Chapter 2

Literature Survey

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2.1 Introduction

Over the past decades, energy consumption has increased significantly due to the improvement in life's quality and industrialization processes. This has widened the gap between the energy demand and supply (Kumar and Rosen, 2011). Energy resources based on fossil fuels are still dominant with the highest share in global energy consumption; however, these sources are limited and they are depleting at a faster rate and also clean energy generation is crucial because of the growing significance of environmental issues (Al-Shamani et al., 2014). Sustainable energy generation is one of the most important challenges faced by our society today. To meet the challenge of the impending energy crisis, renewable energy has been growing rapidly in the last decade (Sarsam at al., 2015). Solar thermal energy is by far the largest exploitable resource. It is a very convenient source of heating. It can be used free of charge, and does not need to be transported. To provide a truly widespread primary energy source, solar energy must be captured, converted, and stored in a cost-effective fashion. The critical problem for solar thermal utilization is to improve the efficiency of the solar collector. During the last two decades, the worldwide research in the field of solar energy has focused on the methods to efficiency enhancement of the solar collection and conversion systems. The most common type of solar thermal collector utilizes a black surface as the absorber, which then transfers heat to a fluid running in tubes embedded within or fused onto the surface. In this case the efficiency is limited by how effective the absorber captures solar energy and how effectively the heat is transferred to the working fluid. Many methods that have been proposed in the past to enhance the efficiency of collectors are to optimize the structure of collector, use of artificial roughness, solar selective coatings and direct absorption solar collectors (He et al., 2015; Suman et al., 2015). This type of collector exhibits several defects, such as limitations on incident flux density and relatively high heat losses (Tyagi et al., 2009). Therefore, these methods have their own limitations and are not able to increase the efficiencies beyond certain limits.

Beside the conventional methods to increase the solar collector efficiency, one of the most effective methods is replacing the working fluid, by high thermal conductivity fluids in direct absorption solar collectors. The term of nanofluids refers to a new kind of fluids which is made by suspending nanoparticles in a base fluid (Choi, 1995). Nanofluids are expected to present exceptional heat transfer properties compared with conventional heat transfer fluids (Yousefi at al., 2012). Moreover, there are plenty of different nanoparticles that can be chosen based on their optical characteristics and application under consideration. Besides, by employing nanofluids in solar receivers, more uniform receiver temperatures can be achieved inside the collector (Veeraragavan et al., 2012; Lenert and Wang, 2012).

In view of this, the literature survey has been carried out to explore the work done in the past on enhancement of efficiency of solar thermal energy absorption systems such as using modified solar collector configuration, use of artificial roughness, deposition of solar selective coatings on absorber, using direct absorption solar collectors and use of nanofluids for in direct absorption solar collectors. In addition to this, work done earlier has been examined to investigate the efficiency of various methods applied for modification of solar energy absorption systems. Some of the relevant nanoparticle synthesis methods also have been reviewed to create a platform for development of required novel methods of synthesis.

2.2 Solar energy harvesting using conventional solar thermal collectors

2.2.1 Collectors basic configuration and performance

Solar collectors need to have good optical performance (absorbing as much heat as possible). For solar thermal applications, solar irradiation is absorbed by a solar collector as heat which is then transferred to its working fluid (air, water or oil). Solar collectors are usually classified into two categories according to concentration ratios: non-concentrating collectors and concentrating collectors. Flat plate collectors, evacuated tube collectors and hybrid photovoltaic/thermal (PVT) collectors are the popular systems in non-concentrating collectors. Flat-plate solar collectors are usually permanently fixed in position, and therefore need to be oriented appropriately. A typical flat-plate solar collector usually consists of glazing covers, absorber plates, insulation layers, recuperating tubes (filled with heat transfer fluids) and other auxiliaries. In concentrating collectors, heliostat field collectors, parabolic dish collectors, parabolic trough collectors are among the few popular ones. Concentrating collectors (usually equipped with sun-tracking techniques) have much higher concentration ratio than non-concentrating collectors (Tian and Zhao, 2013).

Due to growing energy problems, solar energy is been looked at as source of infinite energy. Solar collector have been greatly studied in this matter. Many of the new designs have been developed after 1990. Various research works are being carried out over the world to improve the thermal performance of solar collectors. Large number of research studies are available on for the heat transfer enhancements in solar water heaters and solar air heaters.

A typical flat plate collectors consist of glazing (sheet of glass), tubes/fins or passages, absorber plates, headers or manifolds and container of casing. The materials and designs for these components are well established now. For example, glass has been widely used to glaze solar collectors because it can transmit as much as 90% of the incoming shortwave solar irradiation while transmitting virtually none of the longwave radiation emitted outward by the absorber plate. Additionally, antireflective coatings and surface texture can also improve transmission significantly (Spate et al., 1999; Schweiger, 1997). Various prototypes of transparently insulated flat plate collectors (FPC) and compound parabolic collectors (CPC) have been built and tested in the last decade. The absorptance of the collector surface for shortwave solar radiation depends on the nature and colour of the coating and on the incident angle (Tripanagnostopoulos at al., 2000; Wazwaz at al., 2002). By suitable electrolytic or chemical treatments, surfaces can be produced with high values of solar radiation absorptance and low values of longwave emittance. Today, commercial solar absorbers are made by electroplating, anodization, evaporation, sputtering and by applying solar selective paints (Kalogirou, 2004). Next type of collector is compound parabolic collectors (CPC). These have the capability of reflecting to the absorber all of the incident radiation within wide limits. Winston (1974) first reported their potential as collectors of solar energy. Compound parabolic concentrators can accept incoming radiation over a relatively wide range of angles. The acceptance angle is one of the deciding parameters of performance of the collector. Pereira (1985) reported that bigger angles are used to enable the collector to collect diffuse radiation at the expense of a lower concentration ratio (aperture area/receiver area). Smaller (less than 3) concentration ratio CPCs are of greatest practical interest. They accept large proportion of diffuse radiation incident on their apertures and concentrate it without the need of tracking the sun. Rabl et al. (1979) gave practical design considerations for maximum efficiencies; such as the choice of the receiver type, the optimum method for introducing a gap between receiver and reflector to minimize optical and thermal loses and the effect of a glass envelope around the receiver. Tripanagnostopoulos et al. (1999) reported the design considerations and performance evaluation of cost-effective asymmetric CPCs. Evacuated tube collectors (ETC) have demonstrated that the combination of a selective surface and an effective convection suppressor can result in good performance at high temperatures. Like FPC, they collect both direct and diffuse radiation. However, their efficiency is higher at low incidence angles. This effect tends to give ETC an advantage over FPC in day-long performance. A large number of variations of the absorber shape of ETC are in the market (Kalogirou, 2004). Energy delivery temperatures can be increased by decreasing the area from which the heat losses occur. Temperatures far above those attainable by FPC can be reached if a large amount of solar radiation is concentrated on a relatively small collection area. This can be done by use of concentrating collectors interposing an optical device between the source of radiation and the energy absorbing surface. Kalogirou et al. (1994) stated certain advantages of concentrating collectors over FPC. Working fluid achieves higher temperatures in concentrator system compared to FPC. The thermal efficiency is greater because of the small heat loss area relative to the receiver area. Reflecting surfaces require less material and are structurally simpler than FPC and also selective surface treatment is economically viable concentrator system due to small receiver area. Disadvantages are they collect little diffuse radiation and also require tracking system.

Many designs have been considered for concentrating collectors. Concentrators can be reflectors or refractors, can be cylindrical or parabolic and can be continuous or segmented. Receivers can be convex, flat, cylindrical or concave and can be covered with glazing or uncovered. Concentration ratios, i.e. the ratio of aperture to absorber areas, can vary over several orders of magnitude, from as low as unity to high values of the order of 10 000. Increased ratios mean increased temperatures at which energy can be delivered but consequently these collectors have increased requirements for precision in optical quality and positioning of the optical system (Kalogirou, 2004).

2.2.2 Collectors with artificial roughness/structural modifications

The heat transfer between a fluid and solid surface can be increased by increasing the contact area (i.e. use of fins or extended surfaces) and by generating turbulence promoting mixing in the fluid layers. Varun et al. (2007) summarized the studies on the use of various roughness geometries and their other quantitative parameters. Flow pattern of each shape have been discussed along with Nusselt number and friction factor correlations. Bhagoria et al. (2002) experimentally reported on the roughness element in the form of transverse wedge shaped rib and varied the relative height and wedge angle during the work. The ribs yielded Nusselt number up to 2.4 times and the friction factor increased up to 5.3 times in comparison to that of smooth duct. Jaurker et al. (2006) carried out experimental investigation on heat transfer and friction characteristics of the solar air heater using rib-grooved artificial roughness to find optimized conditions for its performance. It was observed that rib-grooved arrangement provides the best thermo-hydraulic performance and yields Nusselt number up to 2.7 times, while the friction factor rises up to 3.6 times. Lanjewar et al. (2011) used W-shaped rib roughness inside the rectangular duct of a solar air heater and investigated the heat transfer along with the friction factor. It has been found that boundary layer along W-ribs is relatively thinner than V-shaped ribs. It was seen that the rate of increase of Nusselt number with increasing Reynolds number is lower than rate of increase of friction factor. Bhushan and Singh (2011) reported experiments on solar air heater duct with circular protrusions in order to determine the Nusselt number and friction factor giving idea of efficiency of heater. On comparison with smooth duct, they observed a maximum enhancement of 3.8 times and 2.2 times in Nusselt number and friction factor, respectively. The benefit of protrusion is that it does not add extra weight to the solar heater. Bhattacharyya et al. (2013) carried out experiments in circular duct solar air heater having a combination of integral transverse ribs and centre-cleared twisted tape as artificial roughness. The major breakthrough reported is that centre-cleared twisted tapes integrated with transverse ribs gives significantly better results than the individual enhancement technique used alone.

Table 2.1

Comparison of various heat transfer enhancement methods based on geometrical modifications in solar air heaters

Reference	Type of roughness	Important findings
Bhagoria et al. (2002)	Wedge shaped rib	Maximum heat transfer occurs for a relative roughness pitch of about 7.57 and at a wedge angle of 10^0

Jaurker et al. (2006)	Rib-grooved	Maximum heat transfer occurs for a relative roughness pitch of about 6.0 and at a groove position to pitch ratio of 0.4
Lanjewar et al. (2011)	W-shaped rib	Maximum enhancement of Nu and f due to artificial roughness is 2.36 and 2.01 times, respectively
Bhushan and Singh (2011)	Circular protrusions	Maximum enhancement of Nu and f due to artificial roughness is 3.8 and 2.2 times, respectively
Bhattacharyya et al. (2013)	Twisted tapes with Integral transverse ribs	Centre-cleared twisted tapes with integral transverse ribs perform significantly better than the individual technique used alone

In water heaters, the heat transfer rate is increased by using turbulence promoters such as twisted tape inserts, perforated twisted tape inserts, wire coil inserts, wire mesh etc. in the flow passage. Garcia et al. (2005) performed experiments with steel wire coil inserts to determine the in-tube heat transfer coefficient using water and water- propylene glycol as working fluids. It has been observed that heat transfer rate increased by 200% for constant pumping power. Garcia et al. (2013) later extended this study for flat plate solar water heaters and found 14-31% increase in thermal efficiency for the mentioned range of mass flow rate. Experiments with helical twisted tape inserts made up of copper were conducted by Jaisankar et al. (2009). Different twist ratios were used inside the copper tubes of flat plate solar water heater to evaluate heat transfer and pressure drop characteristics. They have found that by using twisted tapes collector area requirement can be reduced by 8-24%. Nanan et al. (2014) performed experiments with perforated helical aluminum twisted tapes. They found enhancement in the efficiency and reduction in pressure drop compared to non-perforated twisted tapes. Sandhu et al. (2014) investigated three different inserts viz., twisted, wire coil, and wire mesh to determine the performance of solar water heater. The concentric wire coils were found to be the best among all other inserts. It is seen that heat transfer coefficient increased by 110% at low Reynolds number and 460% at high Reynolds number.

The nature of working fluid actually decides the type of geometrical modifications to be made in the absorber system. If the working fluid is air or gas, which has very low convective heat transfer coefficient, the extended surfaces/fins/corrugations are provided on the absorber plate. For water or liquid as the working fluid, twisted tapes/perforated tapes/wire coils, inserts/baffle plates, and internally finned tubes are provided to generate turbulence, which eventually increase heat transfer coefficient (Suman et al., 2015). However, the use of surface modifications and turbulence promoters result in an increase in pressure drop increasing consumption of pumping power and cost. Any heat transfer enhancement method is acceptable only if the gain in heat transfer rate is more than increase in the pumping power. Hence, this method has its own limitations to improve solar conversion efficiencies beyond certain limits.

Table 2.2

Comparison of various heat transfer enhancement methods based on geometrical modifications in solar water heaters

Reference	Structural modification		Important findings
	Shape	Material	
Garcia et al. (2005)	Wire coil	Steel	200% increase in heat transfer coefficient for constant pumping power
Jaisankar et al. (2009)	Helical twisted tapes	Copper	Collector area requirement reduced by 8-24%
Garcia et al. (2013)	Wire coil	Steel	14-31% increase in thermal efficiency
Nanan et al. (2014)	Perforated helical twisted-tapes	Aluminium	Increase in turbulence and reduction in pressure drop compared to non-perforated twisted tapes.
Sandhu et al. (2014)	Twisted tape, wire coil, and wire mesh	Steel and copper	Concentric wire coil was best among all. heat transfer coefficient increased by 110% at low Reynolds number and 460% at high Reynolds number

2.2.3 Collectors with solar selective absorber coating

An effective way to maximize the absorption of solar radiation is to apply coatings of some specific materials on the absorber surface. Coatings are broadly classified as non-selective coatings, and solar selective coatings as shown in Fig. 2.1.

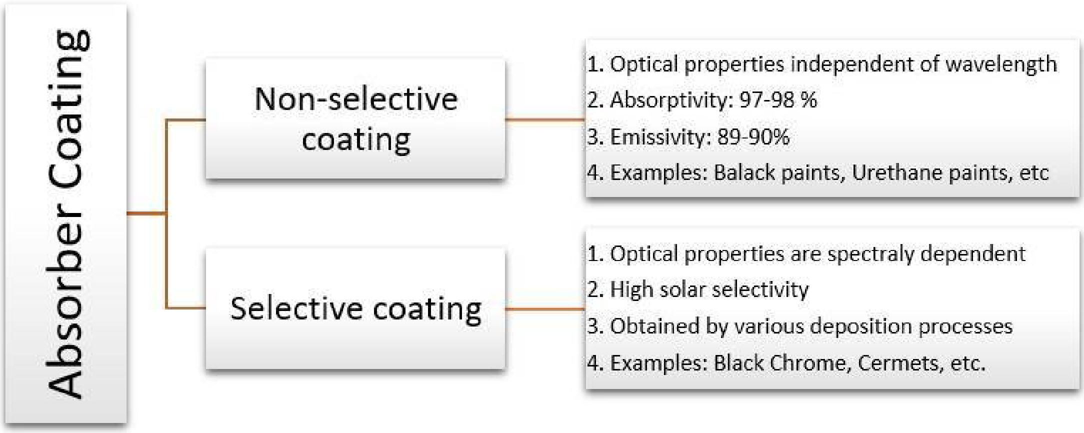

Fig. 2.1 Types of solar absorber coatings

Optical properties of non-selective coatings such as absorptivity, reflectivity, emissivity, etc. are independent of wavelength. This group of coatings is certainly is the easiest to apply and probably the least expensive of all the collector coatings. Non-selective black coatings consist of paints, chemical conversion finishes sometimes even electroplated surfaces. Ordinarily, high temperature and heat resistant black paints are used in industry as protective coatings for metals. In some cases specific colors are used for their heat control properties. Very few of these paints were formulated with solar energy collection in mind. One of the examples of non-selective coatings is ordinary black paint applied on the absorber's surface. Common pigments used to manufacture black paint are carbon black (0.02-0.09 μm), iron oxide Fe_3O_4 (0.5 μm), amorphous graphite, bone black (325 mesh) and asphalt bases as mentioned by Bolz and Tuve (1973). It increases both absorptivity and emissivity of the absorber plate. Recently Tulchinsky et al. (2014) developed a new non-selective coating formed by thermal reaction of sol-gel titania with copper manganese spinel. This novel coating has exhibited the absorption of more than 95% in the visible range. This coating is easy to apply manually or by spray technique. This has potential to be applied in solar thermal conversion systems. However, coatings with other similar combination of materials needs to be investigated for further optimizing their optical properties.

Normally, non-selective coatings have poor solar selectivity (ratio of solar absorptivity to emissivity at a given temperature) and also they are thermally unstable at an elevated temperature resulting lower absorber efficiency. In solar thermal application, a coating should have large absorptivity and low emissivity, so that it holds the absorbed thermal energy. This limits the applicability of non-selective coatings for solar thermal conversion technology as they have high emissivity in addition to high absorptivity. This is the reason research in this area is limited and no significant attention has been given to explore area of non-selective coatings (Suman et al., 2015).

Solar selective coatings on the other hand, exhibit different absorptivity and emissivity in different spectral regions. It means, optical properties of these coatings are spectrally dependent. The body at high temperature emits thermal radiation at shorter wavelength and vice-versa. Thus the incoming solar radiation has shorter wavelength and thermal radiation emitted by absorber surface will obviously have longer wavelength. The solar selective coatings allow incoming solar radiation to pass through it and block the emittance of longer wavelength thermal radiation. Thus, they help in capturing the radiative energy to achieve high temperatures. There are many types of coatings based on different absorption mechanisms such as light trapping, particulate coatings, semiconductor-metallic layers, multi-layer films, quantum size effects, and intrinsic absorption. Besides having a long-term thermal stability, these coatings should have high absorptivity in the 0.3–2.5 μm spectral range and low emissivity in the far infrared range (0.7 μm onwards) for given operating range of temperature (Kaushal, 1997). The optical characteristic of the coating is expressed in terms of 'solar selectivity', which is the ratio of solar absorptivity to emissivity at a given temperature. By improving the optical characteristic and making it thermally stable at high temperatures will eventually increase the working fluid temperature, thereby improving the overall efficiency of solar collectors.

Abbas (2000) reported black chrome or solchrome, which is a metal based coating, has high absorptivity and requires less maintenance. The experiments were conducted with three different collector types. Solchrome coatings were found to enhance the collector efficiency by more than 30% even for low temperature applications. Schuler et al. (2000) and Schuler et al. (2001) developed titanium containing amorphous hydrogenated carbon coating (a-C:H/Ti) and amorphous hydrogenated silicon carbon coating (a-Si:C:H/Ti) by combined physical vapor deposition (PVD) and plasma-enhanced chemical vapor deposition (PECVD) process. The optical properties were found to be function of different parameters and strongly dependent upon the amount of titanium. The a-C:H/Ti coating yielded a solar selectivity of 14.4 at 100^0C without any optimization. Results of accelerated ageing test predicted service life period of 25 years. Adding silicon in the coating materials significantly improves the lifetime stability, irrespective of the substrate. However silicone has challenges of fast degradation under humid conditions and can be tackled by controlling content of silicone. Nonetheless, this coating is very good candidate for vacuum collectors since they have long service life under high temperature. Teixeira et al. (2001) prepared a coating materials with metallic chromium and molybdenum embedded in the matrix of chromium oxide and aluminum oxide respectively. It is spectrally dependent multilayer coating with thickness of 300 nm. The method of manufacture was magnetron sputtering. Copper and glass were used as substrates. They have proposed reactive sputtering as a potential process for the production of graded selective coating with the advantage of controlling the addition of metallic phases. Farooq and Hutchins (2002a, 2002b) produced a multilayer metal-dielectric graded index spectrally dependent coating using co-sputtering technique. Computer simulations and experimental results confirmed that variation of optical performance is not considerable beyond certain number of layers. Out of the studied batch of coatings, four layer prime graded selective absorber coating of V: Al_2O_3 shown the best results with solar absorptivity of 0.98 and emissivity of 0.02. Cindrella (2007) studied the effectiveness of selective coatings in solar thermal systems of different concentration ratios for two composite coatings viz. cobalt-cadmium and nickel- cadmium. It is concluded that coating with high value of absorptivity is required for solar thermal systems with higher concentration ratio (CR>10) whereas low emittance coatings should be considered for systems with CR equal to unity. Liu et al. (2012) synthesized solar selective film having NbTiON and SiON layers on copper and stainless steel substrates using magnetron sputtering. Experimental results proposed the optimum thickness of 150 nm and 70 nm for NbTiON and SiON layers, respectively. Coating on stainless steel substrate shown better thermal stability at high temperature. Nuru et al. (2012) developed solar selective multilayer coating $Al_xO_y/Pt/Al_xO_y$ on glass, silicon and copper substrates using electron beam evaporator technique. It is dielectric/metal/ dielectric arrangement. Optimum coating thickness of 1370 Å deposited on copper revealed a solar selectivity of 15.6. However, Nuru et al. (2014) showed that thermal stability of Pt layer in 300 to 600^0C is a problem and it forms CuO and Cu_2O at 700^0C. Cespedes et al. (2014) after optimal simulations, deposited multilayered selective coating using magnetron sputtering. It consists of silver infrared reflector, molybdenum- silicon nitride as absorber and silicon nitride as anti-reflective layer. This coating demonstrated a high solar absorptivity of 0.926 and low thermal emissivity of 0.017 even at elevated temperature of 600^0C making it suitable for concentrated solar power (CSP) technology. Kumar et al. (2014) developed solar selective coating at room temperature by chemical oxidation of copper at various alkaline conditions. The nanostructure of copper oxide layer was found to be dependent on pH of the preparing solution. Porous nature of nanolayer accelerates multiple absorptions. This coating has shown solar selectivity of 12 making it suitable for photothermal conversion.

The challenge lies in the developing coatings, which should not only be compatible with absorber surface but also economical and easy to produce in bulk (Suman et al., 2015). The high temperature stability of most of the solar selective coatings is not good. Few of them though are stable in vacuum, but they have limited stability in presence of air. Further, optical properties of these coatings degrade with rise in temperature or over a period of use and they do not give consistent performance or efficiency over the service life. That's why only few of them are useful, despite the fact that many coatings materials are reported in the literature. Also coating deposition methods are difficult to carry out and are expensive (Barshilia, 2014; Amri et al., 2014).

Table 2.3

Comparison of various solar selective coatings

Reference	Material		Solar Selectivity	Important findings
	Substrate (s)	Coating(s)		
Abbas (2000)	Nickel plated copper	Black chrome	8	Efficiency increase by more than 30%
Schuler et al. (2000)	Aluminum	a-C:H/Ti	14.6	High selectivity. Service life more than 25 years
Teixeira et al. (2001)	Glass, Aluminum and Copper	$Cr–Cr_2O_3$/ $Mo–Al_2O_3$	5.87 to 23.5	Excellent thermal stability.
Farooq and Hutchins (2002)	Copper and aluminum	$V-Al_2O_3$	49	High selectivity. Four layer PGSAC gives the best efficiency
Cindrella (2007)	Nickel-plated copper	Co–Cd/Ni–Cd	13.29	Coating with high absorptivity required for high concentration ration (CR>10). Low emittance coatings for concentration ratio equal to unity
Liu et al. (2012)	Copper and stainless steel	NbTiON/ SiON	13.57	Better thermal stability over 500^0C

Nuru et al. (2012)	Glass, silicon and copper	Al_xO_y/ Pt/Al_xO_y	94	Dielectric/metal/dielectric coating exhibits high performance
Cespedes et al. (2014)	Silicon and stainless steel	$Mo–Si_3N_4$	54.47	High selectivity at temperature above 600^0C
Kumar et al.(2014)	Copper	CuO nanoparticles	14	Coating nanostructures varies with pH of reaction. Multiple absorption takes place in porous structure of coating

2.3 Solar energy harvesting using direct absorption solar collectors

The important part of a solar thermal system is the solar thermal collector; a particular heat exchanger device in which the photothermal conversion of the incident solar radiation takes place. Typical solar collector configurations consist of surface-based absorbers. The absorber has a solid surface of thermally stable materials such as copper, aluminium, steel or polymers, to which a matte black or solar (wavelength) selective coating is applied. This solid surface is backed by a coil of fluid tubing placed in an insulated casing with a transparent glazing. The heat absorbed by surface based absorber is conducted through its wall and then convected away to the working fluid circulating through the tubing; as a result, the absorber plate is the hottest component of the system. Hence, large amount of heat is lost to the ambient by radiation and convection and to other components by conduction (Phelan et al., 2013). This indirect absorption process decreases the collector efficiency critically (He et al., 2013). In this system, there are four resistances heat transfer will face, viz., resistance to absorption, thermal resistance to conduction through the absorber surface, resistance to convection from absorber surface to working fluid and finally resistance to heat transfer from working fluid to heat exchanger. Due to the existing thermal resistance in converting the incoming radiation into the internal energy of the transport medium; an alternative design idea is proposed in which the working fluid is directly exposed to the incident radiation and the heat is volumetrically absorbed within the transport medium instead of within a thin surface layer. Hence, in this arrangement conduction resistance through the surface and convection resistance from the surface to working fluid is practically eliminated thereby increasing the energy conversion efficiency.

Minardi and Chuang (1970) initially proposed the concept of direct absorption solar collector (DASC) in which working fluid was flowing through the transparent tubing directly absorbing the solar radiation. India ink -a carbon black additive was seeded in the ethylene glycol- water working fluid to increase the absorption capability of the transport medium. Heat losses are reduced with this arrangement since energy is directly absorbed by working fluid, improving thermal performance of the system significantly. This first of its kind study also opened new avenues for the future directions of the research in this area. The seeding materials proposed were non-selective black materials such as carbon black: for example Acheson's Aquadag and India ink and selective black material such as black Antimony Sulphide (Sb_2S_3). Huang et al. (1979) extended this concept to a parabolic trough collector which used highly absorbent black dye liquid water flowing in a glass tube to directly absorb the concentrated solar radiation.

Presently, available heat transfer working fluids such as water, engine oil and ethylene glycol are widely used in many industrial applications like heating or cooling processes, chemical production, microelectronics, power generation, air-conditioning, and transportation. These conventional heat transfer fluids have inherently low thermophysical properties as compared with solids. Hence, there is a pronounced need to develop alternative heat transfer fluids with higher cooling capability which can improve the compactness and effectiveness of heat exchangers. To ensure that heat exchangers deliver their best performance, working fluids with greater thermal conductivity are required. Since solid particles have larger thermal conductivity than conventional fluids, dispersing these particles in to the base fluid is anticipated to increase the thermal conductivity of the whole mixture. Therefore, in order to overcome the limited heat transfer capabilities of common fluids, Maxwell (1881) first proposed a theoretical work which showed the possibility of enhancing the thermal conductivity of liquids by mixing micron-sized solid particles. His efforts were followed by numerous theoretical and experimental studies, such as those by Hamilton and Crosser (1962). New type of volumetric solar collector was reported by Arai et al. (1984) which utilized three kinds of micro-particle semitransparent liquid suspensions: graphite (black), carborundum (gray) and silicon dioxide (white) in diethylphthalate as the working fluid. Measurements of the absorption coefficient of each suspension demonstrated the effectiveness of using fine-particle additives. Further studies on high flux direct absorption collector utilizing molten salt established the need of adding particulate solids to molten salt in order to increase its absorption ability as molten salt is a relatively weak absorber in the visible and near infrared regions of the solar spectrum. Webb and Viskanta (1985) studied this molten salt based system and concluded that the more highly absorbing substrate and inclusion of a diffuse flux component are expected to enhance significantly the collector efficiency of such a system. Studies conducted by Burke et al. (1982), Bohn and Wang (1988) and Kumar and Tien (1990) also showed similar results.

These models and experimental work reported above proved very well in establishing the thermal conductivity of slurries. However, all of these studies were limited to the suspension of micro- to macro-sized particles, and such suspensions bear the following major disadvantages (Das et al., 2006):

a. The micro- to macro-sized particles settle down rapidly, developing a layer on the surface and decreasing the heat transfer capacity of the fluid.
b. If the circulation rate of the fluid is increased, sedimentation is reduced, but the erosion of the heat transfer devices, pipelines, etc., increases rapidly.
c. The large size of the particles tends to clog the flow channels, particularly if the cooling channels are narrow.
d. The pressure drop in the fluid increases significantly.
e. Finally, conductivity enhancement based on particle concentration is achieved (i.e., the greater the particle volume fraction is, the greater the enhancement and greater the problems, as indicated in 'a-d' above).

Thus, the route of suspending micro- to macro-sized particles in liquid was a well-known but rejected option for specifically solar thermal and in general all heat transfer enhancement applications.

2.4 Solar energy harvesting using nanofluids

Modern materials science and technology provided an opportunity to synthesize nanometer-sized particles which are reasonably different from the parent material in mechanical, thermal, electrical, and optical properties (Das et al., 2006). This opens up new avenue for revisiting the earlier studies of suspensions containing micro-and macro-sized particles discussed in last section. The concept of nanoparticle suspension was coined by Choi (1995). The attractive features which made nanoparticles potential candidates for suspension in fluids are the large surface area to volume ratio, less particle momentum, and high mobility. With respect to conductivity enhancement, starting from copper, one can go up to multi-walled carbon nanotubes (MWCNTs), which at room temperature exhibit 20,000 times greater conductivity than engine oil

(Kim et al., 2001). When nanoparticles are well-dispersed in the base fluids, features of nanofluids are expected to give following benefits (Das et al., 2006):

a. High heat transfer rates: large surface to volume ratio of nanoparticles enhances the rate of heat transfer several times. Nano-sized particles have large number of atoms available on the surface compared to that in bulk which are instantaneously available for thermal interaction. Secondly, mobility of tiny sized particles brings about the enhanced micro-convection of fluid and hence increased heat transfer. This also increases the dispersion of heat in the fluid at faster rate.
b. Suspension stability: particles are very small and hence their bulk density is less, hence chances of sedimentation are also low. Brownian motion of tiny particles keeps them dispersed in the solution. This overcomes the major drawback of solid suspensions.
c. Microchannel cooling without clogging: since nanoparticles are order of magnitude smaller than microchannels, they can be used for heat transfer enhancement for microchannel applications without clogging them.
d. Reduced erosion compared to micro- or macro-suspensions: due to small size, momentum imparted by nanoparticles on solid surface or wall is much smaller. This reduces the chances of erosion of components such as heat exchangers, pipelines and pumps.
e. Reduction in pumping power: To increase the heat transfer of conventional fluid by a factor of two, pumping power must usually be increased by a factor of ten. It can be shown that if one can multiply the thermal conductivity by a factor of three, the heat transfer in the same apparatus doubles (Choi, 1995). The required increase in the pumping power will be very moderate unless there is a sharp increase in fluid viscosity. Thus, a very large savings in pumping power can be achieved if a large thermal conductivity increase can be brought about with a small volume fraction of particles.

The immense need was anticipated to enhance the poor thermal properties of conventional heat transfer fluids such as water, ethylene glycol and various heat transfer oils. A way to overcome this obstacle is using ultrafine solid particles suspended in common fluids to improve their thermal performance. The suspension of nanosized particles (1-100 nm) in a conventional base fluid is called a nanofluid (Choi, 1995). Nanofluids, compared to suspensions of millimeter-or-micrometer size particles, show better stability, rheological properties, and considerably higher thermal conductivities.

In recent years, various research groups have reported the use of nanofluids for enhancement of efficiencies in heat exchanging devices. Researchers have also used variety of preparation methods for nanofluids, have found out characteristics, and proposed different models for the calculation of thermophysical properties of nanofluids i.e., thermal conductivity, viscosity, density, specific heat capacity, etc. (Trisaksri and Wongwises, 2007; Li et al., 2009; Lee et al., 2010; Ghadimi et al., 2011; Ramesh and Prabhu, 2011; Khanafer and Vafai, 2011; Fan and Wang, 2011; Vajjha and Das, 2012). Some investigators have reported the flow behavior and natural and forced convection heat transfer studies of nanofluids (Daungthongsuk and Wongwises, 2007; Kakaç and Pramuanjaroenkij, 2009; Godson et al., 2010; Sarkar, 2011). In past two decades many studies have reported intensification of heat transfer using nanofluids. Lee et al (1999) reported that Al_2O_3- water and CuO-ethylene glycol enhances the thermal conductivity of base fluid. The investigations of Choi et al. (2001) on engine oil containing 1% by volume carbon nanotubes reported enhancement of thermal conductivity by 160%. Numerous studies have reported effects of nanofluids on convective of heat transfer coefficient and friction factor (Sundar et al., 2012; Sundar and Sharma, 2010; Sharma at al., 2009; Sundar and Singh, 2013). Some reports of effect of size and volume % concentration of nanoparticles on the heat transfer performance are also seen in the literature. Enhancement in heat transfer with increase in size and concentration of nanoparticles has been reported (Perarasu et al., 2012; Kumar et al., 2010; Mahmoodi and Sebdani, 2012; Moraveji et al., 2011; Sundar and Sharma, 2010). Studies are also found indicating heat transfer intensification up to certain volume fraction and decrease in performance beyond that value (Fotukian and Esfahany, 2010). On the contrary, Beck et al. (2009) observed decrement in thermal conductivity for alumina-water and alumina- ethylene glycol nanofluid with decrease in particle size. The same results were obtained by Shalkevich et al. (2010) for gold-water nanofluid.

Recently solar based energy systems have attracted attention of researchers and started playing important role in the production of energy from renewable sources by converting solar radiation into useful heat or electricity. Looking at environmental protection concerns and large uncertainty over future energy supplies, solar energy is better alternative energy source in spite of its high cost of production. Heat transfer enhancement in these devices is key issue and nanofluid can prove to be one of the best working fluids for direct absorption solar collectors. More recently researchers have reported the use of nanofluids in collectors, water heaters, solar cooling systems, solar cells, solar stills, solar absorption refrigeration systems, and a combination of different solar devices due to higher thermal performance of nanofluids and the radiative properties of nanoparticle (Bozorgan and Shafahi, 2015). How to select suitable nanofluids in solar applications is the key issue. Taylor et al. (2013) summarized that the effectiveness of nanofluids as working fluids in a solar device strongly depends on the type of nanomaterial and base fluid, volume fraction of nanoparticles, radiative properties of nanofluids, temperature of the liquid, size and shape of the nanoparticles, pH values, and stability of the nanofluids. Otanicar et al. (2010) investigated the efficiency of DASC with carbon nanotubes, graphite and silver based nanofluids. It is observed that addition of nanoparticles improve the optical properties of the base fluid causing considerable enhancement in the efficiency of the collector. Efficiency is found to increase with increase in particle concentration with slight decrease at high particle concentrations. Yousefi et al. (2012a) studied the flat plate solar collector with Al_2O_3-water nanofluid. Effect of mass flow rate, mass fractions of Al_2O_3 nanoparticles and effect of surfactant was investigated. They reported 28.3% efficiency enhancement at 0.2 % (by weight) concentration of Al_2O_3 nanoparticles compared to the value only with water as working fluid. Effect of surfactant, Triton X-100 on efficiency was also studied. The maximum enhanced efficiency was 15.63 % in the presence of the surfactant. Yousefi et al. (2012b) also investigated the use of multi-walled carbon nanotube (MWCNT)/H_2O nanofluid and effect of pH variation on efficiency of flat plate solar collector. Triton X-100 was also used as surfactant and working fluids were prepared with and without the use of surfactant. It was established that the efficiency of the collector significantly enhanced with 0.4% (by weight) nanofluid without surfactant and efficiency was reported more at lower pH values.

Taylor et al. (2011) examined nanofluid based concentrating solar system with the conventional system. Efficiency enhancement by 10% was observed with nanofluid based system. The useful particle concentration in graphite/therminol VP-1 nanofluid is 0.001% or less (by volume). Ladjevardi et al. (2013) numerically investigated the effects of using graphite nanofluid on the performance of a solar collector. Their numerical results proved that nanofluid collector thermal efficiency increases by 88% compared with that of only water being used in the collector. Filho et al. (2014) worked on silver nanoparticles based nanofluid in solar thermal collector. It was observed that efficiency increases by 52%, 93% and 144% for silver particle concentration of 1.62, 3.25 and 6.5 ppm respectively. This is because of the good photothermal properties of the silver nanoparticles. Also at high particle loadings (65 and 650 ppm) specific absorption rate was found to decrease because of number of reasons such as formation of agglomerates, deposited particles reducing absorption, difference in absorption efficiency of each particle at different fluid depth and heat loss through radiation. Kameya and Hanamura (2011) reported the effect of nickel nanoparticle suspension in alkyl naphthalene-based fluid for solar thermal conversion. Particle volume fraction of 0.001 was kept with size of particles between 4-9 nm. Higher absorption coefficients were reported over the base fluid. Sokhansefat et al. (2014) numerically studied the heat transfer performance of Al_2O_3/synthetic oil nanofluid with concentrations up to 5% in a parabolic trough collector tube. Nanofluid was found to enhance the convective heat transfer coefficient. Khlebtsov et al. (2005) examined the effects of the size, shape, and structure of gold and silver nanoparticles on the optical properties of the nanofluids and observed that the shape and size of the nanoparticle have great effect on the optical properties of a nanofluid. Sani et al. (2011) and Mercatelli et al. (2011) found out the potential of utilizing single wall carbon nanohorns (SWCNHs) in ethylene glycol suspension and confirmed that as a good choice for using in solar collectors. Khullar et al. (2013) numerically studied the enhancement of solar irradiance absorption capacity of nanofluid based concentrating parabolic solar collectors and compared the results with experimental data of conventional similar collectors which demonstrated 5-10% higher efficiency as compared to conventional models. Lenert and Wang (2012) carried out experimental and numerical studies on carbon-coated cobalt nanoparticles (size: 28 nm) with base fluid VP-1(Therminol). They reported 35% enhancement in the efficiency. Gnanadason et al. (2011) reported that using nanofluids in a solar still can increase its efficiency. They explored the effects of adding carbon nanotubes (CNTs) to the water inside a single basin solar still to desalinate the brackish water. Their results revealed that adding nanofluids increases the efficiency by 50%. Kabeel et al. (2014) performed experiments with Al_2O_3 - water nanofluid for use in single basin solar still. Results indicate that use of nanofluid increases the solar still water production capacity by 116% and 76% with and without operating the vacuum fan. This is attributed to the increase in the evaporation rate inside the still.

Following literature studies specifically focus on solar energy absorption using different nanofluids falling in four material groups viz., metal group (copper and aluminium), metal oxide group (copper oxide and iron oxide), semiconductor group (SiO_2, ZnO, TiO_2) and non-metal (carbon).

2.4.1 Metal nanofluids (copper & aluminium)

a. Copper nanofluid

Luo et al. (2014) numerically simulated the performance of DASC with nanofluids using 2D model solving the radiative transport equations of particulate media considering conduction and convection heat transfer equations. A solar radiation simulator was used to validate the model. Copper along with other nanoparticles (TiO_2, Al_2O_3, Ag, SiO_2, graphite) were dispersed in the texatherm oil. It was observed that use of nanofluid enhances the collector efficiency. Also they have found that efficiency of most of nanofluids were similar and larger than that of only oil. Numerical studies of Rahman et al. (2014) performed on triangular shape solar collector with Cu, Al_2O_3 and TiO_2 nanofluids with the use of Galerkin weighted residual finite element method reveals better heat transfer augmentation with Cu-water nanofluid. Results showed 24.28% improvement in efficiency at Cu nanoparticles concentration of 10% (by volume). However, size of the particle was not mentioned in the study. Parvin et al. (2014) numerically examined the effects of nanoparticle concentration (0, 1, 3, 5, and 7% by volume) on the collector efficiency apart from several other parameters. It was proposed that the collector efficiency can be enhanced nearly 2 times by using Ag-water and Cu-water nanofluids with concentration of 3%. Taylor et al. (2011) studied the optical property characterization of various nanoparticles such as graphite, silver, copper, gold, and aluminum in water and Therminol (VP1) as the based fluids for checking their potential to be used in direct absorption solar collectors. Results indicated that over 95% of incoming sunlight can be absorbed (in a nanofluid thickness $\geq$ 10 cm) with very low nanoparticle concentration (10 ppm). Colangelo et al. (2012) performed experiments with copper nanoparticles along with several other nanomaterials. Results concluded that thermal conductivity enhancement of nanofluids with diathermic oil is higher than that with water. Jamal-Abad et al. (2013) found out the performance of flat plate collector based for copper-water nanofluid with an average particle size of 35 nm. Experimental results showed increase in efficiency with particle concentration in water and maximum 24% improvement in efficiency was observed with 0.05% (by weight) of copper nanoparticles in water. Nasrin and Alim (2014) numerically investigated the heat transfer performance of flat plate collector with sinusoidal corrugated absorber with alumina and copper nanoparticles in water nanofluid. Improved heat transfer performance of the collector was observed at larger volume fractions of nanomaterials. Zamzamian et al. (2014) performed experiments on flat plate solar collector with copper nanoparticles in ethylene glycol nanofluid. Average size of copper nanoparticles was 10 nm with concentration of 0.2 and 0.3% by weight. Experiments were performed with different volume flow rates of the nanofluid. Solar collector efficiency was found to decrease with decreasing flow rate. Also solar collector efficiency increases with weight fraction concentration of copper nanoparticles in ethylene glycol. He et al. (2013) studied photo thermal properties of nanofluids for direct absorption solar collectors. For Cu-H_2O-based absorbing fluid experiments confirm that small addition of particles in base fluid widens its solar energy absorption spectrum. Nanoparticles make the transmittance of nanofluid lower in the range of 250-1350 nm wavelength. The transmittance of Cu-H_2O nanofluid (0.1%) is closer to zero and a 25.3% rise in temperature was observed compared to de-ionized water.

Kabeel and El-Said (2014) worked on desalination of sea water using copper nanofluid based solar collector coupled with water desalination unit. The system consists of a solar water heater (flat plate solar collector), a mixing tank and a flashing chamber plus a helical heat exchanger and a condenser. The desalination process is based on the evaporation of sea water under a very vacuum. The evaporated water is then condensed to obtain fresh water. Numerical simulation carried out reveals that increase in the nanoparticle concentration increases the efficiency of the desalination process. For 5% (by volume) of nanoparticles in working fluid; 30% reduction in the cost was observed.

Table 2.4

Solar energy absorption using copper nanofluid

Reference	**Particles**	**Base fluid**	**Field of study**	**Research findings**
Luo et al. (2014)	Copper, TiO_2, Al_2O_3, Ag, SiO_2, graphite	Texatherm oil	DASC	Use of nanofluid in the solar collector can improve the outlet temperature and the efficiency

Rahman et al. (2014)	Copper, Al_2O_3, TiO_2	Water	Corrugated bottom triangular solar collector	Results showed 24.28% improvement at 10% volume fraction of copper particles. The convective heat transfer performance is better when the solid volume fraction is kept at 0.05 or 0.08.
Parvin et al. (2014)	Copper	Water	Numerical analysis	Nusselt number and entropy generation increases with particle concentration and remains constant after 0.3% (by volume) concentration.
Taylor et al. (2011)	Copper, 20 nm	Water and Therminol (VP1)	DASC	Nanofluid helps to improve efficiency by 5–10%
Colangelo et al. (2012)	Copper	Water and diathermic oil	Property analysis	Thermal conductivity enhancement of the nanofluids with diathermic oil is higher than that with water
Jamal-Abad et al. (2013)	Copper	Water	FPC	The efficiency of solar collector operated with nanofluid increases with the increase of particle loading
Nasrin and Alim (2014)	Copper	Water	FPC	Improved heat transfer performance of the collector was observed with nanofluid
Zamzamian et al. (2014)	Copper, 10 nm	Ethylene glycol	FPC	Solar collector efficiency increases with weight fraction concentration of copper nanoparticles
He et al. (2013)	Copper	Water	DASC	Small addition of nanoparticles in the base fluid can widen solar energy absorption spectrum. Transmittance of Cu-H_2O nanofluid (0.1%) is closer to zero and a 25.3% rise in temperature could be observed as compared to de-ionized water.
Kabeel and El-Said (2014)	Copper	Water	FPC	Increase in the nanoparticle concentration increases the efficiency of the desalination process with 30% reduction in cost.

Following conclusions can be drawn based on the thorough literature survey carried out for the use of copper nanoparticles in the solar thermal collectors:

i. Very few studies on copper-water nanofluid are available. Most of the work is theoretical and detailed experimental work is lacking.
ii. Many studies report the work on flat plate collectors and few on direct absorption collectors. Studies on concentrating solar collector has not been reported to the best of our knowledge. Therefore effect of particle loading (volume % concentration) is must in this category.
iii. Studies using other important base fluids such as ethylene glycol, silicone oil, etc were not found in the literature.
iv. Application of copper nanoparticles in hard water desalination has not been reported in the literature.

b. *Aluminium nanofluid*

Tyagi et al. (2009) performed theoretical analysis on aluminium-water nanofluid to check the effect of particle concentration (volume %) and size of the nanoparticles on the efficiency of DASC. Particle concentration was varied from 0.1 to 0.5% (by volume). Results indicated that, efficiency increases for low values of particle concentration and when it was increased more than 2%, the efficiency remains nearly constant, hence adding more nanoparticles is not beneficial. Also efficiency was found to increase slightly with increase in the size of nanoparticles. They attributed the increase of collector efficiency to the increase in absorption and scattering of sunlight passing through the collector due to the nanoparticles addition. Khullar et al. (2013) numerically investigated aluminium nanofluid based concentrating parabolic solar collector and the results were compared with the conventional similar collectors under the same conditions. Nanoparticle concentration of 0.05 vol.% was kept in a base fluid Therminol VP-1. Thermal efficiency of nanofluid based collector was estimated to be 5-10% higher than the conventional parabolic solar collector. Saidur et al. (2012) experimentally studied the aluminium-water nanofluid in direct absorption solar collector. Aluminium nanoparticles have very strong extinction coefficient and can absorb more light in visible and short wavelength region. Nanoparticle concentration of 1% (by volume) shows maximum absorption. Particle size has minimal influence on efficiency but in order to have Rayleigh scattering the size of nanoparticles should be less than 20 nm. They also found that the extinction coefficient varies linearly with volume fraction. It was also suggested that the volume fraction of particles should be kept minimal after obtaining desired maximum efficiency to avoid drawbacks like clogging and instabilities of the suspensions. Gan and Qiao (2012) performed experimental studies on optical property characterization of ethanol based nanofluids containing multiwalled carbon nanotubes (MWCNTs), carbon and aluminium nanoparticles. The results concluded that MWCNTs leads to more absorption than aluminum and carbon nanoparticles because of high radiation absorptive properties of MWCNTs over carbon and aluminium nanoparticles. Aluminium shows lowest transmission of only 2%. Consequently, studies were also carried out by the same group, Gan and Qiao (2012) to compare aluminium and Al_2O_3 nanoparticles with ethanol as a base fluid to verify the droplet evaporation rates. It was reported that nanofluids containing Al nanoparticles can significantly enhance droplet evaporation rates at all radiation levels. At high particle loadings, enhancement in absorption was declined due to aggregation of particles which inhibits diffusion of heat and suppress evaporation.

Table 2.5

Solar energy absorption using aluminium nanofluid

Reference	Particles	Base fluid	Field of study	Research findings
Tyagi et al. (2009), Theoretically	Aluminum (20 nm)	Water	DASC	Efficiency remarkably increases for volume fraction less than 2% and remains nearly constant after that. Efficiency increases slightly with an increase in the size of nanoparticles.
Khullar et al. (2013) , Theoretically	Aluminum (5 nm)	Therminol VP-1	Concentrating Parabolic Collector	Efficiency about 5-10% higher with aluminium nanofluid compared to conventional collectors
Saidur et al. (2012)	Aluminum (20 nm)	Water	DASC	Nanoparticle concentration of 1% (by volume) shows maximum absorption. Particle size has minimal effect. Volume fraction should be kept minimal to avoid clogging and settling
Gan and Qiao (2012)	MWCNTs, Carbon,	Ethanol	100W mercury lamp radiation	MWCNTs absorbs more light than carbon and Al. droplet evaporation rate

	Aluminium, Al_2O_3			enhanced with Al nanoparticles over Al_2O_3
Taylor et al. (2011)	Aluminum, copper, graphite, and silver	Water and Therminol (VP1)	DASC	Efficiency improvement in solar thermal systems

Important findings based on the literature review (aluminium nanoparticles based nanofluid):

i. Most of the work is with direct absorption solar collector. Single study reports concentrating solar collector with aluminium nanoparticles and Therminol VP-1 as base fluid.
ii. Studies using other important base fluids such as water, ethylene glycol, silicone oil, etc are not reported in the literature.
iii. Possibility of hard water desalination using aluminium nanoparticles has not been reported in the literature.

2.4.2 Metal oxide nanofluid (copper oxide & iron oxide)

a. Copper oxide nanofluid

Colangelo et al. (2012) experimentally evaluated the thermal conductivities of different nanoparticles CuO, Al_2O_3, ZnO and Cu in diathermic oil as a base fluid. Concentrations were varied from 0 to 3 % (by volume). They found out that thermal conductivity enhancement is directly proportional to volume fraction of nanoparticles in oil. The thermal conductivity enhancement of the nanofluids with diathermic oil is higher than that with water. They proposed the use of this study for high temperature applications such as in solar collectors. Lu et al. (2011) investigated the effect of CuO-water nanofluid on the performance of open thermosyphon device used in high-temperature evacuated tubular solar collectors. Nanofluid improved the thermal performance of evaporator compared to only water. Also, heat transfer coefficient was enhance by 30% with the use of CuO nanoparticles. Different concentrations (% weight) from 0.8-1.5% were studied. It has been observed that concentration has remarkable influence on the heat transfer coefficient in the evaporation section. The concentration of 1.2% corresponds to the optimal heat transfer enhancement. Liu et al. (2013) studied evacuated tubular solar air collector and special open thermosyphon using water based CuO nanofluid as working fluid. Mass concentration of CuO was varied from 0.8 to 1.5%. It was found that heat transfer coefficient values enhanced considerably with the addition of nanoparticles. Heat transfer coefficient was found to increase with increase in the particle concentration up to 1.2% (by weight). By using CuO nanoparticles, outlet temperature of air was significantly increased.

Goudarzi et al. (2015) experimentally investigated effect of pH variation of CuO nanofluid on the thermal efficiency of new cylindrical solar collector. This collector consists of a cylindrical glass tube with helical pipe as the receiver of the solar energy. The experiments were performed using 0.1 % (by weight) CuO nanoparticles in water. Collector efficiency was found to increase by 52% in acidic pH conditions (pH=3) compared to basic conditions (pH=10.5). Efficiency increased was observed when there is variation of pH of nanofluids far from isoelectric point of nanoparticles. Alim et al. (2013) performed numerical analysis on entropy generation, augmentation heat transfer capability and pressure drop of flat plate solar collector under laminar flow. Nanofluids considered were, Al_2O_3, CuO, SiO_2 and TiO_2. It was observed that CuO based nanofluid reduces entropy generation by 4.34%. However, 1.58% increase in pumping power was observed. Friction factor did not altered significantly after addition of nanoparticles. Faizal et al. (2013) investigated flat plate solar collector for energy, economic and environmental analysis of metal oxides nanofluid. This study focusses on potential size reduction of collector with the use of nanofluids for same output temperature. The nanoparticles studied were Al_2O_3, SiO_2, TiO_2, and CuO. It was observed that 25.6, 21.6, 22.1, and 21.5 % solar collector area reduction has been achieved using CuO, SiO_2, TiO_2, and Al_2O_3, respectively. The reason behind CuO giving highest solar collector area reduction was attributed to the higher density and lower specific heat of nanoparticles. Moghadam et al. (2014) performed experiments on flat plate solar collector using CuO-water nanofluid. Nanoparticle concentration was kept at 0.4% (by volume). Average particle size of CuO was 40 nm. Heat absorption was studied by varying the working fluid and mass flow rate. At optimum mass flow rate, for CuO nanofluid, 16.7% increase in solar collector efficiency was observed compared to that of only water.

Table 2.6

Solar energy absorption using CuO nanofluid

Reference	Particles	Base fluid	Field of study	Research findings

Colangelo et al. (2012)	CuO, Al_2O_3, ZnO and Cu	Diathermic oil	Property analysis	Thermal conductivity of oil increases with addition of nanoparticles and it is directly proportional to particle concentration in the fluid. This has large potential in high temperature solar collectors.
Lu et al. (2011)	CuO (50 nm)	Water	ETC	Heat transfer coefficient enhanced by 30% at 1.2% (by weight) particle concentration
Liu et al. (2013)	CuO (50 nm)	Deionized water	ETC	Heat transfer coefficient enhanced with the addition of CuO nanoparticles. It increases with particle concentration up to 1.2% (by weight)
Goudarzi et al. (2015)	CuO (40 nm)	Water	Cylindrical solar collector	For CuO nanofluid at the acidic condition (pH = 3), the efficiency increases by about 52% compared with that for pH = 10.5.
Alim et al. (2013)	CuO, Al_2O_3, SiO_2, TiO_2	Water	FPC	CuO based nanofluid reduces entropy generation by 4.34%. Pumping power increased by 1.58%
Faizal et al. (2013)	CuO, Al_2O_3, SiO_2, TiO_2	Water	FPC	CuO gives highest solar collector area reduction of 25.6%. The payback period is shortest for SiO_2 and CuO nanofluid solar collector
Moghadam et al. (2014)	CuO (40 nm)	Water	FPC	16.7% increase in solar collector efficiency with CuO nanofluid at 0.4% (by volume) concentration

Important findings based on the literature review (CuO nanofluid):

i. Almost all the studies reported in the literature for solar energy absorption using CuO nanofluid are based on indirect solar collectors i.e. flat plate solar collector. In this category of collectors, flat absorber surface coated with selective coating absorbs solar radiation first and then it is transferred to working fluid via conduction and convection.

ii. Direct absorption of solar radiation by copper oxide suspended in fluid has not been reported yet. This opens up new avenues for further research since copper oxide optical properties could enhance absorption of solar radiation considerably.

iii. Experiments with concentrating solar collectors such as parabolic dish are missing and opens up new possibilities of research in this area.

iv. Almost all the studies report water as a working fluid. Promising heat transfer fluids such as ethylene glycol, silicone oil, etc with copper oxide nanomaterial have not been studied yet.

v. Studies on the effect of size of CuO nanoparticles on solar energy absorption and collector efficiency were not found in the literature.

b. Iron oxide (Fe_2O_3) nanofluid

Colangelo et al. (2013) investigated the performance of flat solar thermal collector using Al_2O_3 (45 nm), ZnO (60 nm) and Fe_2O_3 (30 nm) nanoparticles based nanofluids in water. Fe_2O_3 nanoparticles was having spherical shape with average diameter of 30 nm. Nanofluids were prepared with three different concentrations viz. 1, 2 and 3% (by volume). Focus of this study was to analyze the stability of nanofluid inside the solar collector. Thermal conductivity and heat transfer coefficient were found out for most stable suspension. Delta backscattering values were obtained for all the suspensions and Al_2O_3 suspensions were found most stable with this analysis. Creti et al. (2013) performed optical absorption measurements on metal oxide nanomaterials viz. ZnO, CeO_2, Fe_2O_3 as a function of temperature in order to study the optical properties, and to investigate how several heating cycles could affect nanoparticle structural stability and absorption characteristics. The results showed that nanoparticles were not modified at high temperature, and in particular the absorption coefficient doesn't change significantly in given temperature range. This result makes these metal oxide nanoparticles suitable for operations at very high temperature, thus encouraging the use of gas-based nanofluids as heat transfer fluid in concentrating solar power (CSP) plants.

Abid et al. (2015) carried out energy and exergy analysis of two types of solar collectors, viz. parabolic dish (PD) and parabolic trough (PT) solar collectors. The absorption fluids used were Al_2O_3, Fe_2O_3, LiCl-RbCl based nanofluids and $NaNO_3$-KNO_3 molten salts. The results showed that the outlet temperature of PD solar collector is higher in comparison to PT solar collector under identical operating conditions. Fe_2O_3 nanofluid has the highest rate of heat absorption among all the solar absorbers used. Also both Al_2O_3 and Fe_2O_3 nanofluids have higher net power produced in comparison to molten salts. Elango et al. (2015) performed study on single basin single slope solar still with water nanofluids of aluminum oxide (Al_2O_3), zinc oxide (ZnO), iron oxide (Fe_2O_3) and tin oxide (SnO_2) at different concentrations of nanoparticles. The still with aluminum Oxide (Al_2O_3) nanofluid has 29.95% higher production and the still with zinc oxide (ZnO) and tin oxide (SnO_2) nanofluids have 12.67% and 18.63% more production respectively than the still with water.

Table 2.7

Solar energy absorption using Fe_2O_3 (iron oxide) nanofluid

Reference	Particles	Base fluid	Field of study	Research findings
Colangelo et al. (2013)	Al_2O_3, ZnO and Fe_2O_3	Water	FPC	Stability analysis for all the suspensions were performed. Al_2O_3 was found to be most stable nanofluid. Therefore ZnO and Fe_2O_3 were not studied for solar energy absorption.
Creti et al. (2013)	ZnO, CeO_2, Fe_2O_3	Gas	CSP	All nanoparticles are structurally stable at very high temperatures thus enabling their use in concentrating solar power plants.
Abid et al. (2015)	Al_2O_3, Fe_2O_3, LiCl-RbCl, $NaNO_3$-KNO_3 molten salts.	Water	PD and PT	Fe_2O_3 nanofluid has the highest rate of heat production among all the solar absorbers used. Also both Al_2O_3 and Fe_2O_3 nanofluids have higher net power produced in comparison to molten salts.
Elango et al. (2015)	Al_2O_3, ZnO, Fe_2O_3, SnO_2	Water	Flat plate solar still	Fe_2O_3 nanofluid was found to be unstable and omitted from the experiments. Use of

				nanofluid increases production rate

Important findings based on the literature review (Fe_2O_3 nanofluid):

i. Literature on iron oxide (Fe_2O_3) is scarce and very few studies are available on use of Fe_2O_3 based nanofluid in solar collectors.

ii. No attempts have been made to investigate the efficiency of Fe_2O_3 based nanofluids with any of the solar collector configurations. Therefore this creates large opportunities to explore potential of these nanomaterials in solar thermal conversion systems.

iii. Further Fe_2O_3 nanoparticles with popular heat transfer fluids such as ethylene glycol, silicone oil, etc. apart from water need to be explored in solar collectors for better heat transfer performance and solar conversion efficiencies.

2.4.3 Semiconductor nanofluids (SiO_2, ZnO, TiO_2)

a. Silica nanofluids

Shin and Banerjee (2011) doped alkali metal chloride salt eutectics with silica nanoparticles at 1% mass concentration and reported 14.5% enhancement in specific heat capacity of high-temperature nanofluids. Therefore this material can be a suitable one to use in solar thermal energy storage facilities. Alim et al. (2013) conducted numerical analysis on entropy generation, augmentation heat transfer capability and pressure drop of flat plate solar collector under laminar flow using nanofluids of Al_2O_3, CuO, SiO_2 and TiO_2. It was observed that SiO_2 based nanofluid reduces entropy generation by 3.94%. As per authors claim minimization of entropy is favorable for augmentation of heat transfer. However, 1.42% increase in pumping power was observed. Friction factor was not altered significantly after addition of nanoparticles. Faizal et al. (2013) studied flat plate solar collector for energy, economic and environmental analysis of metal oxides nanofluid. This study focusses on potential size reduction of collector with the use of nanofluids for same output temperature. The nanoparticles studied were Al_2O_3, SiO_2, TiO_2, and CuO. It was observed that 21.6% solar collector area reduction has been achieved using SiO_2 based nanofluid second highest after 25.6% reduction by CuO. Said et al. (2014) performed theoretical studies on entropy analysis, heat transfer enhancement and pressure drop of flat plate solar collector utilizing nanofluids of Al_2O_3, single walled carbon nanotubes (SWNT), SiO_2

and TiO_2. It was concluded that SWNT based nanofluid showed better thermal and exergetic efficiencies compared to other nanofluids.

Table 2.8

Solar energy absorption using SiO_2 nanofluid

Reference	Particles	Base fluid	Field of study	Research findings
Shin and Banerjee (2011)	SiO_2	Alkali metal chloride salt eutectics	Solar thermal storage	14.5% enhancement in specific heat capacity of base fluid
Alim et al. (2013)	SiO_2, CuO, Al_2O_3, TiO_2	Water	Flat plate solar collector	SiO_2 based nanofluid reduces entropy generation by 3.94%. Pumping power increased by 1.42%
Faizal et al. (2013)	SiO_2, CuO, Al_2O_3, TiO_2	Water	Flat plate solar collector	SiO_2 gives second highest solar collector area reduction of 21.6% after CuO. Small payback period.
Said et al. (2014)	SiO_2, Al_2O_3, SWNT, TiO_2	Water	Flat plate solar collector	SWNT based nanofluid showed better thermal and exergetic efficiencies compared to other nanofluids

Important findings based on the literature review (SiO_2 nanofluid):

i. Limited studies are available for the SiO_2 nanofluid applications in solar thermal energy absorption.

ii. Focus of most of the studies being flat plate solar collector only. In this collector type, energy is first absorb by flat absorber plate coated with solar selective material. This energy is then transferred to working fluid by conduction and convection. During this transfer there are heat losses due to thermal resistance of conduction and convection.

iii. Direct solar energy absorption by virtue of optical properties of silica nanoparticles dispersed in base fluid have not been carried out yet. Further, concentrating solar collector has not been reported using silica nanofluids.

iv. Use of several promising heat transfer fluids such as ethylene glycol, silicone oil, etc. apart from water is suspended with silica nanoparticle was not found in the literature.

v. Effect of size of silica nanoparticle on performance of solar thermal collector is not reported in the literature.

b. ZnO nanofluids

Li et al. (2011) experimentally investigated performance of Al_2O_3/water, ZnO/water, and MgO/water nanofluids in tubular solar collector. It was concluded from experiments that, heat transfer efficiencies with all three nanofluids increase in comparison to water. The viscosities and heat transfer efficiencies were found to increase with increase in particles concentration in ZnO nanofluids. Their results showed that ZnO–H_2O nanofluid with concentration of 0.2% (by volume) is the best selection for the collector. Colangelo et al. (2012) experimentally found out the thermal conductivities of different nanoparticles CuO, Al_2O_3, ZnO and Cu in diathermic oil as a base fluid. Thermal conductivity enhancement of nanofluid is more than that of only oil and it increases with particle concentration in oil. This study has large potential for application of diathermic oil in solar collectors. Colangelo et al. (2013) studied the performance of flat solar thermal collector using Al_2O_3 (45 nm), Fe_2O_3 (30 nm), ZnO (60 nm) nanoparticles based nanofluids in water. Average particle size of ZnO was 60 nm. Delta backscattering values were obtained for all the suspensions for stability analysis and Al_2O_3 suspensions were found most stable. Chen et al. (2015) studied experimental simulation of photothermal conversion efficiency and specific absorption rate using ZnO, TiO_2, and silver nanofluid at different concentrations. Under simulated sunlight, the efficiency of silver nanofluid was 84.61 % at 80.94 ppm concentration which was almost twice that of water and also much higher than that of ZnO nanofluid (mass concentration of 1.02%) and TiO_2 nanofluid (concentration of 0.7%). Efficiency was found to increase with particle concentration. Zhu et al. (2013) investigated the thermal radiative properties of ZnO-water, AlN-water, ZrC-water, and TiN-water nanofluids. The effects of dispersants, mass fractions, and nanoparticle materials on the thermal radiative properties of nanofluids were also investigated, and the characteristics of wavelength selectivity of solar absorption of nanofluids were analyzed. Study concluded that dispersants used to obtain stable nanofluids reduced the directional–directional transmittance of the solution. The solar weighted absorptance of AlN-, ZnO-

, ZrC-, and TiN-water nanofluids were 45 %, 31 %, 87 %, and 99 %, respectively, when the liquid film was 10 mm thick. Experiments performed by Elango et al. (2015) on single basin single slope solar still with water nanofluids of Al_2O_3, ZnO, Fe_2O_3 and SnO_2 revealed desalinated water production rate of 29.95%, 12.67% and 18.63% more for Al_2O_3, ZnO and SnO_2 nanofluids respectively than the still with water.

Table 2.9

Solar energy absorption using ZnO nanofluid

Reference	Particles	Base fluid	Field of study	Research findings
Li et al. (2011)	ZnO, Al_2O_3, MgO	Water	Tubular solar collector	Efficiency increases with increase in concentration of ZnO nanoparticles. ZnO-H_2O nanofluid with concentration of 0.2% (by volume) gives higher efficiencies.
Colangelo et al. (2012)	ZnO, CuO, Al_2O_3, Cu	Diathermic oil	Property analysis	Thermal conductivity of nanofluid is higher than diathermic oil and it increases with increase in nanoparticle concentration. Useful in solar energy harvesting.
Colangelo et al. (2013)	Al_2O_3, Fe_2O_3 ZnO (60 nm)	Water	FPC	Stability analysis for all the suspensions were performed. Al_2O_3 was found to be most stable nanofluid. Therefore ZnO and Fe_2O_3 were not studied for solar energy absorption.
Chen et al. (2015)	ZnO, TiO_2, and silver	Water	Simulated sunlight	Silver nanoparticles show twice efficiency than water and much higher than ZnO and TiO_2 nanoparticles.
Zhu et al. (2013)	AlN, ZnO, ZrC, TiN	Water	Property analysis	The solar weighted absorptance of AlN-, ZnO-, ZrC-, and TiN-water nanofluids were 45 %, 31 %, 87 %, and 99 %, respectively, when the liquid film was 10 mm thick.

Elango et al. (2015)	Al_2O_3, ZnO, Fe_2O_3, SnO_2	Water	Flat plate solar still	Desalinated water production rate with ZnO was 12.67% higher than with only water, highest being Al_2O_3 with 29.95%

Important findings based on the literature review (ZnO nanofluid):

i. Only one work (Colangelo et al., 2013) directly relates to the analysis of solar thermal efficiency with ZnO nanofluid

ii. Studies report tubular solar collector and flat plate collectors. Studies using concentrating solar collector were not found in the literature

iii. Further, only water as a base fluid is reported in the literature. Other important base fluids such as ethylene glycol, silicone oil, etc were not analyzed for the solar thermal conversion efficiencies.

iv. Reports using different shapes of ZnO nanomaterials such as quantum dots, nanowires were not found in the literature.

c. TiO_2 nanofluids

Alim et al. (2013) studied numerically entropy generation, augmentation heat transfer capability and pressure drop of flat plate solar collector under laminar flow. Nanofluids considered were, Al_2O_3, CuO, SiO_2 and TiO_2. It was observed that TiO_2 based nanofluid reduces entropy generation by 3.99% second highest after CuO (4.34%). However, 1.44% increase in pumping power was observed which is smaller than CuO. Friction factor was not altered significantly after addition of nanoparticles. Faizal et al. (2013) reported flat plate solar collector for energy, economic and environmental analysis of metal oxides nanofluid. Size reduction of collector was achieved with the use of various nanofluids replacing working fluid. The nanoparticles studied were Al_2O_3, SiO_2, TiO_2, and CuO. It was observed that 25.6, 21.6, 22.1, and 21.5 % solar collector area reduction has been achieved using CuO, SiO_2, TiO_2, and Al_2O_3, respectively. Hence, TiO_2 stands second after Al_2O_3 for reduction in collector area. Chen et al. (2015) carried out experimental simulation of photothermal conversion efficiency using ZnO, TiO_2, and silver nanofluid at different concentrations. Under simulated sunlight, the efficiency of silver nanofluid was 84.61 % at 80.94 ppm concentration which was almost twice that of water and also much higher than that of ZnO nanofluid (mass concentration of 1.02%) and TiO_2 nanofluid (concentration of 0.7%). Efficiency was found to increase with particle concentration. He et al. (2011)

reported the light to heat conversion characteristics of water–TiO_2 and water–carbon nanotube (CNT), in a vacuum tube solar collector under sunny and cloudy weather conditions. It was observed that use of nanoparticles enhance light to heat conversion characteristics of the base fluid. CNT/H_2O nanofluid has a much better light-heat conversion characteristic than TiO_2/H_2O nanofluid. Chaji et al. (2013) studied the performance of flat plate solar collector by using European Standard EN12975-2. Working fluid was replaced with TiO_2-water nanofluid. Experiments were performed at different particle concentrations (0, 0.1, 0.2 and 0.3 % weight) and flow rates. Results indicated that index of collector efficiency increased between 2.6 and 7% relative to the base fluid at same conditions.

Table 2.10

Solar energy absorption using TiO_2 nanofluid

Reference	Particles	Base fluid	Field of study	Research findings
Alim et al. (2013)	TiO_2, CuO, Al_2O_3, SiO_2	Water	FPC	TiO_2 based nanofluid reduces entropy generation by 3.99%. Pumping power increased by 1.44%
Faizal et al. (2013)	TiO_2, CuO, Al_2O_3, SiO_2,	Water	FPC	TiO_2 gives second highest solar collector area reduction of 22.1% after CuO.
Chen et al. (2015)	TiO_2, ZnO, silver	Water	Simulated sunlight	Silver nanoparticles show twice efficiency than water and much higher than ZnO and TiO_2 nanoparticles.
He et al. (2011)	TiO_2, CNT	Water	Vacuum tube solar collector	Nanofluid enhances light to heat conversion characteristics of base fluid. CNT-water nanofluid shows better results.
Chaji et al. (2013)	TiO_2	Water	FPC	Index of collector efficiency with TiO_2 increased between 2.6 and 7% relative to the base fluid

Important findings based on the literature review (ZnO nanofluid):

i. All the studies are performed on flat plate solar collector except one on vacuum tube solar collector. Reports on concentrating solar collector were not found in the literature.
ii. Further, other base fluid such as ethylene glycol, silicone oil, etc. are not examined with TiO_2 nanoparticles for better performance of solar energy absorption.
iii. Effect of other TiO_2 nanoparticle sizes and various shapes such as nanotubes, nanowires, etc on solar thermal conversion performance are not studied in the literature.

2.4.4 Non-metal nanofluid (carbon)

Gan and Qiao (2012) evaluated the optical properties of ethanol based nanofluids containing multiwalled carbon nanotubes (MWCNTs), carbon nanoparticles (CNPs) and aluminium nanoparticles. The results reveal that the ethanol-based nanofluids with the addition of MWCNTs or CNPs both have a higher droplet evaporation rate than pure ethanol. In comparison to pure ethanol, the nanofluids with Al nanoparticles, CNPs, and MWCNTs have a much lower transmittance. MWCNTs in nanofluid are more effective for radiation absorption in comparison to Al or CNPs because less energy is scattered away. Zhang et al. (2014) theoretically and experimentally examined the radiation properties of Ni, Cu and carbon-coated Ni (Ni/C) nanofluids. It was observed that nanofluid containing the carbon-coated Ni (Ni/C) nanoparticles exhibits lower transmittance and higher extinction coefficient, compared with the one containing the Ni nanoparticles with the similar average size. Therefore carbon coating of nanoparticles helps to improve optical properties of nanofluid significantly. Han et al. (2011) performed experiments on carbon black nanofluid for solar energy absorption. Results showed that nanofluid of high volume fraction improved photo- thermal properties in the whole wavelength range from 2000 to 25,000 Å. The thermal conductivity of carbon black nanofluids increased with the increase of volume fraction and temperature. Carbon black nanofluids had good absorption ability of solar energy and can effectively enhance the solar absorption efficiency. Hence, carbon black nanofluids have high potential for the application in solar thermal conversion collectors. Khullar et al. (2014) explored amorphous carbon nanoparticles as the source of direct solar energy-absorbing material. Amorphous carbon nanoparticles (Size 50 nm) were mixed with equal amount of Triton X-100 surfactant, dispersed and sonicated in base fluid taken as ethylene glycol (99.0% purity).

Neumann et al. (2013) proposed breakthrough idea of direct vapor generation by suspending SiO_2/Au and N115 carbon nanoparticles in water. Solar illumination of broadly absorbing metal or carbon nanoparticles dispersed in a liquid produced vapor without the requirement of heating the fluid volume. It was observed that, when particles were dispersed in water at ambient temperature, energy was directed primarily to vaporization of water into steam, with a much smaller fraction resulting in heating of the fluid. They also carried out the distillation of ethanol-water mixture by suspending nanoparticles in the mixture at azeotropic composition. They showed that the distillate contains a higher percentage of ethanol than what is predicted by the water-ethanol azeotrope. Thus, new method of breaking the azeotrope was proposed by this group.

Table 2.11

Solar energy absorption using carbon nanofluid

Reference	Particles	Base fluid	Field of study	Research findings
Gan and Qiao (2012)	MWCNTs, carbon, aluminium	Ethanol	Optical property characterization	Additional of nanoparticles enhanced droplet evaporation rate. Nanofluids have lower transmittance compared to ethanol.
Zhang et al. (2014)	Ni, Cu and carbon-coated Ni (Ni/C)	Water	Radiative property characterization	Carbon-coated Ni (Ni/C) nanoparticles exhibits lower transmittance and higher extinction coefficient, compared with Ni nanoparticles
Han et al. (2011)	Carbon black	Water	Measurement of thermal, physical and optical properties	Carbon black nanofluids had good absorption ability of solar energy and can effectively enhance the solar absorption efficiency
Khullar et al. (2014)	Amorphous carbon	Ethylene glycol	DASC	Explored amorphous carbon nanoparticles as the source of direct

				solar energy-absorbing material
Neumann et al. (2013)	SiO_2/Au and N115 carbon nanoparticles	Water and ethanol-water mixture	Fresnel lens	Direct steam generation without bulk heating. Azeotrope can be broken with the concept of nanofluid.

Important findings based on the literature review (carbon nanofluid):

i. Despite of high potential of carbon nanomaterials, very few studies have been reported utilizing carbon black or amorphous carbon based nanofluids for solar thermal applications.

ii. Despite of many reports stating important thermal and optical properties of carbon, it is hardly been reported in the actual application.

iii. Studies on effect of particle concentration, effect of size of the particle, effect of different base fluids such as ethylene glycol, silicone oil, etc apart from water are the few important parameters which need attention for further investigations into the solar collectors for performance enhancement.

iv. Studies on concentrating solar collector were not found in the literature to the best of our knowledge.

v. Concept of direct vapor generation, azeotropic mixture separation and solar desalination opens up new avenues for further research. Various nanoparticles can be examined for this application for improved performance and reduction in cost.

2.5 Overall findings from the literature review

Thorough literature review of existing methods and systems for solar thermal energy harvesting was carried out. Various solar thermal collector configurations are available and utilized currently to harvest the solar thermal energy. Primary disadvantage associated with these collector configurations is losses associated at various stages in the system. Further the use of porous insertions, oscillating flow, double pass structure and internal fins could not improve efficiency considerably. Rather high manufacturing costs limit the use of such collectors in general. Large floor space requirement is another disadvantage of these systems. The key component of a flat plate solar thermal collector is the solar absorber surface, the properties of which strongly affect the efficiency of the solar thermal conversion system. Solar selective coatings are applied on primary absorber surface to enhance the absorption of solar energy. Very few solar selective absorber materials have been commercial success because of high cost material, expensive processing while making coatings, specificity to high selectivity, materials stability problems at high temperature and problems of durability and performance degradation over the period.

Concept of direct absorption collector is attracting but high transmittance of most of the working fluids limits the efficiency enhancement beyond certain limit. Few research groups proposed the idea of using India ink or suspending micro- and macro-sized particles in the working fluid to increase the absorption and scattering of solar radiation inside the fluid so that transmittance can be minimized. But the micro- to macro-sized particles settle down rapidly, developing a layer on the surface and decreasing the heat transfer capacity of the fluid. Problems of high erosion of heat transfer devices and pipelines were predominant. Large size particles also were found to clog the flow channels and overall increase in the pressure drop. Therefore, despite the high absorption efficiencies, the idea of suspending micro- and macro- sized particles in the working fluid could not be a commercial success. But the idea was not completely discarded. Researchers started working on the concept of utilizing nanosized particles and it lead to emergence of new class of fluid called ‘Nanofluid’ – stable suspensions of nanosized particles.

Use of nanofluids in solar collectors lead to – high absorption rates of solar radiation, large heat transfer rates, high suspension stability, minimum problems of erosion and clogging, and reduction in pumping power compared to gross particles. Various material groups such as metals, metal oxides, semiconducting materials and non-metals were identified and detailed literature review has been carried out on use of different materials under these groups for their applications in nanofluid based solar thermal collectors. It is observed that various parameters affect the efficiency of absorption of solar radiation. Various collector types such as flat plate, tubular and parabolic concentrators have been studied with the nanofluid as working fluid. Every collector configuration has reported the efficiency enhancement with the use of nanofluids. Selection of appropriate collector configuration is also important for optimization of performance. Different materials have different optical, thermal, chemical and mechanical properties. Type and phase of material also decides the amount of solar energy absorbed by particular nanofluid. Therefore selection of appropriate material is also a key issue. Further it has been found that concentration of nanoparticles also affects the efficiency of nanofluid to absorb solar radiation. Various studies carried out indicate that for every particle-fluid combination, there exist some optimum concentration which leads to maximum efficiency with minimum settling. So finding out the optimum concentration of nanoparticles in base fluid is vital. Nanomaterial size, shape and overall morphology also play important role in solar energy absorption. Very few studies have been reported depicting effect of size and shape on the absorption capabilities of the nanofluids. It is well known that nanomaterial properties change with changes in size and shape, so it could be interesting to know how different sizes and shapes of nanomaterial affect the collector performance.

On the other hand, selection of appropriate base fluid is also important along with nanomaterial. The choice of base fluid decides suspensions stability, ability to absorb solar radiation and other important fluid properties such as thermal conductivity, viscosity, density and specific heat. Applications, such as direct steam generation, desalination, separation of complex mixtures seek attention for improvement in energy efficiency and economic savings since very few research groups have reported the use of nanofluids for such applications.

2.6 Scope of the present work based on the gaps of the earlier studies

The gaps of earlier solar energy absorption studies using nanofluids were found out after critically assessing the literature and were used to decide the scope of present research work. The stable suspensions of various nanomaterials such as copper, aluminium, copper oxide, iron oxide (Fe_2O_3), silica, zinc oxide, titanium dioxide and carbon in base fluids such as ethylene glycol, silicone oil apart from water has not been yet reported in the literature to the best of our knowledge. Some studies have reported few of these materials with water as a base fluid but the work has not been carried out to the fullest extent with the use of different solar thermal collectors. Although, researchers have started using nanofluid as a working fluid for solar thermal collectors, focus of attention was always flat plate collector. It absorbs solar radiation with the absorber plate coated with solar selective material. This configuration has its own limitations because of the several associated losses before the heat is transferred to working fluid. Therefore, promising optical properties of the nanofluids cannot be utilized. Use of direct absorption collector improves absorption of solar radiation significantly as it reaches directly to the working fluid with minimal thermal resistance.

Handful of studies report above mentioned nanomaterials for direct absorption of solar radiation with parabolic solar concentrators.

Further, many parameters such as effect of particle concentration, effect of size and shape, effect of doping are still not explored. There exists and optimal particle concentration for every particle-fluid combination which gives maximum performance. Limited studies report the effect of range of different concentrations for various nanomaterials to choose best or optimal concentration from the studied range. It is well established that nanomaterial properties change with changes in its size and shape. The studies reporting effect of size and shape of the nanomaterial in solar thermal absorption applications were hardly found in the literature. These parameters are critical in determining the overall performance of any solar energy absorption system. On the other hand, choice of suitable base fluid also plays critical role in solar thermal energy absorption. Important heat transfer fluids such as ethylene glycol, silicone oil, etc. have not been explored for solar heating applications. Use of water as a base fluid also has not been explored to the fullest extent. Performance of these base fluids with various nanomaterials mentioned above have not been established yet. The use of nanofluids in solar desalination and separation of complex mixtures such as azeotropic mixtures like ethanol-water, etc are emerging applications and require detailed investigations to establish concrete solutions.

In view of this, light absorbing conducting nanomaterials were identified and grouped in to various materials categories. There are four material groups proposed for the study: metal group (copper and aluminium nanomaterials), metal oxide group (copper oxide and iron oxide i.e. Fe_2O_3 nanomaterials), semiconductor group (SiO_2, ZnO and TiO_2 nanomaterials) and non-metal group (carbon nanoparticles). Majority of nanomaterials were synthesized with either novel route or established routes with some changes, few of them were commercially obtained. Further stable suspensions of these nanomaterials were prepared in three different base fluids viz. water, ethylene glycol and silicone oil. Nanofluid properties like heat transfer coefficient, viscosity and density were established experimentally and theoretically. These nanofluids were focused with solar radiation in parabolic solar concentrator and efficiencies of solar energy absorption were established. Further ides of enhanced solar energy absorption by nanofluids was extended to application of solar desalination of hard water. Effect of type of nanomaterial, size, shape, etc. on efficiency of desalination was also studied to propose best possible and useful nanomaterials for this process. Few selected nanomaterials were also suspended in ethanol-water and isopropanol-water mixture at azeotropic composition. The nanofluid solution is focused with solar radiation in parabolic concentrator. Condensate was recovered and analyzed for composition to study the possible separation of components of mixture.

2.7 Outline of the present work

Various nanomaterials were synthesized and suspended in different base fluids to study the performance of nanofluid based parabolic solar concentrator for solar thermal heating, desalination and azeotropic separation processes. The present work has been divided into the use of four main material groups for above applications as given below:

System*-1: *Metal nanofluids (Cu & Al) for solar heating, desalination & azeotropic separation applications

- Synthesis of copper nanoparticles and parametric study
- Synthesis of stable nanofluids in water, ethylene glycol and silicone oil, nanofluid property evaluation, solar thermal heating in parabolic solar concentrator, solar desalination of hard water/sea water and solar enabled separation of azeotropic mixture

System*-2: *Metal oxide nanofluids (CuO & Fe_2O_3) for solar heating, desalination & azeotropic separation applications

- Synthesis of copper oxide nanomaterial and parametric study
- Synthesis of stable nanofluids in water, ethylene glycol and silicone oil, nanofluid property evaluation, solar thermal heating in parabolic solar concentrator, solar desalination of hard water/sea water and solar enabled separation of azeotropic mixture

System*-3: *Semiconductor nanofluids (SiO_2, ZnO, TiO_2) for solar heating, desalination & azeotropic separation applications

- Synthesis of SiO_2 nanomaterial by with three different sizes using Stober’s method and novel microwave assisted route and further synthesis of silver doped silica nanoparticles
- Synthesis of ZnO quantum dots and nanowires
- Synthesis of TiO_2 nanomaterial, carbon doped TiO_2, nanotubes and nanowires

- Synthesis of stable nanofluids in water, ethylene glycol and silicone oil, nanofluid property evaluation, solar thermal heating in parabolic solar concentrator, solar desalination of hard water/sea water and solar enabled separation of azeotropic mixture

System-4*: *Nonmetal nanofluids (carbon) for solar heating, desalination & azeotropic separation applications

- Synthesis of carbon nanoparticles with three different sizes
- Synthesis of stable nanofluids in water, ethylene glycol and silicone oil, nanofluid property evaluation, solar thermal heating in parabolic solar concentrator, solar desalination of hard water/sea water and solar enabled separation of azeotropic mixture

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