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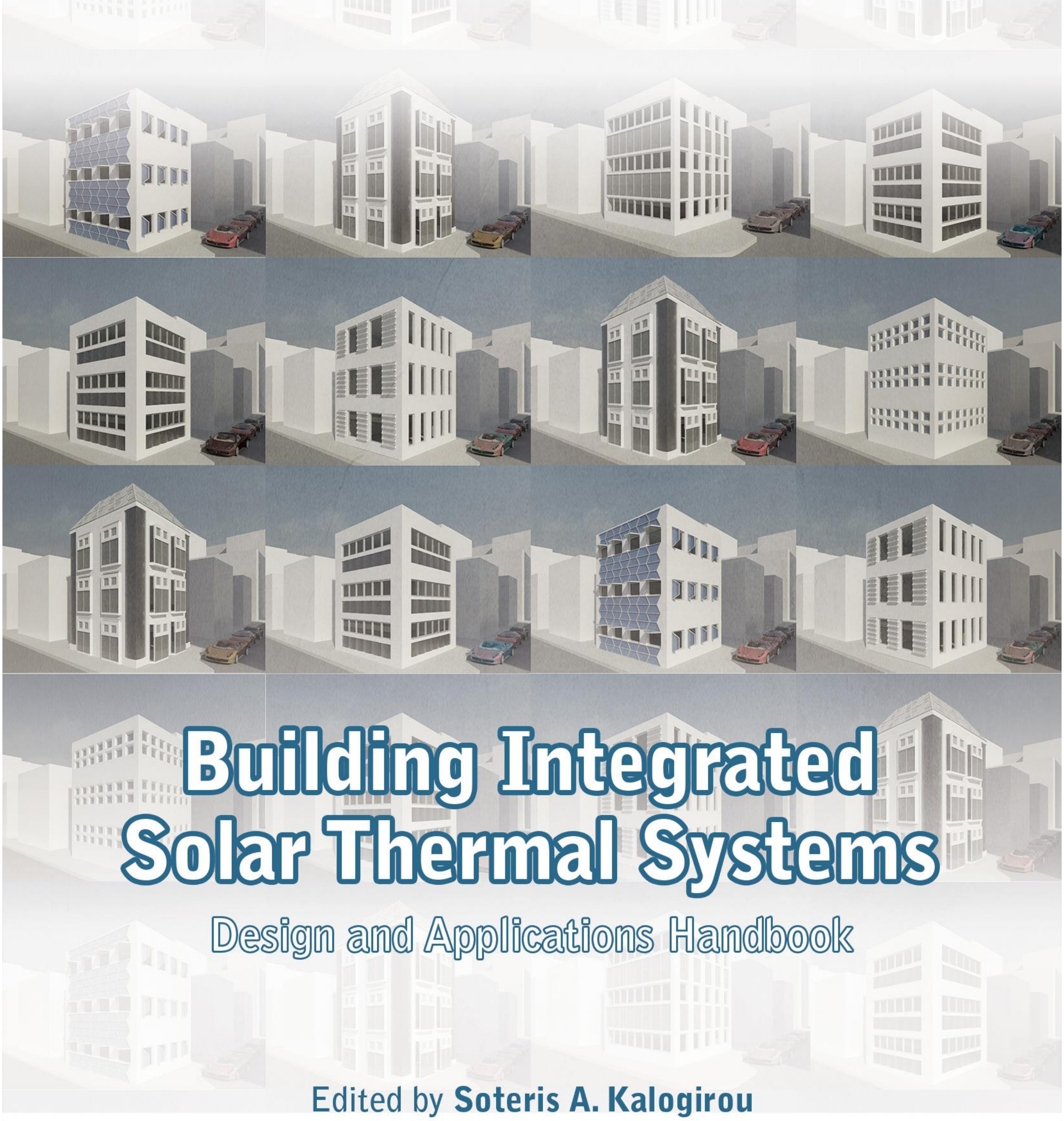

Building Integrated Solar Thermal Systems

Design and Applications Handbook

Edited by **Soteris A. Kalogirou**

CYPRUS UNIVERSITY OF TECHNOLOGY
2004

COST Action TU1205 (BISTS)

COST Action TU1205 - An Overview

Energy use in buildings represents 40% of the total primary energy used in the EU and therefore developing effective energy alternatives is imperative. Solar thermal systems (STS) will have a main role to play as they contribute directly to the heating and cooling of buildings and the provision of domestic hot water. STS are typically mounted on building roofs with no attempt to incorporate them into the building envelope, creating aesthetic challenges and space availability problems. The Action will foster and accelerate long-term development in STS through critical review, experimentation, simulation and demonstration of viable systems for full incorporation and integration into the traditional building envelope. Viable solutions will also consider economic constraints, resulting in cost effective Building Integrated STS. Additionally, factors like structural integrity, weather impact protection, fire and noise protection will be considered. The most important benefit of this Action is the increased adoption of RES in buildings. Three generic European regions are considered; Southern Mediterranean, Central Continental and Northern Maritime Europe, to fully explore the Pan-European nature of STS integration. The Action consortium presents a critical mass of European knowledge, expertise, resources, skills and R&D in the area of STS, supporting innovation and conceptual thinking.

Domain: Transport and Urban Development (TUD)

Action Webpages: http://www.tu1205-bists.eu/ & http://www.cost.eu/COST_Actions/tud/Actions/TU1205

Countries participating: Austria, Belgium, Bulgaria, Cyprus, Denmark, France, Germany, Greece, Hungary, Ireland, Israel, Italy, Lithuania, Malta, Netherlands, Poland, Portugal, Romania, Serbia, Spain, Turkey, United Kingdom.

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COST Action TU1205 (BISTS)

Building Integration of Solar Thermal Systems

DESIGN AND APPLICATIONS HANDBOOK

Edited by Soteris A. Kalogirou

***Notice**: The compilation of the various chapters contained within this handbook have been produced by COST Action TU1205 members having sole responsibility of the material presented therein.*

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CONTENTS

PREFACE

This handbook produced by the members of the COST Action TU1205 – Building Integrated Solar Thermal Systems (BISTS), funded by COST, 2013-2017. It covers introductory subjects on the presentation of the Action, the classification and characterisation of BISTS and basic resource (solar radiation) analysis. Following on, Section 2 details the basic BISTS design, including architectural planning, thermal and optical design of BISTS, modelling of the systems, installation, testing, commissioning and maintenance as well as life cycle analysis, economics and legal issues. Section 3 presents new options with respect to emerging architectural design concepts, system and application options, materials, retrofitting BISTS and thermal storage integration. Section 4 presents five different innovative BISTS designs developed by various Action members, a building erected in Israel where BISTS are applied extensively, as well as the modelling of novel solar thermal collectors suitable for building integration. The last two sections deal with the outlook of the technology and basic conclusions obtained from this Action with supporting material, including journals that publish material relevant to BISTS, participant research and testing centres and infrastructures, international activities, networks and projects and a comprehensive database of BISTS applications, presented in a connected publication produced by this Action. Many more details can be found in the Action website: http://www.tu1205-bists.eu/.

We hope that the material presented in this handbook will be of interest to architects, solar engineers, building services engineers, government bodies and anyone who has an interest in this subject. Many thanks to the Action members and non-members who participated in the writing of the various chapters and of course to the COST Office for funding this Action.

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SECTION 3

NEW OPTIONS

CONTENTS

3.3 NEW MATERIALS

Jasna Radulovic, Danijela Nikolic

3.3.1 Introduction

Standard BISTSs use solar collectors, which are built in a wide variety of designs and from many different materials. Solar collector absorbers are usually black painted metal (mostly copper because of the corrosion resistance, rarely aluminium and steel) or plastic plates. Low-iron glass has been widely used for solar collector glazing. Also, BIPV systems are based on different technologies. The material most commonly used is silicon (Si). Silicon is a leading material in PV cells technology, due to its high efficiency.

With the great development of technology in the last decades of the twentieth century, there has been an appearance of numerous new materials suitable for use in BISTS. Phase change materials (PCMs), nanomaterials and nanofluids have shown many interesting properties which have been reported in the past decades. The distinctive feature of these materials offer unprecedented potential for many applications, including application in Building Integrated Solar Thermal Systems.

3.3.2 Phase Change Materials

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.

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). One classification is given in Fig. 3.3.1.

Another classification, where difference in melting enthalpy and melting temperature for some of the most common materials used as PCMs was suggested by Cabeza et al. (2011).

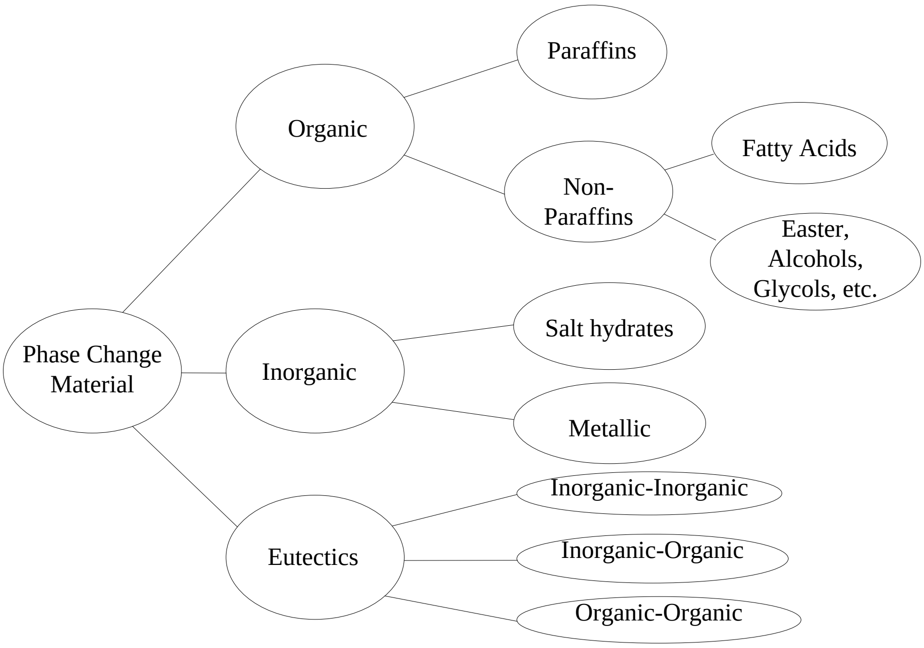

Figure 3.3.1. General categorization of PCMs.

Organic PCMs

Organic PCMs are divided into paraffin and non-paraffin. Organic materials include congruent melting, self-nucleation and usually non-corrosiveness to the container material (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 PCMs

Inorganic materials are classified as either 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 are low in cost in comparison to organic compounds and are non-flammable.

For building applications however, metallic materials are not within the desired temperature range and have severe weight penalties making them unsuitable. Hydrated salts consist of an alloy of inorganic salts and water and provide a cost-effective PCM due to easy availability and low cost. The phase change transformation involves hydration or dehydration of the salts in a process that resembles typical melting and freezing. The salt hydrate may either melt to a salt hydrate containing less water or to an anhydrous form where salt and water is completely separated (Sharma et al., 2009).

Eutestic mixtures

An 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). Eutectics can be made as combinations of organic–organic, inorganic–inorganic or organic–inorganic mixtures. This gives options for a wide variety of combinations that can be appropriate for specific applications.

The most commonly studied organic eutectic mixtures consist of fatty acids. Karaipekli and Sari (2008) have investigated 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. Capability to obtain more desired properties such as a specific melting point or a higher heat storage capacity per unit volume is one of advantages of eutectic mixtures. The thermo-physical properties are to be tested and proved in the future, which makes them adequate for further investigations (Kalnæs and Jelle, 2015).

Comparison summary

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 °C for cooling applications, (2) 22–28 °C for human comfort applications, and (3) 29–60 °C for hot water applications.

Many substances have been studied as potential PCMs, but only a few of them are commercialised. 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). Some of their thermo-physical properties are included (melting point, heat of fusion, thermal conductivity and density), although some authors give further information (congruent/incongruent melting, volume change, specific heat, etc.). Zalba et al. (2003) also shows a list of the commercial PCMs available in the market with their thermo-physical properties as given by the companies (melting point, heat of fusion and density).

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, shown in Table 3.3.1.

Table 3.3.1. 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

3.3.3 Nanomaterials

New opportunities for the development of nanoelectronic devices for solar cell applications were brought by nanotechnology as new technology in processing PV solar cell. 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). There are three devices used in nanotechnology for PV cell production: carbon nanotubes (CNT), quantum dots (QDs) and “hot carrier” (HC). The advantages of nanotechnology are:

- Enhance material mechanical characteristic,
- Low cost,
- Lightweight and
- Good electrical performances.

Carbon nanotubes (CNT)

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. Carbon 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 et al., 2016).

A p-n junction which generate electrical current is formed of PV nanometer-scale tubes coated by special p and n type semiconductor materials and this methodology improves and increases the surface area available for electricity production. CNTs can be used as reasonably efficient photosensitive materials as well as other PV materials.

Nanotubes are currently used as the transparent electrode for efficient, flexible polymer solar cells. Naphthalocyanine (NaPc) dye-sensitized nanotubes have been developed. These resulted in higher short circuit current, while the open circuit voltage is reduced. Totally inorganic based nanoparticle solar cells, based on nanoparticles of CdSe, CdTe, CNTs and nanorods made out of the same material are studied by number of research groups. The efficiencies are still in the 3–4% range but much research is being conducted in this field.

Quantum dots (QD)

Nanometer-sized crystallite semiconductors produced by a 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 materials thus makes it a special semiconductor system with an ability to control the band-gap of energy. If band-gap energy size increases voltage output can also be increased. On the other hand, smaller band-gap can also increase current output. QDs are found as appropriate solution since they can vary light absorption and emission spectra of light (Tyagi et al., 2013).

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”. With QDs closely packed, the confined levels overlap to form minibands in QD superlattices, which extends the range of electronic and optical properties that can be provided by semiconductor materials. QD superlattices have interesting possible applications in “third-generation” PV with the control of miniband energy level and bandwidth, especially for tandem solar cells. The basic principle behind the efficiency increases offered by QD intermediate-band solar cells is that the discrete states that result from the inclusion of the dots allow for absorption of sub-bandgap energies. When the current is extracted, it is limited by the host bandgap and not by the individual photon energies, and that is the reason why this approach can exceed the efficiency of an ordinary dual-junction cell.

Aroutiounian et al. (2005) developed a mathematical model to calculate photo current for the solar cell that is QD based. Two assumptions are made: (1) QDs are located in subsequent layers, (2) periodically stacked M times together at a distance of d, d>>0, where a0 is typical size of QDs are contained in this model. Efficiency of solar cells based on QD are easily influenced by the defects on them (Gorji, 2012).

Hot Carrier solar cells (HC)

This 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 high efficiency under concentration.

The 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 solutions to the main material challenges are found. Furthermore, away from incorporating multiple absorption path devices into a shorter time realization since most of these devices are more suitable for the high energy portion of the spectrum (Hosenberg et al., 2007), meaning to date that HC solar cells are just an experimented technology. The schematic of HC solar cell is presented in Fig. 3.3.2., adapted from Tyagi et al. (2013).

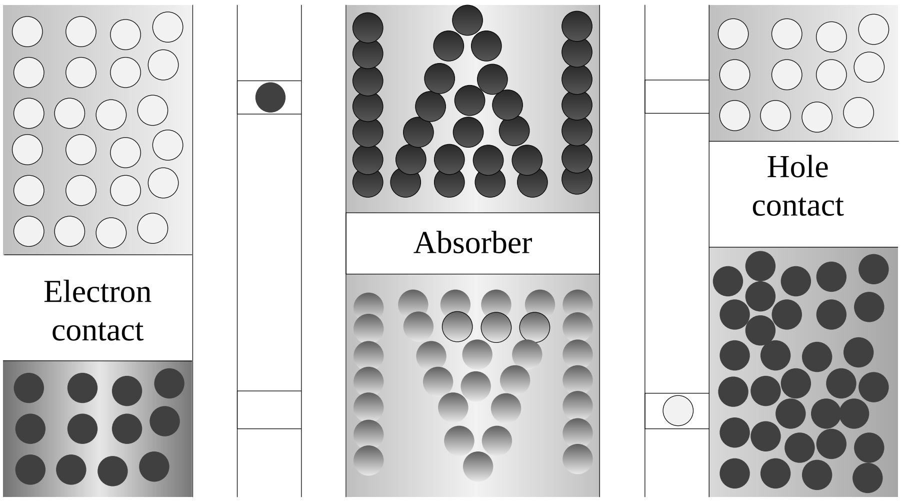

Figure 3.3.2. HC schematic (Adapted from Tyagi et al., 2013).

3.3.4 Nanofluids

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 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). Nanofluids have great potential in a wide range of fields, and their concept is extended by use of PCMs, going well beyond simply increasing the thermal conductivity of a fluid.

Unlike micron-sized suspensions, nanofluids, known as the suspension of nano-sized solid particles in a liquid, were found to form stable systems with next to no settling under static conditions (Arthur et al., 2016). Even at small concentrations of nanoparticles (~ 1% mass fraction) these stable suspensions anomalously increase the thermal conductivity compared to that of the base fluid. In some cases, increases in specific heat capacity have been observed (Shin et al., 2013).

Taylor et al. (2013) gave the nanofluid possible advantages over the traditional heat transfer fluids:

1. Due to the incredibly small size of the particles they are essentially fluidized. Allowing them to pass through pumps, micro-channels and piping without any adverse effects.

2. Nanoparticles act as the absorption medium allowing the nanofluid to directly absorb solar energy.

3. Optically selective, allowing for high absorption in the solar range while obtaining low emittance in the infrared. Allowing for a volumetric receiver instead of a selective surface system, which is favorable as selective surfaces have a poorer temperature profile resulting in higher emissive losses.

4. Enhancement of efficiency and uniformity of receiver tem perature is possible by tuning nanoparticle size and concentration.

5. Enhanced heat transfer may result in improved receiver performance.

6. Absorption efficiency can be altered by tuning the size, shape and concentration to suit conditions.

The main step in experimental studies with nanofluids is their preparation (Devendiran, 2016). Nanofluids are produced by dispersing nanometer-scale solid particles into base liquids such as water, ethylene glycol (EG), oils, etc. The major problem in synthesis of nanofluids is agglomeration. The delicate preparation of a nanofluid is important because nanofluids need special requirements such as an even suspension, stable suspension, low agglomeration of particles, and no chemical change of the fluid.

Classification of nanofluids

Nanofluids can be normally classified into two categories: metallic and non-metallic nanofluids. The third category is hybrid nanofluids (Nagarajan et al., 204).

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 (Al2O3), copper oxide (CuO) and silicon carbide (SiC, ZnO, TiO2) are considered as non-metallic nanofluids, semiconductors (TiO2), 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.

In addition, new materials and structure are attractive for use in nanofluids where the particle liquid interface is doped with various molecules.

Types of nanofluids

Two techniques are mainly used to produce nanofluids, the one-step and the two-step method. 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;
- Hybrid nanofluids.

Characterization of nanofluids

The nanofluids are characterized by the following techniques: SEM, TEM, XRD, FT-IR, DLS, TGA and zeta potential analysis (Devendiran, 2016).

SEM analysis is carried out to study the microstructure and morphology of nanoparticles or nanostructured materials. TEM is like SEM, but with much higher resolution. XRD images are taken to identify and study the crystal structure of nanoparticles. FT-IR spectroscopy is done to study the surface chemistry of solid particles and solid or liquid particles. DLS analysis is performed to estimate the average disperse size of nanoparticles in the base liquid media and TGA is performed to study the influence of heating and melting on the thermal stabilities of nanoparticles. Zeta potential value is related to the stability of nanoparticle dispersion in base fluid.

Review of characterization studies reveals that the important information like nanoparticle size, shape, chemical bonds, distribution and stability are found from characterization techniques.

Nanofluids properties

The properties of nanofluids are mainly based on five parameters: thermo fluids, heat transfer, particles, colloid and lubrication.

- Thermo fluid property includes temperature, viscosity, density, specific heat and enthalpy.
- Based on the heat transfer are thermal conductivity, heat capacity, Prandtl number and pressure drop.
- The parameters based on particles are size, shape, BET (surface area analysis) and crystalline phase.
- Based on the colloidal properties are suspension stability, Zeta potential and pH.
- The final properties based on lubrication are viscosity, viscosity index, friction coefficient, wear rate and extreme pressure.

The physical properties of nanofluids are quite different from the base fluid, and density, specific heat and viscosity are also changed which enhance the heat transfer coefficient exceeding the thermal conductivity enhancement results as reported in some experimental studies.

3.3.5 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 the following requirements: high sensitive heat capacity and heat of fusion; stable composition; high density and heat conductivity; chemical inert; non-toxic 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 30 °C to 80 °C that is interesting for solar applications. PCMs are chemical substances that undergo a solid-liquid transition at temperatures within the desired range for heating purposes and during the transition process, the material absorbs energy as it goes from a solid to a liquid and releases energy as it goes back to a solid. Most organic PCMs are non-corrosive and chemically stable. They exhibit little or no subcooling, and are compatible with most building materials and have a high latent heat per unit weight and low vapour pressure.

The integrated PCM solar collector storage concept is economically promising in low temperature solar water heating systems for domestic, agricultural and industrial applications. A system of this type combines collection and storage of thermal energy into a single unit. This integrated solar collector storage water heater approach was developed from early systems and comprised simply a simple black vessel placed in the solar collector. Integrated PCM solar collector for a low-temperature SDHW system using salt hydrate eutectic mixture (48% CaCl2, 4.5% KCl, 0.4% NaCl and 47.1% H2O) 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. 3.3.3.

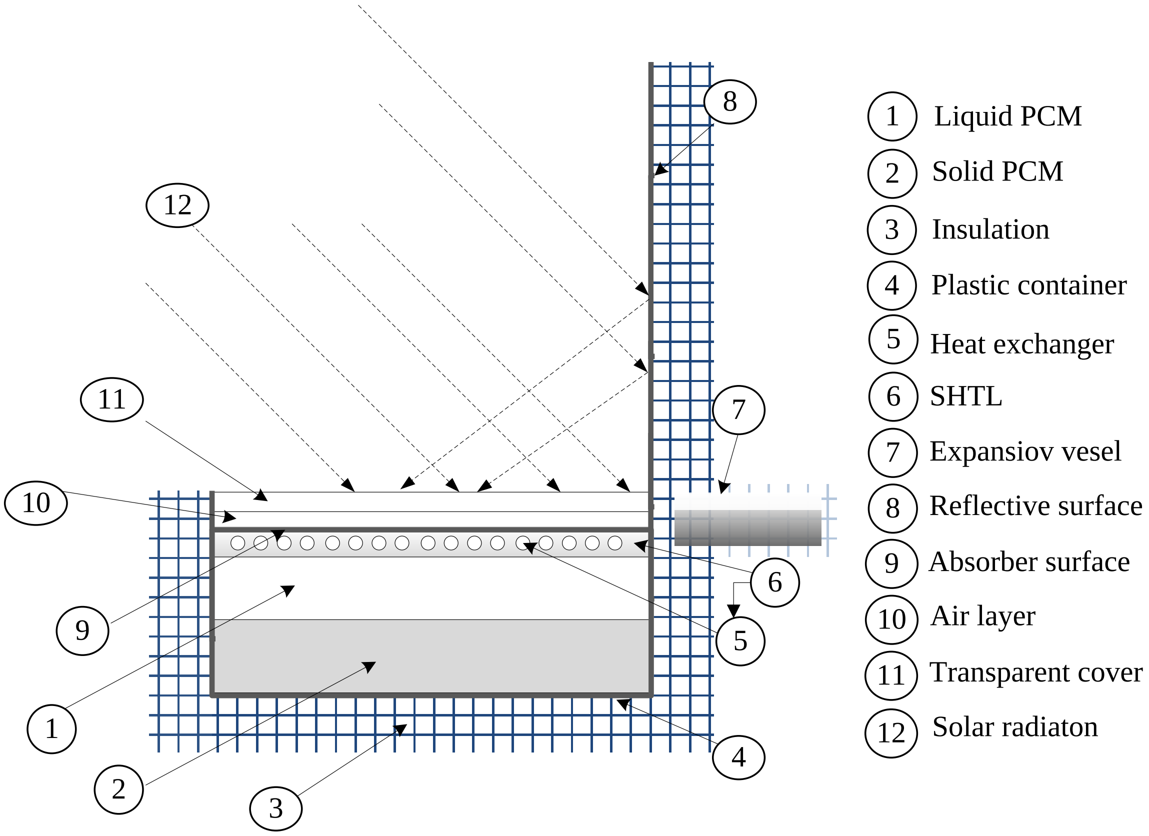

Fig. 3.3.3. Integrated PCM solar collector storage system designed.

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 °C, as shown Fig. 3.3.4. The experimental results indicated that the water temperature could exceed 55 °C during a typical day of high solar radiation and remain over 30 °C during the whole night.

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 the latent heat storage unit, in order to improve the energy storage and thermal performance of solar hot water systems. Two main fields of interest are configuration of the latent heat storage unit to improve heat transfer inside the unit, and the heat transfer mechanism in the PCM (Seddegh et al., 2015).

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).

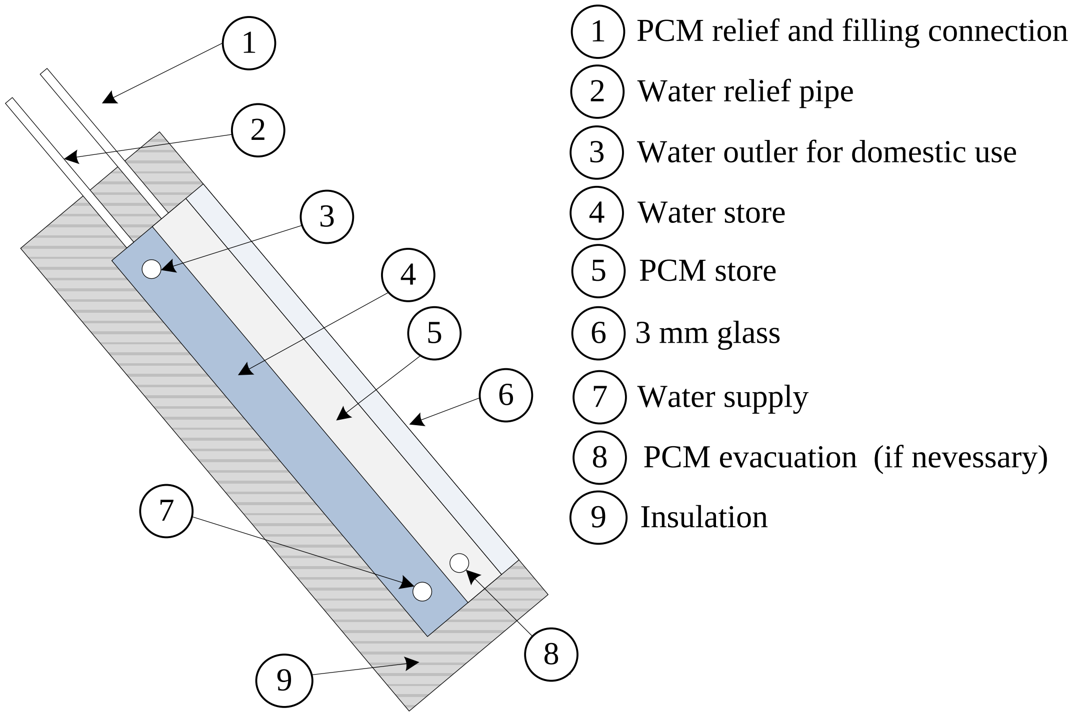

Figure 3.3.4. Schematic view of solar collector construction with PCM.

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. Photovoltaic 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 quantum dots, 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). Quantum dots are efficient light emitters because they emit multiple electrons per solar photon, with different absorption and emission spectra depending on the particle size, thus notably raising the theoretical efficiency limit by adapting to the incoming light spectrum.

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. 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). Low-temperature solar collectors mainly include flat-plate collectors where the operational temperature is below 100 °C. In this section, the review of flat-plate solar collectors using a nanofluid as the heat transfer medium has been carried out. It is found that different nanofluids significantly increase the collector's efficiency under non concentrated radiation.

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