Chapter

Titanium Dioxide: Advancements and Thermal Applications

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Abstract

Distinctive characteristics of titanium dioxide such as high refractive index, overwhelmingly high melting and boiling point, high toughness, and hardness, photocatalytic nature, ability to absorb or reflect UV-rays, DeNox catalyst, nontoxicity, inert behavior, etc., have brought about the massive use of TiO_2 in a variety of conventional as well as advanced engineering applications. Broad commercial utilization of titanium dioxide in products including paints, anti-air pollutants, cosmetics, skincare and sunblock, pharmaceuticals, surface protection, building energy-saving, etc., accounts for its multibillion dollars market worldwide. Titanium dioxide carries unique thermal and optical characteristics and therefore has gained significance as a potential candidate for advanced applications such as clean hydrogen fuel harvesting, photoelectric solar panels, photothermal conversion, treatment of exhaust gases from combustion engines and power plants, thermal energy storage, thermal management of electronic devices and photovoltaics, and nano-thermofluids. This chapter presents a brief insight into some of the noteworthy characteristics and a comprehensive overview of advanced thermal applications of $TiO_{2.}$

Keywords: titanium dioxide, thermal management, energy harvesting, energy storage, nanoparticles

1. Introduction

Titanium dioxide (TiO_2)—a ceramic, commonly known as titania—is a naturally occurring oxide of titanium and is among the most widely used metals. Titania exists in three crystallographic forms, i.e., rutile, anatase, and brookite [1]. Titanium dioxide carries engrossing characteristics, needed to have for a material to be used in a broad range of applications. Some of the key properties of titania have been narrated in **Table 1**. Titania has been used primarily as a pigment in paints for the past hundred-odd years; however, it has been under the spotlight for the past couple of decades as it is deemed as the potential substitute for many of the metals owing to its nontoxic and chemically stable nature. A comprehensive overview of vital features and potential applications of titania has been presented in **Table 2**.

Titanium dioxide is employed in bulk form as well as nanoparticle form. Conventionally, bulk titania (of 0.20 μm general size [4]) has been used; however, avant-garde thermal applications of titania make use of nano-sized particles (100 nm) in medicine, nano-phase changing thermal energy storing materials, and nanofluids. Low cost, durability, and ease to handle are the most fascinating aspects of titania. Moreover, further growth in titania utilization in the future has been projected by the researchers.

Property	Detail
Molecular mass	79.86 (g/mol)
Density	3.9–4.2 (g/cm^3)
Refractive index	2.5–2.75
Mohs hardness	5.5–7
Band gap (rutile)	3.0 eV
Band gap (anatase)	3.2 eV
Structural shape	Tetragonal structure (rutile) Tetragonal structure (anatase) Orthorhombic structure (brookite)

Table 1.
General properties of titanium dioxide [2].

Key feature	Applications	Industrial sectors
Mechanical: • Titania is anticorrosive • Titania has high hardness and toughness • Wear resistant	• Used as an additive for strengthening the material and reducing the wear effects.	• Paint industry • Cosmetics industry • Power sector • Pharmaceuticals • Biomedical • Food industry • Plastic industry
Optical: • High refractive index • UV resistant • UV absorbent	• Used as pigment as it acts as whitener and shimmer brightener as it reflects the light and acts opaque. • Used for scattering UV-rays in skincare and sunblock applications.	
Chemical: • Chemically inert • Insoluble in water • Nontoxic • Photocatalytic • Hydro catalytic • DeNox catalyst	• Used in thin or thick protective paints. • Used for hydrogen extraction from water through hydro catalysis. • Used for decomposing the air pollutants through photocatalysis. • Used for exhaust gas purifier	
Electrical: • Semiconductor • Specific variation in electrical resistance at high temperature in the presence of specific gases	• Due to the semiconductor characteristics, it is used for photoelectric energy harvesting as a solar panel material. • Change in electrical resistance in presence of specific gases is used to detect gases.	
Thermal: • High melting point • High boiling point	• Used for thermal energy storage and energy transportation when used as nanofluid, etc.	

Table 2.
Key in-demand features and applications of titania [3].

State-of-the-art thermal applications of titania include hydrogen fuel extraction, photoelectric energy harvesting, photothermal energy harvesting, thermal energy storage and transportation, thermal management of electronics, automotive engines, electric batteries and photovoltaics, temperature control of buildings, etc. This chapter discusses the mechanism of employing titania in the aforementioned thermal applications, and an in-depth discourse on the performance of titania is presented.

2. Thermal utilization of titanium dioxide

Titania has been utilized for various thermal applications such as heat relieving, photoprotection, storing heat, heat transportation, solar thermal energy cultivation, etc. Utilization of titania in the aforementioned thermal applications has been carried out in the form of bulk titania, titania nanoparticles, titania-based nanofluids, and titania nanoparticle enhancement phase change heat storage materials. The following section contains a detailed discourse on the mechanism of titania-based thermal management and the performance of titania-based nanofluids when employed to perform thermal management of various advanced thermal systems.

2.1 Thermal management

Thermal management stands for the process of relieving excessive heat of components such as electronic devices, solar modules, vehicle engines, electrical batteries, etc., since the prolonged heating of these objects leads to performance deterioration, system size maximization, manufacturing surcharge, operational and handling complications, and system failure.

Thermal management can be carried out either by thermofluids-based cooling or by thermally conductive and solar photoprotection metallic coatings.

2.1.1 Thermal management of photovoltaic modules

Photovoltaic (PV) modules are used to harvest solar photoenergy to generate electrical energy through a photoelectric conversion mechanism. Standalone PV modules are made of semiconducting crystalline materials. There are three categories of PV panels, i.e., monocrystalline, polycrystalline, and amorphous. The photoelectric conversion efficiency of solar panels is quite limited due to certain characteristic constraints of panels' material, and their efficiency range is 10–20% [5]. A substantial component of the solar photoenergy is converted into thermal energy, which gives rise to the heating of panels. Temperature elevation decreases the band gap (energy gap); therefore, the efficiency of solar panels tends to drop by 0.5% when the panel temperature increases by 1°C past 25°C [6]. The relationship between the band gap and the temperature of the semiconductor was presented by Varshni [7] (Eq. (1)). Rodriguez [8] appraised the influence of temperature on the efficiency of PV panels, and he observed a drastic decline in efficiency as evident in **Figure 1**.

$$E_g(T) = E_g(0) - \frac{\sigma T^2}{T + \beta} \tag{1}$$

In Eq. (1), E_g is the energy gap, T is the temperature (in Kelvin), and α and β are the constants of semiconductor materials, and the values of these constants for various semiconducting materials have been presented by Varshni [7].

Complications caused by temperature escalation of PV modules are addressed by heat relieving techniques. Both passive and active methods of cooling have been tested to carry out thermal management of solar modules. Heat absorbed from the cooling fluid is used for thermal applications, and this system is named as photovoltaic thermal (PV/T) system [9]. The efficacy of PV/T systems is evaluated in terms of PV or electrical efficiency, thermal efficiency, and overall efficiency [9].

The electrical efficiency of the PV/T system is appraised by Eq. (2).

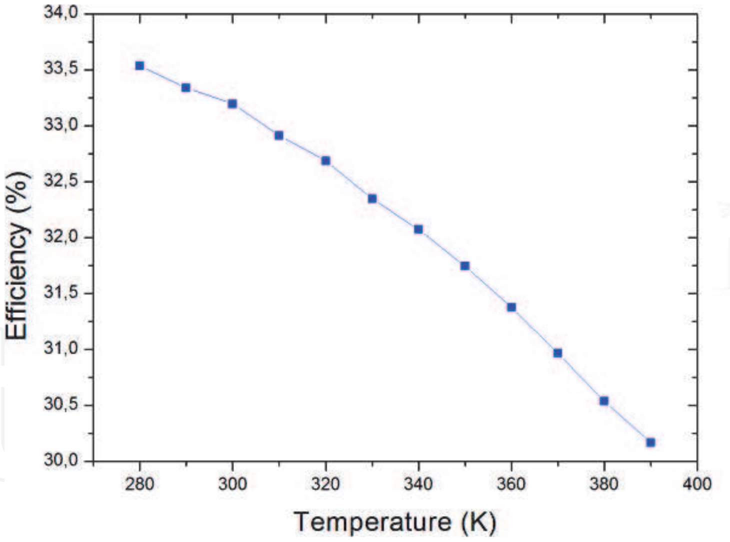


Figure 1.
Influence of temperature variation on the efficiency of PV panels [8].

$$\eta_{el} = \frac{\dot{E}_{el}}{\dot{E}} = \frac{V_{oc} \times I_{sc} \times FF}{G_{eff}} \tag{2}$$

In Eq. (2), $\dot{E}_{el}$ is the output electrical energy, $\dot{E}$ is the incident irradiation, which is converted into electrical energy output, thermal energy output, and energy losses, V_{oc} is the output voltage, I_{sc} is the short-circuit current, G_{eff} represents the absorbed irradiation (effective), and FF stands for fill factor, which is evaluated by Eq. (3), and it depends on the quality of solar cells.

$$FF = f \times \left(\frac{V_{oc}}{T}\right) \tag{3}$$

In Eq. (3), T is the temperature of the solar cell.

The thermal energy output of the PV/T system is appraised by Eq. (4).

$$\dot{E}_{th} = m_f \times C_{pf} \times (T_o - T) \tag{4}$$

In Eq. (4), $\dot{E}_{th}$ is thermal efficiency, m_f is the cooling fluid's mass flow rate, C_{pf} is the specific heat capacity of the cooling fluid, and T_o and T are the fluid outlet and inlet temperature, respectively.

The overall efficiency of the PV/T system is appraised by Eq. (5).

$$\eta_{PV/T} \sim \frac{\dot{E}_{el} + \dot{E}_{th}}{\dot{E}_{th}} \Rightarrow \eta_{PV/T} = \eta_{th} + r \times \eta_{el} \tag{5}$$

In Eq. (5), r is the packing factor, which is calculated by Eq. (6).

$$r = \frac{A_{PV}}{A_c} \tag{6}$$

In Eq. 6, A_{PV} is the photovoltaic area, and A_c is the collector area.

Avant-garde research studies suggest the use of nano-thermofluids for effective thermal management and efficient operation of PV modules. Nanofluids are regarded as the most efficient mean of thermal management that has been widely recommended for temperature regulation of solar panels. Nanofluids are among the most advanced thermofluids, and they carry exceptional thermophysical and optical characteristics. The principal element of nanofluids is the nanoparticles that are uniformly spread in the conventional fluids, e.g., water, ethylene glycol, engine oil, etc. Dispersion of nanoparticles is carried out to tailor the thermophysical and optical characteristics such as thermal conductivity, viscosity, pumping power, and solar light absorption range of conventional thermofluids.

Thermal management of solar modules can be executed by various methods that include rear-end cooling, front-end cooling, double-pass cooling. In rear-end cooling, thermally efficient nanofluid flows beneath the surface of the solar module and takes off the heat of the panel. In front-end cooling, optically efficient nanofluid flows across the frontal surface of the solar panels, and the nanofluid absorbs the UV and IR part of solar radiation that will not be converted into electrical energy and would cause heating of the panel. The front-end method of cooling employs the spectral splitting mechanism. The double-pass method of PV cooling is the combination of rear-end and front-end cooling. The aforementioned PV cooling techniques have been elaborated in **Figure 2**.

Titanium-dioxide-based nanofluids are engineered by dispersing nanoparticles of titania in the base fluid through rigorous nanofluids' preparation techniques. Nanoparticles of titania carry good thermal conductivity and have been reported to have impressive thermohydraulic performance results [10]. The thermal conductivity of titania nanoparticles is 8.4 W/m °C, and they are spherical in general with white color [11].

Rukman et al. [12] appraised the efficiency of a PV/T system using TiO_2/water nanofluid as a coolant. They analyzed the effect of fluid's flow rate (0.012–0.0255 kg/s), irradiation (700 W/m^2 and 900 W/m^2), and nanoparticle concentration (0.5 wt.% and 1.0 wt.%) on the performance of the PV/T system. They reported the overall efficiency of the PV/T system to range from 75–90%, and the electrical efficiency approached 9.9–10.6%. The thermal efficiency of the titania

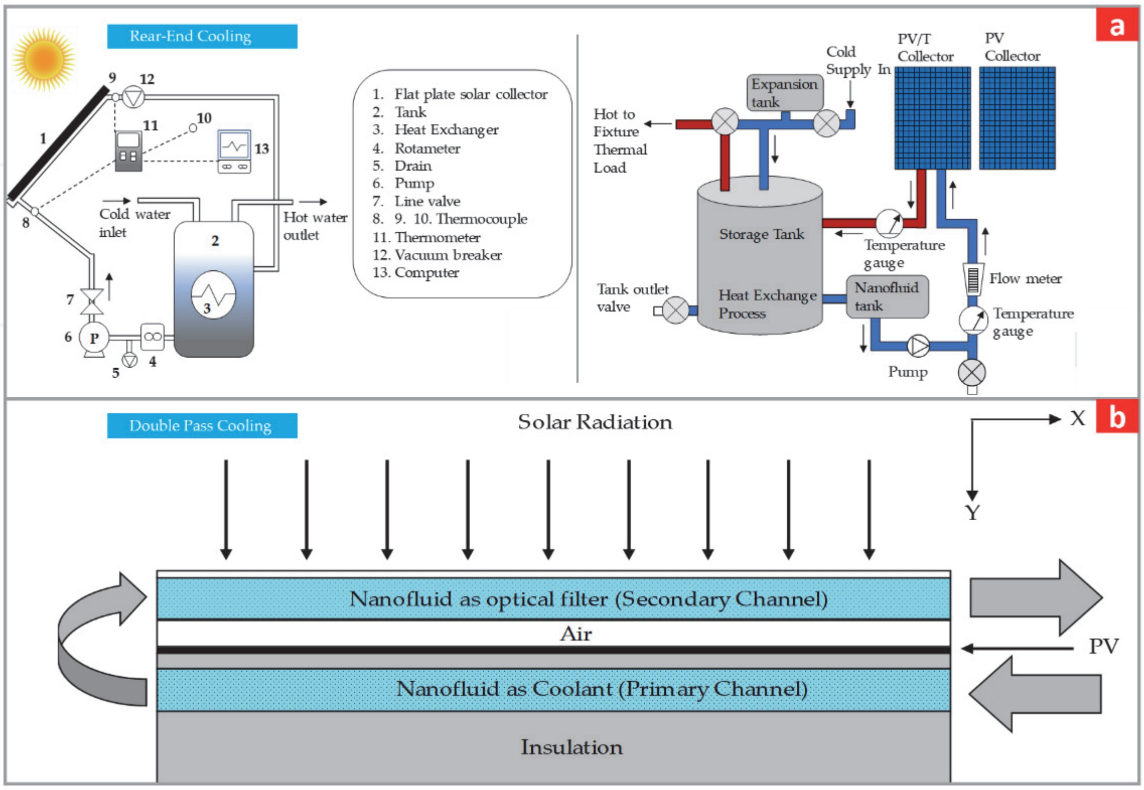


Figure 2.
Methods of PV cooling using nanofluids (a) rear-end cooling, and (b) double-pass cooling [6].

nanofluid-based PV/T system reached 65–80%. At 900 W/m^2 irradiance, electrical efficiency increased by 6.95% and 7.32% at 0.5 wt.% and 1.0 wt.% titania nanoparticle concentration, respectively, as compared with the uncooled PV panel. In another study, Rukman et al. [13] analyzed the performance of the PV/T system using MWCNT and TiO_2_based nanofluids. They concluded that the flow rate increment causes the module surface temperature to decrease, whereas the irradiation increase causes the temperature to increase, and the efficiency gets dropped.

Fadli et al. [14] tested the effect of using TiO_2/water nanofluid on the performance of the PV modules. They observed an increase of 2.6% in PV efficiency and a 10.38 W increase in power output as compared with the reference PV module. At 1100 W/m^2 irradiance, a decline of 11.4°C in PV module temperature was observed. Increased temperature decreased the module efficiency and the use of nanofluid increased the efficiency as compared with the water-cooled module and reference module (**Figure 3**). Maadi et al. [15] analyzed the effect of thermophysical characteristics of nanofluids on the performance of PV/T system using various nanofluids, i.e., 0.2 wt.% Al_2O_3/water, 0.2 wt.% ZnO/water, 0.2 wt.% TiO_2/water, 1.0 wt.% SiO_2/water, and 3.0 wt.% SiO_2/water through comprehensive experimentation and numerical method. They observed that due to greater thermal conductivity, Al_2O_3/water outperformed the rest of the nanofluids in terms of efficiency enhancement of the PV module. Numerical analysis revealed that at 10 wt.% concentration of nanoparticles in the base fluid, the PV efficiency could be improved by 6.23%, 6.02%, 6.88%, and 5.77% by using Al_2O_3/water, ZnO/water, TiO_2/water, and SiO_2/water nanofluids respectively as compared with the water-cooled PV module. Similar analysis was performed by Hasan et al. [16]. They tested SiC/water, TiO_2/water, and SiO_2/water nanofluids and SiC-based nanofluid since superior thermophysical characteristics outperformed TiO_2 and SiO_2-based nanofluids and yielded 12.75% electrical, 85% thermal, and 97.75% combined efficiency. Whereas TiO_2 outperformed SiO_2 as it carries better thermal characteristics such as convective heat transfer coefficient and thermal conductivity. They used the method of jet impingement to achieve a maximum cooling effect (**Figure 4**).

Sardarabadi et al. [17] performed a similar analysis using 0.2 wt.% nanofluids of Al_2O_3/water, TiO_2/water, and ZnO/water. They reported an overall energy efficiency enhancement of 12.34% for water, 15.45% for ZnO/water, 15.93% for TiO_2/water, and 18.27% for Al_2O_3/water. Ebaid et al. [18] and Sardarabadi and Fard [19] performed a similar analysis and reported the same trends as discussed in the previous studies.

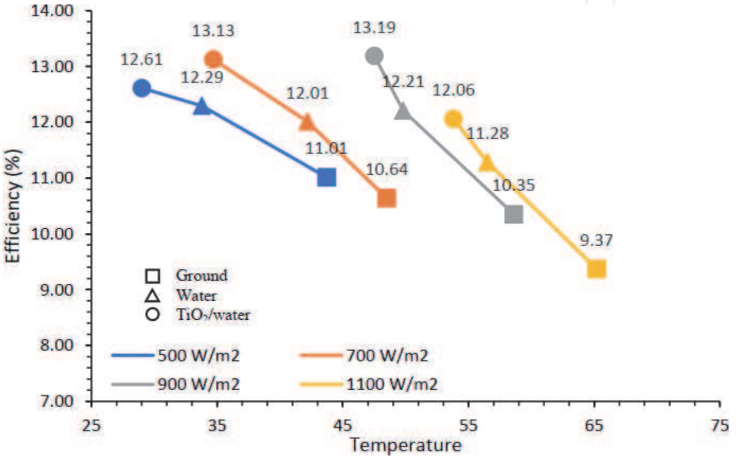


Figure 3.
Effect of temperature, irradiation, and cooling media on the efficiency of PV modules [14].

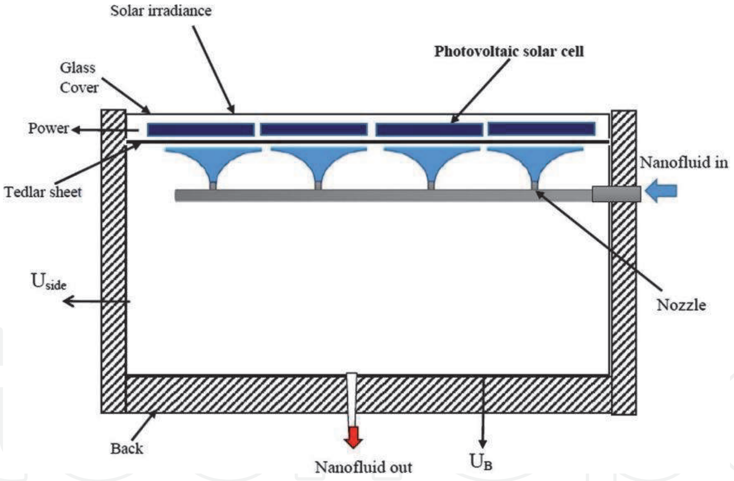


Figure 4.
Nanofluid-assisted PV cooling by jet impingement [16].

Key factors that influence the performance of nanofluids-based PV/T systems are the irradiance, PV cell surface temperature, and flow rate, inlet temperature, and thermophysical characteristics of nanofluids. An increase in irradiation causes higher energy photons to strike the PV surface, which causes the temperature to rise, and therefore, the efficiency tends to drop. The higher flow rate of fluid results in higher convective heat transfer, and therefore, greater cooling of PV panels takes place. Better thermophysical characteristics of nanofluids also intensify the rate of heat transfer and heat storage capacity, which help in achieving higher electrical power output from the PV modules. The bottom surface of solar modules holds considerable significance, and therefore, some studies have also suggested the use of metallic fins to improve temperature regulation [20]. Proper handling of nanofluids is also a crucial aspect of these systems [21].

2.1.2 Thermal management of automotive engines

Automotive engines make use of fuel combustion to generate mechanical energy to power the vehicles. Combustion and the resulting exhaust gases raise the temperature of the combustion chamber up to 2500°C [22]. Extreme temperature can cause the piston to melt, and the molten piston upon solidification causes the welding effect, and it eventually seizes the engine. To prevent failure, automotive engines have a cooling loop in which a coolant is set to flow that takes the heat of the engine and releases the heat in the environment through the radiator heat exchanger. Water, ethylene glycol, and the mixture of water and ethylene glycol have been conventionally utilized as automotive coolants, and the radiator plays a pivotal role in the process of automotive cooling.

State-of-the-art research studies on automotive cooling have extensively tested nanofluids as a potential candidate to replace the conventional automotive coolants to improve the heat transfer performance and system miniaturization [23]. The experimental setup used to simulate the automotive cooling system and test the nanofluids is presented in **Figure 5**.

Titania-based nanofluids have been tested for automotive cooling purposes as well, and quite encouraging results have been reported in recent studies. Chen et al. [25, 26] tested the performance of TiO_2/water nanocoolant for automotive cooling, and they observed 10% enhancement in heat transfer coefficient at 1.0 wt.% concentration of titania nanoparticle. They performed a pump cavitation test and recorded a pump corrosion rating of 10, which means no corrosion/erosion. They

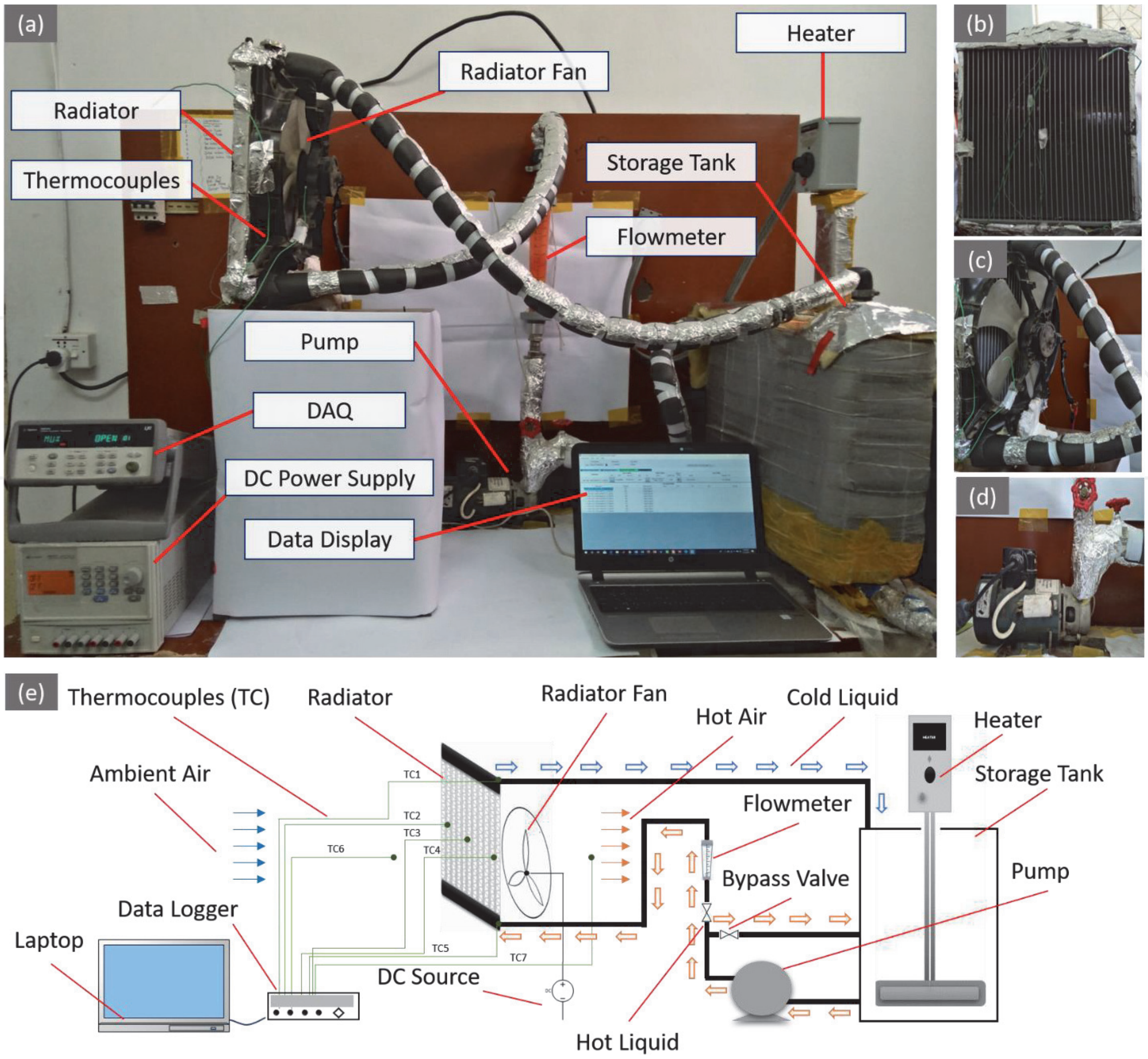


Figure 5.
Automotive cooling experimental setup and components (a–d), and schematic elaboration of the experimental setup (e) [24].

recommended the use of titania in automotive cooling as it has corrosion inhibition characteristics, and therefore, the pumping system and the fluid channels are estimated to operate efficiently and for a longer period. Salamon et al. [27] conducted experiments to analyze the effect of using TiO_2/water-propylene glycol (70:30) nanocoolant of 0.1 vol.% and 0.3 vol.% nanoparticle concentration with flow rate varying from 3 LPM to 6 LPM and inlet temperature ranging from 60°C to 80°C. The use of titania nanofluid resulted in an 8.5% increased heat transfer rate. Moreover, at lower inlet temperature, base fluid outperformed the nanofluids. Usri et al. [28] tested TiO_2/water-ethylene glycol (60:40) nanocoolant and at optimum operating conditions and 1.5 vol.% nanoparticle concentration and 70°C inlet temperature 33.9% increase in heat transfer was reported. An increase in heat transfer rate was recorded as 20.9% at 1.0 vol.% nanoparticle concentration. Titania nanofluids samples were observed to be stable for 2 months after the preparation. Devireddy et al. [29] appraised the performance of TiO_2/water-ethylene glycol (60:40) nanocoolant, and they reported a 37% increase in heat transfer rate at 0.5 vol.% nanoparticle concentration as compared with the base fluid. They observed an increase in Nusselt number (Nu) with an increase in nanoparticle concentration **Figure 6**. Hussein et al. [31] reported a 20% increase in heat transfer efficiency by using TiO_2/water nanocoolant as compared with the water base fluid. Ahmed et al. [32] investigated the automotive cooling potential of TiO_2/water nanocoolant and reported a 47% improvement in radiator effectiveness.

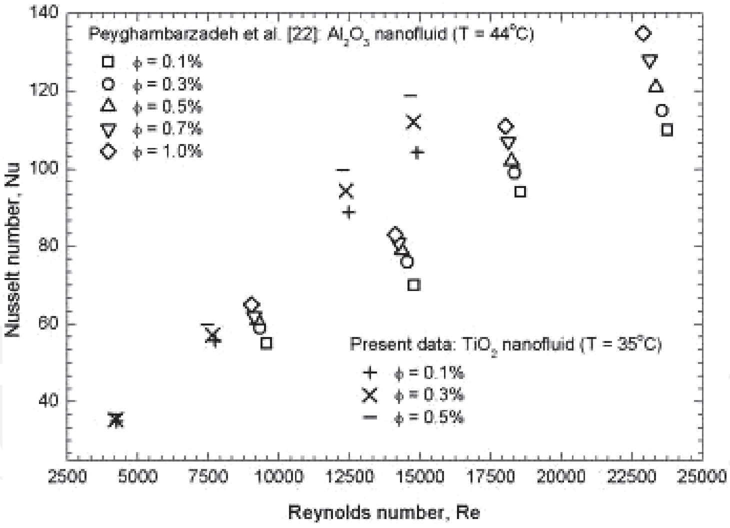


Figure 6.
Effect of titania nanoparticle concentration on Nu, and a comparison of results of Devireddy et al. [29] and Peyghambarzadeh et al. [30].

Titania has also been combined with other nanoparticles to form hybrid nanofluids that carry tunable thermal and optical characteristics. Abbas et al. [33] appraised the performance of avant-garde hybrid nanocoolant having Fe_2O_3-TiO_2 nanoparticles dispersed in water. They reported a 26.7% enhancement in heat transfer rate at a very low nanoparticle concentration of 0.009 vol.% due to the synergistic effect of ferric oxide and titania nanoparticles. The noteworthy finding of their study was that hybrid nanofluids produced quite impressive repeatability tests. They recorded as much as 3% deviation in heat transfer results when the experiments were performed after 12 hours of reference experimentation and 56°C inlet temperature and 15 LPM flow rate (**Figure 7**).

There are some major associated challenges as well when using nanocoolants in automotive cooling. Due to the presence of nanoparticles, there are chances of clogging, and due to high operating temperatures, the nanocoolant can become ineffective as it can cause clustering. High temperature also results in surfactant ineffectiveness. Successive heating and cooling of nanocoolant are also a challenge as it causes the development of thermal stresses.

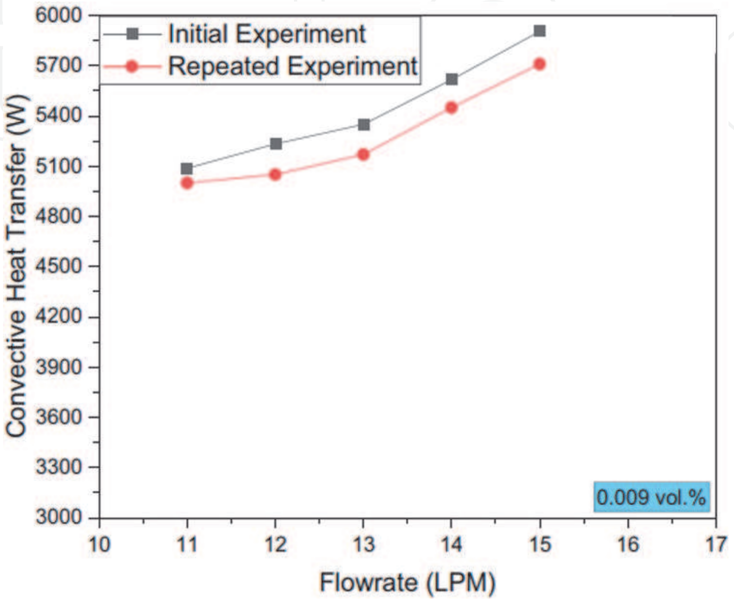


Figure 7.
Heat transfer repeatability test results of 0.009 vol.% Fe_2O_3-TiO_2/water automotive nanocoolant [33].

2.1.3 Thermal management of electronic components

Electronic devices/components produce a considerable extent of heat during their operation. Excessive heat generation causes performance deterioration; therefore, electronic devices/components require temperature regulation for smooth operation. Temperature regulation of these systems is carried out by cooling mechanisms. Conventionally, these components were cooled by air or water; however, modern cooling techniques use metallic heat sinks, nanofluids, heat pipes, and phase change materials [34]. The combined use of metallic heat sinks and nanofluids has been a subject of wide interest by researchers for the past couple of decades. Continuous efforts of researchers have brought massive innovation in heat sink designs. Modern heat sink designs include fins of various shapes and engraved micro/mini channels with different geometries to achieve efficient cooling [35].

Nanofluid and heat-sink-based electronic cooling setup used to evaluate the heat transfer effect has been presented in **Figure 8**. Babar and Ali [36] evaluated the performance of ferric oxide and titania-based nanofluids with pin fin heat sink for the sake of thermal management of electronics. They discussed the performance of nanofluids in terms of Nu and pressure drop/pumping power. They observed Nu improvement of 15.89% for Fe_2O_3/water nanofluid and 14.5% for TiO_2/water nanofluid at nanoparticle concentration of 0.01 vol.% as compared with water. However, the pumping power augmentation for TiO_2/water nanofluid was 30.5% and for Fe_2O_3/water, nanofluid 42.46% enhancement was recorded. Since titania is a corrosion inhibitor and water has no environmental disadvantages and the pumping power enhancement for titania-based nanofluids is also quite low as compared with the ferric oxide, they recommended the use of titania nanofluids for metallic heat sinks. Sajid et al. [37] reported 40.57% augmentation in Nu by using 0.012 vol.% TiO_2/water nanofluid with wavy-mini channel heat sink for electronic cooling. They reported an increase in Nu with increasing Re and nanoparticle loading (**Figure 9**). Arshad and Ali [38] analyzed the performance of TiO_2/water nanofluid in a straight mini channel heat sink. They reported the pressure drop to decrease with an increased heating power of the heating source since the viscosity of the nanofluid tends to decrease with the temperature rise. Qi et al. [39] also reported a drop in surface temperature of the spherically bulging aligned and staggered heat sinks when cooled by a titania-water nanofluid. Similar studies were conducted by Narendran et al. [40], Kumar et al. [41], Tariq et al. [42], and Nitiapiruk et al. [43].

2.1.4 Thermal management of buildings and energy saving

Titania has a high reflection index, and when it is used in paint/coatings for the exterior of buildings, it reflects the solar radiations and prevents the heating of the building. This, in turn, reduces the heating load and saves the cost of air-conditioning. The reflectance of sunlight by the titania nanoparticles has been presented in **Figure 10**. As it is evident in **Figure 10**, UV radiations are reflected by the titania nanoparticles and a minute portion of sunlight is absorbed by the particles, which results in a very minute flow of solar heat inside the buildings. Titania-implanted paints provide thermal resistance, brilliance, protection, and resistance against pollution. Future infrastructure planners are keen to make the modern residential and office buildings energy self-sufficient, which are named as Zero-Energy Buildings or Positive Energy Building with energy surplus [45]. These buildings make use of building integrated photovoltaic panels known as BIPVs [46]. BIPVs have been tested in many countries and have shown positive results. However, the challenge of uneven module temperature could be addressed via titania nanofluids as well [47].

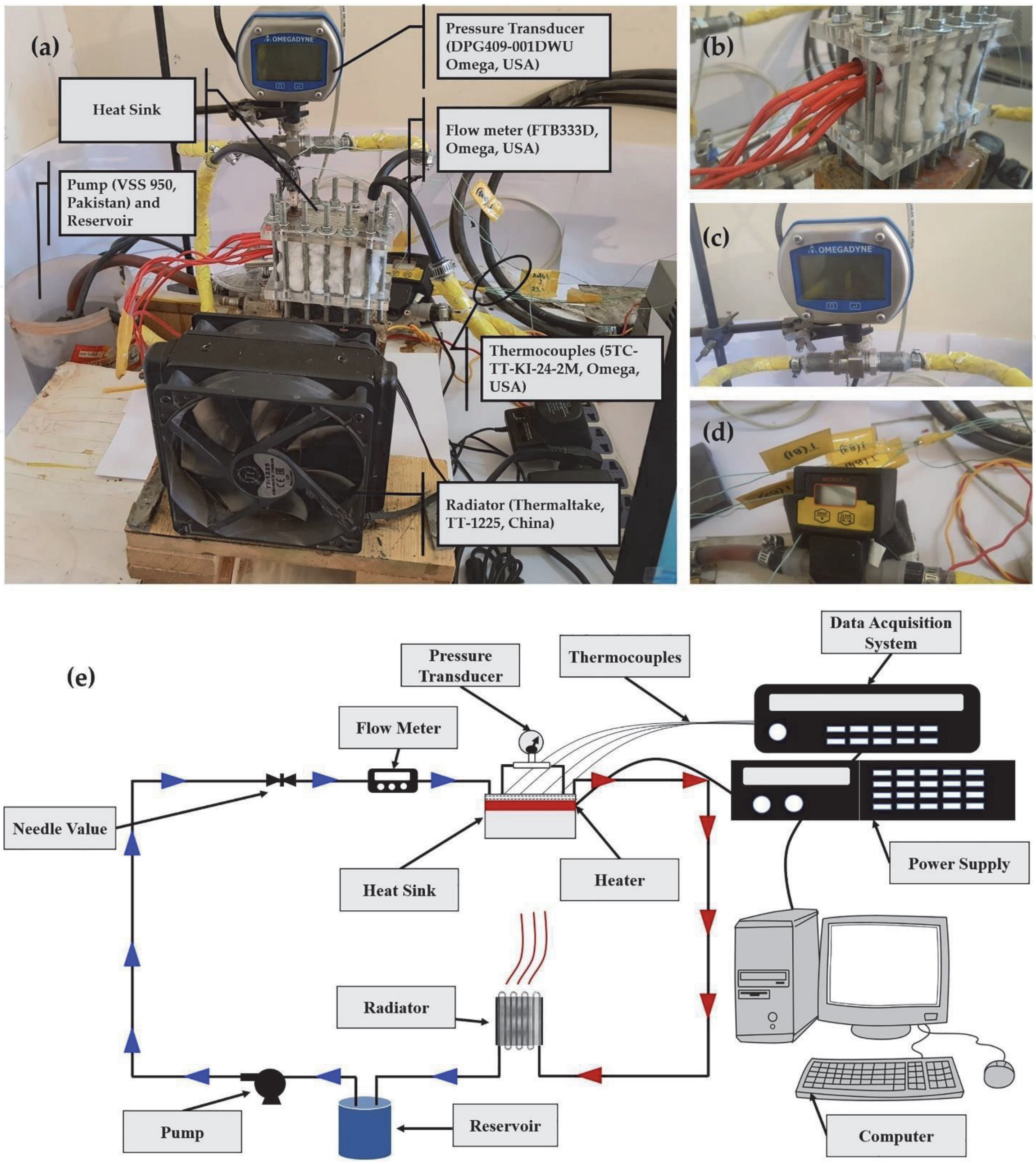


Figure 8.
Heat sink and nanofluid-based electronic cooling experimental setup [36].

2.2 Energy harvesting

Titania is also used for harvesting photoelectric and photothermal energy. The following sections discuss in detail the use of titania in various energy harvesting applications.

2.2.1 Photoelectric energy harvesting

Photoelectric energy is harvested by photovoltaic modules, and titania has also been used to fabricate PV modules for efficient electricity generation from solar energy. Dye-sensitized TiO_2 is used in Grätzel photoelectric solar cells to generate electricity from solar energy. Titania is the essential element of these solar cells. These photovoltaic modules were invented by Grätzel [48] and known as dye-sensitized solar cells (DSSC). The working mechanism of DSSC has been presented in **Figure 11**. These modules are cheaper and produce good efficiency. Initially, the

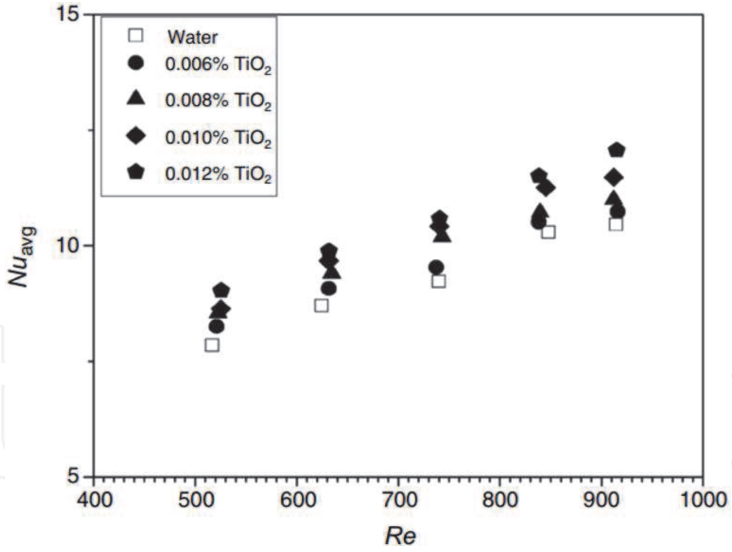


Figure 9.
Effect of Re and nanoparticle concentration on Nu at 35 W source power [37].

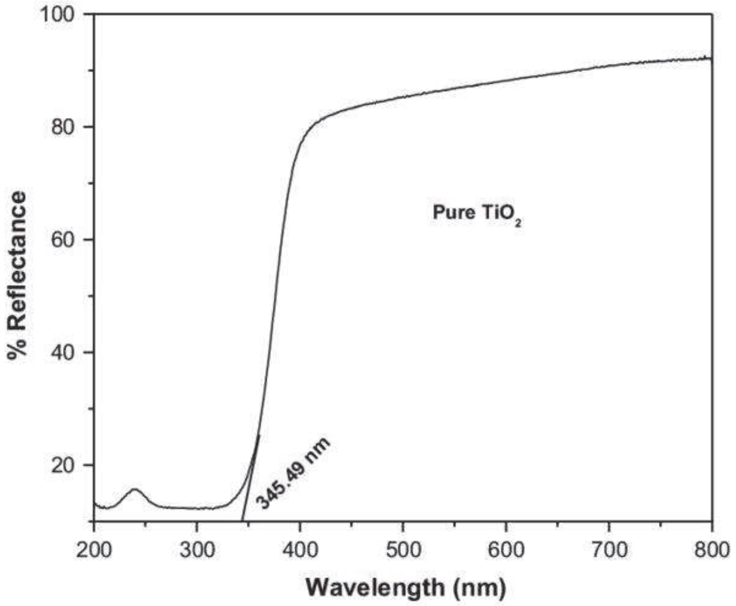


Figure 10.
Reflectance of titania nanoparticles [44].

efficiency of these modules was about 7% as reported by Kay and Grätzel [50]. Later on, the claim of achieving 7%, the photoelectric conversion efficiency was verified by Hagfeldt et al. [51]. The limited efficiency of these modules is attributed to very high resistance and losses due to the cells being in series and resulting in a lower fill factor. Kim et al. [52] conducted a detailed study on power conversion efficiency (PEC) evaluation of these cells and reported 9.4% PEC. Several studies have been conducted on these cells to analyze the performance and environmental and economic aspects [48, 53–56].

2.2.2 Photothermal energy harvesting

Photothermal energy harvesting is carried out by various types of solar collectors (**Figure 12**). The basic element of solar collectors is the receiver tube in which a fluid flows to capture the solar energy by absorbing solar radiations energy and converting it into heat energy through the photothermal conversion process. The

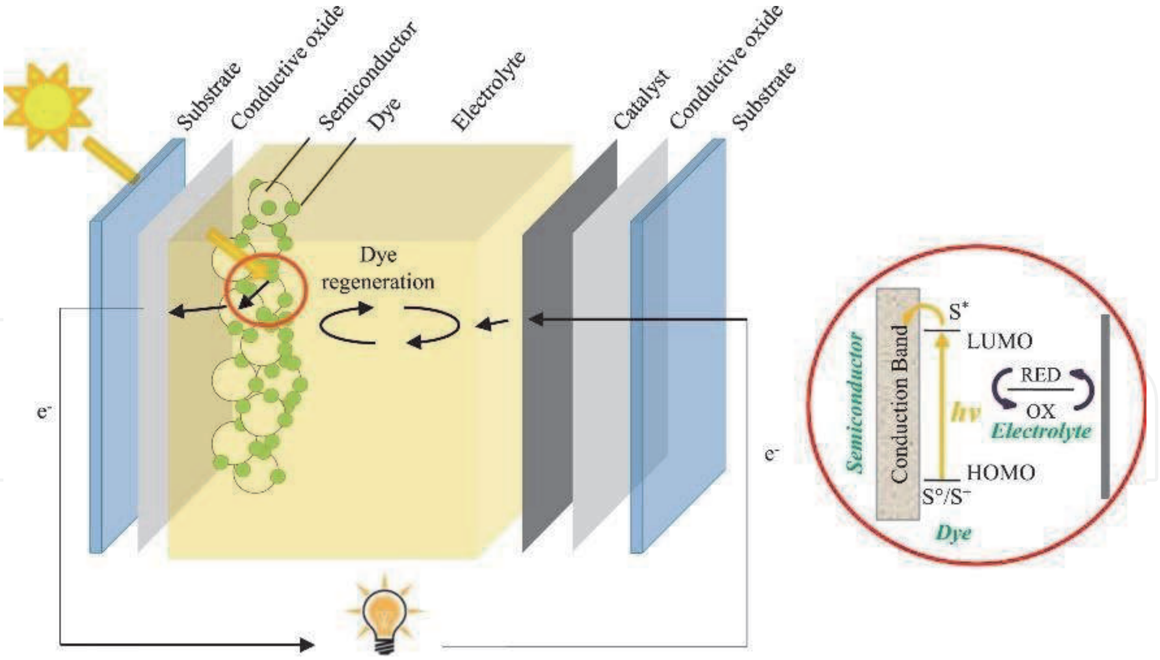
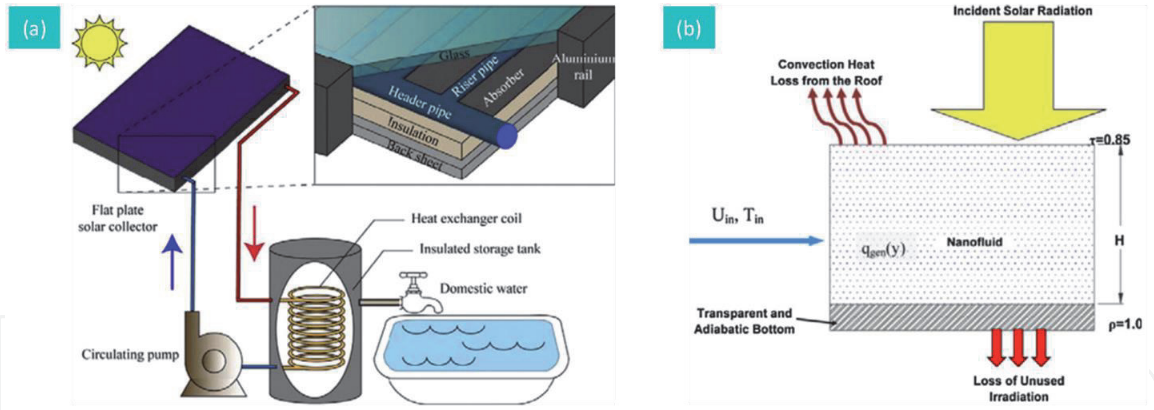


Figure 11.
Schematic illustration of DSSC [49].

photothermal efficiency of these collectors is mainly dependent on the material and geometrical characteristics of the receiver tube and the thermophysical and optical characteristics of the working fluid. Conventionally, water has been utilized as a working fluid in solar collectors; however, water has a very limited range of solar absorbance, which means the rest of the energy is wasted in the form of reflected energy and thermal losses.

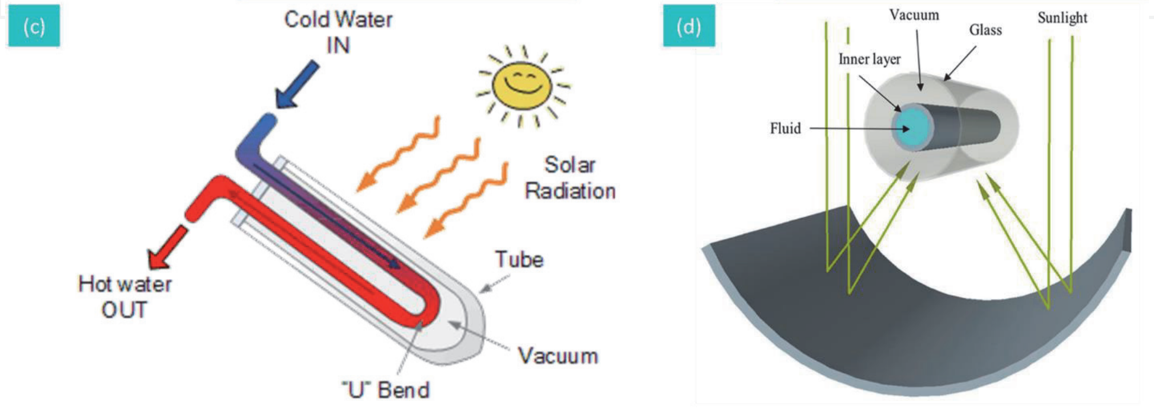
In the latest studies, nanofluids have been tested for photothermal conversion since the presence of nanoparticles increases the range of solar absorption, which results in increased thermal energy output and increased efficiency [58]. Moreover, the two types of nanoparticles are also dispersed in the base fluid (called hybrid nanofluids) to tailor the fluid's absorption range through the synergistic effect of different nanoparticle types [59]. Greater thermal conductivity and heat transfer coefficient of nanofluids also intensify the efficiency of solar collectors such as parabolic trough collectors. Since TiO_2 carries good thermal conductivity, titania-based nanofluids have widely been tested for photothermal energy conversion and heat energy transportation in solar collectors [60–62]. Titania depicts higher reflectance and smaller spectral absorbance. However, titania nanoparticles are used to broaden the spectral absorption range of water and other base fluids. Moreover, the combined use of titania nanoparticles with other types of nanoparticles in the base fluid further broadens the solar spectral absorption range and thermal efficiency of solar collectors (**Figure 13**).

Kiliç et al. [63] studied the performance of TiO_2/water nanofluid as a working fluid in a flat plate collector (FPSC). They obtained 48.67% topmost efficiency of the collector when using titania-water nanofluid, and the efficiency of the collector reached 36.20% in the case of water as working fluid. They attributed the efficiency increase to the increased heat transfer surface area and higher heat capacity of the nanofluid. Said et al. [64] also appraised the performance of FPSC using titania-water nanofluid and reported a 76.6% increase in energy efficiency at a 0.5 kg/min flow rate of 0.1 vol.% TiO_2/water nanofluid as compared with water. The topmost energy efficiency was observed to be 16.9%. They reported negligible enhancement in pumping power for nanofluid as compared with the base fluid. Tehrani et al. [65] analyzed the performance of ribbed FPSC using TiO_2/water nanofluid. Ribs



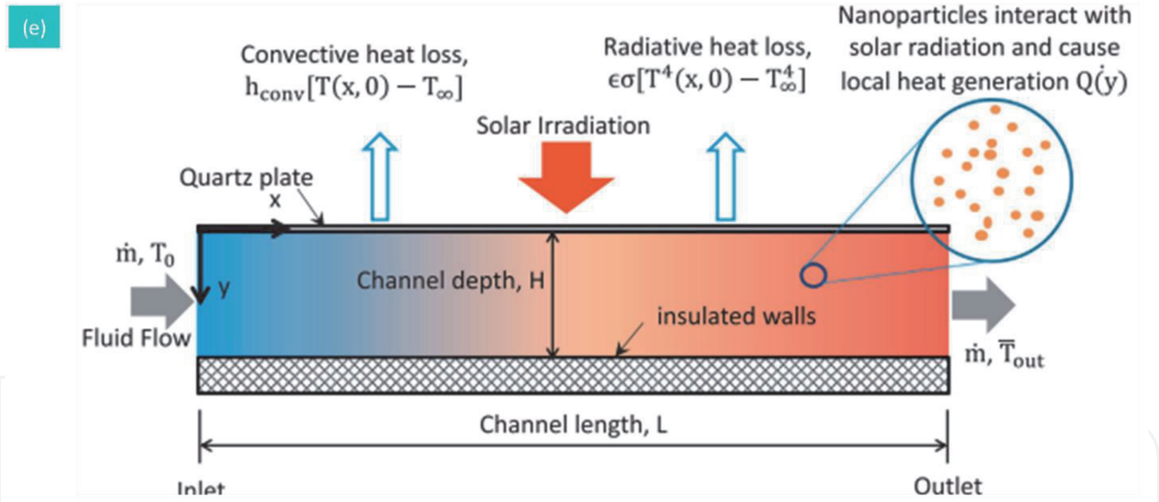
Flat Plate Solar Collector

Volumetric Solar Collector



Evacuated Tube Solar Collector

Parabolic Trough Solar Collector



Direct Absorption Solar Collector

Figure 12.
Photothermal energy-generating solar collector [57].

improved the performance of FPSC by 10%. They reported slight improvement with increasing nanoparticle concentration as well.

Gan et al. [66] appraised the performance of evacuated tube solar collectors ETSC using TiO_2/water nanofluid. They recorded a 16.5% increase in thermal efficiency of the collector by using optimized titania-water nanofluid as compared with the efficiency of the water-based collector. The obtained collector's thermal efficiency was 44.85%. An increase in nanoparticle concentration improved the thermal conductivity of the nanofluid, which resulted in higher thermal efficiency. Hosseini and Dehaj [67] also tested the performance of U-shaped ETSC using titania-water nanofluid. They evaluated the effect of titania particle shape on the collector's efficiency. TiO_2 nanowires (NWs) and nanoparticles (NPs) dispersed in

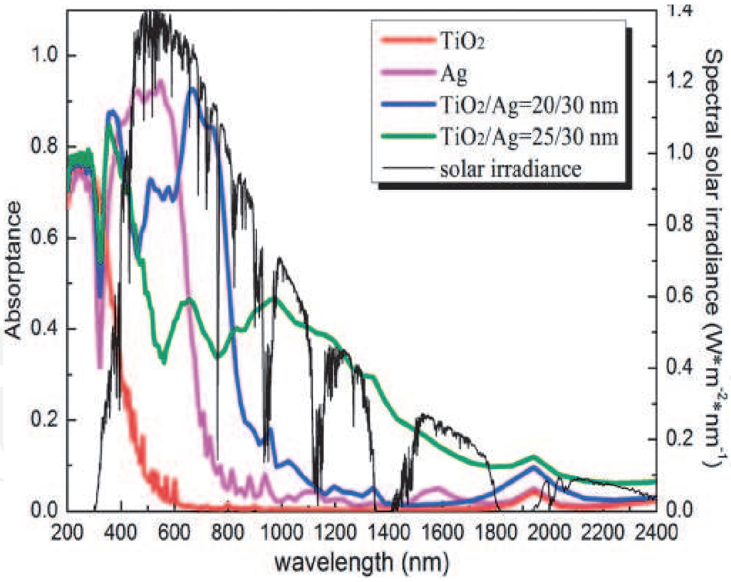


Figure 13.
Absorptance of titania, silver, and combined titania-silver [60].

the base fluid. Efficiency improvement of 21.1% for TiO_2 NWs nanofluid and 12.2% for TiO_2 NPs nanofluid was recorded. However, NWs nanofluid depicted a higher pressure drop.

2.2.3 Thermal energy storage

Titanium holds porous properties and a good ability to stay stable when impregnated in some chemical. Therefore, titania is extensively used in thermal energy storage applications. Thermal energy-storing phase change materials (PCMs) have good thermal storage capacity, but due to their small thermal conductivity, the rate of thermal storage is much slower, which causes them to store a small amount of thermal energy. The addition of titania nanoparticles improves their thermal conductivity, and therefore, the capacity to store thermal energy becomes much higher. Titania also provides chemical stability.

Fikri et al. [68] added titania nano-powder in paraffin wax (PW) PCM to overcome the challenge of low thermal conductivity and small spectral absorption. They also reported the thermal and optical advantages of adding titania in PCMs. Sun et al. [69] reported a 26% elevation in thermal conductivity of polyethylene glycol (PEG) PCM by adding titania nanoparticles.

The challenge associated with nano-enhanced PCMs is the deterioration of thermal conductivity and heat storage capacity due to the thermal cycles. Sami and Etesami [70] reported that the thermal conductivity of nano-titania enhanced PW-PCM dropped below the thermal conductivity of pure PW after several thermal cycles. Deterioration of characteristics takes place due to structural and chemical degradation. Chemically stable nano-PCMs are direly needed for the successful operation of PCMs. Deka et al. [71] impregnated TiO_2 powder in 1-tetradecanoic acid to prepare chemically stable composite-PCM. They observed good chemical stability through rigorous testing techniques. Due to the inclusion of titania, the thermal conductivity of PCM increased by 188% and latent heat storage (LHS) of 97.75 J/g at 52.04°C melting temperature was recorded of composite-PCM. However, after thermal cycling, the LHS declined by only 16.65%.

Another important aspect of PCMs is the time taken for melting and solidification. Common PCMs such as PW take very long to melt and solidify, which reduces the heat storage rate. Studies have suggested the combined use of metallic heat sinks and nanofluids with PCMs to increase the rate of the phase change process. Ding et al. [72] reported a 32.90% reduction in melting time and a 22.57% decrease in solidification time of PW PCM by incorporating a microchannel heat sink with 1.0 wt.% TiO_2/water nanofluid. An increase in nanoparticle concentration increased the rate of melting and solidification due to an increased rate of heat transfer. **Figure 14** represents the effect of varying nanoparticle concentration on Nu and melting and solidification time of PCM.

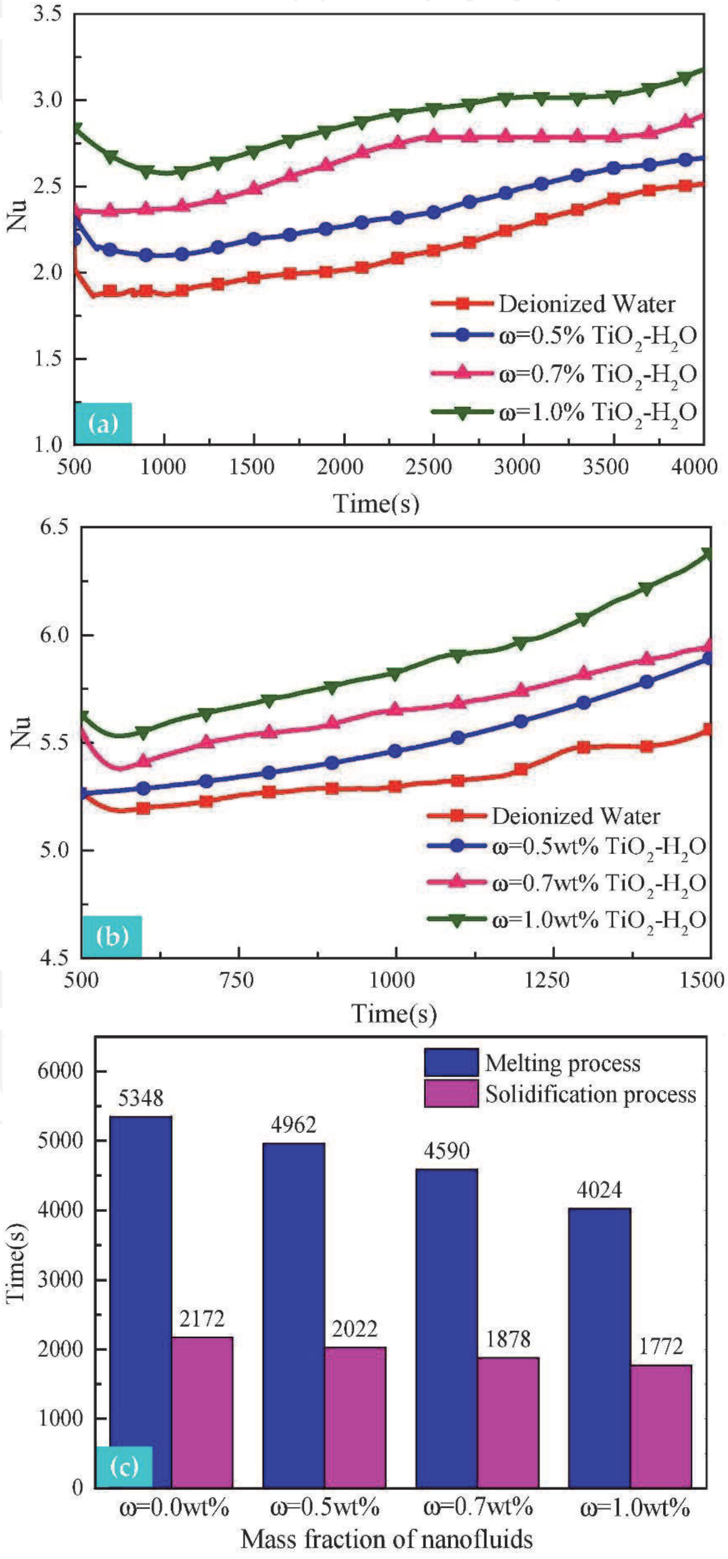


Figure 14.
Nu variation (a) during the melting process, (b) during the solidification process of PCM for different samples of nanofluid, and (c) time of melting and solidification of PCM [72].

3. Conclusions

The chapter presented an insight into the thermal utilization of titanium dioxide. Titania being an abundant metal with unique thermophysical and optical characteristics has been used in many applications for the past hundred years. Titania is expected to attain more advanced applications in the future due to its fascinating environmental and economic aspects. Important findings of the discussed research are as follows.

- Due to corrosion-resistant characteristics, titania is highly recommended for thermal applications such as thermal management systems, thermal energy harvesting systems, and surface coatings.

- High UV-rays reflectance characteristics make the titania best suitable for applications such as sunscreens, cosmetics, textile, and building coating.

- Owing to its semiconducting nature, titania is used in photoelectric solar modules called Grätzel solar panels.

- Titania carries unique optical characteristics; therefore, it is widely used for broadening the spectral absorption range of conventional optical fluids and advanced nanofluids.

- Titania provides chemical stability to the thermal energy storing PCMs and mitigates the effects of thermal cycling.

- Due to excellent thermophysical features, titania is extensively used in thermal transportation, thermal storage rate enhancement, and improving rate melting and solidification of PCMs. The combined use of titania nanofluid and metallic heat sinks is also employed to increase the melting and solidification rate.

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