Green Energy and Technology

M. Masud K. Khan
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Application of Thermo-fluid Processes in Energy Systems

Key Issues and Recent Developments for a Sustainable Future

Springer

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ISSN 1865-3529 ISSN 1865-3537 (electronic)
Green Energy and Technology
ISBN 978-981-10-0695-1 ISBN 978-981-10-0697-5 (eBook)
https://doi.org/10.1007/978-981-10-0697-5

Library of Congress Control Number: 2017947862

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Printed on acid-free paper

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The registered company is Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Preface

The demand for clean energy technologies is increasing because of its environmental benefits, future energy security and diversity in securing energy sources. Research on current and future application of thermo-fluid processes associated with clean energy generation, distribution and conservation is viewed fundamental for seeking solutions for clean energy and a sustainable future.

This edited book volume introduces research works and their findings on how energy efficient technologies and thermo-fluid processes are analysed and applied in engineering practices. It presents a number chapters focusing on cutting edge research work on key issues and recent developments of the thermo-fluid processes, including but not limited to, energy technologies in process industries, application of thermo-fluid processes in mining industries, application of electrostatic precipitator in thermal power plant, biofuel, energy efficiency in building systems.

These chapters will be a valuable resource to researchers, practising engineers, technologist and students and will help the reader to develop intuitive understanding of the relevant concept and solution to the global issues to achieve sustainability in medium- and large-scale industries.

The chapters of this book have been carefully selected, and they include both the relevant technical and social issues that have a significant impact on the society and the stakeholders. This edited book comprises two parts. Part I contains five chapters focusing on energy technologies in process industries, and Part II contains seven chapters emphasizing on the application of thermo-fluid processes in energy systems and the key issues and recent developments for a sustainable future. A brief summary of each part is given below.

Part I Energy Technologies

Chapter "Utilization of Nanofluid in Various Clean Energy and Energy Efficiency Applications" focuses on energy efficiency and utilization of alternative clean energy technologies by replacing fossil fuel as primary source of energy. It also reviews the uses of nano-fluid in various clean energy and energy efficiency applications such as solar energy, solar thermal collectors and solar water heaters for utilization of nano-fluid for improving solar to thermal energy conversion.

Chapter "Gaseous and Particle Emissions from a Compression Ignition Engine Fueled with Biodiesel-Diesel Blends" investigates the sustainability of rice bran biodiesel from environmental point of view. In this study, 5 and 20% biodiesel was tested in a naturally aspirated four stroke multi-cylinder diesel engine at different load and speed conditions. It was found that all biodiesel-blended fuel reduces the brake power (BP) and increases brake-specific fuel consumption (BSFC) slightly than diesel fuel. Engine emission results indicated that blended fuel reduces the average particulate matter (PM), carbon monoxide (CO) and hydrocarbons (HC) except nitric oxides (NO) emissions than diesel fuel. Finally, the chapter concludes that up to 20% rice bran biodiesel could replace diesel fuel to help in controlling the air pollution to a great extent without sacrificing engine power significantly.

Chapter "Correlation Between Physicochemical Properties and Quality of Biodiesel" introduces biodiesel feedstocks, production process, chemical compositions, standards, physicochemical properties and in-use performance to investigate the relationships between biodiesel properties and chemical composition using a principal component analysis (PCA). The PCA analysis is presented graphically and described in this chapter. Although individual biodiesel properties have a complex relationship with the parameters of chemical compositions, the PCA analysis determines the dominant relationships which were the average number of double bonds and polyunsaturated fatty fractions. This chapter will help the reader to better understanding of the physicochemical properties of biodiesel.

Chapter "A Review of Microalgal Biofuels, Challenges and Future Directions" introduces biofuels from micro-algae that have the potential to provide a sustainable and carbon-neutral energy source, complementing the shortfall of fossil fuels and enhancing the mitigation of global warming. Coupling micro-algae cultivation with wastewater and CO_2 from power plants is considered a promising route for the production of bioenergy and bio-based by-products. This chapter presents a review of current status, challenges and future of biofuel from algae as a renewable source.

Chapter "Performance Assessment of an Electrostatic Precipitator of a Coal Fired Power Plant—A Case Study for Collecting Smaller Particles" presents the collection efficiency of particles affected by different flow distribution and recommends the possible modification in physical model to increase the collection capacity of smaller particles in the existing electrostatic precipitators (ESPs) used in power plants.

Part II: Thermo-fluid Process Applications

Chapter "Experimental Investigation and Molecular-Based Modeling of Crude Oil Density at Pressures to 270 MPa and Temperatures to 524 K" investigates new experimental density data for crude oil sample obtained from the Gulf of Mexico region, and these density data were measured at pressures to 270 MPa and temperatures to 524 K. These conditions simulate those encountered from ultra-deep formations to platforms. These density data points are then used to validate both empirical-based and molecular-based equation of state models. Results show that the molecular-based perturbed chain statistical associating fluid theory (PC-SAFT) models, without the use of any fitting parameters, produced crude oil density predictions within 1% of the experimental data. These results represent an improvement over high-temperature, high-pressure density predictions from volume-translated cubic equations of state.

Chapter "Heat Transfer Enhancement in a Baffled Attic-Shaped Space" numerically investigates the natural convection heat loss in an attic-shaped enclosure introducing a single baffle under the top tip, which is a cost-effective approach. The chapter examines a wide range of governing parameters such as Rayleigh number, aspect ratio, baffle length. It is observed that the heat transfer due to natural convection in the enclosure reduces when the baffle length is increased. The chapter also discusses the effects of other parameters on heat transfer and flow field in this study.

Chapter "Enhanced Thermo-fluid Dynamic Modelling Methodologies for Convective Boiling" presents the logical development of novel thermal and dynamical enhancement approaches that overcome existing modelling limitations, and creates a precise and realistic foundation for advanced boiling design methodology with applicability over the entire boiling flow regime. The effectiveness and advantages of these model enhancements are highlighted through three special cases of boiling processes, namely convective boiling typically occurring in a straight pipe, convective boiling in a curved pipe influenced by secondary flow and pool-to-convective transitional boiling. Finally, the potential for energy saving by these techniques is identified that contributes to cleaner thermal energy generation.

Chapter "A Method of Three-Dimensional Thermo-fluid Simulation of the Receiver of a Standard Parabolic Trough Collector" develops a three-dimensional (3D) computational conjugate heat transfer (CCHT) model of a bare receiver of Luz Solar 2 (LS2) PTC. The chapter also describes the method of this CCHT modelling and its verification. The CCHT model was developed applying finite volume (FV) technique of the state-of-the-art computational fluid dynamics (CFD). The solar irradiance profile (IP) around the receiver surface of the collector was calculated using the Monte Carlo ray tracing (MCRT) technique. Moreover, the MCRT calculated-IP functions specific to the Luz Solar 2 (LS2) collector are given for facilitating further CCHT modelling of the collector system.

Chapter "Enhancement of Confined Air Jet Impingement Heat Transfer Using Perforated Pin-Fin Heat Sinks" examines the effects of fin perforations on the thermal performance of pin fin heat sinks. Results show that thermal resistance decreases and fin efficiency increases with the increase of Reynolds number due to perforation and also reduces cooling power consumption rate.

Chapter "Multiphase Flow in Porous Media: Cake Formation During Extreme Drilling Processes" emphasizes on multiphase flow in porous media to closely mimic the actual drilling fluid composed of fine particles and viscous fluid rather than focused only on single-phase flow phenomena in porous media and also simulates the fluid flow and cake formation in extreme drilling processes.

Chapter "Optimising Pyrolysis Conditions for Thermal Conversion of Beauty Leaf Tree (*Calophyllum inophyllum* L.) Press Cake" focuses on biodiesel production from beauty leaf tree (BLT) as it can thrive well in degraded soils and produces up to 3600 l of non-edible oil that can be readily converted into biodiesel. The current study tested thermal conversion of BLT press cake using a batch reactor. This study showed that up to 93% of the energy contained in the BLT press cake be recovered as biochar, bio-oil, bioliquor and syngas. The results also show that the additional products (biochar, bio-oil) from BLT press cake can make a significant contribution to the economic viability of BLT biodiesel production. It is suggested that the use of a portable and continuous feeding auger reactor could be conveniently used to convert BLT whole fruits, press cake or husks into biofuels.

We hope the selected chapters will help in enhancing your understanding and practicing of current and future application of thermo-fluid processes associated with clean energy generation, distribution and conservation and sustainability and the environment.

Rockhampton, Australia M. Masud K. Khan
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Scope

The demand for energy technologies is increasing because of its environmental benefits, future energy security and diversity in securing energy sources. The objectives of this edited book volume are to provide the industries and the academia with an update on current and future application of thermo-fluid processes associated with clean energy generation, distribution and conservation. The book will provide resources and case studies in the field of energy technology, clean energy, energy efficiency, sustainability and the environment to academics, researchers, practising engineers, technologist and students. It will be a valuable resource to undergraduate, honours and postgraduate research students in the field of thermo-fluid engineering.

The chapters of the book will present cutting edge research work on key issues and recent developments of the thermo-fluid processes, including but not limited to, energy technologies in process industries, application of thermo-fluid processes in mining industries, application of electrostatic precipitator in thermal power plant, biofuel, energy efficiency in building systems. These chapters will help to develop and intuitive understanding of the relevant concept and solution to the global issues to achieve sustainability in medium- and large-scale industries.

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Part I
Energy Technologies

Utilization of Nanofluid in Various Clean Energy and Energy Efficiency Applications

Sayedus Salehin, M. Monjurul Ehsan, Syed Rafat Faysal and A.K.M. Sadrul Islam

Abstract Policy makers around the globe, both at the national and international level, have been emphasizing on energy efficiency and utilization of alternative clean energy technologies by replacing fossil fuel as a primary source of energy. This interest was initiated when the adverse effects of fossil fuel on the environment such as greenhouse gas emission and global warming were unfolded. Multidisciplinary researches are being carried out in the research laboratories to provide effective clean energy solutions. Nanofluid, a colloidal mixture of nanoparticles in the base fluid, e.g., water, ethylene glycol, oil, offers efficiency improvements in many clean energy applications due to the improvement in its thermophysical property. In this chapter, use of nanofluid in various clean energy and energy efficiency applications is reviewed. Solar energy, the dominant clean energy source, is a potential field of application where nanofluid can be employed. Solar thermal collectors and solar water heaters are the ideal candidates for utilization of nanofluid for improving solar to thermal energy conversion. Thermal storage system employs phase change material (PCM) for storing thermal energy, and nanofluid may be added to the PCM for enhanced performance. Nanofluid can be used in carefully designed heat exchangers for extracting energy from geothermal resources. This mixture can also be used in waste heat collector to improve efficiency for its thermophysical property causing a heat transfer enhancement. Adding nanoparticles to the refrigerants improves the heat transfer characteristics of refrigerants and improves the performance of the refrigeration system from an energy efficiency perspective. However, there are challenges associated with nanofluid which are needed to overcome for optimal performance of the working fluid.

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M.M.K. Khan et al. (eds.), *Application of Thermo-fluid Processes in Energy Systems*,
Green Energy and Technology, https://doi.org/10.1007/978-981-10-0697-5_1

1 Introduction

To meet the ever-increasing energy demand, petroleum-based fossil fuels have been extensively used in all sectors irrespective of geographic locations. However, this energy source is associated with adverse environmental effects such as greenhouse gas emission and global warming. In this aspect, the regulatory authorities across the globe, both at government and non-governmental level, are emphasizing on reducing the use of fossil fuel and replace it with clean and renewable energy resources and utilize energy efficiency to reduce energy consumption. The research laboratories in academia and the industry alike are working relentlessly on finding effective clean energy solutions.

Nanofluid is a comparatively new kind of synthesized fluid which is a colloidal mixture of nanoparticles, usually metals or metal oxides, in a base fluid, with enhanced thermophysical property as compared to the base fluid. This type of fluid can be used in many clean energy and energy efficiency application because of its enhanced thermal, optical, and rheological properties. In this chapter, the utilization of nanofluid in various clean energy and energy efficiency applications is reviewed. Focus has been given to the application of nanofluid in solar thermal energy, thermal energy storage, heat exchangers, refrigeration and air-conditioning, electronics cooling, and transportation.

2 Nanofluid: Definition

In last few decades, numerous researches have been carried out in a search of more suitable heat transfer fluid in thermal engineering science due to its great demand in various industrial and engineering applications such as heat exchangers, electronic devices, refrigerators, solar thermal storage, nuclear system, biomedical applications, engine cooling, and transmission oil. [85, 104]. Heat transfer properties of the working fluid can be substantially augmented by the implementation of newly emerged promising method called nanotechnology. In sustainable energy, it is one of the effective, inexpensive, and innovative ways of intensifying the heat transfer characteristics of working fluid by the stable and homogeneous dispersion of nanosized solid particles in traditional base fluid such as water, oil, ethylene glycol so called nanofluid. By the addition of nanoparticles of size below 100 nm in base fluid, the overall thermal and hydrodynamic behavior of working fluid can be significantly improved due to its improvement in thermophysical properties such as specific gravity, density, viscosity, convective heat transfer coefficient, electrical conductivity, Seebeck coefficient, and optical scattering coefficients [19, 106, 108]. The solid nanoparticles have higher thermal conductivity compared to base fluid which potentially assists in enhancing heat transfer characteristics. The fluid flow characteristics of nanofluid flowing through different channels are altered due to recirculation, vortex generation, interruption of thermal boundary layer, and flow separation. The implementation of nanofluid within a preferred volume fraction offers reduced pumping power in order to accomplish equivalent heat transfer enhancement [65, 66]. In many engineering applications, nanofluids are a novel approach for significant improvement in thermal efficiency due to its superior thermophysical properties [16, 44, 61, 80, 101, 107, 108].

Some of the examples of solid nanoparticles are copper, silver, nickel, gold, and metal oxides, and magnetic and ferromagnetic types are Al_2O_3, TiO_2, ZnO, SiO_2, Fe_2O_3, MgO, etc. Various forms of carbon are diamond, graphite, carbon nanotubes, etc. The nanoparticles could be of different size and shape and are mixed within a desired volume concentration in base fluid such as water, engine oil, ethylene glycol, ethanol, car engine coolant, terpineol, diesel oil and polydimethylsiloxane, propylene glycol, ethanol–isopropanol, or any other mixture of two homogeneous liquids.

3 Synthesis of Nanoparticles

The synthesis of nanofluid can be made by two mechanisms: one-step method and two-step method. In one-step method, the preparation and synthesis of nanoparticles to the desired size, shape, and volume fraction are performed by a combined process with minimized agglomeration [53]. In this method, nanoparticles are synthesized by physical vapor deposition (PVD) technique or a liquid chemical method and limited to small-scale production and low-pressure fluids [79, 114]. In two-step method, firstly the nanoparticles are synthesized to preferred size and shape and finally the particles are dispersed to base fluid with desired volume fraction by the addition of some additives for better stabilization [92]. Here, the nanoparticles' manufacturing and preparation is performed separately. In order to obtain better stability, minimum sedimentation, and controlling p^H to a desired level, surfactant and additives are employed during the synthesis process [74, 103]. In this process, the synthesis of nanoparticles is performed by grinding, milling, sol–gel, wet chemical methods, laser ablative technology, hydrothermal technique, gas-phase synthesis, etc., depending upon the types, size, shape of nanoparticles, and their applicability [87].

4 Thermophysical Properties of Nanofluid

4.1 Thermal Conductivity

The Maxwell model for [57] thermal conductivity for solid–liquid mixtures of relatively large particles (micro-/mini-sized) is good for low solid concentrations. The effective thermal conductivity, k_{nf}, is given by

$$k_{nf} = \frac{k_p + 2k_{bf} + 2\left(k_p - k_{bf}\right)\varphi}{k_p + 2k_{bf} - \left(k_p - k_b\right)\varphi} k_{bf} \tag{1}$$

Hamilton and Crosser [29] proposed a model for liquid–solid mixtures of non-spherical particles. They introduced a shape factor, n, to account for the effect of the shape of the particles. The thermal conductivity, in which the ratio of conductivity of the solid and fluid phases is larger, than 100 ($k_p/k_{bf} > 100$), can be expressed as follows:

$$k_{nf} = \frac{k_p + (n-1)k_{bf} + (n-1)\left(k_p - k_{bf}\right)\varphi}{k_p + (n-1)k_{bf} - \left(k_p - k_b\right)\varphi} k_{bf} \tag{2}$$

where "n" is the empirical shape factor given by $n = 3/\psi$, and ψ is the particle sphericity, defined as the ratio of the surface area of a sphere with volume equal to that of the particle, to the surface area of the particle. Yu and Choi [111] proposed a modified Hamilton–Crosser model to include the particle liquid interfacial layer for non-spherical particles. The effective thermal conductivity was expressed as

$$k_{nf} = (1 + \frac{n\varphi_{nf}A}{1 - \varphi_{nf}A})k_{bf} \tag{3}$$

where A is defined by

$$A = \frac{1}{3}\sum_{j=a,b,c} \frac{k_{pj} - k_{bf}}{k_{pj} + (n-1)k_{bf}})$$

And, $\varphi_{nf} = \varphi\sqrt{\frac{(a^2+t)(b^2+t)(c^2+t)}{\sqrt{abc}}}$ is the equivalent volume concentration of complex ellipsoids, which is an imaged structure of elliptical particles ($a > b > c$) with surrounding monolayers, with a general empirical shape factor n ($n = 3\psi^{-\alpha}$, here α is an empirical parameter and ψ is the particle sphericity).

Xue [109] developed a model for the effective thermal conductivity of nanofluids. His model is based on the average polarization theory and includes the effect of the interface between the solid particles and the base fluid. The derived equation for the effective thermal conductivity is

$$9\left(1 - \frac{\varphi}{\lambda}\right)\frac{k_{nf} - k_{bf}}{2k_{nf} + k_{bf}} + \frac{\varphi}{\lambda}\left[\frac{k_{nf} - k_{c,x}}{k_{nf} + B_{2,x}\left(k_{c,x} - k_{nf}\right)} + 4\frac{k_{nf} - k_{c,y}}{2k_{nf} + \left(1 - B_{2,x}\right)\left(k_{c,y} - k_{nf}\right)}\right] = 0 \tag{4}$$

where $\lambda = \frac{abc}{(a+t)(b+t)(c+t)}$ with half radii (a, b, c) of the assumed elliptical complex nanoparticles, which consist of nanoparticles and interfacial shells between particles and the base fluids. $k_{c,j}$ is the effective dielectric constant, and $B_{2,x}$ is the depolarization factor along the x symmetrical axis, which is derived from the polarization theory.

Koo and Kleinstreuer [40] developed another model for nanofluids, which includes the effects of particle size, particle volume fraction, and temperature dependence as well as properties of the base fluid and the particle subject to Brownian motion. The resulting formula is

$$k_{nf} = \frac{k_p + 2k_{bf} + 2\left(k_p - k_{bf}\right)\phi}{k_p + 2k_{bf} - \left(k_p - k_{bf}\right)\phi} k_{bf} + 5 \times 10^5 \beta\phi\rho_{bf} C_{pbf} \sqrt{\frac{K_B T}{\rho_p D}} f(T, \phi) \tag{5}$$

where $f(T,\phi) = (-6.04\phi + 0.4705)T + (1722.3\phi - 134.63)$.

The first part of the equation is obtained from the Maxwell model, while the second part accounts for Brownian motion, which causes the temperature dependence of the effective thermal conductivity. β is related to the particle motion. Based on the investigation of pressure gradients, temperature profiles, and Nusselt numbers, Koo and Kleinstreuer also claimed that addition of 1–4% CuO nanoparticles and high Prandtl number base fluid such as ethylene glycol and oil could significantly increase the heat transfer performance of microheat sinks.

4.2 Viscosity

Neilsen proposed a generalized power law-based model for the relative elastic moduli of composite materials, which is also widely used for relative viscosity. The simplified form of this model is given as [64]

$$\mu_{nf} = \left(1 + 1.5\varphi_p\right) e^{\varphi_p/(1-\varphi_m)} \mu_b \tag{6}$$

where φ_m is the maximum packing fraction. For randomly dispersed spheres, the maximum close packing fraction is approximately 0.64. In order to find out the effect of Brownian motion of particles on the viscosity of a statistically homogenous suspension, Batchelor derived the following equation [5]:

$$\mu_{nf} = \left(1 + 2.5\varphi_p + 6.2\varphi_p^2\right) \mu_b \tag{7}$$

Maiga et al. studied the forced convection flow of water–Al_2O_3 and ethylene glycol–Al_2O_3 nanofluids inside a uniformly heated tube that is submitted to a constant and uniform heat flux at the wall and proposed a correlation of the effective viscosity of the nanofluid which is given as follows [55]:

$$\mu_{nf} = \left(1 + 7.3\varphi_p + 123\varphi_p^2\right)\mu_b \tag{8}$$

Koo and Kleinstreuer proposed the following correlation to calculate the effective viscosity of the nanofluid [40].

$$\mu_{Brownian} = 5 \times 10^4 \beta \rho_{bf} \varphi_p \sqrt{\frac{K_B T}{2\rho_p r_p}((-134.63 + 1722.3\varphi_p) + (0.4705 - 6.04\varphi_p)T} \tag{9}$$

where the particle motion is related to empirical parameter

$$\beta = 0.0137\left(100\varphi_p\right)^{-0.8229} \varphi_p < 0.01$$

And $\beta = 0.0011\left(100\varphi_p\right)^{-0.7272} \varphi_p > 0.01$

Kulkarni et al. proposed the following correlation to calculate the effective viscosity of nanofluid where the dependence on the temperature is shown [41].

$$\ln \mu_{nf} = -\left(2.8751 + 53.548\varphi_p - 107.12\varphi_p^2\right) + \left(1078.3 + 15857\varphi_p + 20587\varphi_p^2\right)\left(\frac{1}{T}\right) \tag{10}$$

The dynamic viscosity of nanofluid is given by the following empirical correlation derived by Corcione with 1.84% of standard deviation [14].

$$\frac{\mu_{nf}}{\mu_{bf}} = \frac{1}{1 - 34.87\left(\frac{d_p}{d_{bf}}\right)^{-0.3} \phi^{1.03}} \tag{11}$$

where dbf is the equivalent diameter of the base fluid particle and is given by

$$d_{bf} = \left[\frac{6M}{N\pi\rho_{fo}}\right]^{1/3}$$

Here, M is the molecular weight of the base fluid, N is the Avogadro number, and ρfo is the mass density of the base fluid calculated at room temperature T = 293 K.

4.3 Density and Specific Heat

The calculation of the effective density and specific heat of nanofluid are calculated in a straightforward way, using the physical principle of the mixture rule,

Density of nanofluid, $\rho_{nf} = (\frac{m}{V})_{nf}$

$$= \frac{m_{bf} + m_p}{V_{bf} + V_p}$$

$$= \frac{\rho_{bf} V_{bf} + \rho_p V_p}{V_{bf} + V_p}$$

$$\text{So,} \quad \rho_{nf} = \left(1 - \varphi_p\right)\rho_{bf} + \varphi_{bf}\rho_p \tag{12}$$

Specific heat of nanofluid is calculated as follows:

$$\begin{aligned}\left(\rho c_p\right)_{nf} &= \rho_{nf}\left(\frac{Q}{m\Delta T}\right)_{nf} \\ &= \rho_{nf}\frac{Q_{bf} + Q_p}{\left(m_{bf} + m_p\right)\Delta T} \\ &= \rho_{nf}\frac{\left(mC_p\right)_{bf}\Delta T + \left(mC_p\right)_p\Delta T}{\left(m_{bf} + m_p\right)\Delta T} \\ &= \rho_{nf}\frac{\left(\rho C_p\right)_{bf}V_{bf} + \left(\rho C_p\right)_p V_p}{\rho_{bf}V_{bf} + \rho_p V_p}\end{aligned}$$

$$\text{So,} \left(\rho c_p\right)_{nf} = \left(1 - \varphi_p\right)\left(\rho C_p\right)_{bf} + \varphi_p\left(\rho C_p\right)_p \tag{13}$$

5 Utilization of Nanofluid in Solar Thermal Energy Applications

Arthur et al. have reported the experimental works showing the enhancement of thermophysical and rheological properties, e.g., specific heat, thermal conductivity, and viscosity of different molten salt nanofluids that are used in solar thermal energy systems. Majority of the work on high-temperature heat transfer fluid employing nanofluid focused on two main molten salts often referred as "solar salt," lithium carbonate + potassium carbonate (Li_2CO_3–K_2CO_3) and sodium nitrate + potassium nitrate salts ($NaNO_3$–KNO_3). Other works are focused on a wide range of ionic fluids. The data on the literature suggest an increase of 10–30% of enhancement of specific heat for the molten salt nanofluids. As for the thermal conductivity, molten salts with particles having high conductivity and larger specific surface area (e.g., MWCNT, graphene, Al_2O_3 whiskers) show significant enhancement in the property. On the other hand, increasing the concentration of the nanoparticles in the base fluid enhances the thermal conductivity as well as the viscosity [4].

Ebrahimnia-Bajestan et al. have investigated water-based TiO_2 nanofluid heat transfer characteristics both numerically and experimentally for possible application in solar heat exchangers. A maximum of 21% of average heat transfer coefficient was observed for TiO_2 water nanofluids. The results indicate that with the increase of nanoparticle concentration and Reynolds number, the heat transfer coefficient increases, whereas inverse effect was observed for particle size in the nanofluid. The authors have suggested to use smaller nanoparticles with higher thermal conductivity in nanofluids to be employed in solar thermal collectors [20].

Chen et al. have conducted experimental investigation on the effect of gold nanoparticles in nanofluids for enhancing photothermal conversion in direct solar absorption solar collector. Gold nanoparticles enhance the solar light absorption due to the localized surface plasmon resonance effect as compared to the base fluids. The experiment used synthesized gold nanoparticles obtained through seed-mediated method. The use of gold nanoparticle at a low mass fraction ($\sim$0.000008% weight) in water increases the photothermal conversion efficiency in direct absorption solar collector. For a cube-shaped direct absorption solar collector, the use of gold nanoparticles augmented the efficiency by 19.9%, whereas for a flat-shaped solar collector, the value is 21.3%. The size of the gold particles has a negative effect on the photothermal conversion efficiency of flat-shaped solar collectors. However, the effect was not as significant in the case of cube-shaped collectors [9] (Fig. 1).

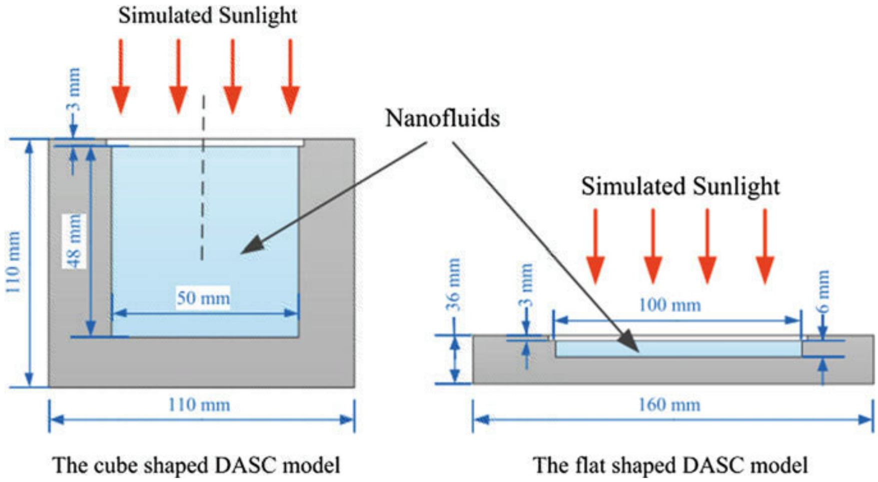

Fig. 1 Schematics of photothermal conversion test equipment (*DASC* direct absorption solar collector) [9]

Colangelo et al. have studied different properties of Al_2O_3–Therminol nanofluids for using as a heat transfer fluid in high-temperature solar energy systems. The authors have investigated the stability, viscosity, thermal conductivity, cluster size, and FT-IR spectra for the nanofluid. They have used oleic acid as a surfactant and studied their effect on the stability of nanofluids. The study revealed that nanofluids prepared without surfactants show greater sedimentation as compared to the nanofluids prepared with surfactant since the presence of surfactants creates bonds between nanoparticles and base fluid resulting in better stability. However, the addition of surfactant has little or no effect on the thermal conductivity of the nanofluid. The viscosity of the nanofluid prepared has increased with the increase of volume fraction of the nanoparticles [13].

Delfani et al. have conducted numerical and experimental investigation on nanofluid-based solar absorption solar collector used for water heating. The authors have presented thermo-optical properties of carboxyl (COOH)-functionalized multiwalled carbon nanotube (MWCNT) in water and ethylene glycol mixture (70%:30% in volume) at different volume fractions. The study reveals that the thermal conductivity of the nanofluids prepared has increased as the volume fraction and the temperature increased. The enhancement in thermal conductivity will increase the heat transfer, which can lead to increased heat transfer and hence an enhancement in collector efficiency. The authors have built prototype of MWCNT nanofluid-based direct absorption solar collector for application in domestic solar heating systems. The effect of internal emissivity, flow rate, and MWCNT nanoparticle volume fraction on the efficiency of the collector is presented in the paper. The arrangement with nanofluid has shown an increase of 29% efficiency as compared to the arrangement with base fluid only with the same flow rate [17] (Fig. 2).

Faizal et al. have reported energy and economic and environmental analysis of four different nanofluids (CuO, SiO_2, TiO_2, and Al_2O_3) for solar thermal collectors. Size reduction of the solar collector is possible due to the higher thermal conductivity. Compared to water, the area of the solar collector can be reduced up to 25.6%, 21.6%, 22.1%, and 21.5% for CuO, SiO_2, TiO_2, and Al_2O_3, respectively. Embodied energy saving is possible due to employing nanofluid in solar collector. The size reduction of the solar collector by using nanofluid leads to cost savings as well [23].

Gorji et al. have reported optical characterization of carboxyl (COOH)-functionalized carbon nanotube aqueous nanofluids for possible application as direct solar absorbers [25]. Gupta et al. have developed a low-temperature Al_2O_3–water nanofluid-based flat plate direct absorption solar collector. By employing alumina nanofluid as a direct absorbing medium, collector efficiency enhancement of 39.6% and 22.1% was observed for 0.005 vol.% and 0.001 vol.%, respectively [27].

Karami et al. have presented the performance study of a prototype of CuO nanofluid-based solar direct absorption collector for residential application of water heating. The prototype solar collector measures 60×60 cm^2 with a channel depth of 1 cm. The solar collector efficiency with CuO nanofluid has increased by 17% as compared to the base fluid at a similar flow rate [35]. In another study, Karami et al.

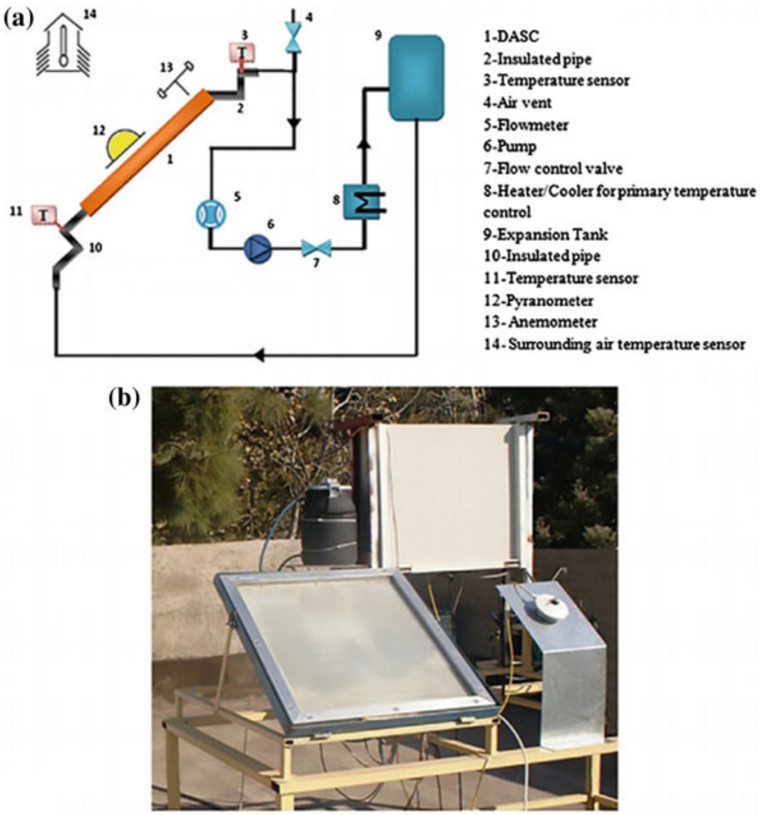

Fig. 2 DASC outdoor performance test **a** schematic of the standard test loop; **b** the photograph of the experimental setup [17]

have investigated the thermo-optical properties of CuO nanofluid (water + EG as base fluid) as the potential working fluid in low-temperature direct absorption solar collector. Even with a low nanoparticle volume concentration, the nanofluid shows greater absorption as compared to the base fluid. The experiments reveal that the dynamic viscosity of the CuO nanofluid decreases with the increase of temperature and increases with the increase in nanoparticle volume concentration. Thermal conductivity was dependent on the nanofluid temperature and volume concentration [36].

Tyagi et al. have investigated the performance of an alumina–water nanofluid-based direct absorption solar collector. In their study, the collector efficiency has increased with the increase of nanoparticle size. Under the same operating conditions, the collector efficiency was 10% higher as compared to collectors using water as the working fluid [98]. Otanicar et al. have studied the effect of different nanoparticles, e.g., carbon nanotubes, silver, graphite, in base fluid on the direct absorption solar collector performance using a microsolar thermal collector. The collector efficiency decreases with the increase of nanoparticle size [69].

Khullar et al. have quantitatively compared nanofluid-based volumetric solar collector to conventional surface-based solar collector by comparing amorphous carbon nanoparticle dispersion in ethylene glycol and multiwalled carbon nanotube (MWCNT) dispersion in distilled water with commercial material as selective solar absorber. The study suggests that the volumetric solar collector with nanoparticle dispersion shows the best performance at an optimum volume fraction [37]. Kim et al. have reported the thermal performance of U-tube solar collector by employing various nanoparticles (MWCNT, Al_2O_3, CuO, SiO_2, and TiO_2) dispersed in PG (propylene glycol)–water as base fluid. All the nanofluids used in the solar collector have increased the thermal efficiency in the following order: MWCNT, CuO, Al_2O_3, TiO_2, and SiO_2 nanofluids [39].

Meibodi et al. have experimentally investigated thermal performance of a SiO_2/EG–water nanofluid-based flat plate solar collector. Despite the low thermal conductivity of SiO_2, this nanoparticle-based nanofluid has the potential to improve the thermal performance of solar collectors. While employing the nanofluids, it is preferable to use low volume fraction since it will reduce the preparation cost and instability problem [58]. Menbari and Alemrajabi have reported the optical properties of a new class of binary nanofluid (Al_2O_3–CuO) as a potential working fluid in direct absorption solar collector. CuO and γAl2O3 are dispersed in water + ethylene glycol. The study suggests that optical coefficients are direct functions of the volume fractions [59].

Rajeb et al. have performed numerical and experimental study on the performance of a photovoltaic thermal (PV-T) nanofluid-based collector. The influence of concentration, types of different nanoparticles (Al_2O_3 and Cu), and different base fluids (water and ethylene glycol) on the electrical and thermal performance of the collector have been studied. The numerical results, validated by the experiments, show that pure water exhibits better performance than ethylene glycol as base fluid. Cu/water nanofluid shows better thermal and electrical efficiency as compared to Cu/ethylene glycol, alumina/water, and alumina/ethylene glycol. The results showed that the thermal and electrical efficiency increases with the increase of nanoparticle concentration [81] (Fig. 3).

Sabiha et al. have performed experimental study to study the thermal performance of an evacuated tube solar collector using single-walled carbon nanotube (SWCNT)-based nanofluid using water as a base fluid. The thermal efficiency of the solar collector was found to be increased with the use of nanofluid. The maximum efficiency was found to be 93.43% for 0.2 vol.% of SWCNT nanofluids at a mass flow rate of 0.025 kg/s. The thermal performance was enhanced with the increase of volume fraction of the nanoparticles and flow rate [82] (Fig. 4).

Said et al. have studied the energy and exergetic efficiency of flat plate solar collector experimentally using pH-treated alumina nanofluid. The study suggested an increase of 83.5% in energy efficiency for 0.3% volume fraction of nanoparticles and mass flow rate of 1.5 kg/min and an increase of 20.3% in exergy efficiency for 0.1% volume fraction of nanoparticles and a mass flow rate of 1 kg/min [84]. In

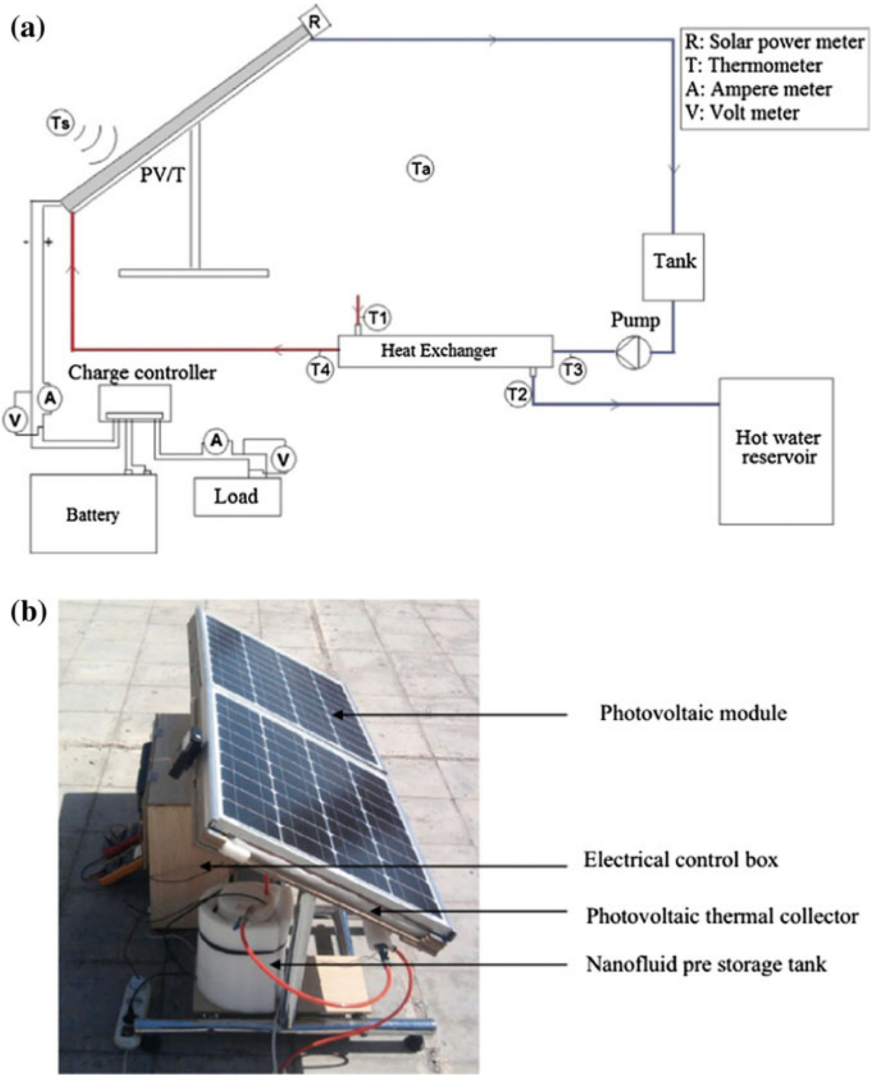

Fig. 3 **a** Schematic diagram and **b** experimental setup of PV/T system used in Rajeb et al. [81]

another study, Said et al. have reported the thermal performance of a TiO_2-based flat plate solar collector with volume fractions of 0.1 and 0.3% and mass flow rate ranging from 0.5 to 1.5 kg/min. PEG 400 dispersant was used reducing the sedimentation of nanoparticles, and its effect on the thermal performance was studied. The energy efficiency of the solar collector employing the nanofluid is increased by 76.6% for 0.1% volume fraction and mass flow rate of 0.5 kg/min, whereas the

Fig. 4 Evacuated solar collector experimental setup used in [82]

highest exergy efficiency obtained is 16.9% for 0.1% volume fraction and mass flow rate of 0.5 kg/min as compared to water as working fluid [83].

Shende and Sundara have investigated the use of N-(rGO-MWNTs), a synthesized mixture of nitrogen-doped hybrid structures of reduced grapheme oxide (rGO) and multiwalled carbon nanotubes (MWNTs) dispersed in water and ethylene glycol as base fluid in direct absorption solar collectors. The study showed that the absorption increases with the increase of particle concentration. The thermal conductivity of the nanofluid increases with the concentration and temperature [89]. Taylor et al. have studied the potential use of different nanoparticles (aluminum, copper, graphite, and silver nanoparticles) dispersed in Therminol VP-1 heat transfer fluid in power tower solar collectors. The results suggest an increase of 10% efficiency as compared to surface-based collectors for solar concentration ratio range of 100–1000 [93] (Fig. 5).

Tong et al. have reported the construction of an enclosed type evacuated U-tube solar collector employing multiwalled carbon nanotube (MWCNT) nanofluid as the working fluid. The experimental results show an increase of 4% efficiency by incorporating the nanofluid in the solar collector [95]. Michael and Iniyan studied the effect of using copper oxide/water (CuO/H_2O) nanofluid as the working fluid on the performance of a 2.08 × 1.05-m flat plate solar collector. A maximum increase of 6.3% in the efficiency was achieved using the CuO/H_2O nanofluid [60].

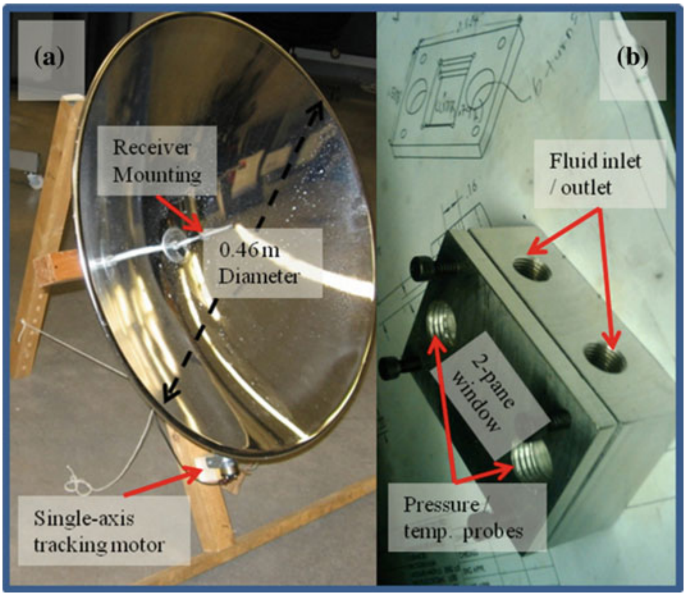

Fig. 5 Experimental scale reflective dish used in the experiments [93]

Tiwari et al. have investigated the effect of Al_2O_3 nanofluid as the working fluid on the performance of a 1 × 2-m flat plate solar collector. The results revealed that there was a maximum increase of 31.64% in the efficiency of the collector using a flow rate of 2 l/min and 1.5% volume fraction of Al_2O_3 as compared to water [94]. Lu et al. analyzed the thermal performance of an open thermosyphon using water-based CuO nanofluids for high-temperature evacuated tubular solar collectors. The study reported that optimum heat transfer augmentation was obtained with 1.2% particle concentration [50].

Liu et al. constructed an evacuated tubular solar air collector integrated with simplified compound parabolic concentrator and open thermosyphon. The authors compared the collector performance with CuO nanofluid or water as working fluid in the thermosyphon. They have remarked that solar collector integrated with open thermosyphon produces better performance [49]. Polvongsri et al. studied the thermal performance of three identical closed-loop flat plate solar collectors employing silver nanofluids as the working fluid. The experiments suggested that the convective heat transfer coefficient of silver nanofluids at 10,000 ppm was twice the value of the water. The results revealed that at high inlet temperatures, nanofluid enhances the thermal efficiency of the solar collectors [78].

Cui and Zhu presented the effect of employing MgO–water nanofluid for a PV/T system. The observations revealed that the output power from the solar cells in PV/T system was reduced with the increase of particle volume fraction and nanofluid film thickness. The results that exhibit the electrical output for a PV system is higher in comparison with PV/T systems; however, the overall efficiency of PV/T systems is more than PV systems [15].

6 Nanofluid Utilization in Thermal Energy Storage

Thermal energy storage is an imperative concept for thermal energy utilization when demand and supply period does not match. The storage allows the energy generation and consumption to be decoupled in terms of time and location. In solar thermal power plants, often the electricity generation and electricity demand are in different periods and thermal energy storage plays a vital role. Also in intermittent cooling applications, e.g., central air-conditioning in buildings, various industrial cooling processes, and electronic cooling applications, cool thermal energy storage is essential due to the intermittent nature. Phase change materials are used as thermal energy storage medium due to their high heat capacity which is stored in the form of latent heat. Nanofluids are often incorporated with these PCMs to improve their heat transfer properties and enhance their specific heat capacity.

Altohamy et al. have experimentally studied a spherical capsule with water-based nanofluid (50 nm Al_2O_3) phase change material during charging process for cool thermal energy application. The results of this study show that there is a substantial effect of alumina nanoparticle concentration on thermal properties of PCM which consecutively decreases complete charging time for all heat transfer fluid volume flow rates and also at different heat transfer fluid inlet temperatures. Also, the addition of nanofluid in the PCM increases the heat transfer coefficient rate [3] (Fig. 6).

Chandrasekaran et al. have studied the heat transfer characteristics of water-based CuO nanofluid PCM (NFPCM) during solidification for cool thermal energy storage system. The experiments show that the NFPCMs exhibit a noteworthy decrease in solidification time due to augmented heat transfer properties. The enhanced heat transfer rate eliminates the problem of subcooling, saves energy, and is beneficial for many cool thermal energy storage systems [7].

On a different study, Chandrasekaran et al. have reported the thermal performance of NFPCM using multiwalled carbon nanotube (MWCNT) nanoparticles in deionized water (DI water) employing pseudomonas as a nucleating agent for cool thermal energy storage. The use of nanofluid in the PCM enhances the heat transfer properties, eliminates undesired subcooling, and accelerates charging. Thus, using nanofluid in PCM will enable energy efficiency design for the cool thermal energy storage systems [8] (Fig. 7).

Cingarapu et al. have presented the thermal and rheological properties of nanofluid consisting of core/shell silica-encapsulated tin (Sn/SiO_2) nanoparticles dispersed in a synthetic HTF Therminol66 (TH66) at loadings up to 5 vol.% as a potential heat transfer fluid in concentrating solar power systems. The incorporation of nanofluid in the HTF has increased the thermal conductivity and improved the total heat adsorption through the latent heat of tin core melting. The addition of the

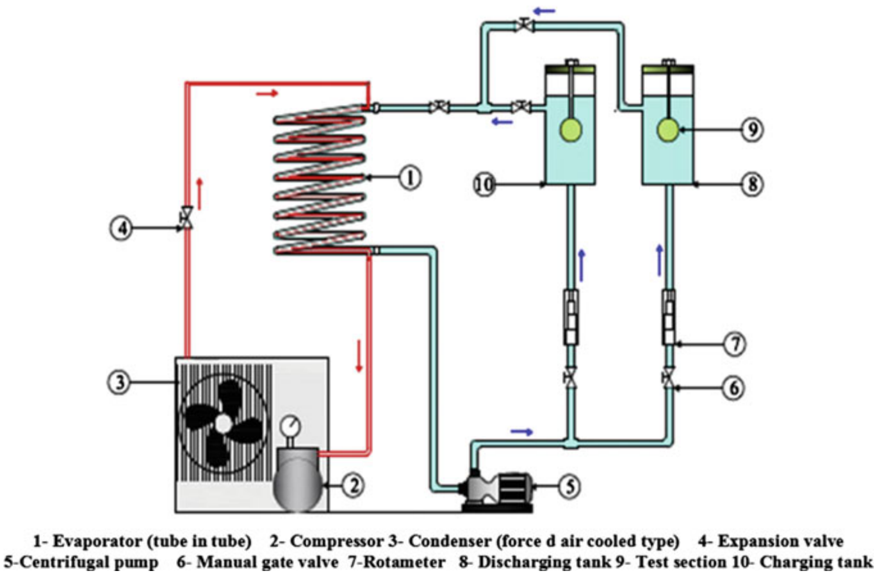

Fig. 6 Schematic diagram of the experimental test rig used in [3]

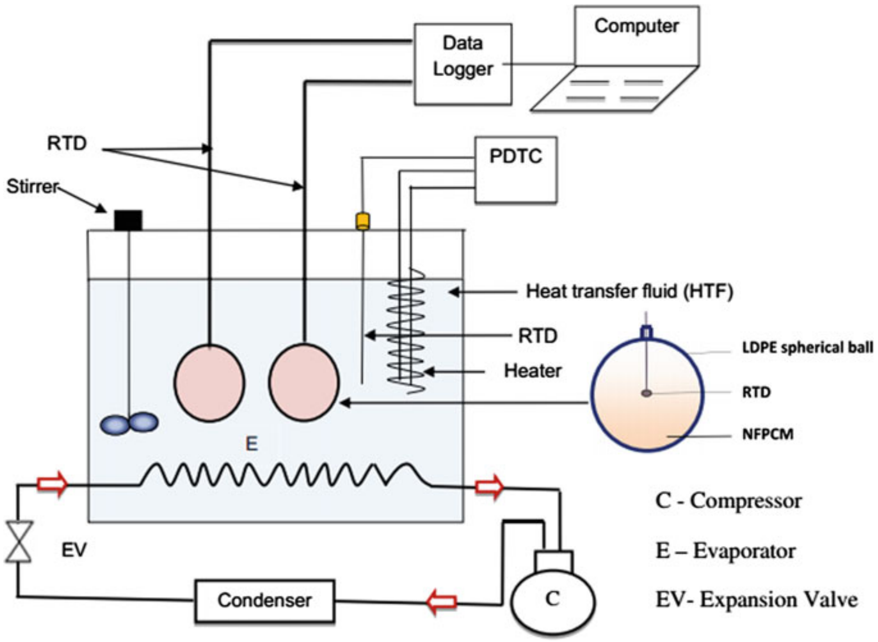

Fig. 7 Experimental setup used in Chandrasekaran et al. [7, 8]