Vacuum insulation in buildings

Means to prolong service life

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Abstract

Vacuum insulation panels, VIPs, constitute a new insulation material, 6 to 8 times better than traditional insulation materials, which utilizes the positive influence vacuum has on the thermal properties of certain materials. A VIP is a composite with a flat core enclosed by an envelope preventing the core to fill with gas. The vacuum in the core is vital to reach thermal conductivities down to 0,0035 W/(m·K), if the vacuum is lost the panel has reached the end of its service life time. Metal sheets would the preferred material to create an impermeable envelope but would creates a large thermal bridge at the edges of a panel when it folds over the edges of the panel.

A serpentine edge has been proposed in order to deal with this large thermal bridge. This serpentine edge has been evaluated first as a numeric model in software and then by measuring on a prototype edge element in a hot and cold plate instrument. Measured temperatures were used to validate the numerical model. Results show that a serpentine edge can greatly reduce the thermal bridge if designed correctly.

Another direction taken in the development of the VIP barrier is to use very thin metal layers, metallization layer or coating, incorporated into multi layered polymer composite film. This creates barrier films with very good barrier properties and only small thermal bridges. The modeling of gas flux through films with more than one coating has only just started. Existing models for flux through multi coated films all assume that flux is only taking place through defects in the coating layers, that all defects are of the same size and that all defects are positioned in square lattices. The model discussed herein use the same assumption of flux through pinholes only but it does take defect sizes and positions into account. Barrier film, from a regular vacuum insulation panel, with double coatings has been evaluated in light microscopy to characterize the defects in each of the coatings. The data found have been fed into the model and the results comply well with reported permeabilities of similar barrier films.

Keywords: Vacuum insulation, thermal bridge, serpentine edge, coated film

Sammanfattning

Vakuum Isolerings Paneler är en ny form av isolering, 6 till 8 gånger mer effektiv är traditionell isolering, där vakuumets positiva inverkan på värmeisoleringsförmågan utnyttjas. Dessa paneler är uppbyggda av ett kärnmaterial vilket är placerat i vakuum, kärnan omsluts av en barriär som har till uppgift att separera kärnan från omgivningen, alltså upprätthålla vakuum på insidan. Som material i barriären kan allt från tjock plåt till tunnaste plastfilm användas, de mest använda barriärerna som finns på marknaden idag består av flera lager of polymera filmer med multipla metalliseringar bestående av ett tunt lager av Aluminium. Metaller som är tjockare än en kritisk tjocklek anses vara ogenomträngliga för gas om de inte innehåller defekter men metall leder värme bra vilket leder till att en köldbrygga skapas när barriären viks runt kanten på en panel. En barriär bestående av metallplåt skulle därför vara mycket bra för att bibehålla vakuumet i kärnan men skulle samtidigt skapa en så stor köldbrygga att den genomsnittliga värmekonduktiviteten för en panel skulle bli medioker. Omvänt skulle en barriär bestående av endast polymera material inte skapa någon köldbrygga att tala om men den skulle inte klara av att bibehålla vakuumet i kärnan, inte med dagens polymer teknologi. En modern panel med fumed silica i kärnan har en initial värmekonduktivitet på 0,004 W/(m·K) men om trycket i kärnan ökas till omgivningens tryck ökar värmekonduktiviteten till 0,020 W/(m·K). Tätheten hos barriären är alltså avgörande för panelens exceptionellt goda termiska egenskaper och därmed är panelens livslängd är alltså starkt beroende av barriärens täthet.

Forskningen som presenteras här behandlar två signifikanta aspekter hos vakuum isolering, dels problematiken med stora köldbryggor hos vakuumisolering med plåthöljen och modellering av transmission av gas genom polymera filmer med dubbla metalliseringar.

För att komma tillrätta med de stora köldbryggorna hos paneler med plåthöljen föreslår och utreds ett kantelement i form av en serpentinformad kant. Designen har modellerats avseende dess termiska egenskaper och en prototypkant har tillverkats och evaluerats genom mätningar. Designen har optimerats både avseende serpentinernas djup samt antal. Resultaten visar att en korrekt utformad kant av serpentintyp reducerar värmeflödet betydligt.

De bästa på marknaden förekommande barriärfilmerna är så bra att existerande instrument har svårt att mäta deras permeabilitet och för de få instrument som har tillräcklig precision tar en sådan mätning väldigt lång tid. En modell av flödet vore därför önskvärd. Alla modeller för gas flöde genom metalliserade polymerer bygger på antagandet att gasen endast kan diffundera genom defekter i metalliseringslagren, så även modellen som presenteras här, men det finns få modeller som över huvudtaget hantera filmer med mer än ett metalliseringsskikt. De modeller som har presenterats antar att alla defekter är av samma storlek och att defekterna är placerade i perfekta rutnät. Modellen

som beskrivs inom ramen för denna Licentiat avhandling inkorporerar både defekternas faktiska storlekar och dess faktiska positioner. Lösningen bygger på tekniker utvecklade för att lösa elektriska nätverk. Barriärfilm tagen från en Vakuumisoleringspanel har evaluerats i ljusmikroskop och data för defekter i de två metalliseringslagren har karakteriserats. Dessa data har använts som indata i modellen och resultaten visar god överensstämmelse med rapporterade resultat från mätningar på likartade filmer.

Preface

This thesis presents research done within the project Advances in Thermal Insulation, Cooperation within EU and IEA which was funded by The Swedish Research Council Formas. The project included involvement in two European projects The EU SAVE EnPeR and the KoPractice project as well as one international IEA project. EnPeR was a project where a European platform for information exchange was established to exchange information on the existing energy regulations in the participating countries and on the development of new procedures and regulatory measures in the EU as a whole. The KoPractice project dealt with an old computer program which basically was a program in which the user could look up building details in a database and receive thermal evaluation of the selected building detail. The IEA/ECBCS Annex 39 dealt with the use of Vacuum Insulation Panels in buildings. My research has come to focus on aspects of Vacuum Insulation and is thereby related to the IEA Annex 39.

Through my years as a doctoral candidate at the Department of Civil and Architectural Engineering I have had the opportunity to collaborate with many great persons, some collaboration have resulted in research other in interesting discussions.

Paper I is in part based on collaborative work with Källebrink I who did his Masters project on the subject of a serpentine edge. The article itself is written by the author of this thesis.

Paper III is written in collaboration with colleges from the Faculty of Architecture Urbanism and Building Sciences at Delft University of Technology, Martin J. Tenpierik who is a doctoral candidate and his supervisor prof. ir. Johannes J.M. Cauberg. I wrote mainly the parts related to thermal performance of vacuum insulation.

I would like to thank all persons that have helped me though the years. I would especially like to thank those persons that have, without any reward, engaged themselves and pushed me in my research.

I also must acknowledge and thank my family, and friends who have been patient with me during this time, I love you all.

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List of papers

Paper I

Thorsell T. and Källebrink I., 2005. Edge loss minimization in vacuum insulation
panels I. Proceedings of the 7th symposium on Building Physics in the Nordic
Countries, June 13-15th, Reykavik, Iceland.

Paper II

Thorsell T., 2006. Edge loss minimization in vacuum insulation panels I. Proceedings
of the 3rd International Building Physics Conference, August 27-31, Montreal,
Quebec, Canada.

Paper III

Tenpierik J., Cauberg J. M. and Thorsell T., Integrating Vacuum Insulation Panels in
Building Constructions: an Integral Perspective. Accepted for publication in
Journal of Construction Innovation

Paper IV

Thorsell T. A hybrid model for diffusion through barrier films with multiple coatings.
Submitted to Nordic Journal of Building Physics.

Contents

Enclosed papers:

Paper I: Edge loss minimization in vacuum insulation panels I.

Paper II: Edge loss minimization in vacuum insulation panels II.

Paper III: Integrating Vacuum Insulation Panels in Building Constructions

Paper IV: A hybrid model for diffusion through barrier films with multiple coatings.

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Introduction

In the whole European Union the total energy use was 930 Million tons oil equivalents, Mtoe, during 1997. Out of this 40.7% is used in the residential and commercial sector. Out of the 40,7%, around 55% is used for space heating, 52% in the residential and 57% in the commercial sector. It has been derived that more than 25% of the EU energy use and thereby CO_2 emissions are caused by heat transfer processes in buildings, (IEAa, 2005).

There are many efforts to reduce the released amount of CO_2 emissions in the world; the Kyoto Protocol for one is a treaty where many countries commit to a relative decrease in the release of carbon dioxide and five other greenhouse gases. Today's energy use is more and more governed by concern of the environment and prices of energy. In past times when it was the open fire or the wood burning stove that was used to keep our dwellings warm at night, the limiting factor for the amount of available heat was the availability of fuel to burn.

Long before the race of Homo sapiens, humans, our predecessors sheltered in caves. Caves provided shelter for protection from wild animals and the weather. Skin and furs from killed animals was used to keep warm and dry. In prehistoric times nature provided insulation materials like fur, feathers, cotton and wool. Homes in early history were built by stone, wood, earth and other easy to come by material. Cork was used by the Romans as insulative soles and by the early settlers in Spain who lined their houses with bark from the cork three. Mineral fibers found in volcanic deposits where first used by Hawaiian natives. The fibers formed when hot steam flowed through lava forming fibers.

In the 12 to 13th century the fireplace was introduced by Norwegians and Icelanders which led to an increased importance of insulation in order to keep the produced heat inside the shelter. Among others, people in the northern Europe used thick layers of straws and thick timber as insulation. People of the southern seas used the hollow fibers of sea grass to insulate their dwellings, (Bynum, 2001).

It was not until the industrial revolution in late 19th century that the use of thermal insulation became main-stream. Cabot's quilt, which is a composition of sea grass stitched between two layers of paper, was developed in the 1890s. The first commercially available mineral wool product was introduced in 1840 in Wales and was applied for pipe insulation. The first commercially produced mineral wool was introduced in the USA in 1875 and in 1897 the Chemical Engineer C. C. Hall managed to produce rock wool for the first time. The rock wool manufacturing expanded fast and by 1928 there were 8 manufacturing plants in US.

When it comes to glass fibers the ancient Egyptians discovered the technique of drawing glass into threads but it was not until 1931 the modern process of glass wool production was developed, (Bynum, 2001).

Price and availability does have strong influence when it comes to building materials, in the western plain states of the United States regular hay bales was used to build houses, it was a readily available material to quickly create a shelter before a "real" house could be afforded. Another insulation material that gained popularity was wooden shavings which still are found in older houses in Sweden.

From the beginning of the 1980's century we have been improving the thermal standard and increased energy consciousness. In a well insulated building of today's standard it is common to find 30 cm or more of high performance insulation materials in a wall and up to one meter of insulation in the roof. The method of increase thermal insulation in buildings by thickening the insulation layers is reaching its realistic limit.

Air as an insulator has reached its limit

In traditional building insulation materials of today, which are mostly developed before the 1960's century, the main insulator is air. Fibers and cellular structures are used, in the material, to prevent any bulk movement of the air within the structure of the material which would lead to increased thermal transport by convection. Convection is one mechanism through which thermal energy is moved through a material. Other mechanisms are conduction and radiation. Thermal transfer mechanisms are described in the chapter Physics of thermal insulation, thermal transport. When air is the insulator the best possible value of conductivity is 0.026 W/(m·K) which represents still air.

A traditional approach to enhance thermal performance of a building envelope is to increase the thickness of the insulation layer. This approach has limitations; economical due to reduced living space if new insulation is added on the inside of an existing building, possible need for a new façade if the building is insulated on the outside. A more effective approach to reduce heat loss would be to minimize thermal bridges, a reduction which can decrease transmission heat losses between 20 to 40 % in well insulated building such as regular buildings in northern countries, (Mao, 1997). Objectives that could be reached by use of an insulation material which had a lower thermal conductivity, in the first case by exchanging traditional materials in the envelope and in the second case by using a good insulation material to prevent thermal bridges. Other problem if traditional insulation materials where to be used in increasing thicknesses other problems would become more apparent such as:

- increased production costs
- more transportation costs
- greater self weight
- fixing problems due to thickness of layers

Particular problems also exist with composite panels where it is difficult to control the rise and cure of deep foam layers, (Ogden and Kendrick, 2005).

To develop more efficient insulation materials than the air based materials a number of techniques have to be used. Some involves replacement of gas contained in a material, addition of radiative absorbers or scatterers into materials or even evacuation of all contained gas within the material. Each of these measures is aimed to prevent one or more of the thermal transport mechanisms; conduction, convection and/or radiation. To improve materials further it is necessary to address these mechanisms and to minimize each of them. One available, well known, example of a successful improved technology which does just this is the insulative multi pane window. Low emission coatings are used to reduce radiative thermal transport and heavy low conduction gases are used to reduce the conduction as well as the convective thermal transport.

Physics of thermal insulation, thermal transport

As already mentioned, thermal transport in any material takes place by the three distinctive mechanisms conduction, radiation and convection. In general the different transport mechanisms are non-additive, even though often assumed as such, instead the resulting heat transport is usually larger than sum of its components. In foams and coherent solid skeleton materials such as fumed silica this coupling effect is negligible, (Fricke, 2001).

Solid conduction

Conduction is mostly associated with solid materials such as metals. Thermal energy which really is movement of molecules within materials is transferred through the material by transfer of energy between molecules as they collide with each other.

Gas conduction

Gas-conduction is heat transfer due to the interaction between molecules in the gas in the same manner as in solid conduction. To prevent gas conduction the mean free path (measure of the average distance traveled by a gas molecule before it interacts with other gas molecule) of the gas molecules has to be longer than the pore size of the core material. This means that if a material with relatively smaller pores is used as core material then the core pressure (amount of gas molecules left) can be allowed to be relatively higher before gas conduction occurs.

Convection

Convective heat transfer is due to movement within a gas or a liquid and the mediums heat capacity. In buildings the most common medium is air. The medium carries heat from one point in a space to another point transferring the heat.

Radiation

Radiation is heat transmitted by electromagnetic radiation due to temperature differences between bodies. All surfaces emit and receive radiation. The radiation exchange between two surfaces depends on the temperature, surface properties and mutual geometric position but will occur independently of the pressure.

Better thermal performance by vacuum

Sir James Dewar, a scientist at Oxford University, introduced the use of vacuum in 1892 when he invented the "vacuum flask" which later was refined by two glass blowers who formed the company Thermos GmbH. Thermos bottles were first commercially manufactured in 1902 by this company, (Thermos, 2005), (Fricke, 2005).
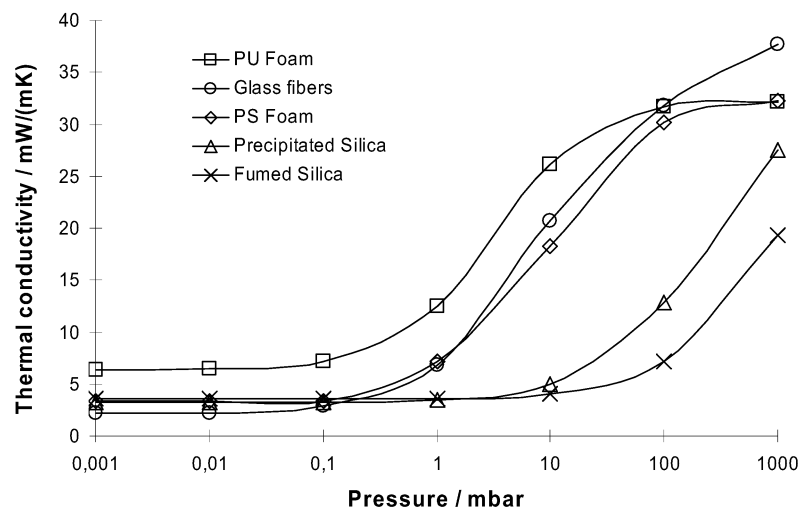
Fig. 1: Heat conductivity of materials as a function of pressure within the material, (IEAa, 2005).

Vacuum can be used to improve thermal properties of most open porous materials that are used as traditional insulation materials. Different levels of vacuum are needed for different materials to reach low thermal conductivities. The particles of the core material have to be so small and of a shape that

4

conduction is limited. Actually many of the currently used insulation materials can be used as core material for vacuum insulation as for example glass wool with its thin glass tubes will improve to similar values as a silica core but at 0,1 mbar. The thermal conductivity, however, will rapidly increase as a function of increased pressure whilst a core of silica or aerogel will maintain the low conductivity at higher pressure, up to a pressure of 1/10 of an atmosphere. This characteristic is essential in reaching lifetimes usable for the building industry. This issue will be discussed more in later chapters.

New insulation materials

There are a number of materials that can be found in literature that utilize new approaches or resurface old knowledge such as vacuum in order to achieve high performance thermal insulation. Aerogels is a product which is a very good insulator just by its material properties due to its fine pore structure it gains some of the advantages as of a material placed in vacuum but in atmospheric pressure. Gas-filled panels are herein the name for a gas filled polymer construction which has a large number of cells filled with a heavy gas such as Argon, Krypton or Xenon. The same gases are used in multi pane windows. Other materials and structures go further by evacuating a large portion of the gas within the structure. Examples that are presented here are evacuated glazing and vacuum insulation panels which is the main subject of this thesis.

Gas filled panels

As in the insulative glazing which uses heavy gases, there are experimental insulation materials which combine gases such as Argon, Xenon and Krypton in combination with high gloss polymer walls in a honey comb geometry, Image 1. The free space in the combs are filled with the gas of choice to improve the performance close to that of the selected filler gas, with a choice of Xenon an improvement of more than a factor of two compared with an air filled version. Laboratory tests where gas filled panels, containing Krypton, where used in the doors of a refrigerator/freezer show an over-all improvement by 6.5% compared with traditionally insulated doors in the same refrigerator/freezer.
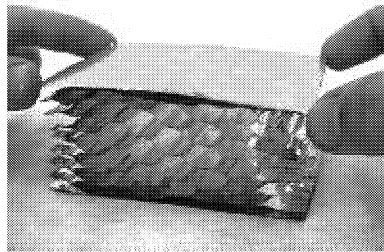
Image 1: A small sample of the internals of a gas filled panel, photographer Windows and Daylighting Group, Lawrence Berkeley Laboratory.

Computer simulations based on the results from the test shows that a performance increase of 25% can be expected if this type of insulation where used throughout the entire refrigerator/freezer, (Griffith et. Al., 1995i). However, to reach the reduction of 6.5% the design of the tested refrigerator had to be improved also. Gas filled panels have not been introduced into the construction market even though some preliminary steps have been performed. In another paper Griffith et. Al. discusses the possibility of using GFP in buildings. Some results in a studded wall were presented in this article. Results was reached by two-dimensional numerical calculations show an improvement of 30 % in a wall containing 45x120 mm studs with cavity insulation, (Griffith et. Al., 1995ii).

Aerogel

Aerogel is a material in which the structure is more than 90% empty. The internal structure of Aerogel limits all three mechanisms of thermal transport which leads to a material with exceptional thermal properties. At atmospheric pressure and combined with carbon black a thermal conductivity of 0,0135 W/(m·K) can be reached at atmospheric pressure, (Berkeley Lab, 2006).

Aerogel was first discovered in 1934 when Kistler and Caldwell reported about a material which had some amazing properties, (Kistler and Caldwell, 1934). This new material had the lowest measured thermal conductivity, so far, in history. The found material is created from drying a gel under critical conditions. What this means is that the gel is dried in a way to prevent the pores of the gel from collapsing. In the same report Kistler and Caldwell suggests a vacuum panel construction for the first time using powdered aerogel as core material. Aerogel today is used mainly as a filter material and is almost exclusively sold for research.

Evacuated glazing

The transparent evacuated insulation is an insulation material utilizing vacuum to eliminate convection and gas conduction. The idea to create a flat material with vacuum inside is was first applied for patent in 1913, only 20 years after

the invention of the Dewar flask according to Collins, (Collins et. Al., 1992). Collins refers to a patent document by Zoller A., in 1913. The insulation material described by Collins et. Al. is basically a window with two glass sheets which are sealed tight around the edges and the intermediate space are evacuated of all gas to create vacuum. The two glass sheets are kept apart by distances of different forms some spherical and some in the form of small pillars. The research in this area seems to be ongoing with several recently published articles, (Weinläder et. Al., 2005), (Dey C. et. Al., 1998).

Vacuum insulation materials

A vacuum insulation insulation, Image 2, is a material which has a volume filled with some kind of core material which is wrapped by another material functioning as a barrier. The gas originally in the core is evacuated to reach extraordinary levels of thermal insulation. A thermal conductivity, at a core pressure of 1 mBar, of 0.004 W/(m·K) is normal, se Fig. 1. The barrier material can be metal sheeting, metal foil, polymer films or combinations of polymer films and metal foils or metallization layers which are composited into single films. Vacuum insulation is divided into different sub categories depending on their structure.
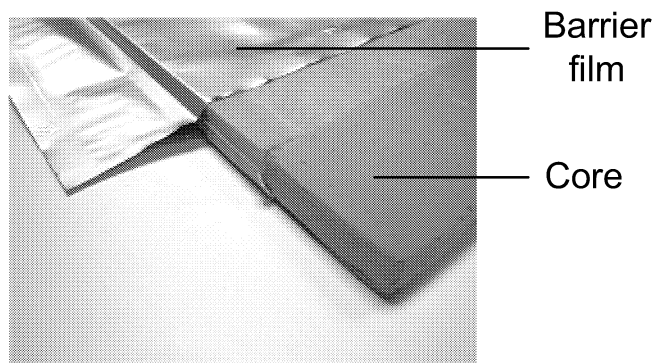
Image 2: A vacuum insulation panel of a design readily available on the European market today.

Panels with barriers of polymer and metal composite films are often referred to as vacuum insulation panels, or VIPs, whilst a panel with a welded all metal barrier are referred to as a Vacuum Insulation Sandwich. The most common core material used is precipitated or fumed silica due to its characteristics at moderate levels of vacuum.

With VIP insulation levels common today can be reached with only 5 to 10 centimeters of insulation, instead of 40. Future even stricter demands can be met without an excessive increase in thickness of the thermal shell in new buildings. VIP is already commonly used in high end appliances such as freezers and refrigerators. Initial markets for VIPs designed to be used in

building applications have been established in Germany and Switzerland (Erb, 2005). The use of VIPs is of course especially advantageous where space is scarce or where another added-value is found.

The research carried out and this report deals mainly with VIP, hence vacuum insulation panels with a core of fumed silica with polymer barriers which has one or more metallization layers within the composite film. In paper I and II some aspects of VIS or vacuum insulation sandwiches are discussed even though the panels are not labeled as such within those particular papers. There they are also are called VIPs.

Vacuum insulation panels.

There was strong interest in Vacuum insulation materials of different sort during the end of the 20th century. Manufacturers of refrigerators and freezers had to replace the commonly used CFC blown foams that were used in appliances at that time. One of many possible replacement materials was vacuum insulation materials. Many different materials were tested and optimized for use as core materials in vacuum insulations during this time.

Materials that where evaluated and used for the core materials in vacuum insulation panels were glass fibers, (Fay, 1991), open pore foams, (De Vos et. Al, 1996), (Tao et. Al., 1997), and powders such as perlite powder, precipitated silica and fumed silica as described by Caps and Fricke (Caps and Fricke, 2000) many where discussed much earlier and summed up in a review article by Alan Fine in 1989 (Fine, 1989).

As the vacuum technology was used in specific applications such as the mentioned refrigerators and freezers as well as in transport packaging, cold storage and others, it became clear that this technology could become an effective mean to save energy. In the presence of the global strive to save energy and lower the amount of release green house gases which is intimately connected to the amount of energy used for heating the building stock in the world; the interest for vacuum insulation in buildings grew strong.

In 2002 a report prepared for the U.S. Department of Housing and Urban Development was published, (U.S. Department of Housing, 2002), as the result of a research project spanning over three years. The aim of this report was to accelerate the use of VIP in building in the U.S.

In Europe an IEA project was started in 2001, the Annex 39-High performance thermal insulation. The work in this project was divided into two subtasks, subtask I dealt with the panel itself and its components whilst subtask II dealt with applications which uses vacuum insulation panels. It was decided early in the project that it was to limit the work to deal with vacuum insulation panels with silica powder core materials.

Hence a VIP, a vacuum insulation panel, has two major components; the core and the envelope. Each component with a specific task, the barrier is to protect the panel from outside agitations as well as prevent, if possible, any gas from penetration into the core. The core on the other hand must be able to support the pressure created on the surface of the envelope when the core is evacuated. The core must also have an internal structure which in the best possible way utilizes the low pressure.

Another important aspect of the barrier is its sealing properties, hence how impermeable will the seams be. This property will be governed by the innermost layer of the barrier composite film. If the barrier is a metal sheet the

preferred method would be welding but in the case of polymer composite films the common method is heat sealing. The properties of the seam by heat welding were investigated by in the IEA Annex 39 work package, (IEAa 2005).

There are several steps included in manufacturing a VIP. The first step is to mix a small amount of fibers into the core material in case of a core consisting of a powder to create a material that can be handled. The core is then enclosed by a fleece envelope and placed in a pressing tool to take the form of a board similar in feel to a very low density wood fiber board. After the board is cut to dimensions it is placed in a barrier envelope then all air is removed from the package and the envelope is sealed under vacuum. The result remind of a package of vacuum packed coffee that has been flattened. As long as the internal vacuum is withheld the board will retain its stiffness.

The panel is evacuated to a lower pressure than what is necessary to reach the low conductivity, this is done to allow some gas leakage into the panel during its life time, such leakage will occur in any panel with polymeric barrier since no currently available polymeric film is absolutely gas tight. The internal pressure is initially much lower than what is required to give a safety factor and to increase the lifetime. Another measure that is used to secure and prolong lifetimes of panels are the addition of getters or desiccants, which is a component or chemical inserted to the core to trap moisture or residual gas.

Vacuum panel lifetime

The single most important component of a VIP is the barrier properties of the envelope. The properties of a polymer barrier is influenced by the surrounding environment, moisture and heat is contributing factors to rapidly increase diffusion into a VIP and thereby decrease the performance of the panel. Fumed silica, which is a commonly used core material in panels used in buildings, has the capacity to bind both water vapor and air to some content oppose performance loss due to permeation. This will obviously decrease initial effects on performance by diffusion of gas into the panel.

A vacuum insulation panel's life time will depend on:

- Minimum performance requirements
- Panel size
- Fabrication quality
- VIP component choices
- Use conditions
- Handling

The first five are identified in the U.S. Department of Housing, 2002 report and each individual aspect will be discussed below, (U.S. Department of Housing, 2002).

Minimum performance requirements
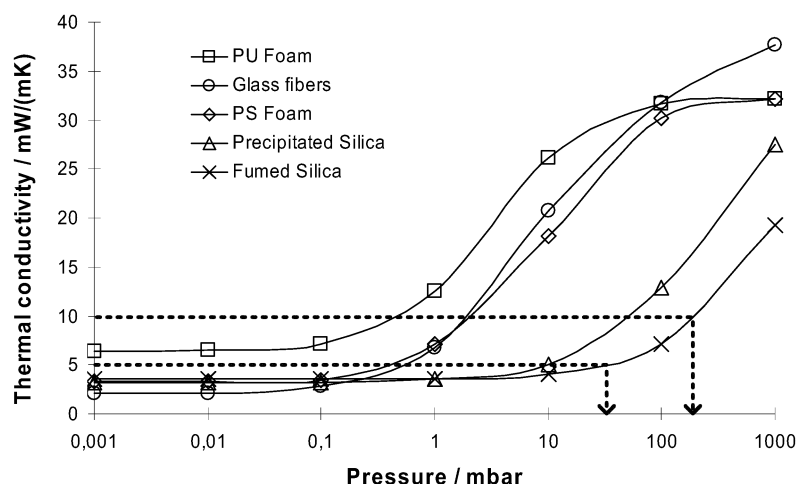
Fig. 2: Show how the minimum performance criteria govern the allowable internal pressure of a VIP.

In a specific application it might suffice to have an insulation material that has a thermal conductivity of 0.010 W/(m·K). If that is the case, some gas can be allowed to leak into the panel before it is deemed as have reached the end of its service life time, whilst if a thermal conductivity of 0.005 W/(m·K) is necessary, then the allowed increase in thermal conductivity due to gas leakage is very small. In this case the panel would reach the end of its service life time in shorter time than in the first case. That is if all other circumstances are equal. In Fig. 2 the two cases, described above, are plotted. The case with a maximum allowable thermal conductivity of 0.010 W/(m·K) can allow five times higher internal pressure before the panel reaches its end of life time. If this is compared with the case with a minimum performance of 0.005 W/(m·K) which can only allow an internal pressure raise up to 50 mbar. This example reflects the case of panels with a fumed silica core.

Panel size

A larger panel will have a longer expected lifetime than a small panel. The effect of the panel size is simply due to that the relation between volume and seam length as well as volume to barrier surface relation changes. The seam is pointed out in several reports as one major area where permeation takes place, (U.S. Department of Housing, 2002), (IEAa 2005). Therefore, if the thickness in this case is increased in relation to the length of the seam then more gas can be allowed to penetrate into the core before the end of life criterion is fulfilled. If the surface size of a panel is increased then this ratio will also increase but not as rapidly. Gases do penetrate also through the barrier film itself unless it is

11

made of metal sheets or thick foils. Also in this case, a larger volume in relation to the surface area is helpful to increase the service lifetime of a panel. In the case of larger panels then the diffusion through the barrier is increasingly taking over in importance over the seam leakage.

Fabrication quality

Into this section goes all care that are being taken during the manufacturing of a panel as well as any quality assurance in order to verify that panels leaving the manufacturer is as good as agreed on with the buyer. It is important that the film is not stressed by bending, wrinkling or pulling during evacuation or later handling, (Roderick et. Al., 2005). For example some manufacturers fix the excessive barrier material onto one surface of the panel creating sharp bending as well as wrinkles at the panel's corners.

Another important aspect is quality assurance. There is a German company which has incorporated a small piece of open porous fleece on top of a piece of a metal plate into their panels which allows them to measure the internal pressure after manufacturing as a step in quality assurance. This has been described in a paper presented by Caps R. at the 7th International vacuum insulation symposium in 2005, (Caps, 2005). Another company relies solely on visible inspection after that the newly manufactured panels have been stored for a specific amount of time. One finding during the testing for the IEA, annex 39 project was that a fraction of panels would fail within a short period of time after manufacturing, (IEAa 2005).

VIP component choices

As can be seen in Fig. 2 different core materials need different levels of inside pressure to reach really low thermal conductivities, for an example fiber-glass reaches the lowest thermal conductivity of close to 0,002 W/(m·K) but in order to do so then the internal pressure must be below 0,05 mbar whilst a fumed silica core does not reach as low but it will maintain a low thermal conductivity of 0,0035 W/(m·K) even at an internal pressure of above 1 mbar. Some core materials that are used also do release residual gases from the panels, even though pretreated before the envelope is closed, (U.S. Department of Housing, 2002).

Another important component is of course the chosen barrier material. A better, hence a more gas tight, barrier material will do a better job at preventing the gas from entering into the core material. The gas permeation through polymer based film with metallization layers are discussed more in depth in later chapters as well as in Paper IV.

Yet another component that greatly influences the allowable amount of penetrating gas is the addition of getters or desiccants. These components can help in absorbing any incoming gas or moisture, preventing increased pressure. These materials are discussed more in the chapter: Getters.

Conditions of use

The conditions under which a panel is used will also affect the life time of the panel. In the report of IEA it is shown that panels do fail under certain circumstances, (IEAa 2005). Similar conclusions are reached in the report from the (U.S. Department of Housing, 2002), both heat and moisture will affect the permeability of a polymer based barrier film. The underlying mechanisms of molecular transport are discussed in the chapter: Polymer and coated polymer film barriers. Another environmental concern for any polymer is exposure to radiation which can lead to radiative degradation as described in the chapter about polymer degradation.

Handling

When handling a panel, both during manufacturing and at a construction site or any other place where the panels are to be installed, great care must be taken. Any break, bend or indentation can be a source for increased permeation due to micro cracks or other defects. This is particularly true for composite films with metallization layers with thickness in the nano-meter range. Any defects no matter, however small, can lead to increased gas permeation through the film, (Roderick et. Al., 2005).

Getters

Desiccants, or getters, are components or chemicals inserted to the core to trap moisture or residual gas to prevent a pressure increase in the core. A pressure increase which would lead to higher thermal conductivity in the core. The difference according to the report from U.S. Department of Housing between a getter and a desiccant is that the latter removes moisture whilst a getter is designed to remove molecules from atmospheric gases, (U.S. Department of Housing, 2002). Getters are more complicated to produce and therefore more expensive.

The characteristics of fumed silica, with its huge specific surface area, results in very high sorption capabilities. 1 kg of the material will adsorb 0.05 kg water at 75 % relative humidity. Thus fumed silica itself is a desiccant, (IEAa 2005).

Thermal performance of a VIP

A vacuum insulation panel can not be regarded as a single material; it is a composite of several different materials. There is the core which by its properties under vacuum is a very good insulator. Fumed silica has a thermal conductivity in the magnitude of 0.004 W/(m·K) an internal pressure of maximum 10 mbar. This is the value that would be found if the conductivity was measured in the middle of a large vacuum panel, herein called the center of panel value.

The barrier on the other hand is the key to the service lifetime of the VIP. If the barrier has very low permeability, the panel will have a longer service life than if the barrier has higher permeability. A core with small pores will reach lower heat conductivity at higher inside pressure than a core with larger pores due to physics of heat transfer as described in chapter: Physics of thermal insulation, thermal transport. Independently of what material is used in the barrier or the core the barrier will create a thermal bridge when wrapped around the edge of a panel even if an all polymer barrier would only create a very small thermal bridge.

Also at the corners of the panel additional thermal bridges will occur, so called point bridges. To calculate the total transmittance through a panel all the thermal bridges have to be added to the center of panel transmittance times the area, se Eq. 1.

$$\Phi = \left(\sum (U \cdot A) + \sum (\Psi \cdot l) + \sum X \right) \cdot (\theta_i - \theta_e) \qquad \text{Eq. 1}$$

Φ Total heat flow rate through the panel (W)

U Thermal transmittance in the centre of the panel (W/(m² ·K))

A Area of the calculated panel (m²)

Ψ Linear thermal transmittance of the edge (W/(m ·K))

l Length of the calculated panel (m)

X Point thermal transmittance (W/K)

θ_i Temperature on the inside (°C)

θ_e Temperature on the outside (°C)

The core

The material that is to be used for the core within a vacuum insulation panel has to have a number of specific properties. The core material must have open pores in order to evacuate any gas in the core; the pores must be small and have a geometry which renders small points of contacts between the structures in the material even under high load. The material must be able to withstand high loads without collapsing. Finally the core must resist radiative transfer. The core material of choice in Europe is currently fumed silica which has all the above properties.

Fumed silica is a product produced in a flame process where $SiCL_2$ is processed to produce SiO_2 aggregates. Fumed silica is stable enough to withstand the pressure of 10 tons per square meter as is created by the pressure difference when the core is evacuated. At the same time it has exceptionally small pores, pore sizes in the order of 10 to 20 nanometers, with a specific surface area higher than $200m^2/g$, the porosity is above 90% and the density is in the range of 160 to 190 kg/m^3. This is data for the fumed silica material which was investigated in IEA, Annex 39, (IEAa 2005).

A VIP is evacuated to suppress convection as well as gas conduction within the core. The small pore size in conjunction with low pressure restricts gases from any bulk movement (convection) within the remaining gas.

To prevent gas conduction the mean free path (the measure of the average distance traveled by a particle during a certain period before it interacts with other particles) of the gas molecules has to be larger than the pore size of the core material. This increases the probability of the vibrating (varm) molecules to hit the structure of the core instead of another molecule, hence not transferring any energy between the molecules. The smaller the pore size, the higher the pressure allowed until gas conduction occurs.

Conduction within the core is limited by the geometric shape of the particles in the material. Glass fibers for example are tubular and most powders have spherical particles leading to a very small area of contact between the particles. Since conduction needs to pass through this small area of contact the total core conduction will be very small.

All surfaces emit and receive radiation; the amount depends on the temperature, surface properties and geometric positioning in regard to other surfaces. This radiative exchange is minimized by adding opacifiers or some molecules to act as scatterers to the core material. A combination of opacifying powders with silica can, in vacuum, reach a conduction of 0.003 W/(m·K) (Caps and Fricke, 2000).

The barrier

The most important objective of the barrier is to prevent surrounding gases from entering the core. If gases are allowed into the core then the pressure inside the core will increase, this pressure increase results in an increased thermal conductivity in the core. When the pressure rises, or the core conductivity, above a certain level, the end of service life time has been reached. Many materials can be used as barrier materials ranging from single layer polymer films to solid metal enclosures. A panel with an enclosure made of metal sheets welded into one piece would be virtually gas tight which would be advantageous for the lifetime of such a panel. A VIP manufactured with an all-polymer barrier would in contrast have a short life time. The most common solution today is a combination of polymer films and metal coatings in a composite film. Such barrier films consist of several polymer layers with one or several metallization layers, coatings, hence a thin metal layer. The gas flux, permeation, through the barrier must be small enough so that the panel will reach the designated life time in the range of 30 to 50, or even 100 years. The IEA report, (IEAa, 2005), states the limiting value for the oxygen permeability to 10^{-2} cm^3/(m^2·day·bar) in order to reach at least 30 to 50 years of service life time. If the vacuum is lost and the internal pressure increases to the ambient pressure the thermal conductivity will increase to 0.020 W/(m·K), hence an increase of 500% of the thermal conductivity in the core. The seam of the envelope usually has larger diffusion than through the film itself, this is overcome through use of wider seams. Another way to decrease permeation through the seam would be to improve the quality of the seam.
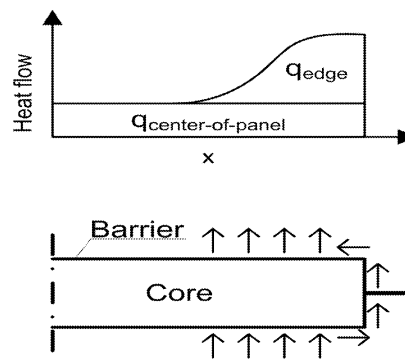
Thermal bridge effect

Fig. 3: The image show a graphic illustration of a section of a typical design of the edges of a vacuum insulation panel and the path for the heat to travel resulting in a linear thermal bridge around all edges of the panel, figure is originally found in Paper I.

16

The best construction in regard to life time is an all-metal enclosure. The down side of a metal enclosure is that metal is generally a good conductor for heat whereas the material binding the two panel faces together would create significant thermal bridges around the edges of the panels as drawn in Fig. 3. On the other hand an all-polymer barrier with low conductivity would be preferable to decrease the thermal bridge effect at the edge but no all-polymer film has good enough barrier properties for panels to reach the desired lifetimes necessary for a building material

Serpentine edge

To make it possible to use the preferred thicker metal material for the edge of a VIP we propose an altered design of the edge part of the barrier, a serpentine edge discussed in Paper I and Paper II. The idea to form a serpentine edge came from an already existing design involving thin metal layers breaking through relatively thick insulation layers, namely the web of a steel stud breaking through an insulation layer as it would in an insulated stud wall. Studs of sheet metal are frequently used in outer walls of modern buildings. The web of the stud breaks through the isolative layer creating a thermal bridge. To minimize the thermal bridge of the stud its web has been slotted to prolong the path that heat has to travel from one side to the other. A similar strategy is proposed in paper I and II to deal with the edge effect of vacuum panels. By designing an edge element with material going back and forth as shown in Fig. 4, the thermal bridge along the edge can be reduced significantly.
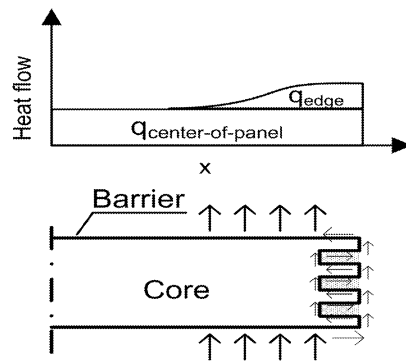
Fig. 4: With a serpentine edge the path for heat is prolonged with a smaller heat flow through the edge as the result

Numerical calculations, presented in paper I, show that an optimized edge design would improve the edge performance by a factor of three, se Table 1. Thermal testing of prototype edges have shown strong improvements compared to the traditional straight edges. Unfortunately it was not possible to make an edge element with neither 17 serpentines nor a vacuumized panel due to limitations in both available materials as well as in equipment. Instead a

17

serpentine edge was formed with 5 slots and PU foam was used to fill the voids. Both versions of edge pieces, one straight and one serpentine, were placed in a hot plate instrument at atmospheric pressure and temperatures were measured.

Barrier type	Ψ_{edge} W/(m·K)
Serpentine 5 slots, depth 30 mm[1] thickness of steel 0.1 mm	0.015
Serpentine >15 slots, depth 30 mm[1] thickness of steel 0.1 mm	< 0.010
Stainless steel foil[2], thickness of 50 μm	0.019
Aluminum foil[2], thickness 6 μm	0.026
Metalized polymer film[2], thickness 97 μm	0.0088

Table 1: Linear heat losses for some different barrier configurations for panels with a thickness of 30 mm. Calculated values from Paper I. Values produced within the work of IEA, Annex 39 (IEA-b 2005).

The measured temperatures show the same behavior as in the numeric model even though the measured temperatures show some deviation from the calculated temperatures, se Paper I and paper II for more details.

Polymer and coated polymer film barriers

If instead an all polymeric film is used then the thermal bridge effect is small but the permeability is much larger. To create an all polymer film with low enough permeability is hard, if not impossible with technology available today. Instead, polymer composite films are used. Composite films consist of multiple layers with basically one layer per needed function. Thin metal layers, so called metallization layers or coatings are added to improve the barrier properties of the composite film. One typical film from one VIP manufacturer is made of Nylon/Polyester/ Polypropylene/Polyethylene, some layers with added metallization. The Nylon layer is there for mechanical protection and the polyethylene layer makes it possible to heat-weld the seam to close the envelope.

Nowadays designs have flexible envelopes of composite type; they are heat-sealed at the short edges creating a flange on at least two ends of the panel. When this flange is bent towards any of the surfaces, as can be seen in Image 3, the thickness of the highly conductive metal, the metallization layer, is tripled. As a consequence the thermal bridge effect is substantially increasing. Even if a barrier film is used with ever so thin layers of Aluminum as when a polymer is metalized it will create a thermal bridge that affects the total

18

performance of the whole panel. In many cases this will significantly impair the performance of the panel.
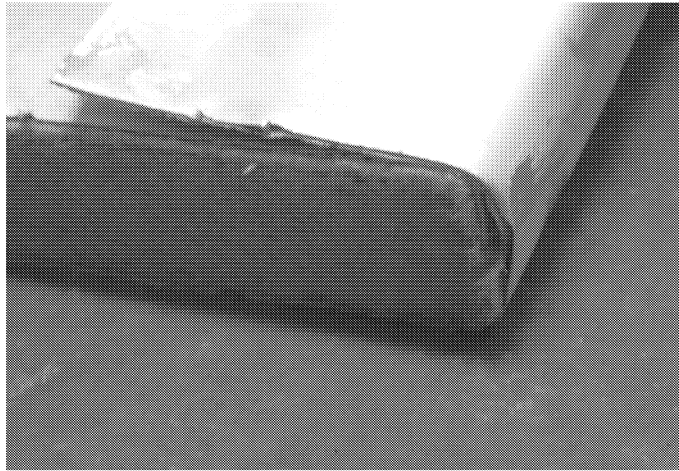
Image 3 show a cross section of a typical current vacuum insulation panel with excess material wrapped around the edge of the panel which increases the thermal bridge.

Some manufacturers still create this additional thermal bridge by wrapping the excess material around the edge as in Image 3, whilst other manufacturers have developed technologies to reduce the number of seems to three and place the longest seem on the face of a panel instead of at the edge, (Ghazi Wakili and Nussbaumer, 2005).

According to (Glicksman, 1991) this thermal bridge can increase the overall performance by a factor of two compared with the centre-of-panel value. A similar conclusion was reached by (Ghazi Wakili et al. 2004) after thermally testing several vacuum panels from different manufacturers. It was also concluded in the same study that there is significant edge-effect due to the wrapping of the barrier material around the edge of the panel reaching from about $6 \cdot 10^{-3}$ W/(m ·K) to $53 \cdot 10^{-3}$ W/(m ·K) depending on material properties of the barrier layer. The best performing barrier was a multi-layer metalized polymeric foil with an aluminum thickness of 90 nanometers and the worst performing barrier contained an aluminum foil with a thickness of 8 micrometers.

It has been shown that that moisture and heat is contributing factors to rapidly increase diffusion into a VIP hence decreasing performance of the panel. Fumed silica, however, has the capacity to bind both water vapor and air which to some extent delays performance loss due to permeation. This will obviously decrease initial effects on performance by diffusion of gas into the panel but in

the long run the internal pressure will increase and cause the center of panel conductivity to increase. It is also important to realize that materials degrade over time, this will in the case of polymer barriers result in an increased permeability through the barrier with a decreased over-all performance of the panel.

Polymer degradation mechanisms

Any materials in a building will be subject to different environments depending on how and were the material is installed. It can be exposed to a number of potential degrading agitations. Some examples are alternating temperature, pollution via the air, solutions with high Ph values which occur if in contact with concrete and mechanical stress during construction. Further a material could potentially be exposed to UV radiation if stored incorrectly at the building site.

a   b
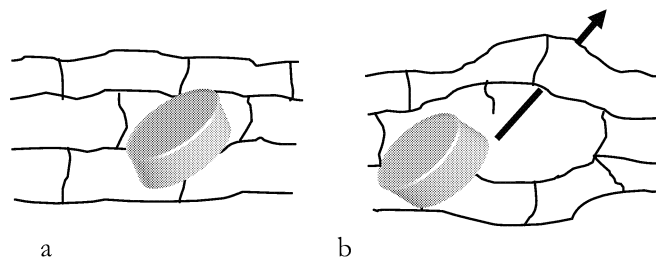
Fig. 5: Degradation that breaks up networked polymers will increase diffusion by allowing greater mobility in the network illustrated in b. Original network illustrated in a.

Many agitations will affect a plastic material greatly through breaking up the backbone chains or by transforming pendant groups. The backbone chain can also be lengthened by reactions between polymers. If a branch in a networked polymer is broken of, it will cause a chain interruption that might allow increased transport trough the material, se Fig. 5.

Degradation of polymers depends on the following factors, (Feldman, 1989):

- chemical environment
- heat and thermal shock
- ultra-violet light
- high energy radiation

In the special case of VIPs also diffusion of gases through barrier films is vital. Any changes allowing more gas into the core will therefore be considered degradation.

Thermal degradation is degradation due to elevated temperature in the material. Raised temperature leads to increased chemical activity. Van deer Waals bindings between polymer backbone chains gets loosened up to give a more flexible material. Thermal degradation in its pure form does not include any chemical reactions.

Chemical degradation in a strict sense is only chemical reactions with the polymer. Pending on influencing chemical the reaction can be named. If a polymer reacts with oxygen it is called oxidation and if influencing chemical is water it is called hydrolysis. More often differentiating thermal and chemical degradation is hard. Speed of a chemical reaction is increased with increased temperature and therefore it is hard to know if degradation is due to increased temperature alone or if the higher temperature induces a chemical reaction.

Photo degradation is due to influence by radiation on the material. In the building industry the UV radiation constitutes a real threat.

Biodegradation is degradation induced by something biological for example bacteria. Biodegradation is not an imminent risk in a building as long as the material is used above ground.

Mechanical stress can lead to mechanical degradation. Mechanical degradation can be as abrupt as a nail penetrating the barrier with immediate pressurization and fall to thermal conductivity of the core material at atmospheric pressure or as subtle as a worker stepping on the material at the construction site without any visible damage which leads to micro cracks in the barrier and increased intrusion of gas and possibly a premature failure. A VIP is such a fragile material that one has to assume careful handling at both the manufacturing site as well as at the construction site. The best route to ensure safe handling of VIPs would be to never allow the bare material at the construction site, instead supply the material integrated into building components which are more durable.

An important note when it comes to degradation of a polymer is that when exposed to more than one degrading factor at a time the sum of degradation is often greater than each factor summed up.

Diffusion, permeation and sorption are driven by the difference in concentration or the chemical potential on either side of the barrier film, (Soney and Thomas, 1999). Polymers with low glass transition temperature possess greater segmental mobility and will have higher diffusivity. It was also reported that the molecular weight, significantly influences the transport process. As polymer molecular weight increases, the number of chain ends

decreases. Every chain end represents a discontinuity and may form sites for permeant molecules to be adsorbed into glassy polymers.
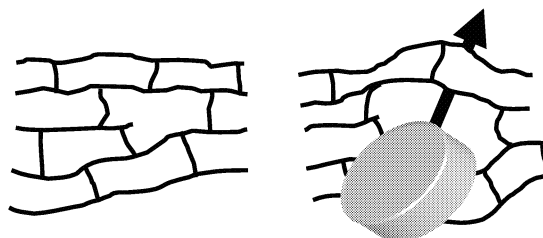
Fig. 6: A chain end can form site for a permeant to be sorbed into the polymer.

As shown in Fig. 5 and Fig. 6 the polymer grid influences permeation greatly. A more flexible grid lead to increased transport, a disrupted grid does the same. Polymer grids can be softened through use of heat, solvents or more permanently by use of plasticizers. Independent of method transport will increase.

The size and shape of the penetrant molecule will influence its rate of transport within the polymer matrix, (Chaney, 1989). A smaller molecule will have a higher transport rate than a larger molecule. Also the permeants shape has noticeable effect on permeability, for instance flattened or elongated molecules have higher coefficient than spherical molecules of equal molecular volume, (Berens, 1981).

If an inert filler is used and the filler is compatible with the polymer matrix, the filler will take up the free volume within the polymer matrix and create torturous path for the permeating molecules, (Feldman, 1989). The degree of tourtourosity is dependant on the volume fraction of the filler and the shape and orientation of the particles. When the filler is incompatible with the polymer, voids tend to occur on the surface, which leads to an increase in free volume of the system and consequently, to an increase in permeability, (Chaney, 1989).

Physics of gas permeation

The transport of small molecules through a polymer membrane occurs due to random molecular motion of individual molecules, (Chaney, 1989). Polymers with low glass transition temperature possess greater segmental mobility and will have higher diffusivity and as polymer molecular weight increases, the number of chain ends decreases. Every chain end represents a discontinuity and may form sites for permeant molecules to be adsorbed into glassy polymers.

Stannet reports that Graham formulated the "Solution diffusion process" as early as 1866 by observing and reporting the inflation of a wet pig bladder with CO_2. According to Stannet this is the first reported study of permeation

through a polymer. The governing function proposed by Fick, in 1855, by analogy with Fourier's law of heat conduction, of diffusion through a material is as shown in Eq. 2, referred to by Stannett, (Stannett V. 1978).

$$J_i = -D_{ij} \cdot \frac{dc}{dx}$$
Eq. 2

J_i is the gas flux of gas i through the matter j ($mol/(m^2\ s)$).

D_{ij} is the diffusion coefficient of gas i in the matter j (m^2/s).

dc_i/dx is the concentration gradient in the x-direction ($mol/(m\ m^3)$).

The diffusion coefficient, D, gives a measure of how fast a molecule of a specific kind can move through a specific material. Stannet describes how Exner (1875) and Stefan (1878) showed that permeation through soap films was proportional to the product of the solubility of the gas in water and the diffusion constant as described by Fick's law (Stannett V. 1978). In 1879, Wroblewski extended this work and showed that Henry's law of solubility, Eq. 3, was valid for gas solubility in rubbers also according to Stannett. The solubility, S, describes how many of a permeant gas's molecules will dissolve in the surface of, in this case, a polymer.

$$c_x = S_{ij} \cdot p_x$$
Eq. 3

c_x is the gas concentration at x

S_{ij} is the solubility of gas i in the matter j

p_x is the pressure at x.

Gas permeation through films with more than one coating

Gas diffusion through an all polymer film could be calculated in one dimension but in the best available barrier films, polymer films are combined with metallization layers into a composite film. As have been mentioned before, there are no all-polymer films that will be impermeable enough to create a vacuum panel with an expected service life time of 30 to 50 years. It is a necessity to add metallization layers into the film matrix. Metal foils could be regarded as gas tight if there weren't any defects, but there are. Se Image 4 for the defects in an Aluminum metallization layer in a barrier film on the market today. The image is a photograph taken through a light microscope, the colors are inverted for clarity and each black dot represents a defect.
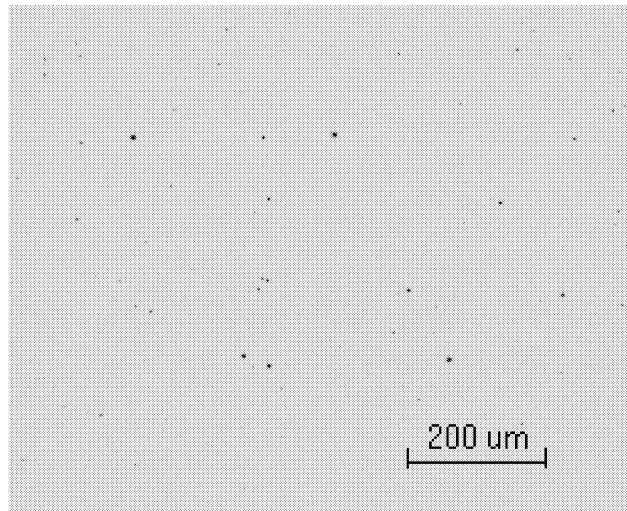
Image 4: Shows an Aluminum coating on the outside part of a VIP barrier including dual Aluminum coatings.

The diffusion of any non reactive gas, such as oxygen, through a crystalline material as in a non-organic coating is very slow and the main diffusion through a coated membrane will take place through areas that lack coatings or through defects in the coating. A number of studies have found clear correlations between defect density and permeation, (Jamieson and Windle, 1983), (Da Silva Sobrinho, 1998), (Chatham, 1996).

When it comes to films with very good barrier properties the measurement equipment can't really keep up. The lowest measurable oxygen transmission rate, OTR, is according to Musgrave, 0.0005 $cm^3/(m^2 \cdot day \cdot atm)$, (Musgrave, 2005). The best barrier films available are promoted by the manufacturers to have much lower permeation than this limit. Another aspect of testing such high barrier films is that, due to the low permeability, it takes a long time to reach steady state conditions. It would be a strong advantage if the gas

transmission through films with multiple coatings could be modeled with some degree of connection with reality.

Modeling of gas transmission through barrier films with dual coatings

There are a number of models of gas flux through barrier films with single coatings, hence a polymer substrate film on which a thin layer of metal has been added. There are also numerical models for permeation through films with two coatings, one coating on either surface of the substrate film. Generalizations are necessary in any model also in purely numerical models such as the models presented by Hanika et. Al. and Musgrave, (Hanika et. Al., 2003), (Musgrave, 2005). In numerical models based on finite elements it is necessary to generalize regarding defect to defect distances as well as defect sizes. Including this data would be strain-full for the user to input into the model as well as to compute for any regular computer. Many more assumptions and generalizations are made but these two are specifically addressed in paper IV, in which, a combined model is proposed for diffusion through a polymer film with double coatings.

Isosurfaces with constant concentration / mol/m^3
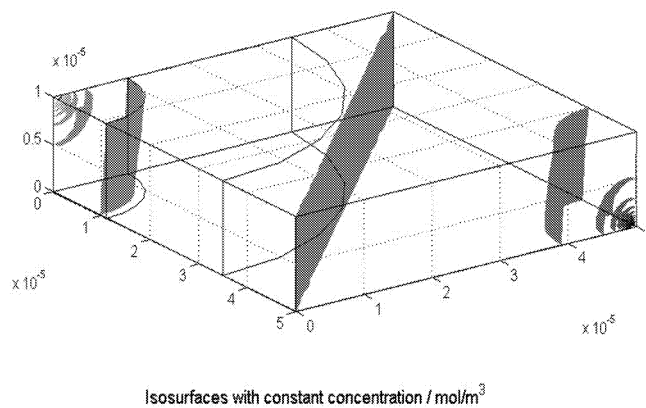
Fig. 7 show an isosurfaces plot from a numerical calculation, in the software package COMSOL Multiphysics, of the concentration between two interacting defects in two coatings on the opposite sides of a substrate film.

If the interactive flux between two defects, one in either opposite coating, is modeled in numerical software as for example COMSOL Multiphysics a resulting plot of isosurfaces can look like in Fig. 7. In this figure it can be seen that there are surfaces at about one substrate thicknesses in radius, from the center of the defect, that are basically constant. This surface was in the proposed model taken as a potential point in a resistance network. These potential points are then interconnected by a new layer of resistances as can be seen in Fig. 8 and a overview of the interaction between a number of defects is plotted in Fig. 9. The resistance near the defect, through which the gas enters

the substrate film as well as the resistance near the defect where the gas finally exits the substrate film, is modeled numerically; in Fig. 8 those resistances are denoted R_{entr} and R_{exit}. The resistance between the two cylinders, which are formed around the two defects, is calculated by theories of magnetic fields, so called dipoles.
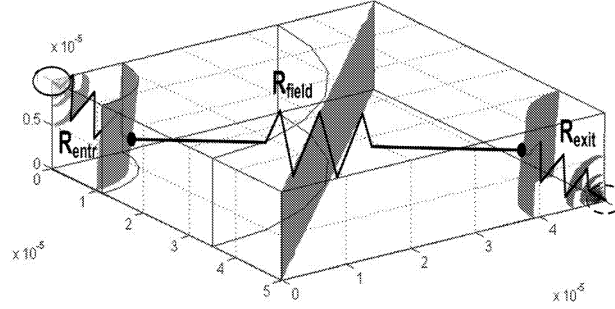

Fig. 8: Is the same as Fig. 7 but with the addition of the used resistances for the hybrid model.

Listing all entry and exiting resistances and interconnecting them by a layer of field resistances results in a large resistance system with as many resistances as there are defects in the coating on the high concentration side plus the number of defects in the coating closest to the low concentration side plus the chosen number of field resistances. The number of field resistances has to be chosen by the user, the optimal would of course be to allow all entry defects interact with all exit defects but that creates a system to large to solve for most computers. In paper IV, where this model is presented and used, four interactions per defect in the defect densest coating have been used based on the fact that in a numerical calculation with evenly spaced positions of defects it is assumed that each defect interact with four others. A representation of a part of such a resistance network is shown in Fig. 9.
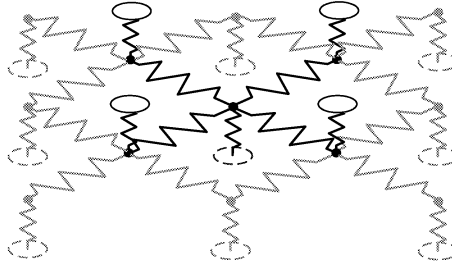

Fig. 9: Show a portion of the resistance network the interconnected defects create. This is the network that in the end is solved to calculate the total flux through the composite film.

If additional polymer layers are added on either outside of the metallization layers then this will add one extra layer of resistances per added polymer layer whilst if a coated layer is added then three layers of resistances would have to be added, one containing the resistance near the defects in the new coating, one containing the resistance near the defects in the existing coating and one layer containing the network web interconnecting the defect resistances. An image of such a common set up can be seen in Fig. 10 where one layer without coating have been added on either side of the original coating. This setup is basically the same as one found as the barrier of a sample vacuum panel that was available to the author at the time this paper was written.
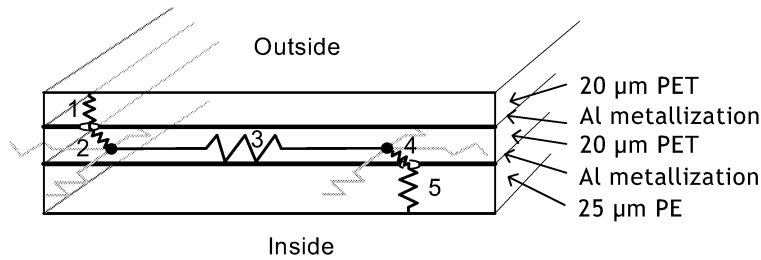
Fig. 10: Image shows the basic build up of the modeled VIP barrier film.

The same films were also evaluated and the defect density as well as defect size distribution and the defect positions of the actual defects were determined. This data was then used as input into the presented hybrid model with reasonable results. Ten samples of each coating, top and bottom, were analyzed and then combined with each other. The calculated fluxes are plotted in Fig. 11.
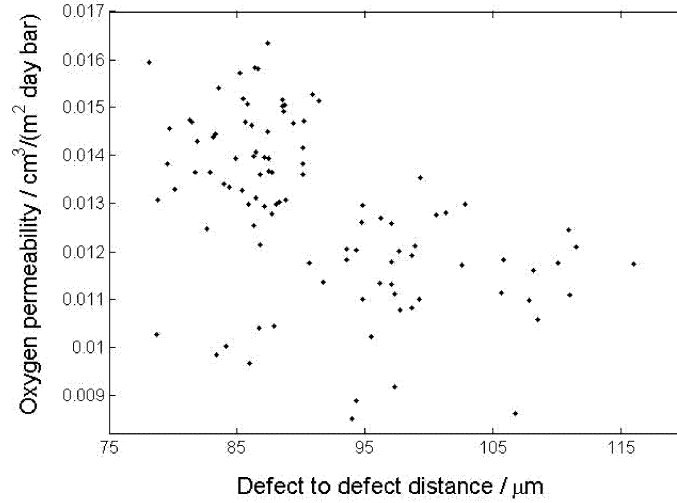
Fig. 11: Plotted Oxygen permeabilities calculated for a combined film with 5 layers: 20 um PET–Al coat–10 um PET–Al coat–20 um PET. The defects are defined by the data from evaluated samples from real VIP barriers. The diffusion coefficient for oxygen in PET used is D = 1.407 ·10⁻¹⁴ m²/s.

The mean OTR of 0.013 cm³/(m² ·day ·bar) was compared with measured OTR values reported in the IEA report from Annex 39, (IEAa, 2005). The measured values from one institute range from 0.01 to 0.02 cm³/(m² ·day ·bar) which agrees very well with the results from our simulations. Another institute reports, in the same report, transmission rates of 0.07 cm³/(m² ·day ·bar) as an upper estimate for one film with dual coating, this film however was reported to have great variations in the measured transmission rate so therefore is the value an upper estimate. The other film tested by this institute was measured to 0.00062 cm³/(m² ·day ·bar) which must be considered a very good dual coating film. Still our model is reasonable in comparison.

28

VIPs in buildings

Even though vacuum panels have been used in many other industries it is no guarantee that they will work in a building. New criterions need to be met in order to work in the built environment since the material will be exposed to new risks and challenges. A material that is to be used in a building;

1. needs to have a documented life time of at least 50 years, preferably a 100.

2. will be forgotten during its lifetimes. Extra measures need to be made to ensure the panels both at the construction site as well as in place during its life time.

3. will be exposed to new climatic conditions such as temperature and moisture content.

Due to the extra cost of vacuum insulation panels the areas of application is limited. Of the same reason there must be an added value of some sort to choose VIP instead of traditional insulation. To my opinion the case where the space is limited will be the strongest case where vacuum panels will be used. Another case is if there are extreme demands of insulation performance. Other scenarios could be where a construction needs to be heavily altered in order to make room for a required amount of traditional insulation; then it might be more favorable to use vacuum insulation instead of altering the design.

In Germany and Switzerland the market for VIP in building has emerged and a number of projects have been realized. In these countries VIP with a metalized polymer film barrier and a fumed silica core is basically the only one used. There are a few projects in Sweden and some test facilities in other European countries whilst in the U.S. work has been done to develop an attic access panel insulated by VIP.

Risk for damages

Panels which have a film based on polymer layers and/or foils are extremely sensitive. If punctured the panel loses the main portion of its thermal performance at the same time as it loses the most of its stability.

At any work site where a building is being erected, remodeled or renovated there are a number of potential dangers to an exposed VIP. When placed flat on the ground a small rock can suffice to puncture the barrier, whilst the indentation of a foot stepping on the panel, even without shoes, will stress the material which might result in shorter lifetimes of the particular panel.

After the panel is positioned and possible covered there are still risks of penetration by screws and nails which might be used to hang things on a wall. It must be remembered that the tenants of a building usually change many

times during the lifetime of a building. It is likely that some time during the buildings life time the vacuum panel insulation will be forgotten so even if the initial tenants do not screw screws or drive nails into the wall chances are that the third or fourth tenant will.

Possible application for vacuum insulation panels in buildings

In the report presented by the U.S. Department of Housing, (U.S. Department of Housing, 2002), a number of building components are identified as more promising than others. The ten most promising applications mentioned where:

- Precast concrete panels
- Manufactured housing floor plans
- Exterior doors
- Garage doors
- Manufactured housing ceiling panels
- Insulated metal roofing panels
- Rectangular duct insulation
- Retrofit exterior insulation
- Acoustical ceiling panels
- Attic access panels/stairway insulation

The selection was based on a number of criterions such as cost of manufacturing, impact, required lifespan, risk of damages and additional installation costs. In a second step the market for each of the ten selected applications was evaluated. The largest market was for use in manufactured homes as floor and ceiling panels. This market was estimated to close to one billion square feet, 88 million square meters annually. In a manufactured home the floor panel is usually located between the floor framing and a bottom board that is installed underneath the chassis. This board protects the house during transport. This concept was dropped due to unwillingness of the manufacturers of such homes; the initial added cost by use of vacuum panels of $3000 to $5000 could not be justified in a pre-manufactured home.

In Europe the research the IEA/ECBCS Annex 39 project HiPTI-High performance Thermal insulation was ongoing during the same time. This project was divided into two parts, the first; subtask A dealt with the Vacuum Insulation Panel itself and the second part; Subtask B dealt with applications of VIPs in buildings. The final reports where published in 2005, (IEAa, 2005), (IEAb, 2005). Issues of the first part have been discussed under the state of the art chapters of this thesis. In subtask B the work dealt mainly with practical issues of vacuum insulation panels. It is clear that the most common application of vacuum panels is underneath terraces floors, especially in Switzerland, (Binz, 2005), but there are a number of other applications that

have been developed and used in Switzerland and Germany. In Sweden there is, at this time, some usage. One use is in glass facades by Schücko and there is at least one terraces floor which uses VIPs for insulation.

Thermal bridges

When it comes to the built in thermal bridge of a vacuum insulation panel, hence the edge effect, the impact of such will decrease as the gradient over the panel is lessen. This happens as soon as a panel is incorporated into a building assembly for example an outer wall or a terrace floor. In such constructions the VIP is only one of many layers of materials.

Thermal bridge dependancy on surrounding insulation
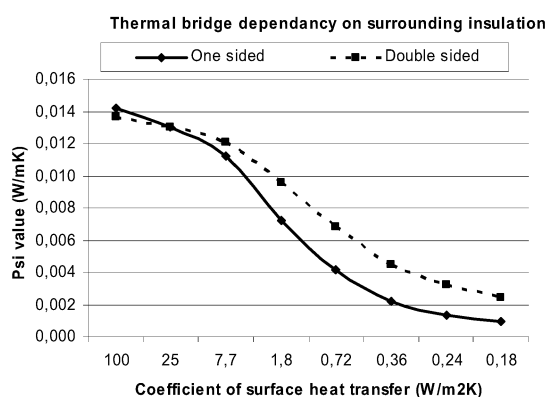
Fig. 12: Diagram shows influence of adjoining insulation. The dotted line shows added insulation on one side of the panel and the solid line shows added insulation on both sides of the insulation, figure originally found in Paper I, p 7.

In Fig. 12 the relation between surrounding materials insulative capacity and the impact of the edge effect of the VIP itself is plotted. As can be seen the impact is decreasing as the surrounding insulation is increasing. In this figure the surrounding insulation is modeled as a surface resistance. The surface resistance of 0,36 W/(m²·K) is equivalent to a 0,10 m thick layer of insulation with a thermal conductivity of 0,036 W/(m·K).

If a thermal bridge is introduced into a thin layer of extreme insulation then the impact of the thermal bridge will be greater. If one look to a facade element for example a VIP is placed in-between two protective skins held in place by some spacers at the edges. This component is then place in a glazing system which itself incorporate a number of thermal bridges into the design. Quenard and Sallée show in a paper published at the 7th International Vacuum Insulation Symposium, (Quenard and Sallée, 2005), that it is very easy with today's design to ruin the thermal performance of the VIP itself. It is stated that vacuum insulation panels must be used with great care in order to create an over-all good thermal design. In particular VIP must be imbedded in low conductive materials to reduce thermal bridges through spacers and frames to

avoid "heat drainage" along surfaces. This recommendation is also made by Ghazi Wakili and Nussbaumer, (Wakili and Nussbaumer, 2005).

Schwab et al did some work on thermal bridges that occur due to the fastening of the panel such as possible air gaps between two panels that are supposed to be in an edge to edge montage and thermal bridges due to fastening devices and mounting systems, (Schwab et. Al., 2005). As one could expect, they found that the thermal bridge effect was large when panels with aluminum foils where used, and further that in this case the influence of an air gap was small. Whilst for the example of a VIP with a polymer barrier including thin metallization layers then the influence of the width of the air gap had a greater relative influence.

New buildings

Vacuum insulation panels are an advanced insulation material with several steps in the manufacturing process. The cost is higher than traditional insulation even if the high insulative capacity is weighted in to the equation. But if there are added values such as a possibility to retain the ceiling height in an apartment below a terrace thanks to the use of VIPs then it could be more economic to use vacuum panels than redesigning the terrace. The option would be to raise the terrace floor which would result in one or two steps up to get to the terrace. This is the design where the use of VIPs is most common in Switzerland at this time, (Binz, 2005).

One example of such is a project in Kerzers, Switzerland which is described in part B of the IEA report, (IEAb 2005). In this project it was planned to use 12 cm of polyurethane as the terrace insulation but by mistake the terrace windows was ordered 100 mm to tall. At this time it was decided to use VIPs instead to lower the thickness of the insulation with maintained thermal insulation. By this decision the use of the to-tall windows was possible.

Another established niche for vacuum panels is in glazed facades. In such facades vacuum insulation is use in opaque parts, before vacuum insulation opanels where used structural glazing manufacturers often used foam insulation materials which require component thicknesses many times thicker than the thickness of the transparent parts where insulative multi pane window are used. Here the use of VIP has many advantages and many of the immediate risks are neutralized since the VIP is enclosed between two panes of glass there are little risk of destruction of the VIP barrier. By using thinner components standard fittings designed for multi pane windows can be used also for the opaque parts of a façade which in the end saves money.

A similar system is described and used in a project in Landschlacht, Switzerland, where the outer wall where a panels with metal faces in which a VIP was imbedded, (IEAb 2005).

Renovation / remodeling

To use vacuum panels in remodeling or renovation great care must be applied to prevent the risks with adding both thermal insulation and a diffusion barrier to an existing wall. The advantages lie in reaching good thermal insulation without using gross amounts of space. One example is the many cellars beneath single family houses in Sweden which have low ceilings and un-insulated slab on ground foundations. Here vacuum panels make it possible to create a usable, well insulated, space with minimal loss of ceiling height.

One example of a similar situation where VIP have been used is, from the IEA report, (IEAb 2005), as floor and ceiling insulation in an existing attachment construction with a terrace on top of the roof and a garage below. The room had extremely limited available height. In this case any other method would have brought along a number of compromises in either thermal insulation or room height requirements. The solution was to use 20 mm VIP which were glued to the ceiling and laid on the floor.

Another example is in a building which was retrofitted, with the passive house standard in mind, VIP was used in outer walls and in a dormer window. The panels were glued to the existing interior plaster without joints. In the dormer window, which was a new addition, the vacuum panels where positioned in the construction, sufficiently far from the inside to ensure the safety against puncturing nails or screws. The reason to use VIP in this project was for the use in the walls to save space and for the use in the window the possibility to create a design which meets with the passive house specifications without being bulky.

Vacuum panels are used and have been used for a while in Germany and Switzerland on among other preservation worthy buildings where the facades are kept and new insulation is added on the inside in the form of vacuum panels. The choice of VIP is taken in order the keep space usable (thermally) without loosing too much floor space.

What would the results be of a wide use of VIPs in buildings?

The total energy use in the European Union as a whole was, in 1997, 930 Million tons oil equivalent, Mtoe, of which about 41% was used in buildings for a diversity of applications. The by far largest is for heating, as can be seen in Fig. 13 and Fig. 14 an average of 55% of the total energy used in buildings is used for heating, (57% in residential buildings, Fig. 13, and 52% in commercial buildings, Fig. 14), (IEAa 2005).

Energy consumption in residential buildings in the European union
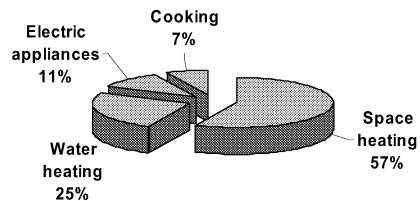
Fig. 13: Energy use of residential buildings in the European union, source IEAa 2005.

It should be noted that even though the energy used for heating is separated from, for example office equipment, other uses of energy this energy still contributes to heating the building. In appliances and equipment most of the feed energy, in the end, is transformed to heat which is released to the surrounding air.

Energy consumption in commercial buildings in the European union
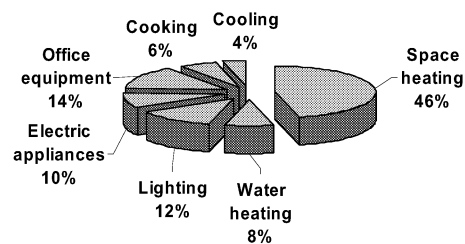
Fig. 14: Energy use of commercial buildings in the European union, source IEAa 2005.

If we assume that it is only the energy marked as heating energy that actually do the task of heating then the European Union used 210 Mtoe of energy for space heating in 1997. This energy is used by the existing building stock which totals in 150 million buildings in Europe, se Fig. 15. The amount of buildings that are built is approx 1-2 % of the existing building stock, hence 1.5 to 3 million new buildings are erected every year.

Buildings age in the European union
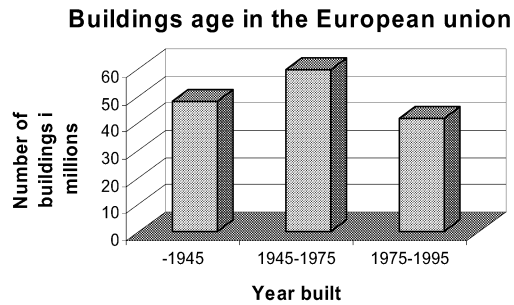
Fig. 15: Million of buildings built up to the year 1995 summed by building year, source IEAb 2005.

The amount of new buildings every year is so small compared to the existing building stock that it would take centuries for improved insulation technologies to impact on the total heating energy demand. If, however, existing buildings where to be renovated and VIP to be used to lower the energy use of those buildings to one third as mentioned in the IEA, (IEAb 2005), report then this reduction would solely secure that the demands of the Koyoto protocol is met.

Conclusions

Vacuum insulation materials are a group of materials that are new to the building sector. Vacuum insulation can provide solutions for thin designs with adequate insulation, prevent thermal bridges, increase thermal performance or open up the possibilities for all new designs that where not possible with traditional materials. Panels on the European market today, used in buildings, are one of two kinds, either panels with soft shells, hence panels with fumed silica cores and barriers of multi layered polymer film with at least two coating or panels with metal enclosures.

VIP, or soft shell panels, has the advantage of being light weight, the shell material is less costly than metal sheets, is comparatively easy to manufacture even though a vacuum chamber is required and finally the coated composite barrier does not create any significant thermal bridge at the panel edges . Some drawbacks of the soft panel are that it is quit fragile and good core materials, which are more expensive, are required to reach necessary life times due to the larger permeation through a coated composite barrier films than through an al-metal enclosure. An all metal barrier on the other hand is very robust and gas tight, long life times can easily be reached which allows more commonly available and less costly materials such as glass-fibers and open porous foams to be used in the core. Metal enclosed panels, when manufactured, are evacuated through a valve on the panel surface eliminating the need for a vacuum chamber and also allows for reinstatement of the vacuum if it is lost for any reason during the panel life time. The drawback of the all metal enclosure is the materials and manufacturing costs and the large thermal bridge the metal enclosure creates at the edges of the panel. Panels of this kind is manufactured in very large dimensions which somewhat decrease the relative impact of the edge effect.

This thesis have addressed two major issues of today's vacuum panels, firstly a serpentine edge design is proposed which can, by design, reduce the large thermal bridge of metal enclosed panels to one third which would allow manufacturers to develop panels with metal faces without the deterring thermal bridge at the edges. There are still challenges to the manufacturing of an enclosure incorporating a serpentine edge. The main challenge is to solve the issues of wrapping the serpentine edge around the corner of the panels without creating defects in the metal. When this is solved strong insensitive panels can be manufactured that can be handled by workers and installed without special training at the construction site.

On the other hand, the polymer barriers are improving rapidly. The other contribution is the diffusion model for diffusion through dually coated composite barrier films which can be used in a design phase to evaluate films without laboratory tests or for film selection. Coating defects of an existing composite barrier was evaluated and statistical data was established for each of

the two coatings incorporated into the evaluated film. Data found revealed that one coating was so superior that a film with two coating of that quality would render a dually coated film with oxygen permeability reduced by 75%. There is still room for improvements on that particular film. The accuracy of the model still need to be verified further to build confidence in the model but all comparisons to this date show that results from the model show promise since they are very reasonable compared with measurements of similar barrier films.

Discussion

Vacuum insulation has been introduced to the builders, architects and engineers. Even though vacuum panels have been used for a while in other areas it is new to the building industry. Architects tend to jump up and down of joy when this material is introduced since it presents an opportunity to design slender designs with acceptable thermal properties. Many engineers se the possibility of using such a material in specific application mostly where space is scarce such as when an attic is furnished or a terrace is created on existing constructions or where exceptional temperature gradients exist such as behind radiators on outer walls.

I personally believe that the entry point for VIP into the Swedish market will be, except for the examples above, as a problem solver, much like described in the case of the project in Kerzer, Switzerland described under the section; New buildings, where a mistake forced the use of VIP. There are other situations where the author has been involved where VIP could potentially be a solution to an existing thermal problem where there is no room for traditional insulation.

However, the adoption of vacuum insulation materials in buildings is just beginning, in Germany as well as Switzerland initial markets have formed. In Sweden VIP are used in glazed facades and there are one example of a terrace insulation in the region of Stockholm. One of the limiting factors for use, at least in Sweden, is the lack of official approvals which is necessary if vacuum panel are to be used more than under special circumstances.

Recommendations

A Vacuum insulation panel with its soft shell and dependency of keeping low pressure in the core it is a new type of material. The closest material in complexity on the market would be a multi pane window. Any one realizes that a window is fragile, it is not as clear that a VIP is fragile. A window is broken when the glass is broken whilst an indentation, an extra wrinkle or a small penetration might ruin a VIP without immediate show of any breakage. A VIP in a building constitutes not only a layer of extreme thermal insulation but also a diffusion barrier layer. Due to the particularities of vacuum insulation in general and vacuum insulation panels, hence with polymer based