-overview/ (Accessed 04.12.2013)
Fi-Foil Company, Inc. 612 Bridgers Ave. W., PO Box 800 Auburndale, Fl 33823 USA Tel: +1-800-448-3401 www.fifoil.com	Silver shield radiant barrier		0.03			Metalized polyvinyl chloride film with aluminium, kraft paper reinforced with tri-directional fibreglass.	http://www.fifoil.com/Builders/Products/ProductInfo/?ID=3 (Accessed 19.06.2013)
	FSK shield					Aluminium foil bonded to kraft paper reinforced with tri-directional fibreglass	http://www.fifoil.com/Builders/Products/ProductInfo/?ID=4 (Accessed 19.06.2013)
	Radiant shield		0.03		0.012 inch	Woven polyethylene sandwiched between two aluminium surfaces.	http://www.fifoil.com/Builders/Products/ProductInfo/?ID=5 (Accessed 19.06.2013)

Manufacturer	Product	Illustration	ε	ε_{aged}	Thickness (mm)	Materials	Additional information
Glidevale Limited 2 Brooklands Road Sale Cheshire M33 3SS UK Tel: 0161 905 5700 Fax: 0161 905 2085 info@glidevale.com www.glidevale.com	Protect VC foil ultra						http://www.glidevale.com/protect_vc_foil_ultra.html (Accessed 19.06.2013)
Energy Efficient Solutions LLC 1126 S Cedar Ridge Dr. Suite 122 Duncanville, TX 75137-302 USA Tel: +1 972.283.0163 Fax: +1 972.852.3151 sales@energyefficientsolutions.com www.energyefficientsolutions.com	ARMA foil		0.05		4		http://www.energyefficientsolutions.com/ARMAFOIL.asp (Accessed 20.06.2013)
	ARMA foil VB		0.05		4		http://www.energyefficientsolutions.com/ARMAFOIL-VB.asp (Accessed 20.06.2013)
Carolina Energy Conservation 100 Lichen Court, Unit A Myrtle Beach, SC 29588 USA Tel: +1 (843) 748 0295 (843) 748 0583 info@carolinaenergyconservation.com www.carolinaenergyconservation.com	ECO-Guard PLUS reflective insulation						http://www.carolinaenergyconservation.com/eco-guard-plus-reflective-insulation.html (Accessed 20.06.2013)

Manufacturer	Product	Illustration	ε	ε_{aged}	Thickness (mm)	Materials	Additional information
INNOVATIVE INSULATION, INC. 6200 W. Pioneer Pkwy. Arlington, TX 76013 USA Tel: (817) 446-6200 Fax: (817) 446-6222 www.radiantbarrier.com	Super R Diamond		0.05			Two sided reflecting metalized film with polyester scrim reinforcement	http://www.radiantbarrier.com/diamond-insulation.htm (Accessed 02.09.2013)
	Super R Platinum		0.05			Two-sided reflecting metalized film with a cross-laminated polyolefin reinforcement	http://www.radiantbarrier.com/platinum-insulation.html (Accessed 02.09.2013)
	Super R Plus		0.05			Two-sided reflecting metalized film with polyethylene reinforcement	http://www.radiantbarrier.com/plus-insulation.htm (Accessed 02.09.2013)
	Tempshield single bubble		0.05		1/8 inch	One layer of barrier bubble film laminated between to layers of reflective metalized film	http://www.radiantbarrier.com/bubble-foil-insulation.htm
	Tempshield double bubble		0.05		1/8 inch	Two layers of barrier bubble film laminated between to layers of reflective metalized film	http://www.radiantbarrier.com/double-bubble-insulation.htm (Accessed 02.09.2013)
DuPont www.dupont.com/	Airguard Reflective		0.05		0.43	A composite of polypropylene, polyethylene and an aluminium foil	http://www2.dupont.com/Tyvek_Construction/en_IE/products/dry_lining/airguard_reflective.html (Accessed 02.09.2013)
Polyair 4 Macdonald Road, Ingleburn, NSW 2565, Australia Tel: +61 2 9829 2299 Fax: +61 2 9829 2211 sales@polyairinsulation.net.au www.reflectiveinsulation.com.au	Polyair Performa 4.0		0.03		4	Core of fire retardant closed cell foam, two external layers of aluminium foils	http://www.reflectiveinsulation.com.au/polyair_performa_4.html (Accessed 02.09.2013)
	Polyair Performa 7.0		0.03		7	Core of fire retardant closed cell foam, two external layers of aluminium foils	http://www.reflectiveinsulation.com.au/polyair_performa_7.html (Accessed 02.09.2013)

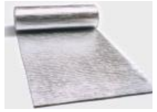
Manufacturer	Product	Illustration	ε	ε_{aged}	Thickness (mm)	Materials	Additional information
Reflectix #1 School Street, P.O. Box 108, Markleville, IN 46056 Tel: (765) 533-4332 Fax: (765) 533-2327 customerservice@reflectixinc.com www.reflectixinc.com	Double reflective insulation		0.06		5/16 inch	Two reflective layers of film bonded to two internal layers of heavy gauge polyethylene bubbles	http://www.reflectixinc.com/basepage.asp?Page=Double+Reflective+Insulation&pageIndex=622 (Accessed 02.09.2013)
	Single reflective insulation		0.06		5/16	One reflective layer of film bonded to two internal layers of heavy gauge polyethylene bubbles	http://www.reflectixinc.com/basepage.asp?Page=Single+Reflective+Insulation&pageIndex=755 (Accessed 02.09.2013)
	Concrete slab insulation				5/16 inch	Aluminium bonded to an external layer of polyethylene and internally bonded to two layers of heavy gauge polyethylene bubbles	http://www.reflectixinc.com/basepage.asp?Page=Concrete+Slab+Insulation&pageIndex=618 (Accessed 02.09.2013)
	Radiant barrier		0.05			Two reflective layers of film bonded together enclosing a heavy gauge poly scrim	http://www.reflectixinc.com/basepage.asp?Page=Radiant+Barrier&pageIndex=624 (Accessed 02.09.2013)
SA.M.E. S.r.l. Via Ferriera, 68 06089 Torgiano (PG) Italy Tel: +39 - 075 599 65 28 Fax: +39 - 075 597 68 46 info@samesrl.com www.same-foil.com	Isoliving		0.06		8	Two layers of bubble polyethylene and two layers of low-e aluminium film	http://www.same-foil.com/public/pdfprodotti/9.pdf (Accessed 02.09.2013)

Table A4 Opaque spray and brush paints

Manufacturer	Product	Illustration	ε	Binder	Solvent	VOC (g/L)	Shelf life	Additional information
SOLEC-Solar Energy Corp. 129 Walters Ave. Ewing, NJ 08638-1829, USA Tel: +1 609-883-7700 Fax: +1 609-883-5489 info@solec.org www.solec.org	LO/MIT-I		0.21-0.37 Depends on surface it is applied too	Silicone	Xylene	664.41	Best if used 1 year from date of manufacture	http://www.solec.org/lomit-radiant-barrier-coating/lomit-technical-specifications/ Conform to ASTM standard C1321-98 (Accessed 19.06.2013)
	LO/MIT-II		0.21-0.37 Depends on surface it is applied too	Silicone emulsion	DI Water	172.73	Best if used 6 months from date of manufacture	
	LO/MIT-II MAX		0.15-0.17 Depends on surface it is applied too	Silicone emulsion	DI Water	215.48	Best if used 1 year from date of manufacture	
	SOLKOTE		0.20-0.49 depending on layer thickness and surface	Silicone polymer	Xylene	812	Best if used 1 year from date of manufacture	http://www.solec.org/solkote-selective-solar-coating/solkote-technical-specifications/ (Accessed 19.06.2013)
STS Coatings, Inc. 347 Hwy 289 Comfort, TX 78013 USA Tel: +1 830-995-5177 Fax: +1 830-995-5705 www.stscoatings.com	HeatBloc-Ultra		0.19			< 50	6 months	Interior use only http://heatbloc.net/heatblocultra.html (Accessed 20.06.2013)

Manufacturer	Product	Illustration	ε	Binder	Solvent	VOC (g/L)	Shelf life	Additional information
Carolina Energy Conservation 100 Lichen Court, Unit A Myrtle Beach, SC 29588 USA Tel: +1 (843) 748 0295 (843) 748 0583 info@carolinaenergyconservation.com www.carolinaenergyconservation.com	ECO-Guard coating		0.15-0.24					http://www.carolinaenergyconservation.com/lo-mit.html (Accessed 20.06.2013)
BASF Corporation/Chemrex USA Tel: +1 973 245-6000 www.basf.com	RADIANCE e-0.25		0.23			212	1 year	http://www.buildingsystems.basf.com/p02/USWeb-Internet/buildingsystems/en_GB/content/microsites/buildingsystems/products/items/Radiance_e-0.25_Attic_Barrier (Accessed 20.06.2013)
Henry Company 999 North Sepulveda Blvd., Suite 800 El Segundo, CA 90245 USA Tel: +1 800-486-1278 productsupport@henry.com http://henry.com	LiquidFoil		0.16			185		http://henry.com/roofing/coolroofcoatings/liquidfoil (Accessed 20.06.2013)

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"Phase Change Materials for Building Applications:
A State-of-the-Art Review and Future Research Opportunities"

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Phase Change Materials for Building Applications: A State-of-the-Art Review and Future Research Opportunities

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Abstract

Phase change materials (PCM) have received considerable attention over the last decade for use in latent heat thermal storage (LHTS) systems. PCMs give the ability to store passive solar heat gains as latent heat within a specific temperature range, leading to a reduction of energy usage, an increase in thermal comfort by smoothing out temperature fluctuations throughout the day and a reduction and/or shift in peak loads.

The interest around PCMs has been growing significantly over the last decade. Hence, several commercial products have arrived on the market with various areas of use in building applications. This study reviews commercial state-of-the-art products found on the market and show some of the potential areas of use for PCMs in building applications, such as peak load shifting, free cooling and passive systems incorporating PCMs. Some examples of how PCMs can be integrated into buildings, and furthermore building materials and projects using PCMs that have already been realised, have also been reviewed. There seems to be a scarcity of data published on actual performance in real life applications so far. However, many laboratory and full scale experiments have shown positive results on energy savings.

PCMs are still a relatively new material solution with regard to their use in buildings. Safety requirements, uncertainty of determining the most adequate PCM to use in a given climate and quantifying the effects with regard to thermal comfort and energy savings, are some of the hurdles which have to be overcome to make PCMs more attractive within the construction sector.

Furthermore, future research opportunities have been explored and known common problems and challenges with the technology as of today have been discussed. The biggest hurdle seems to be the lack of common test standards for PCMs. This leads to uncertainties around the given properties of PCMs. New standards should include uniform and proper test methods for PCMs so all material properties can be evaluated on equal terms. Furthermore, standards should also mention optimum phase change temperatures for various climates and applications. Selecting the correct phase change temperature is vital for the optimum effect of a PCM system. It would also be of interest to have more data published on the payback times for various PCM systems.

Keywords: Phase change material; PCM; Building; State-of-the-art; Review; Future.

Contents

1 Introduction

The constant increase of energy demand in the world is an increasing issue with regard to climate change and energy supply. The world consumes large amounts of fossil fuels that drive climate changes and empties the supplies of fossil fuels more rapidly. One action that will benefit energy usage globally is to increase the energy efficiency of buildings. In the European Union, the building sector is a major energy consumer and accounts for around 40% of the total energy usage. Large parts of this energy usage is directly related to the heating and cooling of buildings (European Union [25]).

Several new technologies are emerging to help realize the goal of reducing energy usage in buildings. Some of these technologies are related to thermal insulation materials applied in the building envelope (Baetens et al. [8], Baetens et al. [10], Baetens et al. [11], Baetens et al. [12], Gao et al. [28], Jelle et al. [42], Jelle [43], Kalnæs and Jelle [55], Sandberg et al. [92], Tenpierik [114]). Also part of the thermal building envelope, although not a thermal insulation material in itself, is the promising technology of phase change materials (PCM) which has received considerable attention over the last decade. PCMs utilize the principle of latent heat thermal storage (LHTS) to absorb energy in large quantities when there is a surplus and releasing it when there is a deficit. Correct use of PCMs can reduce peak heating and cooling loads, i.e. reduce energy usage, and may also allow for smaller dimensions of technical equipment for heating and cooling. An added benefit is the ability to maintain a more comfortable indoor environment due to smaller temperature fluctuations. Over the past few years there have been written several reviews on the use of PCMs in buildings for thermal energy storage systems and indoor climate comfort purposes (Agyenim et al. [1], Baetens et al. [9], Cabeza et al. [17], Kuznik et al. [65], Osterman et al. [79], Pomianowski et al. [82], Soares et al. [108], Zhou et al. [123], Zhu et al. [124]), clearly showing that the interest for PCMs is increasing worldwide.

For building applications the possible areas where PCMs can be utilized are many. Some of the areas that have been studied to this day include ventilation systems, passive heating and cooling systems, floors, roofs and wallboards. PCMs can also be incorporated directly into building materials such as concrete (Ling and Poon [72]) and wallboards (Kuznik et al. [63]), enabling them to be applied in constructions with minimal alterations to the original design.

The objective of this study is twofold, i.e. (a) to present a comprehensive state-of-the-art overview of different PCM producers and products, including an evaluation of the effect and durability of these products, and (b) to explore possible future research opportunities. Furthermore, it is of interest to see how phase change materials are tested with respect to lifetime performance in building applications, and then especially with respect to cycle testing for long-term stability, fire safety and energy saving potential. These investigations may help developing guidelines for a new testing scheme and point to future research possibilities. This work presents many tables with a considerable amount of information, e.g. manufacturers, product names and various properties, both in the main text and in the appendix. Some of these values are crucial to the performance of phase change materials. The tables should provide the readers with valuable information regarding phase change materials and their use. Unfortunately, it is currently hard to obtain all the desired information from every manufacturer. In general, many of the desired property values are not available on the manufacturers websites or other open information channels, which is hence seen as open spaces in the various tables. Hopefully, our addressing of these facts could act as an incentive for the manufacturers to state all the important properties of their products at their websites or other open information channels, and also as an incentive and reminder for consumers and users to demand these values from the manufacturers.

2 Phase change materials in general

2.1 General

Phase change materials (PCM) utilize the latent heat of phase change to control temperatures within a specific range. When the temperature drops below a certain point, the material will absorb the heat in an endothermic process and change state from solid to liquid. As the temperature rises, the material will give off energy and return to a solid state. The energy used to alter the phase of the material, given that the phase change temperature is around the desired comfort room temperature, will lead to a more stable and comfortable indoor climate, as well as cut peak cooling and heating loads (Baetens et al. [9]). Hence, phase change materials can provide an increase in heat storage capacity, especially in buildings with low thermal mass. The temperature range varies depending on the materials used as the phase change material.

Schröder and Gawron [98] summarized some of the desired properties that should be required from phase change materials:
- High heat of fusion per unit volume and unit weight, and high specific heat
- Phase change temperature suitably matched to the application
- Low vapour pressure at operational temperature
- Chemical stability and low corrosion rate
- Not hazardous or poisonous
- Highly inflammable
- Reproducible crystallization without degradation
- Small degree of supercooling and a high rate of crystal growth
- Small volume change during solidification
- High thermal conductivity
- Use materials that are abundant and cheap

2.2 General categorization of phase change materials

There are several materials that can be used as PCMs. A common way to distinguish PCMs is by dividing them into organic, inorganic and eutectic PCMs. These categories are further divided based on the various components of the PCMs (Fig.1). Figure 2 shows the difference in melting enthalpy and melting temperature for some of the most common materials used as PCMs.

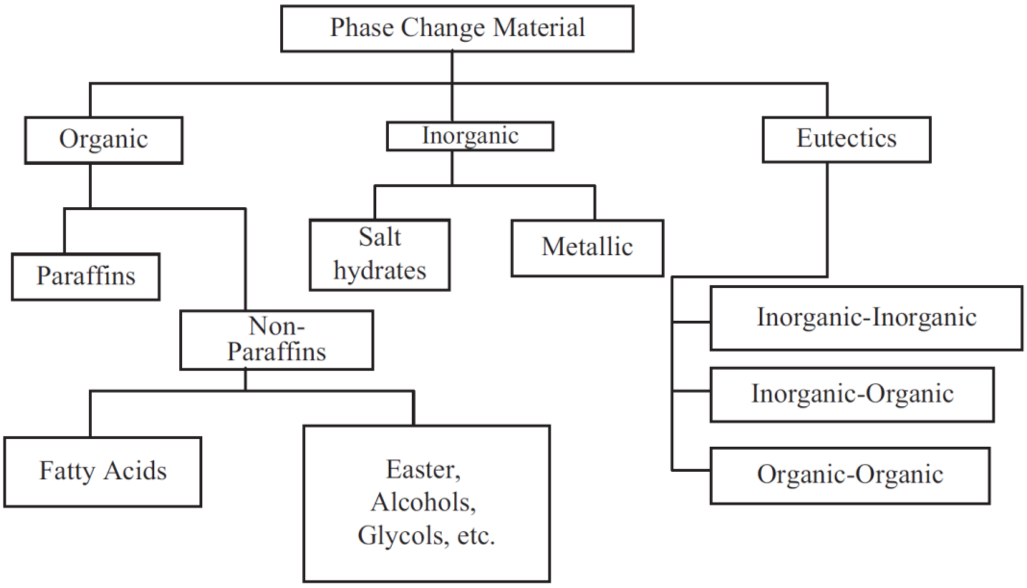

Figure 1 General categorization of PCMs (Rathod and Banerjee [85]).

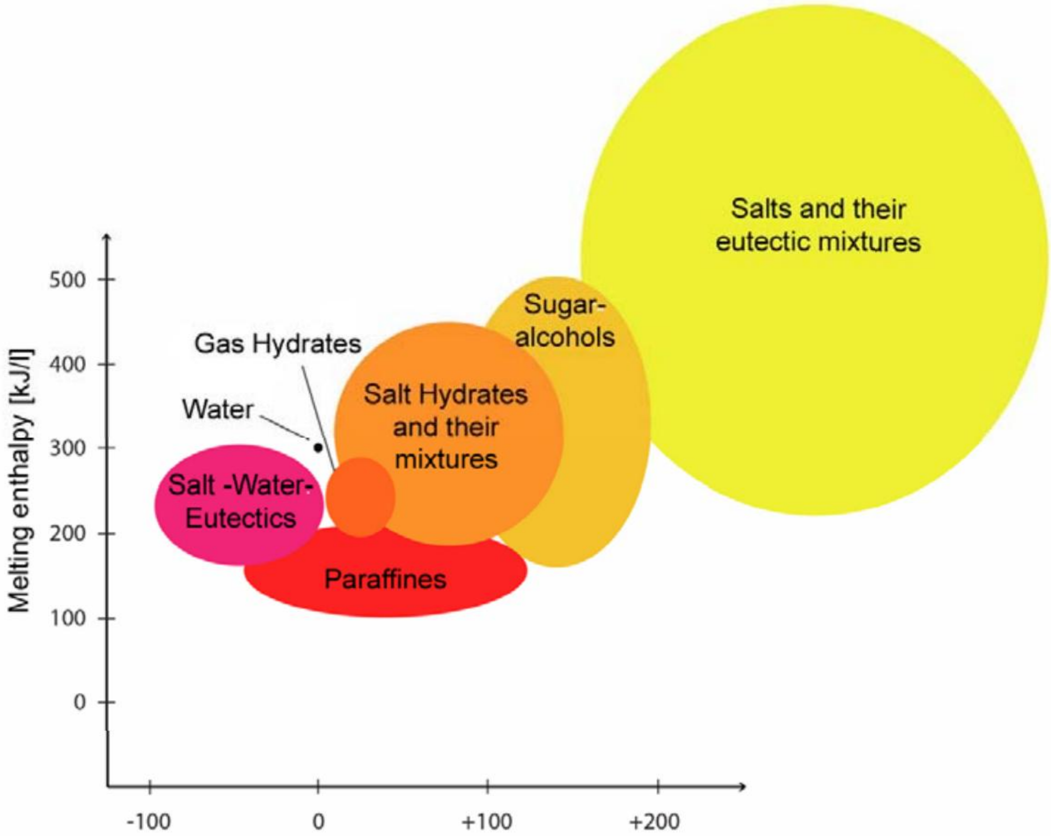

Figure 2 Melting enthalpy versus melting temperature for various materials used in PCMs (Dieckmann [24]).

2.2.1 Organic

Organic phase change materials are divided into paraffins and non-paraffins. In general, organic PCMs do not suffer from phase segregation and crystallize with little or no supercooling (Rathod and Banerjee [85]).

Paraffins are available in a large temperature range (Fig.2) opening up for use in various other areas besides building related applications. The latent heat is mass based, they show no signs of phase separation after repeated cycling through solid-liquid transitions, and have a low vapour pressure (Alkan [3]). However, paraffins used as PCMs have some drawbacks. They have low thermal conductivity (around 0.2 W/(mK)), they are not compatible with plastic containers and they are moderately flammable (Sharma et al. [102]).

Non-paraffins used as PCMs include fatty acids and their fatty acid esters and alcohols, glycols, etc. Fatty acids have received the most attention for use as PCMs in buildings. An extensive review on fatty acids used for PCM purposes has been written by Yuan et al. [119]. In this review fatty acids and their esters and alcohols were reviewed for their potential as PCMs. The most interesting fatty acids for PCM purposes include lauric acid, myrisitic acid, palmitic acid and stearic acid. As with paraffins, these also suffer from low thermal conductivity, ranging from 0.15 to 0.17 W/(mK).

In overall, organic PCMs have many qualities which make them suited for building applications. However, the fact that many organic PCMs are considered flammable is a crucial drawback for which impacts the safety aspect of organic PCMs considerably when aimed at building applications.

2.2.2 Inorganic

Inorganic phase change materials of interest consists of hydrated salts and metallics. For building applications however, metallics are not within the desired temperature range and in addition they have severe weight penalties making them unsuited. Hence, they will not be further addressed in this review.

Hydrated salts consist of an alloy of inorganic salts and water and enable a cost-effective PCM due to easy availability and low cost. The phase change transformation involves hydration or dehydration of the salts in a process that resembles typical melting and freezing. The salt hydrate may either melt to a salt hydrate containing less water or to an anhydrous form where salt and water is completely separated (Sharma et al. [102]).

Desirable properties of salt hydrates used as PCMs include high latent heat of fusion per unit volume, higher thermal conductivity than organic PCMs and small volume change and easy availability at a lower cost.

Hydrated salts suited for commercial use suffer from incongruent melting in many cases, giving a solution where not all of the solid material will completely melt. Thus, reducing the overall effectiveness of the PCM. Another issue for hydrated salts is supercooling, which alters the temperature of the phase change.

2.2.3 Eutectic mixtures

An eutectic is a minimum melting composition of two or more components, each of which melts and freezes congruently. During the crystallization phase, a mixture of the components is formed, hence acting as a single component. The components freeze to an intimate mixture of crystals and melt simultaneously without separation (Lane [68]). Eutectics can be mixtures of organic and/or inorganic compounds. Hence, eutectics can be made as either organic-organic, inorganic-inorganic or organic-inorganic mixtures (Baetens et al. [9]). This gives room for a wide variety of combinations that can be tailored for specific applications.

Of organic eutectic mixtures, the most commonly tested consist of fatty acids. Some organic eutectics that have been studied include capric acid/myristic acid (Karaipekli and Sari [56]), lauric acid/stearic acid, myristic acid/palmitic acid and palmitic acid/stearic acid (Sari et al. [94]) and capric acid/lauric acid (Shilei et al. [104]). The most common inorganic eutectics that have been investigated consist of different salt hydrates.

The benefits of eutectic mixtures is their ability to obtain more desired properties such as a specific melting point or a higher heat storage capacity per unit volume.

Though it has been given significant interest over the last decade by researchers, the use of eutectic PCMs for use in (LHTS) systems is not as established as pure compound PCMs. Hence, thermophysical properties of eutectics is still a field for further investigations as many combinations have yet to be tested and proved.

2.2.4 Comparison summary

The advantages and drawbacks for organic, inorganic and eutectic PCMs are compared and summarized in Table 1.

Table 1 Overview of advantages and drawbacks for PCMs.

Organic		Inorganic		Eutectics	
Advantages	Drawbacks	Advantages	Drawbacks	Advantages	Drawbacks
-No supercooling -No phase segregation -Low vapour pressure -Large temperature range -Self-nucleating -Compatible with conventional construction materials -Chemically stable -Recyclable -High heat of fusion	-Flammable -Low thermal conductivity -Low volumetric latent heat storage capacity	-High volumetric latent heat storage capacity -Higher thermal conductivity than organic PCMs -Low cost -Non-flammable -Sharp phase change	-Corrosive to metals -Supercooling -Phase segregation -Congruent melting -High volume change	-Sharp melting points - Properties can be tailored to match specific requirements	-Limited data on thermophysical properties for many combinations - High cost

2.3 Encapsulation

As most PCMs designed for building applications go through a liquid phase, encapsulation is needed to avoid problems such as leaking of PCM to the surface and diffusing of low viscous liquids throughout the material (Özonur et al. [125]). Hence, methods such as direct incorporation and immersion of PCMs in building materials are not well suited for long-term applications (Zhou et al. [123]). As direct incorporation and immersion are techniques that are not wide spread for PCMs intended for building applications, they will not be discussed further in this study. PCMs undergo a change in phase, thus it is important to note that this may also lead to change in both volume and thermal conductivity. A large volume change is not desirable as it may put pressure on the encapsulating material.

The material used to encapsulate should not react with the PCM or show signs of deterioration over time. Currently, two main methods are used for encapsulating PCMs, i.e. micro- and macroencapsulation. These two methods give various sizes and shapes of the PCMs and affect how PCMs may be incorporated into a material or construction.

2.3.1 Microencapsulation

Microencapsulation of PCMs involves packing the PCM materials in capsules which range from less than 1 µm to more than 300 µm (Hawlader et al. [33]). The end product consists of the outer shell and the PCM fill in the centre (Fig.3). The process can either be perfomed physically through e.g. spray-drying (Hawlader et al. [33]) or a coating process (Kaygusuz et al. [57]) or chemically through e.g. coacervation (Hawlader et al. [33], Saihi et al. [90]) or interfacial polymerization (Cho et al. [20], Liang et al. [71] and Saihi et al. [91]).

The shell materials commonly used for microencapsulation consists of organic polymers or silica. Recently materials such as SiO_2, AlOOH and TiO_2 have also been studied (Cao et al. [18]).

Figure 3 Model of a microencapsulated PCM with a wax core and polymeric shell (Phase energy [81]).

The advantages of microencapsulation include an increased heat exchange surface giving an increased heat transfer, reduced reactivity with surrounding materials and the PCM's volume can expand without affecting the structure around it. Due to the microencapsulated PCMs' small size they can be produced in either powder form or dispersed in a liquid (Fig.4) and they do not need additional protection from destruction (Tyagi et al. [115]). This makes it possible to add the PCM directly to materials such as concrete and gypsum without the risk of leakage. However, considerations have to be made as adding microcapsules may affect the structural strength of a material.

Microencapsulation has shown to be the most promising method of encapsulation for integration of PCMs in building materials. However, microencapsulation leads to a lower latent heat storage capacity per unit volume and unit weight than the pure PCM due to the adding of the encapsulating material.

Figure 4 Microencapsulated PCM dispersed in liquid and as powder (BASF [14]).

2.3.2 Macroencapsulation

Macroencapsulation refers to PCMs encapsulated in any type of container such as tubes, spheres or panels which can be incorporated into building materials or serve as heat exchangers by themselves (Fig.5). The size of these containers are usually larger than 1 cm (Cabeza et al. [17]). Because many PCMs have low thermal conductivity, a disadvantage of macroencapsulation is the tendency to solidify/melt at the edges leading to a slower energy uptake and release which may prevent the system from discharging completely overnight. The size of the macrocapsules imply that they have to be protected against destruction or perforation and may also make them more difficult to integrate into the building structure, which hence may make these systems more expensive (Schossig et al. [96]).

Figure 5 Examples of macroencapsulation of commercial PCMs (RGEES [86], RGEES [87], Salca [100]).

2.4 Long-term stability

For successful large scale application of PCMs into the building sector it is crucial that the PCM and PCM-container system can withstand cycling over an extended period of time without showing signs of degradation. There are two main factors which govern the long-term stability of PCM storage materials. Poor stability of the materials, e.g. super cooling and phase segregation, and corrosion between the PCM and the container system (Mehling et al. [75], Shukla et al. [106]). Degradation of PCMs may result in decreased ability to store latent heat and a difference in phase change temperature.

Accelerated ageing tests on stearic acid and paraffin wax, both organic PCMs, have been conducted by Sharma et al. [101]. Both stearic acid and paraffin wax performed well and showed no regular degradation of their melting point over 1500 thermal cycles. However, of the fatty acids, palmitic acid and myristic acid showed to have the best long-term stability (Sari and Kaygusuz [93]), which may make them more suited for building applications compared with other fatty acids.

A comprehensive review on the thermal stability of organic, inorganic and eutectic PCMs have recently been given by Rathod and Banerjee [85]. This work covers the investigations on thermal stability of PCMs done over the past few decades. Parrafins have shown good thermal stability. For fatty acids the purity plays an important role. Industrial grade fatty acids may experience changes in its thermal behaviour over time and should be tested by accelerated ageing. Of inorganic PCMs, salt hydrates are the most widely studied. Most studies have shown that the thermal stability of salt hydrates is poor due to phase separation and supercooling. However, the thermal stability may be improved to a certain extent by introducing gelled or thickened mixtures and suitable nucleating materials. In general, new building materials, components and structures should be examined by accelerated climate ageing (Jelle [48]), PCMs being no exception. Furthermore, a robustness assessment may also be performed (Jelle et al. [51]).

3 State-of-the-art phase change materials

As mentioned earlier, PCMs can be found in a wide variety of temperature ranges. The PCMs in this study have been limited to PCMs with phase change temperatures in the appropriate range for efficient in buildings. Cabeza et al. [17] has listed several tables of PCM properties where the potential areas of use have been divided by the PCMs' phase change temperature. For use in buildings, three temperature ranges were suggested. i) up to 21 ^{o}C for cooling applications, ii) 22-28 ^{o}C for human comfort applications and iii) 29-60 ^{o}C for hot water applications. For this study, PCMs with phase change temperatures ranging from 15-32 ^{o}C have been included. Note that many of the manufacturers included in this study offer PCMs outside this temperature range as well.

3.1 Phase change material compounds

By PCM compounds it is referred to products that are made up of PCMs and their prospective encapsulation materials. These are products that have not been combined into products ready for building applications.

Table 2 shows an overview of manufacturers and their commercial products with some important properties. More information about the products can be found in the appendix.

Table 2 Manufacturers and properties of commercial PCMs (see Table A1 in appendix for further information).

Manufacturer	Product	Phase change temperature (°C)	Latent heat capacity (kJ/kg)	Material	Type*	Encapsulation
BASF	DS 5030	21	37	Dispersed wax mixture	Organic	Microencapsulation
	DS5007	23	41	Dispersed wax mixture	Organic	Microencapsulation
	DS 5000	26	45	Dispersed wax mixture	Organic	Microencapsulation
	DS 5029	21	90	Powder form wax mixture	Organic	Microencapsulation
	DS 5008	23	100	Powder form wax mixture	Organic	Microencapsulation
	DS 5001	26	110	Powder form wax mixture	Organic	Microencapsulation
RGEES	PCM-OM21P	21	120	Organic chemicals	Organic	
	PCM-HS22P	22	185	Inorganic salts	Inorganic	
	PCM-HS24P	24	185	Inorganic salts	Inorganic	
	PCM-HS29P	29	190	$CaCl_2$ and other salts	Inorganic	
	PCM-OM32P	32	235	Organic chemicals	Organic	
Phase change products	PC14	14	145	Hydrated calcium chloride and calcium bromide	Inorganic	
	PC17	17	145	Hydrated calcium chloride and calcium bromide	Inorganic	
	PC25	25	150	Hydrated calcium and magnesium and chlorides	Inorganic	
	PC29	29	188	Hydrated calcium chloride	Inorganic	
Entropy Solutions Inc.	PureTemp 15	15	165	Vegetable based		Micro- and macroencapsulation
	PureTemp 18	18	189	Vegetable based		Micro- and macroencapsulation
	PureTemp 20	20	180	Vegetable based		Micro- and macroencapsulation
	PureTemp 23	23	203	Vegetable based		Micro- and macroencapsulation
	PureTemp 24	24	185	Vegetable based		Micro- and macroencapsulation
	PureTemp 25	25	185	Vegetable based		Micro- and macroencapsulation

Manufacturer	Product	Phase change temperature (°C)	Latent heat capacity (kJ/kg)	Material	Type*	Encapsulation
	PureTemp 27	27	200	Vegetable based		Micro- and macroencapsulation
	PureTemp 28	29	205	Vegetable based		Micro- and macroencapsulation
	PureTemp 29	29	189	Vegetable based		Micro- and macroencapsulation
	PureTemp 31	31		Vegetable based		Micro- and macroencapsulation
Salca	Thermusol HD26	26		Salt hydrate	Inorganic	Microencapsulation
	Thermusol HD32	32	150	Salt hydrate	Inorganic	Microencapsulation
Climator Sweden AB	ClimSel C21	21		Sodium sulphate	Inorganic	
	ClimSel C24	24		Sodium sulphate	Inorganic	
	ClimSel C28	28		Sodium sulphate	Inorganic	
	ClimSel C32	32		Sodium sulphate	Inorganic	
Phase Change Material Products Ltd.	S15	15	160	Salt hydrate	Inorganic	
	S17	17	160	Salt hydrate	Inorganic	
	S19	19	160	Salt hydrate	Inorganic	
	S21	22	170	Salt hydrate	Inorganic	
	S23	23	175	Salt hydrate	Inorganic	
	S25	25	180	Salt hydrate	Inorganic	
	S27	27	183	Salt hydrate	Inorganic	
	S30	30	190	Salt hydrate	Inorganic	
	S32	32	200	Salt hydrate	Inorganic	
	A15	15	130		Organic	
	A16	16	213		Organic	
	A17	17	150		Organic	
	A22	22	145		Organic	
	A22H	22	216		Organic	
	A23	23	145		Organic	
	A24	24	145		Organic	
	A25	25	150		Organic	
	A25H	25	226		Organic	
	A26	26	150		Organic	
	A28	28	155		Organic	
	A29	29	226		Organic	
	A32	32	130		Organic	
	X25	25	110			Solid-solid phase change
	X30	30	105			Solid-solid phase change
PCM Energy P. Ltd.	Latest 18T	17-19	175	Inorganic salts	Inorganic	
	Latest 20T	19-20	175	Inorganic salts	Inorganic	
	Latest 25T	24-26	175	Inorganic salts	Inorganic	
	Latest 29T	28-30	175	Inorganic salts	Inorganic	
	Latest 32S	31-32	>200	Inorganic salts	Inorganic	
Microtek Laboratories	MPCM 18	18	163-173	n-Hexadecane	Organic	Microencapsulation
	MPCM 18D	18	163-173	n-Hexadecane	Organic	Microencapsulation
	MPCM 24	24		Special blend		Microencapsulation
	MPCM 24D	24		Special blend		Microencapsulation
	MPCM 28	28	180-195	n-Octadecane	Organic	Microencapsulation
	MPCM 28D	28	180-195	n-Octadecane	Organic	Microencapsulation
	MPCM28D-IR	25-32	160-180	Special blend		Microencapsulation
	MPCM 32	32		Special blend		Microencapsulation
	MPCM 32D	32		Special blend		Microencapsulation
Cristopia	AC 27	27				Nodules filled with PCM

Manufacturer	Product	Phase change temperature (°C)	Latent heat capacity (kJ/kg)	Material	Type*	Encapsulation
Rubitherm Technologies GmbH	RT 18 HC	18	250			
	RT 21	21	160			
	RT 21 HC	21	190			
	RT 22 HC	22	200			
	RT 24	24	150			
	RT 25	25	148			
	RT 25 HC	25	230			
	RT 27	27	179			
	RT 28 HC	28	245			
	RT 31	31	170			
	SP 21 E	21-23	160	Salt hydrates and organic compounds		
	SP 22 E	22-23	180	Salt hydrates and organic compounds		
	SP 24 E	24-25	222	Salt hydrates and organic compounds		
	SP 25 E	24-26	200	Salt hydrates and organic compounds		
	SP 26 E	25-27	200	Salt hydrates and organic compounds		
	SP 31	31-33	240	Salt hydrates and organic compounds		
	PX 15	10-17	85			Microencapsulation
	PX 25	22-25	96			Microencapsulation
	PX 27	25-28	102			Microencapsulation
	PX 31	27-31	110			Microencapsulation

* Many manufacturers do not give a full description of the mixtures used in PCMs. Hence, type has only been limited to organic and inorganic, though some of these may be eutectic mixtures as well.

3.2 Phase change materials in products for building applications

The PCM technology has already been combined with several other products which are directly aimed at the building sector. PCM enhanced materials include e.g. wallboards, floor tiles, ventilation systems, mats and tubes. Table 3 shows an overview of manufacturers and their commercial products with some important properties. More information about the products can be found in the appendix

Table 3 Manufacturers of products ready for building applications (see Table A2 in appendix for further information).

Manufacturer	Product	Phase change temperature (°C)	Latent heat capacity (kJ/kg)	PCM material	Type*	Building product
Dupont	Energain	18-24	515 kJ/m^2	Paraffin wax compound	Organic	Thermal mass panels
Knauf	Comfort board			BASF micronal		Gypsum board with microcapsules of PCM
	Smartboard 23	23	200 kJ/m^2	BASF micronal		No longer available on the market?
	Smartboard 26	26	330 kJ/m^2	BASF micronal		No longer available on the market?
RGEES	PB29P	29	33 kWh/cbm		Organic	Spheres of 75 mm in diameter filled with PCM
	PB22P	22	0.1 kWh/(ft^2)		Inorganic	Tubes filled with PCM

Manufacturer	Product	Phase change temperature (°C)	Latent heat capacity (kJ/kg)	PCM material	Type*	Building product
	PB24P	24	0.1 kWh/(ft^2)		Inorganic	Tubes filled with PCM
	PB29P	29	0.1 kWh/(ft^2)		Inorganic	Tubes filled with PCM
Phasechange energy solutions	BioPCMat M27	23		Bio-based	Organic	Mats filled with PCM
	BioPCMat M51	25		Bio-based	Organic	Mats filled with PCM
	BioPCMat M91	27		Bio-based	Organic	Mats filled with PCM
	Thermastix			Bio-based	Organic	Stick filled with PCM
Dörken	Delta-cool 24					No longer available on the market?
	Delta-cool 28					No longer available on the market?
Salca	K-Block		590 kJ/m^2	Salt hydrate	Inorganic	Mat filled with PCM
SGL Group	Ecophit GC20	22	85			
	Ecophit LC20	22	140			
Phase Change Material Products Ltd.	FlatICE					Flat container filled with PCM
	TubeICE					Tubes filled with PCM
	BallICE					Spheres filled with PCM
National gypsum	ThermalCORE			BASF micronal		Gypsum board with microcapsules of PCM covered with a fibreglass mat
H+H Deutschland	CelBLoc Plus			BASF micronal		Concrete blocks with microcapsules of PCM
Maxit Deutschland	Maxit clima					Plaster with integrated microcapsules of PCM
Ilkazell Isoliertechnik	Ilkatherm air conditoning systems					
Monodraught	Coolphase					Ventilation system with PCM
Tate	EcoCore	75.2 °F	147 Btu	vegetable bio based	Organic	Floor tiles
Emco	Emcovent					Decentralised PCM modules
Autarkis						PCM heat exchangers
Armstrong World Industries	Coolzone			BASF micronal	Organic	Chilled roof system
Trox	FSL-B-PCM					Supply air unit with PCM

* Many manufacturers do not give a full description of the mixtures used in PCMs. Hence, type has only been limited to organic and inorganic, though some of these may be eutectic mixtures as well.

3.3 Phase change materials in windows

Windows incorporating PCMs are highly limited on the market. There can be several reasons for this. First of all, the PCM relies on a process where the materials solidifies below a certain temperature. Windows are in many cases used for aesthetic purposes, to allow visibility towards the outside or allow daylight in to the building. Most PCMs in use on the market are not transparent in both their liquid and solid state. Hence, PCM windows will be blurry and reduce transmission of daylight and solar radiation in general. Only one manufacturer of windows including PCMs has been found in this study. The products currently on the market are categorized as translucent. Table 4 shows an overview of the manufacturers of PCM windows and some of their important properties.

Table 4 Manufacturers of windows incorporating PCMs (see Table A3 in appendix for further information).

Manufacturer	Product	Phase change temperature (^{o}C)	Heat storage capacity (Wh/m^{2})	T_{vis} solid/liquid (%)	Material	Type
GLASSX	GLASSX crystal	26-30	1185	0-28/4-45	Salt hydrates	Inorganic
	GLASSX comfort	26-30	1185	0-38/4-55	Salt hydrates	Inorganic
	GLASSX slim	26-30	1185	0-38/4-45	Salt hydrates	Inorganic
	GLASSX store	26-30	1185	0-38/4-55	Salt hydrates	Inorganic

3.4 Comparison of commercial products

Commercial PCMs come in a variety of forms and solutions, e.g. PCM infused wallboards, microcapsules filled with a PCM dispersed in a liquid or in powder form or mats that can be installed directly. There is no clear preference towards organic or inorganic PCMs in commercial products and both are ready and available for use. A market study performed by Markets and Markets [73] showed that organic PCMs held the highest market share in terms of value due to higher cost, while inorganic PCMs held the highest market share in terms of volume.

The tables includes manufacturers who produce the raw PCM material, as well as manufacturers who produce building materials based on their own or other manufacturers PCMs. All commercial building materials produced with PCMs use some form of encapsulation. None of the commercial building products found in this study are created using direct incorporation or immersion. This may be due to the fact that these techniques will lead to a material with a large probability of leakage of the PCMs to the surface. Hence, it does not meet the strict requirements for building applications with regard to lifetime expectancy.

Both products created by macro- and microencapsulation are already commercialized. Macroencapsulated products include tubes, flat containers and spheres ranging from some millimetres up to about 75 millimetres. Microencapsulated PCMs are generally already integrated into building materials such as gypsum and plaster.

Several producers state that there is no sign of degradation after 10 000 cycles for their organic PCMs, giving the PCMs a lifetime of approximately 30 years or more.

An aspect which is of most importance is how the various manufacturers have solved the issue of organic PCMs with respect to fire resistance. Materials that are aimed for building applications have to overcome some strenuous requirements with regard to safety. And as mentioned earlier, one drawback of organic materials is the fact that many of them are flammable and may release toxic fumes during combustion.

4 Phase change materials in building applications

4.1 Building applications

Zhu et al. [124] presented an overview of research conducted on PCMs with regards to their dynamic characteristics and energy performance in buildings. This overview divided the possible building applications of PCMs into four categories:

- Free cooling.
- Peak load shifting.
- Active building systems.
- Passive building systems.

Besides these suggested applications, another interesting possible benefit of PCMs is their ability to increase thermal comfort by smoothing out temperature fluctuations. The study given herein is mostly focused on the effect of passive building systems through the integration of PCM enhanced building materials. However, a short overview and explanation of some of the research that has been performed and possibilities for the other systems will be given.

4.1.1 Free cooling

Free cooling systems with PCMs works by storing outdoor coolness in periods where the ambient temperature is low, and then supply this cooling indoors in the day when temperatures are higher and the need for cooling arises. These systems work because of temperature difference between the nightly outdoor temperature and indoor temperature during the day (Zalba et al. [120].

Mosaffa et al. [77] described a free cooling system using PCM slabs separated by air gaps for air to flow through (Fig.6). The model developed from this can be used to evaluate performances of latent heat storage systems for free cooling air conditioning systems.

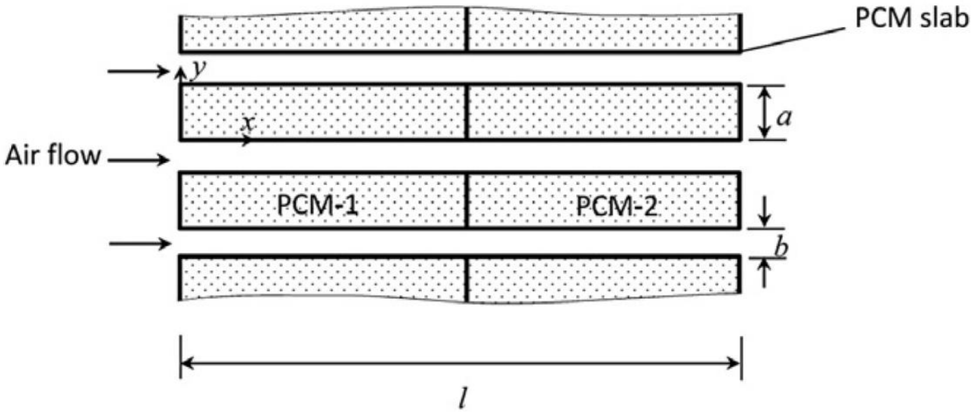

Figure 6 Schematic of a free cooling air conditioning system (Mosaffa et al. [77]).

4.1.2 Peak load shifting

Peak loads that hit during the day put pressure on the electrical grid and also lead to the need for heating, ventilation and air conditioning (HVAC) systems being dimensioned for higher heating or cooling loads. Ultimately, this could lead to a need for more power generation facilities being built. By shifting the peak load away from the peak hours of electrical demand using PCMs, the peak load may be divided throughout the day reducing the highest peaks (Halford and Boehm [32]). Figure 7 illustrates how the peak may be both reduced and shifted by the use of PCMs.

Sun et al. [111] reviewed strategies involving PCMs for peak load shifting and control that have been tested so far. From the studies reviewed, peak load reductions ranging from 10% to 57% were found. However, the cost saving potential of these systems could be further improved if more sophisticated load shifting control strategies were developed.

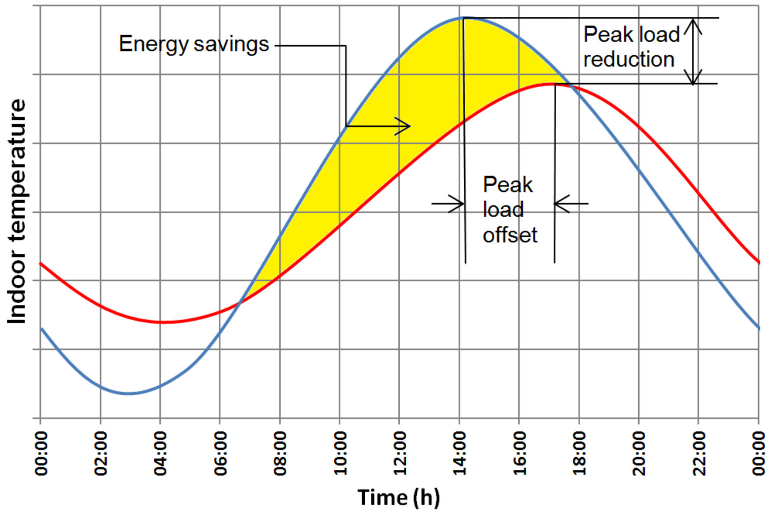

Figure 7 Illustration of peak load offset and peak load reduction (Redrawn from Tate [113]).

4.1.3 Active building systems

The storage capability of PCMs can be integrated into systems such as e.g. solar heat pump systems, heat recovery systems and floor heating systems. Such systems can be combined to attain a peak load reduction as described in the previous chapter. However, if they are made even more effective they can achieve further savings through reduced electrical demand for HVAC systems.

An example of a radiant floor incorporating PCMs in an active system has been described by Ansuini et al. [5]. The system investigated consists of a lightweight piped radiant floor system with an integrated PCM layer aimed at buffering internal gains during the summer season without affecting the winter warming capacity.

4.1.4 Passive building systems

Passive building systems is the use which has attained the most interest as of yet. For passive applications, PCMs are integrated into the building envelopes to increase the thermal mass. This is especially beneficial in lightweight constructions, which suffer from low thermal

inertia. A known issue for these buildings are large temperature fluctuations in the summer due to excessive overheating caused by a lack of thermal mass. This is especially the case in cold climates where buildings have been built according to passive house standards, often involving large amounts of insulation to reduce heating loads in the winter.
The materials incorporating PCMs will melt during the daytime and solidify during nighttime. This will help rooms from overheating during the daytime in warm months and may also reduce the need for heating during nighttime in the winter.

An issue that has been brought up is the importance of getting passive PCM systems to completely discharge during nighttime in warm periods. If the PCM is not able to completely solidify, the effectiveness of the system may be considerably reduced. This point makes PCMs more effective in climates with large daily variation in temperatures. For areas where the discharge does not happen naturally, cool air has to be supplied during nighttime to reset the PCMs completely.

4.1.5 Thermal comfort control

Though PCMs show potential for energy savings, another important factor to highlight is the benefits PCMs may have towards increasing the overall indoor thermal comfort. Lan et al. [67] showed a correlation between workers' performance and productivity compared to the sensation of thermal comfort due to shifting temperatures. Seppänen and Fisk [99] showed that elevated air temperatures had a negative effect on performance and productivity. When temperatures increased up to 20 ^{o}C there was an increase in working performance. However, when temperatures increased above 23 ^{o}C there was a decrease in productivity. Maintaining a steady temperature around the comfort zone for longer periods without relying on HVAC systems may be possible with PCMs.

With PCMs installed temperature fluctuations are reduced. The focus should be placed on selecting a PCM within the desired melting/freezing point so temperatures stay stable around the comfort temperature. This will benefit the indoor climate in two ways. First, the temperature will be held more stable, reducing the feelings of thermal discomfort due to temperature fluctuations throughout the day. Second, the peak temperature will be reduced and should not reach a temperature which leads to increasing thermal discomfort. Another possible benefit of PCMs can be that they lead to a more uniform temperature between surfaces and air temperature, reducing thermal discomfort from radiative heat.

4.2 Solar energy storage

PCMs hold the ability to store energy given off by the sun. Where solar cell panels can produce energy during hours of solar radiation, PCMs can store some of the excess energy and release it at a more needed time of the day. This can be combined with different energy distribution systems such as a heat pump.

For PCMs to best utilize the solar energy it is important that the surfaces are positioned in areas where they can fully absorb the energy coming from the sun, e.g. wallboards or PCM windows. PCM incorporated into concrete floors is an example of a position which poorly utilizes the possible energy gains from the sun as such floors are covered with other materials in most traditional structures.

4.3 Examples of integration of phase change materials for passive systems

Though there have been few detailed studies on the overall effect of PCMs in real life constructions, commercial PCM products have already been used in several projects. In the following, examples from some of these constructions, reasoning for the use of PCMs as well as general thoughts around possible areas and materials where PCMs can be incorporated beneficially, will be explored. The solutions treated in this chapter are all seen as part of a passive system.

When used in buildings, PCMs can be integrated into other building materials. This has attracted a lot of interest as it will enable buildings to be built fairly similar to the way they are built today, but with materials that have an increased thermal energy storage capacity.

In the reviewed literature it is obvious that wall systems integrating PCMs have received the most attention. Studies on floor and roof systems are limited.

4.3.1 Walls

The most common solution for implementing PCMs into buildings so far is by installing PCM enhanced wallboards towards the interior side of the building envelope. For lightweight structures, which have low thermal inertia, PCMs can provide a significant increase in thermal storage capacity. When facing the interior rooms of a building or being used in partition walls, wallboards will be able to absorb and release heat throughout the room for large parts of the day. Several investigations, both experimental and practical, have been conducted to see how this affects overall indoor climate and energy usage.

Experimental hot box tests have shown that PCM wallboards give an obvious reduction in temperature fluctuations as demonstrated in Figure 8, (Sunliang et al. [112]).

A full-scale investigation was performed on a lightweight building's inner partition walls. In this study, several positive effects could be seen when a room with PCM wallboards was compared to one without PCMs added. Air temperature fluctuations were reduced, the overheating effect was lower, the PCM wall was shown to release energy when temperatures fell and the surface temperature of the PCM wall was reduced, enhancing thermal comfort by radiative effects (Kuznik et al. [63]).

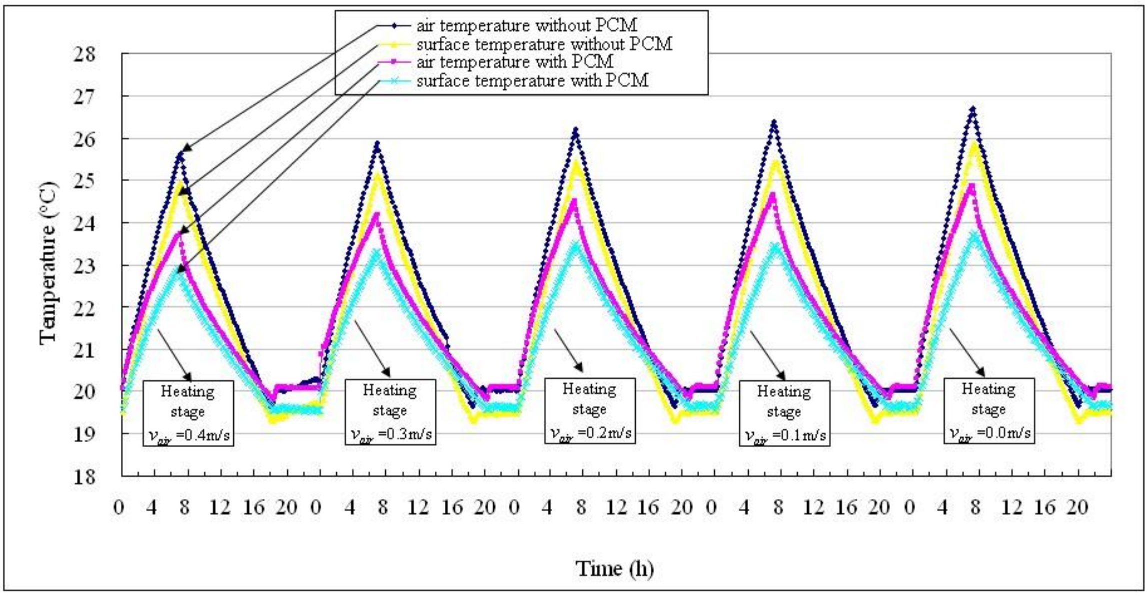

Figure 8 Indoor air and surface temperatures of a test wall with and without PCM panels versus elapsed time, demonstrating the ability of the PCM panels to decrease the indoor temperature variations with about 2 °C. Redrawn from Sunliang et al. [112].

Kuznik and Virgone [64] performed an experimental investigation in a full-scale test room for a typical day in the winter, summer and mid-season with PCM enhanced wallboards. The PCM wallboards were created by adding 60% microencapsulated paraffins in a flexible sheet of 5 mm thickness. The PCMs were shown to reduce overheating effects, reduce the surface temperature on the walls and enhance the natural convection mixing of the air.

Evola et al. [26] performed a simulated case study of an office building refurbished with PCM enhanced wallboards during summer conditions. The wallboards were made of an aluminium honeycomb matrix and filled with 60% microencapsulated PCMs with paraffin as the core material. This simulation showed that even if the PCMs are frequently activated, on average they only utilized 45% of their total latent heat storage potential.

Diaconu [23] studied the influence of the occupancy pattern and ventilation may be affected by PCM enhanced envelopes. Through numerical simulations the potential for thermal energy savings for heating was investigated. It was clear that occupancy patterns and ventilation must be considered when attempting to select the optimal PCM melting temperature.

Ascione et al. [6] investigated the possibility of refurbishing a building with PCM plaster on the inner side of the exterior building envelope and the effect it would have on energy savings and indoor comfort in the cooling season. The results were simulated while varying the phase change temperature, thickness of the wallboard and the location of the PCM layer. Phase change temperatures ranging from 26 ^{o}C to 29 ^{o}C were tested. With a melting temperature of 29 ^{o}C the highest energy saving potential and increase in comfort hours were seen. However, the achievable benefit for energy savings in climates simulating Seville and Naples were no more than 3%, while Marseille and Athens received a benefit of 4.1 and 3.5% respectively. The highest energy saving effect was reached in Ankara, with energy savings of 7.2%. The comfort hours during the occupied hours increased by 15.5% (Seville), 22.9% (Naples), 19.8% (Marseille), 15.8% (Athens) and 20.6% (Ankara).

Shilei et al. [103] tested the impact of PCM incorporated gypsum boards at winter climate conditions in the northeast of China. The experiment was performed on two similar rooms, one with PCM and one without PCMs. The PCM room showed that it could reduce the heat transfer to outdoor air and improve the thermal comfort. Furthermore, the possibility to reduce the scale of the heating equipment was shown.

A renovation project in the south of Lyon using PCM enhanced wallboards was monitored over a one year period by Kuznik et al. [66]. The room was compared to a room in the same building that was renovated without PCMs. The effect of the PCM showed through increased thermal comfort of the occupants due to air temperature and radiative effects. However, the PCMs seemed to be unable to utilize its latent heat storage capacity over several periods over the year due to excessive temperatures and the lack of a complete discharge overnight.

Becker [15] investigated how thermal and energy performance of a building would be affected by placing PCMs on the inner surface of the walls during summer conditions. By using EnergyPlus and a simplified model the thickness of the PCMs needed to store heat gains from solar radiation and occupancy patterns occurring during the day, and ventilation needed by night to discharge they system were studied for lightweight buildings, semi-lightweight buildings and heavyweight buildings in a Mediterranean climate. In heavyweight constructions, PCMs could improve thermal conditions, but had a marginal effect on energy savings. For lightweight dwellings and offices and semi-lightweight schools the analyses showed positive effects on both thermal and energy performance. The greatest effect was seen in lightweight office buildings, where energy savings up to 57% were found. However, this study also pointed out the importance of occupancy patterns and the focus on including night ventilation needed for discharging when studying PCMs. It is still important to get full-scale validation in occupied buildings under normal working and climate conditions.

4.3.2 Floors

Areas which are in direct contact with solar radiation hold large potential for storage of thermal heat energy. Floor solutions incorporating PCMs in areas of a building where the sun shines for large parts of the day may benefit from incorporating PCMs. Figure 9 shows flat profiles filled with PCMs that were used in the floor in North House, a competitor in the US Department of Energy's solar decathlon.

Figure 9 Flat profiles which can be installed under floor to store and release latent thermal heat energy (Cosella-Dörken [21]).

Xu et al. [117] performed a simulation on the thermal performance of PCMs used in a passive floor system during the winter season. The performance on the systems was influenced by the choice of covering material, the air gap between the PCM and covering material and the thickness of the PCM. For the simulations performed, the thickness should not exceed 20 mm as this would not increase the influence of the thermal storage significantly.

4.3.3 Roofs

Implementing PCMs into roof systems does not seem to have received much attention. Only a few studies on the possible effects of PCMs in passive roof systems have been found. The thought is that PCMs placed on the roof will be able to absorb the incoming solar energy and the thermal energy from the surroundings to reduce temperature fluctuations on the inside.

Pasupathy and Velraj [80] studied the effects of a double layer of PCM for year round thermal management in Chennai, India. An experiment was performed with a PCM roof panel compared to a reference room without the PCM panel. The PCM used was an inorganic eutectic of hydrated salts. The experiment showed that the PCM panel on the roof narrowed the indoor air temperature swings, and that such a system could perform during all seasons when the top panel had a melting temperature 6-7 ^{o}C higher than the ambient temperature in the early morning during the peak summer month, and the bottom panel had a melting temperature near the suggested indoor temperature.

Kosny et al. [60] set up a naturally ventilated roof with a PV module and PCMs to work as a heat sink (Fig.10). The goal was that the PCM would absorb heat during the day in winter and release it in the night to reduce cooling loads. In the summer the PCM would absorb heat to reduce the cooling loads in the attic beneath. A full scale experiment was performed over a whole year from November 2009 until October 2010 in Oak Ridge, Tennessee. The data from the tests were compared with a conventional asphalt shingle roof. The PV-PCM attic showed a 30% reduction in heating loads during the winter and a 55% reduction in cooling loads. Furthermore, 90% reduction in peak daytime roof heat fluxes were observed.

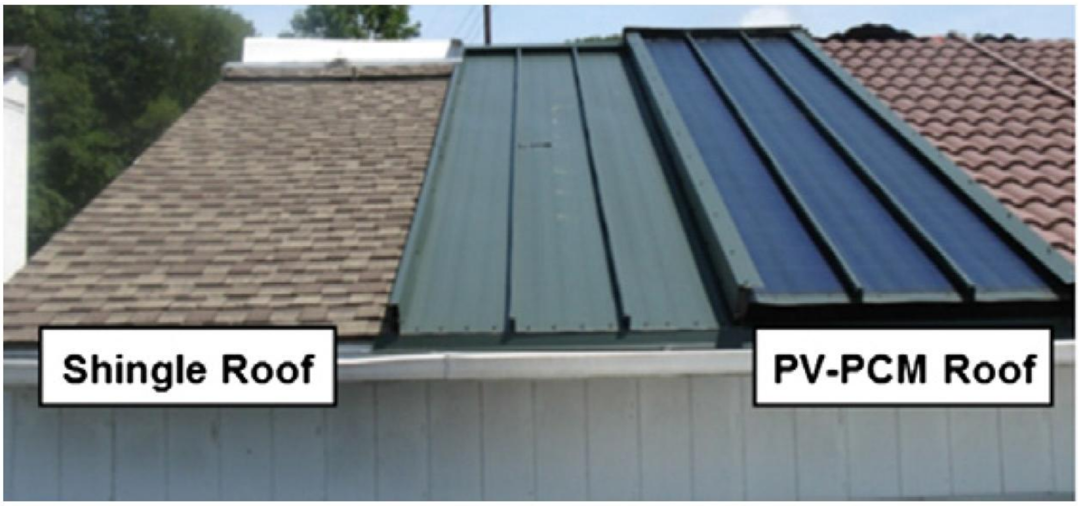

Figure 10 PV-PCM roof (Kosny et al. [60]).

4.3.4 Windows and shutters

Windows represent a part of the building that is considered to lead to a higher energy consumption. In warm climates dominated by cooling loads, excessive solar heat gain lead to an increased need for mechanical cooling. In cold climates, large parts of the energy escapes through glazed facades, leading to a need for mechanical heating (Ismail et al. [34]). Several new advanced window technologies such as electrochromic windows, low-e glazing, evacuated glazing, self-cleaning glazing, building integrated photovoltaics (BIPV) as solar glazing, etc., have been explored to counter these issues (Baetens et al. [11], Jelle et al. [36], Jelle et al. [37], Jelle and Hagen [38], Jelle et al. [39], Jelle and Hagen [40], Jelle et al. [41], Jelle et al. [44], Jelle et al. [45], Jelle and Breivik [46], Jelle and Breivik [47], Jelle [49], Jelle [50], Midtdal and Jelle [76]). However, glazed facades still suffer from low thermal inertia, and has no way of storing excess heat. Transparent PCMs for use in windows is an opportunity that has been explored for this purpose.

The first issue to overcome is the desire to have sufficiently transparent windows. Figure 11 shows a commercialized glazing filled with a PCM, also depicting the visibility in its liquid state. As of today, only translucent PCMs have been used for PCM windows, though they enable relatively high amounts of visible light to pass through, they do not offer the same visibility as regular windows.

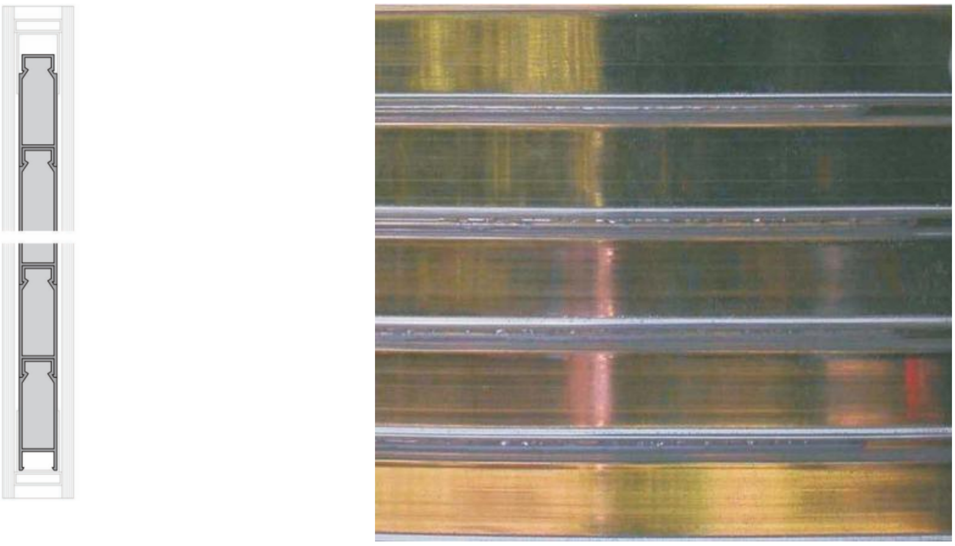

Figure 11 (Left) Illustration of a PCM filled window, (Right) Commercialized PCM window in its liquid stated (GlassX 2013).

The solar transmittance of a commercial grade PCM was tested by Jain and Sharma [35]. For a pure PCM with a thickness of 4 to 30 mm the solar transmittance was found to be 90.7 to 80.3% respectively. Due to the fact that PCMs have low thermal conductivity, they concluded that PCMs may be interesting as a transparent thermal insulating medium.

Goia et al. [29] compared a prototype PCM glazing system with a traditional double glazed insulating unit with regard to the effect on thermal comfort in the winter, summer and mid season. The two glazing systems were measured over a six-month experimental campaign, and this data was used to numerically evaluate an indoor office room. The thermal conditions were considerably improved for most parts of the year with the PCM prototype compared to the regular double glazing. However, on cloudy days, the two systems showed similar properties on thermal comfort. The study also highlighted the importance of selecting the correct melting temperature for the PCM as this could affect the system negatively if not optimized.

A similar study was performed by Weinläder et al. [116], comparing a double glazing unit combined with PCM compared to a regular double glazing unit. The test specimens were studied experimentally in an outdoor test facility and the data gained from the experiment was used for further simulations. The light transmittance from this solution was found to be 0.4, giving them the ability to be used as daylighting elements. Compared to regular double glazing they gave a more equalised energy balance, achieving moderate heat gains with very low heat losses. During the winter season, PCM windows improved the thermal comfort considerably and in the summer they shifted heat gains to later in the evening. However, the PCM windows can not be used where visual contact to the environment is desired.

Goia et al. [30] performed a full-scale test on a PCM glazing prototype. The test was performed on a south facing wall during summer, mid-season and winter days in a sub-continental climate and compared to a conventional double glazing for reference. The experiment showed that PCM glazing can reduce the energy gain in the summer by more than 50%. In the winter, heat loss reduction during the day was observed, however this technology might not be effective if the purpose is to achieve solar heat gains. The experiment also pointed out the importance of removing the stored heat during the night via, e.g. night cooling, and selecting the correct phase change temperature, if the system is to function optimally.

Grynning et al. [31] performed measurements on a state-of-the-art commercial glazing including a PCM in a large scale climate simulator. The tested glazing was a 4-layer glazing with a prismatic glass in the outer pane and a PCM fill in the cavity between the inner panes. The study showed that characterization of static components (e.g. U-value, solar heat gain coefficient, thermal transmittance) is insufficient for describing the performance of PCMs due to its dynamic nature.

A zero energy office building using translucent PCMs in the window construction has been built in Kempen, Switzerland (Fig.12). In this project, each second window panel has been equipped with PCM windows. The aim for the windows is to effectively store solar energy during the warmer parts of the day, and release thermal energy throughout the colder periods of the day to reduce the total energy required for space heating.

Figure 12 Zero energy office building from Kempen, Switzerland (Cosella-Dörken [22]).

Alawadhi [2] investigated the possibility to implement PCM in window shutters, where the goal was to see of the solar heat could be absorbed before it reached the indoor space. When compared to foam shutters, the shutters containing a PCM could lead to a reduction in heat gain through the windows by as much as 23.29%.

4.3.5 Concrete

Adding PCMs directly into concrete has shown some promising results through lower thermal conductivity and an increase in thermal mass at specific temperatures. However, PCM concrete has shown some undesirable properties such as lower strength, uncertain long-term stability and lower fire resistance (Ling et al. 2013). Several studies have been conducted on PCM-concrete and have shown positive effect through reduced indoor temperatures in warm climates (Cabeza et al. [16]).

Combining concrete structures with PCMs have been tried in several various ways. One studied solution is to drill holes in the concrete which may then be filled with a PCM (Alqallaf and Alawadhi [4]).

Royon et al. [89] tested the possibility of filling the already hollow areas in a hollow concrete floor with PCMs. The concrete was filled with a paraffin PCM with a melting temperature of 27.5 ^{o}C. This test showed that the temperature on the other side of the hollow concrete was lower during summer conditions. Hence, such floors can be used as a passive thermal conditioner during the summer. However, more tests are needed with real life climate conditions to validate the effects.

4.3.6 Thermal insulation materials

Recently, incorporation of PCMs into fibrous thermal insulation materials has received considerable attention. Kosny et al. [59] performed an experimental and numerical analysis of a wood-frame wall containing PCM enhanced fibre insulation. The wall assembly had an R-value of 4.14 (m^2K)/W (U-value of 0.241 W/(m^2K)). For fibre insulation filled with 30wt%

PCM in summer conditions, results showed a reduced peak hour heat gain of 23-37% in Marseille and 21-25% in Cairo and Warsaw.

4.3.7 Furniture and indoor appliances

A point that has not been investigated for this study, but should be mentioned, is the possibility of using PCMs in furniture and other indoor appliances. The benefit of PCMs is as mentioned its ability to store heat in periods where there is a surplus, and release it when there is a deficit. It would be interesting to study how incorporation of PCMs into other components in a building besides the structural components, could benefit energy savings and thermal comfort. PCMs have already been widely studied for textile applications (Sarier and Onder [95]), showing that there is a possibility of adding PCMs to various forms of materials.

4.4 Retrofitting

Building retrofitting is an important measure to reduce the total energy usage worldwide. PCMs may offer an increase in a building's overall energy efficiency with little or no additional space required (Rodriguez-Ubinas et al. [88]). The impacts on the design of the building can be minimalised through solutions such as PCM enhanced wallboards, PCM shutters etc.

4.5 Safety requirements

The safety requirements for materials used in buildings is a crucial point for the PCMs to fulfil. As mentioned earlier, PCMs should not be toxic or flammable. However, for many organic PCMs flammability and possible release of toxic fumes during combustion have been an issue. Solutions have been made to counter this issue, such as ignition resistant microcapsules for PCMs and the adding of fire retardants.

Hence, it is of significance that manufacturers of PCMs for building applications are required to give reliable information about the fire performance of their products. Nguyen et al. [78] reviewed the work that has been carried out to improve fire safety of PCMs. This work investigates the use of fire retardants to increase fire resistance of composite PCMs.

5 Future research opportunities

5.1 Improving the current technologies

5.1.1 Increasing thermal storage capacity

A desirable trait for PCMs is a high thermal storage per unit volume and unit weight. Hence, there is always a focus on finding new materials and solutions that may increase the thermal storage capacity for a given volume or weight of a PCM. However, as mentioned earlier, this should not come at the cost of using potentially environmental harmful materials and chemicals.

Microencapsulation reduces the risk of PCMs leaking from the material in their liquid state. Unfortunately, the encapsulation leads to a lower latent heat storage capacity. The method is a promising way for integrating PCMs with building materials, so finding new methods or materials to encapsulate with, which will give a better thermal storage capacity, is desirable. Possibilities to achieve this may include developing a thinner shell for the capsules, which will increase the weight percent of PCMs in the final products.

5.1.2 Enhancing heat transfer

A problem that has been addressed throughout the literature is the low thermal conductivity for many promising PCMs (around 0.15 - 0.2 W/(mK) for organic PCMs and around 0.5 W/(mK) for inorganic salts). Low thermal conductivity reduces the rate of heat absorption or heat release throughout the PCM, i.e. reducing the effectiveness at which it can store and release thermal energy. This may lead to a system which does not fully utilize the full latent heat storage of PCM materials. In the study conducted on wallboards under summer conditions by Evola et al. [26] they found that the wallboards tested only took advantage of about 45% of the possible latent heat storage. Note that this is affected by several other factors than thermal conductivity alone, such as local climacte conditions and the way the system is installed.

Fan and Khodadadi [27] reviewed methods that have been used to enhance the thermal conductivity for the last few decades. Recently, graphite based PCM systems and metal foams have been getting increased attention.

One solution that has been investigated includes adding of a material with a high thermal conductivity to the PCM. A material that has been investigated for this purpose is various carbon-based nano-fillers (Babaei et al. [7], Ji et al. [52], Yu et al. [118]). Though the results are varying, the increase in thermal conductivity has increased between 65 and 336% in these studies.

Another solution is to add the PCM to a material with a porous structure and a high thermal conductivity (Fig.13). Investigations on graphite foam composites (Sedeh and Khodadadi [98], Zhong et al. [122], Song et al. [110]) and metal foams based on aluminium (Jiang et al. [53]) have been conducted. Graphite foam composites have shown potential for creating a structure with high thermal conductivity (ranging from 230-570 times higher than the original PCM).

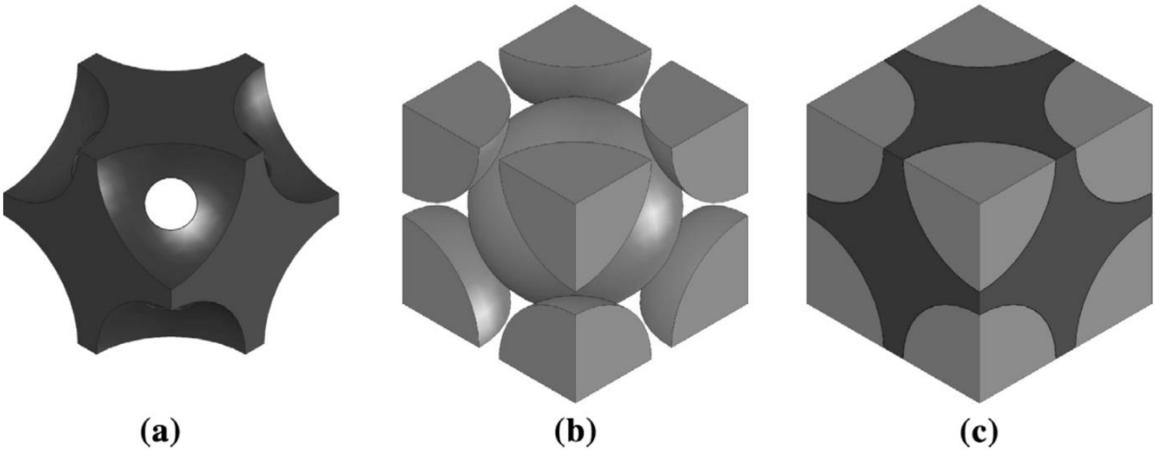

Figure 13 Illustration of (a) graphite foam, (b) PCM material, (c) graphite foam and PCM composite (Sedeh and Khodadadi [98]).

Note that adding a new material to the PCM and creating a composite material reduces the total latent heat storage ability per unit weight due to the adding of new particles. The energy uptake and release of the system may improve, but as of yet, this comes at the cost of less thermal heat storage per unit weight.

5.2 New technologies

5.2.1 Nanoencapsulated PCMs

Though it has not yet been used in commercial products, nanoencapsulation of PCMs may have a potential to improve PCM materials. The idea is similar to that of microencapsulation, but with even smaller capsules ranging in the size of nanometres. A smaller size of the capsules could be interesting due to a higher heat transfer area, leading to a higher heat transfer speed. Several studies have been performed and given functional nanocapsules with PCMs.

Chen et al. [19] prepared nanocapsules containing *n*-dodecanol by miniemuslion polymerization. These capsules reached a latent heat capacity of 98.8 J/g.

Rao et al. [84] performed a simulation on nanocapsules by using *n*-octadecane as the core material and SiO_2 as the shell material. This study pointed out that the possibilities of creating excessive thick or thin shells might be problematic for the current nanocapsules.

Latibari et al. [69] created nanocapsules containing palmitic acid as the core material and SiO_2 as the shell material by a sol-gel method. The latent heat was measured by a differential scanning calorimeter (DSC) analysis and was found to be 180.91 kJ/kg when melting and 181.22 kJ/kg when freezing.

Nanoencapsulation is still a novel technology. However, it would be interesting to see how the nanocapsules perform in comparison to microcapsules when integrated into building materials. Both with regards to energy usage and structural stability in materials such as concrete. An issue that has not been discussed in the studies found is how nanocapsules will compare with respect to overall cost.

5.2.2 Adjustable phase change temperature

Through most of the studies investigated in this review it is clear that the phase change temperature is one of the most important criteria for optimising a PCM system. It is also clear that the optimal phase change temperature for summer conditions will not be optimal for winter conditions and vice versa. Some systems have been described where PCMs of different phase change temperatures are used to partly counter this issue. These systems work by adding different layers of PCMs with different phase change temperatures that can work optimally at different temperatures (Jin and Zhang [54], Pasupathy and Velraj [80]). However, if this could be taken a step further, and a system with an adjustable phase change temperature could be created, the efficiency could be significantly improved. This could either be performed through a controllable or adaptive system and would enable a dynamic change of the phase change temperature in response to user preferences, different climates and different seasons.

5.3 Further reflections

5.3.1 Developing a standard test scheme

With more and more commercial PCM products reaching the market, properties relevant for their use in constructions have to be identified and tested. Mehling et al. [74] showed that PCMs cannot be measured accurately enough by using standards that have been developed for other materials. These tests do not fully map all relevant effects around the phase change process due to PCMs' low thermal conductivity and large melting enthalpy. This leads to an error in the stored heat as a function of temperature and may give errors that can not be tolerated when evaluating the application of PCMs.

It has been pointed out that there is a lack of common test methods to compare and model the results of various PCMs (Agyenim et al. [1], Shrestha et al. [105]). This makes it difficult to assess the suitability for each individual application. Accurate knowledge of a PCM's enthalpy as a function of temperature or storage capacity at each temperature is important for design purposes (Lázaro et al. [70]).

Kousksou et al. [62] reviewed the applications and challenges for energy storage systems, including PCMs. From this study it was found that there were still discrepancies between the literature and actual measurements of thermophysical properties of technical grade PCMs. Thus, further proving that a uniform test standard is needed.

It is important to note that the values measured for pure PCM compounds will not be representative when they are integrated into buildings. Adding encapsulation materials and combination with building materials will alter the response of the PCMs. It is therefore of importance that finished products aimed for the use in buildings are tested properly. Having a standard test scheme will also be beneficial for future work within field testing of PCMs as all values can be compared with respect to the same conditions.

There are still many issues regarding correct modelling of PCM behaviour. Some of these issues include:
- Properly representing PCM subcooling.
- Incorrect DSC data for whole building simulations.
- Non-uniform PCMs can not be tested in DSC.
- Need for development of Δ-enthalpy charts for PCM-enhanced materials.

Subcooling, which is a common problem for PCMs based on salt hydrates, is still an effect which can not be treated analytically or numerically. If salt hydrate PCMs become widespread, this is an effect that can have major effect on a system's performance, even at just 1 or 2 ^{o}C of subcooling (Mehling et al. [75]).

The most common test methods used for evaluating the performance of PCMs to date are mentioned in the following. Further research into these methods may give a method that can be used as a common standard for testing PCMs in the future.

5.3.2 Differential scanning calorimeter (DSC)

Currently, DSC is the most used method to determine a PCMs thermophysical properties (Barreneche et al. [13]). DSC can only be used for testing small samples of PCMs. Through DSC it is possible to obtain melting temperatures and the heat of fusion. For this purpose, DSC is the most used method. However, for small samples, the degree of supercooling may be increased while the degree of phase segregation may be decreased, giving a different results from actual use of the bulk materials used in practical systems (Zhang and Jiang [121]). DSC can only be performed on relatively uniform test specimens, which is not very realistic when testing building envelope products (Kosny et al. [59]).

5.3.3 T-history

The T-history method allows for testing of the melting temperature, degree of supercooling, heat of fusion, specific heat and thermal conductivity of several PCMs simultaneously (Zhang and Jiang [121]).

Solé et al. [109] wrote a review on the T-history method as it has been used to test PCMs up until recently. The aim of their study was to increase the consensus around the use of this method as it has several advantages when measuring PCMs. The T-history method is efficient at determining fusion enthalpy, specific heat and thermal conductivity for large PCM samples. Nevertheless, there is still no commercial T-history equipment available yet.

5.3.4 Dynamic heat flow apparatus method

The dynamic heat flow apparatus method is based on the traditional heat flow meter apparatus method, which is used to determine steady-state heat transfer properties, thermal conductivity and thermal resistance of flat slab specimens. The traditional heat flow apparatus method is already used in accordance with standards such as EN 12667, ISO 8301 and ASTM C518 to determine these properties for traditional insulation materials. When performing a dynamic heat flow test, the plates on each side of the specimen to be tested are held at the same temperature, and both plates are changed to a different temperature, whereas different temperatures are used in normal heat flow tests. By using the dynamic method, results were found to be more accurate when testing PCMs. Dynamic properties such as heat capacity profiles, peaks of melting and solidification cycles and amount of sub-cooling were found to be relatively similar to those measured by DSC (Shukla et al. [107]).

5.3.5 Dynamic hot box method

The dynamic hot box method can be used to simulate changes in temperature on the climate side of a test specimen. From this, the dynamic thermal characteristics of a building component can be found. When testing PCMs it is important to get as correct picture as possible of their dynamic properties. With the dynamic hot box, the temperature is held constant until a steady-state is reached, then the temperature on one side is changed and results are measured until a new steady-state has been reached.

5.3.6 Dynamic guarded hot plate method

A study recently performed by Pomianowski et al. [83] investigated the possibility of using a dynamic guarded hot plate apparatus to determine the specific heat capacity as a function of the temperature for PCM incorporated concrete. The study describes the experimental set-up and proposes various methods to calculate the specific heat capacity of PCM concrete. The advantage of this method is the possibility to attain a very small heating rate, which can imitate the temperature increase in real building constructions. Thus, simulating realistic thermal conditions of the PCM in actual use. Though the study focuses on PCM concrete, it is also pointed out that this experimental set-up could also be used on various other PCM composites.

5.3.7 M-value

Phase change materials are added to structures and lead to an increase in thermal mass. As PCMs have a specific temperature range, they have also been referred to as "smart thermal mass". However, the phase change temperature of a PCM is not always absolute. It may happen over a small temperature interval and differ between melting and freezing (Fig.14). This is a cause for confusion as there is no standard which specifies in which part of the phase change process this value should be stated. A new energy performance label for PCMs has been mentioned. The M-value, which should express the phase transition related enthalpy change of the PCM within a standardised range so that all values given for a PCM can be evaluated on an equal basis.

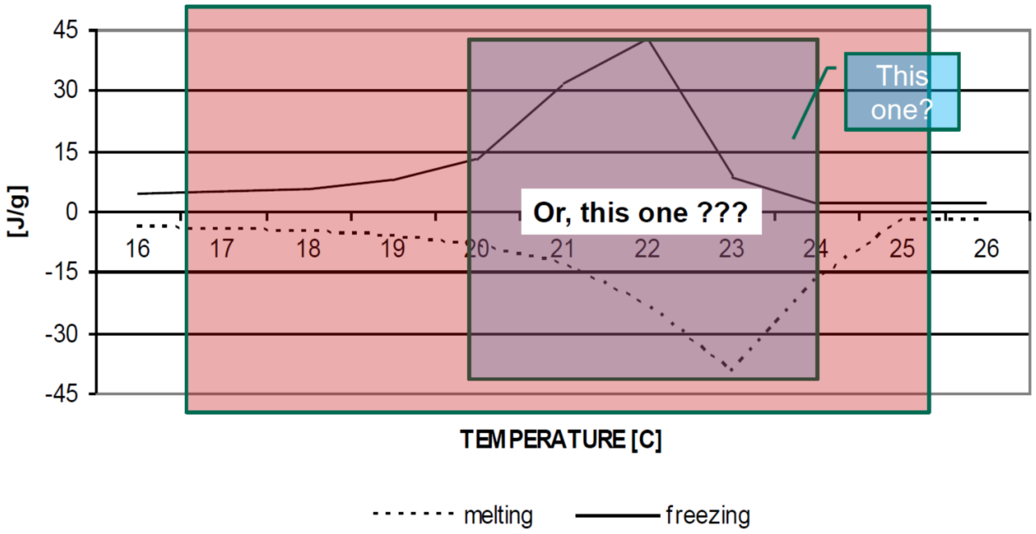

Figure 14 The current confusion around the correct enthalpy value for phase change (Kosny [58]).

5.3.8 Environmental impact assessments

New materials that may be suitable for use as PCMs are continuously being investigated. As mentioned earlier, it is critical that PCMs for use in buildings are not hazardous or poisonous in any ways. This also includes during production and handling after a PCM's useful lifetime. It is important that possible new materials are evaluated with regards to waste from the production and necessary treatment when they are to be disposed. As there may be many different chemicals in use in PCMs, environmental assessments could be conducted to avoid unknown pollutants of any kind.

5.3.9 Expected lifetime predicament of phase change materials

As a thawing/freezing cycle may happen thousands of times, some phase change materials may be prone to deterioration over time. Gradual breakdown of the material will end up reducing the amount of latent heat storage per phase transition and may also affect the phase change temperature. Thus, reducing the overall energy performance. Such deterioration is particularly common in inorganic PCMs, and to some extent in less pure organic PCMs. It is important that future possible PCMs are tested with regard to their ageing over time. As of today there is no standard method to do this. An aim for the future should be to develop a standard testing scheme which all commercial grade PCMs will have to follow when stating the lifetime of their products.

5.3.10 Quantifying the effect of PCMs in real life buildings

Though the theory behind PCMs shows that they have the ability to reduce temperature fluctuations in buildings, there has been no studies to prove an increase in overall thermal comfort or productivity. Some way of measuring the effect and number of full cycles in different environments is needed.

To fully utilize the effect of PCMs an overview of how they perform in different climates are needed. Ideally, a PCM should undergo a full phase change cycle once a day. However, the lack of guidelines for selecting PCMs for various climates is a source for uncertainty when used for building applications. It would be preferable, if a detailed overview of the effect that could be expected for various PCMs in various climates was developed. It has been pointed out that it is difficult to select a PCM that functions optimally for every season and location.

From all the experiments and simulations reviewed in this study, one of the most important factors for implementing PCM enhanced materials is found to be selecting the correct phase change temperature. They also highlight the difficulty of selecting the correct PCM for specific climates and that the effect of PCMs will vary with varying climate conditions over the year.

The selection of a PCM based on a specific phase change temperature in one climate region will not be appropriate for another. Important factors that govern the selection of a PCM includes phase change temperature, local climate, type of PCM and design and orientation of the building (Pasupathy and Velraj [80]). Several other authors have also highlighted the need for guidelines to select PCMs for specific and different climates (Kosny et al. [61], Ascione et al. [6]).

From the various manufacturers that have been investigated in this study a large amount of reference projects have been found. However, to the authors knowledge, there has been no studies to evaluate and quantify the effect of PCMs in these projects. Although every project has been deemed to increase energy efficiency and thermal comfort, monitoring projects from real life buildings should be conducted and evaluated so the beneficial effects of PCMs can be documented and shared.

5.3.11 Investigating payback times for various systems

As PCMs offer a decrease in overall energy usage, in many cases through minimal interference with the original structure, it is highly relevant to know what the payback of the initial investment can be expected to be. To the authors' knowledge, little research has been carried out on this topic. This may come from several factors. The most important being that there is still a lack of knowledge on how PCMs actually perform in real life constructions in all sorts of various climates.

There is still much uncertainty regarding the overall effect of PCMs. Showing the long-term economical benefits of selecting PCMs may help to increase the interest among customers to use PCMs. Should the results of such analyses show unfavourable payback times, it may also help to drive the research and development forward towards more cost-efficient solutions.

Conclusions

Incorporating phase change materials (PCM) into a building enables a more dynamic use of energy. Due to the storage capabilities of PCMs, excess heat can be stored during warm periods and released during cold periods. It may also work the other way around, storing cold energy and using it for free cooling systems in warm periods. The benefits of using PCMs in buildings mainly revolve around a decrease in energy usage along with a peak load shifting of energy required for heating or cooling and an increase in thermal comfort by decreasing temperature fluctuations.

Commercial products have been developed and released on the market with some success. What makes PCMs particularly interesting is the fact that many PCM solutions, e.g. wallboards and floor tiles, can be added to the construction with fairly little alterations to the current way of building. However, there are a wide range of materials which can be used as PCMs and identifying the correct PCM for the specific application and for the specific climate conditions is an area which need further research. Calculations of payback periods for PCM installations are also needed to further validate the use of PCM technology.

Though solutions have been tested to increase thermal conductivity for more effective absorbance and discharge cycles, this has come at the cost of a lower latent heat storage per unit weight and unit volume i.e. and hence giving the PCMs less storage potential. Fire safety is still an issue for organic PCMs, though here as well, solutions which show promise have been introduced.

The PCM technology seems promising, however there are still some hurdles which need to be overcome for a large-scale application of this technology. Standards which state test methods and can help identify the correct PCMs for various climates to enable proper cycling and optimisation of PCM systems are needed. Research into new PCM technologies is also of major importance, e.g. the possibility of having a dynamically adjustable and even controllable phase change temperature.

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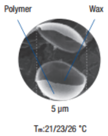
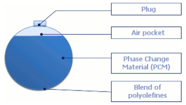
Appendix

Table A1 Manufacturers of PCM compounds.

Manufacturer	Product	Illustration	Phase change temperature (°C)	Latent heat capacity (kJ/kg)	Latent heat capacity (kJ/m^2)	Thermal conductivity (W/(mK))	Volume expansion (%)	Materials	Type	More info
BASF Tel: +49 (0)621 60-0 Fax: +49 (0)621 60-42525 www.basf.com/group/corporate/en/	DS 5000		26	45				Dispersed wax mixture	Organic	http://www.micronal.de/portal/basf/ien/dt.jsp?setCursor=1_290798 (Accessed 10.12.2013)
	DS5007		23	41				Dispersed wax mixture	Organic	
	DS 5030		21	37				Dispersed wax mixture	Organic	
	DS 5001		26	110				Wax mixture in powder form	Organic	
	DS 5008		23	100				Wax mixture in powder form	Organic	
	DS 5029		21	90				Wax mixture in powder form	Organic	
RGEES North America 1465 Sand Hill Road, Suite #2016, Candler, NC – 28715 Tel: +1 828 708 7178 info@rgees.com http://rgees.com/	PCM-OM21P		21	120				Organic chemicals	Organic	http://rgees.com/products.php (Accessed 10.12.2013)
	PCM-HS22P		22	185		0.54 liquid 1.09 solid		Inorganic salts	Inorganic	
	PCM-HS24P		24	185		0.54 liquid 1.09 solid		Inorganic salts	Inorganic	
	PCM-HS29P		29	190		0.54 liquid 1.09 solid		Mixture of $CaCl_2$ and other salts	Inorganic	
	PCM-OM32P		32	235				Organic chemicals	Organic	

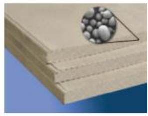
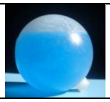
Manufacturer	Product	Illustration	Phase change temperature (°C)	Latent heat capacity (kJ/kg)	Latent heat capacity (kJ/m^2)	Thermal conductivity (W/(mK))	Volume expansion (%)	Materials	Type	More info
Phase change products Ground Floor 57 Havelock Street West Perth Western Australia 6005 Tel: +61 8 9324 8520 Fax: + 61 8 9324 8560 keith.coakley@pcpaustralia.com.au http://pcpaustralia.com.au/	PC14		14	145		0.010 "J/sec/cmK"		Hydrated calcium chloride and calcium bromide	Inorganic	http://pcpaustralia.com.au/pcm-range-products/pc14/ (Accessed 10.12.2013)
	PC17		17	145		0.010 "J/sec/cmK"		Hydrated calcium chloride and calcium bromide	Inorganic	http://pcpaustralia.com.au/pcm-range-products/pc17/ (Accessed 10.12.2013)
	PC25		25	150		0.011 "J/sec/cmK"		Hydrated calcium and magnesium and chlorides	Inorganic	http://pcpaustralia.com.au/pcm-range-products/pc25/ (Accessed 10.12.2013)
	PC29		29	188		0.011 "J/sec/cmK"		Hydrated calcium chloride	Inorganic	http://pcpaustralia.com.au/pcm-range-products/pc29/ (Accessed 10.12.2013)
Entropy Solutions Inc. 151 Cheshire Lane, Suite 400, Plymouth MN 55441 Tel: +1 952-941-0306 Fax: +1 952-944-6893 info@puretemp.com www.puretemp.com	PureTemp 15		15	165				Vegetable based	Organic	http://www.puretemp.com/technology.html (Accessed 10.12.2013)
	PureTemp 18		18	189				Vegetable based	Organic	
	PureTemp 20		20	180				Vegetable based	Organic	
	PureTemp 23		23	203				Vegetable based	Organic	
	PureTemp 24		24	185				Vegetable based	Organic	
	PureTemp 25		25	185				Vegetable based	Organic	
	PureTemp 27		27	200				Vegetable based	Organic	
	PureTemp 28		29	205				Vegetable based	Organic	
	PureTemp 29		29	189				Vegetable based	Organic	
	PureTemp 31		31					Vegetable based	Organic	

Manufacturer	Product	Illustration	Phase change temperature (°C)	Latent heat capacity (kJ/kg)	Latent heat capacity (kJ/m^2)	Thermal conductivity (W/(mK))	Volume expansion (%)	Materials	Type	More info
Salca www.salcabv.nl	Thermusol HD26		26					Salt-crystals	Inorganic	http://www.salcabv.nl/index.asp?CategorieID=2&Taal=EN (Accessed 10.12.2013)
	Thermusol HD32		32	150				Salt hydrate	Inorganic	
Climator Sweden AB Norregårdsvägen 18 SE-541 34 Skövde Tel: +46 (0)500 48 23 50 climator@climator.com www.climator.com	ClimSel C21		21		43 Wh/Litre	0.5-0.7		Sodium sulphate	Inorganic	http://www.climator.com/en/climsel/ (Accessed 10.12.2013)
	ClimSel C24		24		58 Wh/Litre	0.5-0.7		Sodium sulphate	Inorganic	
	ClimSel C28		28		64 Wh/Litre	0.5-0.7		Sodium sulphate	Inorganic	
	ClimSel C32		32		64 Wh/Litre	0.5-0.7		Sodium sulphate	Inorganic	
Phase Change Material Products Limited Unit 32, Mere View Industrial Estate, Yaxley, Cambridgeshire PE7 3HS United Kingdom Tel: +44 -(0)-1733-245511 Fax: +44 -(0)-1733-243344 info@pcmproducts.net www.pcmproducts.net	S15		15	160		0.43		Salt hydrate	Inorganic	http://www.pcmproducts.net/Salt_Hydrate_PCMs.htm (Accessed 10.12.2013)
	S17		17	160		0.43		Salt hydrate	Inorganic	
	S19		19	160		0.43		Salt hydrate	Inorganic	
	S21		22	170		0.54		Salt hydrate	Inorganic	
	S23		23	175		0.54		Salt hydrate	Inorganic	
	S25		25	180		0.54		Salt hydrate	Inorganic	
	S27		27	183		0.54		Salt hydrate	Inorganic	
	S30		30	190		0.48		Salt hydrate	Inorganic	
	S32		32	200		0.51		Salt hydrate	Inorganic	
	A15		15	130		0.18			Organic	http://www.pcmproducts.net/Organic_Positive_Temperature_PCMs.htm (Accessed 10.12.2013)
	A16		16	213		0.18			Organic	
	A17		17	150		0.18			Organic	
	A22		22	145		0.18			Organic	
	A22H		22	216		0.18			Organic	
	A23		23	145		0.18			Organic	
	A24		24	145		0.18			Organic	
	A25		25	150		0.18			Organic	
	A25H		25	226		0.18			Organic	
	A26		26	150		0.21			Organic	
	A28		28	155		0.21			Organic	
	A29		29	226		0.18			Organic	
	A32		32	130		0.21			Organic	
	X25		25	110		0.36				http://www.pcmproducts.net/Solid_Solid_PCMs.htm Solid-solid (Accessed 10.12.2013)
	X30		30	105		0.36				

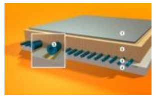
Manufacturer	Product	Illustration	Phase change temperature (°C)	Latent heat capacity (kJ/kg)	Latent heat capacity (kJ/m^2)	Thermal conductivity (W/(mK))	Volume expansion (%)	Materials	Type	More info
PCM Energy P. Ltd Mazgaon, Mumbai 400 010, India Tel: +91-22-23770100 Fax: +91-22-23728264 anmol@pcmenergy.com http://pcmenergy.com	Latest 18T		17-19	175		1		Inorganic salts	Inorganic	http://pcmenergy.com/products.htm (Accessed 10.12.2013)
	Latest 20T		19-20	175		1		Inorganic salts	Inorganic	
	Latest 25T		24-26	175		1		Inorganic salts	Inorganic	
	Latest 29T		28-30	175		1		Inorganic salts	Inorganic	
	Latest 32S		31-32	>200		0.6		Inorganic salts		
Microtek Laboratories, Inc. 2400 E. River Rd. Dayton, OH 45439 Tel: +1 937.236.2213 Fax: +1 937.236.2217 microtek@microteklabs.com www.microteklabs.com	MPCM 18		18	163-173				n-Hexadecane	Organic	http://www.microteklabs.com/micropcm_products.html (Accessed 10.12.2013)
	MPCM 18D		18	163-173				n-Hexadecane	Organic	
	MPCM 24		24					Special blend		
	MPCM 24D		24					Special blend		
	MPCM 28		28	180-195				n-Octadecane	Organic	
	MPCM 28D		28	180-195				n-Octadecane	Organic	
	MPCM28D-IR		25-32	160-180				Special blend		
	MPCM 32		32					Special blend		
	MPCM 32D		32					Special blend		
Cristopia Energy Systems info@cristopia.com www.cristopia.com	AC.27		27							http://www.cristopia.com/cristopia/english/products/indproducts.html (Accessed 10.12.2013)
Rubitherm Technologies GmbH Sperenberger Str. 5a D-12277 Berlin Tel: +49 30 720 004 62 Fax: +49 30 720 004 99 info@runitherm.com http://rubitherm.com	RT 18 HC		18	250		0.2	12.5			http://rubitherm.com/english/index.htm (Accessed 10.12.2013)
	RT 21		21	160		0.2	12.5			
	RT 21 HC		21	190		0.2	14			
	RT 22 HC		22	200		0.2	12.5			
	RT 24		24	150		0.2	12.5			
	RT 25		25	148		0.2	14			
	RT 25 HC		25	230		0.2	12.5			
	RT 27		27	179		0.2	12.5			
	RT 28 HC		28	245		0.2	12.5			
	RT 31		31	170		0.2	12.5			

Manufacturer	Product	Illustration	Phase change temperature (^{o}C)	Latent heat capacity (kJ/kg)	Latent heat capacity (kJ/m^2)	Thermal conductivity (W/(mK))	Volume expansion (%)	Materials	Type	More info
Rubitherm Technologies GmbH Sperenberger Str. 5a D-12277 Berlin Tel: +49 30 720 004 62 Fax: +49 30 720 004 99 info@runitherm.com http://rubitherm.com	SP 21 E		21-23	160		0.6	3-4	Inorganic components		http://rubitherm.com/english/pages/02f_latent_heat_blend.htm (Accessed 10.12.2013)
	SP 22 E		22-23	180		0.6	3-4	Inorganic components		
	SP 24 E		24-25	222		0.6	3-4	Inorganic components		
	SP 25 E		24-26	200		0.6	3-4	Inorganic components		
	SP 26 E		25-27	200		0.6	3-4	Inorganic components		
	SP 31		31-33	240		0.6	3-4	Inorganic components		
	PX 15		10-17	85		0.2				http://rubitherm.com/english/index.htm (Accessed 10.12.2013)
	PX 25		22-25	96		0.1				
	PX 27		25-28	102		0.2				
	PX 31		27-31	110		0.1				

Table A2 Manufacturers of PCM enhanced products for building applications.

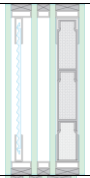
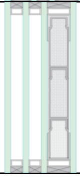
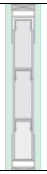
Manufacturer	Product	Illustration	Phase change temperature (^{o}C)	Latent heat capacity (kJ/kg)	Latent heat capacity (kJ/m^2)	Thermal conductivity (W/(mK))	Volume expansion (%)	Materials	Type	More info
Dupont Tel: + 352 3666 5772 www.dupont.com	Energain		18-24		515			Paraffin wax	Organic	http://energain.co.uk/Energain/en_GB/index.html (Accessed 10.12.2013)
Knauf AG Kägenstrasse 17 CH- 4153 Reinach Tel: +41 58 77 58 800 Fax: +41 58 77 58 801 info@knauf.ch www.knauf.ch	Comfort board		23		200	0.23		BASF micronal	Organic	http://www.knauf.ch/files/produkts/K763_ch_0213_ger_screen.pdf (Accessed 10.12.2013)
	Smartboard 23		23		330	0.20				http://vanoncinicommerciale.it/schede_tecniche/Knauf/Lastre%20ok/Smartboard%20PCM%20K764_10_2008_EN.pdf (Accessed 10.12.2013)
	Smartboard 26		26		330	0.20				
RGEES North America 1465 Sand Hill Road, Suite #2016, Candler, NC – 28715 Tel: +1.828.708.7178 info@rgees.com http://rgees.com/	PB29P		29		33 kWh/cbm				Organic	http://rgees.com/products_pcm-ball.php (Accessed 10.12.2013)
	PB22P		22		0.1 kWh/(ft^2)				Inorganic	http://rgees.com/products_pcm-pipe.php (Accessed 10.12.2013)
	PB24P		24		0.1 kWh/(ft^2)				Inorganic	
	PB29P		29		0.1 kWh/(ft^2)				Inorganic	
Phase Change Energy Soutions 120 E Pritchard St., Asheboro, North Carolina, 27203 USA Tel: +1 800 283-7887 info@phasechange.com www.phasechange.com	BioPCmat M27		23					Bio-based	Organic	http://www.phasechange.com/index.php/en/standard-products/biopcmat (Accessed 10.12.2013)
	BioPCmat M51		25					Bio-based	Organic	
	BioPCmat M91		27					Bio-based	Organic	
	ThermaStix							Bio-based	Organic	http://www.phasechange.com/index.php/en/standard-products/therma-stix (Accessed 10.12.2013)

Manufacturer	Product	Illustration	Phase change temperature (^{o}C)	Latent heat capacity (kJ/kg)	Latent heat capacity (kJ/m^{2})	Thermal conductivity (W/(mK))	Volume expansion (%)	Materials	Type	More info
Dörken GmbH & Co. KG Wetterstraße 58 D-58313 Herdecke Tel: +49 23 30/63-0 Fax: +49 23 30/63-355 bvf@doerken.de www.doerken.de	Delta-cool 24									No longer available on the market?
	Delta-cool 28									No longer available on the market?
Salca BV Koggelsteeg 2, NL-7631 AH Ootmarsum Tel: +31 (0)541 291143 Fax: +31 (0)541 291175 infor@salcabv.nl www.salcabv.nl	K-Block				590			Salt hydrate	Inorganic	http://www.salcabv.nl/index.asp?CategorieID=5&Taal=EN (Accessed 10.12.2013)
SGL Group www.ecophit.com	Ecophit GC20		22	85		2-5	5-10			http://www.sglgroup.com/cms/_common/downloads/products/product-groups/eg/construction-materials-ecophit/ECOPHIT_GC_LC_e.pdf (Acessed 19.12.2013)
	Ecophit LC20		22	140		5-20	5-10			
Phase Change Material Products Limited Unit 32, Mere View Industrial Estate, Yaxley, Cambridgeshire PE7 3HS United Kingdom Tel: +44 -(0)-1733-245511 Fax: +44 -(0)-1733-243344 info@pcmproducts.net www.pcmproducts.net	FlatICE									Filled with various of their own PCMs listed in Table A1. http://www.pcmproducts.net/Encapsulated_PCMs.htm (Accessed 19.12.2013)
	TubeICE									
	BallICE									
National gypsum 2001 Rexford Road, Charlotte, NC 28211 Tel: +1 704-365-7300 ng@nationalgypsum.com www.thermalcore.info/	ThermalCORE		73^{o} F		22 Btu/(ft^{2})			BASF micronal		http://www.thermalcore.info/tech-specifications.htm (Accessed 10.12.2013)

Manufacturer	Product	Illustration	Phase change temperature (°C)	Latent heat capacity (kJ/kg)	Latent heat capacity (kJ/m^2)	Thermal conductivity (W/(mK))	Volume expansion (%)	Materials	Type	More info
H+H Deutschland GmbH Industriestr. 3 23829 Wittenborn Tel: +49 4554 7000 Fax: +49 4554 700223 www.hplush.de/home	CelBloc Plus							BASF micronal		No longer available on the market?
Maxit Deutschland GmbH	Maxit clima							BASF micronal		No longer available on the market?
Ilkazell Isoliertechnik GmbH Talstraße 17 08066 Zwickau/Germany PF 20 05 34 08005 Zwickau/Germany Tel: +49 03 75 / 43034 -0 Fax: +49 03 75 /43034 -33 mail@ilkazell.de www.ilkazell.de	Ilkatherm air conditioning systems							BASF micronal		http://www.ilkazell.de/en/climate-systems/ilkatherm-ceiling-and-wall.html (Accessed 08.01.2014)
Emco Bau- und Klimatechnik GmbH & Co. KG Post box: 1860 49803 Lingen (Ems) Germany Tel: +49 (0) 591 9140-0 Fax: +49 (0) 591 9140-851 klima(at)emco.de www.emco-klima.com	Emcovent									http://www.emco-klima.com/de-en/products/emcovent/pcm-systems.html (Accessed 05.01.2014)
Monodraught Ltd Halifax House Cressex Business Park High Wycombe Bucks HP12 3SE United Kingdom +44 (0)1494 897700 info@monodraught.com www.cool-phase.net/	Coolphase									http://www.cool-phase.net/ (Accessed 05.01.2014)

Manufacturer	Product	Illustration	Phase change temperature (^{o}C)	Latent heat capacity (kJ/kg)	Latent heat capacity (kJ/m^2)	Thermal conductivity (W/(mK))	Volume expansion (%)	Materials	Type	More info
Tate 7510 Montevideo Road Jessup, MD 20794 Tel: +1 (800) 231-7788 Fax: +1 (410) 799-4207 tateinfo@tateinc.com www.tateinc.com	EcoCore 60cm		75.2 ^{o}F	147 Btu				Vegetable bio based	Organic	http://www.tateinc.com/products/ecocore.aspx (Accessed 08.01.2014)
Autarkis BV Ondernemersweg 2 7451 PK HOLTEN (NL) Tel: +31 (0)548 - 374 374 Fax: +31 (0)548 - 364 165 info@autarkis.nl http://www.autarkis.nl/en										Offers various systems incorporating PCMs, however no specific product information can be found on the website http://www.autarkis.nl/en (Accessed 07.01.2014)
Armstrong World Industries Ltd. Armstrong House, 38 Market Square, Uxbridge, UB8 1NG, United Kingdom Tel: +44 0800 371849 Fax: +44 1895 274287 www.armstrong.co.uk	CoolZone				136.2 Wh/m^2			BASF micronal	Organic	http://www.armstrong.co.uk/content2/commclgeu/files/71629.pdf (Accessed 06.01.2014)
Trox GmbH Heinrich-Trox-Platz D-47504 Neukirchen-Vluyn Germany Tel: +49(0)28 45 / 202-0 Fax: +49(0)28 45 / 202-265 e-mail trox@trox.de www.troxtechnik.com	FSL-B-PCM									http://www.troxtechnik.com/en/products/air_water_systems/facade_ventilation_units/under_sill_units/fsl-b-pcm/index.html (Accessed 10.01.2014)

Table A3 Manufacturers of PCM windows.

Manufacturer	Product	Illustration	Phase change temperature (°C)	Latent heat capacity (kJ/kg)	Heat storage capacity (Wh/m^2)	Light transmission of PCM solid/liquid (%)	Solar heat gain coefficient solid/liquid	Materials	Type	More info
GLASSX Tel: 778.285.8530 Fax: 778.285.8520 www.glassxpcm.com	GLASSX crystal		26-30		1185	0-28/4-45		Salt hydrate	Inorganic	http://www.glassxpcm.com/products/ (Accessed 15.12.2013)
	GLASSX comfort		26-30		1185	0-38/4-55		Salt hydrate	Inorganic	
	GLASSX comfort "slim"		26-30		1185	0-38/4-45		Salt hydrate	Inorganic	
	GLASSX comfort "store"		26-30		1185	0-38/4-55		Salt hydrate	Inorganic	

Article 3:

S.E Kalnæs and B.P. Jelle,
"Vacuum Insulation Panel Products:
A State-of-the-Art Review and Future Research Pathways"

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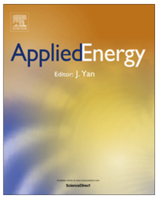

Vacuum insulation panel products: A state-of-the-art review and future research pathways

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HIGHLIGHTS

- State-of-the-art review of vacuum insulation panel products.
- Future research pathways for vacuum insulation panels.
- Vacuum insulation panel cores and envelopes.
- Vacuum insulation panel properties.
- Vacuum insulation panels for building applications.

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ABSTRACT

Vacuum insulation panels (VIP) are regarded as one of the most upcoming high performance thermal insulation solutions. At delivery, thermal conductivity for a VIP can be as low as 0.002–0.004 W/(mK) depending on the core material. VIPs enable highly insulated solutions, and a measure to reduce the energy usage in both hot-water applications, cold applications and for the construction industry in general. This study gives a state-of-the-art review of VIP products found available on the market today, and explore the future research opportunities for these products.

VIPs have been utilized with success for applications such as freezers and thermal packaging, and during the last decade they have also been used for building applications in increasing numbers, where one of the main driving forces is the increased focus on e.g. passive houses, zero energy buildings and zero emission buildings. Hence, VIPs are now in the early market stages as a building product. Implementation of VIPs in various building constructions have given an increased interest in the possibilities of this product, both in new and refurbished constructions. Even though there is not enough data to conclude the effect over a lifetime of a building yet, the immediate result in decreased energy usage can be seen. However, the problem of guaranteeing a set lifetime expectancy, along with high costs, are some of the major reasons why VIPs are met with scepticism in the building industry. Aiming to give better quality assurance for the users, make further advances in envelope technologies and the development of core materials, along with a further cost reduction, are crucial aspects for VIPs to become a competing thermal insulation solution for buildings.

Contents

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1. Introduction

The world today relies on a large amount of fossil fuels to produce energy. The continued use of fossil fuels will strain our resources, as well as lead to large amounts of pollution, especially through CO_2 emissions. The heating and cooling of buildings require a considerable amount of energy. A reduction in energy usage for the building sector will have a beneficial effect on CO_2 emissions. In the European Union buildings represent 40% of the total energy usage, and the existing building stock represents the single largest potential sector for energy savings [19]. By the principle of the Kyoto Pyramid, the most cost effective method of reducing energy usage is to provide better thermally insulated buildings.

To reach the demanded *U*-values with traditional insulation materials, buildings are required to have walls up to 50 cm thick. This leads to more complex building details and transportation of thicker materials to the building sites [28].

One of the most promising building insulation materials in its early stages of commercialization now, is vacuum insulation panels (VIP). VIPs have an insulation performance which normally ranges from 0.004 W/(mK) in pristine condition to typical 0.008 W/(mK) after 25 years of ageing. This is 5–10 times better, depending on ageing, than traditional insulation used in buildings today [28]. Therefore, VIPs enable highly insulated constructions for walls, roofs and floors, especially within refurbishing of older buildings where space is often limited. Integrating VIPs successfully into constructions requires careful planning with regard to its durability, the lack of flexibility, thermal bridging and lifetime expectations [60].

Especially the uncertainties around expected lifetime is a crucial factor for scepticism concerning VIPs. Research is being conducted on determining ways of interpreting in situ measurements and conduct reliable accelerated ageing tests. The need to better understand the mechanisms of ageing and general loss of thermal resistance over time has been mentioned by Simmler and Brunner

[57] and Baetens et al. [5]. Various forms of accelerated climate ageing tests have been described by Wegger et al. [69]. Quality assurance of VIPs is an important factor to promote the use of VIPs the building sector. It is important to be able to differentiate between panel damage as a consequence of production errors, and damages caused by ageing and service failure, which hence will help the technology improve further [13].

The objective of this study is to present an overview of the different VIP producers and products, and to evaluate the effect and durability of these products. Furthermore, it is important to know how VIPs are tested with respect to lifetime performance in building applications. These investigations may help form guidelines for a new testing scheme and point to future research opportunities. That is, this state-of-the-art VIP review builds on already existing VIP reviews, e.g. by Alam et al. [1], Baetens et al. [5], Jelle [28], Johansson [35], Tenpierik [60] and Wang et al. [68], and is extending these further by collecting and focusing on a comprehensive review of existing VIP manufacturers and products, as well as discussing future research pathways for VIPs.

This work presents many tables with a lot of information, e.g. manufacturers, product names and various properties, both in the main text and in the appendices. Some of these properties are crucial to the performance of the VIPs. The tables provide the readers with valuable information concerning VIPs. Unfortunately, it is currently hard to obtain all the desired information from all the manufacturers. In general, many of the desired property values are not available on the manufacturers' websites or other open information channels, which is hence seen as open spaces in the various tables. Hopefully, our addressing of these facts could act as an incentive for the manufacturers to state all the important properties of their products at their websites or other open information channels, and also as an incentive and reminder for the consumers and users to demand these values from the manufacturers.

2. Vacuum insulation panel (VIP) concepts

2.1. General

A VIP consists of a porous core enveloped by an air and vapour tight barrier, which is heat sealed. The core is of an open pore structure to allow all the air to evacuate, and create a vacuum. The envelope needs to be air and vapour tight for the panel to uphold its thermally insulating properties over time. Fig. 1 shows a normal schematic of a VIP. The initial pristine thermal conductivity of the core is normally around 0.004 W/(mK), however increasing with elapsed time due to air and moisture diffusion through the barrier envelope and into the core.

The thermal transport in a VIP may be divided as the following:

$$\lambda_{tot} = \lambda_{sol} + \lambda_{gas} + \lambda_{rad} + \lambda_{conv} + \lambda_{coup} \quad (1)$$

where λ_{sol} is the solid state thermal conductivity, λ_{gas} is the gas thermal conductivity, λ_{rad} is the radiation thermal conductivity, λ_{conv} is the convection thermal conductivity, and λ_{coup} is the thermal conductivity of coupling effects. Coupling accounts for second order effects between the various thermal conductivity terms, and is relevant for powder and fibre materials. This means that the total thermal conductivity will be larger than the sum of the four first terms in Eq. (1), due to interactions between them. The coupling effect has been described more closely by Heinemann [27]. Another view on the coupling term stems from the interaction between the gas molecules and the solid material in the pore walls. However, this last coupling term is often included as a factor when the gas conductivity is calculated by the Knudsen effect [28]. Coupling effects is a complex effect and is considered to be negligible in most theoretical approaches for the thermal performance of VIPs [69]. Conventional insulation can never aim to achieve a thermal conductivity lower than still air at around 0.026 W/(mK). VIPs as a high performance thermal insulation solution by far surpasses this with a much lower value.

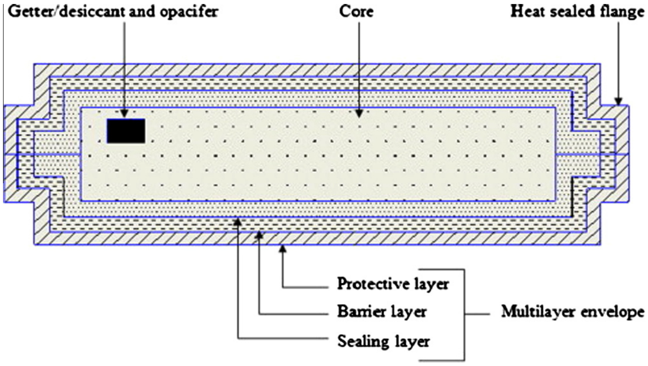

Fig. 1. Schematic of a VIP [1].

The development of VIPs focuses on two main aspects of the panel, i.e. the core and the envelope. Hence, a description for the two parts will be given separately in the following.

2.2. The core

2.2.1. Cores in general

The purpose of the core material is to provide the VIP's insulating and mechanical properties. Hence, there is a lot of focus on the core material, as this is important for a VIP to attain the highest possible thermal resistance. To optimize the conditions of the VIPs, the core needs to fulfil certain requirements. These are described in a comprehensive review by Baetens et al. [5]:

1. The core material's pore diameter needs to be small. In materials with large pores, the pressure has to be very low to obtain a low thermal conductivity. This is difficult to maintain with methods and materials in use today. By using a nano-porous material the pressure is not required to be as low, and a low thermal conductivity can be reached with a higher pressure. The relation between effective thermal conductivity of different potential VIP core materials as function of the internal gas pressure is shown in Fig. 2.
2. The pore structure needs to be 100% open so all the gas in the panel can be easily evacuated.
3. The core material needs to withstand compression. The normal range of the initial internal pressure in VIPs is between 0.2 and 3 mbar. The external pressure on the panel is around 1 atm, or about 101 kPa.
4. The material has to be impermeable to infrared radiation, which will reduce the radiative heat transfer in the panel.

Several different materials are being tested for use as core materials in VIPs, such as fibre-powder composites [44], polycarbonates [38], phenolic foam [36] and ultrafine glass fibres [15]. Different core materials have different advantages and drawbacks. Hence, the type of core material needs to be determined for each application. Core materials found in commercialized VIP products will be presented in the following chapters.

2.2.2. Fumed silica

Fumed silica is produced by pyrolysis of $SiCl_4$, which is then vaporized and reacts with oxygen, thus forming SiO_2 which is a fine white powder. This powder is pressed into boards, normally

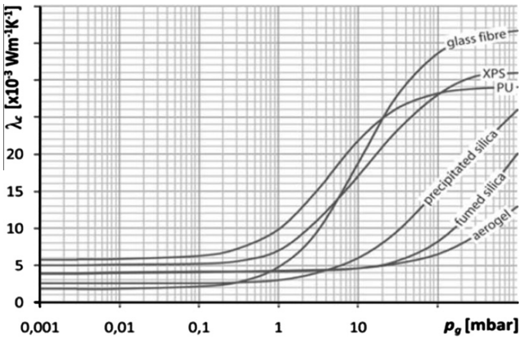

Fig. 2. Effective thermal conductivity of different potential VIP core materials as function of internal gas pressure [60].

with added fibres for structural stability. Fig. 3 shows a VIP with fumed silica as a core.

Due to its small pore size, ranging from 30 to 100 nm, and ability to withstand compression, the fumed silica core fulfils all the criteria stated earlier. The normal material properties for fumed silica are a mass density of around 200 kg/m^3 and a thermal conductivity of 0.003–0.006 W/(mK) under a pressure of 20–100 mbar [68]. However, fumed silica is not able to block thermal radiation very well. Seeing as the heat transfer through gas conductivity in a vacuum panel is especially low, the contribution from radiation will give a significant increase in the total thermal conductivity. Therefore, it is a common solution to add opacifiers to the fumed silica for it to reach an initial thermal conductivity as low as around 0.004 W/(mK).

Fumed silica is by far the most commonly used core-material for VIPs in the building sector today. Several advantages of fumed silica makes it a good choice for building applications. Silica is non-toxic, incombustible, recyclable and it does not release harmful emissions to the environment. A core of fumed silica works as a desiccant, absorbing water vapour permeating through the envelope.

In the case of panel perforation, fumed silica will still have a rather low thermal conductivity of around 0.020 W/(mK) at atmospheric pressure. Note then that the difference between 0.004 W/(mK) (pristine condition) and 0.020 W/(mK) (punctured) of 0.016 W/(mK) is due entirely to gas thermal conductivity (not taking into account any changes to the solid core due to the loss of vacuum). That is, the combined solid state and radiation thermal conductivity of fumed silica is as low as 0.004 W/(mK) or in principle somewhat lower (as there is still a very small concentration of air inside a VIP a small part of the 0.004 W/(mK) value is due to gas conduction). Hence, as it is possible to make materials with such a very low solid state and radiation conductivity, there are rather good opportunities to make a high performance thermal insulation material functioning at atmospheric pressure by lowering the gas thermal conductivity.

Fig. 3. VIP with a fumed silica core [64].

2.2.3. Aerogels

Aerogels are produced in two steps. First, wet gel formation by acidic condensation or sol–gel process. Second, the wet gel is dried by using supercritical or ambient drying. This produces a nanoporous material with pore sizes around 20 nm and a mass density that can vary from 3 to 350 kg/m^3. When used as a core material for VIPs, aerogel delivers a low thermal conductivity. At an ambient pressure of 50 mbar, and with an addition of carbon black to suppress the radiative transfer, aerogel may reach a low thermal conductivity of 0.004 W/(mK), whereas at ambient pressure the thermal conductivity rises to 0.0135 W/(mK) [3].

Aerogel is non-flammable and non-reactive. However, due to its high cost, aerogel-core VIPs are not yet an economically reasonable product for building applications. Nevertheless, aerogel may be used as a heat bridge breaker in buildings and structures where space is restricted. Furthermore, in its translucent or transparent state aerogel has and added value which may be exploited in several building applications.

2.2.4. Polyurethane foam

Polyurethane (PUR) foam is a widely used thermal insulation material by its own. The first vacuum insulation panels were created with PUR foams as the core material. PUR has the mechanical strength and the open pore structure required for a core material. However, the pore size in the PUR is larger than in fumed silica and aerogel. That is, PUR requires a lower vacuum to reach the same low thermal conductivity as the fumed silica and aerogel. For a PUR core VIP to maintain its designed low thermal conductivity value, the pressure has to stay below 1 mbar, over this value the conductivity will rise sharply [70]. This is not feasible with the envelopes of today. PUR foam core VIPs are less expensive to produce, but the short effective lifetime of these panels do not make them as fit for building applications.

2.2.5. Glass fibre

Glass fibre cores have similar issues as PUR foam cores. Because of the relatively large pore size, ranging from 1 to 12 μm, the gas pressure needs to be very low for the panel to maintain its low thermal conductivity. At a gas pressure of about 0.1 mbar the thermal conductivity is as low as 0.0015 W/(mK). Because of its high thermal stability, Araki et al. [2] have investigated the use of glass fibre core VIPs for high-temperature applications. The core material itself is relatively inexpensive, but Di et al. [15] concluded that the lifetime expectancy for a glass fibre core vacuum insulation panel is about 15 years. This is far too low for glass fibre VIP cores to be considered as a choice for building applications. As of today it is still mostly used for shipping containers, freezers, etc.

Using ultrafine glass fibre core VIPs for building applications has recently been mentioned in an article by Boafo et al. [7]. However, no monitoring tests have been found with these VIP types.

2.2.6. Desiccants, getters and opacifiers

A major and crucial drawback of VIPs, are that their thermal conductivity increases over time. The low conductive heat transfer of VIPs is highly dependent on a low gas pressure inside the panel. Vapour and gases that permeate through the envelope therefore contribute to a lower effectiveness of VIPs. To counteract this and increase the expected service lifetime of VIPs, desiccants and getters are added to the core. These are components or chemicals that adsorb residual or permeating gases or water vapour. They will maintain a steady thermal conductivity inside the core until their capacity is reached. Desiccants are made of highly hydroscopic materials and work by entrapping moisture. Getters are highly porous structures with large surfaces. They work by attracting and bonding with permeating gases to maintain a low pressure inside the panel. Some core materials have properties that fulfils the functions of desiccants and getters themselves, so they are not always necessary to add. Even though these materials slightly increase the solid state thermal conductivity and increase the costs of a panel they are important to add [62].

Opacifiers are added to the core of the panel to reduce the heat loss through radiation. With added opacifiers the radiative thermal conductivity can be decreased to a value below 0.001 W/(mK) [8].

2.3. The envelope

2.3.1. Envelopes in general

The main purpose of the envelope is to provide an air and vapour tight enclosure for the core material, i.e. to maintain a vacuum in the VIP core. As the thermal performance of VIPs is highly dependent on the conservation of the vacuum inside, any gases or water vapour that permeate through the barrier will diminish the effectiveness of VIPs. This makes a VIP a fragile thermal insulation material compared with conventional insulation [69]. Permeation through the envelope is also affected by the outer environment. Changes in temperature and relative humidity will affect the permeation rate [57].

Depending on the choice of envelope, thermal bridging around a VIP is also a factor to consider. The core material has great insulating properties, however thermal bridging from the envelope material will increase the panels total thermal conductivity. An increase in panel dimensions will lead to a decrease in the thermal bridging effect. Hence, one should aim to use the largest panel dimensions possible [66]. Further studies on the thermal bridging effect of VIPs in both single and double layers have been conducted by Wakili et al. [67]. Note that with larger panel dimensions larger areas and volumes of the building envelope will have a reduced thermal resistance when some of the VIPs are punctured.

The envelope is often divided into the sealing layer, the barrier layer and a protective layer as seen in Fig. 4. These layers are described by Alam et al. [1].

The inner layer is the sealing layer. This layer seals the core material in the envelope, and traditionally consists of low or high density polyethylene. The film surfaces are heat sealed by two hot bars under pressure to bond together.

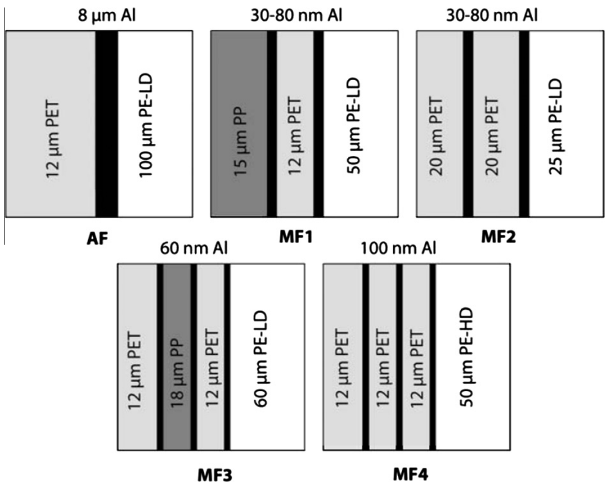

Fig. 4. Illustration of an Al foil and multilayer foils [69].

The middle layer is the barrier layer. As seen in Fig. 4, this layer may be an aluminium foil or a multilayer laminate. The purpose of the barrier layer is to protect against water vapour and air transmission through the envelope.

The outer layer is the protective layer. Environmental and handling stresses may damage the panel, so a protective layer aims to make the panel more robust. The material chosen for the envelope should also be able to withstand general handling through transportation and installation without tearing. It also works as a substrate for the barrier layer.

The sealed edges in a panel may often be a weak point in maintaining the vacuum. The sealing is a complex process which it is important to develop a further understanding for in order to maximize the lifetime of VIPs. Important factors in the heat sealing process is mentioned by Marouani [42].

2.3.2. Metal laminate

The solution with a metal laminate, most commonly aluminium laminate, consists of a central aluminium foil (with a thickness of 5–10 µm) as a barrier layer, laminated between an outer polyethylene terephthalate (PET) protective layer for better scratch resistance and an inner polyethylene (PE) sealing layer, the complete aluminium laminate (AF) also commonly called an aluminium foil (AF), see Fig. 4.

Aluminium laminate as a barrier layer lowers the permeation through the envelope, increasing the lifetime of a panel. However, the thickness of the metal laminate contributes to a higher thermal bridging effect as the thermal conductivity for aluminium is 210 W/(mK), compared to the core at around 0.004 W/(mK), and the polymer layers at 0.25–0.30 W/(mK). For a high performance insulation material this thermal bridge effect will have severe effects on the total thermal resistance of VIPs [9,12].

2.3.3. Metalized multilayer polymer laminate

The metalized multilayer foil (MF) solution consists of up to three barrier layers of metal coated PET films and an inner sealing layer of PE. The coating is performed with aluminium with a thickness of 20–100 nm, see Fig. 4.

The MF solution is, as of today, the common solution for VIPs intended for building applications. The multiple aluminium layers give the envelope a better protection from permeation compared with a single layer and thus with a reduced total thickness, while the polymers reduce the thermal bridging effect. The MF consists of two to three barrier layers, though triple layered MF is most common among VIPs for building applications as of today. However, the reduced total metal layer thickness for MFs compared to AFs leads to a considerably faster moisture and air permeation through the VIP envelope and into the core for VIPs with MF envelopes. Hence, during several years the thermal conductivity will increase much faster in VIPs with MF envelopes than with AF envelopes. For thermal conductivity versus time up to 100 years for various VIP dimensions and envelopes, it is referred to the studies by Baetens et al. [3] and Wegger et al. [69], see Fig. 5 (various VIP envelopes).

3. State-of-the-art vacuum insulation panel products

3.1. VIP products

Vacuum insulation panels (VIP) are most commonly used for shipping containers for temperature sensitive materials, domestic appliances like freezers, etc. However, for the last decade the most interesting aspect of VIPs has been their introduction to the building sector. In the following, a short explanation of the use of VIPs in appliances will be given. Thereafter, the use of VIPs in constructions up until today will be looked upon. Both laboratory

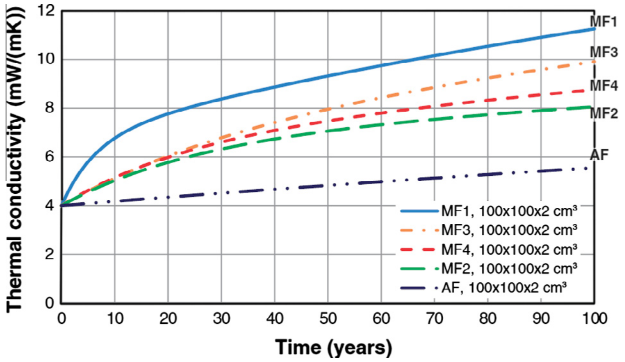

Fig. 5. Thermal conductivity versus time for different envelope solutions [69].

experiments and in situ measurements will be treated. As it would be too extensive to show all the possible buildings that have been tested with VIPs till now within this study, only a handful of selected examples will be given. Through these examples, the use of VIPs, experiences learned during construction and monitoring after completion will be explored.

Tables 1–3 show different vacuum insulation panel products available on the market today. The tables have been divided into VIPs for appliances (Table 1) and VIPs specified as possible to use in buildings (Tables 2 and 3). The VIPs for building applications have been further divided into VIPs that are delivered as unprotected panels (Table 2), and VIPs that are delivered with various protective coverings (Table 3). These tables give a short overview of the different products. Further information about the manufacturers and the products are given in the appendices.

The core materials for VIPs that are intended for appliances mostly consist of materials with larger pores or aerogel. As explained earlier aerogel is still too expensive to be a reasonable choice for most building applications, but its excellent thermal properties at a higher pressure gives aerogel a higher expected lifetime. Core materials with larger pore sizes are expected to lose the low thermal conductivity earlier than materials with a smaller pore size due to permeation through the envelope. However, these materials with larger pore sizes are also less expensive. More detailed information about the manufacturers and products can be found in Table A1.

Table 2 shows manufacturers of VIPs that can be applied for building constructions. The general choice for core material among these VIPs are dominantly fumed silica. One important factor which is lacking for almost all producers are an expected lifetime of the VIP. As mentioned earlier, the difficulty in predicting a useful lifetime for VIPs is one of the main reasons VIPs are still struggling to become a renowned choice for thermal building insulation. Some manufacturers do however mention a theoretical rise in gas pressure per year. This value is in the range of 0.5–4 mbar/year.

Note that VIPs applied for building constructions may also be used for other purposes. More information about the manufacturers of VIPs intended for buildings and their products can be found in Table A2.

Table 3 shows manufacturers which produce VIPs with added protective coverings for building applications. The benefits of such sandwich panels are explained in more detail later. More information about the manufacturers of sandwich VIPs and their products can be found in Table A3.

From the products found on the market it is clear that fumed silica is the current choice for building applications, while various core materials are used for all other applications. Product-related requirements that separate VIPs intended for buildings from other VIPs have been discussed by Tenpierik et al. [61]. These are requirements concerning structural stability, fire protection, hygiene, health and environment, application safety and fitness for use, acoustic performance, thermal performance and service life. VIPs for building applications put more requirements on the core material.

As seen in Fig. 2, fumed silica cores can maintain a stable thermal conductivity up to about 10 mbar and has a centre of panel thermal conductivity of about 0.008 W/(mK) at 100 mbar. This gives VIPs with silica cores a higher expected lifetime. Further advantages of fumed silica for building applications have been discussed earlier in this review. Even though the costs of fumed silica is higher than glass fibre or PUR foam, it is necessary to fulfil the requirements for building applications.

VIPs have been used with success in applications for some years. Glass fibre and PUR foam give the same initial thermal conductivity as silica core VIPs, but the expected lifetime is lower and various other requirements are not so strict for VIP cores of glass fibre or PUR foam. Glass fibre or PUR foam cores are also less expensive to produce, making these VIP cores a better choice whenever they are possible to use.

In this study, it is found that producers of building intended VIPs from Europe offer a large variety of different covering solutions for their products, which is well intended for use in buildings as they make the products more robust. However, the VIP coverings may also represent some drawbacks. For example, covering a VIP with expanded polystyrene (EPS) makes it more difficult to detect loss of vacuum, and furthermore the EPS has a higher thermal conductivity than the VIP area and thickness (volume) it replaces [28].

Table 1
Literature data for manufacturers of VIPs for appliances. See Table A1 for further information.

Manufacturer	Product	λ_{tot}[e] (W/(mK))	Initial gas pressure	Core	Envelope
Jinko	VIP	0.001–0.006[a]			
Rparts	VIP				
va-Q-tec	va-Q-pur	0.007–0.009[a]	<1 mbar	PUR-foam	Al foil
	va-Q-mic	0.0028–0.0035[a]	<1 mbar	Micro fleece	
Foamcore INC	Therm-max	R-40 per inch[a]		Aerogel	MF
Nanopore	VIP	0.004		Silica, titania and/or carbon	MF
Guangdong	VIP				
Xiamen Goot	VIP	0.004[a]	<0.1 Pa	Fibre glass	
American Aerogel	Aerocore VIP	0.0019–0.0042[a]		Organic aerogel	MF
Fujian Supertech	VIP	0.0025[a]			
Unifrax	Exelfrax 200	0.00375		Fumed silica, opacifiers	Laminated PE film

[a] No specific information given,
[b] Aged value allowing for edge effect.
[c] Initial value.
[d] Rated value.
[e] Aged thermal conductivity values and lifetimes are not given for most of the VIP products, although these are very crucial properties for the VIPs.

Table 2
Literature data for manufacturers of VIPs for building applications. See Table A2 for further information.

Manufacturer	Product	λ_{tot}[e](W/(mK))	Initial gas pressure	Core	Envelope
va-Q-tec	va-Q-vip	0.005[a]	<5 mbar	Fumed silica	High gas barrier film
	va-Q-plus	0.0035[a]	<5 mbar	80% fumed silica, opacifiers, organic fibres	
	va-Q-plus A	0.0035[a]	<5 mbar		
Panasonic USA	U-Vacua	R-60 per inch[a]			
Neofas AG	Vakutherm	0.0045[c]–0.008[b]		Pyrogenic silica	MF
Qingdao	Creek VIP	0.0035[a]	<0.001 Pa	Fibre glass	
ThermoCor	VIP				
Caralon Global	CG Max-Thermic	0.0038[a]	<1 mbar	Inert alkaline earth silicate glass wool	Al_2O_3
LG Hausys	VIP	0.004[a]		Glass fibre board	Al laminated film
Porextherm	Vacupor NT-B2-S	0.005[c]	<5 mbar	Fumed silica, opacifiers and fibre filaments	MF
	Vacupor RP-B2-S	0.005[c]	<5 mbar	Fumed silica, opacifiers and fibre filaments	Al laminate
	Vacupor PS-B2-S	0.005[c]	<5 mbar	Fumed silica, opacifiers and fibre filaments	Al laminate
	Vacupor TS-B2-S	0.005[c]	<5 mbar	Fumed silica, opacifiers and fibre filaments	Al laminate + sound absorbing plastic board
	Vacuspeed	0.0043[c]	<5 mbar	Fumed silica, opacifiers	Al laminate
	Vacupor NT		<5 mbar		
Dow Corning	VIP	0.00369[c]		Fumed silica	MF
Microtherm	Slimvac	0.0042[c]	<5 mbar	Filament reinforced silica and opacifier	MF
Vaku-isotherm	Standard	0.005[c]		Fumed silica, opacifiers and cellulose fibres	MF
	VakuVIP B2	0.005[c]		Fumed silica, opacifiers and cellulose fibres	MF
Variotec	QASA	0.007[a]	<7 mbar	Pyrogenic silica, opacifiers	
Suzhou VIP	VIP	0.008[a]		Glass fibre	
Kingspan	OPTIM-R	0.007[b]			
Nanopore insulation	VIP				

[a] No specific information given.
[b] Aged value allowing for edge effect.
[c] Initial value.
[d] Rated value.
[e] Aged thermal conductivity values and lifetimes are not given for most of the VIP products, although these are very crucial properties for the VIPs.

Table 3
Literature data for manufacturers of VIPs with added protective coverings, i.e. sandwich VIPs, for building applications. See Table A3 for further information.

Manufacturer	Product	λ_{tot}[e] (W/(mK))	Initial gas pressure	Core	Envelope
va-Q-tec	va-Q-vip B	0.0043[c]	<5 mbar	Fumed silica	Foil and glass fibre
	va-Q-plus B	0.0035[c]	<5 mbar	80% fumed silica, opacifiers, organic fibres	Foil and glass fibre
Porextherm	Vacupor XPS-B2-S	0.005[c]	<5 mbar	Fumed silica, opacifiers and fibre filaments	Al laminate + EPS
Vaku-isotherm	Gum-1	0.005[c]		Fumed silica, opacifiers and cellulose fibres	MF + rubber granulate
	SP-1	0.005[c]		Fumed silica, opacifiers and cellulose fibres	MF + polystyrene
	SP-2/E	0.005[c]		Fumed silica, opacifiers and cellulose fibres	MF + polystyrene plates and sides covered with EPS
	Protekt-1	0.005[c]		Fumed silica, opacifiers and cellulose fibres	MF + fleece
	Bauplatte	0.005[c]		Fumed silica, opacifiers and cellulose fibres	MF + plastic plates and sides covered with EPS
	Sandwich Paneel 1	0.005[c]		Fumed Silica, opacifiers and cellulose fibres	MF + glass plates and sides covered with EPS
	Sandwich Paneel 2	0.005[c]		Fumed Silica, opacifiers and cellulose fibres	MF + glass/Al and sides covered with EPS
	Sandwich Paneel 3	0.005[c]		Fumed Silica, opacifiers and cellulose fibres	MF + Al/Al and sides covered with EPS
Variotec	QASA	0.007[a]	<7 mbar	Pyrogenic silica, opacifiers	

[a] No specific information given.
[b] Aged value allowing for edge effect.
[c] Initial value.
[d] Rated value.
[e] Aged thermal conductivity values and lifetimes are not given for most of the VIP products, although these are very crucial properties for the VIPs.

Overall, there are very few producers who state an expected lifetime and a guarantee for their panels. Some manufacturers state a lifetime which is only valid for specific conditions, and therefore not possible to compare with conditions in use. Many of the thermal conductivities are given without stating anything else. For the customers of this product, an aged value or an intended design value is important. However, as this study will discuss later, these values rely on many factors concerning the environment in which the product is applied. Therefore, many manufacturers state that the values are only for guidance, and that each case has to be considered specifically.

3.2. VIPs in appliances

VIPs have shown good results in domestic appliances and for logistic purposes. Recently, research on VIPs that can withstand higher temperatures have also been performed. These VIPs have been introduced to insulate hot-water equipment and other high-temperature applications [2]. For most typical appliances like refrigeration, thermal packaging and so on the normal lifetime expectancy for these panels are seldom required to exceed 15 years. This makes it possible to use glass fibre or polyurethane cores for these VIPs. Requirements are not so strict for general applications as broken panels rarely leads to anything else than replacing a broken ware.

3.3. VIPs in the building sector

3.3.1. VIPs in monitoring projects

Even though VIPs show great promise as a thermal insulation material solution of tomorrow there are several drawbacks that have to be addressed when considering VIPs for building applications. A VIP requires a low pressure inside. If the panel is perforated or broken in any way which leads to a loss of this vacuum, the thermal conductivity will increase to about 0.020 W/(mK) for VIPs containing fumed silica. Cutting and adapting the panel on-site is not possible. Insulating a building with VIPs therefore requires detailed planning from an early stage and a layout plan of how and where the panels shall be put into place. Practice also shows that the most common cause of damage to the panels occurs before and during installation [37]. Extra precautionary matters need to be taken with the handling of VIPs as they are a fragile construction material. Damaged panels do not only decrease the thermal resistance of the building, but depending on how the VIPs are implemented there is also a risk of condensation and possibly mould growth [52].

In Germany there have been a lot of test projects with constructions implementing VIPs, both refurbished and new constructions. Some were built as early as 2001 and have been monitored on a regular basis since. Bayerisches Zentrum für Angewandte Energieforschung (ZAE Bayern) in collaboration with various VIP producers have many interesting projects which show how the implementation of VIPs into buildings have proceeded. ZAE Bayern conducted a research project called VIP Prove, where the aim was to see how VIPs behaved under practical conditions. To choose these projects ZAE Bayern had certain criteria the buildings had to fulfil, giving them a score of up to 85 points, where the higher the score was the more suitable a construction was for monitoring.

The first criterion [26] depended on how suited the construction elements were for a thermographic scanning. When conducting a thermographic scan of the building element the VIPs should not be covered with heavy building elements or air-filled spaces that would disrupt the measurements and give unclear results to whether the panels are functioning as planned or not. Fig. 6 shows a thermographic scan which clearly shows a broken panel, where it is also seen that many of the joints between the panels have been poorly executed.

The second criterion was how many different areas the VIPs could be applied to. More areas which could be applied with VIPs were to prefer, as this would give more and comparable results within the same building.

The third criterion was the age of the panel. Preferably VIPs that had been implemented before 2005 should be monitored. The longer the panels had been in the building the more interesting it was to study if and how their properties had changed.

The fourth criterion was the possibility to conduct other measurements to show the results of the thermal performance of the panels. These results could be used in comparison with the thermography measurements.

For the VIP Prove project a total of 29 objects, with an area of 8206 m^2 installed with VIPs were assessed. Out of these, 19 objects with an area 3224 m^2 installed with VIPs were found to be suitable for investigation by thermographic scanning. These 19 objects were also further investigated by determining the heat transfer coefficient and the internal pressure of the VIPs. The results showed that 12.8% of the VIPs in these 19 objects were classified as faulty. However, three buildings were particularly faulty and stood out in the statistical evaluation. By removing these three buildings the percent of broken panels fell to 4.9%. This might mean that these three projects have failed to handle the panels properly, that they have been installed wrongly or that a production error has affected many of the panels [17].

Some of these monitoring projects will be mentioned in the following chapters about new and refurbished constructions.

3.3.2. Lifetime predictions

The useful lifetime can be explained as the time until the centre of panel thermal conductivity reaches a critical level. Usually this point is at around 0.008 W/(mK), meaning that when *U*-values are being calculated this should be the design value [57]. The VIPs will still function when this value is reached, but the thermal conductivity will continue to increase, thus also increasing the *U*-value and heat loss.

For VIPs meant for building applications the lifetime is one of the most important and crucial properties. Buildings should be dimensioned with a lifetime of up to at least 50 years in mind, preferably up to 100 years. Today most VIPs using a MF3 laminate can be said to have a lifetime of over 25 years under specific conditions [5,26,57].

The uncertainties surrounding the exact lifetime of VIPs when they are in use, are still major factors for scepticism. Predicting the useful lifetime of VIPs have therefore been an aim of many studies. Accelerated climate ageing and comparative ageing of in situ panels and panels kept in laboratories have been conducted. The focus here is on permeating gases and water vapour through the envelope, as this increases the thermal conductivity. VIPs for building purposes should never have an increase of more than 2 mbar/year [56]. For a panel with fumed silica an increase of 2 mbar/year would equal a lifetime of almost 50 years.

A laboratory ageing test of 20 VIPs performed by The National Research Council – Institute for Research in Construction (NRC–IRC) in Canada over 7 years showed that the average loss of *R*-value was about 2% per year. In a test hut wall of the NRC construction 18 months of field exposure was performed with 5 different VIP products, 15 specimens from different manufacturers showed 5% ageing in 4 out of 5 products and 2 out of 15 specimens failed. Therefore, they concluded that VIPs show promising longterm performance for service life of 25–50 years [49].

Wegger et al. [69] mentioned that there are no standardized ways of performing accelerated ageing tests for VIPs. To get a prediction of a VIP's effective lifetime within a shorter time frame, such tests will be necessary to define. Several factors such as pressure, temperature, ultraviolet and infrared radiation, moisture, water exposure and freezing/thawing were tested, along with various climate cycling tests. The results showed that the change in performance was relatively low compared to the initial thermal performance. However, two of the panels which were tested showed signs of failure from other factors than the accelerated ageing testing. This shows that VIPs are still a fragile material when exposed to high moisture and temperature, or that they may have defects from the manufacturing process.

3.3.3. Economics

Modern day passive houses built with traditional thermal insulation require a wall thickness of 35 cm or more, meaning that a

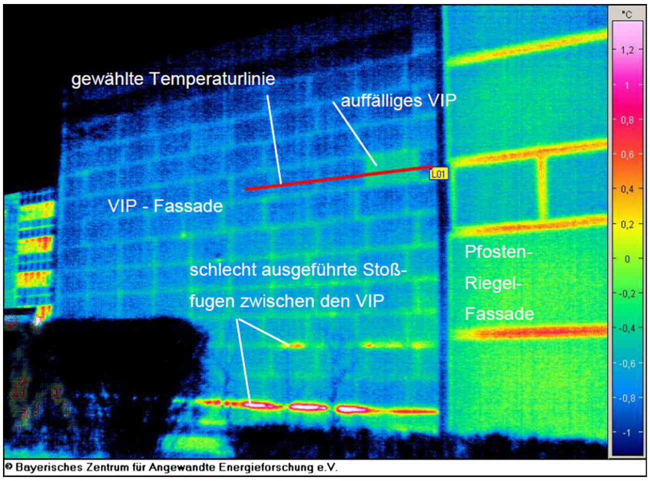

Fig. 6. Thermography of a VIP facade from the outside. The green square (auffälliges VIP) shows a broken VIP and the green lines shows poorly executed joints [26].

large part of the building volume is filled up by insulation. By building with VIPs the required thickness can be reduced, hence increasing the value of a building through increased living space. VIPs are still far more expensive than conventional insulation, however studies have been made to show that the increased living space achieved by decreasing the wall thickness may still make VIP a more economically favourable choice. Studies that mention the cost benefit of the increased living space have been conducted by Alam et al. [1] and Jelle [28]. Alam et al. [1] also show that the payback time for VIPs is drastically reduced if the benefit of the increased usable area is included. This is based on that each square meter gained will lead to increased market value, which naturally is highly dependent on the value per square meter in the given area.

For frame constructions there is also a possibility to reduce the use of materials where the size of the cavity traditionally has been increased to fit the thickness of conventional thermal insulation beyond what has been required for structural strength, i.e. by applying VIPs instead. This will lead to a reduction in use of materials and also reduce the transportation of materials to the building site. The economical impact of this has so far not been discussed in detail.

3.3.4. Acoustic performance

The benefit of constructing with VIPs shows through slimmer layers of thermal insulation. However, from a building physical point of view, thermal insulation is not the only factor to consider. The impact on acoustic performance must also be taken into account [40]. Baetens et al. [5] mentioned that the acoustical properties and knowledge of VIPs could be divided into three groups when used for building insulation purposes: (i) A single VIP, (ii) VIPs built into sandwich elements and (iii) insulated massive walls with built-in VIPS. Maysenhölder [43] studied the three different groups. For a single VIP it was found that it has a critical frequency in the range of speech and traffic noise ($\sim$1 kHz), which reduces the sound reduction in this range. It was also found that perforating a VIP would reduce the sound reduction. However, he concluded that it would be more beneficial to study the acoustical properties in layered systems with internal VIPs, rather than single VIPs by themselves. Various sizes and core materials will also affect how a VIP performs acoustically. Further information concerning acoustical properties of VIPs may be found in the work by Tenpierik [60]. The focus forward for acoustic studies should be on VIPs in such practical applications, i.e. layered systems. To the authors knowledge, there is limited literature on the acoustical properties of VIPs available. Forward, field measurements on VIP systems should be conducted to obtain more results on how VIPs perform acoustically.

3.4. VIP sandwich elements

In the building projects which have been completed so far, it is clear that most of the damaged panels have been damaged during transport or while they are being installed at the building site. To protect VIPs, both under construction and in use, encasing it with other materials is a good solution. Such sandwich elements will reduce the risk of damaging the panel unintentionally. Some of the solutions also completely envelope the sides of the panel with expanded polystyrene (EPS) [50]. This is a favourable solution for adapting the panels on site as the EPS can be cut to fit the panels in the construction without harming the VIP. Note that the EPS (or other) covering makes it more difficult to discover loss of vacuum. Besides, EPS has a higher thermal conductivity than the VIP area and thickness (i.e. volume) it replaces [28].

Some producers already manufacture finished sandwich elements of different kinds, with protective layers such as granulated rubber, glass fibre boards, aluminium or glass plates and polystyrene plates. Different sandwich solutions have been given in Table 3. Another solution, where it is possible, is to prefabricate building elements with integrated VIPs. This is by some referred to as a structural vacuum panel (SVP) as demonstrated in Fig. 7. Producing SVPs can be performed under controlled conditions where the risk of damaging panels can be reduced. The VIPs inside the finished elements will also be a lot less likely to be damaged during transport.

A prefabricated building from Scotland has been built using SVPs, showing that it is possible to attain a low *U*-value. This building was built with 125 mm thick SVPs with a 25 mm VIP at its core. The overall *U*-value for the wall ended up at 0.10 W/(m^2K) for a thickness of 234 mm [48]. However, prefabrication of buildings and various building elements are an entirely different issue which will have to be addressed for each individual project and the desires of the end users.

3.5. Constructing with VIPs

VIPs can be applied to many different areas of a construction. This chapter will shortly describe some of the most common areas which are suited for VIP applications and discuss some important considerations when they are applied to these areas. More detailed information about different areas where VIPs can be implemented, and more detailed descriptions on building details have been made by Johansson [35].

3.5.1. Facades and walls

For facades it is possible to either insulate the exterior or the interior part of the wall. For frame constructions there is a third possibility to insulate inside the cavity as well.

Internal facade insulation with VIPs may be an excellent choice for retrofitting. The thin layers of VIPs required, compared to conventional insulation, will enable lower *U*-values after retrofitting without the same loss of indoor space. This is especially interesting for listed buildings where the outside design is not allowed to be altered. However, careful planning concerning low exterior surface temperatures, increased number of freezing/thawing cycles and the risk of condensation has to be made to avoid damages and mould forming.

Insulating the outer facades is beneficial for the reduction of thermal bridging, and can be made easy by using adhesives to stick the VIPs to the facade.

In wall constructions VIPs will not only give positive results in reduced energy usage, but also be quite visible through slimmer wall constructions. As mentioned earlier this will work towards making VIPs more economically favourable with respect to increased indoor living space.

3.5.2. Glazing structures

For glazing structures, the transition between glass areas and opaque areas can be made more architecturally appealing by insulating with VIPs. The high thermal resistance enables slim facades and smoother transitions (see e.g. Fig. 8). In some areas VIPs were integrated into the glazed parts between enamelled glass panes [54].

3.5.3. Doors

Doors are a part of a construction which is hard (due to a restricted thickness) to insulate properly with traditional insulation, and therefore the doors become a source for heat to leave the building. By inserting a VIP into a door it is possible to increase the thermal resistance of doors and thus reduce the total heat loss from the building. Nussbaumer et al. [51] showed that a wooden

Fig. 7. Illustration of a SVP [48].

door system with an implemented VIP reduced the energy usage for the doors by 25%.

3.5.4. Roofs

VIPs for roofing purposes have been tested for both flat roofs and sloped roofs. VIPs have shown to be especially good for roofs under terrace floors, where conventional insulation often makes it hard to get the entrance in line with the outer floor because of the requirements for insulating properly over the room below. Here the VIPs enable a slimmer insulation layer making it possible to insulate within the requirements and at the same time enabling an entrance in line with the outside floor.

Brunner and Simmler [10] have monitored VIPs in a flat roof construction over a 3 year period. Assuming that the initial thermal conductivity was 0.0045 W/(mK) and the practical service life ended when the thermal conductivity exceeded 0.008 W/(mK) the panels used had an expected lifetime of about 25 years.

3.5.5. Floors

Gaining space through insulating with VIPs in the floor is not highly economically beneficial. However, for rooms with large temperature difference demands such as e.g. cold storages the use of VIPs can be a good choice for reducing energy demands. In heated floors VIPs may increase the efficiency of the floor heating system. VIPs may also represent a good choice when there are different space or thickness restrictions, e.g. restricted floor to ceiling height. Furthermore, transitions between floors and outdoor areas can be made stepless by insulating with VIPs.

Refurbishing poorly insulated floors can also be accomplished with VIPs. An example from UK showed that insulating over an existing concrete floor slab could reduce the *U*-value from 0.78 W/(m^2K) to 0.15 W/(m^2K) by using 20 mm VIPs. The new floor had a minimal increase in thickness [47].

Fig. 8. Residential and office building in Munich [6].

3.6. New construction examples

A few examples of new constructions with VIPs will be shown here. These examples will be given to illustrate how VIPs can be implemented in new buildings. General considerations and experiences that were learned from these examples will be given as well. Building details will not be discussed in detail as these vary from each individual project. As VIPs are still considered as a new material solution in the construction sector, there are still a lot of uncertainties about how they actually perform when implemented in a building, and how to plan the construction phase with VIPs. Different forms of buildings affect the way VIPs have to be applied to the construction. In Nordic countries the most common way to build houses is by building with a lightweight timber frame construction. However, central European countries such as Germany and Switzerland, where most studies on VIPs have been conducted, rely more on massive structures like brick and concrete for housing purposes.

3.6.1. Munich

The first building over two storeys to be entirely insulated with VIPs was a residential and office building in Munich (Figs. 8 and 9). Here the goal was to show the economic benefit of achieving a slimmer facade through VIPs. With a total area of 1350 m^2 the building's heating requirement is just 22 kWh/(m^2year). This project was also a part of the earlier discussed ZAE Bayerns VIP Prove project. Under an inspection in 2009, 450 m^2 out of a total of 750 m^2 of VIPs were monitored with thermographic scans. None of these showed any signs of damage [6].

This project showed that a big hurdle for VIPs, in addition to the uncertainties considering lifetime, is the lack of certified building systems. Getting the required certifications took several months and added extra costs to the project. Planners took on a lot of extra risk and work to make this happen [54].

3.6.2. Freiburg

Fig. 10 shows the Sun Ship from Freiburg, completed in 2006. The supporting structure is made from reinforced concrete and the facade is constructed from a wooden post-beam construction.

A total of 1198 m2 of VIPs are fit into place within the facade. Energy efficient design, along with the VIPs and installation of photovoltaic solar cell modules have made the Sun Ship the first commercial plus-energy building. The building has won several awards for its energy efficient profile [58]. This shows that VIPs can be implemented and acknowledged in the aim for a more energy efficient architecture.

3.6.3. Leipzig

In Leipzig in 2006 a single family house was built using a total of 265 m^2 of VIPs (Fig. 11). The VIPs were implemented in the outer part of the wall construction. The building was raised with a steel skeleton. The goal was to build a light construction that was energy efficient, ecologically flexible and of materials that were recyclable. When the construction was finished the energy used for heating was under 15 kW h/m^2.

3.6.4. Laboratory examples with timber frame constructions

Hot box measurements on a timber frame construction with 40 mm thick VIPs demonstrated that it was possible to reach a U-value of 0.10 W/(m^2K) with a wall thickness of ~20 cm. However, it was clear that building with VIPs requires more effort in the planning phase because of the lack of adaptability [25]. Hot box experiments with VIPs in a timber frame construction were also conducted by Grynning et al. [24], including single and double layers, tape, and stacking/overlapping effects. Retrofitting of timber frame walls with VIPs between two climate rooms and subsequent investigations of the condensation risks were studied by Sveipe et al. [59]. Furthermore, accelerated climate ageing of VIPs in a timber frame construction was carried out by Wegger et al. [69].

3.7. Retrofitting examples

VIPs hold great possibilities within the refurbishing of existing constructions. High performance thermal insulations such as VIP can be applied even where space is limited and help to reduce the heat loss from the building considerably. That is, reducing the total energy usage. In constructions where it is difficult to modify the thickness of the building, implementation of high performance insulation is an efficient option to achieve a greater energy efficiency through insulation. The efficient use of space also opens up for possibilities of renovating listed buildings, which are not allowed to be renovated at the expense of changing the building design.

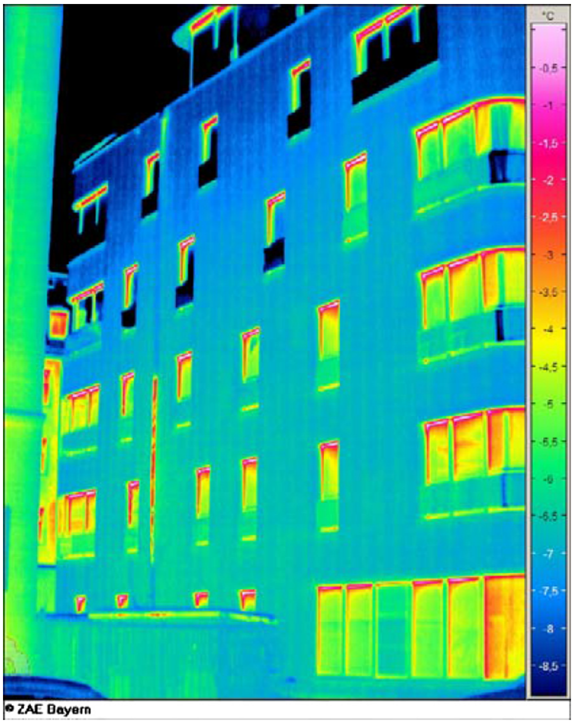

Fig. 9. Thermographic scan of the VIP project from Munich [54].

Fig. 10. The Sun Ship in Freiburg [65].

ZAE Bayern has also conducted monitoring projects on retrofitted buildings. From the VIP Prove project of ZAE Bayern, the highest score for a refurbished construction was achieved from a project in Berlin. For this project a total area of 96 m^2 of wall were built with VIPs.

3.7.1. Laboratory example with a timber frame construction

An investigation of retrofitting with VIPs in a timber frame structure has been conducted by Sveipe et al. [59]. This study looked at the potential to retrofit old Norwegian buildings with VIPs, thus lowering the energy usage to that of a passive house. A test module was built between two climate rooms to test how the VIP constructions performed with respect to moisture transport and risk of condensation, both when applied on the inside and outside of the wall.

Insulating the outside will enable the reduction of thermal bridges, which is one reason this is normally the preferred solution when applying conventional vapour open systems. However, when using vapour tight VIPs retrofitted at the exterior side, there may be a risk of condensation on the inner side of the VIPs. With 100 mm mineral wool retrofitted with 30 mm VIPs, the wall achieved an U-value of 0.143 W/(m^2K) for VIPs in pristine condition. When ageing of the panels were considered (panels reaching

Fig. 11. Single family house in Leipzig [65].

a thermal conductivity of 0.008 W/(mK)) the wall had an *U*-value of 0.181 W/(m^2K). These results did not account for the small thermal bridging of the vertical VIP joints.

3.7.2. Practical example from Canada

During the 10th international vacuum insulation symposium (IVIS-X) in Canada in 2011 a few construction retrofit examples from Canada were presented. One of these was the retrofitting of an institutional building in Yukon. The interest for a new and high performing insulation material with high insulation values per units of thickness and weight is increasing. Determining the VIP qualities in the harsh environment of northern Canada was of interest. Initially, one exterior facade was insulated using VIPs. As costs were high, contractors were hesitant to insulate an entire building with this new technology. By testing one section of the building first, the results might lead to increased trust and willingness to conduct more projects with VIPs.

After the project, the construction experience was positive. Local interest around VIPs was said to increase. The low weight and small thickness made the installation easy, and as a result the labour was completed under budget. The VIPs were easily installed with adhesives, i.e. they were stuck directly on the wall as shown in Fig. 12. However, the project is still being monitored further so there are no conclusive results of the VIP performance yet, even though the initial indications are positive.

An important point that were highlighted during this project was the need to train all staff on how to install and handle VIPs. The panels are still expensive and difficult to replace. At the end of a workday the VIPs should always be covered by some form of protective layers. The areas where the VIPs are to be installed must always be investigated for elements that may harm the envelope through mechanical rubbing [41].

4. Future research pathways

4.1. Other state-of-the-art insulation materials

Though VIPs show great promise as an insulation material for tomorrow, it is not the only one under development. Other interesting materials that may compete with VIPs in the future will be mentioned in the following chapters.

4.1.1. Aerogel

Aerogels are dried gels with a very high porosity, high specific surface area, low apparent density and a low refraction index. The pore volume of aerogel may vary from 85 up to 99.8%. This gives the material a bulk density as low as 3 kg/m^3, making it the lightest solid state material known. For building applications the density is in the range of 70–150 kg/m^3. At ambient pressure the thermal conductivity may be as low as 0.0135 W/(mK), which can be reduced down to 0.004 W/(mK) at a pressure of 50 mbar [3].

Aerogel at ambient pressure has thermal conductivity values 2–3 times lower than conventional insulation, and unlike VIPs, it can be cut and adjusted at the building site. However, aerogel has a very low tensile strength, making the material very fragile.

The optical properties of aerogel are quite remarkable. It is possible to produce aerogel which is opaque, translucent or transparent (Fig. 13) making it possible to use it for a wide spectrum of applications, such as windows, facades and roofs which will allow solar radiation and daylight to pass through [3].

4.1.2. Gas-filled panels (GFP)

Gas-filled panels (GFP) consist of a gas between reflective layers sealed within a low-emissivity barrier envelope. The reflective layers inside a GFP is called a baffle. Fig. 14 shows the cross-section of a normal GFP. The gas inside the core can either be air or other heavier gases that further reduce the thermal conductivity. Theoretical values of 0.020 W/(mK) and 0.012 W/(mK) for argon and krypton filled panels, respectively, have been found. However, prototype GFPs have given a thermal conductivity of 0.040 W/(mK) for panels filled with argon in practical use in a building construction. As a technology with the same fragility and lack of flexibility as VIPs, but still showing a higher thermal conductivity, the future of GFPs is questionable [4].

Fig. 12. Installation of VIPs with adhesives [41].

4.1.3. Nano insulation materials (NIM)

Nano insulation materials (NIM) can be described as materials that are basically homogenous and which achieve high performance thermal insulating qualities mainly due to their open or closed nanoporous structure. By reducing the pore size until the maximum pore size in the material is lower than the mean free path of air the gaseous thermal conductivity can be substantially reduced. From the conceptual ideas of NIMs [5,28–30], the first experimental steps have been carried out in order to actually make NIMs in the laboratory [21,22,31,55]. One main focus for trying to make NIMs today is manufacturing of hollow silica nanospheres (Fig. 15), where powder samples of these spheres have measured thermal conductivity values typically in the range 0.020–0.090 W/(mK), though some uncertainties in the Hot Disk apparatus measurement method have to be further clarified [23,34]. Production and measurements on the thermal insulation ability of hollow silica nanospheres are further described by Liao et al. [39] and Sandberg et al. [55].

Fig. 13. A photo of translucent/transparent aerogel [16].

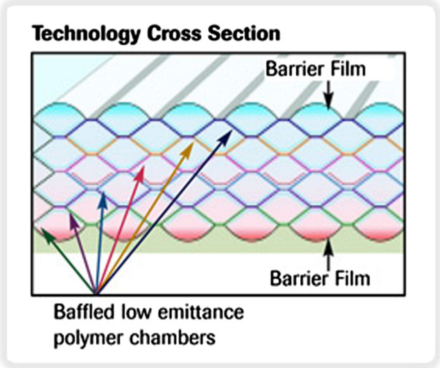

Fig. 14. Technology cross-section of a GFP [20].

4.2. Possible future research on current VIP technologies

4.2.1. Various requirements

When addressing the future possibilities of VIPs the problem areas of today should be considered. Thermal insulation materials intended for building applications should fulfil several requirements as suggested by Jelle et al. [28–30].

It is proposed that the initial thermal conductivity should be 0.004 W/(mK) or below, whereas it should not exceed 0.005 W/(mK) after 100 years. Perforation should not affect the thermal performance of the material, and it should be robust when considering climate stresses such as freezing/thawing cycles and ageing. The thermal insulation material should be adjustable on the building site and furthermore it should have a low negative environmental impact. In addition, the insulation material should be cost-competitive in comparison with other products.

For VIPs of today, a lot of the suggested requirements are not met. The path forward can either focus on improving the current technologies or explore new technologies based on similar principles as those that have been used while working with VIPs. In the following some of the work and reflections about the future of VIPs will be discussed.

As mentioned earlier the two main components that lead to and maintain the low thermal conductivity of VIPs are the core and the envelope. However, they are not directly depending on each other. That is, improving one of the two individually will contribute positively to a VIP. Hence, research being conducted on improving the core and envelope can be explored separately.

4.2.2. The core

There are several factors with the current core technology that can be addressed to make VIPs more attractive.

1. Developing core materials that better resist permeating gases and water vapour. Introducing getters and desiccants to the core is not a permanent solution to gases permeating through the envelope. They will eventually reach their capacity for adsorbing water vapour and gases and the core material will begin to lose its thermal resistance properties. New core materials with smaller pores, a stronger structure and generally better resistance may increase the expected lifetime of a VIP.
2. Producing core materials that can achieve a lower solid and radiative conductivity. Further reduction of the thermal conductivity may be achieved through reducing the heat loss from conduction in the solid material and the radiative heat transfer through the voids in a VIP. However, as noted earlier, the solid state conductivity and radiation conductivity are already very low, i.e. 0.004 W/(mK) or lower.
3. Reducing the production cost of the current core materials or seek new materials that can be produced at less costs. For VIPs manufactured for the building sector, the core materials are mainly nanoporous materials. As of today the production costs for these materials are still very high. Exploring new methods to produce the core materials can therefore make VIPs more cost competitive.
4. Developing core materials that are better at maintaining a vacuum, and less vulnerable towards perforation and cutting (e.g. vacuum insulation materials VIM), and ultimately core materials that have low thermal conductivities at atmospheric pressure (e.g. nano insulation materials NIM) [5,28–30]. That is, such core material developments are moving beyond the very concept of *vacuum* insulation *panels*, i.e. not requiring vacuum or (enveloped) panels.

The National Research Council – Institute for Research in Construction (NRC–IRC) has noted the costs of VIPs to be one of the major factors that is stopping the wide use of VIPs in the construction sector. To meet this challenge, they have started ongoing research to find less expensive core materials. By using a vacuum guarded hot plate (VGHP) different open porous insulating materials can be tested at different pressure levels. None of the materials tested so far have been commercialized, but work is still ongoing [45].

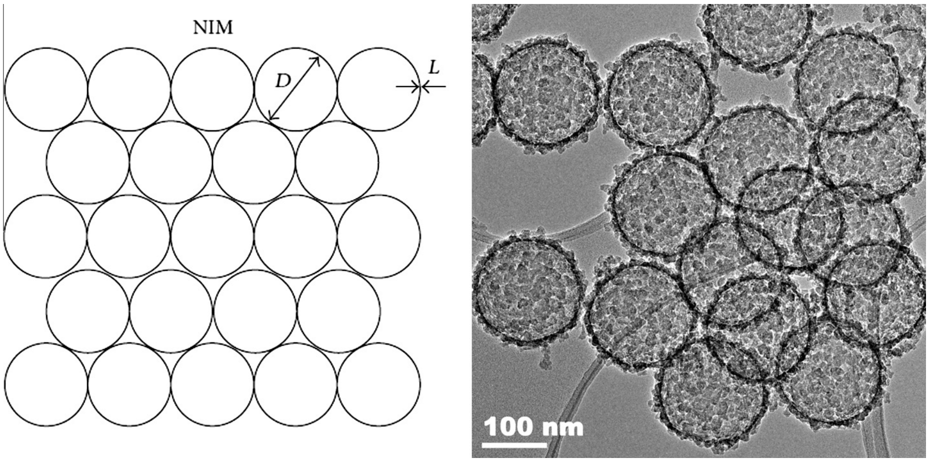

Fig. 15. Conceptual model of a NIM based on hollow nanospheres (left), TEM image of actual hollow silica nanospheres (right) [55].

4.2.3. The envelope

The envelope is the weak point of VIPs as of today. Permeation through the envelope leads to an increase in thermal conductivity, heat bridging contributes to a higher thermal conductivity and the envelope is fragile and can easily be perforated. These are some of the major issues that need to be further improved. One aim is to develop an envelope without the aluminium layers. The aluminium in today's laminates leads to an increase in thermal bridging. However, they are necessary to reduce the permeability through the envelope as polymers do not have the same resistance against permeation. If a polymer material with better resistance could be introduced this would work favourably for the reduction of thermal bridging. Reducing the permeation sufficiently would also allow for less expensive materials such as glass fibres and PUR foams to be used as core materials with an extended life time. Note the earlier discussion herein concerning the faster increase in thermal conductivity for thin metalized foils (MF) than the thicker aluminium foils (AF).

The production method may also lead to flaws with today's envelopes. Material imperfections and processing errors need to be handled to increase the trust in VIPs. Material imperfections such as pinholes are impossible to notice by just a visual inspection, but may reduce the lifetime of the panel. New methods of assuring the quality should be considered. This will also be beneficial as it will allow monitoring of panels without results being affected by a faulty production process.

There is also the problem with the lack of robustness for the envelope. Steel casings have already been tried for use as envelopes. Stainless steel makes for an almost impermeable envelope with only a few mm thickness. The steel will also represent a robust panel, which is not easily perforated. However, there is the issue of a greatly increased thermal bridging. A method with serpentine edging to minimize edge loss, has been investigated by Thorsell [63]. Fig. 16 shows an illustration of how serpentine edges work. For a steel casing with 11 serpentines with a depth of 20 mm, the thermal bridging effect was found to be 0.010 W/(mK).

Further research must also be made on the sealing technique for the envelope. The heat sealed flange is often considered as a weak point in the modern VIPs. Understanding the processes around the sealing process may help to improve the seals and reduce the permeation through them. There are also investigations going on as to where it is most beneficial to put the seal, i.e. either along the panel edges, or on one of the large area surfaces on the panel.

4.3. Further reflections

One important factor to consider is the 'economies of scale'. VIPs have not yet been widely used as a thermal insulation material, and even though there are a variety of manufacturers, the production scale is not comparable to conventional insulation. As VIPs gain confidence as an insulation material, the scale of production will increase and most likely lead to a reduction of production costs for VIPs [46].

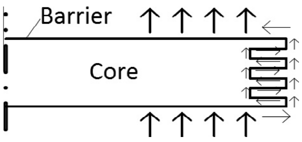

Fig. 16. Serpentine edging in VIPs [63].

As mentioned earlier, there are other insulation materials in development that may end up competing with VIPs in the future. The outlook is interesting for both aerogels and nano insulation materials (NIM), and further studies are being conducted on these materials. Their ability to be adapted at the building site, lack of inherent thermal bridges, and generally higher robustness makes them more suited for building applications. The nature of the construction industry is known to be conservative. Introducing VIPs, that are a fragile and not a very flexible material, will put new demands on contractors and building planners for how to plan, handle and implement the VIPs correctly. Aerogels and NIMs however, could be implemented much like conventional insulation today, and would make for a much more seamless adaption [60].

4.4. Producing vacuum insulation with new technology

The general idea of VIPs is that the vacuum greatly reduces the gaseous conductivity through a material. However, with the current manufacturing technology, an open porous structure is a requirement for panels to be totally evacuated to a vacuum. A new thought is to create a material with a closed pore structure in combination with vacuum (Fig. 17). This would give the same low thermal conductivities as a VIP, but without the need for a sealing envelope. Should a material like this be perforated the result would just be a local thermal bridge, and the material could also be cut and adjusted at the building site. Such a material is referred to as a vacuum insulation material (VIM) [5,28–30].

However, a problem for this solution would be that gases and water vapour would also permeate through the solid state pore walls similar to as it would through the envelope of a VIP.

Synthesis of a closed porous silica has been studied by Pei et al. [53]. A challenge concerning a closed pore structured material is that the material can no longer be evacuated. Therefore, a material like this may have to be manufactured under vacuum to create an evacuated closed pore structure or a material blowing itself up from within or pore walls absorbing all of the initial gases in the pores [29,30].

4.5. The path forward for VIPs in the construction sector

As VIPs improve and becomes a part of the building envelope of tomorrow, it will be necessary to create standards for their use. As of today, the building projects which have been completed have had to be approved individually. Applying for approval for each individual building from local building regulators is time consuming and makes it harder for VIPs to gain access to the building sector at a larger scale. As we have seen however, many of the reference projects have given positive results. New standards should include how to properly handle, store and install VIPs. As mentioned by Brunner [11] a

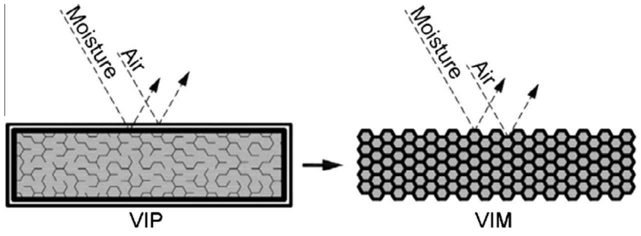

Fig. 17. Illustration of a vacuum insulation material (VIM) [5].

standard which is in line with the other European product standards EN13162 to EN13171 on how to handle thermal insulation, should be made for VIPs as well. These standards do, among other issues, state initial testing and production control for the materials. Other important factors that need to be described are design guidelines, more clear material specification standards, and handling instructions.

Another goal for the building sector may also be to innovate how constructions are being built around VIPs. It is a weak point of VIPs that the thermal conductivity increases by a factor of about 5 times should the panel be punctured. New planning of constructions to make it possible to monitor the VIPs and easily replace broken VIPs might make them more suitable and desired for constructions. For various experimental tests on VIPs for building applications it is referred to the investigations by Grynning et al. [24], Haavi et al. [25], Sveipe et al. [59] and Wegger et al. [69], whereas for more general information about accelerated climate ageing of building materials, components and structures, including new materials and solutions (e.g. VIPs), it is referred to the studies by Jelle [32] and Jelle et al. [33].

The manufacturers of VIPs and contractors should also work together to establish a common norm for the use of VIPs in buildings. Enabling standard formats for VIPs would be beneficial for all participants. Allowing VIPs to be stored in the factory after production may enable the manufacturers to notice broken panels before they are shipped out. Broken panels will be easier to re-order from stock and a standardized production process may lead to fewer defect panels. As of today, production problems are still critical for faith in the VIP technology [71]. The need for quality assurance is present in the market. Standardized tests to assure there are no microscopical damages or relatively large leakages through weak seals should be guaranteed to the customers through a quality label [18].

Measuring the gas pressure inside the panels is still difficult. When defect panels are discovered the only solution is to exchange the panels. Caps et al. [14] have demonstrated that technology for measuring the gas pressure inside the panels is available. For the future, the use of measuring technology has to be more common so that the quality of all VIPs can be assured.

In Europe a Common Understanding of Assessment Procedure (CUAP) and globally an ISO Working Group have been established to deal with testing procedures for VIPs. The definition of clear test methods will help to define when panels are damaged because of faults in production versus bad handling during transport and installation [13].

5. Conclusions

This study shows and presents a variety of vacuum insulation panel (VIP) manufacturers on the market today, offering a wide variety of VIP products. VIPs in general applications have already been used on the market for nearly two decades with success. For the construction sector there are still challenges to overcome. The lack of certified building systems and official approvals from governmental agencies are providing hurdles that will need to be handled. Education and further promotion of VIPs are important in order to accelerate the implementation of VIPs in constructions. Thus, the challenges are placed with the manufacturers. They need to improve the quality assurance of their VIP products, and to be able to give a guarantee the end users can rely on.

For the future it is important that data from already finished constructions are gathered and shared, so that the uncertainty of how VIPs perform at practical conditions can be reduced. Removing uncertainties around VIPs, and reducing the costs, will be an important factor for a larger commercialization of this product.

VIPs show great promise as a building insulation material in the near future. Many projects have already been completed with VIPs, where many show good initial results. If the technology can be further improved, and the current lifetime can be extended and guaranteed, VIPs will become a more trusted choice for thermal insulation. However, even if the moisture and air diffusion into the VIP core somehow could be reduced to almost zero (which is far from the situation today), the lack of flexibility and the risk of perforation will always be major drawbacks for the use of VIPs. Other high performance insulation solutions have been described briefly. Some show great promise, combined with the possibilities of increased flexibility and being able to adapt at the building site. These may become a favourable choice over VIPs if or when they are able to be further developed and commercialized.

Acknowledgements

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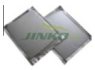
Appendix

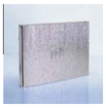
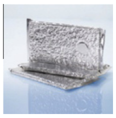
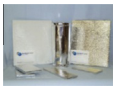
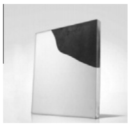
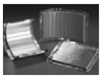
See Tables A1–A3.

Table A1
Manufacturers of VIPs for appliances or applications that are not specified.

Manufacturer	Product	Illustration	Thermal conductivity[e] (W/(mK))	Mass density (kg/m^3)	Initial gas pressure (mbar)	Specific heat capacity (kJ/(kgK))	Standard dimensions (L × W) (mm × mm)	Thickness (mm)	Core/ Envelope	Additional information
JINKO Qingdao Jinko New Materials Co., Ltd Haier Rd, High-tech industrial zone, Laoshan Section, Qingda, Shandong Province China Tel.: 86-532-88964006 jinkovip@gmail.com http://www.jinkovip.com	Vacuum insulation panel		0.001–0.006[a]							Does not mention building applications http://jinkovip.com/product/detail.php/id-35.html [Accessed 04.06.2013]
Rparts Refrigeration Parts Solution, LLC Santa Cruz, CA 95066 USA Tel.: (831)600-7878 sales@rparts.com http://www.rparts.com	VACUUM INSUL: 082-1817						18 inch × 18 inch	1 inch		Produced for refrigeration http://www.rparts.com/index.php?cPath = 9_32 [Accessed 04.06.2013]

(*continued on next page*)

Table A1 (*continued*)

Manufacturer	Product	Illustration	Thermal conductivity[e] (W/(mK))	Mass density (kg/m^3)	Initial gas pressure (mbar)	Specific heat capacity (kJ/(kgK))	Standard dimensions (L × W) (mm × mm)	Thickness (mm)	Core/ Envelope	Additional information
va-Q-tec AG-Würzburg, Headquarters Karl-Ferdinand-Braun Strasse 7 97080 Wuerzburg /Germany Tel.: +49 (0)931 35 942 0 Fax: +49 (0)931 35 942 10 info@va-q-tec.com http://www.va-q-tec.com/	va-Q-pur		0.007–0.009[a]	65	<1 mbar		max 1200 × 1000	10-40	**Core** Polyurethane foam **Envelope** Aluminium foil/ film	Developed for applications, freezers, etc. Service life up to 15 years http://www.va-q-tec.com/ va-q-pur_en,2756.html [Accessed 04.06.2013]
	va-Q-mic		0.0028–0.0035[a]	220	<1 mbar		max 1300 × 1000	14 and 20	**Core** Micro fleece	For applications with extremely little space Service life approx 5 years http://www.va-q-tec.com/ va-q-mic_en,2757.html [Accessed 04.06.2013]
Foamcore, Inc. 1704 Wayneport Road Macedon, New York 14502 USA Phone: 315-986-4390 Fax: 315-986-4391 sales@foamcoreinc.com http://foamcoreinc.com/	Therm-Max Panels		R-40 at 1 inch[a]						**Core** Aeroblack (aerogel) **Envelope** Aluminized polyester laminate	For thermal packaging http://foamcoreinc.com/ public/Panels.html [Accessed 04.06.2013]
Nanopore NanoPore Incorporated 2501 Alamo Avenue SE Albuquerque, New Mexico 87106 USA Tel.: (505) 247-4041 Fax: (505) 247-4046 info@nanopore.com http://www.nanopore.com	Vacuum insulation panel		<0.004[a], 0.008[b]	170			25–900 × 25–600	6–30	**Core** Silica, titania and/or carbon **Envelope** Three-layer laminate with aluminium metalization on two of the layers to enhance barrier performance.	Use for building applications not specified http:// nanopore.com/vip.html [Accessed 04.06.2013]
Guangdong Alison Hi-Tech Co., Ltd. Rm 1202, Golden Lake Building, No.2 Donghu Road West, Guangzhou, China Tel.: 86-20-8386-0079 Fax: 86-20-8384-7308 ydalison@hotmail.com http://www.ydalison.com	Alison Aerogel Insulation									For refrigerant insulation http://alisonaerogel.en. ecplaza.net/alison-aerogel-vacuum-insulation-panel--237903-2182851.html [Accessed 04.06.2013]
Xiamen Goot Advanced Material Co., Ltd. 99 Liantang Road, North Jimei Industrial Region, Xiamen City, Fujian Province. China Tel.: 86-592-6688857/66866 Fax: 86-592-6689988 market@goot.com.cn http://www.goot.com.cn	Vacuum insulation panel		<0.004[a]	230	<0.1 Pa		Max 1600 × 700	10–35	**Core** Fibre glass	10–15 years service life http://xgamcl.en.china. cn/selling-leads/ detail,1067096931, Vacuum-Insulation-Panels-VIP.html [Accessed 04.06.2013]
American Aerogel 460 Buffalo Rd. Suite 200A Rochester, NY 14611 USA Tel.: (585) 328-2140 Fax: (585) 785-8624 info@americanaerogel.com http://americanaerogel.com/	Aerocore VIP		0.0019–0.0042[a]	0.15–0.2 g/cc	O2TR <0.0005 cc/m^{2}day		up to 500 × 600	12–25	**Core** Organic aerogel **Envelope** Aluminized polyester laminate	Building applications not mentioned http:// americanaerogel.com/ wordpress/wp-content/uploads/ 2012/02/Aerocore-Properties.pdf [Accessed 04.06.2013]
Fujian supertech advanced material Co, Ltd Lianguan Industrial Area, Liancheng County, Longyan City, Fujian Province, China Tel.: +86-0592-6199925 market@supertech-vip.com http://www.supertech-vip.com/En/	Vacuum insulation panel		<0.0025[a]	240–314						http://www.supertech-vip.com/ En/products.aspx [Accessed 04.06.2013]
Unifrax Corporation 2351 Whirlpool Street Niagara Falls, N.Y. 14305-2413 USA Tel.: 716-278-3800 Fax: 716-278-3900 http://www.high-temperature-insulation.com/	Exelfrax 200 VIP Insulation		0.00375[a]	185			490–980 × 490–1225	10–30	**Core** Fumed silica, opacifiers **Envelope** Laminated PE film	Building applications not mentioned http://www. high-temperature-insulation.com/files/ Excelfrax-200-VIP-Insulation.pdf [Accessed 06.06.2013]

[a] No specific information given.

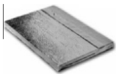
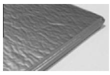
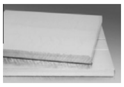
[b] Aged value allowing for edge effect.

[c] Initial value.

[d] Rated value.

[e] Aged thermal conductivity values and lifetimes are not given for most of the VIP products, although these are very crucial properties for the VIPs.

Table A2
Manufacturers of VIPs specified for building applications.

Manufacturer	Product	Illustration	Thermal conductivity[e] (W/(mK))	Mass density (kg/m^3)	Initial gas pressure (mbar)	Spesific heat capacity (kJ/(kgK))	Standard dimensions (L × W) (mm × mm)	Thickness (mm)	Core/ Envelope	Additional information
va-Q-tec AG-Würzburg, Headquarters Karl-Ferdinand-Braun Strasse 7 97080 Wuerzburg /Germany Tel.: +49 (0)931 35 942 0 Fax: +49 (0)931 35 942 10 info@va-q-tec.com http://www.va-q-tec.com/	va-Q-vip		<0.0043[a]	180–210	<5 mbar, pressure rise approx. 1 mbar/year	0.8	1000 × 600, 500 × 600	10–50	**Core** Fumed silica **Envelope** High gas barrier film	Triangle, trapezium, special shape, cornet cut, hole cut and recessed surface Lifetime, extrapolated, depending on application up to 60 years. http://www.va-q-tec.com/va-q-vip_en,2754.html [Accessed 04.06.2013]
	va-Q-plus		<0.0035[a]	170–200	<5 mbar, pressure rise approx. 1 mbar/year	0.8	400–1750 × 250–1000	3–35	**Core** 80% fumed silica, Opacifiers, organic fibres	Can be made in various shapes Lifetime, extrapolated, depending on application up to 60 years. http://www.va-q-tec.com/va-q-plus_en,2758.html [Accessed 04.06.2013]
	va-Q-plus A		<0.0035[a]	170–200	<5 mbar	0.8				Lifetime, extrapolated, depending on application up to 60 years. http://www.va-q-tec.com/en/va-Q-plus-A-277,30322.html [Accessed 04.06.2013]
Panasonic USA Panasonic Industrial Company Applied Technologies Group 3 Panasonic Way, 7E-2 Secaucus, NJ 07094 USA Fax: (201) 271-3068 Vip@us.panasonic.com http://www.panasonic.com	U-Vacua		R-60 per inch[a]							http://www.panasonic.com/industrial/appliances-hvac-devices/vacuum-insulation/panel.aspx [Accessed 04.06.2013]
NEOFAS AG Vogelsangstrasse 14 CH- 8307 Effretikon Switzerland Tel.: +41 52 354 51 00 Fax: +41 52 354 51 01 info@neofas.ch http://www.neofas.ch	Vakutherm		0.0045[c] –0.008[b]	180–220			300–1000 × 200–800	15–45	**Core** Pyrogenic silica **Envelope** Multiple metalized polymer foil	http://www.neofas.ch/produkte/vakutherm/vakutherm.html [Accessed 04.06.2013]
Qingdao Kerui New Environmental Materials Co., Ltd. 39 Donghai West Road Qingdao, 30th Floor, Century House China Tel.: 400-670-8338 Fax: 0532-80778338 qingdaokerui@163.com http://www.cncreek.net	Creek VIP		<0.004[a]		<0.001 Pa		150–1800 × 100–600	10–50	**Core** Fibre glass	http://cncreek.net/en/product.aspx?id = 2 [Accessed 04.06.2013]
ThermoCor 2900 Dryden Road Dayton, OH 45439 USA Tel.: (937) 312-0114 http://www.thermocorvip.com	Vacuum insulation panel									http://www.thermocorvip.com/vacuum-insulation-panels/ [Accessed 04.06.2013]
Caralon Global Bletchley Park Science and Innovation Centre Bletchley Park Milton Keynes MK3 6 EB United Kingdom Tel.: +44 (0)1908 880721 http://www.caralonglobal.com	CG Max-Thermic		0.0038[a]	150–300	<1 mbar		300–1200 × 250–1000	3–20 mm	**Core** Inert alkaline earth silicate glass wool **Envelope** Al_2O_3	Lifetime up to 45 years http://www.caralonglobal.com/index.php/products [Accessed 04.06.2013]
LG Hausys EUROPE (Frankfurt) Lyoner str 15, Atricom C8, D-60528, Frankfurt/m, Germany Tel.: 49-69-58302-9400 VIPinfo@lghausys.com http://www.lghausys.com	Vacuum insulation panel		<0.004[a]	175			max 1800 × 700	1–30	**Core** Glass Fibre Board **Envelope** Al foil laminated film	http://www.lghausys.com/eng/product/highfunctional/vacuum/subindex.jsp [Accessed 04.06.2013]
Porextherm Dämmstoffe GmbH Heisinger Straße 8/10 D-87437 Kempten Germany Tel.: +49(0)831-575360 Fax: +49(0)831-575363 info@porextherm.com http://www.porextherm.com	Vacupor NT-B2-S		<0.005[c], 0.007[d]	170–210	<5 mbar, pressure rise 1.0 mbar/ year (theoretical)		150–2200 × 150–1000	10–50	**Core** Fumed silica, opacifiers **Envelope** Metalized, multilayer plastic film	http://www.porextherm.com/en/products/vacupor/vacupor-nt-b2-s.html [Accessed 04.06.2013]
	Vacupor RP-B2-S		<0.005[c], 0.007[d]	150–300	<5 mbar, pressure rise 0.5 mbar/ year (theoretical)		150–1500 × 150–1000	10–50	**Core** Fumed silica, opacifiers, fibre filaments **Envelope** Aluminium foil	http://www.porextherm.com/en/products/vacupor/vacupor-rp-b2-s.html [Accessed 04.06.2013]

(*continued on next page*)

Table A2 (*continued*)

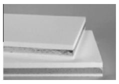
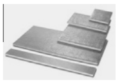
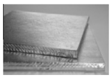
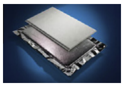
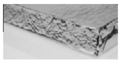
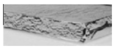
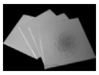
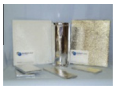
Manufacturer	Product	Illustration	Thermal conductivity[e] (W/(mK))	Mass density (kg/m^3)	Initial gas pressure (mbar)	Spesific heat capacity (kJ/(kgK))	Standard dimensions (L × W) (mm × mm)	Thickness (mm)	Core/ Envelope	Additional information
	Vacupor PS-B2-S		<0.005[c], 0.007[d]	150–300	<5 mbar, pressure rise 0.5 mbar/ year (theoretical)		150–1500 × 150–1000	10–50	**Core** Fumed silica, opacifiers, fibre filaments **Envelope** Aluminium foil	authorities http://www.porextherm.com/en/products/vacupor/vacupor-ps-b2-s.html [Accessed 04.06.2013]
	Vacupor TS-B2-S		<0.005[c], 0.007[d]	170–210	<5 mbar, pressure rise 1.0 mbar/ year (theoretical)		150–1500 × 150–1000	10–50	**Core** Fumed silica, opacifiers, fibre filaments **Envelope** Aluminium foil and sound absorbing plastic board	http://www.porextherm.com/en/products/vacupor/vacupor-ts-b2-s.html [Accessed 04.06.2013]
	Vacuspeed		0.0043[c], 0.008[e]	170–210	<5 mbar, pressure rise 1.0 mbar/ year (theoretical)		250–1000 × 250–500	15–25	**Core** Fumed silica, Opacifiers **Envelope** Aluminium foil, double-middle seam	http://www.porextherm.com/en/products/vacupor/vacuspeed.html [Accessed 04.06.2013]
	Vacupor NT		<0.005[c]	150–300	<5 mbar, pressure rise 0.5 mbar/ year (theoretical)		150–2200 × 150–1000	10–30	**Core** Fumed silica, Opacifiers **Envelope** Aluminium foil	http://www.porextherm.com/en/products/vacupor/vacupor-nt.html [Accessed 04.06.2013]
Dow Corning Corporation Corporate Center PO Box 994 MIDLAND MI 48686-0994 USA Tel.: 49 611 2371 Fax: 49 611 237620 http://www.dowcorning.com	Vacuum Insulation Panel		0.00369[c]	150–300			up to 900 × 600		**Core** Fumed silica **Envelope** Aluminized multilayer barrier	80% of initial thermal resistance after 30 years Nonrectangular shapes are possible http://www.dowcorning.com/content/publishedlit/62-1556-01.pdf [Accessed 04.06.2013]
Microtherm N.V. Industriepark-Noord 1 9100 Sint-Niklaas Belgium Tel (+32) 3 7601980 Fax (+32) 3 760 1999 info@microthermgroup.com http://www.microthermgroup.com	SlimVac		0.0042[c]	160–220	<5 mbar		up to 1400 × 800	6–40	**Core** Filament reinforced silica and an opacifier **Envelope** Multiple metalized polymer layers	http://www.microthermgroup.com/low/EXEN/site/vip-intro.aspx [Accessed 04.06.2013]
Vaku-Isotherm GmbH Schönborner strasse 37 09669 Frankenberg/ OT Sachsenburg Germany Tel.: +49(0)37 206 89 14 50 Fax: +49(0)37 206 89 14 49 info@vaku-isotherm.de http://www.vaku-isotherm.de	Standard		<0.005[c]	150–220	Pressure rise 1–4 mbar/ year		150–3000 × 150–1250	10–50	**Core** Fumed silica, opacifiers and cellulose fibres **Envelope** Multiple metalized polymer layer	http://www.vaku-isotherm.de/vaku_isotherm.html [Accessed 04.06.2013]
	VakuVIP B2		<0.005[c]	170–210	Pressure rise 1–4 mbar/ year		150–3000 × 150–1250	10–30	**Core** Fumed silica, opacifiers and cellulose fibres **Envelope** Multiple metalized polymer layer	http://www.vaku-isotherm.de/vaku_isotherm.html [Accessed 04.06.2013]
Variotec GmbH & Co. KG Weißmarterstraße 3-5 D-92318 Neumarkt/ OPf. Germany Tel.: +49 9181 6946-0 Fax: +49 9181 6946-50 info@variotec.de http://www.variotec.de	QASA		0.007[a]	190–220	<7 mbar, pressure rise ca. 1 mbar/year	1	250–1000 × 250–1000		**Core** Pyrogenic silica, opacifiers	Different covering solutions available http://variotec.de/hp3600/2-Newsletter-VIP-QASA.htm [Accessed 04.06.2013]
Suzhou V.I.P. New Material Co., Ltd. No. 136, Yanshan Road (W), Chengxiang Town, Taicang, Suzhou, Jiangsu, China Tel.: 53665668/53665669 Fax: 0512-53 524 981 czn@hdfydq.com http://www.es-vip.com	Vacuum insulation panel		0.008[a]	240–280					**Core** Glass fibre	http://www.es-vip.com/English/a/chanpinjieshao/VIPzhenkongjuereban/ [Accessed 04.06.2013]
Kingspan Insulation Ltd Pembridge Leominster Herefordshire HR6 9LA United Kingdom Tel.: 01544 388 601 Fax: 01544 388 888 info@kingspaninsulation.co.uk http://www.kingspaninsulation.co.uk/	OPTIM-R		0.007[b]	180–210			300–1200 × 300–600	20–40	**Core** Microporous material	http://www.kingspaninsulation.co.uk/Products/Optim-R/Optim-R/Overview.aspx [Accessed 04.06.2013]

Table A2 (*continued*)

Manufacturer	Product	Illustration	Thermal conductivity[e] (W/(mK))	Mass density (kg/m^3)	Initial gas pressure (mbar)	Spesific heat capacity (kJ/(kgK))	Standard dimensions (L × W) (mm × mm)	Thickness (mm)	Core/ Envelope	Additional information
Nanopore Insulation Limited The Factory, Rectory Lane, Brimfield, Shropshire, SY8 4NX, United Kingdom. Tel.: +44 (0) 1584 711333 Fax: +44 (0) 1584 711838 info@nanoporeinsulation.com http://www.nanopore.eu	Vacuum insulation panel		<0.004[c], 0.008[b]	170			25–900 × 25–600	6–30	**Core** Silica, titania and/or carbon **Envelope** Three-layer laminate with aluminium metalization on two of the layers to enhance barrier performance.	http://nanopore.com/vip.html [Accessed 04.06.2013]

[a] No specific information given.

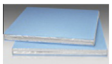
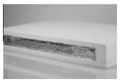
[b] Aged value allowing for edge effect.

[c] Initial value.

[d] Rated value.

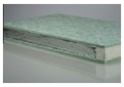
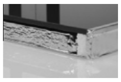
[e] Aged thermal conductivity values and lifetimes are not given for most of the VIP products, although these are very crucial properties for the VIPs.

Table A3
Manufacturers of VIPs with protective coverings.

Manufacturer	Product	Illustration	Thermal conductivity[e] (W/(mK))	Mass density (kg/m^3)	Initial gas pressure (mbar)	Spesific heat capacity (kJ/(kgK))	Standard dimensions (L × W) (mm × mm)	Thickness (mm)	Core/ Envelope	Additional information
va-Q-tec AG-Würzburg, Headquarters Karl-Ferdinand-Braun Strasse 7 97080 Wuerzburg / Germany Tel.: +49 (0)931 35 942 0 Fax: +49 (0)931 35 942 10 info@va-q-tec.com http://www.va-q-tec.com/	va-Q-vip B		<0.0043[c]	180–210	<5 mbar, pressure rise 1 mbar/ year	0.8	1000 × 600, 500 × 600	10–50	**Core** Fumed silica **Envelope** Foil and glass fibre	Approved for building applications http://www.va-q-tec.com/va-q-vip_b_en,2755.html [Accessed 04.06.2013]
	va-Q-plus B		<0.0035[c]	170–200	<5 mbar, pressure rise 1 mbar/ year	0.8	1100 × 600, 550 × 600	5–20	**Core** 80% fumed silica, opacifiers, organic fibres **Envelope** Foil and glass fibre	Specially designed for building applications with a shiplap for gapless joints extrapolated, depending on application up to 60 years http://www.va-q-tec.com/va-q-plus_b_en,19393.html [Accessed 04.06.2013]
Porextherm Dämmstoffe GmbH Heisinger Straße 8/10 D-87437 Kempten Germany Tel.: + 49(0)831-575360 Fax: + 49(0)831-575363 info@porextherm.com http://www.porextherm.com	Vacupor XPS-B2-S		<0.005[c], 0.007[d]	170–210	<5 mbar, pressure rise 1.0 mbar/ year (theoretical)		150–1500 × 150–1000	10–50	**Core** Fumed silica, opacifiers, fibre filaments **Envelope** Aluminium foil and EPS	Approved for building applications by the german building and construction authorities http://www.porextherm.com/en/products/vacupor/vacupor-xps-b2-s.html [Accessed 04.06.2013]
Vaku-Isotherm GmbH Schönborner strasse 37 09669 Frankenberg/ OT Sachsenburg Germany Tel.: +49(0)37 206 89 14 50 Fax: +49(0)37 206 89 14 49 info@vaku-isotherm.de http://www.vaku-isotherm.de	Gum-1		<0.005[c]	150–250	Pressure rise 1–4 mbar/year		150-3000 × 150–1250	10–50	**Core** Fumed silica, opacifiers and cellulose fibres **Envelope** Multiple metalized polymer layer + 3 mm rubber granulate	http://www.vaku-isotherm.de/vaku_isotherm.html [Accessed 04.06.2013]
	SP-1		<0.005[c]	150–220	Pressure rise 1–4 mbar/year		150–3000 × 150–1250	10–50	**Core** Fumed silica, opacifiers and cellulose fibres **Envelope** Multiple metalized polymer layer and 10 mm polystyrene plates	http://www.vaku-isotherm.de/vaku_isotherm.html [Accessed 04.06.2013]
	SP-2/E		<0.005[c]	150–220	Pressure rise 1–4 mbar/year		150–3000 × 150–1250	10–50 + Polystyrol-Envelope	**Core** Fumed silica, opacifiers and cellulose fibres **Envelope** Multiple metalized polymer layer, 10 mm polystyrene plates and sides covered with EPS	http://www.vaku-isotherm.de/vaku_isotherm.html [Accessed 04.06.2013]

(*continued on next page*)

Table A3 (*continued*)

Manufacturer	Product	Illustration	Thermal conductivity[e] (W/(mK))	Mass density (kg/m^3)	Initial gas pressure (mbar)	Spesific heat capacity (kJ/(kgK))	Standard dimensions (L × W) (mm × mm)	Thickness (mm)	Core/ Envelope	Additional information
	Protekt-1		<0.005[c]	150–220	Pressure rise 1–4 mbar/year		150–3000 × 150–1250	10–50 + fleece envelope	**Core** Fumed silica, opacifiers and cellulose fibres **Envelope** Multiple metalized polymer layer and 1.4 mm fleece	http://www.vaku-isotherm.de/vaku_isotherm.html [Accessed 04.06.2013]
	Bauplatte		<0.005[c]	150–220	Pressure rise 1–4 mbar/year		150–3000 × 150–1250	10–50 + kunststoff-recyclingplatte	**Core** Fumed silica, opacifiers and cellulose fibres **Envelope** Multiple metalized polymer layer, 4 mm plastic plates and sides covered with EPS.	http://www.vaku-isotherm.de/vaku_isotherm.html [Accessed 04.06.2013]
	Sandwich Paneel 1		<0.005[c]	150–220	Pressure rise 1–4 m bar/year		150–3000 × 150–1250	10–50 + glass envelope	**Core** Fumed silica, opacifiers and cellulose fibres **Envelope** Multiple metalized polymer layer, glassplates and sides covered with EPS.	http://www.vaku-isotherm.de/vaku_isotherm.html [Accessed 04.06.2013]
	Sandwich Paneel 2		<0.005[c]	150–220	Pressure rise 1–4 mbar/year		150–3000 × 150–1250	10–50 + glass and Al envelope	**Core** Fumed silica, opacifiers and cellulose fibres **Envelope** Multiple metalized polymer layer and glass/Al and sides covered with EPS	http://www.vaku-isotherm.de/vaku_isotherm.html [Accessed 04.06.2013]
	Sandwich Paneel 3		<0.005[c]	150–220	Pressure rise 1–4 mbar/year		150–3000 × 150–1250	10–50 + Al envelope	**Core** Fumed silica, opacifiers and cellulose fibres **Envelope** Multiple metalized polymer layer and Al/Al and sides covered with EPS	http://www.vaku-isotherm.de/vaku_isotherm.html [Accessed 04.06.2013]
Variotec GmbH & Co. KG Weißmarterstraße 3-5 D-92318 Neumarkt/ OPf. Germany Tel.: +49 9181 6946-0 Fax: +49 9181 6946-50 info@variotec.de http://www.variotec.de	QASA		0.007[a]	190–220	<7 mbar, pressure rise ca. 1 mbar/year	1	250–1000 × 250–1000		**Core** Pyrogenic silica, opacifiers	Different covering solutions available Can be used for building applications http://variotec.de/hp3600/2-Newsletter-VIP-QASA.htm [Accessed 04.06.2013]

[a] No specific information given.

[b] Aged value allowing for edge effect.

[c] Initial value.

[d] Rated value.

[e] Aged thermal conductivity values and lifetimes are not given for most of the VIP products, although these are very crucial properties for the VIPs.

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