A review of new materials used for building integrated systems

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Abstract: Solar energy has a significant impact on the environment, so the development of new technologies in this field is very important for many reasons and is subject of many researches nowadays. Incorporation of phase change materials (PCMs) into building structures has been found as useful for reduction of temperature fluctuations, while maintaining the thermal comfort. Numerous methods were developed by previous researchers using this type of materials. This paper reviews some latest publications on the use of new materials in buildings, covering PCMs, nanomaterials and nanofluids, current building applications and their thermal performance analyses. These materials have predictable applications in buildings for effective use of solar energy. There are large numbers of PCMs that melt and solidify at a wide range of temperatures, making them attractive in a number of applications. Also, nanofluid technology has been developed in the past decade. Nanofluids have a great potential for solar thermal applications, especially because of their specific heat and thermal conductivity increasing. Uses of hybrid nanofluids for solar thermal collectors are expected to give excellent performance improvement. This paper also investigates the feasibility of using PCMs for thermal management of Building Integrated Solar Thermal Systems (BISTS).

Keywords: Phase change materials, Nanomaterials, Nanofluids, Building Integrated Systems

1. Introduction

The fast paced technology development during the last decades of XX century led to the appearance of several new materials suitable for use in BISTS, such as phase change materials (PCMs), nanomaterials and nanofluids which revealed many interesting properties reported in the past decades. The unique set of features of these materials offers unprecedented potential for various applications, including Building Integrated Solar Thermal Systems.

Over the last decade PCMs are very attractive for research as they represent an innovative solution that can contribute to the improvement of the energy performance of buildings. A trend towards integrating PCMs into transparent envelope components is observed recently (Fokaides et al., 2015). Thus integration of these materials into buildings is their significant application, and it enables more dynamic use of energy. A large number of PCMs are available in any required temperature range. PCMs utilize the latent heat of phase change to control temperatures within a specific range. Sharma et al. (2009) review summarizes the investigation and analysis of the available thermal energy storage systems incorporating PCM for use in different applications.

New opportunities for the development of nanoelectronic devices for solar cell applications were brought by nanotechnology as new technology in processing PV solar sell. Characteristics

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Characteristics of bulk materials are substantially different than semiconductor particles with dimensions in nanometer range. Due to quantum confinement effects in nanocrystalline semiconductors an effective increase in bandgap is achieved. As energy band-gap can be controlled by nanoscale components, nanotechnology referred as "third generation PV" is used to help increasing conversion efficiency of solar cell (Tyagi et al., 2013).

Nanofluids can be tailored to provide superior optical and thermo-physical properties and thus have increasingly attracted attention for use in solar thermal applications. Up to a 10% increase in the efficiency has been reported through the use of nanofluids compared to conventional collectors (Mesgari S. et al, 2016). As a colloidal mixture made of a base fluid and a nanoparticle, nanofluid is a new generation of heat transfer fluids becoming a high potential fluid in heat transfer applications due to enhanced thermal conductivity (Devendiran, 2016).

2. Phase Change Materials

Three general categories of PCMs are organic, inorganic and eutectics, and they can be further classified according to various components of the PCMs, (Sharma et al., 2009; Kalnæs and Jelle, 2015).

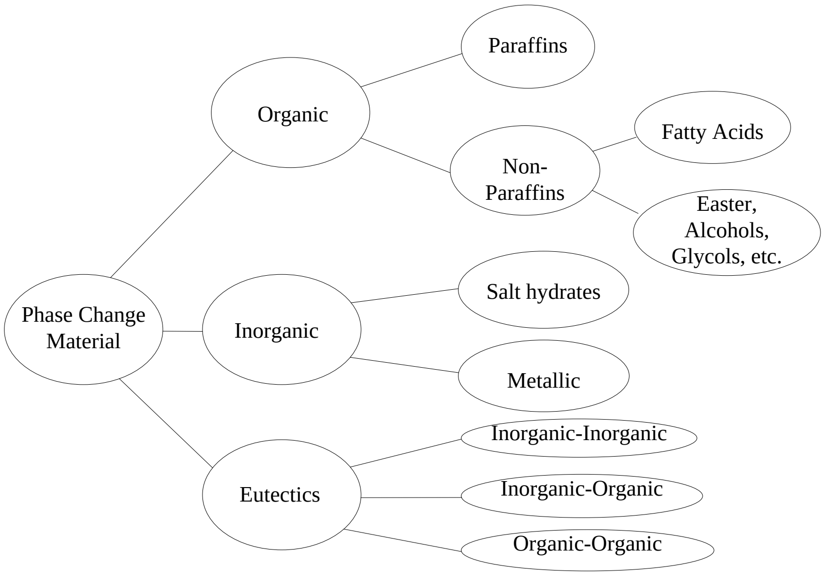

Fig. 1. General categorization of PCMs

PCMs can be found in a wide variety of temperature ranges. The PCMs in number of studies have been limited to PCMs with phase change temperatures in the appropriate range to be efficient in buildings. Cabeza et al. (2011) have listed several tables of PCM properties where the potential areas of use have been divided by the PCMs' phase change temperature. For use in buildings, three temperature ranges were suggested: (1) up to 21 ^{o} C for cooling applications, (2) 22–28 ^{o} C for human comfort applications, and (3) 29–60 ^{o} C for hot water applications

Only a few of many substances studied as potential PCMs are commercialised as so. Detailed review of the different substances (organic, inorganic and eutectic) that have been studied by different researchers for their potential use as PCMs is given by Zalba et al. (2003).

Fokaides et al. (2015) summarized the employed testing facilities, equipment and measurements for the investigation of the thermal performance of PCMs for transparent building elements from literature. Also, this study presented the main solutions proposed in the literature for applications in the past few years for PCMs integrated into transparent buildings elements. Kalnæs and Jelle (2015) have compared and summarized the advantages and drawbacks of organic, inorganic and eutectic PCMs, Table 1.

Table 1. Overview of advantages and drawbacks for PCMs.

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

Organic PCMs are divided into paraffin and non-paraffin (Tyagi and Buddhi, 2007; Sharma et al., 2009).Paraffins are available in a large temperature range, which make them suitable for use in various other areas besides building related applications. Non-paraffins used as PCMs include fatty acids and their fatty acid esters and alcohols, glycols, etc. Fatty acids have received the most attention for use as PCMs in buildings and the most interesting ones include lauric acid, myristic acid, palmiticacid and stearic acid. Organic PCMs have many qualities which make them suited for building applications, but the fact that many organic PCMs are considered flammable is a crucial drawback for which impacts the safety aspect of organic PCMs considerably when aimed at building applications (Kalnæs and Jelle, 2015).

Inorganic materials are further classified as salt hydrate and metallic. These phase change materials do not supercool appreciably and their heats of fusion do not degrade with cycling (Sharma et al., 2009). Inorganic compounds have a high latent heat per unit mass and volumes. In comparison to organic compounds, they are low cost and are non-flammable. Inorganic metallic materials are not within the desired temperature range and in addition they have severe weight penalties, which make them unsuited for building applications. Hydrated salts consist of an alloy of inorganic salts and water and enable a cost-effective PCM due to their easy availability and low cost. The phase change transformation contains of hydration or dehydration of the salts. These processes are typical melting and freezing. The salt hydrate may either melt to a salt hydrate containing less water or to an anhydrous form where salt and water are completely separated (Sharma et al., 2009).

A eutectic is a minimum-melting composition of two or more components, each of which melts and freeze congruently, forming a mixture of the component crystals during crystallization (Tyagi and Buddhi, 2007). Combinations of organic–organic, inorganic–inorganic or organic– inorganic components make eutectics appropriate for specific applications. Organic eutectic mixtures consisting of fatty acids are mostly investigated. Karaipekli and Sari (2008) have explored organic eutectic which consist of capric acid and myristic acid, Sari et al. (2004) have studied some organic eutectics: lauric acid and stearic acid, myristic acid and palmitic acid and palmitic acid and stearic acid and Shilei et al. (2006) have analysed organic eutectic consist of capric acid and lauric acid. The most common inorganic eutectics that have been investigated consist of different salt hydrates. One of advantages of eutectic mixtures is their capability to obtain more desired properties such as a specific melting point or a higher heat storage capacity per unit volume. The thermo-physical properties are to be tested and proved in the future, which makes them adequate for further investigations (Kalnæs and Jelle, 2015).

3. Nanomaterials

Nanomaterials have predictable applications in buildings for effective use of solar energy, especially for PV applications. There are three devices used in nanotechnology for PV cell production: carbon nanotubes (CNT), quantum dots (QDs) and "hot carrier" (HC).

Carbon nanotubes (CNT) are constructed of a hexagonal lattice carbon with excellent mechanical and electronic properties (El Chaar et al., 2011). With *n* lines and *m* columns the nanotube structure is a vector which defines how the graphene (an individual graphite layer) sheet is rolled up. Nanotubes can be metallic or semiconducting. CNTs provide the highest spectral absorptivity (particularly on a per unit mass basis) over the entire solar range and they are present in different forms: single-walled carbon nanotubes (SWCNTs), double-walled carbon nanotubes (DWCNTs) and multi-walled carbon nanotubes (MWCNTs) (Chaar et al., 2011). SWCNTs are formed by wrapping a one-atom-thick layer of graphene into a seamless cylinder while DWCNTs and MWCNT are formed by concentrically wrapping two and multiple layers of graphite, respectively (Mesgari S. et al., 2016).

Naphthalocyanine (NaPc) dye-sensitized nanotubes have been developed. These resulted in higher short circuit current, while the open circuit voltage is reduced. The efficiencies are still in the 3–4% range but much research is being conducted in this field.

Nanometer-sized crystallite semiconductors produced by number of methods are quantum dots (QDs) (Razykov et al., 2011). Their ability to tune the absorption threshold simply by choosing the dot diameter is the main advantage. QDs can be described as a material that is built with many forms of material thus makes it a special semiconductor system with an ability to control band-gap of energy. According to opportunity to control the energy of carrier states by adjusting the confinements in all three spatial dimensions QDs are known as "artificial atoms". Aroutiounian et al. (2005) developed a mathematical model to calculate photo current for the solar cell that is QD based. Efficiency of solar cells based on QD are easily influenced by the defects on them (Gorji, 2012).

The Hot Carriers solar cells technique utilizes selective energy contacts to extract light generated by "hot carriers" (HC) (electrons and holes) from semiconductor regions without transforming their extra energies to heat. That is why it is the most challenging method compared to CNT and QD (El Chaar et al., 2011). HCs have to be collected from the absorber over a very small energy range, with selective energy contacts, which is the most novel approach for PV cell production and it allows the use of one absorber material that yields to high efficiency under concentration.

Efficiency of HC reaches 66% which is three times higher than existing cell made from silicon (Ross, 1982), but this technology will never fully develop until a solutions to the main material challenges are found. The schematic of HC solar cell is presented in Fig. 2, adapted from Tyagi et al. (2013).

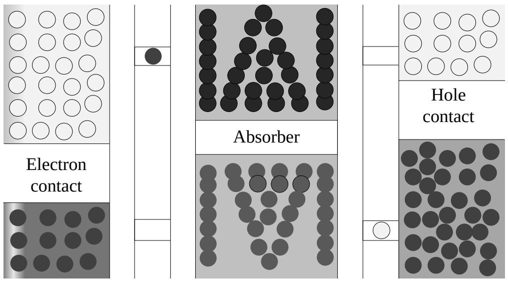

Fig. 2. HC schematic

4. Nanofluids

Nanofluids can be normally classified into two categories: metallic and non-metallic nanofluids. The third category is hybrid nanofluids (Nagarajan et al., 2014). Metallic nanofluids refer to those containing metallic nanoparticles (Cu, Al, Zn, Ni, Si, Fe, Ti, Au and Ag), while nanofluids containing non-metallic nanoparticles such as aluminium oxide (Al_2O_3), copper oxide (CuO) and silicon carbide (SiC, ZnO,TiO_2) are considered as non-metallic nanofluids, semiconductors (TiO_2), Carbon Nanotubes and composites materials such as nanoparticles core polymer shell composites. A single material does not possess all the favourable characteristics required for a particular purpose. It may have either good thermal properties or good rheological properties. In many practical applications it is required to trade-off between several properties, and that is where hybrid nanofluids come, exhibiting remarkable physicochemical properties that do not exist in the individual components.

Mainly two techniques are used to produce nanofluids. One-step technique combines the production of nanoparticles and dispersion of nanoparticles in the base fluid into a single step, and this technique have some variations. The two-step method is extensively used in the synthesis of nanofluids considering the available commercial nanopowders supplied by several companies. In this method, nanoparticles are first produced and then dispersed in the base fluids.

Based upon the preparation methods, there are different types of nanofluids: alumina nanofluids, aluminum nitride nanofluids, zinc oxide nanofluids, titanium dioxide nanofluids, silicon dioxide nanofluids, iron oxide nanofluids, copper nanofluids, carbon nanofluids, gold and silver nanofluids, graphene nanofluids, and hybrid nanofluids.

The properties of nanofluids mainly based on five parameters: thermo fluids, heat transfer, particles, colloid and lubrication. The physical properties of nanofluids are quite different from the base fluid.

5. PCM, nanomaterial and nanofluid applications in BISTS

PCM can be used in thermal energy storage applications. The ideal PCM to be used for any thermal storage system must meet following requirements: high sensitive heat capacity and heat of fusion; stable composition; high density and heat conductivity; chemical inert; nontoxic and non-inflammable; reasonable and inexpensive. The salt hydrates, paraffin and paraffin waxes, fatty acids and some other compounds in the nature have high latent heat of fusion in the temperature range from 30ºC to 80ºC that is interesting for solar applications.

The integrated PCM solar collector storage concept is economically promising in low temperature SWH systems for domestic, agricultural and industrial applications. A system of this type combines collection and storage of thermal energy into a single unit. Integrated PCM solar collector for a low-temperature SDHW system using salt hydrate eutectic mixture where the PCM is held inside the collector and thermally discharged to cold water flowing through a heat exchanger is developed by Rabin et al. (1996). Integrated system is shown in Fig. 3.

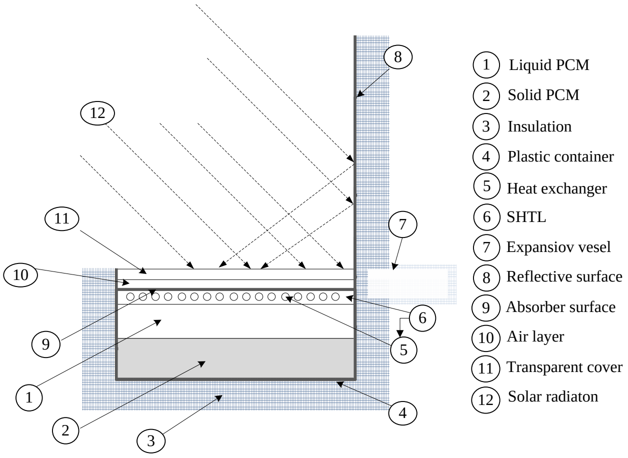

Fig. 3. Integrated PCM solar collector storage system designed

A type of water-PCM solar collector consisting of two adjoining sections is developed by Kürklü et al, (2002). One section is filled with water and the other with paraffin wax, where melting temperature is in range 45–50 ^{o}C, as it is shown Fig. 4. The experimental results indicated that the water temperature could exceed 55 ^{o}C during a typical day of high solar radiation and remain over 30 ^{o}C during the whole night.

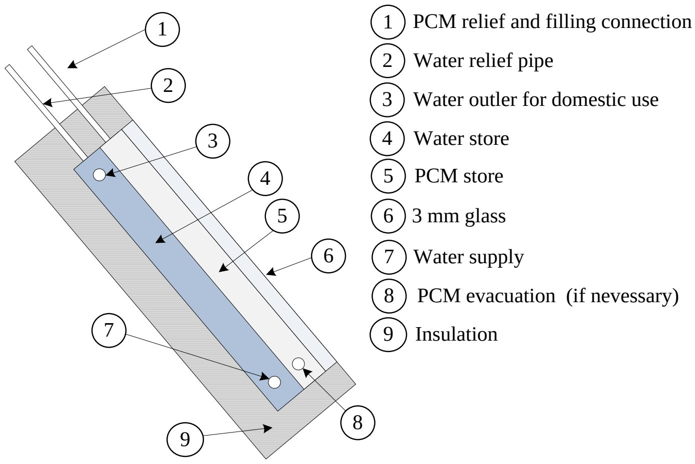

Fig. 4. Schematic view of solar collector construction with PCM

The key component in the solar domestic hot water system using phase change materials is the latent heat storage unit. Many researchers focused on improving the heat transfer inside it, in order to improve the energy storage and thermal performance of solar hot water systems. Recently, the incorporation of PCM in different applications has grown interest to the researcher. A large number of solid–liquid PCMs have been investigated for heating and cooling applications (Sharma et al., 2009).

Nanotubes can potentially replace indium tin-oxide in solar cells as a transparent conductive film in solar cells to allow light to pass to the active layers and generate photocurrent (Kaushik and Majumder, 2015). CNTs in organic solar cells help reduce energy loss and increase resistance to photooxidation. Germanium CNT diode can be fabricated and it exploits the photovoltaic effect. PV technologies may incorporate CNT-Silicon hetero junctions to leverage efficient multiple-exaction generation at p-n junctions formed within individual CNTs.

The inclusion of nanoscale components in PV cells (BIPV or PV/T) is a way to reduce some limitations. First, the ability to control the energy bandgap provides flexibility and inter-changeability. Second, nanostructured materials enhance the effective optical path and significantly decrease the probability of charge recombination.

The use of nanocrystal QDs, which are nanoparticles usually made of direct bandgap semiconductors, lead to thin film solar cells based on a silicon or conductive transparent oxide (CTO), like indium-tin-oxide (ITO), substrate with a coating of nanocrystals (Razykov et al., 2011).

Initially, the nanofluid applications in solar collectors and water heaters are investigated from the efficiency, economic and environmental points of view. The experimental analysis of thermal conductivity done by some authors, and optical properties of nanofluids are also reviewed. The reason is that these parameters show the capability of the nanofluid to work as an enhanced HTF under high temperature. Sani et al. (Reddy et al, 2016) reported the optical characterization of single-wall carbon nanohorn (SWCNH) nanoparticles for solar energy application. The result shows that carbon nanohorn-based nanofluids can be useful for increasing the efficiency and compactness of thermal solar devices.

Some authors carried out the investigation of nanofluids in the flat-plate collector for low-temperature applications and they found that a nanofluid-based solar collector is more efficient than a conventional solar collector (Reddy et al, 2016).

6. Conclusion

Incorporation of phase change materials (PCMs) into building structures has been found as useful for reduction of temperature fluctuations, while maintaining the thermal comfort. The applications in which PCMs can be applied are vast, and mainly includes heat and coolness storage in buildings. The nano-technology has brought new opportunities for the development of nanoelectronic devices for solar cell applications. Nanofluids have been utilized to improve the efficiency of several solar thermal applications. But the most important challenge in front of the scientist is the cost of nanoparticles, their synthesis, and instability and agglomeration problem. These problems need to be resolved in the coming future with improvement in nanotechnology. All these materials (PCMs, nanomaterials and nanofluids) have predictable applications in buildings for effective use of solar energy, but many more applications are yet to be discovered.

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