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Zero Energy Building Envelope Components: A Review

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Abstract

With some recent developments, the zero energy building and near zero energy building has gained a worldwide attention and now it is seen as the future building concept. Since such buildings are now the center of attraction, various advancements in this area are being reported. This paper is a detailed review of the literature on the zero (or near zero) energy building (ZEB) envelope components. The paper provides a detailed overview of the zero energy building envelope components along with the possible developments in the future for the benefit of the building designers and constructors. It strives to provide the state of the art on the various building envelope components such as insulation materials, future insulation materials, walls, roofs, windows, doors and glazing from the prospects of energy efficiency. Photovoltaic integration with the building envelope is also discussed for on-site power generation to meet the operational energy demand so as to achieve the goal of Zero Energy Building.

Keywords: Zero energy building, Net zero energy building, Insulation materials, Building envelope.

1. Introduction

The building industry and scientific communities across the world have identified the importance and need for energy efficiency in the buildings, and initiated significant efforts in this direction. So far, the WGBC (World Green Building Council) has involved 82 nations all across the globe in taking up green building initiatives to some degree. LEED (Leadership in Energy and Environmental Design), an internationally recognized green building certification system, also identifies energy efficiency as an important attribute of green buildings (Suresh et al., 2011).As the energy use in the building sector accounts for a significant part of the world’s total energy use and greenhouse gas emissions, there is a demand to improve the energy efficiency of buildings. In order to meet the demands of improved energy efficiency, the thermal insulation of buildings plays an important role. To achieve the highest possible thermal insulation resistance, new insulation materials and solutions with low thermal conductivity values have been and are being developed, in addition to using the current traditional insulation materials in ever increasing thicknesses in the building envelopes (Bjorn ,2011).

Building energy efficiency can be improved by implementing either active or passive energy efficient strategies. Improvements to heating, ventilation and air conditioning (HVAC) systems, electrical lighting, etc. can be categorized as active strategies, whereas, improvements to building envelope elements can be classified under passive strategies. Recent years have seen a renewed interest in environmental-friendly passive building energy efficiency strategies. They are being envisioned as a viable solution to the problems of energy crisis and environmental pollution. A building envelope is what separates the indoor and outdoor environments of a building.

It is the key factor that determines the quality and controls the indoor conditions irrespective of transient outdoor conditions. Various components such as walls, fenestration, roof, foundation, thermal insulation, thermal mass, external shading devices etc. make up this important part of any building. Several researchers around the world carried out studies on improvements in the building envelope and their impact on building energy usage. Energy savings of 31.4% and peak load savings of 36.8% from the base case were recorded for high-rise apartments in the hot and humid climate of Hong Kong by implementing passive energy efficient strategies. The strategies include adding extruded polystyrene (EPS) thermal insulation in walls, white washing external walls, reflective coated glass window glazing, 1.5 m overhangs and wing wall to all windows (Cheung et al., 2005). In a different study, the thermal and heat transfer performance of a building envelope in sub-tropical climatic conditions of Hong Kong was studied using the DOE-2 building energy simulation tool. An energy effective building envelope design saved as much as 35% and 47% of total and peak cooling demands respectively (Chan & Chow, 1998). In Greece, thermal insulation (in walls, roof and floor) and low infiltration strategies reduced energy consumption by 20–40% and 20% respectively. According to the same study, external shadings (e.g. awnings) and light-colored roof and external walls reduced the space cooling load by 30% and 2–4%, respectively (Balaras et al., 2000). Several numerical studies were also carried out on building envelopes and individual building envelope components. A detailed model of transient heat transfer through a typical building envelope developed by Price et al. (Price & Smith, 1995) takes into account the convection and thermal radiation heat exchange at the interior and exterior surfaces of the building.

Today, buildings worldwide account for up to 40% of total end-use energy. There is over 50% saving potential in the building sector and thus it is considered as a potential sector to meet the challenges of global energy and climate change. The building sector is a driver of the world economy. According to a report by McGraw-Hill Construction, the green building market in both the residential and non-residential sectors was predicted to increase from $36 bn in 2009 to $60 bn in 2010 and in a range of $96-$140 bn by 2013. There is a significant opportunity for those entering this market (McGraw-Hill Construction, 2008; Zhang & Cooke, 2010). Hence it is very important for the zero energy, net zero energy, passive housings and eco friendly building concepts to be implemented. This paper has presented a detail review on the zero energy building envelope components. Apart from the previously used envelope future building envelope components are also reviewed.

2. Walls

Walls are a predominant fraction of a building envelope and are expected to provide thermal and acoustic comfort within a building, without compromising the aesthetics of the building. The thermal resistance (R-value) of the wall is crucial as it influences the building energy consumption heavily, especially, in high rise buildings where the ratio between wall and total envelope area is high. The market available center-of-cavity R-values and clear wall R-values consider the effect of thermal insulation. However, the influence of framing factor and interface connections is not taken into consideration (Christian &Konsy, 2006). Walls with thermal insulation have a higher chance of surface (Aelenei & Henriques, 2008). Conventionally, based on the materials used in construction, walls can be classified as wood-based walls, metal-based walls and masonry-based walls (Sadineni et al., 2011).

2.1 Passive solar walls

Typically used in cold climates, the walls that trap and transmit the solar energy efficiently into the building are called passive solar walls (as shown in fig.1). A glazing is used as an outer covering of the wall to provide the greenhouse effect. Several developments resulted from the basic designs of classical Trombe wall and composite Trombe–Michell wall (Zalewski et al., 1997; sharma et al., 1989; zalewski et al., 2002; Ji et al., 2009; Zerkem& Bilgen., 1986; Ji et al., 2009; Zerkem& Bilgen., 1986; Jie et al., 2007). This design improved the operating efficiency of the classical Trombe wall by 56% (Ji et al., 2009).

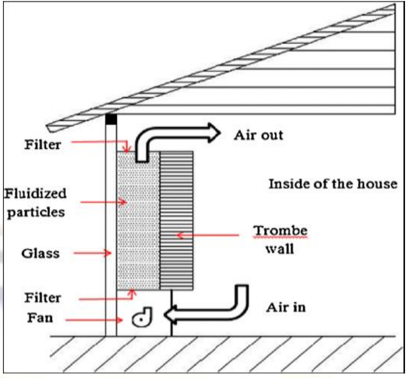

Fig 1: Passive Solar Walls

Phase change material (PCM) based Trombe walls have been reviewed (Tyagi & Buddhi, 2007). A Transwall (as shown in Fig. 2) is a transparent modular wall that provides both heating and illumination of the dwelling space. Fig. 6 A cross-sectional view of Transwall system with part detail (Nayak, 1987).

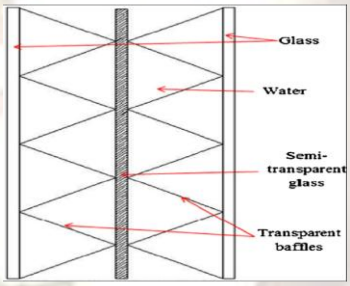

Fig 2: Trombe Wall

2.2 Walls with latent heat storage

The phase change material (PCM) is incorporated in light weight wall structures to enhance the thermal storage capacity. PCM material is impregnated commonly in gypsum or concrete walls. Porous material such as plasterboard has better PCM impregnation potential than pumice concrete blocks. The microencapsulation of PCM material in wall construction material has allowed this PCM weight ratio to about 30% in gypsum. Recent years have seen the advent of composite materials that can encapsulate PCM up to 60% by weight. Athienitis et al. (Athienitis et al., 1997) compared PCM based and non-PCM based gypsum board for inside wall lining and concluded that the PCM based wall lining lowered the maximum room temperature by 4 ◦C and reduces the heating demand during night (Kuznik &Virgone ,2009).

2.3 T-MASS Walls:

Thermal mass walls consist of 4 inches of concrete facing the interior, 2 inches of concrete on the exterior and 2 inches of Styrofoam extruded polystyrene board insulation sandwiched in between. Fiber composite connectors, spaced 16 inches on center, hold the assembly together. These plastic connectors are one of the keys to the energy efficiency of the T-Mass walls, says John Gajda of Construction Technologies Laboratory. "Others systems use steel connectors, which readily conduct heat. Steel connectors greatly reduce the R-value and reduce the energy efficiency of the walls."
Thermal mass walls come in two forms: precast and poured. Precast panels are manufactured at a plant and delivered to the job site (Foss Asa 2005).

2.4 Riverdale NetZero Deep Wall System

The Riverdale NetZero DWS is a double-stud wall system forming a 406 mm (16 in.) cavity that is filled with blown-in cellulose insulation to achieve an impressive insulation value of RSI-9.9 (R-56). The wall has the following composition, as detailed in (fig.4) (Equilibrium TM housing in sight 2010).

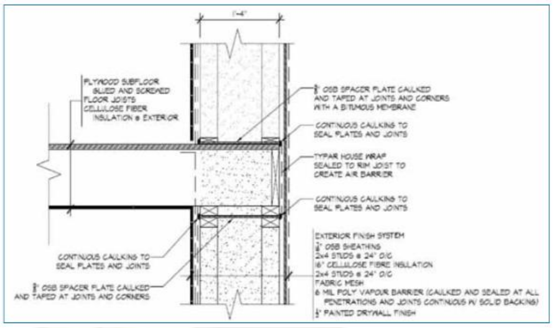

Fig 4: Cross-Section of Riverdale NetZero Deep Wall System

2.5 Green Walls:

Greenery helps to reduce heat transmittance into a building through direct shading and evapotranspiration. Evapotranspiration refers to the movement of water to the air (evaporation) and the movement of water within a plant and the subsequent loss of water as vapour through its leaves (transpiration). The intent of installing vertical greenery is to study the effectiveness of these systems on reducing the heat transfer through building walls into the interior building space and the possible energy savings. The three types of vertical system being tested in ZEB are (Greenest Building Singapore, 2012) as shown in the fig. 5

1. Panel type
2. Mini planter box
3. Cage system.

Panel Type Mini planter Cage SystemBox

Fig 5: Various Green Wall Structures

1. Roofs

Roofs are a critical part of the building envelopes that are highly susceptible to solar radiation and other environmental changes, thereby, influencing the indoor comfort conditions for the occupants. Roofs account for large amounts of heat gain/loss, especially, in buildings with large roof area such as sports complexes, auditoriums, exhibition halls etc. In accordance with the UK building regulations, the upper limits of U-value for flat roofs in 1965, 1976 and 1985 were 1.42 W/m2 K, 0.6 W/m2 K and 0.35 W/m2 K, respectively. Currently, 0.25 W/m2 K or less is required for all new buildings in the UK (Grffin et al., 2005)]. This reduction in the U-value over the years emphasizes the significance of thermal performance of roofs in the effort to increase the overall thermal performance of buildings. This section provides a number of highly efficient roofs for zero energy building design:

3.1 Lightweight roofs

Lightweight aluminum standing seam roofing systems (LASRS) are popularly used on commercial and government buildings as they are economical. Two easy ways to improve thermal characteristics of these roofs are by adding thermal insulation and using light colored roof paint. It was determined that the lighter colored surfaces such as white, off-white, brown and green yielded 9.3%, 8.8%, 2.5% and 1.3% reduction in cooling loads compared to an black-painted LASRS surface . (Han et al 2009) Recent investigations have revealed that the LASRS with glass fiber insulation does not suit well for hot and humid climates due to the interstitial condensation in the glass fiber layer. Alternative thermal insulation materials such as polyurethane, polystyrene or a combination of these have been evaluated (Han et al 2009).

3.2 Solar-reflective/cool roofs

Solar-reflective roofs or cool roofs are high solar reflectance and high infrared emittanceroofs(Fig 6). They maintain lower roof surface temperature and inhibit the heat conduction into the building. Two surface properties that affect the thermal performance of these roof surfaces are solar reflectance (SR) (reflectivity or albedo) and infrared emittance (or emissivity). Special roof coatings can raise the infrared emittance of bare metal roofs (Liu ,2006).To find the influence of highly reflective roofs on cooling and peak load variations, six different types of buildings were retrofitted with high reflectance white coatings or white PVC single-ply membrane at three different geographical sites in California (USA) (Akbari et al .,2005).

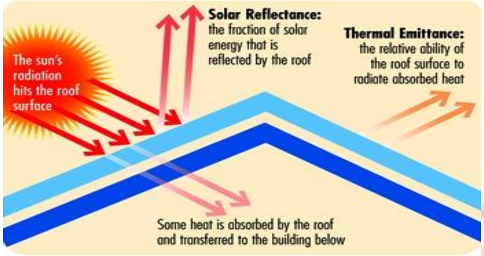

Fig 6: Working of Solar reflective roofs

3.3 Green roofs

A building roof that is either fully or partly covered with a layer of vegetation is called a green roof. It is a layered composite system consisting of a waterproofing membrane, growing medium and the vegetation layer itself. Often, green roofs also include a root barrier layer, drainage layer and, where the climate demands, an irrigation system. There are two types of green roofs: intensive and extensive, the former has a deeper substrate layer and allows to cultivate deep rooting plants such as shrubs and trees; while the latter with thinner substrate layer allows to grow low level planting such as lawn or sedum (Fig.7) (Castleton et al., (2010).

Fig 7: Green roof

A green roof system incurs higher annual savings when installed on a poorly insulated roof rather than a well-insulated roof. The moisture content in growing media of the green roof influences its insulating properties. A 100 mm increase in the thickness of dry clay soil led to an increase in resistance by 0.4 m^2K/W, whereas for 40% moisture clay soil the increase was only 0.063 m2K/W (Wong et al., 2003). The wetter the medium, the poorer the insulating behavior compared to the dry growing media (Gaffin et al., 2005). Therefore, green roofs reflect solar radiation more efficiently than most conventional roofs. The building energy savings and the retrofit potential of green roofs in UK have been evaluated (Balararas, 1996).

3.4 Photovoltaic roofs

There have been significant efforts in recent years in integrating photovoltaic's (PV) into building envelope. PV roof tiles replace roofing material and are installed directly on to the roof structure (Fig 8). Ceramic tiles or fiber-cement roof slates have crystalline silicon solar cells glued directly on them. Another type of roof-integrated system has a PV element (glass-glass laminate) positioned in a plastic supporting tray anchored to the roof (Bahaj, 2003).

Fig 8: Photovoltaic Roof System

3.5 Roof Vents

When assessing a desired roof type one has to keep in mind underlying requirements such as roof vents (fig.10). The selection of a roof vent will depend on its intended function and the type of ventilation system it is paired with. Roof vents help prevent the build-up of moisture and heat. Extra heat in the attic will cause an increase in cooling costs. Residential vent types can include the Ridge vent, Dormer vent, Roof Louver vent, and the Passive vent (Roof types ,2012).

Fig 10: Roof Vents

3.6 Rubber Roofs

Rubber roofing is something that has gained popularity in the modern era with the development of a variety of rubber materials. Rubber roofing is usually made of EPDM (ethylene propylenediene Monomer) rubber (fig.11). It can be applied as roofing in large sheets or as rubber shingles advantages of rubber roofing include very good resistance to weathering, abrasion, heat and ozone. It also has flexibility with large temperature changes. The energy efficiencies associated with rubber roofing coupled with its highly recyclable nature make it a leading environmentally friendly roofing material. It does not pollute run off rainwater making the water usable if collected with a suitable rainwater harvesting system (Roof types, 2012).

Fig 11: Rubber Roof Structure

2. Windows and Doors:

Fenestration refers to openings in a building envelope that are primarily windows and doors. The fenestration plays a vital role in providing thermal comfort and optimum illumination levels in a building. They are also important from an architectural standpoint in adding aesthetics to the building design. In recent years, there have been significant advances in glazing technologies. These technologies include solar control glasses, insulating glass units, low emissivity (low-e) coatings, evacuated glazing, aerogels and gas cavity fills along with improvements in frame and spacer designs (Robinson &Hutchins, 1994) insulation level, floor area, etc. For passive solar heating applications, windows with low U-value and high total solar energy transmittance (Γ) are preferred. A tradeoff should be made between U-value and solar transmission as most likely the measures to lower U-value shall lower the solar transmission (Robinson & Hutchins, 1994).

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4.1 Windows:

Many building designers are aware of the key role that windows play in the performance of the built environment. Heat loss and heat gain through windows occurs at 20–30 times the rate they occur through walls. Proper window performance can ensure that the heating and cooling equipment can maintain a reasonable level of comfort without excessive operating costs. This section deals with the windows performance parameters, types of windows, glazing’s etc(McGowaon Alex).

4.1.1 Windows Performance Parameters

To determine the desired performance of a window, the designer must be able to Specify the appropriate performance indices (fig.12). Apart from understanding what the various performance indices are intended to measure, the designer should understand how to quantify and measure these indices and how to specify the parameters of interest. The parameters in (Table 1) are of interest in window performance. They are quantifiable, and they can be specified in accordance with existing standard procedures (McGowaon Alex).

Table 1 Windows Performance Parameters

• U-Factor	Colour / Esthetics
• Solar Heat Gain Coefficient	Visible Light Transmission
• Air Leakage	Sound Transmission

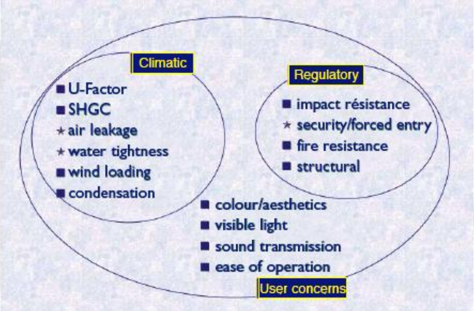

Fig 12: Windows Performance Parameters

4.1.2 Types of Glazing Materials:

4.1.2.1 Aerogel glazing

Aerogels are a category of open celled mesoporous solids with a volume porosity of greater than 50%. They have a density in the range of 1–150 kg/m3, and are typically 90–99.8% air by volume. They can be formed from a variety of materials, including silica, alumina, lanthanide and transition metal oxides, metal chalcogenides, organic and inorganic polymers and carbon. Aero-gel glazing entered the contemporary glazing market in the year 2006 and is, essentially, a granular aerogel encapsulated between polycarbonate construction panels that weigh less than 20% of the equivalent glass unit and have 200 times more impact strength. Light transmission and U-value of aerogel panels are a function of panel thickness. Their high performance, low density and outstanding light diffusing properties make them an appropriate choice for roof-light applications (Bahaj et al., 2008).

4.1.2.2 Vacuum glazing

Vacuum space is created between two glass panes to eliminate the conductive and convective heat transfers between the glass panes reducing the center-of-glass U-value to as low as 1 W/m2 K. Most often, low-e coating is applied on one or both of the glass panes to reduce the re-radiation into the indoor space (Sullivan et al., 1996). An exhaustive study is presented on the processes and the costs involved in the fabrication of vacuum glazing (Garrison & Collins, 1995). Also a comparison between the vacuum and argon filled double glazing is discussed. Heat transfer through evacuated triple glazing, a prospective glazing technology, was investigated by using analytical thermal network modeling and numerical finite element modeling (Manz et al., 2006). The findings suggested that a triple vacuum glazing with a center-of-glazing thermal transmittance of less than 0.2 W/m2 K is achievable (Suresh et al., 2011).

4.1.2.3 Switchable reflective glazing

Switchable reflective glazing is essentially a variable tint glazing and is typically suitable for cooling load dominant buildings with large solar gain (Sullivan et al., 1996). In some types of switchable reflective glazing, the optical properties change as a function of the incident solar radiation, either by applying a low DC voltage (electrochromics (EC)) or by using hydrogen (gasochromics) to change from bleached to colored state. In others, light guiding elements such as switch-able reflective light shelves reflect solar radiation (Bahaj et al., 2008). A life cycle energy analysis performed on EC windows, operating in Greece, have shown an energy reduction of 54% which corresponding to 6388 MJ, compared to a standard window during a life of 25 years (Papaefthimios et al., 2006) . The payback period was found to be about 9 years and the total energy cost savings ranged from 228 to 569 D /m2 for 10 and 25 years of EC window operation respectively (Suresh et al., 2011).

4.1.2.4 Suspended particle devices (SPD) film

An SPD film is laminated between two glass panes. The SPD film has light absorbing particles that are randomly aligned in their normal state forming an opaque barrier. When voltage is applied, the particles align perpendicular to the plane of the glazing creating a transparent glass. The switching time (~1 s) is faster than EC glazing. This technology suffers from drawbacks such as radiant temperature, glare, color rendering, clearness and lifetime (Bahaj et al., 2008).

4.1.2.5 Holographic optical elements

Holographic optical elements (HOE) are light guiding elements comprising a holographic film sandwiched between two glass panes. The incident solar radiation is redirected, at a predefined angle through diffraction at the holographic film layer, usually onto the ceiling of the building interior. This can be used as a possible day lighting application. It suffers from some setbacks such as glare effects, light dispersion, milky clearness, limited exposure range of azimuth and zenith angles, etc. This technology is not yet commercialized (Bahaj et al., 2008).

4.1.3 Three Generations of Advanced Window Glazing:

4.1.3.1 High Thermal Performance Glazing

Fenestration systems with low u-factors reduce the heat flux (both into and out of) the building. Improving on common dual pane systems, low-e with a typical full frame performance of a u-factor of 0.50 to 0.254 will achieve u from-factors of 0.20 to ≥ 0.10. There are multiple, well established methods to achieve these benchmarks (fig.13, fig.14), with the greatest success found in three or more separated coated panes (with internal panes of either glass or suspended coated films) having the greatest commercial success (Tinianov Brandon,2010).

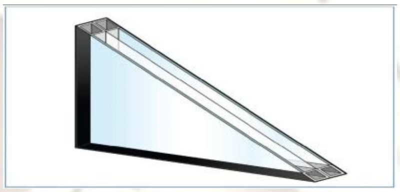

Fig 13: Cutaway of triple- pane insulated glass unit.

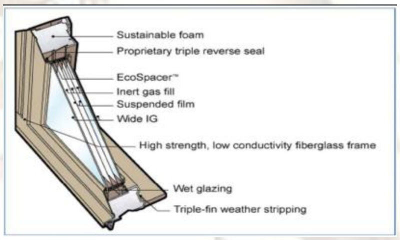

Fig 14: Cutaway of a quad pane window including the frame.

4.1.3.2 Dynamic Glazing

Dynamic glazing can admit solar heat when it is needed to offset heating energy needs, reject solar gain to reduce cooling loads, possibly reduce a building's peak electricity demand, and offset much of a building's lighting needs during daylight hours. To do so, the solar heat gain coefficient (SGHC) of the window may vary from approximately 0.50 to 0.05. The trigger for this performance switching can be controlled either actively (user) or passively (environment) (Tinianov Brandon,2010).

4.1.3.3 Building integrated photovoltaic glazing

The last generation of energy efficient fenestration is one that generates its own renewable energy, effectively reducing the total building consumption. Generation 3 fenestration products are commonly known as building integrated photovoltaics (BIPV) (fig.15). Third generation BIPV will come in two main forms: partially opaque/light transmitting; and transparent. As implemented today, light transmitting BIPV consists of solar cells made from thick crystalline silicon either as single or poly-crystalline wafers (Figure 16). These deliver about 10 to 12 Watts per ft^2 of PV array (under full sun). Such technology is best suited for areas with no light transmission requirements (e.g. spandrels) or shading areas such as overhangs and sunshades (Tinianov Brandon,2010).

Fig 15: Image of a commercially available "light thru" BIPV Product.

Fig 16: Image of a commercially available "see thru"

4.2 Frames

The edge components (frame and spacer) of advanced fenestrations should minimize thermal bridging and infiltration losses. The effect of various combinations of frames and spacers on the U-value of different types of windows is described by Robinson and Hutchins (Robinson & Hutchins, 1994). Also, these edge effects are more pronounced in case of smaller size windows. The emphasis of low conductance frames was reiterated by Gustavsen et al. (Gustavsen et al., 2008) in their review on low conductance window frames.

4.3 Types of Insulations:

As the energy use in the building sector accounts for a significant part of the world's total energy use and greenhouse gas emissions, there is a demand to improve the energy efficiency of buildings. To achieve the highest possible thermal insulation resistance, new insulation materials and solutions with low thermal conductivity values have been and are being developed, in addition to using the current traditional insulation materials in ever increasing thicknesses in the building envelopes (McKinsey, 2009).This section deals with the emergent, recent and future building insulation materials. A brief literature is represented here. A detailed description can be found out from (Al-homoud, 2005; Papadopoulos, 2005).

4.3.1 Traditional Building Insulations:

4.3.1.1 Mineral Wool

Mineral wool covers glass wool (fiber glass) and rock wool, which normally is produced as mats and boards, but occasionally also as filling material. Light and soft mineral wool products are applied in frame houses and other structures with cavities. Mineral wool may also be used as a filler material to fill various cavities and spaces. Glass wool is produced from borosilicate glass at a temperature around 1400 ◦C, where the heated mass is pulled through rotating nozzles thus creating fibres. In both glass wool and rock wool dust abatement oil and phenolic resin is added to bind the fibres together and improve the product properties. Typical thermal conductivity values for mineral wool are between 30 and 40 mW/ (mK). The thermal conductivity of mineral wool varies with temperature, moisture content and mass density.

4.3.1.2 Expanded polystyrene (EPS)

Expanded polystyrene (EPS) is made from small spheres of polystyrene (from crude oil) containing an expansion agent, e.g. pentane C6H12, which expand by heating with water vapour. The expanding spheres are bond together at their contact areas. Typical thermal conductivity values for EPS are between 30 and 40 mW/(mK). The thermal conductivity of EPS varies with temperature, moisture content and mass density. As an example, the thermal conductivity of EPS may increase from 36mW/(mK) to 54mW/(mK) with increasing moisture content from 0 vol% to 10 vol%, respectively.

4.3.1.3 Extruded polystyrene (XPS)

Extruded polystyrene (XPS) is produced from melted polystyrene (from crude oil) by adding an expansion gas, e.g. HFC, CO2 or C6H12, where the polystyrene mass is extruded through a nozzle with pressure release causing the mass to expand. The insulation material is produced in continuous lengths which are cut after cooling. XPS has a closed pore structure. Typical thermal conductivity values for XPS are between 30 and 40 mW/(mK).

4.3.1.4 Cellulose

Cellulose (polysaccharide, (C6H10O5)n) comprises thermal insulation made from recycled paper or wood fibre mass. The production process gives the insulation material a consistence somewhat similar to that of wool. Boric acid (H3BO3) and borax (sodium borates, Na2B4O7·10H2O or Na2 $[B_4O_5(OH)_4]\cdot 8H_2O$) are added to improve the product properties. Cellulose insulation is used as a filler material to fill various cavities and spaces, but cellulose insulation boards and mats are also produced. Typical thermal conductivity values for cellulose insulation are between 40 and 50 mW/(mK).

4.3.1.5 Cork

Cork thermal insulation is primarily made from the cork oak, and can be produced as both a filler material or as boards. Typical thermal conductivity values for cork are between 40 and 50 mW/(mK). Cork insulation products may be perforated, and also cut and adjusted at the building site, without any loss of thermal resistance.

4.3.1.6 Polyurethane (PUR)

Polyurethane (PUR) is formed by a reaction between isocyanates and polyols (alcohols containing multiple hydroxyl groups). During the expansion process the closed pores are filled with an expansion gass, HFC, CO2 or C6H12. The insulation material is produced as boards or continuously on a production line. PUR may also be used as an expanding foam at the building site, e.g. to seal around windows and doors and to fill various cavities. Typical thermal conductivity values for PUR are between 20 and 30 mW/(mK), i.e. considerably lower than mineral wool, polystyrene and cellulose products.

4.3.2 Recently Developed Building Insulations

4.3.2.1 Vacuum insulation panels (VIP)

Vacuum insulation panels (VIP) consist of an open porous core of fumed silica enveloped of several metallized polymer laminate layers, see Fig. 17 (left) and (right). The VIPs represent today's thermal insulation with thermal conductivities ranging from between 3 and 4mW/(mK) in fresh

Fig171: (Left) typical VIP structure showing the main component and (right) a comparison of equivalent thermal resistance thickness of traditional thermal insulatioand VIP.

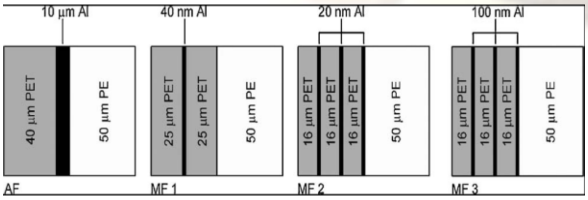

Fig18. Cross-sections of typical envelope materials for VIPs: (a) metal film, (b) single layer metalized film and (c and d) three layer metalized films. The four foil types are commonly named (a) AF, (b) MF1, (c) MF2 and (d) MF3 in literature. Note that different types of foil with the same name are used in the literature

Condition to typically 8mW/ (mK) after 25 years ageing due to water vapour and air diffusion through the VIP envelope and into the VIP core material which has an open pore structure. Several authors have been studying various aspects of VIPs, ranging from analytical models, thermal bridges and conductivity, air and moisture penetration, ageing and service life, quality control and integration of VIPs in building construction, e.g. (Beck et al., 2007;brunner et al., 2006;Brunner &simmler, 2007;Brunner &Simmler, 2008;Caps & Fricke ,2000;Caps, 2005;Caps et al., 2008;Fricke, 2005;Fricke et al., 2006;grynning et al., 2011;Schwab et al., 2005;Schwab et al., 2005;schwab et al., 2005;Schwab et al., 2005;schwab et al., 2005;Simmler & brunner,2005;Simmler &brunner ,2005;Simmler &brunner ,2005;Sveipe et al., in press;tenpierik et al., 2007;Tenpierik et al., 2007;Tenpierik et al., 2007;tenpierik et al., 2008;Wegger et al., in press; Zwerger& Klein, 2005), where comprehensive reviews on VIPs for building applications have been made recently by (Tenpierik, 2009) and (Baetens et al., 2010).

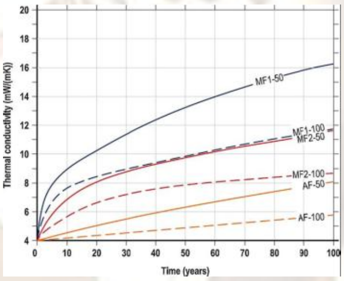

Fig. 19: Centre-of-panel thermal conductivity for VIPs with a fumed silica core as function of elapsed time. For two different panel sizes 50cm×50cm×1 cm and 100cm×100cm×2 cm, and for three different foil types AF, MF1 and MF2.

4.3.2.3 Aerogels

Aerogels (Fig.21) represent a state-of-the-art thermal insulation solution, and may be the most promising with the highest potential of them all at the moment, studied by (Baetens et al., 2010 ;Hostler et al., 2008;Schultz et al., 2005;Schultz et al., 2008) among several others. Using carbon black to suppress the radiative transfer, thermal conductivities as low as 4mW/(mK) may be reached at a pressure of 50 mbar. However, commercially available state-of-the art aerogels have been reported to have thermal conductivities between 13 and 14mW/(mK) at ambient pressure (Aspen Aerogels,2008; Aspen Aerogels,2008)

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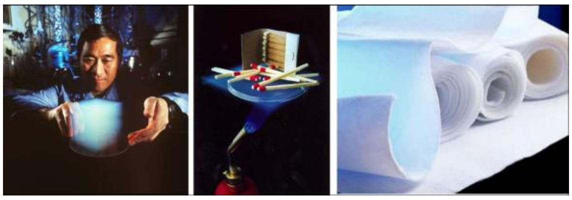

Fig. 21.:(Left) Peter Tsou from NASA with a translucent aerogel sample developed for space missions (ciampi et.al 2005), (middle) matches on top of aerogel are protected from the flame underneath (ciampi et.al 2005) and (right) an example of aerogel as a high performance thermal insulation material.

4.4 Future Building Insulations

This section provides a brief description of the building insulations that might be used in the near future:

4.4.1 Vacuum insulation materials (VIM)

A vacuum insulation material (VIM) is basically a homogeneous material with a closed small pore structure filled with vacuum with an overall thermal conductivity of less than 4mW/(mK) in pristine condition (Fig. 22). The VIM can be cut and adapted at the building site with no loss of low thermal conductivity. Perforating the VIM with a nail or similar would only result in a local heat bridge, i.e. no loss of low thermal conductivity. For further details on VIMs it is referred to (Jelle at al., 2010).

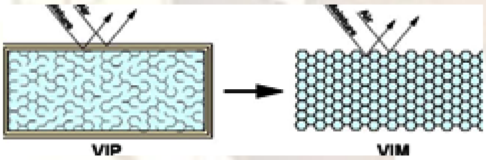

Fig. 22: The development from VIPs to VIMs

4.4.2 Nano insulation materials

The development from VIPs to nano insulation materials (NIM) is depicted in (Fig. 23). In the NIM the pore size within the material is decreased below a certain level, i.e. 40nm or below for air, in order to achieve an overall thermal conductivity of less than 4mW/(mK) in the pristine condition. That is, a NIM is basically a homogeneous material with a closed or open small nano pore structure with an overall thermal conductivity of less than 4mW/(mK) in the pristine condition.

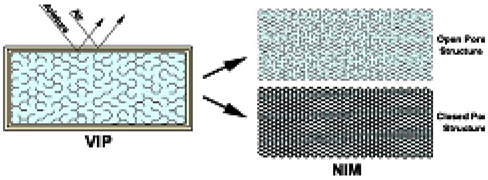

Fig. 23: The development from VIPs to NIMs

4.4.3 Dynamic insulation materials (DIM)

A dynamic insulation material (DIM) is a material where the thermal conductivity can be controlled within a desirable range. The thermal conductivity control may be achieved by being able to change in a controlled manner:

1 The inner pore gas content or concentration including the mean free path of the gas molecules and the gas-surface interaction.
2 The emissivity of the inner surfaces of the pores.
3 The solid state thermal conductivity of the lattice.

The thermal insulation regulating abilities of DIMs give these conceptual materials a great potential. However, first it has to be demonstrated that such robust and practical DIMs can be manufactured. It is referred to (Aspen Aerogels, 2008) for further details and elaborations concerning DIMs.

4.4.4 NanoCon

NanoCon is basically a homogeneous material with a closed or open small nano pore structure with an overall thermal conductivity of less than 4W/(mK) (or another low value to be determined) and exhibits the crucial construction properties that are as good as or better than concrete (Fig. 24). The term "Con" in NanoCon is meant to illustrate the construction properties and abilities of this material, with historical homage to concrete (Bjørn et al., 2011).

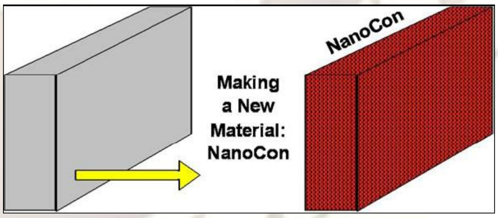

Fig. 24:.NanoCon is essentially a NIM with construction properties matching or surpassing those of concrete (Bjorn et al., 2011).

CONCLUSIONS

This paper has provided a detailed review on building envelope components in order to achieve the goal of Zero Energy Buildings. A number of traditional approaches and future components are investigated along with their advantages and disadvantages. Currently, while some of these advances in envelope component technologies are easy and cost effective to adopt, others still remain in the research and development phase for future applicability. Several studies have been performed to find the economic feasibility of various building energy efficiency strategies. Cost-benefit analysis of some of these energy efficiency strategies for a cooling dominated desert climate is presented by Sadineni et al (Suresh et al., 2011). Energy efficiency approaches sometimes might not require additional capital investment. For example, a holistic energy efficient building design approach can reduce the size of mechanical systems compensating the additional cost of energy efficiency features.

References

1. Abdou OA, Murali K, Morsi A (1996)"Thermal performance evaluation of a prefabricated fiber-reinforced plastic building envelope system" Energy and Buildings ,Volume 24,Issue 1, pp.77–83
2. Aelenei D, Henriques FMA(2008),"Analysis of the condensation risk on exterior surface of building envelopes. Energy and Buildings, Volume 40,Issue 10), pp.1866–71.
3. Ahmad I(2010), "Performance of antisolar insulated roof system. Renewable Energy, Volume 35,Issue 1, pp.36–41.
4. Akbari H, Levinson R, Rainer L(2005), " Monitoring the energy-use effects of cool roofs on California commercial buildings" Energy and buildings, Volume 37,Issue 10, pp.1007–16.
5. Alcazar SS, Bass B(2005),"Energy performance of green roofs in a multi-storey residential building in Madrid", Proceedings of 3rd annual conference on greening rooftops for sustainable communities, University of Toronto.
6. Al–HomoudM.S. (2005),"Performance characteristics and practical applications of common building thermal insulation materials", Building and Environment Volume 40, pp.353–366.
7. Al-Jabri KS, Hago AW, Al-Nuaimi AS, Al-Saidy AH(2005), "Concrete blocks for thermal insulation in hot climate", Cement and Concrete Research, Volume 35 ,Issue 8,pp.1472–9.
8. Alvarado JL, Terrell Jr W, Johnson MD(2009), "Passive cooling systems for cement-based roofs" Building and Environment, Volume 44,Issue 9, pp.1869–75.
9. Aspen Aerogels(2008), "SpaceloftTM 6250(2008), "Extreme protection for extreme environments", retrieved October 7 from www.aerogel.com,
10. Aspen Aerogels(2008),"Spaceloft® 3251, 6251, 9251, Flexible insulation for industrial, commercial and residential applications", retrieved October 7,from www.aerogel.com,
11. Athienitis AK, Liu C, Hawes D, Banu D, Feldman D(1997), "Investigation of the thermal performance of a passive solar test-room with wall latent heat storage", Building and Environment, Volume 32 Issue 5, pp.405–10.
12. BaetensR., JelleB.P., GustavsenA. (2011), "Aerogel insulation for building applications:a state-of-the-art review", Energy and Buildings Volume 43, pp.761–769.
13. BaetensR., JelleB.P., GustavsenA., GrynningS. (2010), "Gas-filled panels for building applications: a state-of-the-art review", Energy and Buildings , Volume 42 , pp.1969–1975.
14. Bahaj AS(2003) " Photovoltaic roofing: issues of design and integration into buildings" Renewable Energy, Volume 28,Issue 14, pp.2195–204.
15. Bahaj AS, James PAB, Jentsch MF(2008), "Potential of emerging glazing technologies for highly glazed buildings in hot arid climates" Energy and buildings, Volume 40,Issue 5, pp.720–31.
16. Balaras CA, Droutsa K, Argiriou AA, Asimakopoulos DN,(2000)"Potential for energy conservation in apartment buildings. Energy and buildings, Volume 31,Issue 2, pp.143–54.
17. Balaras CA.(1996)," The role of thermal mass on the cooling load of buildings. An overview of computational methods", Energy and buildings, Volume 24,Issue 1, pp.1–10.
18. BeckA, Frank.O, BinderM. (2007), " Influence of water content on the thermal conductivity of vacuum panels with fumed silica kernels" in: Proceedings of the 8th International Vacuum Insulation Symposium, ZAEBayern/UniWue, Würzburg, 18–19 September.
19. Bjorn Petter , Jelle,(2011)" Traditional, state-of-the-art and future thermal building insulation materials and solutions – Properties, requirements and possibilities", Energy and Buildings Vol. 43 , pp.2549–2563.
20. BrunnerS , SimmlerH. (2007)," In situ performance assessment and service life of vacuum insulation panels (VIP) in buildings" in: Proceedings of the 8th International Vacuum Insulation Symposium, ZAEBayern/UniWue, Würzburg, 18–19 September.
21. BrunnerS.,GasserPh., SimmlerH., GhaziK. (2006)," Investigation of multilayered aluminium-coated polymer laminates by focused ion beam (FIB) etching" Surface & Coatings Technology Volume 200, pp.5908–5914.

22. BrunnerS., SimmlerH. (2008),"In Situ performance assessment of vacuum insulation panels in a flat roof construction" , Volume 82, pp.700–707.
23. Canada Mortgage and Housing Corporation(2007) Research Highlights "Monitered Thermal Performance of ICF Walls in MURBs", Volume 7,Issue 119 of Technical Series pp.07-119.,CMHC Publisher
24. Capeluto IG(2003),"Energy performance of the self-shading building envelope. Energy and buildings, Volume 35, Issue 3, 327–336.
25. CapsR. (2005)," Monitoring gas pressure invacuuminsulation panels" in: Proceedings of the 7th International Vacuum Insulation Symposium, EMPA Dübendorf 28–29 September, , 2005, pp. 57–66.
26. CapsR., BeyrichenH., KrausD., WeismannS. (2008), "Quality control of vacuum insulation panels: methods of measuring gas pressure" Vacuum 82 pp.691–699.
27. CapsR., FrickeJ. (2000), "Thermal conductivity of opacified powder filler materials for vacuum insulation", International Journal of Thermo physics Volume 21, pp.445–452.
28. Castleton HF, Stovin V, Beck SBM, Davison JB(2010), " Green roofs: building energy savings and the potential for retrofit", Energy and Buildings, Volume 42,Issue 10, pp.1582–91.
29. Chan KT, Chow WK(1998). "Energy impact of commercial-building an envelopes in the sub-tropical climate". Applied Energy, Volume 60,Issue 1, pp.21–39.
30. Cheung CK, Fuller RJ, Luther MB(2005)"Energy-efficient envelope design for high-rise apartments" Energy and Buildings, Volume 37, Issue 1,pp.37–48.
31. Christian JE, Kosny J. Thermal Performance and wall ratings; 2006.
32. Ciampi M, Leccese F, Tuoni G. (2005) , "Energy analysis of ventilated and micro ventilated roofs" Solar Energy, Volume 79,Issue 2, pp.183–92.
33. Equilibrium TM Housing Insight,(1996-2010)"Riverdale NetZero Deep Wall System", Canada, http://www.cmhc-schl.gc.ca
34. Foss Asa, The PATH Partners November 13, 2005).Retrieved http://www.housingzone.com
35. FrickeJ, Schwab H , Heinemann U. (2006), "Vacuum insulation panels exciting thermal properties and most challenging applications "International Journal ofThermophysics Volume 27, pp.1123–1139.
36. FrickeJ. (2005), "From dewars to VIPs – one century of progress in vacuum insulation technology" in: Proceedings of the 7th International Vacuum Insulation Symposium, EMPA, Dübendorf, Switzerland, 28–29 September, pp.5–14.
37. Gaffin S, Rosenzweig C, Parshall L, Beattie D, Berghage R, O'Keefe G, Braman D(2005), "Energy balance modeling applied to a comparison of white and green roof cooling efficiency", In: Presentation at greening rooftops for sustainable communities.
38. Garrison JD, Collins RE.(1995)," Manufacture and cost of vacuum glazing" Solar Energy, Volume 55,Issue 3, pp.151–61.
39. Goodhew S, Griffiths R(2005)," Sustainable earth walls to meet the building regulations. Energy and Buildings,Volume 37,Issue 5, pp.451–459.
40. Green Buildings in Indian Cities(2009),CMS Environment Workshop, Retrieved from Http:// www. cmsvatavaran.org
41. Griffith B.T., ArashtehD., TürlerD. (1995)," Gas-filled panels: an update on applications in the building thermal envelope", in: Proceedings of the BETEC Fall Symposium, Superinsulation's and the Building Envelope, Washington, DC, 14 November.
42. GrynningS, JelleB.P, Uvsløkk .S, Gustavsen .A, Baetens.R, CapsR, Meløysund V. (2011),"Hot box investigations and theoretical assessments of miscellaneous vacuum insulation panel configurations in building envelopes", Journal of Building Physics Volume 34 ,pp.297–324.
43. Gustavsen A, Arasteh D, Jelle BP, Curcija C, Kohler C(2008)" Developing low conductance window frames: capabilities and limitations of current window heat transfer design tools—state-of-the-art review", Journal of Building Physics;Volume 32 Issue 2, pp.131–153.
44. Halwatura RU, Jayasinghe MTR(2008), "Thermal performance of insulated roof slabs in tropical climates", Energy and Buildings,Volume 40,Issue 7, pp.1153–60.
45. Han J, Lu L, Yang H (2009), "Investigation on the thermal performance of different lightweight roofing structures and its effect on space cooling load", Applied Thermal

Engineering; Volume 29,Issue 11–12, pp.2491–9.

46. Hernandez Patxi. , Kenny Paul.(2008),"Defining Zero Energy Buildings - A life cycle perspective", in Proc. Of .25th Conference on Passive and Low Energy Architecture, Dublin, 22nd to 24th October.
47. HostlerS.R., Abramson A.R, GawrylaM.D., BandiS.A., SchiraldiD.A. (2008),"Thermal conductivity of a clay-based aerogel", International Journal of Heat and Mass Transfer, Volume 52, pp.665–669.
48. Jelle B.P., Gustavsen A , Baetens R. (2010),"The high performance thermal building insulation materials and solutions of tomorrow", in: Proceedings of the Thermal Performance of the Exterior Envelopes of Whole Buildings XI International Conference (Buildings XI), Clearwater Beach, Florida, U.S.A., 5–9 December.
49. JelleB.P, GustavsenA, BaetensR. (2010)," The path to the high performance thermal building insulation materials and solutions of tomorrow", Journal of Building Physics, volume 34,pp.99–123.
50. Ji J, Luo C, Sun W, Yu H, He W, Pei G(2009),"An improved approach for the application of Trombe wall system to building construction with selective thermo-insulation fac¸ ades. Chinese Science Bulletin, Volume 54,Issue 11, pp.1949–56.
51. Jie J, Hua Y, Wei H, Gang P, Jianping L, Bin J(2007), " Modeling of a novel Trombe wall with PV cells. Building and Environment, Volume 42,Issue 3, pp.1544–52.
52. Kuznik F, Virgone J. (2009), "Experimental assessment of a phase change material for wall building use", Applied Energy;86(10):pp.2038–46.
53. Lazzarin RM, Castellotti F, Busato F(2005), "Experimental measurements and numerical Modelling of a green roof" Energy and Buildings,Volume 37,Isasue 1, pp.–7.
54. Liu KKY(2006), "Green, reflective, and photovoltaic roofs" Construction Canada, Volume 48,Issue 5.
55. Manz H, Brunner S, Wullschleger L(2006)," Triple vacuum glazing: heat transfer and basic mechanical design constraints" Solar Energy, Volume 80,Issue 12, pp.1632–42.
56. McKinsey(2009), "Pathways to a Low-Carbon Economy" Version 2 of the Global Greenhouse Gas Abatement Cost Curve, McKinsey & Company.
57. McKinsey, Pathways to a Low-Carbon Economy (2009)Version 2 of the Global Greenhouse Gas Abatement Cost Curve, McKinsey & Company.
58. MillsG.L., ZellerC.M. (2008), "The performance of gas filled multilayer insulation, Advances of cryogenic engineering", Transactions of the cryogenic engineering conference ,Volume 53, pp.1475–1482.
59. Nayak JK(1987), "Transwall versus Trombe wall: relative performance studies. Energy Conversion and Management; Volume 27, Issue 4, pp.389–93.
60. PapadopoulosA.M. (2005),"State of the art in thermal insulation materials and aims for future developments" Energy and Buildings Volume 37 ,pp.77–86.
61. Papaefthimiou S, Syrrakou E, Yianoulis P. (2006), "Energy performance assessment of an electrochromic window", Thin Solid Films, Volume 502,Issue (1–2), pp.257–64.
62. Price BA, Smith TF. (1995)"Thermal response of composite building envelopes accounting for thermal radiation "Energy Conversion and Management, Volume 36,Issue 1, pp.23–33.
63. Robinson PD, Hutchins M. G(1994), "Advanced glazing technology for low energy build-ings in the UK", Renewable Energy, Volume 5,Issue (1–4), pp.298–309.
64. Robinson PD, Hutchins M. G. (1994),"Advanced glazing technology for low energy build-ings in the UK. Renewable Energy; Volume 5,Issuue (1–4) ,pp.298–309.
65. Roof types 2012 .Retrived From http://rooftypes.org/
66. Sanjay M, Prabha Chand(2008), " Passive cooling techniques of buildings: past and present—a review" ARISER,Volume 4 Issue (1), pp.37–46.
67. SchultzJ.M., JensenK.I. (2008), "Evacuated aerogel glazing's", Volume 82, pp.723–729.
68. SchultzJ.M., JensenK.I., Kristiansen F.H. (2005), "Super insulating aerogel glazing", Solar Energy Materials & Solar Cells Volume 89, pp.275–285.
69. SchwabH., Heinemann U, BeckA., EbertH.-P., FrickeJ. (2005), "Permeation of different gases through foils used as envelopes for vacuum insulation panels, Journal of Thermal Envelope & Building Science Volume 28,pp.293–317.
70. SchwabH., HeinemannU., Beck A., EbertH.-P., FrickeJ. (2005), "Dependence of thermal conductivity on water content in vacuum insulation panels with fumed silica

kernels”, Journal of Thermal Envelope & Building Science Volume 28 , pp.319–326.

71. SchwabH., HeinemannU., BeckA., EbertH.-P., FrickeJ. (2005), “Prediction of service lifefor vacuum insulation panels with fumed silica kernel and foil cover”, Journal of Thermal Envelope & Building Science Volume 28 , pp.357–374.
72. SchwabH., HeinemannU., WachtelJ.,. EbertH.-P, FrickeJ. (2005), “Predictions for the increase in pressure and water content of vacuum insulation panels (vips) integrated into building constructions using model calculations”, Journal of Thermal Envelope & Building Science Volume 28 ,pp.327–344.
73. SchwabH.,. StarkC, WachtelJ., EbertH.-P, FrickeJ. (2005), “Thermal bridges in vacuuminsulatedbuilding facades”, Journal of Thermal Envelope & Building Science Volume 28, pp.345–355.
74. Sharma AK, Bansal NK, Sodha MS, Gupta V(1989), ”Vary-therm wall for cooling/heating of buildings in composite climate. International Journal of Energy Research, Volume 13,Issue 6, pp.733–9.
75. SimmlerH., BrunnerS. (2005), “Ageing and service life of VIP in buildings”, in: Proceedings of the 7th International Vacuum Insulation Symposium, EMPA, Dübendorf, Switzerland, 28–29 September, pp. 15–22.
76. SimmlerH., BrunnerS. (2005), “Vacuum insulation panels for building application basic properties, ageing mechanisms and service life”, Energy and Buildings Volume 37, pp.1122–1131.
77. SimmlerH., BrunnerS., HeinemannU., SchwabH., KumaranK., MukhopadhyayaP.,QuènardD., SallèeH., NollerK., Kücküpinar-NiarchosE., StrammC., TenpierikM., CaubergH., ErbM. (2005), “Vacuum insulation panels. Study on VIPcomponents and panels for service life prediction in building applications (subtask A)”, HiPTI – High Performance Thermal Insulation (September), IEA/ECBCS Annex 39.
78. Singapore’s Greenest Building, 2012.Retrived from www.bca.gov.sg/zeb/greenerysystems.html
79. Steering through the maze #2,(2011)” Nearly zero energy buildings, achieving the EU 2020 target”, European Council for an Energy Efficient Economy. Retrived from http://www.eceee.org/buildings/Steering-2-zerobldgs.pdf
80. Sullivan R, Beck FA, Arasteh DK, Selkowitz SE(1996),”Energy performance of evacuated glazings in residential buildings”, Transactions—American Society of Heating Refrigerating and Air Conditioning Engineers, Volume 102, pp.220–7.
81. Suresh B. Sadineni∗, Srikanth Madala, Robert F. Boehm (2011),”Passive building energy savings: A review of building envelope components", Renewable and Sustainable Energy Reviews 15, Elsevier Ltd., pp.3617– 3631.
82. Suzlon One Earth,2012. Retrieved from http://en.wikipedia.org/wiki/Suzlon_One_Earth.
83. SveipeE., JelleB.P., WeggerE., UvsløkkS., GrynningS., ThueJ.V., Time B. and GustavsenA., “Improving thermal insulation of timber frame walls by retrofitting with vacuum insulation panels – experimental and theoretical investigations", Journal of Building Physics, in press.
84. Tang R, Meir IA, Wu T(2006), ”Thermal performance of non air-conditioned buildings with vaulted roofs in comparison with flat roofs. Building and Environment, Volume 41,Issue 3, pp.268–76.
85. TenpierikM., CaubergH. (2007), “Analytical models for calculating thermal bridge effects caused by thin high barrier envelopes around vacuum insulation panels", Journal of Building Physics Volume 30, pp.185–215
86. TenpierikM., van der SpoelW., CaubergH. (2007), “Simplified analytical models forservice life prediction of a vacuum insulation panel”, in: Proceedings of the 8thInternational Vacuum Insulation Symposium, ZAEBayern/UniWue, Würzburg,18–19 September.
87. TenpierikM., van der SpoelW., CaubergH. (2008),” An analytical model for calculating thermal bridge effects in high performance building enclosure”, Journal of Building Physics Volume 31, pp.361–387.
88. TenpierikM.J. (2009), “Vacuum insulation panels applied in building constructions (VIPABC)”, Ph.D. Thesis, Delft University of Technology, Delft, The Netherlands.
89. TenpierikM.J., CaubergJ.J.M., ThorsellT.I. (2007), “Integrating vacuum insulation panelsin building constructions: an integral perspective”, Construction Innovation Volume 7, pp.38–53.

90. Tinianov Brandon(2010),”Developing The Next Three Generation of Zero Energy Windows”,BEST2-Fenestration 1,Session WB9-4

91. Tunc¸ M, Uysal M(1991), ”Passive solar heating of buildings using a fluidized bed plus Trombe wall system. Applied Energy, Volume 38,Issue 3, pp.199–213.
92. Tyagi VV, Buddhi D.(2007)” PCM thermal storage in buildings: a state of art”, Renewable and Sustainable Energy Reviews, Volume 11,Issue 6, pp.1146–66.
93. USAID India Energy Conservation and Commercialization (2012) . Retrieved from http://eco3.org/NZEBs
94. WeggerE., JelleB.P., SveipeE., GrynningS., GustavsenA., BaetensR. and ThueJ.V., “Aging effects on thermal properties and service life of vacuum insulation panels”, Journal of Building Physics, in press.
95. Wong NH, Chen Y, Ong CL, Sia A(2003), ” Investigation of thermal benefits of rooftop garden in the tropical environment”, Building and Environment, Volume 38,Issue 2, pp.261–70.
96. Wong NH, Cheong DKW, Yan H, Soh J, Ong CL, Sia A(2003), ”The effects of rooftop garden on energy consumption of a commercial building in Singapore”, Energy and Buildings, Volume 35,Issue 4, pp.353–64.
97. Zalewski L, Chantant M, Lassue S, Duthoit B(1997),” Experimental thermal study of a solar wall of composite type” Energy and Buildings,Volume 25,Issue 1, pp.7–18.
98. Zalewski L, Lassue S, Duthoit B, Butez M(2002), ”Study of solar walls—validating a simulation model. Building and Environment, Volume 37,Issue 1, pp.109–21
99. Zhang Fangzhu & Cooke Philip(2010),“Green Buildings and Energy Efficiency”, Centre for Advanced Studies, Cardiff University,UK pp. 1-28
100. Zrikem Z, Bilgen E(1986),”Theoretical study of a non-convective trombe wall collector with honeycomb structure. Solar & Wind Technology, Volume 3,Issue 1,pp.–44.
101. ZwergerM., KleinH. (2005), “Integration of VIPs into external wall insulation systems", in: Proceedings of the 7th International Vacuum Insulation Symposium, EMPA, Dübendorf, Switzerland, 28–29 September, pp. 173–179.