Advancements in Thermal Energy Storage System by Applications of Nanofluid Based Solar Collector: A Review

Vednath P. KALBANDE^{1*}, Pramod V. WALKE², C. V. M. KRIPLANI³

¹⁻³Department of Mechanical Engineering, G H Raisoni College of Engineering, Nagpur, 440016, India

Abstract – In the recent years, a lot of research has been carried out in the field of nanofluid based solar collector, leading towards the enhancement of working efficiency even at low atmospheric temperature or at low sunlight levels regions of the world. The present review pertains to the research progress related to the performance execution of solar collector using nanofluid. It is observed that the thermal energy storage system (TES), using solar collector, is a useful device for storing sensible and latent heat in a unit volume. Nanofluid plays an important role in various thermal applications such as heat exchanger, solar power generation, automotive industries, electronic cooling system, etc. The nanoparticles find the use in various industrial applications because of its properties, such as thermal, mechanical, optical and electrical. Most of the investigations carried out earlier on the applications of nanofluid in solar energy are related to their uses in the solar collector and thermal storage system. The parabolic solar collector using nanofluid is still a challenge. This article presents an exhaustive review of thermal storage system using nanofluid based solar collector and a scope of using nanofluid based solar collector for performance enhancement.

Keywords – Energy Storage; Nanofluid; Phase change material; Solar collector.

Nomenclature

C_p	Specific heat of the substance	J/kg K
F	Latent heat of evaporation or fusion	J/kg
h	Convective heat transfer coefficient	W/m ² K
k	Thermal conductivity	W/m K
L	Length of tube	m
D_i	Inner diameter of tube	m
M	Mass of the PCM material that undergoes a phase change	kg
m	Mass of medium in which energy is to be stored	kg
Q_s	Heat energy stored	J
T	Temperature	°C
u	Free stream velocity	m/s
β	Coefficient of thermal expansion	K ⁻¹
ρ	Density	Kg/m ³
μ	Absolute viscosity	N-s/m ²

* Corresponding author.
E-mail address: vednathkalbande@gmail.com

q	Heat flux	W/m ²
ø	Concentration	
Dimensionless parameter		
Nu	Nusselt number	hDi/k
Pe	Peclet number	$uD_i\rho C_p / k$
Pr	Prandtl number	$C_p\mu / k$
Ra	Rayleigh number	$g\beta\Delta TD_i^3\rho^2C_p / \mu k$
Re	Reynolds number	$uD_i\rho / \mu$
Greek symbols		
E	Effectiveness	
η	Efficiency	
Abbreviation		
ASHRAE	American society of heating refrigerating and air-conditioning Engineers	
CNT	Carbon nanotubes	
CFD	Computational fluid dynamics	
DAC	Direct absorption collection	
DASC	Direct absorption solar collector	
ESS	Energy storage system	
f-CNT	Alkaline functionalized carbon nanotubes	
[HMIM]BF ₄	1-hexyl-3-methylimidazolium tetrafluoroborate	
HTFs	Heat transfer fluids	
IL	Ionic liquids	
LHTES	Latent heat thermal energy storage	
MWCNT	Multi-walled carbon nanotubes	
NCPSC	Nanofluid-based concentrating parabolic solar collector	
NEIL	Nanoparticle enhanced ionic liquids	
NVR	Nanofluid volumetric receiver	
PCM	Phase change material	
PTC	Parabolic trough collector	
PV/T	Photovoltaic/thermal	
SH	Sensible heat	
SHTES	Sensible heat thermal energy storage	
SWCNT	Single-walled carbon nanotubes	
TES	Thermal energy storage	
TC	Thermocouple	
Subscripts		
nm	Nanometre	
AR	Aspect ratio	

1. INTRODUCTION

Solar energy is the most populous form of energy due to its green and environmentally friendly nature. Using solar energy, thermal energy storage can be charged, which is coupled with solar collectors. Preferably, the concentrating and non-concentrating solar collector are mostly used by the researcher. The nanofluid as a heat transfer fluid (HTF) is used to transfer heat from solar collector to thermal storage. Nanofluid is used in solar system to improve the performance. Researchers were taking efforts for solar based thermal storage system which is the cheapest, and easy to construct and design.

The solar energy device efficiency can be enhanced by introducing nanofluid in it [1]. It has been observed from comprehensive study that the replacement of conventional fluid with nanofluid enhances the efficiency of solar collector. The efficiency of the direct solar collector is significantly improved by using nanofluid as a working medium [2]. Nanofluid is a fluid containing a uniform suspension of very small particles having a size in nanometres. Nanofluids have one basic heat transfer fluid which is called base fluid, the nano-sized particles or tubes are then added in proportion into these base fluids. Also, by using a low temperature process, it is seen that this technology can reduce manufacturing costs of the whole system [3], [4]. However, there is a need to determine the effectiveness of thermal energy storage system for integration with solar collector gadgets. A lot of investigations have been reported on phase change materials (PCM) for the latent heat storage system to analyse thermal physical properties for selection criteria, classifications and potential of PCM [5]. For various industrial applications the use of nanofluid is more attracting for cooling. The nanofluids improve the heat transfer rate, thermal properties, optical properties, efficiency, extinction coefficients and transmission of solar systems as compared to conventional fluids [6]. The solar collector efficiency using Cu-water (25 nm, 0.1 wt%) nanofluids increased by 23.83 %, but decreases while using nanofluid of Cu-water (25 nm, 0.2 wt%) as an engrossing medium. As nanoparticle size is increased; the solar collector efficiency will be decreases [7]. Said *et al.* [8] investigated the effect of TiO₂ nanofluid and polyethylene glycol on flat plate solar collector. They varied mass flow rate in the range of 0.0083 to 0.025 kg/s, and recorded 76.6 % increase in efficiency for 0.1 % volume fraction and 0.0083 kg/sec flow rate.

The flat plate collector efficiency, can be enhanced by using Alumina- water based nanofluid, as working fluid. The experimental investigation using Al₂O₃/water nanofluid showed that efficiency of flat plate solar collector increased up to 28.3 % by using 0.2 wt% nanofluid as absorption medium as compared with water [9]. The four types of receivers were compared to analyse the thermal characteristic properties of the solar collector. The receivers were steel tube with black painted vacuum and black chrome covering with glass enveloped evacuated copper tube [10]. The efficiency of the nanofluid based volumetric receiver (NVR) has been considered on the key engineering parameters, for example, the concentration of nanoparticles, the Nusselt number and Peclet number of heat transfer, and aspect ratio [11]. A numerical analysis of the mixed convection boundary layer flow of a nanofluid along a slanted plate implanted in a permeable medium was carried out with incompressible nanofluid flow [12]. From the above discussion on the nanofluid based solar system can be started from the basic information of nanofluid which is discussed in the following sections.

1.1. Nanofluids

Nanofluid is a suspension of nano-sized particles in the base fluid which exhibit the enhanced thermal conductivities than the conventional fluid (base fluid) such as water,

ethylene glycol and oil [13], [14]. Nanofluids have potential to enhance the properties such as thermal conductivity, viscosity, surface tension, etc., for various applications such as energy, chemical, thermal engineering, electronic, material, environmental, bio-pharmaceutical, industrial, and medical [15].

The term nanofluid is first given by Choi *et al.* [14], [16], [17] to describe the suspension of nano-sized (1 to 100 nm) solid particles in ethylene glycol and water for stability of nanoparticles. The base fluid properties can be enhanced by dispersion of nanoparticles in it. Thermal conductivity of nanoparticles is mainly responsible for improving the properties of nanofluid. Experimental results in the past report that nanofluid demonstrate essentially higher thermal properties, particularly, thermal conductivity even when suspended nanoparticles concentrations are very low [13], [14], [16]–[19]. The properties details of nanoparticles and base fluid are shown in table 1.

TABLE 1. DETAILS OF DIFFERENT NANOPARTICLES AND BASE FLUID PROPERTIES [20]–[29]

Name of nanoparticles and base fluid/formula	Specific heat, Cp in kJ/kg K	Density, ρ in kg/m ³	Thermal conductivity, k in W/m-K
Alumina/Al ₂ O ₃ [20], [26]	0.773	3958	40
Copper Oxide/CuO [20], [26]	0.553	6000	33
Titanium di Oxide/TiO ₂ [20], [26]	0.688	4228	8.400
Silicon di Oxide/SiO ₂ [21], [26]	0.765	3968	36
Silver/Ag [20], [27]	0.235	10485	428
Ferro/Fe ₃ O ₄ [28]	0.670	5180	9.700
Graphene [29]	0.708	2098	5000
Carbon nanotubes [22], [24]	0.738	1352	3000
Graphite [20], [24]	0.702	2157	120
Ethylene Glycol/EG [28]	2.415	1115	0.252
Methanol/methyl [28]	2.547	794	0.204
Water (H ₂ O) base fluid [26], [27]	4.184	996	0.600

Applications of nanofluids can be found in engine cooling, engine transmission oil, solar water heating, thermal storage, refrigeration (domestic and chillers), cooling of electronic circuits, defense and space application, nuclear system cooling, bio-medical application, drilling and lubrication and many such applications [1], [4], [30]–[32].

Nanofluid properties, preparations, nanomaterial, base fluid, nanoparticle volume, and size and heat transfer enhancement are discussed below.

1.1.1. Properties of Nanofluid and its Preparation

Properties of nanofluid and its preparation are both dependent parameters. Nanofluid can be prepared with the help of ultra-sonication methods. The concentration ratio of nanoparticles, particles size and shape play an important role in this regard. Authors thoroughly discussed the properties of nanofluid such as viscosity, surface tension, thermal conductivity, etc. with its applications. Research on thermal conductivity of nanofluid has to be further investigated [1], [31], [33]–[37].

The Yang *et al.* [38] reported elaborative preparation of nanofluid, which is schematically shown in Fig. 1.

Fig. 1. Diagram of nanofluid preparation flow chart [38].

1.1.2. Nanoparticle Material and Base Fluid

The nanoparticles such as Al_2O_3 , TiO_2 , CuO , SiO_2 , Au, Ag, Fe, and Cu are frequently used in nanofluid preparation; and carbon nanotubes, graphite, grapheme, etc. are used in nanofluid research. Table 1 shows various materials that can be used in nanofluids preparation. The nanoparticles are suspended in common working base fluids (water, engine oil, ethylene glycol, etc.) for heat transfer applications. The additives with small amount are added in the nanofluid mixture to improve nanoparticle stability in the base fluid.

1.1.3. Nanoparticle Volume Fraction, Size and Shape

Literature on the suspension of nanoparticles in the base fluid is available. The effect on thermal conductivity of nanofluid due to volume fraction and volume concentration was studied. The qualitative results are usually accounted by many experimental studies to show the effect of volume fraction of nanoparticles with a wide range of base fluid on heat transfer system. The linear relation was found in between thermal conductivity and volume fraction of nanoparticles. The higher volume fraction increases viscosity and it will cause for the higher pumping power requirement due to large shear stresses of nanoparticles. Another important parameter to enhance the properties such as thermal conductivity, viscosity, surface tension, etc. is the nanoparticles size and shape. Researchers mostly prefer 10 nm to 100 nm diameter sizes of nanoparticles to prepare nanofluid for the experimental and numerical investigations. The viscosity of smaller diameter nanoparticles is better. Nanoparticles of tiny size increases micro-convection level of heat transfer [3], [17], [46]–[53], [26], [39]–[45].

1.1.4. Heat Transfer Enhancement with Nanofluids

The efficiency of the heat transfer system improves by increasing the thermal conductivity of nanofluid. Forced convection is considered in tube for heat transfer process. While natural convection is considered in the cylinder for the analysis of heat transfer with nanofluid. According to the definition of dimensionless number, the thermal conductivity enhancement obtained by using nanofluid is equal to the enhancement in heat transfer coefficient of the nanofluid, which is expected. The experimental and numerical studies about the convective

heat transfer of nanofluid shows that the enhancement in thermal conductivity of nanofluid is obtained due to heat transfer coefficient enhancement of nanofluid. Heat transfer coefficient was enhanced with higher rate in developed region of tube flow. The heat transfer through convection is more dominant in the thermal system where working fluid is nanofluid [3], [54], [63]–[70], [55]–[62].

Suspension is made with the help of magnetic stirring or ultrasonic stirring in the base fluid, the nanoparticles used may either be metallic or non-metallic. Nanoparticles aggregation forms large size particles which will create clustering. Clustering of nanoparticles exhibit the enhancement in thermal conductivity of nanofluid [41], [71]. Nanoparticles enhance optical properties of base fluid and improve the absorption properties of flat plate solar collector [39], [72]. The forced convection and thermophysical study of alumina-menthol was carried out and it was found that the heat capacity enhanced by 50 % at nanoparticles volume concentration of 0.05 % [73]. The optical properties are enhanced by nanoparticles with lesser concentrations in water and glycol base fluids, and nanofluids can be used for low temperature applications, on other had for high temperature application there is the need of oil based nanofluids which are suitable for up to 300 °C [74], [75]. Arshad *et al.* [76] experimentally investigated the hydrodynamic and thermal performance of graphene based nanofluid. It is found that the convective heat transfer enhanced by 13.6 %, 15.38 % and 21.51 % at heat flux of 71.94 kW/m², 59.95 kW/m² and 47.96 kW/m², respectively. Saidur *et al.* [39] have investigated potential use of Al₂O₃ nanoparticles in direct absorption type solar collectors. They found that Al₂O₃ has improved the absorption when used in concentration up to 1 % in volume fraction. Also they concluded that for direct solar collector the use of nanofluids as volumetric absorber shows excellent improvement in thermal properties and it can be a good solution for direct solar collector. Qiao *et al.* [77] found that evaporation rate of MWCNT nanofluid is higher than pure ethanol by 25.6 % and is also higher than carbon nanoparticles or Al nanofluid by 18.7 %. Faizal *et al.* [26], [40] have concluded that with the use of aluminum oxide nanoparticles as absorbing medium the size of the collector can be reduced up to 24 %. Also the aluminum oxide is cheaper as compared to other nanoparticles which makes it ideal for this application.

1.2. Thermal Energy Storage

The thermal energy system principle is applicable for all the systems. The energy can be removed or used later from thermal storage system. Thermal storage can be categorized in two crucial groups: sensible heat thermal storage (SHTES) and latent heat thermal storage (LHTES) [78].

1.2.1. Sensible Heat Storage

Sensible heat (SH) is the heat related with an adjustment in temperature of a solid or liquid. The heat energy (Q_s) stored in such solid or liquid is given by the Eq. (1):

$$Q_s = (T_2 - T_1) \cdot C_p \cdot m, \quad (1)$$

where

Q_s heat energy stored, J;

m mass of medium in which energy is to be stored, kg;

C_p specific heat of the substance, J/kg·K;

T_1 and T_2 are the initial and final temperature, respectively, °C.

1.2.2 Latent Heat Storage

Latent heat (LH) is the heat retained or freed by a phase change or transition and it occurs when the temperature is constant. The latent heat (Q_s) through a change of phase is given by the Eq. (2):

$$Q_s = M \cdot F, \quad (2)$$

where

- Q_s storage energy, J;
- M mass of the PCM material that undergoes a phase change, kg;
- F is the latent heat of evaporation or fusion, J/kg.

1.3. Phase Change Material for Thermal Energy Storage with Nanofluid

A phase change material (PCM) is used in a thermal storage system due to its high heat of fusion. It can store the heat while melting and releasing it during solidification. The material changes its phase from solid to liquid and vice versa, when it is absorbed or released the heat. PCM is the latent thermal storage material. The phase change materials are substances to store and discharge the heat, due to which transfer of thermal energy occurs when a material changes from solid to liquid and vice versa. Advantages of phase change system are a high storage capacity, the phase change of the storage material proceed at an almost constant temperature, and a high density [79]–[82]. The phase change material is divided into three basic types i.e. organic, inorganic and eutectic. Further organic phase change material is divided into paraffin and non-paraffin compound. The inorganic phase change material is divided into salt hydrate and metallic. Eutectic phase change material is divided into organic-organic, inorganic-inorganic and inorganic-organic [83].

Thermal storage coupled with solar collector using nanofluid as a HTF is the better option to store energy in thermal energy storage. The nanofluid plays key role in the enhancement of efficiency of the solar based thermal storage system. As discussed in section 1.1.4, as heat transfer rate of nanofluid increases, it will improve the performance of solar collector to store energy in thermal energy storages. The TiO_2 + water nanofluid as HTF was used in solar heat exchanger. The average heat transfer coefficient increases by 21 % due to use of TiO_2 /water nanofluid [84]. The ionic-liquid and molten-salt based nanofluid was studied for thermal storage system to improve its performance. Molten salts properties such as specific heat, thermal conductivity etc. have been studied with higher range of temperature using nanofluid as a HTFs [85].

The detailed study regarding thermal storage systems using concentrated and non-concentrated solar collector is given in sections 2, 3 and 5.

The thermal storages are basically coupled with solar collector. The solar collector using nanofluid as a working fluid transfer energy to thermal storage. So, the various types of solar collector that can be useful for the thermal storage system is discussed in the following section.

1.4. Solar Concentrating Systems

Mirrors or lenses are used in concentrated solar power systems to concentrate a whole incident sunlight or solar thermal energy, into a small area to generate solar power. The concentrating type solar collector having operating temperature range is maximum [86]. Nanofluid for the thermal storage system is basically operated at higher temperature. So these category of solar collector is best suitable for the thermal storage system using nanofluid as

HTF [87]. There are different types of solar collector and they are described in the next sections.

1.4.1. Parabolic Trough System

The linear parabolic reflector in parabolic trough system concentrates light on receiver along the reflector focal line. The working fluid is filled with a tube which is situated directly above the centre of the parabolic mirror of receiver [88]. Working fluid in receiver is utilised as a heat source for a power generation system and can be heated up to 150–350 °C. The concentrated solar power with trough systems are the most developed technology.

1.4.2. Parabolic Dish

Solar energy concentrates on a single focal point by using one or more parabolic dish in parabolic dish collector such as the way reflecting telescope focuses starlight. For the solar furnaces and solar power plant, this type of collector may be used. The incoming light rays are reflected towards the focus due to parabolic shape and rays parallel to the dish's axis.

The incident ray of light from the sun to earth is almost parallel. So, all incoming rays of the sun reflected towards the focal point of the dish due to the fact that the dish is aligned with its axis at the sun.

1.4.3. Power Tower

A power tower is a tracking mirrors called heliostats are surrounded on a large tower. At the top of the tower of receiver sunlight is focused by tracking mirrors. The optical fiber cable can be used as illuminating buildings for redirecting concentrated light to a suitable location.

During cloudy and overnight conditions, the heat storage is accomplished for power production by the underground tank storage of heated fluids. The liquid metals can be proposed as the working fluid due to superior thermal properties. To maintain sunlight focus at the collector, the sun tracking is required for concentrating system. The diffused light cannot be concentrated; therefore, concentrating system drops drastically in cloudy condition.

1.4.4. Stationary Concentrating Collector

The compound parabolic reflectors and flat reflectors are used in the stationary concentrating collector for directing solar energy to an absorber or aperture through a wide acceptance angle. There is no need of sun tracker, due to the wide acceptance angle in reflectors. In this category parabolic trough flat plate solar collectors, flat plate solar collectors with parabolic boosting reflectors and solar cooker are include. These solar collector with nanofluid was used by researcher to enhance the performance of solar based system. Stationary collector with nanofluid as working fluid is easy to handle.

2. NANOFLUID BASED THERMAL STORAGE SYSTEM WITH SOLAR COLLECTOR

The thermal properties of nanofluid for various applications can be achieved at small concentration and with stable suspension and homogeneous dispersion of nanoparticles in the base fluid. Energy saving and operational temperature in solar collector is affected due to the

heat transfer augmentation. Nanofluids can satisfy the specific needs and constraints if heat transfer increases in solar thermal based system [1].

The physical and thermal properties of host fluid can be improved by suspending of nanoparticles into a liquid. The efficiency and performance of solar collector can be improved by decreasing energy losses and increasing energy transfer. The energy losses can be reduced by glazing and washing the absorber and improving sun radiation reflection. Suspension of nanoparticles will result into enhancement of the optical properties of base fluid. Suspended nanoparticle of very small diameter has a higher extinction coefficient in nanofluid when contrasted with ordinary base fluid. The extinction coefficient is obtained about $17 \cdot 10^5$ at a diameter of 20 nm [39]. In this way, it is more competent to absorb the energy from incident sunlight in a solar collector [2].

To enhance the efficiency of the solar system nanofluid can be used, but the efficiency does not always enhance by a higher solid volume fraction. For solar collector efficiency it is needed to study the effect of nanoparticle size. Nanofluid research is essential for development of particle production and decreasing in cost [3]. The nanoparticles to enhanced efficiency of the system is discussed below.

2.1. Nanoparticles for Thermal Storage System Using Solar Collector

The phase change materials for latent heat storage system using nanofluid as working medium is much more effective method to store the solar energy through a solar collector. Phase change materials (PCM) are for the most part favoured because of the wide range of temperature, congruent melting and high latent heat, but these PCMs have low transfer of heat and low thermal conductivity. It is observed that the metals, metal oxides and carbon-based nanomaterial such as Ag, Cu, Al, Al_2O_3 , MgO, CuO, ZnO, TiO_2 , expanded graphene nanosheets, graphite sheets, MWCNT, SWCNT, active carbon, graphene flakes, nanofibers all these are incorporated with phase change materials to get efficient phase change properties [5]. Solar system with nanofluid is having many challenges to use, such as instability and agglomeration problem, high cost of production, erosion and increased pumping power. This can be reduced with further research in nanoscience [4].

The nanoparticle suspension in conventional fluid is resulting into a new generation of heat transfer fluid. The thermal conductivity of suspended nanoparticles in nanofluid has substantially higher than host fluid. Nanofluids have good forced and natural convective heat transfer properties as compared to base fluid due to suspension of nanoparticles [6].

The thermal solar collector has been developed using new configurations for the solar water collector on residential building for the experimental findings. The absorber with cold water tube and less insulation is having better performance than the actual prototype [89], [90]. A review was conducted for CFD analysis on a flat plate solar collector to analyse the thermal storage system. Review summarized that the solar collector design for better performance and less expensive for simplest outdoor test to optimize thermal performance of system [91]. The solar energy stored in the thermal storage system using PCM is the effective methods for the domestic applications. The thermal conductivity and photo-thermal properties show that the nanoparticles have a very good ability to absorb solar energy. The base fluid properties improve by using suspended nanoparticles, which are subject to particle shape, particle size, the optical properties of the particle and base fluid [92], [93].

2.2. Effect of Nanofluid on Solar Collector and Thermal Storage Efficiency

The nanofluid having nanoparticles absorbed heat from the sun through solar collector and will transfer its heat to thermal storage. Due to the higher thermal conductivity of metallic nanoparticles, the heat transfer rate will be increased. The increasing heat transfer rate increases the efficiency of the system. Absorption of heat from the heat source is increases due to nanoparticles and it transfers heat to thermal storage at higher rate than that of base fluid. Also, the heat in thermal storage increases rapidly due to the effect of nanoparticles. So, the efficiency of solar collector and thermal storage unit is increased by using nanofluid.

3. NON-CONCENTRATING SOLAR COLLECTOR

3.1. Flat Plate Solar Collector

Kabeel *et al.* [94] numerically investigated nanofluid based solar collector using the novel integrated system for small scale needs by using the flashing desalination technique. The production of desalted water and the cost of system was estimated. The five parameters which are affecting the cost of system and production were studied. These parameters are nanoparticles volume fraction, cooling water mass flow rate, feed water mass flow rate, feed water salinity and cooling water inlet temperature. The investigation was carried out on flat plate solar collector and the working fluid of copper nanoparticles.

He *et al.* [7] experimentally carried out efficiency of nanofluid based flat plate solar collector by the addition of copper nanoparticles with different mass fraction in pure water, which is shown in Fig. 2. The addition of nanoparticles to pure water results in increasing thermal conductivity of the base fluid. The size of the nanoparticles affects the efficiency of the system. The temperature and heat gain by water is increased up to 12.24 % and 24.5 %, respectively, by using nanofluid (25 nm, 0.1 wt%) in water. If hot water temperature for application is not achieved, it will recirculate by water pump to the heat exchanger, until desired temperature is achieved.

Fig. 2. Experimental setup of solar thermal energy measuring system [7].

Said *et al.* [95] studied pumping power and exergy efficiency of SWCNT based nanofluid for the conventional flat plate collector. The study was compared between two nanofluids, SWCNT and metal oxide (Al_2O_3 , TiO_2 and SiO_2) based nanofluid for flat plate collector. The thermal properties and exergy efficiency of SWCNT was found to be better than of the metal oxide nanofluid. Schuchardt *et al.* [96] experimentally studied the impact on exergy and energy efficiency on centralized and decentralized heat storage systems and it is found to be 82.4 % and 84.2 %, respectively. Faizal *et al.* [26] compared study of different nanofluids for flat plate solar collector on the basis of economic and environmental parameters. The properties of CuO nanofluid had the highest values as compared to alumina, titanium di-oxide and silicon di-oxide nanofluids. The environmental and economic analysis of different nanofluids is shown in Table 2.

TABLE 2. COMPARISON OF DIFFERENT NANOFLUID FOR FLAT PLATE SOLAR COLLECTOR [26]

	Electric Heater	Solar based Heater, water	Solar based Heater, Alumina	Solar based Heater, Titanium di Oxide	Solar based Heater, Silicon di Oxide	Solar based Heater, Copper Oxide
Capital costs, Rs	6 563.68					
Independent costs, Rs		49 227.57	49 227.57	49 227.57	49 227.57	49 227.57
Area based costs, Rs		16 409.19	12 873.83	12 776.03	12 871.04	12 208.77
Nanoparticles cost, Rs			1804.35	1544.60	1215.92	1 924.80
Total cost, Rs	6 563.68	65 636.76	63 905.75	63 548.20	63 314.53	63 361.14
Electricity cost saving per year, Rs		26 353.16	26 353.16	26 353.16	26 353.16	26 353.16
Years of electricity savings		2.49	2.42	2.41	2.40	2.40

Said *et al.* [8] carried out a performance using polyethylene glycol dispersant and $\text{TiO}_2\text{-H}_2\text{O}$ nanofluid in flat plate collector as shown in Fig. 3. The volume fraction with 0.3 % of titanium dioxide is enhancing the thermal conductivity of titanium dioxide-water nanofluid up to 6 %. The exergy efficiency, improved by up to 16.9 % for 0.1 vol% of nanoparticles concentration and 0.0083 kg/s of flow rate, while the energy efficiency obtained at 0.1 vol% and 0.0083 kg/s is 76.6 % by using nanofluids instead of water.

Yousefi *et al.* [9] studied experimentally an alumina-water nanofluid effect on flat plate solar collector efficiency as shown in Fig. 4. The effects of mass fraction of nanoparticles, mass flow rate and surfactant on the efficiency of the solar collector were studied. The nanoparticles weight fraction was 0.2 % and 0.4 % and 15 nm size nanoparticles were studied. The efficiency was calculated by using ASHRAE standard, where water as the assimilation medium with and without X-100 as a surfactant.

Fig. 3. Detail assembled diagram of solar collector, cooling water tank, and heat exchanger [8].

Fig. 4. The detailed schematic diagram of experimentations [9].

Nasrin *et al.* [97] studied numerically forced convective analysis of semi-empirical relation for a solar collector shown in Fig. 5. The flow, temperature, and heat flux fields as well as average velocity, collector efficiency, mean bulk temperature, heat transfer rate and mid-height temperature of the fluids through the riser pipe has been considered for various Prandtl No. and Reynolds No. values. Al- Kayiem *et al.* [98] evaluated the performance of integrated solar water heater (shown in Fig. 6) using a PCM nanocomposite for TES at an inclination of 10°, 20° and

30° angles. Three cases (shown in Table 3) were investigated, they are without TES material, with phase change material and with nanocomposite. The paraffin wax was a PCM and nanocomposite of 1.0 wt% of 20 nm copper nanoparticles and paraffin wax with base material. At 10° inclinations the system performance was getting optimal.

Fig. 5. Schematic diagram of solar collector for forced convection analysis [97].

Fig. 6. Schematic view of the solar – thermal energy storage integrated collector [98].

Sekhar *et al.* [99] experimentally studied the Al_2O_3 +water nanofluids heat transfer characteristics enhancement on twisted tapes in a pipe. Prakasam *et al.* [100] performed experimentally the effects of mass flow rates on flat plate solar water heater using aluminum/water based nanofluid. The flow rates of Al_2O_3 /water vary from 1 to 3 lit/min for lower volume concentration of 0.01 %. The performance of flat plate solar water heater system was compared with two working fluid, i.e. distilled water and Al_2O_3 /water nanofluid. It was found that the flat plate solar water heater efficiency, enhanced by 14.3 % at the nanofluid flow rate 2 lit/min and if flow rate increases then the efficiency of collector also decreases.

Dasaen *et al.* [101] investigated experimentally the enhancement of flat plate solar water heater through thermosyphon system using copper oxide nanofluid. The performance of solar collector was carried out for different mass concentration of nanoparticles and mass flow rates of nanofluid. The efficiency of the collector has been enhanced by 5.7 % at 0.0033 kg/s flow rate of CuO nanofluid. The computational and experimental analysis shows that using CuO nanofluid can improve the performance of solar collector through thermosyphon system.

TABLE 3. MEASURED SYSTEM EFFICIENCIES ARE AT INCLINATION ANGLES OF 10, 20 AND 30 DEGREES RESPECTIVELY OF OPERATIVE CASES [98]

Case	Max efficiency in percentage	Percentage of improvement	Overall efficiency in percentage	Percentage of improvement
At 10-degree inclination				
Case I	68.8	–	47.6	–
Case II	69.0	0.3	51.1	6.8
Case III	69.7	1.3	52.0	8.5
At 20-degree inclination				
Case I	65.8	–	44.8	–
Case II	66.2	0.6	47.6	5.9
Case III	66.8	1.5	48.0	6.7
At 30-degree inclination				
Case I	56.0	–	37.1	–
Case II	57.0	1.8	39.0	4.9
Case III	58.0	3.4	39.6	6.3

Colangelo *et al.* [102] studied numerically influence of nanoparticle concentration on the thermal efficiency of solar thermal collector by using water and Al_2O_3 nanofluid. The numerical model was developed for the solar thermal collector to study the behaviour of concentration of Al_2O_3 nanoparticles

3.2. Flat Panel and Cover Type Solar Collector

The efficiency of flat panel solar collector has been enhanced by using Water- Al_2O_3 nanofluid. The nanofluid with 1 vol% to 3 vol% was prepared to avoid sedimentation in system. Thermal conductivity (k) and heat transfer coefficient (h) were measured by using a hot wire technique as shown in Fig. 7. It was found that at 3 % volume fraction, the efficiency of flat panel solar collector increases by up to 6.7 % [103].

The water- Al_2O_3 nanofluid was used in the solar collector and investigated the impact of Prandtl number on natural convection boundary layer flow. Results shows that the heat transfer and fluid flow for various Prandtl number range. From the results it is observed that the isothermal contours get affected considerable by Prandtl number range from 1.73 to 6.62. The heat transfer rate of water-alumina nanofluid was most effective at higher Prandtl number [104].

An optical collocation method was used for the heat transfer analysis of flow over infinite stretching solar plate through two phase nanofluid flow. The effect of stretching rate, nanoparticles concentration, Schmidt number, Prandtl number and Brownian motion parameter has been discussed [105].

Fig. 7. Experimental setup for the measurement of convective heat transfer coefficient [103].

3.3. Nanofluid with Non-concentrated Solar Collector for Applications

The weight fractions of nanoparticles 0.1–0.5 % were used by researcher and the size of the nanoparticles, from 25 nm to 100 nm was experimentally studied with non-concentrated solar collector. Non-concentrated solar collector maximum temperature is reached up to the 150 °C and required sophisticated design to reach this temperature. The efficiency of non-concentrated solar collector using nanofluid is comes up to 25 % or less. To achieve 200 °C temperature non-concentrated solar collector is replaced with the concentrated solar collector. The nanoparticles weight fractions may vary from 0.1 % to 1 % for the detailed investigations. The nanoparticles size from 25 nm to 300 nm can be used for further research. Therefore, it is required to conduct further research to achieve new goals and applications.

Thermal storage unit require temperature higher than 200 °C temperature to stored energy for cooking, heating, and industrial applications. Concentrated type solar collector with nanofluid is more efficient for the set of above applications.

4. DIRECT ABSORPTION SOLAR COLLECTOR

The direct absorption solar collector system using carbon nanotube as a working fluid for low temperature was investigated experimentally. The thermal conductivity, stable suspension and optical properties of f-CNT are more preferable to use as a working fluid in DASCs. The addition of 150 ppm of f-CNT significantly enhanced the thermal conductivity of the working fluid (water) by up to 32.2 %. Also, it increases the extinction coefficient of

working fluid [106]. The efficiency of DASCs has been investigated on the basis of flow rate of $\text{Al}_2\text{O}_3\text{-H}_2\text{O}$ nanofluid as shown in Fig. 8. The flow rates of nanofluid of 1.5, 2.0, 2.5 lpm were taken for experimentation. The optimum collector efficiency was achieved at a flow rate of 2.0 and 2.5 lpm in this study [107].

Fig. 8. The schematic diagram of DASCs for experimentation [107].

The direct absorption solar thermal collector using graphene/ionic liquid based nanofluid was experimentally and numerically investigated (see Fig. 9). Graphene concentration regulates the radiative properties of graphene/[HMIM]BF₄. The effect on convective heat transfer loss and thermal re-emission due to graphene was investigated by numerical model to predict the temperature profile. Also, graphene water based nanoplatelets was experimentally tested for the fin heat sink [76], [108], [109].

Fig. 9. (a) Schematic diagram of direct absorption solar thermal collector system; (b) Experimental setup with solar simulator and a receiver with graphene/[HMIM]BF₄ [108].

The conduction and convection heat transfer equation for solving the radioactive transfer equation was developed through numerical model of nanofluid solar collector. The nanofluids enhanced the efficiency and outlet temperature by 2–25 % and 30–100 K respectively, than the base fluid [110]. The direct absorption solar thermal collectors using CNT nanofluids for study of high temperature and long-term stability of nanofluid was experimentally investigated. The solar energy absorption using MWCNTs was close to 100 % at various concentrations of nanofluid due to its optical properties [74].

The Ni and Cu nanoparticle with 10 ppm volume fraction has been compared through lowest transmittance and higher extinction coefficient in high-temperature DASCs to investigate the radiative properties of [HMIM] [NTf₂]. The incident light penetrated the nanofluid for a distance of 1 cm and absorbed 100 % energy fraction [111]. The transmittance of nanofluid was affected from mass fraction, nanoparticle size and optical path. The Cu-H₂O nanofluid having transmittance is close to zero and 25.3 % temperature was increased as compared to deionized water. The solar absorption efficiency can be enhanced by using Cu-H₂O nanofluids due to its photothermal properties [92], [112].

4.1. Nanoparticles Uses Effect on Direct Absorption Solar Collector

The nanotubes, graphene and copper nanoparticles were used by researcher. The cost of these nanoparticles is much higher than Al₂O₃, SiO₂ and TiO₂. Direct absorptions solar collector system is very complicated in construction and costly. Al₂O₃, SiO₂ and TiO₂ may be used with same system for lowering the system cost. Direct absorption system may be replaced by concentrated or non-concentrated solar collector to avoid the complications in the system. The thermosyphon is better option for the direct absorption solar collector system using nanofluid. The nanoparticles give much more heat transfer through thermosyphon unit.

5. CONCENTRIC SOLAR COLLECTOR

The capability evaluation of PTC using nanofluid was experimentally performed. A black chrome coating was introduced on copper tube to enhance the performance of the system. The vacuumed tube global efficiency was 11 % higher than that of bare tube efficiency [10]. The heat transfer improvement of alumina/synthetic oil nanofluid in parabolic trough solar collector tube was studied numerically. The simulation and a turbulent mixed convection heat transfer with non-uniform heat flux was investigated by using a synthetic oil and Al₂O₃ nanofluid in a solar collector absorber tube ($L = 7.8$ m and $D = 0.07$ m). Utilizing nanofluid in PTC has natural advantages and causes enhancing heat transfer [113], [114].

The parabolic concentrating solar collector using nanofluid for solar energy harvesting system was studied which is shown in Fig. 10. The analysis was carried out for termonol VP-1 as the base fluid and Aluminium nanoparticles with 0.05 vol% suspended in it. It is found that the thermal efficiency of the system is about 5 to 10 % higher than conventional parabolic solar collector under the same weather conditions [115].

An experimental performance was carried out on evacuated tubular solar collectors through open thermosyphon using nanofluid. It is seen that the mass concentration of CuO nanoparticles in open thermosyphon enhances the heat transfer effect up to 1.2 % [116]. To evaluate the thermal efficiency of a cylindrical solar collector with helical pipe receiver using CuO-H₂O nanofluid an investigation was carried out as shown in Fig. 11. The CuO-H₂O nanofluids and distilled water were used as the working fluid for the experiment [117].

Fig. 10. Schematic diagram of parabolic concentrating solar collector using nanofluid [115].

Fig. 11. Experimental setup. (1) Copper coil, (2) cylindrical glass, (3) datalogger system, (4) thermocouple wires, (5) line valve, (6) rotameter, (7) water supply and drainer, (8) water pump, (9) heat exchanger, (10) reservoir tank and (11 and 12) thermocouples [117].

The effect of therminol D-12 as the working fluid on the performance of evacuated tube solar collector coupled with parabolic trough was experimentally investigated. The temperature of the hot water produced was 40 °C at 06:45 hr in the presence of 0.240 kW/m² solar radiations [118].

5.1. Concentric Solar Collector Efficiency Enhancement

From the above discussion on the topic of concentrated solar collector using nanofluid is the better option to store energy in thermal storage. Researcher is getting more efficiency on this system. Al₂O₃, CuO, TiO₂, SiO₂ nanoparticles is more suitable for the concentrated solar collector for the cooking, heating and industrial applications. Using nanofluid in concentrated solar collector for thermal storage system is more efficient and cheaper.

6. DISCUSSION

This paper introduced a survey of the utilizations of nanofluids in solar thermal engineering using CuO, SiO₂, TiO₂, Al₂O₃, CNT, graphene and graphite nanoparticles. It is worth to do an experimental investigation on the size of the nanoparticles.

In the solar collector and thermal storage system limited studies have been reported regarding the thermophysical properties of nanofluid. Only thermal conductivity is not important other properties also need to be taken into consideration [1]–[3]. Mixture of more than one nanoparticle in nanofluid is difficult and required new research in this area. Most of the researchers used water as base fluid for nanofluid preparation, so it is desired to search for the new suitable base fluid for the dispersion of nanoparticles. In this paper nanofluid with non-concentrated, concentrated, and direct absorption solar collector is deeply discussed. Effect of thermophysical, dimensional and chemical properties of nanoparticles on heat transfer system is discussed with applications. The enhancement of heat transfer efficiency in thermal storage system using nanofluid based solar collector is elaborated. Heat transfer through nanofluid use in thermal storage system is studied in detail. Table 4 shows the summary of applications of nanofluid in thermal energy based solar collectors.

7. CONCLUSION AND RESEARCH IN FUTURE

In the present paper, an endeavour has been made to survey different nanofluids based solar collector with thermal energy storage system. Nanotechnology is an established and effective innovation utilized for a long time. However, proper understanding of the role of nanoparticles in improving their performance will definitely provide more opportunities for developing nanofluid based solar collector. The efficiency and extinction coefficient of nanofluid depends on the diameter of nanoparticles and volume concentration.

Nanofluid based solar collectors and thermal storage systems are likely to overcome the challenges in the near future particularly for cooking industry. Experimental methods and procedure to take care of issues related to the utilization of PCMs such as supercooling, low thermal conductivity and incongruent melting through nanomaterial incorporation and encapsulation have also been presented.

From the above review it can be concluded that the nanofluids application in solar energy is still in its beginning periods. The major factors such as synthesis methods, production cost, physical and chemical parameters are affected from practical implications of nanofluids. So far, the hypothetical examinations have been accounted for on PTC; additional experimental studies can be performed. The introduction of nanotechnology in the future may overcome such problems with continuous research and development.

Thermo-physical properties of nanofluid are more suitable for the solar based thermal storage system using PCM with different nanoparticle size and volume are to be thought of for future work. The nanofluid for the solar collector with different nanoparticles require further research for different domestic application.

Solar collector based thermal storage system using nanofluid for the application of cooking, water heating, refrigeration etc. is the need of an hour. The physical, thermal and optical properties of nanofluid play an important role to enhance the performance of thermal storage system. Therefore, research on nanofluid with different nanoparticles size, shape and concentration is to be further carried out to analyse its different properties such as thermal conductivity, surface tension and viscosity, etc.

TABLE 4. SUMMARY OF APPLICATIONS OF NANOFUID IN THERMAL ENERGY BASED SOLAR COLLECTORS (ADAPTED FROM [1]–[3]).

Sr. No.	Nanofluid	Author	Type of investigation	Collector type	Base fluid	Particle size and volume fraction	Results and remarks
1.	MWCNT	Yousefi <i>et al.</i> [119]	Experimental	Flat plate solar collector	Water	D = 10–30 nm, 0.2 wt%	<ul style="list-style-type: none">• Higher efficiency achieved by the big difference of pH values with respect to the pH of isoelectric.
		Yousefi <i>et al.</i> [120]			Water (Surfactant: Triton X-100)	D = 10–30 nm, 0.2 & 0.4 wt%	<ul style="list-style-type: none">• The solar collector efficiency was remarkably increased due to 0.4 wt% of nanofluid, but for 0.2 wt% the efficiency decreased.• The surfactant was used for increasing efficiency of collector with 0.2 wt% nanofluid.
		Faizal <i>et al.</i> [121]			Absorbing medium and used as surfactant	0.2 wt% and 0.4 wt%	<ul style="list-style-type: none">• The size of the flat plate solar collector can be reduced up to 37 % by using MWCNT nanofluid as a working fluid.
		Kasačian <i>et al.</i> [10]		Parabolic trough solar collector	Mineral oil	0.2 % to 0.3 % (weight fraction)	<ul style="list-style-type: none">• The efficiency, absorptivity and thermal conductivity were higher for copper absorber tube and efficiency raised by up to 11 % for vacuumed tube in comparison with bare tube.• Global efficiency of PTC can be enhanced up to 4–5 % and 5–7 % by using MWCNT/ mineral oil nanofluid at 0.2 % and 0.3 %, respectively.

							<ul style="list-style-type: none">Optical characterization of MWCNT is higher for solar energy absorption, it's nearly 100 %.The stability of nanoparticle observed for a long time with glycol while gradually agglomeration was observed with water based nanofluid.
2.	Alumina/ Al_2O_3	Nasrin <i>et al.</i> [104]	Numerical	Glass cover plate with sinusoidal absorber	Water	5.0 vol%	<ul style="list-style-type: none">The higher Prandtl number has improved the performance rate of heat transfer by using Al_2O_3 nanofluid.The convective heat transfer rate is increasing up to 18 % and 26 % with the increasing value of Prandtl number from 1.73–6.62 by using water and $\text{Al}_2\text{O}_3/\text{H}_2\text{O}$ respectively as a working fluid.In the same condition radiation rate enhances by about 8 %.
		Nasrin <i>et al.</i> [122]			Water	5.0 vol%	<ul style="list-style-type: none">For the nanofluid and base fluid rates of heat transfer improves by 19 % and 12 % respectively.Convection has a higher average heat transfer than radiation.
		Tiwari <i>et al.</i> [123]	Theoretical	Flat plate	Water	0.5–2 vol%	<ul style="list-style-type: none">Using 1.5 vol% of Al_2O_3 can increase thermal efficiency by 31.64 %$\text{Al}_2\text{O}_3/\text{water}$ (1.5 vol%) has a capability to decrease 31 % kgCO_2/kWh

	Yousefi <i>et al.</i> [9]	Experimental			Water (Surfactant: Triton X-100)	D = 15 nm, 0.2 and 0.4 wt%	<ul style="list-style-type: none"> By using 0.2 wt%, nanoparticles improve efficiency by up to 28.3 %. 15.63 % is the maximum efficiency enhancement in case surfactant is used.
	Kasacian <i>et al.</i> [124]	Theoretical	Concentrating parabolic solar collector		Synthetic oil nanofluid		<ul style="list-style-type: none"> The convective heat transfer coefficient increases by enhancing the nanoparticles concentration. Increase in temperature of nanofluid results into heat transfer coefficient decreases at a given mass flow rate.
	Khullar <i>et al.</i> [115]				Therminol VP-1		<ul style="list-style-type: none"> The efficiency of parabolic solar collector is 5–10 % higher than conventional model by using nanofluid.
	Tyagi <i>et al.</i> [125]		Direct absorption solar collector		Water	0–20	<ul style="list-style-type: none"> The volume fraction enhanced the efficiency by up to 2 % and beyond that remains nearly constant. The nanoparticle sizes also enhance the collector efficiency with ascendance.
	Saidur <i>et al.</i> [39]				Water	<20	<ul style="list-style-type: none"> The lower extinction coefficient increases due to visible light and shorter wavelengths used for light absorption. Volume fraction and extinction coefficient were linearly proportionate.
	Elmir <i>et al.</i> [126]		Solar cell cooling		Water		<ul style="list-style-type: none"> The low Reynolds number enhances the 27 % heat transfer by changing

							the solid volume fraction from 0–10 %.
3.	Copper Oxide /CuO	He <i>et al.</i> [112]	Experimental	Direct absorption solar collector	Deionized water (surfactant)	D = 25–50 nm and 0.01, 0.02, 0.04, 0.1, 0.2 wt%	<ul style="list-style-type: none"> As optical depth, mass fraction and nanoparticle size increase the transmittance of collector will decrease. Cu-H₂O nanofluid has less transmittance and good assimilation capacity for solar energy.
		Liu <i>et al.</i> [127]		Evacuated tubular solar air collector	Water	D = 50 nm, 1.2 wt%	<ul style="list-style-type: none"> By using nanofluid in collector with open thermosyphon, the maximum and mean value of the collecting efficiency can increase by 6.6 % and 12.4 %.
		Risi <i>et al.</i> [128]	Numerical	Parabolic trough collector	Nitrogen gas	V = 0.01–0.3 %	<ul style="list-style-type: none"> The maximum efficiency of solar to thermal is 62.5 % (Outlet temp. of nanofluid = 923 K) Over 0.3 vol% the disadvantages of pressure drop overpower is the beneficial effects in thermal properties.
4.	MgO	Cui and Zhu [129]	Experimental	PV/T system	Water	10	<ul style="list-style-type: none"> The solar cell output power in the PV/T system decreases by enhancing both nanofluid film thickness and particle volume fraction.
5.	Al ₂ O ₃ , ZnO & MgO	Li <i>et al.</i> [130]	Experimental	Tubular	H ₂ O	<20 nm	<ul style="list-style-type: none"> The volume concentration with 0.2 % of ZnO/water nanofluid is the best selection for the collector.

6.	CNT	Chougule <i>et al.</i> [131]	Experimental	Flat plate	Water	D = 10–12 nm and L = 0.1–10 μm , 0.15 vol%	<ul style="list-style-type: none"> The efficiencies of solar collector for nanofluid and water are 45 % and 25 % at 31.5° tilt angle The efficiencies of solar collector for nanofluid and water are 61 % and 36 % at 50° tilt angle.
7.	Graphite, Silver and Carbon nanotube	Onanear <i>et al.</i> [132]	Theoretically and experimentally	Direct absorption solar collector	Water	D = 6–40 nm, L = 1000–5000 nm	<ul style="list-style-type: none"> Particle size enhancement decreases the efficiency. The volume fraction improves the efficiency of system up to 5 % and beyond that it may even diminish.
8.	Graphite, aluminum, copper and silver	Taylor <i>et al.</i> [133]	Theoretically and experimentally	Nanofluid-based concentrating solar thermal system	Therminol VP-1	20	<ul style="list-style-type: none"> The solar thermal energy efficiency of the system is increased by using nanofluid.
9.	Carbon-coated cobalt	Lenert and Wang [134]	Theoretically and experimentally	Nanofluid volumetric receivers	Therminol VP-1	28	<ul style="list-style-type: none"> With increase in nanofluid height and incident solar flux increases the receiver efficiency. Nanofluid volumetric receiver coupled to a power cycle is improving 35 % receiver efficiency.
10.	Ag, Al, Au and SiO ₂	Taylor <i>et al.</i> [135]	Theoretical	PV/T systems	Water or VP-1	2–40	<ul style="list-style-type: none"> The PV/T systems using low-cost nanofluid-based filters, enhanced the optical properties of base fluid.
11.	TiO ₂ , Ag, Cu, Al, Au and graphite	Taylor <i>et al.</i> [136]	Theoretically and experimentally	Direct absorption solar collector	Water	30	<ul style="list-style-type: none"> 95 % incident sunlight can be absorbed by using nanofluid layer thickness ≥ 10 and volume fractions of nanoparticle have been less than ten parts per million.

REFERENCES

- [1] Nagarajan P. K., Subramani J., Suyambazhahan S., Sathyamurthy R. Nanofluids for solar collector applications: A review. *Energy Procedia* 2014;61:2416–2434. <https://doi.org/10.1016/j.egypro.2014.12.017>
- [2] Javadi F. S., Saidur R., Kamalisarvestani M. Investigating performance improvement of solar collectors by using nanofluids. *Renewable and Sustainable. Energy Reviews* 2013;28:232–245. <https://doi.org/10.1016/j.rser.2013.06.053>
- [3] Kasaeian A., Eshghi A. T., Sameti M. A review on the applications of nanofluids in solar energy systems. *Renewable and Sustainable. Energy Reviews* 2015;43:584–598. <https://doi.org/10.1016/j.rser.2014.11.020>
- [4] Khanafer K., Vafai K. A review on the applications of nanofluids in solar energy field. *Renewable Energy* 2018;123:398–406. <https://doi.org/10.1016/j.renene.2018.01.097>
- [5] Dheep G. R., Sreekumar A. Influence of nanomaterials on properties of latent heat solar thermal energy storage materials – A review. *Energy Conversion and Management* 2014;83:133–148. <https://doi.org/10.1016/j.enconman.2014.03.058>
- [6] Al-Shamani A. N. et al. Nanofluids for improved efficiency in cooling solar collectors – A review. *Renewable and Sustainable Energy Reviews* 2014;38:348–367. <https://doi.org/10.1016/j.rser.2014.05.041>
- [7] He Q., Zeng S., Wang S. Experimental investigation on the efficiency of flat-plate solar collectors with nanofluids. *Applied Thermal Engineering* 2015;88:165–171. <https://doi.org/10.1016/j.applthermaleng.2014.09.053>
- [8] Said Z. et al. Performance enhancement of a Flat Plate Solar collector using Titanium dioxide nanofluid and Polyethylene Glycol dispersant. *Journal of Cleaner Production* 2015;92:343–353. <https://doi.org/10.1016/j.jclepro.2015.01.007>
- [9] Yousefi T., Veysi F., Shojaeizadeh E., Zinadini S. An experimental investigation on the effect of Al₂O₃–H₂O nanofluid on the efficiency of flat-plate solar collectors. *Renewable Energy* 2012;39(1):293–298. <https://doi.org/10.1016/j.renene.2011.08.056>
- [10] Kasaeian A., Daviran S., Azarian R. D., Rashidi A. Performance evaluation and nanofluid using capability study of a solar parabolic trough collector. *Energy Conversion and Management* 2015;89:368–375. <https://doi.org/10.1016/j.enconman.2014.09.056>
- [11] Lee S. H., Jang S. P. Efficiency of a volumetric receiver using aqueous suspensions of multi-walled carbon nanotubes for absorbing solar thermal energy. *International Journal of Heat and Mass Transfer* 2015;80:58–71. <https://doi.org/10.1016/j.ijheatmasstransfer.2014.08.091>
- [12] Rana P., Bhargava R., Bég O. A. Numerical solution for mixed convection boundary layer flow of a nanofluid along an inclined plate embedded in a porous medium. *Computers and Mathematics with Application* 2012;64(9):2816–2832. <https://doi.org/10.1016/j.camwa.2012.04.014>
- [13] Yu W., Choi S. U. S. The role of interfacial layers in the enhanced thermal conductivity of nanofluids: A renovated Maxwell model. *Journal of Nanoparticle Research* 2003;5:167–171. <https://doi.org/10.1023/A:1024438603801>
- [14] Choi S. U. S., Eastman J. A. Enhancing thermal conductivity of fluids with nanoparticles. Argonne National Lab., IL United States, 1995.
- [15] Wang L., Fan J. Nanofluids research: Key issues. *Nanoscale Research Letters* 2010;5(8):1241–1252. <https://doi.org/10.1007/s11671-010-9638-6>
- [16] Eastman J. A., Choi S. U. S., Li S., Yu W., Thompson L. J. Anomalous increased effective thermal conductivities of ethylene glycol-based nanofluids containing copper nanoparticles. *Applied Physics Letters* 2001;78(6):718–720. <https://doi.org/10.1063/1.1341218>
- [17] Hong T.-K., Yang H.-S., Choi C. J. Study of the enhanced thermal conductivity of Fe nanofluids. *Journal of Applied Physics* 2005;97(6):64311. <https://doi.org/10.1063/1.1861145>
- [18] Das S. K., Putra N., Thiesen P., Roetzel W. Temperature Dependence of Thermal Conductivity Enhancement for Nanofluids. *Journal of Heat Transfer* 2003;125(4):567. <https://doi.org/10.1115/1.1571080>
- [19] Patel H. E., Das S. K., Sundararajan T., Sreekumaran Nair A., George B., Pradeep T. Thermal conductivities of naked and monolayer protected metal nanoparticle based nanofluids: Manifestation of anomalous enhancement and chemical effects. *Applied Physics Letters* 2003;83(14):2931–2933. <https://doi.org/10.1063/1.1602578>
- [20] Kamyar A., Saidur R., Hasanuzzaman M. Application of Computational Fluid Dynamics (CFD) for nanofluids. *International Journal of Heat and Mass Transfer* 2012;55(15–16):4104–4115. <https://doi.org/10.1016/j.ijheatmasstransfer.2012.03.052>
- [21] Namburu P. K., Kulkarni D. P., Dandekar A., Das D. K. Experimental investigation of viscosity and specific heat of silicon dioxide nanofluids. *Micro & Nano Letters* 2007;2(3):67–71. <https://doi.org/10.1049/mnl:20070037>
- [22] Collins P. G., Avouris P. Nanotubes for electronics. *Scientific American* 2000;283(6):62–69. <https://doi.org/10.1038/scientificamerican1200-62>
- [23] Kumar H. G. P., Xavier M. A., Ashwath P. Ultrasonication and microwave processing of aluminum alloy-Graphene-Al₂O₃ nanocomposite. *Materials and Manufacturing Processes* 2018;33(1):13–18. <https://doi.org/10.1080/10426914.2016.1244852>

- [24] Yuan W., Zhang Y., Cheng L., Wu H., Zheng L., Zhao D. The applications of carbon nanotubes and graphene in advanced rechargeable lithium batteries. *Journal of Materials Chemistry A* 2016;4(23):8932–8951. <https://doi.org/10.1039/C6TA01546H>
- [25] Pop E., Varshney V., Roy A. K. Thermal properties of graphene: Fundamentals and applications. *MRS Bulletin* 2012;37(12):1273–1281. <https://doi.org/10.1557/mrs.2012.203>
- [26] Faizal M., Saidur R., Mekhilef S., Alim M. A. Energy, economic and environmental analysis of metal oxides nanofluid for flat-plate solar collector. *Energy Conversion and Management* 2013;76:162–168. <https://doi.org/10.1016/j.enconman.2013.07.038>
- [27] Turkyilmazoglu M. Anomalous heat transfer enhancement by slip due to nanofluids in circular concentric pipes. *International Journal of Heat and Mass Transfer* 2015;58:609–614. doi: <https://doi.org/10.1016/j.ijheatmasstransfer.2015.02.015>
- [28] Jamshed W., Aziz A. A comparative entropy based analysis of Cu and Fe₃O₄/methanol Powell-Eyring nanofluid in solar thermal collectors subjected to thermal radiation, variable thermal conductivity and impact of different nanoparticles shape. *Results in Physics* 2018;9:195–205. <https://doi.org/10.1016/j.rinp.2018.01.063>
- [29] Cárdenas Contreras E. M., Oliveira G. A., Bandarra Filho E. P. Experimental analysis of the thermohydraulic performance of graphene and silver nanofluids in automotive cooling systems. *International Journal of Heat and Mass Transfer* 2019;132:375–387. <https://doi.org/10.1016/j.ijheatmasstransfer.2018.12.014>
- [30] Elsheikh A. H., Sharshir S. W., Mostafa M. E., Essa F. A., Ahmed Ali M. K. Applications of nanofluids in solar energy: A review of recent advances. *Renewable and Sustainable Energy Reviews* 2017;82:3483–3502. <https://doi.org/10.1016/j.rser.2017.10.108>
- [31] Ganvir R. B., Walke P. V., Kriplani V. M. Heat transfer characteristics in nanofluid—A review. *Renewable and Sustainable Energy Reviews* 2015;75:451–460. <https://doi.org/10.1016/j.rser.2016.11.010>
- [32] Gulum M., Bilgin A. An experimental optimization research of methyl and ethyl esters production from safflower oil. *Environmental and Climate Technologies* 2018;22(1):132–148. <https://doi.org/10.2478/rtuct-2018-0009>
- [33] Bait O., Si-Ameur M. Enhanced heat and mass transfer in solar stills using nanofluids: A review. *Solar Energy* 2018;170:694–722. <https://doi.org/10.1016/j.solener.2018.06.020>
- [34] Babar H., Sajid M., Ali H. Viscosity of hybrid nanofluids: A critical review. *Thermal Science* 2019;23(3B):1713–1754. <https://doi.org/10.2298/tsci181128015b>
- [35] Sajid M. U., Ali H. M. Recent advances in application of nanofluids in heat transfer devices: A critical review. *Renewable and Sustainable Energy Reviews* 2019;103:556–592. <https://doi.org/10.1016/j.rser.2018.12.057>
- [36] Bazri S., Badruddin I. A., Naghavi M. S., Bahiraei M. A review of numerical studies on solar collectors integrated with latent heat storage systems employing fins or nanoparticles. *Renewable Energy* 2018;118:761–778. <https://doi.org/10.1016/j.renene.2017.11.030>
- [37] Verma S. K., Tiwari A. K. Progress of nanofluid application in solar collectors: A review. *Energy Conversion and Management* 2015;100:324–346. <https://doi.org/10.1016/j.enconman.2015.04.071>
- [38] Yang L., Du K. A comprehensive review on heat transfer characteristics of TiO₂ nanofluids. *International Journal of Heat and Mass Transfer* 2017;108(A):11–31 <https://doi.org/10.1016/j.ijheatmasstransfer.2016.11.086>
- [39] Saidur R., Meng T. C., Said Z., Hasanuzzaman M., Kamyar A. Evaluation of the effect of nanofluid-based absorbers on direct solar collector. *International Journal of Heat and Mass Transfer* 2012;55(21–22):5899–5907. <https://doi.org/10.1016/j.ijheatmasstransfer.2012.05.087>
- [40] Faizal M., Saidur R., Mekhilef S., Faizal M. Potential of Size Reduction of Flat-Plate Solar Collectors when Applying Al₂O₃ Nanofluid. *Advanced Material Research* 2014;832:149–153. <https://doi.org/10.4028/www.scientific.net/amr.832.149>
- [41] Lomascolo M., Colangelo G., Milanese M., Risi A. De. Review of heat transfer in nanofluids: Conductive, convective and radiative experimental results. *Renewable and Sustainable Energy Reviews* 2015;43:1182–1198 <https://doi.org/10.1016/j.rser.2014.11.086>
- [42] Vajjha R. S., Das D. K., Kulkarni D. P. Development of new correlations for convective heat transfer and friction factor in turbulent regime for nanofluids. *International Journal of Heat and Mass Transfer* 2010;53(21–22):4607–4618 <https://doi.org/10.1016/j.ijheatmasstransfer.2010.06.032>
- [43] Xie H., Wang J., Xi T., Liu Y., Ai F., Wu Q. Thermal conductivity enhancement of suspensions containing nanosized alumina particles. *Journal of Applied Physics* 2002;91(7):4568–4572. <https://doi.org/10.1063/1.1454184>
- [44] Gherasim I., Roy G., Nguyen C. T., Vo-Ngoc D. Experimental investigation of nanofluids in confined laminar radial flows. *International Journal of Thermal Science* 2009;48(8):1486–1493 <https://doi.org/10.1016/j.ijthermalsci.2009.01.008>
- [45] Peyghambarzadeh S. M., Hashemabadi S. H., Jamnani M. S., Hoseini S. M. Improving the cooling performance of automobile radiator with Al₂O₃/water nanofluid. *Applied Thermal Engineering* 2011;31(10):1833–1838. <https://doi.org/10.1016/j.applthermaleng.2011.02.029>
- [46] Putra N., Yanuar, Iskandar F. N. Application of nanofluids to a heat pipe liquid-block and the thermoelectric cooling of electronic equipment. *Experimental Thermal and Fluid Sciences* 2011;35(7):1274–1281. <https://doi.org/10.1016/j.expthermflusci.2011.04.015>

- [47] Bhogare R. A., Kothawale B. S. Performance investigation of Automobile Radiator operated with Nanofluids Based Coolant. *IOSR Journal of Mechanical and Civil Engineering* 2014;11(3):23–30. <https://doi.org/10.9790/1684-11352330>.
- [48] Mehtre D. N., Kore S. S. Experimental Analysis of Heat Transfer From Car Radiator Using Nanofluids. *International Journal of Medicinal Chemistry and Analysis* 2014;2(4):101–106.
- [49] Mohammed H. A., Gunnasegaran P., Shuaib N. H. Heat transfer in rectangular microchannels heat sink using nanofluids. *International Communications in Heat and Mass Transfer* 2010;37(10):1496–1503. <https://doi.org/10.1016/j.icheatmasstransfer.2010.08.020>
- [50] Shalchi-Tabrizi A., Seyf H. R. Analysis of entropy generation and convective heat transfer of Al₂O₃ nanofluid flow in a tangential micro heat sink. *International Journal of Heat and Mass Transfer* 2012;55(15–16):4366–4375. <https://doi.org/10.1016/j.jheatmasstransfer.2012.04.005>
- [51] Tiecher R. F. P., Parise J. A. R. A comparative parametric study on single-phase Al₂O₃-water nanofluid exchanging heat with a phase-changing fluid. *International Journal of Thermal Sciences* 2014;74:190–198. <https://doi.org/10.1016/j.jthermalsci.2013.06.014>
- [52] Naraki M., Peyghambarzadeh S. M., Hashemabadi S. H., Vermahmoudi Y. Parametric study of overall heat transfer coefficient of CuO/water nanofluids in a car radiator. *International Journal of Thermal Sciences* 2013;66:82–90. <https://doi.org/10.1016/j.jthermalsci.2012.11.013>
- [53] Khairul M. A., Saidur R., Rahman M. M., Alim M. A., Hossain A., Abdin Z. Heat transfer and thermodynamic analyses of a helically coiled heat exchanger using different types of nanofluids. *International Journal of Heat and Mass Transfer* 2013;67:398–403. <https://doi.org/10.1016/j.jheatmasstransfer.2013.08.030>
- [54] Wen D., Ding Y. Experimental investigation into convective heat transfer of nanofluids at the entrance region under laminar flow conditions. *International Journal of Heat and Mass Transfer* 2004;47(24):5181–5188. <https://doi.org/10.1016/j.jheatmasstransfer.2004.07.012>.
- [55] Namburu P. K., Das D. K., Tanguturi K. M., Vajjha R. S. Numerical study of turbulent flow and heat transfer characteristics of nanofluids considering variable properties. *International Journal of Thermal Sciences* 2009;48(2):290–302. <https://doi.org/10.1016/j.jthermalsci.2008.01.001>
- [56] Lee S., Choi S. U.-S., Li S., Eastman J. A. Measuring Thermal Conductivity of Fluids Containing Oxide Nanoparticles. *Journal of Heat Transfer* 1999;121(2):280. <https://doi.org/10.1115/1.2825978>
- [57] Seyf H. R., Feizbakhshi V. Computational analysis of nanofluid effects on convective heat transfer enhancement of micro-pin-fin heat sinks. *International Journal of Thermal Sciences* 2012;58:168–179. <https://doi.org/10.1016/j.jthermalsci.2012.02.018>.
- [58] Choi S. U., Eastman J., Phillpot S., Keblinski P. Mechanisms of heat flow in suspensions of nano-sized particles (nanofluids). *International Journal of Heat and Mass Transfer* 2002;45(4):855–863. [https://doi.org/10.1016/S0017-9310\(01\)00175-2](https://doi.org/10.1016/S0017-9310(01)00175-2)
- [59] Jmai R., Ben-Beya B., Lili T. Heat transfer and fluid flow of nanofluid-filled enclosure with two partially heated side walls and different nanoparticles. *Superlattices and Microstructures* 2013;53(1):130–154. <https://doi.org/10.1016/j.spmi.2012.10.003>
- [60] Xuan Y., Li Q. Investigation on Convective Heat Transfer and Flow Features of Nanofluids. *Journal of Heat and Mass Transfer* 2003;125(1):151. <https://doi.org/10.1115/1.1532008>
- [61] Putra N., Roetzel W., Das S. K. Natural convection of nano-fluids. *Journal of Heat and Mass Transfer und Stoffuebertragung* 2003;39(8–9):775–784. <https://doi.org/10.1007/s00231-002-0382-z>
- [62] Huminic G., Huminic A. Heat transfer characteristics in double tube helical heat exchangers using nanofluids. *International Journal of Heat and Mass Transfer* 2011;54(19–20):4280–4287. <https://doi.org/10.1016/j.jheatmasstransfer.2011.05.017>
- [63] Chandrasekar M., Suresh S., Chandra Bose A. Experimental studies on heat transfer and friction factor characteristics of Al₂O₃/water nanofluid in a circular pipe under laminar flow with wire coil inserts. *Experimental Thermal and Fluid Science* 2009;34(2):122–130. <https://doi.org/10.1016/j.expthermflusci.2009.10.001>
- [64] Suresh S., Venkataraj K. P., Selvakumar P. Comparative study on thermal performance of helical screw tape inserts in laminar flow using Al₂O₃/water and CuO/water nanofluids. *Superlattices and Microstructures* 2011;49(6):608–622. <https://doi.org/10.1016/j.spmi.2011.03.012>
- [65] Zamzaman A., Oskouie S. N., Doosthoseini A., Joneidi A., Pazouki M. Experimental investigation of forced convective heat transfer coefficient in nanofluids of Al₂O₃/EG and CuO/EG in a double pipe and plate heat exchangers under turbulent flow. *Experimental Thermal and Fluid Science* 2011;35(3):495–502. <https://doi.org/10.1016/j.expthermflusci.2010.11.013>
- [66] Keshavarz Moraveji M., Esmaeili E. Comparison between single-phase and two-phases CFD modeling of laminar forced convection flow of nanofluids in a circular tube under constant heat flux. *International Communications in Heat and Mass Transfer* 2012;39(8):1297–1302. <https://doi.org/10.1016/j.icheatmasstransfer.2012.07.012>
- [67] Anoop K. B., Sundararajan T., Das S. K. Effect of particle size on the convective heat transfer in nanofluid in the developing region. *International Journal of Heat and Mass Transfer* 2009;52(9–10):2189–2195. <https://doi.org/10.1016/j.jheatmasstransfer.2007.11.063>

- [68] Ahmed M. A., Shuaib N. H., Yusoff M. Z., Al-Falahi A. H. Numerical investigations of flow and heat transfer enhancement in a corrugated channel using nanofluid. *International Communications in Heat and Mass Transfer* 2011;38(10):1368–1375. <https://doi.org/10.1016/j.icheatmasstransfer.2011.08.013>
- [69] Garoosi F., Bagheri G., Talebi F. Numerical simulation of natural convection of nanofluids in a square cavity with several pairs of heaters and coolers (HACs) inside. *International Journal of Heat and Mass Transfer* 2013;67:362–376. <https://doi.org/10.1016/j.ijheatmasstransfer.2013.08.034>.
- [70] Fotukian S. M., Nasr Esfahany M. Experimental study of turbulent convective heat transfer and pressure drop of dilute CuO/water nanofluid inside a circular tube. *International Communications of Heat and Mass Transfer* 2010;37(2):214–219. <https://doi.org/10.1016/j.icheatmasstransfer.2009.10.003>
- [71] Daviran S., Kasaeian A., Tahmooressi H., Rashidi A., Wen D., Mahian O. Evaluation of clustering role versus Brownian motion effect on the heat conduction in nanofluids: A novel approach. *International Journal of Heat and Mass Transfer* 2017;108(A):822–829. <https://doi.org/10.1016/j.ijheatmasstransfer.2016.12.071>
- [72] Fan L., Khodadadi J. M. Thermal conductivity enhancement of phase change materials for thermal energy storage: a review. *Renewable and Sustainable Energy Reviews* 2011;15(1):24–46. <https://doi.org/10.1016/j.rser.2010.08.007>
- [73] Dehury P., Singh J., Banerjee T. Thermophysical and Forced Convection Studies on (Alumina + Menthol)-Based Deep Eutectic Solvents for Their Use as a Heat Transfer Fluid. *ACS Omega* 2018;3(12):18016–18027. <https://doi.org/10.1021/acsomega.8b02661>
- [74] Hordy N., Rabilloud D., Meunier J. L., Coulombe S. High temperature and long-term stability of carbon nanotube nanofluids for direct absorption solar thermal collectors. *Solar Energy* 2014;105:82–90. <https://doi.org/10.1016/j.solener.2014.03.013>
- [75] Kalbande V. P., Walke P. V. Oil-and Aluminum-Based Thermal Storage System Using Flat Plate Solar Collector. In Kolhe M., Labhasetwar P., Suryawanshi H. (eds) *Smart Technologies for Energy, Environment and Sustainable Development. Lecture Notes on Multidisciplinary Industrial Engineering*. Springer, 2019:553–562. https://doi.org/10.1007/978-981-13-6148-7_53
- [76] Arshad W., Ali H. M. Graphene nanoplatelets nanofluids thermal and hydrodynamic performance on integral fin heat sink. *International Journal of Heat and Mass Transfer* 2017;107:995–1001. <https://doi.org/10.1016/j.ijheatmasstransfer.2016.10.127>
- [77] Gan Y., Qiao L. Optical properties and radiation-enhanced evaporation of nanofluid fuels containing carbon-based nanostructures. *Energy and Fuels* 2012;26(7):4224–4230. <https://doi.org/10.1021/ef300493m>
- [78] Mussard M., Nydal O. J. Charging of a heat storage coupled with a low-cost small-scale solar parabolic trough for cooking purposes. *Solar Energy* 2013;95:144–154. <https://doi.org/10.1016/j.solener.2013.06.013>
- [79] Mussard M., Nydal O. J. Comparison of oil and aluminum-based heat storage charged with a small-scale solar parabolic trough. *Applied Thermal Engineering* 2013;58(1–2):146–154. <https://doi.org/10.1016/j.applthermaleng.2013.03.059>
- [80] Mussard M., Gueno A., Nydal O. J. Experimental study of solar cooking using heat storage in comparison with direct heating. *Solar Energy* 2013;98(C):375–383. <https://doi.org/10.1016/j.solener.2013.09.015>
- [81] Rucevskis S., Akishin P., Korjajins A. Performance Evaluation of an Active PCM Thermal Energy Storage System for Space Cooling in Residential Buildings. *Environmental and Climate Technologies* 2019;23(2):74–89. <https://doi.org/10.2478/rtuct-2019-0056>
- [82] Sirmelis R., Vanaga R., Freimanis R., Blumberga A. Solar Facade Module for Nearly Zero Energy Building. Optimization Strategies *Environmental and Climate Technologies* 2019;23(3):170–181. <https://doi.org/10.2478/rtuct-2019-0087>
- [83] Sharma A., Tyagi V. V., Chen C. R., Buddhi D. Review on thermal energy storage with phase change materials and applications. *Renewable and Sustainable Energy Reviews* 2009;13(2):318–345. <https://doi.org/10.1016/j.rser.2007.10.005>
- [84] Ebrahimnia-Bajestan E., Charjouei Moghadam M., Niazmand H., Daungthongsuk W., Wongwises S. Experimental and numerical investigation of nanofluids heat transfer characteristics for application in solar heat exchangers. *International Journal of Heat and Mass Transfer*. 2016;92:1041–1052. <https://doi.org/10.1016/j.ijheatmasstransfer.2015.08.107>
- [85] Wang W., Wu Z., Li B., Sundén B. A review on molten-salt-based and ionic-liquid-based nanofluids for medium-to-high temperature heat transfer. *Journal of Thermal Analysis and Calorimetry* 2019;136(3):1037–1051. <https://doi.org/10.1007/s10973-018-7765-y>
- [86] Mussard M. A solar concentrator with heat storage and self-circulating liquid. Norwegian University of Science and Technology, 2013.
- [87] Kalbande V. P., Walke P. V., Shelke R. Aluminum-based thermal storage system with solar collector using nanofluid. *Energy Storage* 2019;1(6):1–7. <https://doi.org/10.1002/est2.99>.
- [88] Gálvez B. J., et al. *Solar Energy Conversion and Photoenergy System-Volume II*. EOLSS, 2009.
- [89] Notton G., Motte F., Cristofari C., Canaletti J. L. Performances and numerical optimization of a novel thermal solar collector for residential building. *Renewable and Sustainable Energy Reviews* 2014;33:60–73. <https://doi.org/10.1016/j.rser.2014.01.061>

- [90] Albatayneh A., Alterman D., Page A., Moghtaderi B. The significance of temperature based approach over the energy based approaches in the buildings thermal assessment. *Environmental and Climate Technologies* 2017;19(1):39–50. <https://doi.org/10.1515/ruect-2017-0004>
- [91] Tagliafico L. A., Scarpa F., De Rosa M. Dynamic thermal models and CFD analysis for flat-plate thermal solar collectors – A review. *Renewable and Sustainable Energy Reviews* 2014;30:526–537. <https://doi.org/10.1016/j.rser.2013.10.023>
- [92] Al-Waeli A. H. A., Chaichan M. T., Sopian K., Kazem H. A., Mahood H. B., Khadom A. A. Modeling and experimental validation of a PVT system using nanofluid coolant and nano-PCM. *Solar Energy* 2018;177:178–191. <https://doi.org/10.1016/j.solener.2018.11.016>
- [93] Lari M. O., Sahin A. Z. Effect of retrofitting a silver/water nanofluid-based photovoltaic/thermal (PV/T) system with a PCM-thermal battery for residential applications. *Renewable Energy* 2018;122:98–107. <https://doi.org/10.1016/j.renene.2018.01.034>
- [94] Kabeel A. E., El-Said E. M. S. Applicability of flashing desalination technique for small scale needs using a novel integrated system coupled with nanofluid-based solar collector. *Desalination* 2014;333(1):10–22. <https://doi.org/10.1016/j.desal.2013.11.021>
- [95] Said Z., Saidur R., Rahim N. A., Alim M. A. Analyses of exergy efficiency and pumping power for a conventional flat plate solar collector using SWCNTs based nanofluid. *Energy and Buildings* 2014;78:1–9. <https://doi.org/10.1016/j.enbuild.2014.03.061>
- [96] Schuchardt G. K. Integration of decentralized thermal storages within district heating (DH) networks. *Environmental and Climate Technologies* 2016;18(1):5–16. <https://doi.org/10.1515/ruect-2016-0009>
- [97] Nasrin R., Alim M. A. Semi-empirical relation for forced convective analysis through a solar collector. *Solar Energy* 2014;105:455–467. <https://doi.org/10.1016/j.solener.2014.03.035>
- [98] Al-Kayiem H. H., Lin S. C. Performance evaluation of a solar water heater integrated with a PCM nanocomposite TES at various inclinations. *Solar Energy* 2014;109(1):82–92. <https://doi.org/10.1016/j.solener.2014.08.021>
- [99] Sekhar Y. R., Sharma K. V., Karupparaj R. T., Chiranjeevi C. Heat transfer enhancement with Al₂O₃ nanofluids and twisted tapes in a pipe for solar thermal applications. *Procedia Engineering* 2013;64:1474–1484. <https://doi.org/10.1016/j.proeng.2013.09.229>
- [100] Prakasam M. J. S., Thottipalayam Vellingiri A. T., Nataraj S. An experimental study of the mass flow rates effect on flat-plate solar water heater performance using Al₂O₃/water nanofluid. *Thermal Science* 2017;21:379–388. <https://doi.org/10.2298/TSCI17S2379P>
- [101] Dasai A. V., Elumalai N. Performance Enhancement Studies in a Thermosyphon Flat Plate Solar Water Heater with CuO Nanofluid. *Thermal science* 2017;21:6B:2757–2768.
- [102] Colangelo G., Milanese M., and De Risi A. Numerical simulation of thermal efficiency of an innovative Al₂O₃nanofluid solar thermal collector influence of nanoparticles concentration. *Thermal Science* 2017;21(6B):2769–2779. <https://doi.org/10.2298/TSCI151207168C>
- [103] Colangelo G., Favale E., De Risi A., Laforgia D. A new solution for reduced sedimentation flat panel solar thermal collector using nanofluids. *Applied Energy* 2013;111:80–93. <https://doi.org/10.1016/j.apenergy.2013.04.069>
- [104] Nasrin R., Parvin S., Alim M. A. Effect of Prandtl number on free convection in a solar collector filled with nanofluid. *Procedia Engineering* 2013;56:54–62. <https://doi.org/10.1016/j.proeng.2013.03.088>
- [105] Hatami M., Khazayinejad M., Zhou J., Jing D. Three-dimensional and two-phase nanofluid flow and heat transfer analysis over a stretching infinite solar plate. *Thermal Science* 2018;22(2):871–884. <https://doi.org/10.2298/TSCI160614266H>
- [106] Karami M., Akhavan Bahabadi M. A., Delfani S., Ghoozloo A. A new application of carbon nanotubes nanofluid as working fluid of low-temperature direct absorption solar collector. *Solar Energy Materials and Solar Cells* 2014;121:114–118. <https://doi.org/10.1016/j.solmat.2013.11.004>
- [107] Gupta H. K., Das Agrawal G., Mathur J. Investigations for effect of Al₂O₃-H₂O nanofluid flow rate on the efficiency of direct absorption solar collector. *Case Studies in Thermal Engineering* 2015;5:70–78. <https://doi.org/10.1016/j.csite.2015.01.002>
- [108] Liu J., Ye Z., Zhang L., Fang X., Zhang Z. A combined numerical and experimental study on graphene/ionic liquid nanofluid based direct absorption solar collector. *Solar Energy Materials and Solar Cells* 2015;136:177–186. <https://doi.org/10.1016/j.solmat.2015.01.013>
- [109] Ali H. M., Arshad W. Effect of channel angle of pin-fin heat sink on heat transfer performance using water based graphene nanoplatelets nanofluids. *International Journal of Heat and Mass Transfer* 2017;106:465–472. <https://doi.org/10.1016/j.ijheatmasstransfer.2016.08.061>
- [110] Luo Z., Wang C., Wei W., Xiao G., Ni M. Performance improvement of a nanofluid solar collector based on direct absorption collection (DAC) concepts. *International Journal of Heat and Mass Transfer* 2014;75:262–271. <https://doi.org/10.1016/j.ijheatmasstransfer.2014.03.072>
- [111] Zhang L., Liu J., He G., Ye Z., Fang X., Zhang Z. Radiative properties of ionic liquid-based nanofluids for medium-to-high-temperature direct absorption solar collectors. *Solar Energy Materials and Solar Cells* 2014;130:521–528. <https://doi.org/10.1016/j.solmat.2014.07.040>

- [112] He Q., Wang S., Zeng S., Zheng Z. Experimental investigation on photothermal properties of nanofluids for direct absorption solar thermal energy systems. *Energy Conversion and Management* 2013;73:150–157. <https://doi.org/10.1016/j.enconman.2013.04.019>
- [113] Sokhansefat T., Kasaeian A. B., Kowsary F. Heat transfer enhancement in parabolic trough collector tube using Al_2O_3 /synthetic oil nanofluid. *Renewable and Sustainable Energy Reviews* 2014;33:636–644. <https://doi.org/10.1016/j.rser.2014.02.028>
- [114] Ghasemi S. E., Ranjbar A. A. Effect of using nanofluids on efficiency of parabolic trough collectors in solar thermal electric power plants. *International Journal of Hydrogen Energy* 2017;42(34):21626–21634. <https://doi.org/10.1016/j.ijhydene.2017.07.087>
- [115] Khullar V., Tyagi H., Phelan P. E., Otanicar T. P., Singh H., Taylor R. A. Solar energy harvesting using nanofluids-based concentrating solar collector. *Journal of Nanotechnology in Engineering and Medicine* 2012;3(3):31003. <https://doi.org/10.1115/1.4007387>
- [116] Lu L., Liu Z. H., Xiao H. S. Thermal performance of an open thermosyphon using nanofluids for high-temperature evacuated tubular solar collectors. Part 1: Indoor experiment. *Solar Energy* 2011;85(2):379–387. <https://doi.org/10.1016/j.solener.2010.11.008>
- [117] Goudarzi K., Shojaeizadeh E., Nejati F. An experimental investigation on the simultaneous effect of $\text{CuO-H}_2\text{O}$ nanofluid and receiver helical pipe on the thermal efficiency of a cylindrical solar collector. *Applied Thermal Engineering* 2014;73(1):1236–1243. <https://doi.org/10.1016/j.applthermaleng.2014.07.067>
- [118] Selvakumar P., Somasundaram P., Thangavel P. Performance study on evacuated tube solar collector using therminol D-12 as heat transfer fluid coupled with parabolic trough. *Energy Conversion and Management* 2014;85:505–510. <https://doi.org/10.1016/j.enconman.2014.05.069>
- [119] Yousefi T., Shojaeizadeh E., Veyssi F., Zinadini S. An experimental investigation on the effect of pH variation of MWCNT-H₂O nanofluid on the efficiency of a flat-plate solar collector. *Solar Energy* 2012;86(2):771–779. <https://doi.org/10.1016/j.solener.2011.12.003>
- [120] Yousefi T., Veisy F., Shojaeizadeh E., Zinadini S. An experimental investigation on the effect of MWCNT-H₂O nanofluid on the efficiency of flat-plate solar collectors. *Experimental Thermal and Fluid Science* 2012;39:207–212. <https://doi.org/10.1016/j.exptthermflusci.2012.01.025>
- [121] Faizal M., Saidur R., Mekhilef S. Potential of size reduction of flat-plate solar collectors when applying MWCNT nanofluid. *ICEE 2013, IOP Conference Series: Earth and Environmental Science* 2013;16(1). <https://doi.org/10.1088/1755-1315/16/1/012004>
- [122] Nasrin R., Alim M. A., Chamkha A. J. Effects of physical parameters on natural convection in a solar collector filled with nanofluid. *Heat Transfer—Asian Research* 2013;42(1):73–88. <https://doi.org/10.1002/htj.21026>
- [123] Tiwari A. K., Ghosh P., Sarkar J. Solar water heating using nanofluids – a comprehensive overview and environmental impact analysis. *International Journal of Emerging Technology and Advanced Engineering* 2013;3(9001):221–224.
- [124] Kasaeian M. S. A. B., Sokhansefat T., Abbaspour M. J. Numerical Study of Heat Transfer Enhancement by using Al_2O_3 /Synthetic Oil Nanofluid in a Parabolic Trough Collector Tube. *World Academy of Science, Engineering and Technology* 2014;69:1154–1159.
- [125] Tyagi H., Phelan P., Prasher R. Predicted Efficiency of a Low-Temperature Nanofluid-Based Direct Absorption Solar Collector. *Journal of Solar Energy Engineering* 2009;131(4):041004. <https://doi.org/10.1115/1.3197562>
- [126] Elmir M., Mehdaoui R., Mojtabi A. Numerical simulation of cooling a solar cell by forced convection in the presence of a nanofluid. *Energy Procedia* 2012;18:594–603. <https://doi.org/10.1016/j.egypro.2012.05.072>
- [127] Liu Z. H., Hu R. L., Lu L., Zhao F., Xiao H. S. Thermal performance of an open thermosyphon using nanofluid for evacuated tubular high temperature air solar collector. *Energy Conversion and Management* 2013;73:135–143. <https://doi.org/10.1016/j.enconman.2013.04.010>
- [128] De Risi A., Milanese M., Laforgia D. Modelling and optimization of transparent parabolic trough collector based on gas-phase nanofluids. *Renewable Energy* 2013;58:134–139. <https://doi.org/10.1016/j.renene.2013.03.014>
- [129] Cui Y., Zhu Q. Study of photovoltaic/thermal systems with MgO -water nanofluids flowing over silicon solar cells. *Asia-Pacific Power and Energy Engineering Conference*, 2012.
- [130] Li Y., Xie H. Q., Yu W., Li J. Investigation on Heat Transfer Performances of Nanofluids in Solar Collector. *Mater. Sci. Forum* 2011;694:33–36. <https://doi.org/10.4028/www.scientific.net/msf.694.33>
- [131] Chougule S. S., Pise A. T., Madane P. A. Performance of nanofluid-charged solar water heater by solar tracking system. *IEEE-international conference on advances in engineering, science and management ICAESM* 2012, 2012.
- [132] Otanicar T. P., Phelan P. E., Prasher R. S., Rosengarten G., Taylor R. A. Nanofluid-based direct absorption solar collector. *Journal of Renewable and Sustainable Energy* 2010;2(3):033102. <https://doi.org/10.1063/1.3429737>
- [133] Taylor R. A. et al. Applicability of nanofluids in high flux solar collectors. *Journal of Renewable and Sustainable Energy* 3(2):023104. <https://doi.org/10.1063/1.3571565>
- [134] Lenert A., Wang E. N. Optimization of nanofluid volumetric receivers for solar thermal energy conversion. *Solar Energy* 2012;86(1):253–265. <https://doi.org/10.1016/j.solener.2011.09.029>
- [135] Taylor R. A., Otanicar T., Rosengarten G. Nanofluid-based optical filter optimization for PV/T systems. *Light: Science and Applications* 2012;1(e34):1–7. <https://doi.org/10.1038/lsa.2012.34>

- [136] Taylor R. A., Phelan P. E., Otonicar T. P., Adrian R., Prasher R. Nanofluid optical property characterization: towards efficient direct absorption solar collectors. *Nanoscale Research Letters* 2011;6(1):1–11. <https://doi.org/10.1186/1556-276X-6-225>

Mr. Vednath P. Kalbande is currently pursuing his doctoral degree from RTMNU Nagpur. He was earned master degree from VNIT, Nagpur in 2011 with a specialization in Heat Power Engineering. He is also currently working as an Assistant Professor in Mechanical Engineering Department of G H Raisoni College of Engineering, Nagpur. Mr. Vednath has eight years of teaching experience.

He won the IVCA Top Innovator award from CII/DST/AICTE in i3 Innovation National Fair 2015 for his project. He guided 50 plus undergraduate students for the projects. Mr. Vednath is strongly involved in research based on solar, thermal and nanofluid. He attended and presented his research work at many international and national conferences. He also published two papers in a reputed journal such as Energy Storage of Wiley publications.

Email: vednathkalbande@gmail.com v.kalbande@raisoni.net

ORCID iD: <https://orcid.org/0000-0002-7862-0563>

Dr. Pramod V. Walke obtained Ph.D. degree in Mechanical Engineering from RTM, Nagpur University; Nagpur in 2011. He is presently working as a Professor in Mechanical Engineering at G H Raisoni College of Engineering, Nagpur. He has teaching and administrative experience of over 25 years and has Dean IQAC. He has been teaching several subjects in thermal engineering and has contributed a number of research papers to technical journals and conferences and has received the grant of Rs. 32 Lacs from various Government agencies for research projects. His research interests include Internal Combustion Engine, solar Energy, wind energy etc. He is a member of ISTE, SESI and Combustion Institute.

ORCID iD: <https://orcid.org/0000-0002-5418-279X>

Dr. V. M. Kriplani received the Ph.D. degree (Heat transfer) from R.T.M. Nagpur University, Nagpur (India) in 1997 and M. Tech (Thermal Engineering) from Indian Institute of Technology, Madras (India).

He worked as Lecturer, Assistant professor, Professor; Principal in Engineering Colleges. He has teaching and administrative experience of 52 years. He has contributed a number of research papers in International Journals and international conferences. Previous publications in journals such as Renewable and Sustainable Energy Reviews (Elsevier), Biofuels (Taylor & Francis). His research interests in I. C. Engines, heat transfer, nanofluids, refrigeration and air-conditioning, solar energy, biodiesel. He is Fellow of Institution of Engineering (India), Life member, Solar Energy Society of India, Life Member, Indian Society of Heating, Refrigeration and Air-Conditioning Engineer (ISHRAE).

ORCID iD: <https://orcid.org/0000-0001-7888-9290>