Applications of Hybrid Nanofluids

Subjects: Engineering, Mechanical | Nanoscience & Nanotechnology | Mathematics, Interdisciplinary Applications
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In response to the issues of environment, climate, and human health coupled with the growing demand for energy due to increasing population and technological advancement, the concept of sustainable and renewable energy is presently receiving unprecedented attention. To achieve these feats, energy savings and efficiency are crucial in terms of the development of energy-efficient devices and thermal fluids. Limitations associated with the use of conventional thermal fluids led to the discovery of energy-efficient fluids called “nanofluids, which are established to be better than conventional thermal fluids. The research progress on nanofluids has led to the development of the advanced nanofluids coined “hybrid nanofluids” (HNFs) found to possess superior thermal-optical properties than conventional thermal fluids and nanofluids.

coolants efficiency energy storage hybrid nanofluids

1. Photothermal Performance of Hybrid Nanofluids

Studies on the thermal-optical properties (κ, μ, c_p, rheology, transmittance, thermal diffusivity, sun intensity, absorbance, and extinction coefficient) of HNFs (with and without the influence magnetic field) at different volume/weight concentrations, temperatures, and shear rates (where applicable). Additionally, short remarks on the key findings from the various studies compiled in this regard were provided in the table. The wavelength is observed to be directly related to the transmittance of the HNF. The addition of different kinds of HNPs at various mixing ratios into diverse base fluids is known to produce different HNFs with varying thermal and optical properties [1][2][3][4]. This is because the individual base fluid and NPs have different absorption capacities (at different wavelengths) and thermal properties lending to synergetic effects on these properties. A shift in the wavelength range (visible and near-infrared) and the peak is mostly observed due to the mixing of different NPs [5][6][7][8]. For broadband absorption to be achieved, a combination of diverse absorption peak HNFs was engaged.

Using DIW-based HNFs (Au (0.5–2.5 ppm) + Ag (0.15 and 0.5 ppm)) as thermal fluids, Chen et al. [9] studied the absorptance, SAR, and photo-thermal performance in DASCs. They observed that the temperature change of DIW-based Au (1.75 ppm) + Ag (0.15 ppm) NF was 15.61% and 8.98% higher than those of Ag (0.15 ppm) and Au (1.75 ppm) NFs, respectively. Increasing the concentration of Au in the DIW (45 °C) was noticed to improve the temperature of Au/DIW (2.5 ppm) NF (64 °C). The PTEC efficiency of 30.97%, 19.01%, and 11.90% was obtained for Au (1.75 ppm) + Ag (0.15 ppm), Au (1.75 ppm), and Ag (0.15 ppm) NFs respectively. The PTEC efficiency of the HNF translated to the sum of the individual efficiency of the MNFs. It was observed that the estimated (43.72 W/μL) and predicted SAR (43.81 W/μL) of Au (1.75 ppm) + Ag (0.15 ppm) NF based on the individual SAR values of Au (1.75 ppm) and Ag (0.15 ppm) NFs and PTEC performance of the HNF were almost equal. Carrillo-Torres et al. [10]

studied the thermal stability and PTEC efficiency of Au-Ag NPs dispersed in water as thermal fluid in solar collectors. This experiment was conducted by exposing the test samples to laser light and the PTEC efficiency was calculated using the existing energy balance model. They reported that temperature change was enhanced as irradiation time, optical density, and heating profile increased. Using the HNF, maximum PTEC efficiency of 74.68% was obtained while a temperature of 20 °C was recorded after exposing the HNF to 15 min of irradiation. Furthermore, the HNF showed no significant change in optical properties after 12 h exposure to irradiation and 10 cycles of cooling/heating, thus, indicating thermal stability.

Chen et al. [11] examined the effect of mixing ratio (1:9–9:1) and *φ* (0.02–0.12 vol%) on the SWEA and PTEC efficiency of DIW-based CuO-ATO NFs in a solar collector. Alaboratory-based simulator was used in the experiment while the PTEC efficiency was evaluated based on the energy balance during the testing process. The temperature change, absorption coefficient, transmittance, SWEA fraction, and PTEC efficiency were noticed to be strongly related to the mixing ratio and *φ* of the HNFs. Increasing the solar radiation exposure of CuO-ATO NFs was noticed to increase temperature change until 7000 s, after which a decline was observed. At an optical distance of 1 cm, optimum absorption coefficient, transmittance, and SWEA fraction were attained with 0.12 vol% CuO-ATO (4:6) NF whereas optimum temperature change and thermal efficiency were reached using 0.1 vol% CuO-ATO (4:6) NF. Peak SWEA fraction, temperature change, and PTEC efficiency of 99.6%, 43.6 °C, and 92.5% were obtained for CuO-ATO NFs against 89.5%, 39.8 °C, and 81.3% and 89.8%, 39.6 °C, and 80.7% recorded for CuO and ATO NFs, respectively. Menbari et al. [12] deployed water and EG-W-based Al_2O_3-CuO NFs as working fluids in a DASC and examined the influence of base fluid type (water and EG-water), *φ* (0.002–0.008% (CuO) and 0.05–0.2% (Al_2O_3)), and volume flow rate (10–100 L/h) on the thermal efficiency. In addition, stability parameters (surfactant mass fraction, sonication time, and pH) on the absorbance and κ of the HNFs were measured. Their results demonstrated that stable HNFs were observed at high and low values of κ and absorbance. An increase in flow rate caused a reduction in temperature difference and outlet temperature while it enhanced inlet temperature and thermal efficiency. A rise in *φ* was demonstrated to improve temperature change, solar irradiation, and thermal efficiency. Both the solar irradiation and thermal efficiency of the collector were noticed to be higher for water-based HNFs than EG-water-based HNFs.

Khashan et al. [13] experimented the PTEC efficiency of DIW and DIW-kerosene-based Fe_3O_4-SiO_2 NFs (1 mg/mL and 2 mg/mL) as thermal fluids in a solar collector. The test samples were exposed to irradiance via a solar similar and the estimation of the PTEC efficiency was carried out using the energy balance empirical equation. Results showed that after 10 min exposure of DIW, Fe_3O_4 (1 mg/mL), and Fe_3O_4-SiO_2 (1 mg/mL) NFs to solar irradiation, the difference in temperature between the top and bottom surface of the collector was 1.4 °C, 2.7 °C, and 3.2 °C, respectively. After 65 min of irradiation, the surface temperature of DW and Fe_3O_4-SiO_2 (1 mg/mL) NF increased by 9.2 °C and 12.7 °C, respectively. This was due to an increase in the absorption capacity of Fe_3O_4-SiO_2 NF. At different collector heights and after 10 min of irradiation, PTEC efficiency of 10–17%, 27–83%, and 30–89% was obtained using DW, Fe_3O_4, and Fe_3O_4-SiO_2, respectively. With 300 min of irradiation on the Fe_3O_4-SiO_2 (1 mg/mL) NF + kerosene mixture, the part with kerosene alone and that with Fe_3O_4-SiO_2 (1 mg/mL) NF recorded top and bottom temperatures of 50.7 °C and 47.8 °C and 57.3 °C and 55.5 °C, respectively. Additionally, after 5 min of irradiation, PTEC efficiency of 65.6%, 85.4%, and 98.5% was attained with DIW, kerosene + 2 mg/mL Fe_3O_4-SiO_2

NF, and kerosene + 1 mg/mL Fe_3O_4-SiO_2 (1 mg/mL) NF, respectively. The authors recommended similar future research using kerosene-based HNFs.

The utilization of DIW-based CuO-ZnO (70:30 and 50:50) NFs with φ = 0.001–0.01% as thermal fluids in solar collectors was investigated by Fang and Xuan [14] for their thermo-optical properties and PTEC efficiency. A simulated sunlight with an irradiance of 1000 W/m^2 was used while a self-designed device was engaged to evaluate the PTEC efficiency. As transmittance is inversely proportional to absorbance, increasing φ was noticed to improve absorbance, κ, and EC for all the tested samples. Peak absorption and κ were observed for CuO and CuO-ZnO (70:30) NFs, respectively. At the optical depth of 1 cm and φ = 0.01%, maximum SWEA efficiency and temperatures of 99.47% and 71.62 °C (CuO/DIW NF), 98.67% and 72.65 °C (CuO-ZnO (70:30)/DIW NF), and 94.78% and 71.81 °C (CuO-ZnO (50:50)/DIW NF) were obtained, respectively. Maximum PTEC efficiency of 97.4% (30 °C) and 34.7% (70 °C) was reported for CuO-ZnO (70:30)/DIW NF. Yu and Xuan [15] examined the influence of volume fraction (0.015–0.025%) and mixing ratio (7:3 and 8:2) on the absorbance and PTEC efficiency of CuO-Ag/DIW NFs engaged as thermal fluids in a DASC. A solar simulator was used to provide irradiance and the PTEC efficiency was calculated using an existing and applicable equation. They reported that the absorbance of the CuO-Ag/DIW NFs was higher than those of CuO/DIW NFs and DIW and it improved with volume fraction increase. The HNFs with a mixing ratio of 7:3 were noticed to produce higher absorbance, temperature change, and PTEC efficiency than those of 8:2. As the concentration of the HNFs (with a mixing ratio of 7:3) and solar irradiation (till 7000 s) increased, temperature change and PTEC efficiency improved. At a volume fraction of 0.025% and irradiation of 7000 s, the highest temperature change and PTEC efficiency of 34.1 °C and 96.11%, respectively, were recorded using CuO-Ag (7:3)/DIW NF as a thermal fluid.

Hjerrild et al. [16] experimented with the stability, thermal treatment, and optical properties of GL-based Ag-SiO_2 NF as a liquid optical filter applied in PV/T collectors. The test samples were exposed to concentrated UV irradiation. They found that the HNF was stable under medium thermal treatment (125 °C) and accelerated high UV irradiation (300–1500 nm) exposure. The Ag-SiO_2/GL NF was noticed to be applicable in a PV/T collector with high temperature and electrical output. Additionally, the Ag-SiO_2/GL NF was observed to considerably enhance light transmission in comparison with Ag-SiO_2/W NF coupled with its low price and wide range of temperatures. Zhou et al. [6] studied the use of GO-Au/DIW NFs at φ = 0.1–0.3 mg/mL as thermal media for steam generation. A solar simulator was used as the light source while a self-built device was used to estimate the PTEC efficiency. They showed that 0.2 mg/mL-GO-Au/DIW NF was the best thermal fluid with the highest evaporation rate, enhancement factor, and PTEC efficiency of 1.34 kg/m^2 h, 2.35, and 84.1%, respectively. The observed results were strongly linked to 0.2 mg/mL-GO-Au/DIW NF possessing the highest absorption characteristics. HNFs of GO-Au/DIW were demonstrated to be better than the MNFs of Au/DIW and GO-DIW as working fluids for solar steam generation. The solar steam generation efficiency of GO-Au/DIW NF (0.2 mg/mL) was 20% higher than GO/DIW NF. Using the same light illumination, the temperature of Au-GO/DIW (0.2 mg/mL) NF was found to be 8–10 °C higher than DIW. The authors stressed the potential application of GO-Au/DIW NFs to include power generation, seawater desalination, and sterilization of waste.

Zeng and Xuan [17] studied the κ and PTEC effectiveness of DIW-based MWCNT-SiO_2/Ag NFs (0.001–0.1%) with mixing ratios of 4:1–1:4 as operating fluids in volumetric solar collectors. To measure the PTEC efficiency, a simulative volumetric solar thermal conversion device was used with the test samples opened to a solar simulator as the light source. They showed that the SWEA fractions of DIW-based MWCNT-SiO_2/Ag NFs ranged from 71.4% to 74.5% with mixing ratios of 4:1 and 1:4 having the highest and lowest values. However, 73.2% and 69.1% were obtained for DIW-based MWCNT and SiO_2/Ag NFs. On exposure to irradiation for 1 h, temperatures of 48.1–59.3 °C, 47.7–56.6 °C, and 48.6–62.3 °C were recorded for MWCNT, SiO_2/Ag, and MWCNT-SiO_2/Ag (with volume fractions of 0.001–0.1%) NFs, respectively, and 46.9 °C for DIW. The HNFs attained maximum PTEC efficiency of 97.6% and 42.7% at 35 °C and 70 °C, respectively. This indicated that the HNFs have higher PTEC efficiency than MNFs and that the PTEC efficiency was reduced with temperature increase. The obtained results were strongly connected to the higher κ and absorbance values recorded for the HNFs in comparison with MNFs and DIW. Shi et al. [5] studied the PTEC and purification capability of Fe_3O_4-TiO_2/DIW NF with φ = 0.1 g/L in solar energy applications. The experiment exposed the HNFs to a solar simulator and the PTEC was evaluated using an empirical equation. The results proved that with increasing solar power intensities (1–10 suns), the thermal receiver efficiency was observed to reduce while the degradation and evaporation (at a steady-state) efficiency slowly increased. At 1 sun, maximum thermal receiver efficiency of 76.4% and degradation efficiency of 85% were recorded. A magnetic field was used to recover the HNPs of the HNF for purification purposes and this led to recovery efficiency of 47.4% and 94.0% with a magnetic field intensity of 25 mT and 100 mT, respectively. After 1200 s, total material recovery was achieved under magnetic field influence and no change in the material was observed in the absence of the magnetic field.

The possible manipulation of the thermal, optical, and photothermal properties of various NFs (TiN, Fe_3O_4, and Fe_3O_4-TiN with volume fractions of 0.005–0.04%) under diverse magnetic field strengths and orientations were investigated by Zeng and Xuan [18]. A simulative volumetric solar thermal conversion set up was used to measure the photo-thermal property of HNFs. They demonstrated that transmittance decreased with an increase in φ whereas the opposite was observed for absorbance. A rise in the temperature of the studied samples was noticed as solar irradiation time and φ increased. With 1 h solar irradiation time and volume fraction of 0.005%, the SWEA fraction and temperature (of studied NFs) increment order of Fe_3O_4-TiN > Fe_3O_4 > TiN was observed. The parallel configuration of the incident light and magnetic field direction was noticed to produce better results than the perpendicular case, except for the absorbance where further reduction was recorded. Under magnetic field exposure, the SWEA fraction, and temperature of Fe_3O_4-TiN and Fe_3O_4 NFs were reduced with increasing magnetic field strength. The obtained findings (under magnetic field influence) were due to the improvement of their κ values and this revealed the potential alteration of absorbance, absorbed solar energy, PTEC performance, and heat transfer of magnetic HNFs for solar applications.

Qu et al. [19] examined the optical properties and PTEC performance of CuO (0.01–0.25 wt%)-MWCNT (0.005–0.0015 wt%)/DIW NFs. Light from a solar simulator was beamed on the test samples for the photothermal property of the samples. The results proved that the transmittance decreased as the concentration of the HNFs increased but the EC enhanced with it. Using DIW-based 0.15 wt% CuO + 0.005 wt% MWCNT NF and at an optical penetration of 1 cm and solar radiation time of 45 min, the SWEA fractions of HNF were 99.2%. The highest terminal temperature surge (14.1 °C) was reached at the optimum mixing ratio of the HNFs and irradiation time of 45 min, in comparison with DIW. The use of HNFs, especially at the optimum mixing ratio yielded working fluids with better PTEC performance than MNFs (in this case DIW-based CuO and MWCNT NFs). The stability, optical, and thermal properties, and PTEC efficacy of DIW-based rGO, rGO-Ag (15), and rGO-Ag (30) NFs at varying concentrations (10–100 mg/L) as thermal fluids in a DASC, were examined by Mehrali et al. [20]. A solar simulator was engaged as a light source in the experiment. An evaluation of the PTEC efficiency was carried out using an established empirical equation. The absorbance, EC, and SWEA fraction of the MNF and HNFs were noticed to improve with concentration while the transmittance decreased with concentration. With an irradiation time of 2000 s, the highest change in temperature on the surface (top) of the collector was 24 °C, 27.4 °C, and 28.6 °C for rGO, rGO-Ag (15), and rGO-Ag (30) NFs, respectively. In addition, PTEC efficiency of 63.3% (at 80 mg/L), 78% (at 100 mg/L), and 77% (at 40 mg/L) was achieved with rGO, rGO-Ag (30), and rGO-Ag (15) NFs, respectively, at 1 sun irradiation and 2000 s irradiation time. The best candidate for DASC application based on cost was rGO-Ag (15) NF with 40 mg/L concentration and 20 mm collector height.

The PTEC performance, SAR, and cost of the deployment of DIW-based Au, Cu, carbon black, and Au-Cu NFs as thermal fluids in DASC were examined by Zeiny et al. [21]. Light was beamed on the test samples using a sun simulator while the PTEC efficiency was estimated using an empirical equation. They observed that increasing the irradiation time slightly increased the temperature of the studied samples while an increase in mass concentration moderately enhanced the temperature of the samples. The PTEC efficiency and enhancement were enhanced as the mass concentration of the MNFs and HNF increased but they decreased as irradiation time increased. Additionally, the SAR and cost of the MNFs reduced and increased with concentration increase, respectively. With PTEC efficiency of 125%, 72%, and 100% for carbon black (100 mg/L), Au (150 mg/L), and Cu (3000 mg/L) NFs, respectively, the HNFs did not show an increase in this parameter. Based on SAR and cost values, the carbon black NF appeared to be the best MNF. Bhalla et al. [22] experimented the PTEC characteristics of DIW-based Al_2O_3 (20–150 mg/L) + Co_3O_4 (20–80 mg/L) NFs in DASCs using surface absorption and blended NF absorption systems. An artificial light source was used to simulate solar irradiation. The effectiveness of these systems was performed under similar working conditions. The results proved that the HNFs have an SWEA fraction of over 80% at a penetration depth of 20 mm. The addition of different mass fractions of Co_3O_4/DIW NFs to various fixed mass fractions of Al_2O_3/DIW NFs showed an increase in the SWEA fraction. At an optimum mass fraction of 40 mg/L Al_2O_3 + 40 mg/L Co_3O_4 NF, the peak temperature rise was attained with the HNFs as thermal media. Under similar working conditions, the blended NF absorption system was observed to yield a higher temperature (5.4 °C) than the surface absorption system due to the deployment of HNFs, therefore, making them good candidates for DASC.

Silicone oil-based ZnO-Au NFs with φ = 0.1–1.0 mg/mL were deployed to examine the optical properties and PTEC performance under varying irradiation duration and intensities [23]. The tested HNFs were subjected to simulated solar radiation. PTEC efficiency was estimated using an empirical equation. Results proved that the transmittance of the studied sample decreased with φ while the EC was enhanced with φ. Increasing solar radiation time, φ, and height (from the bottom of the beaker) improved the temperature of the studied samples at a stirring rate of 1000 rpm. On exposure of the silicone oil-based ZnO-Au NFs (φ = 1.0 mg/mL) to 10 kW/m^2 solar radiation for less than 1 h, the temperature was raised to around 125 °C. The PTEC efficiency of 36%, 49%, and 60% was obtained for

ZnO-Au/silicone oil NFs with concentrations of 0.1, 0.5, and 1 mg/mL, respectively. In comparison with silicone oil (17%), PTEC efficiency improvement of 240% was achieved using 1 mg/mL ZnO-Au/silicone oil NF. Increasing the solar radiation intensity was observed to enhance the temperature of 1 mg/mL ZnO-Au/silicone oil NF. They demonstrated that ZnO-Au/silicone oil NFs were effective working fluids for application in DASCs.

Using EG-based FeNi/C NFs with concentrations of 5–50 ppm, Wang et al. [24] investigated their optical properties and PTEC performance under forced convection flow conditions in the absence and presence of a rotating magnetic field (50 mT). The HNFs were exposed to simulated solar radiation as the PTEC efficiency was evaluated using an equation. Results revealed that an increase in concentration led to the enhancement of EC and SWEA fraction and a reduction in transmittance for the studied samples. At an optical depth of 1 cm, absorbed energy was observed to appreciate with an increase in concentration and irradiation time. With solar irradiation time of 3600 s, the FeNi/C-EG NFs recorded absorbed energy of 1024.9 J, 1088.3 J, 1036.4 J, and 1022.4 J (without magnetic field) and 1069.9 J, 1233.6 J, 1269.2 J, and 1254.8 J (with the magnetic field) at 5 ppm, 15 ppm, 25 ppm, and 50 ppm, respectively, in comparison with EG (872 J). In addition, PTEC efficiency of 47.4%, 50.4%, 47.9%, and 47.3% (without magnetic field) and 49.5%, 57.1%, 58.7%, and 58.1% (magnetic field) was obtained for FeNi/C-EG NFs at 5 ppm, 15 ppm, 25 ppm, and 50 ppm, respectively, as compared with EG (40.4%). The magnetic field manipulation of the magnetic FeNi/C-EG NFs as working fluids in a DASC appears to improve its PTEC efficiency. Gulzar et al. [25] investigated the doping of a high-temperature thermal fluid (therminol-55) with Al_2O_3, TiO_2, and Al_2O_3-TiO_2 NPs as working fluids for concentrated solar collectors. To estimate the photothermal energy conversion, the test samples were subjected to simulated solar radiation as a light source. The MNFs and HNFs were formulated at weight concentrations of 0.05–0.5 wt% and subsequently studied the increase in heat gain, temperature, and temperature enhancement. Results demonstrated that due to higher absorption, maximum PTEC (heat gain) was observed with the HNFs followed by Al_2O_3 and TiO_2 NFs. Though TiO_2 NFs yielded the highest absorbance, Al_2O_3-TiO_2 and Al_2O_3 NFs showed maximum temperatures of 158.6 °C and 152.9 °C, respectively, compared with 149.6 °C for TiO_2 NFs and 125.8 °C for therminol-55. With the same irradiation time of 5000 s, a peak temperature improvement of 34 °C was noticed with 0.5 wt% Al_2O_3-TiO_2/therminol-55 NF. For both Al_2O_3 and TiO_2 NFs, increasing the weight concentration was observed to increase the maximum temperature enhancement.

Zhu et al. [26] examined the utilization of EG-based ZNGs, Au/, Ag/, and Ag-Au/ZNGs NFs (with concentrations of 10–100 ppm) as working fluids in DASC systems. With the use of a laboratory-built device, the PTEC efficiency was evaluated. A solar simulator was utilized as a source of light beamed on the tested samples. The optical properties and the PTEC capacity of the MNFs and HNFS were studied. With an increase in the concentration of the MNFs and HNFs, the SWEA fraction and EC were enhanced while the transmittance was reduced. This led to the improvement of PTEC efficiency with a rise in temperature, irradiation time, and concentration for all the studied samples due to the plasmonic effect and hybridization of HNPs. At an optical depth of 1 cm, a concentration of 100 ppm, and solar irradiation of 3000 s, SWEA fraction and PTEC efficiencies of 90.1%, 94.9%, 95.4%, and 97.1% and 69.25%, 70.35%, 72.41%, and 74.35% were obtained for ZNGs, Ag/, Au/ and Ag-Au/ZNGs NFs, respectively. The temperature of Ag/, Au/, and Ag-Au/ZNGs NFs were more than that of ZNGs, with Au/ZNGs NFs having the highest temperature (58.61 °C).

For a PV/T system, He et al. [27] examined the SWEA and PTEC performance of EG-W (60:40)-based Ag-TiO_2 NFs with concentrations of 50–200 ppm as beam-splitter in a temperate region. A theoretical model based on energy balance was used to evaluate PTEC efficiency. A solar simulator was deployed as a light source to illuminate the test samples. The transmittance and absorbance were inversely and directly proportional to the concentration of the HNFs. After 35 min of exposure to solar radiation, the temperature of Ag-TiO_2 NFs (200 ppm) was increased to 16.6 K. The current and power density were noticed to improve as voltage decreased and increased, respectively, while a reduction in concentration enhanced the current and power density of all the samples. The PTEC efficiency of Ag-TiO_2 NF (at 200 ppm) and EG-W (60:40) was 39.9% and 78.1%, respectively, while the PV efficiency was 5.6% for Ag-TiO_2 NF (at 200 ppm). The overall PTEC efficiency of Ag-TiO_2 NF was 70.7%, 74.8%, and 83.7% at concentrations of 50, 100, and 200 ppm whereas 54.1% was recorded for EG-W (60:40). With higher merit functions of 1.89 (50 ppm), 1.91 (100 ppm), and 2.04 (200 ppm) for the HNF-based splitters compared with 1.64 for the base fluid, coupled with worth factor of 3 for Ag-TiO_2 NF (at 200 ppm), the HNF-based splitter at the highest concentration appeared suitable for PV/T applications.

Campus et al. [28] studied the thermal and optical properties, and PTEC performance of water-based spherical (Au, Cu, and Ags), non-spherical (Agc, GOh, and GOl), and hybrid (GOl-Ag) NFs as working fluids in DASC. The influence of particle types and shapes, natural and artificial irradiation, irradiation time (600 s and 3000 s), and concentration (40 mg/L and 100 mg/L) on the PTEC efficiency were studied. They noticed that SWEA efficiency increased with a decrease in temperature while the temperature change increased with irradiation time. With 1 sun and irradiation of 3000 s, an order of GOl-Ag NF (91%) > GOl NF (73%) > GOh NF > Agc NF (71%) > Au NF (65%) > Cu NF (60%) > Ags NF (40%) was observed for the SWEA efficiency under different concentrations of 40 mg/L and 100 mg/L. The subjection of the MNFs and HNFs to natural solar irradiation (high flux) for 600 s resulted in a higher influence of the NPs shapes on the temperature difference and SWEA efficiency in comparison with artificial irradiation of 1 sun for 3000 s.

For the first time, an attempt was made by Kimpton et al. [8] to investigate the optical and stability properties and PTEC efficiency of water-based Ag, Ag-SiO_2, and SiO_2 NFs under natural and simulated solar exposure. Simulated sunlight was deployed as a light source in the experiment while the PTEC efficiency was estimated using the applicable existing equation. Results demonstrated the instability of Ag-SiO_2 and Ag NFs on exposure to natural solar irradiation, with a higher tendency observed for Ag NF. With all the studied samples and under simulated solar irradiation, the temperature change rose as irradiation time increased. The highest temperature was observed with Ag NF (44.1 °C), followed by Ag-SiO_2 NF (41.7 °C) and SiO_2 (23.6 °C), with corresponding enhancements of 102%, 91%, and 8% in comparison with water (21.8 °C), respectively. The PTEC efficiency of Ag-SiO_2 and Ag NFs was around three-fold more than that of SiO_2 NF. The stability, optical properties, SWEA, and PTEC performance of therminol®66-based GO-MWCNT NFs (with φ = 10–150 ppm) as potential working fluids in a DASC under indoor and outdoor conditions were studied by Qu et al. [29]. Tested samples were subjected to simulated and real sunlight and the evaluation of the PTEC efficiency was calculated using an empirical equation. Similar to other studies, increasing φ enhanced EC and SWEA fraction and reduced the transmittance of the studied samples. Maximum temperature and PTEC efficiency were accomplished with HNF at an optimum concentration of 100 ppm. At an optical depth of 1.75 cm, a concentration of 150 ppm, and a solar radiation time of 45 min, 99% SWEA capacity was recorded. Under indoor and outdoor conditions, the temperature of 100 ppm-GO-MWCNT/therminol®66 NF was 94 °C and 153 °C and 11.6 °C and 97 °C higher than therminol®66, respectively.

2. Solar Energy Application of Hybrid Nanofluids

2.1. Direct Absorption Solar Collectors

The influence of flow rate (20–100 cc/min) and mixing ratio (1:0–0:1) of DIW-based CeO_2-CuO NFs (with φ = 0.1 vol%) on the thermal performance of a DASC was experimented in an outdoor and indoor environment under constant irradiation by Mohan and Sajeeb [30]. They showed that the thermal efficiency of the studied samples was enhanced as the flow rate increased while the same was improved as the mixing ratio of CuO NPs in the HNFs increased from 0.5 to 1.0 and as the CeO_2 mixing ratio decreased from 1 to 0. In comparison with DIW and at a flow rate of 100 cc/min, the thermal efficiency of 13.8%, 18.1%, 24.3%, 24.9%, and 26.1% was obtained for the HNFs with mixing ratios of 1:0, 1:0.5, 1:1, 0.5:1, and 0:1, respectively. With the CeO_2-CuO (1:1)/DIW NF, increasing the flow rate (20 to 100 cc/min) enhanced thermal efficiency by 16.5–51.5%. Additionally, at a flow rate of 100 cc/min, the thermal efficiency of CeO_2-CuO/DIW NF was enhanced from 45.5% to 51.5%, when the mixing ratio of the HNF changed from 1:0 to 0.5:1. It was noticed that under indoor conditions, the thermal efficiency of all samples was improved as the flow rate increased with DIW-based CuO NF recording 35.4% thermal efficiency as the flow rate increased from 20 cc/min to 100 cc/min. It was observed that for the mixing ratios of 0:1, 1:1, and 0.5:1, the efficiency was almost the same.

Hong et al. [31] experimentally explored the efficiencies and solar vapor generation rates of HNFs (rGO + Ag, GO + Ag, rGO-Ag, and GO-Ag) with varying concentrations (0.113–1 mg/mL) under different light intensities (1–4 suns) as working fluids in different DASCs. The results showed that water mass loss increased as illumination time and concentration increased. Additionally, the relative efficiency and evaporation rate were observed to enhance with concentration increase. An order of rGO + Ag NFs > GO + Ag NFs > rGO-Ag NFs > GO-Ag NFs was noticed for the water mass loss, evaporation rate, and relative efficiency. At 3 suns, the relative efficiency ranges of 73.2–91.6%, 60.2–86.3%, 64.3–85.1%, and 54.1–79.9% were obtained for the GO + Ag, rGO + Ag, rGO-Ag, and GO-Ag NFs with concentrations of 1, 0.45, 0.225, and 0.1125 mg/mL, respectively. The elevated absorbance and plasmonic influence of the HNPs and high κ of graphene nanosheets were responsible for the obtained results. The future utilizations of rGO + Ag NF in applications such as desalination, power generation, and water treatment were recommended. Sreekumar et al. [32] investigated the thermal and exergy analysis of the deployment of DIW-ATO/Ag NF as a working fluid in a PTDASC. To formulate stable ATO-Ag/DIW NF, the mass fraction, surfactant mass fraction, and SWEA fraction were optimized. They reported an optimum mass fraction of 0.1% for ATO/Ag NF and surfactant with the corresponding SWEA of 90.1%. The results also demonstrated the enhancement of collector and exergy efficiency with an increase in temperature difference, irradiation intensity, and mass flow rate. At a mass flow rate of 0.022 kg/s and using the HNF, peak thermal efficiency due to a temperature surge of 12.6 °C was 63.5% while the highest exergy efficiency as a result of temperature difference of 8°C was 5.6%. Optical efficiency was noticed to improve as the angle of incidence decreased with a maximum value of 75% at 0°. Increasing the radiation penetration depth depreciated the transmittance of ATO-Ag/DIW NF while a rise in mass fraction enhanced its EC. This implied that the absorption of solar radiation can be achieved by either increasing the radiation penetration depth or mass fraction of the HNF. The authors proposed a mathematical model for the estimation of κ and SWEA fraction as dependent on mass fractions of ATO-Ag and SDS.

The influence of volume flow rate (1–5 L/h) and mixing ratio (0:100–100:0) of different HNFs (DW-based Al_2O_3-fly ash and SiO_2-fly ash with φ = 2 vol%) employed as working fluids in a microchannel-based DASC on the energy and exergy performance was carried out by Thakur et al. [33]. The authors reported that increasing the volume flow rate enhanced thermal efficiency, pumping power, PEC, EGR, and exergy efficiency. The collector thermal and exergy efficiency was 72.82% and 59.23% and 73% and 68.09% for Al_2O_3-fly ash (80:20) and SiO_2-fly ash (80:20) NFs, respectively. Higher pumping power of 30% and 33% than DW was obtained for Al_2O_3-fly ash (80:20) and SiO_2-fly ash (80:20) NFs, respectively. In addition, at low flow rates, the Al_2O_3-fly ash (80:20) NF possessed a higher PEC (3.5) than SiO_2-fly ash (80:20) NF with a PEC of 3.08. The Al_2O_3-fly ash (80:20) NF was observed to be a better working fluid compared with SiO_2-fly ash (80:20) NF. This was because of the improved thermophysical properties of Al_2O_3-fly ash (80:20) NF relative to SiO_2-fly ash (80:20) NF.

The collector performance of therminol®66-based GO-MWCNT NFs (with φ = 10–150 ppm) as potential working fluids in a DASC under indoor and outdoor conditions was studied by Qu et al. [29]. Under these conditions, the temperature of 100 ppm-GO-MWCNT/therminol®66 NF was 94 °C (indoor) and 153 °C (outdoor) compared with those of therminol®66 (11.6 °C and 97 °C). At irradiation times of 5 min and 45 min (under outdoor conditions), the collector efficiency using 100 ppm-GO-MWCNT/therminol®66 NF was 97% and 70%, respectively. The thermal stability of GO-MWCNT/therminol®66 NFs as determined prior to and after the experiments coupled with the obtained results emphasized the potential application of these thermal fluids for low-to-medium temperature in a DASC.

2.2. Flat Plate Solar Collectors

The influence of varying φ (0.5–2%) and thermal properties (ρ, κ, and μ) on the thermal efficiency of EG-W (75:25 wt%)-based Al_2O_3-CuO (70:30) NFs deployed as working fluids in an FPSC was investigated by Tahat and Benim [34]. They reported that a rise in the volume fraction led to the improvement of μ, ρ, κ, and thermal efficiency in comparison with water. Collector efficiency of 42–52% was obtained as the volume fraction increased from 0.5% to 2% when compared with water. The average improvement of the thermal efficiency for the FPSC relative to water was 45%. The improvement of h as κ increased for the HNFs resulted in thermal efficiency enhancement of the FPSC. Verma et al. [35] examined the effect of mass flow rate (0.01–0.05 kg/s), φ (0.25–2 vol%), solar intensity (380–1200 W/m^2), and temperature parameter (0.0075–0.035) on the energetic and exergetic performance of MNFs (CuO/, MgO/, and MWCNT/DIW) and HNFs (MgO-MWCNT (80:20)/DIW and CuO-MWCNT (80:20)/DIW) in an FPSC. Results revealed that optimum values of 0.75–0.8 vol%, 800–900 W/m^2, 298, and 0.025–0.03 kg/s were recorded for the φ, solar intensity, temperature parameter, and mass flow rate, respectively. Energetic efficiency was enhanced as φ, mass flow rate, and solar irradiation increased and as temperature parameter reduced. However, after the peak energetic efficiency was attained, increasing φ and mass flow led to a decrease in value, while with solar intensity, the energetic efficiency remained constant. Entropy generation and pumping power ratio were found to increase with φ. In comparison with DIW, the energetic and exergetic efficiency and entropy generation drop of 23.47%, 9.26%, 12.65%, 18.05%, and 20.52%; 29.8%, 12.3%, 17.1%, 23.4%, and 25.1%; and 65.52%, 45.57%, 48.16%, 56.86%, and 57.44% were obtained for the DIW-based MWCNT, MgO, CuO, CuO-MWCNT, and MgO-MWCNT NFs, respectively. With the MWCNT/DIW NFs having the highest κ and lowest viscosity followed by MgO-MWCNT NFs and then CuO-MWCNT NFs, the best working fluids followed a similar trend (MWCNT > MgO-MWCNT > CuO-MWCNT).

Farajzadeh et al. [36] explored the thermal efficiency of utilizing DIW-based Al_2O_3-TiO_2 (1:1) NFs (with φ = 0.1 wt% and 0.2 wt%) in an FPSC under varying volume flow rates (1.5–2.5 L/min). The thermal efficiency of all the samples was noticed to reduce as the temperature parameter increased while the temperatures at the inlet, outlet, and tank increased as solar radiation increased. Maximum thermal efficiency was recorded with Al_2O_3-TiO_2/DIW NF at a flow rate of 2 L/m and 0.2 wt% concentration. At 0.1 wt% and in comparison, with DIW, efficiencies of 19%, 21%, and 26% were obtained for TiO_2/, Al_2O_3/, and Al_2O_3-TiO_2/DIW NFs, respectively. Increasing the concentration of the HNF (from 0.1 wt% to 0.2 wt%) led to a 5% enhancement of the thermal efficiency of the collector. Additionally, at flow rates of 2.0 L/m and 2.5 L/m, the thermal efficiency was noticed to be 8% and 5% above that of the flow rate of 1.5 mL, respectively. The heat loss parameter of DIW was the highest whereas that of HNFs was the lowest. The authors stressed that using HNFs of Al_2O_3-TiO_2/DIW reduced the cost coupled with the higher thermal efficiency of the collector.

Okonkwo et al. [37] experimented the deployment of water-based Al_2O_3 and Al_2O_3-Fe_2O_3 NFs as working fluids in an FPSC. The thermodynamic performance (first and second laws) and optimization (of mass flow rate, φ (0.05–0.2 vol%), and temperature) were carried out. Their results showed that the exergy and energy efficiency, h, f, exergy destruction, absorbed energy parameter, exergy loss, and generation strongly depended on φ, mass flow rate, and temperature parameter. Energy efficiency was observed to increase as mass flow increased and as φ and temperature parameter decreased whereas the reverse was the case with exergy efficiency. Using 0.1 vol%, the HNF enhanced exergetic efficiency by 6.9% against 5.7% for the MNF while the energy efficiency was augmented by 2.16% for the MNF and depreciated by 1.79 for the HNF, as compared with water. Of the useful exergy (1123 W) absorbed from the sun using the collector, 73% was used up in the collector with the destruction of 59% of the total exergy. The h was observed to enhance as the temperature and mass flow rate increased with the MNF (72%) recording the highest value followed by the HNF (56%) and water. The reverse was noticed for f as the HNF was slightly higher than the MNF. This finding was due to the higher nano-size, viscosity, and density of HNF in comparison with the MNF despite the higher κ value.

Under varying mass fluxes (420 kg/s m^2 and 598 kg/s m^2) and mixing volume concentrations, the efficiency of MWCNT (0.003 vol% and 0.005 vol%) + Fe_3O_4 (0.01 vol% and 0.015 vol%) NFs as working fluids was investigated in an FPSC [38]. They noticed that the collector efficiency was improved as the mass flux and MWCNT concentration increased and Fe_3O_4 concentration decreased. The efficiency of water was 62.7% while those of the HNFs ranged from 73.5% to 80.3% and this translated to 17.2–28.1% above that of water. The use of MWCNT (0.005 vol%) + Fe_3O_4 (0.01 vol%) NF was observed to produce maximum efficiency. Similarly, increasing the mass flux of water enhanced the efficiency of the collector by 6.5% whereas that of MWCNT (0.005 vol%) + Fe_3O_4 (0.01 vol%) NF was improved from 74.5% to 80.3%.

2.3. Parabolic Solar Collectors

Bellos and Tzivanidis [39] investigated the energetic and exergetic performance of Syltherm 800-based Al_2O_3 (3 vol%), TiO_2 (3 vol%), and 1.5 vol% Al_2O_3 + 1.5 vol% TiO_2 NFs deployed as thermal fluids in a parabolic solar collector under varying inlet temperatures (300–650 K). They observed that the thermal efficiency augmented with a decrease in inlet temperature while the exergetic efficiency, Nu, and h enhanced as the inlet temperature increased. The average thermal efficiency enhancement, Nu, and h of Al_2O_3 (3 vol%), TiO_2 (3 vol%), and 1.5 vol% Al_2O_3 + 1.5 vol% TiO_2 NFs were 0.340%, 0.341%, and 0.790% (0.33–1.80%); 23.5%, 23.8%, and 121.7%; and 34.9%, 35.2%, and 142.1%, respectively, compared with Syltherm 800. This translated to average h and Nu ratios of 2.4 and 2.2 and 1.35 and 1.23 for HNFs and MNFs, respectively. Using the HNF, exergetic efficiency of 38.35% was achieved against 37.94% for MNFs and 37.68% for Syltherm 800.

2.4. Vacuum Tube Solar Collectors

Lee et al. [38] experimented the deployment of MWCNT (0.003 vol% and 0.005 vol%) + Fe_3O_4 (0.01 vol% and 0.015 vol%) NFs as working fluids in a vacuum tube solar collector under varying mass fluxes (420 kg/s m^2 and 598 kg/s m^2) and mixing volume concentrations. The results demonstrated that the highest efficiency was achieved using MWCNT (0.005 vol%) + Fe_3O_4 (0.01 vol%) NF and at a mass flux of 598 598 kg/s m^2. The HNFs recorded an efficiency range of 73.6–79.3% compared with 54.9% for water. They noticed that using both water and HNFs as working fluids, the FPSC recorded a higher efficiency compared to the vacuum tube solar collector under the same working condition. The heat gain revealed a 17.1–28.1% and 17.2–27.3% increase while the loss parameter recorded a 25.7–47.6% reduction and 6.93–17.1% improvement for the FPSC and vacuum tube collector, respectively. This result was mainly due to the characteristics of the working fluids, collector types, and operating conditions. Increasing the mass flux enhanced the efficiency of MWCNT (0.005 vol%) + Fe_3O_4 (0.01 vol%) NF from 73.7% to 79.8% and also increased the effectiveness of the vacuum tube collector. Under wide operating conditions, the vacuum tube collector was observed to perform better than the FPSC.

Salman et al. [40] investigated the thermal performance of DW-based Al-Al_2O_3 NFs having volume fractions of 1%, 3%, and 5% under increasing volume flow rates (15, 30, and 45 L/h) in a vacuum tube solar collector. They reported an improvement in thermal efficiency as volume fraction and flow rate increased. The maximum thermal efficiency of >60% was achieved at a flow rate of 45 L/h and a volume fraction of 5%, which was 24.89% higher compared with DW. Increasing the concentration of the HNF was also noticed to improve heat gain. At a flow rate of 15 L/h, the heat gain for water ranged from 40.46 W to 68.35 W, while at a flow rate of 30 L/h and volume fraction of 5%, a heat gain of 75.14–83.69 W was recorded for the HNF. The performance index of the HNF was found to be better than that of DW. Thus, deploying HNFs as working fluids in the vacuum tube collectors yielded improved thermal efficiency.

Under varying flow rates (0.56–1.35 L/min), Sundar et al. [41] examined the h, f, and collector thermal efficiency of DW-based ND-Co_3O_4 (67:33) NFs (φ = 0.05–0.15 wt%) as nano-coolants in an FPSC. The μ and κ of the hybrid nano-coolants were observed to enhance with φ and temperature increase. They showed that the Nu and h of the hybrid nano-coolants were improved with an increase in the flow rates, Re, and φ whereas the f was reduced as the φ and flow rate increased. Increasing the temperature parameter diminished the collector efficiency as increasing φ enhanced it. At a flow rate of 1.35 L/min, maximum Nu, h, f, and collector efficiency of 21.23%, 36.41%, 1.13-fold, and 59.78% were achieved using 0.15 wt% ND-Co_3O_4 nano-coolant, respectively, with the collector of efficiency of 49.81% recorded for DW. These peak values were obtained at 13:00 h in the day after which a decline was generally observed in these values. Additionally, correlations were proposed to estimate the Nu and f of the hybrid nano-coolants engaged in the FPSC.

2.5. Photovoltaic-Thermal Solar Collectors

The influence of mixing ratio (0.2–0.8), φ (0.01% and 1%), mass flow rate (0.01 kg/s and 0.1 kg/s), and solar irradiance on the energy (electrical and thermal) and exergy performance of water-Al_2O_3-ZnO NFs as thermal fluids in a PV/T solar collector was studied by Wole-Osho et al. [42]. The results proved that at an optimum mixing ratio of 0.47 of Al_2O_3 NPs in the HNF, exergy, thermal, and electrical efficiency of 15.13%, 55.9%, and 13.8%, respectively, was obtained for the PV/T collector. They noticed that the cell temperature of the PV/T diminished exponentially as the mass flow rate increased leading to a cell temperature reduction of 21% as the mass flow rate increased from 0.01 kg/s to 0.1 kg/s. At the maximum solar irradiation, cell temperatures of 37.5 °C and 46.8 °C were obtained for a mass fraction of 0.01% and flow rate of 0.01 kg/s while 37.8 °C and 47.8 °C were recorded for a 1% mass fraction and flow rate of 0.1 kg/s. The overall maximum thermal efficiency attained using water-Al_2O_3-ZnO NF in the PV/T collector was 91%, which translated to a 34% improvement over the use of water.

3. Thermal Energy Storage Application of Hybrid Nanofluids

Due to the ability of PCM to collect, store, and transfer latent thermal energy storage at high energy storage density under isothermal conditions, it is preferred to sensible thermal energy storage. However, the PCMs are known to possess very low κ, making them disadvantageous in terms of the reduction in their rate of energy stored and released. The advent of nanotechnology informed the addition of HNPs (with higher κ) to PCMs to enhance the κ of PCMs and thus, improve the efficiency and energy storage and release characteristics [43][44]. By incorporating heat storage into a solar collector, the overall efficiency is improved while minimizing the levelized energy cost of the system.

Chieruzzi et al. [45] experimentally explored the thermal storage performance of binary salt ($NaNO_3$-KNO_3)-based SiO_2-Al_2O_3 (82:18) NFs with φ = 0.5–1.5 wt% prepared using the direct method. They observed that the 1 wt% SiO_2-Al_2O_3 NF yielded the highest heat of fusion (127.2 kJ/kg) and lowest solidification (209.3 °C) and melting (223.9 °C) temperature compared with Al_2O_3, SiO_2, and TiO_2 NFs. Additionally, the highest stored energy was noticed with 1 wt% SiO_2-Al_2O_3 NF. The doping of the binary salt with SiO_2-Al_2O_3 NPs using φ = 1 wt% enhanced the specific heat by 57% (solid phase) and 22% (liquid phase), and reduced the melting temperature by 8 °C and solidification temperature by 10 °C. The improvement of the specific heat capacity of SiO_2-Al_2O_3/binary salt NF was noticed to encourage its utilization as an energy storage medium in concentrated solar power plants, which could lessen the quantity of the storage media and the cost of electricity.

Harikrishnan et al. [46] examined the thermal properties and energy storage performance of paraffin-based CuO-TiO_2 (50:50) NFs with φ = 0.25–1 wt%. They observed that the κ and μ of CuO NFs were highest, followed by CuO-TiO_2 NFs and then TiO_2 NFs. Increasing φ increased κ, μ, FT, and MT, and reduced MLH and FLH. The FT and MT of the HNFs ranged from 56.54 °C to 56.96 °C and 60.34 °C to 60.84 °C compared with 56.47 °C and 60.23 °C for paraffin, respectively. Additionally, the FLH and MLH of 1 wt% CuO-TiO_2 NF were 182.7 kJ/kg and 190.1 kJ/kg compared with 189.5 kJ/kg and 197.6 kJ/kg for paraffin, which corresponded to 1.83% and 2.27% reduction, respectively. After 2000 cycles to examine the thermal stability of the HNF-based energy storage materials, the melting and freezing processes were achieved between 8–11 min and 16–22 min, respectively, with 1 wt% CuO-TiO_2 NF recording the lowest time. A reduction of 29.8% (melting time) and 28.7% (freezing time) was attained using 1 wt% CuO-TiO_2 NF.

Organic ester-based functionalized Ag-TiO_2 NFs with φ = 0.1–1.5 wt% were examined by Parameshwaran et al. [47] for their thermal properties and thermal energy storage characteristics. Increasing φ caused a direct improvement of μ (0.35–3.8%) and κ (10–52%) while it diminished latent heat capacity and enthalpy of latent heat. The HNFs were observed to be thermally more stable than the organic ester, with maximum mass loss at 191 °C for 0.8 wt% Ag-TiO_2 HNF and 179 °C for the organic ester. After 1000 melting and freezing cycles, the 0.8 wt% HNF possessed a latent heat capacity of 90.69 kJ/kg (1.00–9.18% reduction) and 87.69 kJ/kg (1.74–7.38% reduction) and onset temperature of 6.91 °C and 6.83 °C, compared with 95.60 kJ/kg and 90.70 kJ/kg and 6.80 °C and 6.75 °C obtained for organic ester during melting and freezing processes, respectively. The supercooling degree of 0.8 wt% HNF was 1.82 °C while that of the organic ester was 2.07 °C. It was noticed that in comparison with the pure organic ester, the duration of the onset of melting and freezing for the Ag-TiO_2 NFs declined by 1.7–8.5% and 5.1–23.9%, respectively. Owing to the enhanced thermal properties and thermal heat storage performance of the ester-based Ag-TiO_2 NFs, the potential application in buildings for thermal storage cooling was proposed.

The dual feasibility of Sn-SiO_2/Ag NPs as a working fluid and energy storage material for DASC was investigated by Zeng et al. [48]. The Sn-SiO_2/Ag NPs were observed to produce an enhanced optical absorption in comparison with Sn-SiO_2 NPs. They reported temperature and enthalpy values of 230.5 °C and 57.7 J/g, 230.3 °C and 47.5 J/g, and 227.1 and 36.0 J/g for the melting of Sn, Sn-SiO_2, and Sn-SiO_2/Ag NPs, respectively. Similarly, temperature and enthalpy values of 123.9 °C and 49.1 J/g, 126.0 °C and 39.5J/g, and 128.0 °C and 29.5J/g were obtained for the freezing of Sn, Sn-SiO_2, and Sn-SiO_2/Ag NPs, respectively. These results showed that the phase change temperatures of Sn-SiO_2 and Sn-SiO_2/Ag NPs were very close to that of Sn NPs due to insignificant changes in the thermal property. The thermal storage efficiency of the encapsulated Sn in Sn-SiO_2 and Sn-SiO_2/Ag NPs was 99.0% and 98.4%, respectively. Thus, indicating that the encapsulated Sn efficiently stored and released the latent heat via phase changes. Under 200 heating–cooling cycles to estimate the thermal stability of Sn-SiO_2/Ag NPs, 227.0 °C and 127.8 °C and 35.7 J/g and 29.2 J/g were recorded as the melting and freezing temperatures and enthalpies, respectively. In addition, the enhancement of volumetric thermal energy storage was found to reduce with a range of operating temperatures and increased with volume fraction. The utilization of Sn-SiO_2/Ag NPs in DASC was reported to effectively enhance thermal and energy storage performance under medium-high operating temperatures.

As a follow-up study to the work of Chieruzzi et al. [45], Chieruzzi et al. [49] prepared binary salt ($NaNO_3$-KNO_3)-based SiO_2-Al_2O_3 (82:18) NF with φ = 1 wt% using a micro-compounder (twin-screw) under varying stirring rates (100 and 200 rpm) and stirring durations (15 and 30 min) at a high temperature (300 °C) and investigated the thermal energy storage performance. Their results demonstrated that at the higher stirring rate (200 rpm) and duration (30 min), maximum c_p (2.42 J/g °C–solid phase and 1.94 J/g °C–liquid phase) and stored energy (373 J/g) were obtained. The specific heat of the SiO_2-Al_2O_3/binary salt NF was improved by 52.1% (solid phase) and 18.6% (liquid phase), the heat of fusion was enhanced by 1.5–7.4%, and the stored energy was augmented by 13.5% while the solidification temperature was reduced up to 9.7 °C, compared with the binary salt. The study showed that engaging the direct method improved the energy storage characteristics of 0.1 wt% SiO_2-Al_2O_3/binary salt NF over the high-temperature mixing technique.

The thermal property and behavior of DIW-based TiNTs-TiNPTs (0:100–100:0) NFs with φ = 0.1–0.3 wt% as cold thermal energy storage materials were investigated by Shao et al. [50]. Authors observed that for both HNFs and MNFs, the supercooling temperature and solidification time surged as solidification–melt cycles increased. Owing to the larger surface area and high κ, the HNFs exhibited lower supercooling temperatures and lesser solidification time compared with MNFs. The enhancement of κ by 54.91% and 56.42% for DIW-based TiNTs-TiNPTs NFs was observed to be responsible for the reduction of supercooling temperature and solidification time by 4.97 °C and 5.27 °C, and 54.91% and 56.42%, respectively, when compared with TiNT and TiNPT NFs. The latent heat of DIW-based TiNTs-TiNPTs NFs (φ = 0.1–0.3 wt%) was lowered by 9.21% (303.4 kJ/kg–269.2 kJ/kg) and 4.72% (298.7 kJ/kg–284.6 kJ/kg) for TiNTs-TiNPTs (75:25) and TiNTs-TiNPTs (50:50) NFs, respectively. In addition, the latent heat of TiNTs-TiNPTs (75:25) and TiNTs-TiNPTs (50:50) NFs for φ = 0.1 wt% was reduced by 10.93% and 9.43%, respectively, relative to DIW.

For concentrated solar power applications, the thermal energy storage characteristics of binary eutectic-based SiO_2-Al_2O_3 nano-PCM with SiO_2 outer layer thickness of 10, 20, and 35 were investigated by Nithiyanantham et al. [51]. They observed that at a temperature range of 250–400 °C, the thermal diffusivity, κ, and μ of 10-SiO_2-Al_2O_3 nano-PCM, 20-SiO_2-Al_2O_3 nano-PCM, and 35-SiO_2-Al_2O_3 nano-PCM were enhanced by −8–−4%, 0–−2%, and 7–14%; −6–−2%, 3–−1%, and 11–19%; and 16–25%, 16–30%, and 25–34%, respectively when compared with eutectic-based PCM. All the tested samples were noticed to be thermally stable before 565 °C with equal decomposition temperature. Thus, indicating no influence of the operating temperature of the eutectic-based PCM on the SiO_2-Al_2O_3 nano-PCMs. These results portend the ability of SiO_2-Al_2O_3 nano-PCMs to improve heat transfer efficiency and reduce the levelized cost of electricity related to concentrated solar power applications.

Harikrishnan et al. [44] examined the deployment of oleic acid-Ni-ZnO NFs with φ = 0.3–1.2 wt% as cool thermal energy storage materials. They revealed that increasing φ caused the enhancement of κ and phase change temperature, and a reduction of latent heat. At φ = 1.2 wt%, peak phase change temperature (improvement) and latent heat (reduction) of −1.13% and 1.34%, and 1.91% and 2.23% for melting and solidification processes were recorded, respectively. These results can be linked to the structure, size, and φ of the Ni and CuO NPs and the existence of strong chemical interaction within oleic acid-Ni-ZnO NFs. An increase in the thermal cycle was noticed to augment phase change temperature and decrease latent heat. Under varying thermal cycles and at φ = 1.2 wt%, the highest difference in phase change temperature and latent heat was 1.62% and −1.54% and 1.51% and 1.62% for solidification and melting processes, respectively. These values indicated that oleic acid-Ni-ZnO NFs possessed better thermal reliability than pure oleic as PCM for long-term operation. The time taken by melting (900–1280 s) and solidification (990–1385 s) processes was observed to be lower for oleic acid-Ni-ZnO NFs than oleic acid. Oleic acid-Ni-ZnO NFs were recorded to have κ improved by 25.43–87.27% relative to oleic acid.

Thermal energy storage characteristics (latent heat, c_p, heat flow, and thermal stability) of hybrid eutectic salt-based GO-TiO_2 material with φ = 0.01–0.1 wt% was investigated by Vaka et al. [52]. They demonstrated that up to 580 °C, the GO-TiO_2/eutectic material was observed to be thermally reliable. Maximum c_p, heat flow, and latent heat were achieved with 0.05 wt% GO-TiO_2/eutectic material. In comparison with the hybrid eutectic salt (1.342 J/g), the c_p of GO-TiO_2/eutectic material was enhanced by 9.8%, 19.1%, and 19.6% for concentrations of 0.01, 0.05, and 0.1 wt%. In addition, the latent heat and c_p of 83.74 J/g and 1.342 J/g, 41.74 J/g and 1.47 J/g, 52.25 J/g and 1.606 J/g, and 35.21 J/g and 1.599 J/g were obtained for hybrid eutectic salt, 0.01, 0.05, and 0.1 wt% GO-TiO_2/eutectic material, respectively.

An eco-friendly and novel hybrid nano-PCM for cold thermal energy systems application was studied by Li et al. [53]. They examined the thermal properties and thermal storage behaviors of functionalized β-CD-TiO_2-Ag/EG-DIW (40:60) PCM with φ = 0.025–0.1 vol%. Results proved that the 0.1 vol% β-CD-TiO_2-Ag PCM possessed a higher melting phase change temperature (−46.99 °C), supercooling temperature (−52.39 °C), freezing phase change temperature (−52.39 °C), freezing phase enthalpy (59.78 J/g), κ (42.17% improvement), melting phase enthalpy (60.99 J/g), lower supercooling degree (5.4 °C), and total freezing time (179.4 s) than the pure PCM. These implied that the 0.1 vol% hybrid nano-PCM was thermally more stable, has higher κ, improved enthalpy, lower supercooling degree, and freezing time compared with pure PCM. The functionalization of TiO_2 was noticed to impact positively on the thermal properties and characteristics of the β-CD-TiO_2-Ag PCM. The deployment of 0.1 vol% β-CD-TiO_2-Ag PCM for cold thermal energy storage applications was envisioned to reduce the environmental pollution footprint and increase the efficiency of energy storage.

Sharma et al. [54] studied the latent heat storage characteristics of paraffin wax (as PCM) through charging with DW-$CoZnFe_2O_4$ (φ = 0.1 wt%) NF and DW as thermal fluids. The results demonstrated that at a heating temperature of 90 °C and initial paraffin wax of 33 °C, the paraffin wax was heated to 60.32 °C and 62.01 °C for 120 min and 90 min using DW and $CoZnFe_2O_4$ NF, respectively. The discharging of the paraffin wax took 100 min (33 °C) using $CoZnFe_2O_4$ NF and 130 min (35 °C) engaging DW. The charging and discharging time reductions of 25% and 23%, respectively, were obtained for the paraffin wax using $CoZnFe_2O_4$ NF. This implied that $CoZnFe_2O_4$ NF was better used for charging while DW was preferred for discharging concerning improving the efficiency of thermal energy storage systems.

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