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Heat carrier nanofluids in solar still – A review

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ABSTRACT

This review discusses heat transfer enhancement of various nanoparticles in solar stills. The thermal conductivities of various nanoparticles, that is, Al_2O_3, CuO, Cu_2O, ZnO, SnO_2, TiO_2, SiO_2, Cu, Fe_2O_3, SiC, and multiwalled carbon nanotubes suspended in water with different volume fractions are analyzed. The factors involved in the thermal conductivity and distillation enhancement of nanofluids are discussed. This review is crucial because thermal conductivity enhancement augments the fresh water yield.

Keywords: Solar still; Desalination; Nanofluids; Heat transfer

1. Introduction

Water is the most crucial fluid on Earth; survival without water is impossible. Water is the source of life on Earth, since it is required for biological processes. Because of its abundant presence and physical and chemical characteristics, water has a stabilizing effect on earthly processes. Civilizations typically start near water. Many people in India store water in copper vessels for drinking purposes. Recently, researchers from the Indian Institute of Science (IISC), Bangalore, have developed a water filter with copper to make drinking water safe. They proposed that the water stored in the copper coated vessels for 16 h killed pathogenic bacteria such as *Escherichia coli* and *Cholera*. This is because of the antibacterial property of the copper [1]. In recent days, researchers are using nanoparticles in different ways (membrane and distillation) to enhance water quality. A solar still is a device to produce distillate water from ocean or brackish water. Recently, some metallic nanoparticles were mixed with water and oil (base fluid) to improve the heat transport of the base fluid in the solar still. A nanofluid is usually defined as a suspension with solid particles smaller than 100 nm, and its advantages are higher heat transfer capability, and large surface area [2]. There are remarkable opportunities for nanotechnology assisted drinking water treatment [3] and wastewater purification [4].

In a conventional solar still, the mechanism is relatively slow. Nanotechnology research is important because it is a sustainable way to augment the fresh water production. Researchers have enhanced fresh water production in different ways, including solar stills with dye in the basin [5,6], wick on the basin [7–16], charcoal pieces [17], rubber scraps [18], internal reflectors [19,20], sponge cubes [21–23], porous basin [24], spherical solar still [25], tubular solar still [26–30], concentrator assisted solar still [31–33], and solar still with phase change material (PCM) [34]. At the same time, scientists and researchers used nanofluids in various thermal applications. Nasrin et al. [35] studied Ag, Cu, Al_2O_3, and CuO water-based nanofluids in a flat plate collector (FPC). The thermal conductivity of the experimental nanoparticles is Ag (429 W/m K), Cu (400 W/m K), Al_2O_3 (40 W/m K), and CuO (20 W/m K). The Ag water-based nanofluids with 5% volume concentration enhanced the heat transfer in the FPC more than the Cu, Al_2O_3, and CuO nanofluids, as expected. He et al. [36] investigated two weight concentrations (ϕ = 0.1 wt%,

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25 nm and 0.2 wt%, 25 nm) of copper nanofluids in the FPC. The results showed that the 25 nm sized 0.1 wt% of copper nanofluids enhanced the collector efficiency by 23.83%. Heat transfer enhancement studies in a heat exchanger using Al_2O_3 (alumina) water-based nanofluids were performed by Albadr et al. [37]. Five different concentrations of 0.2%, 0.3%, 0.5%, 0.7%, 1%, and 2% were analyzed in their experiment. They concluded that the 0.2% concentration of Al_2O_3 water-based nanofluids enhanced the heat transfer rate in FPC more than the other concentrations. Subramani et al. [38] experimentally studied TiO_2 nanofluids in a parabolic trough collector (PTC) for efficiency and heat transfer enhancement. Three particle concentrations of 0.05%, 0.1%, and 0.2% were analyzed. The result reveals that the 0.2% particle concentrations gave a higher convective heat transfer in the PTC. Kabeel and El-Said [39] theoretically analyzed a flashing desalination system using water-based Cu nanofluids (ϕ = 5%) for collector thermal efficiency enhancement. They discovered that the nanofluid enhanced the flashing desalination system and produced a maximum productivity of 7.7 L/m^2/d.

Bhattad et al. [40] reviewed and discussed refrigeration system performance improvement. Their review summarizes that nanofluids in refrigeration systems enhanced the performance due to their excellent thermo-physical properties. Recent advancement in engine cooling techniques was reviewed by Sidek et al. [41]. The high diffusivity of the nanofluids plays a vital role in engine cooling systems. Hawwash et al. [42] investigated the FPC thermal efficiency improvement by alumina nanofluids with different volume concentrations of 0.1%–3%. The results were that the alumina nanofluids enhanced the collector efficiency by 18%.

Ebaid et al. [43] experimentally investigated the cooling of photovoltaic (PV) panels using TiO_2 and Al_2O_3 water-based nanofluids. They observed that these nanofluids decrease the temperature in the PV panels. The TiO_2 nanofluids showed better cooling performance than the Al_2O_3 nanofluids. Senthilkumar et al. [44] conducted an experiment investigating the convective heat transfer characteristics of a carbon nanotube (CNT) coated brass surface under natural convection. Experimentally the temperature distributions for coated and noncoated fins were observed. There is a significant drop in surface temperature for nanocoated brass surface for different heat inputs. Simultaneously, the convective heat transfer increases for coated brass surface due to considerable increase in surface area of the CNTs. The average increase in heat transfer rate was around 12% for CNT-coated rectangular brass fins. Prasher et al. [45] investigated the effect of aggregation on the water-based nanofluids. They discovered that the thermal conductivity enhancement of nanofluids is due to the clusters of nanoparticles in their base fluid. Masuda et al. [46] investigated Al_2O_3, SiO_2, and TiO_2 nanoparticles for thermal conductivity enhancement. They discovered that 13 nm particle sized Al_2O_3 nanoparticles enhanced the thermal transport property by 30%. It was concluded that the nanofluids were suitable for FPC, heat exchangers, PTCs, refrigeration systems, desalination units, and cooling PV panels to enhance the heat transfer properties.

There have been recent reviews in solar still and productivity enhancement not relating to nanofluids. For instance, Nayi and Modi [47] reviewed the various pyramid type solar still designs. They concluded that tracking is not required for pyramid type solar stills and that the side walls are not involved in the shadow effect in the distiller. Sathyamurthy et al. [48] reviewed the integration of collectors into various solar still designs to augment the productivity. The top cover cooling effect of different solar still designs was reviewed by Omara et al. [49]. Different water and air flow cooling techniques were investigated. The air flow and water flow over the tubular and SSSS enhanced the productivity. The flow of water/air affects the glass cover temperature and increases the temperature difference ($T_w - T_g$). Kabeel et al. [50] reviewed the three important possible heat exchange enhancement mechanisms in the solar still. They are (1) heat transfer through PCM, (2) different absorbing materials, and (3) cooling techniques on the top cover.

Many research works have been conducted by authors on solar stills to enhance the freshwater productivity. A collection of a compact review (knowledge bundle) of recent advances is essential for researchers to prioritize further work. The review focuses on thermal conductivity enhancement through different nanofluids; the effect of concentration and composition is discussed. Based on the literature survey, it is found that, very few review studies have been performed in nanofluids in solar stills to best of authors' knowledge.

2. Heat transfer in nanofluids

Prospective applications of nanostructured systems include drinking water filtration, desalination, ultrapure water production, and industrial wastewater treatment. Nanofluids are stable suspensions of nanoparticles in a liquid. Typically, nanofluids contain up to 10 vol% of nanoparticles, and usually more than 10 vol% of surfactant [2]. Either oil or water is used as a carrier liquid, and the suspensions are designed in such a way that *Brownian* molecular movement thwarts the sedimentation of the particles. Some factors to be analyzed before choosing the nanoparticles are thermal conductivity, specific heat capacity, density, viscosity of fluid, safety, and compatibility with base fluid. Nanotechnology enhances the heat transfer of a working fluid with solid nanoparticles. By incorporating nanoparticles, the thermophysical properties of the working fluid such as thermal conductivity, viscosity, and convective heat transfer coefficient are altered.

2.1. Thermal conductivity

Koo and Kleinstreuer [51] proposed an equation to calculate the thermal conductivity of nanofluids. The thermal conductivity of nanofluid is a function of diameter of nanoparticles, volume fraction, nanoparticle temperature, and Brownian motion of the nanoparticles in the base fluid.

$$k_{\mathrm{nf}} = \frac{k_p + 2k_{\mathrm{bf}} + 2(k_p - k_{\mathrm{bf}})\phi}{k_p + 2k_{\mathrm{bf}} - (k_p - k_{\mathrm{bf}})\phi} k_{\mathrm{bf}} + 5\times 10^5 \beta\phi\rho_{\mathrm{bf}} C_{\mathrm{bf}} \sqrt{\frac{K_B T}{\rho_p D}} f(T,\phi) \quad (1)$$

where

$$f(T,\phi) = (-6.04\phi + 0.4705)T + (1{,}722.3\phi - 134.63),$$

Table 1
Solar still with different nanofluids in the basin

Sl. no.	Author, reference, & country	Solar still design	Base fluid	Nanofluid	Thermal conductivity of nanoparticle (W/m K)	Volume concentration	Observation in experiment
1	Sahota and Tiwari [58], India	DSSS	Water	Al_2O_3	46	0.04%, 0.08%, and 0.12%	The productivity increased by 16.83% due to Al_2O_3 nanofluids with the concentration of 0.12%.
2	Sahota and Tiwari [59], India	PVT FPC integrated with DSSS	Water	• Al_2O_3 • TiO_2 • CuO	46 11.8 17.6	• 0.063%–0.124% • 0.041%–0.1085% • 0.082%–0.0161%	CuO nanofluids have better results than Al_2O_3 and TiO_2 nanofluids.
3	Sahota and Tiwari [60], India	DSSS	Water	• Al_2O_3 • TiO_2 • CuO	46 11.8 17.6	0.2%, 0.25%, and 0.3% for each type	The productivity is Al_2O_3 > TiO_2 > CuO.
4	Sahota et al. [61], India	DSSS	Water	• Al_2O_3 • TiO_2 • CuO	46 11.8 17.6	0.044%–0.272% for each type	Annual enhancement of productivity: Al_2O_3: 19.10%; TiO_2: 10.38%; and CuO: 5.25%.
5	Kabeel et al. [62], Egypt	SSSS with external condenser	Water	• CuO • Al_2O_3	17.6 46	CuO: 0.02% Al_2O_3: 0.02%	CuO gave higher efficiency of 84.16% than Al_2O_3 nanofluids (73.85%).
6	Kabeel et al. [63], Egypt	SSSS with external condenser	Water	Al_2O_3	46	0.2%	The nanofluid increased the productivity by 116%.
7	Kabeel et al. [64], Egypt	SSSS with external condenser	Water	• Al_2O_3 • Cu_2O	46 76.5	0.02%–0.2%	The productivity results of Cu_2O (ϕ = 0.16%) and Al_2O_3 nanofluids are 2,240 and 2,095 mL/m²/d, respectively.
8	Omara et al. [65], Egypt	Corrugated wick solar still with reflector and fan	Water	• Al_2O_3 • Cu_2O	46 76.5	1.97%	Corrugated wick, reflector, and fan along with Cu_2O nanofluids enhanced the system productivity by 285.10%, and Al_2O_3 nanofluids by 254.88%.
9	Mahian et al. [66], Iran	SSSS with FPC	Water	• Cu • SiO_2	400 1.4	1%–4% for both types	Cu nanofluids enhanced the evaporation more than SiO_2 nanofluids.

Continued

Table 1 *Continued*

Sl. no.	Author, reference, & country	Solar still design	Base fluid	Nanofluid	Thermal conductivity of nanoparticle (W/m K)	Volume concentration	Observation in experiment
10	Elango et al. [67], India	SSSS	Water	• Al_2O_3 • ZnO • Fe_2O_3 • SnO_2	46 29 6 1.34–1.38	0.05%–0.1% for all types	Al_2O_3 nanofluids enhanced productivity by 29.95%, SnO_2 by 18.63%, and ZnO by 12.67%.
11	Madhu et al. [68], India	SSSS	Water	• Al_2O_3 • CuO • TiO_2	46 17.6 11.8	0.2% for all types	Al_2O_3 nanofluids gave a yield of 4.03 kg/m^2/d, CuO 2.25 kg/m^2/d, and TiO_2 2.17 kg/m^2/d.
12	Saleh et al. [69], Egypt.	TSS	Water	ZnO	29	600 mg/100 mL (0.11%)	ZnO nanorod shape enhanced the productivity by 38% and ZnO-spherical shape by 30%.
13	Gupta et al. [70], India	SSSS	Water	CuO	17.6	0.12%	The CuO nanoparticle produced a higher productivity of 3,445 mL/m^2/d than conventional still (2,814 mL/m^2/d).
14	Gupta et al. [71], India	SSSS	Water	Cu_2O	76.5	–	The productivity of with and without Cu_2O nanofluid is 4,000 and 2,900 mL/m^2/d, respectively.
15	Abhinav and Harikumar [73], India	SSSS	Water	Al_2O_3	46	0.1%, 0.5%, 1.0%, and 1.5%	Al_2O_3 nanofluids enhanced the system productivity by 20%.
16	Navale et al. [74], India	Masonic solar still	Water	• Al_2O_3 • CuO	46 17.6	0.1%, 0.2%, and 0.3% for both types	CuO nanofluid with 0.3% concentration enhanced the distillate productivity by 89.42%, while Al_2O_3 by 45.19% (0.3% concentration).
17	Kabeel et al. [75], Egypt	SSSS	Mixed with black paint	Cu_2O	76.5	10%–40%	Productivity increased by 25% compared with conventional solar still (CSS).
18	Sain and Kumawat [76], India	SSSS	Mixed with black paint	Al_2O_3	46	–	Enhanced productivity by 38.09%.

Continued

Table 1 *Continued*

Sl. no.	Author, reference, & country	Solar still design	Base fluid	Nanofluid	Thermal conductivity of nanoparticle (W/m K)	Volume concentration	Observation in experiment
19	Sharshir et al. [77], China	SSSS	Water	• Graphite flakes • CuO	129 17.6	0.125%–2%	Graphite-microflakes enhanced the productivity by 53.95% versus CuO nanofluids by 44.91%.
20	Chen et al. [78], China	SSSS	Water	SiC	490	0.1%, 0.2%, 0.3%, and 0.4%	0.4% concentration enhanced thermal conductivity by 6%.
21	Gnanadeson et al. [79], India	SSSS	Water	MWCNT	2,000–3,000	–	Enhanced overall system performance.
22	Gnanadeson et al. [80], India	SSSS	Water	MWCNT	2,000–3,000	–	
23	Abdelal and Taamneh [81], Jordon	PSS	Water	• Carbon fabrics • Graphene • CNT	–	Carbon fabrics 2.5%, Graphene 2.5%, CNT 2.5%, and CNT 5%.	CNT with 5% of weight concentration enhanced the productivity by 30%.
24	Elfasakhany [82], Saudi Arabia	SSSS	–	• Cu • Paraffin wax • Cu-Paraffin wax	387.6 0.172 0.226	2.2 kg of PW and 0.2%–4% Cu	The Cu-paraffin wax composites enhanced the system performance by 5%.
25	Methre and Easwaramoorthy [84], India	SSSS	–	• Paraffin wax • Al_2O_3 + PW	–	PW–2%wt Al_2O_3 and PW–4%wt Al_2O_3	Paraffin wax with-4%wt Al_2O_3 exhibited better performance.
26	Chaichan and Kazem [85], Iraq	SSSS	–	Paraffin wax + Aluminum powder	–	4.8 g of PW	PW with aluminum powder enhanced the productivity by 21.19%.
27	Rajasekar and Easwaramoorthy [86], India	SSSS	–	Paraffin wax + Al_2O_3	–	15 kg of PW	The daily efficiency of the Al_2O_3 + PW is 45% and PW alone 38%.

k_p is the thermal conductivity of nanoparticle (W/m K), k_{bf} is the thermal conductivity of the base fluid (W/m K), ϕ is the volume fraction of the nanoparticles, k_B is the Boltzmann's constant, ρ_{bf} is the density of the base fluid (kg/m^3), C_{bf} is the specific heat capacity of the base fluid (J/kg K), k_{nf} is the thermal conductivity of the nanofluid and (W/m K), and T is the temperature (K).

2.2. Dynamic viscosity

Corcione [52] developed the correlation to calculate the dynamic viscosity of the nanofluids:

$$\frac{\mu_{nf}}{\mu_{bf}} = \frac{1}{1 - 34.87(d_p/d_{bf})^{-0.3}\phi^{1.03}} \quad (2)$$

where d_{bf} is the equivalent diameter of the base fluid (m), μ_{nf} is the dynamic viscosity of the nanofluid (kg/m/s), μ_{bf} is the dynamic viscosity of the base fluid (kg/m/s), d_p is the particle diameter, and ϕ is the volume fraction of the nanoparticle. Also,

$$d_{bf} = \left[\frac{6M}{N\pi\rho_{f0}}\right]^{1/3} \quad (3)$$

where M is the molecular weight of the base fluid, N is the Avogadro number, and ρ_{f0} is the mass density of the base fluid (kg/m^3).

2.3. Density

Pac and Cho [53] developed an empirical equation to calculate the density of the nanofluid as given by:

$$\rho_{nf} = \rho_p\phi + \rho_{bf}(1-\phi) \quad (4)$$

where ρ_{nf} is the density of the nanofluid (kg/m^3), ρ_p is the mass density of the nanoparticle (kg/m^3), ϕ is the volume fraction, and ρ_{nf} is the mass density of the base fluid (kg/m^3).

2.4. Specific heat capacity

Pac and Cho [53] developed an empirical equation to calculate the specific heat of the nanofluid as given by:

$$C_{nf} = (1-\phi)C_W + \phi C_p \quad (5)$$

where C_{nf} is the specific heat capacity of the nanofluid (J/kg K), ϕ is volume fraction, C_W is the specific heat capacity of the water (J/kg K), and C_p is the specific heat capacity of the particle (J/kg K).

The random motion of the nanoparticles in the base fluid is termed Brownian motion. The Brownian motion is described by the Brownian coefficient D_B, which is governed by the Einstein–Stokes equation [54]:

$$D_B = \frac{K_B T}{3\pi\mu d_p} \quad (6)$$

where k_B is the Boltzmann's constant, T is the temperature of nanofluid (K), μ is dynamic viscosity of the nanofluids (kg/m/s), and d_p is nanoparticle diameter (m).

3. Mechanism

Many authors have examined the heat conduction mechanism in nanofluids [55–57]. They proposed the following possible mechanisms of heat conduction enhancement in the nanofluids, which are as follows (1) Brownian motion and (2) aggregation of nanoparticles. Early researchers believed that the Brownian motion was the major reason for the thermal conductivity increase inside a nanofluid but recent research shows that the "Clustering/aggregation" plays a vital role. Solar radiation, when transmitted through the transparent glazing, gets directly absorbed by the nanoparticles suspended in the water. Nanoparticles can absorb the visible solar radiation as well as infrared thermal radiation. The heat absorption by the nanoparticles increases the temperature of base fluid (water). Additionally, the basin liner, due to its black color, absorbs solar radiation which further heats the base fluid by conduction and free convection. Both heat absorption mechanisms (basin liner and nanoparticles) enhance the heat transfer process and raise the water temperature.

4. Nanoparticles in a solar still with their base fluid

Sahota and Tiwari [58] conducted experiments in a passive double slope solar still with Al_2O_3 nanoparticles in the basin water. The inner surface area of the double slope solar (DSSS) still is 2 × 1 m. Two different masses of water (35 and 80 kg) were used in the solar still. Three different concentrations of nanoparticles (0.04%, 0.08%, and 0.12%) were used to measure the enhancement of the freshwater productivity. The different components in the DSSS such as basin liner, fluid, and east and west sides were theoretically modeled. The results showed that the productivity enhancement for 35 and 80 g of the base fluid was 12.2% and 8.4%, respectively. This is partly due to the absorption of direct solar radiation in the nanoparticles. This and the higher thermal conductivity of suspended nanoparticles increased the water temperature above hot basin liner. The increased fluid temperature enhances evaporative heat transfer and augments the freshwater productivity.

Sahota and Tiwari [59] experimentally tested a DSSS with three different nanofluids in the basin liner as shown in Fig. 1. The nanofluids with the mass concentrations were Al_2O_3–0.2%; TiO_2–0.25%, and CuO–0.3%. The inner surface area of the DSSS is 2 × 1 m. The different components of DSSS were modeled and validated. The better optical properties of Al_2O_3 metallic nanoparticles enhanced absorptivity as well as increased the basin water temperature. The test results showed that Al_2O_3 water-based nanofluids gave the highest productivity compared with the TiO_2 and CuO nanofluids. The mass concentration beyond 0.25% (TiO_2 and CuO) decreased the thermal energy transferred from nanoparticles to the fluid.

Sahota and Tiwari [60] experimentally studied the DSSS with water-based TiO_2, CuO, and Al_2O_3 nanofluids as shown in Fig. 2. Two modes of operation were conducted experimentally: (1) with helically coiled heat exchanger and (2)

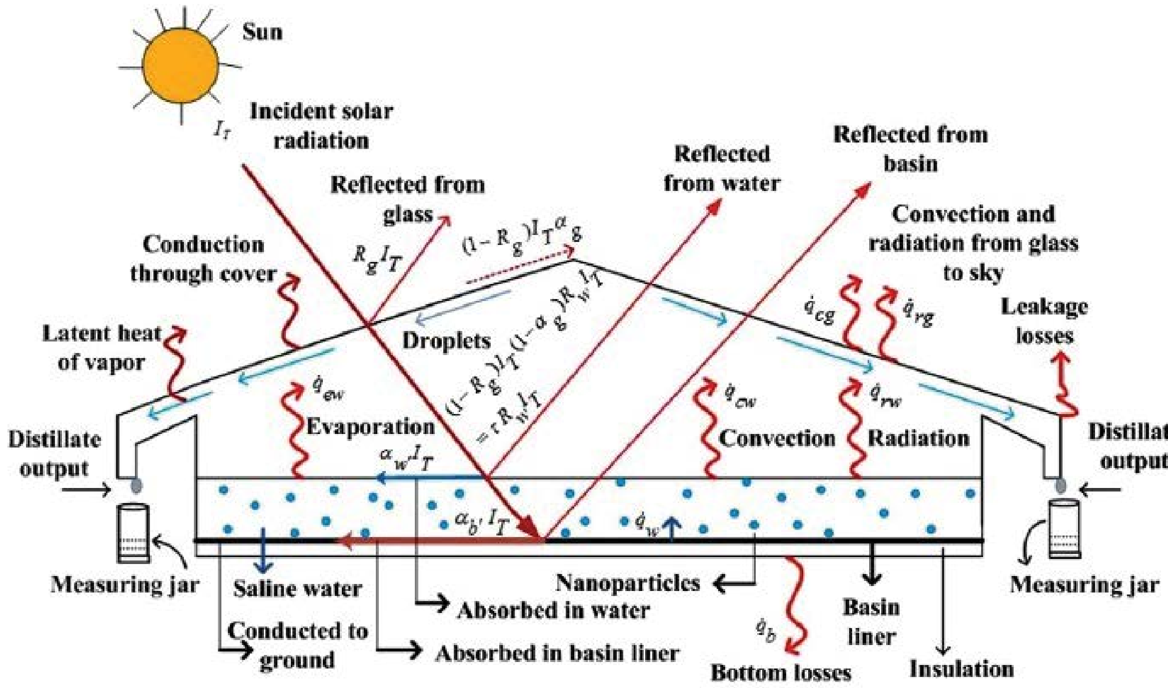

Fig. 1. Schematic view of double slope solar still with nanoparticles in the basin [59].

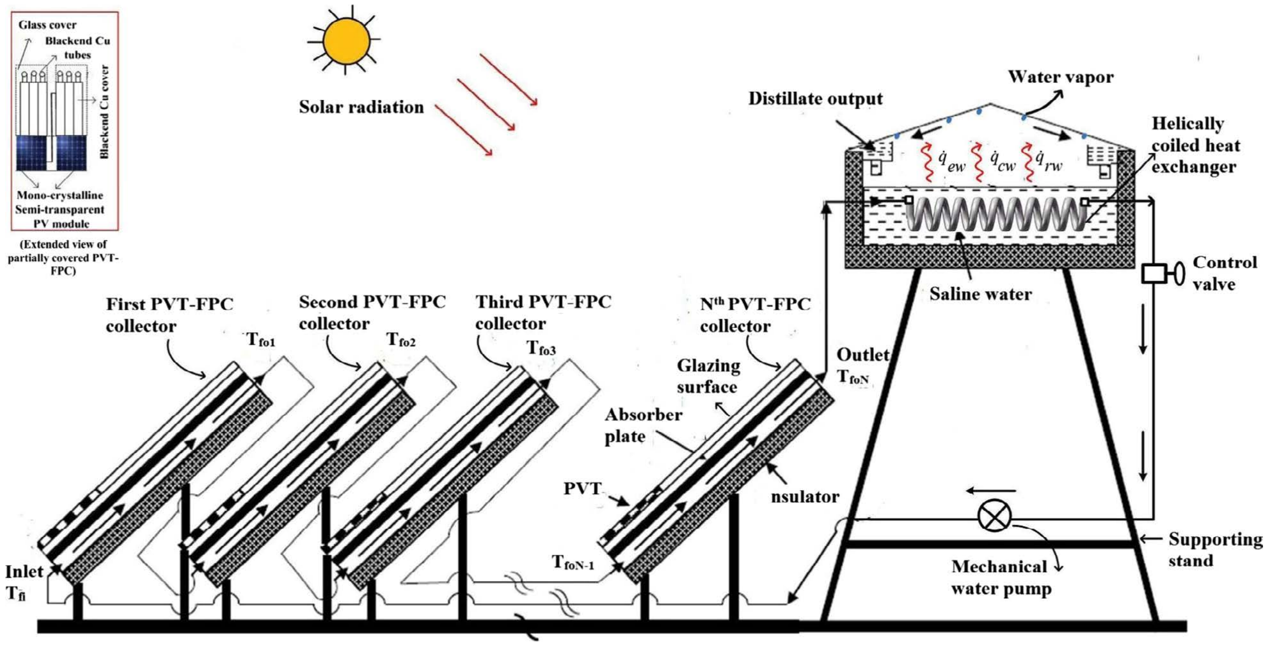

Fig. 2. Double slope solar still integrated with PVT-FPC [60].

without heat exchanger. The collectors were monocrystalline semitransparent PV thermal FPC integrated with a DSSS. The inner surface area of the DSSS is 2 × 1 m. The PV panels generate the electrical power that circulates the basin water under forced mode operation. The different components in the DSSS such as basin liner, basin fluid mass, and east and west sides of the double basin solar stills were theoretically modeled. The energy payback time, energy production factor, life cycle conversion efficiency, enviroeconomics, and exergoeconomics were analyzed. The results concluded that the exergoeconomics were improved due to water-based nanofluids. They showed that the water-based CuO nanofluids gave the highest productivity relative to the TiO_2 and Al_2O_3 nanofluids.

Sahota et al. [61] studied the incorporation of three different nanofluids, Al_2O_3, TiO_2, and CuO, into the DSSS as shown in Fig. 3. The results were that the annual distillate

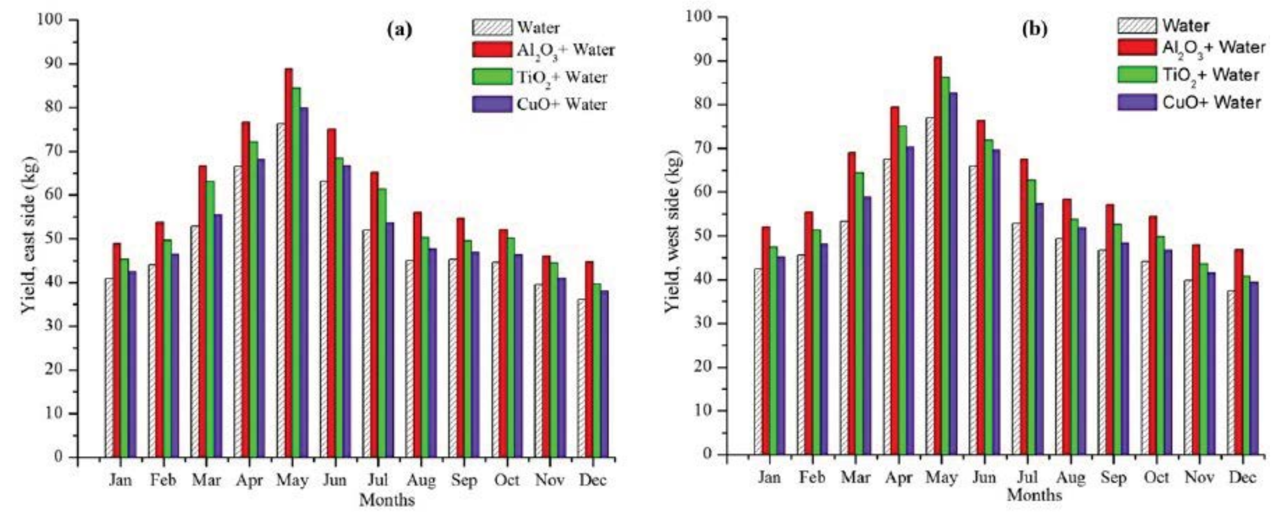

Fig. 3. (a) and (b) Productivity graph of different nanofluids in the double slope solar still (east and west sides) [61].

productivity, energy efficiency, and exergy efficiency were found to be the highest for the Al_2O_3 water-based nanofluid.

Kabeel et al. [62] conducted a numerical investigation on the SSSS integrated with an external condenser. Additionally, Al_2O_3 and Cu_2O were added to water and used as a heat transfer fluids in the basin liner (see Fig. 4). They demonstrated that the water yield was enhanced by 84.16%. This is due in part to the higher thermal energy storage of Cu_2O nanofluids than Al_2O_3 nanofluids.

Kabeel et al. [63] experimentally studied two SSSSs integrated with an external condenser as shown in Fig. 5. Two identical solar stills were designed and constructed each with an area of 0.5 m^2. The modified SSSS consisted of an exhaust fan operated by a DC motor powered by PV panels. Additionally, a water-based Al_2O_3 nanofluid was used in the basin liner. The solar still equipped with Al_2O_3 had overall productivity increased by 116% (with the exhaust fan). The fan increases turbulence above the saline water and takes the evaporated content from the saline water surface. They have also observed that, the fan sweeps the noncondensable gases away from the solar still and hence increases the condensation rate.

Kabeel et al. [64] experimentally examined two different water-based nanofluids of Al_2O_3 and Cu_2O in the solar still as shown in Figs. 6(a) and (b). Two identical SSSSs were constructed and tested under the same climatic conditions of Egypt. The particle size of the Al_2O_3 and Cu_2O varied from 10 to 14 nm. The particle volume concentrations varied from 0.02% to 0.2%. The overall experimental results revealed that with the fan, the Cu_2O water-based nanofluids enhanced the productivity by 133.64% and the Al_2O_3 nanofluids by 125.0%. The enhancement is a function of thermal conductivity of the Al_2O_3 and Cu_2O nanoparticles. The thermal conductivity of Cu_2O increases the water temperature, which results in faster evaporative heat transfer and hence greater productivity.

Omara et al. [65] experimentally examined a wick type solar still with Al_2O_3 and Cu_2O nanofluids in the basin as shown in Fig. 7. Two identical solar stills were constructed and tested under same climatic environment. The fabricated area of each of the solar stills was 0.5 m^2. Three different

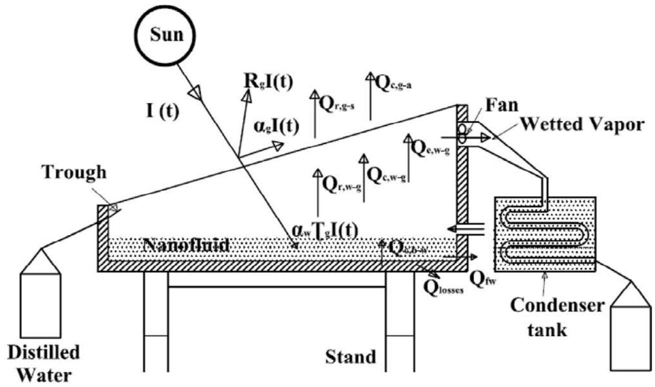

Fig. 4. SSSS with nanofluid in the basin [61].

water depths (1, 2, and 3 cm) were maintained during the experimentation. The experimental results reveal that the wick type solar still with Cu_2O nanofluids has better performance than the Al_2O_3 water-based nanofluids.

Mahian et al. [66] experimentally studied a solar still with SiO_2 and Cu water-based nanofluids as shown in Fig. 8. Two identical FPCs were connected with an SSSS's heat exchanger in series mode. After heating, a pump moved the nanofluids into the SSSS via pipes to enhance the heat transfer as well as productivity. Two different size of nanoparticles (7 and 40 nm), two depths of basin water (4 and 8 cm), and two mass flow rates (0.04 and 0.12 kg/s) were examined. A mathematical model was also developed and validated with experimental results. It was found that the Cu water-based nanofluids had higher evaporation rate than SiO_2 nanofluids.

Elango et al. [67] experimentally tested ZnO, SnO_2, Fe_2O_3, and Al_2O_3 water-based nanofluids in the SSSS as shown in Fig. 9. Two identical solar stills (0.25 m^2) were designed and tested in the same climatic conditions. They concluded that the Al_2O_3 gave the highest productivity enhancement (29.95%) relative to ZnO nanofluids (12.67%) and SnO_2 (18.63%). The thermal conductivity of Al_2O_3 plays a significant role in the productivity. The Al_2O_3 nanoparticles absorb

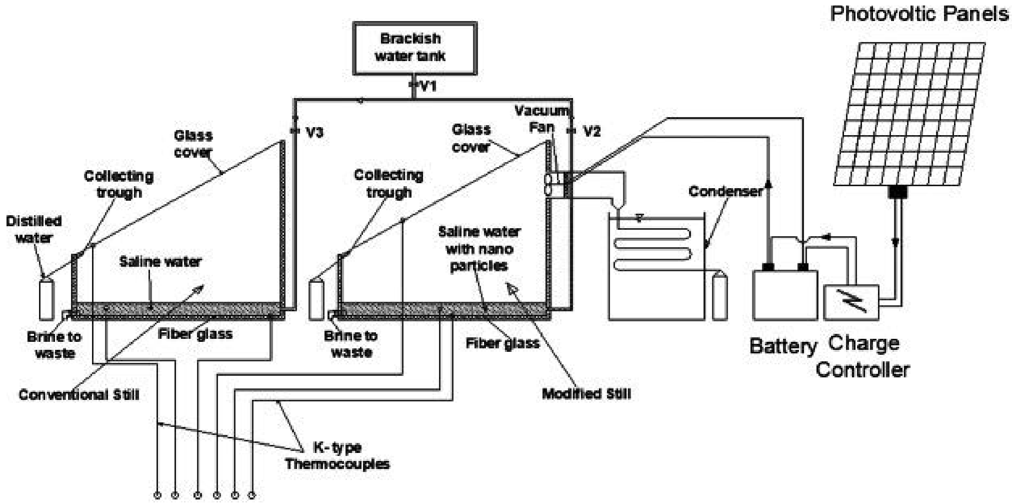

Fig. 5. Solar still with nanoparticles with external condenser [63].

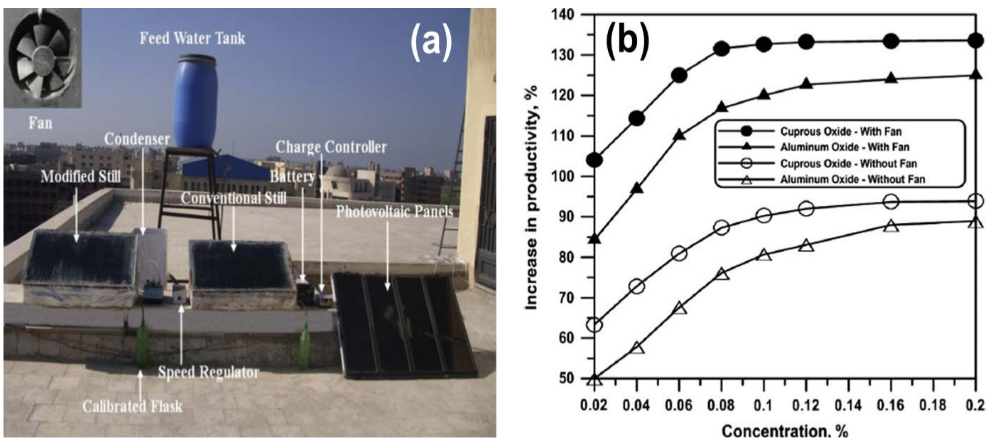

Fig. 6. (a) Pictorial view of experimental arrangement, and (b) effect of nanoparticle concentration [64].

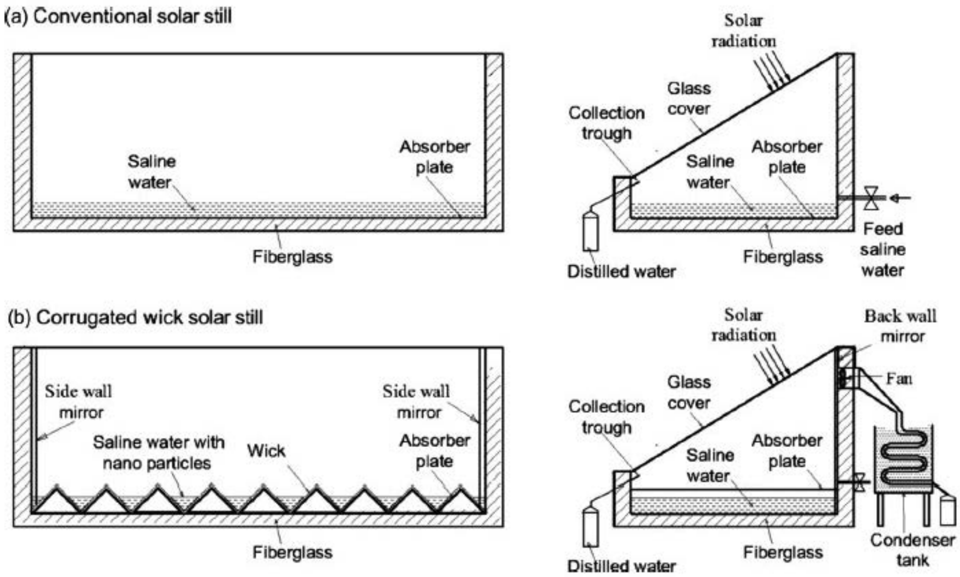

Fig. 7. Cross-sectional view of modified solar still with nanoparticles [65].

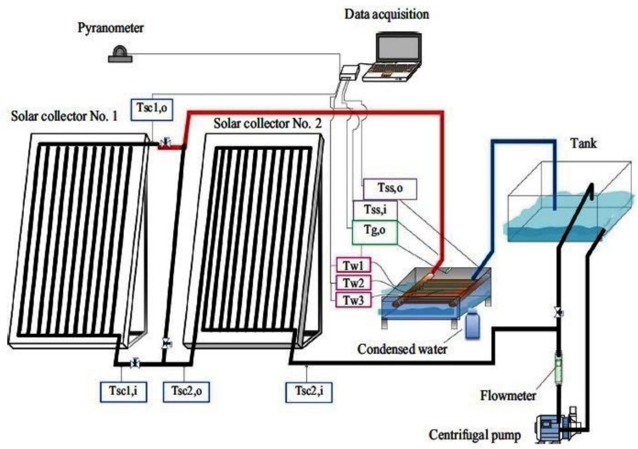

Fig. 8. SSSS integrated with FPC and heat exchanger coil [66].

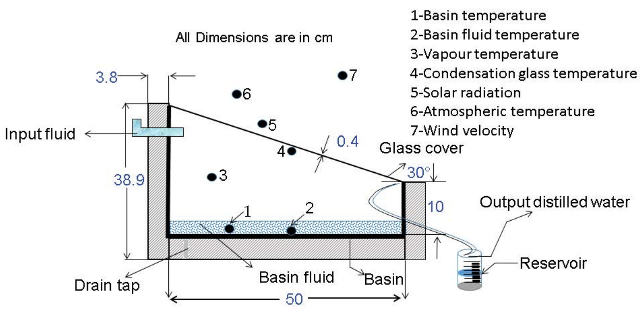

Fig. 9. Schematic diagram of solar still with basin fluid [67].

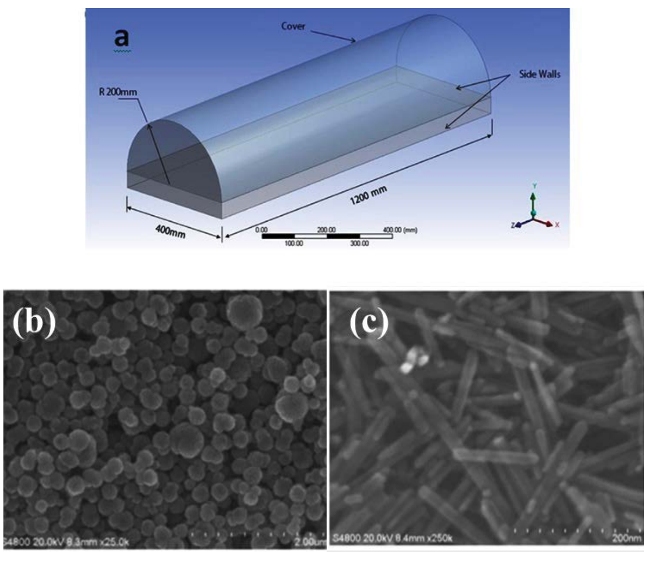

Fig. 10. (a) Tubular solar still, (b) ZnO spherical nanoparticles, and (c) ZnO nanorods [69].

more direct solar radiation than water. So the nanoparticles transferred the heat to water and increased the temperature difference between the water and glass cover, which resulted in more distillate output.

Madhu et al. [68] experimentally studied a single basin solar still with Al_2O_3, CuO, and TiO_2 nanofluids in the basin. The Al_2O_3 nanofluids of 0.2% concentration gave the highest daily productivity of 4.03 kg/m^2 compared with CuO nanofluids (2.25 kg/m^2) and TiO_2 nanofluids (2.17 kg/m^2).

Saleh et al. [69] studied the ZnO nanoparticles used in a half-tubular solar still for distillate enhancement (see Fig. 10(a)). The ZnO nanoparticles were prepared by a hydrothermal synthesis process. Two different solvents of methanol and ethylene glycol were used to prepare the ZnO nanoparticles. By using methanol and ethylene glycol as solvents, they achieved a morphology of ZnO nanorods and ZnO nanospheres, respectively (Figs. 10(b) and (c)). The rods seemed to be transparent and had a length of 100 nm. The synthesized nanoparticles were mixed with black paint and used to coat the basin of the tubular solar still. Their results showed that nanorod structured ZnO nanoparticles in the black paint gave the highest efficiency of 38% and productivity enhancement of 30% was achieved.

Gupta et al. [70] investigated a passive SSSS with CuO nanoparticles in the basin. Two identical solar stills were designed and constructed with 1 m^2 area each. Two different water depths of 5 and 10 cm were tested with 0.12% weight concentration of CuO nanoparticles. It was discovered that the CuO nanoparticles enhanced the freshwater productivity by 22%. The overall thermal efficiency of the solar distiller with 5 cm water depth was found to be 37.40%. Gupta et al. [71] experimentally studied the SSSS for brackish water distillation. Three interventions were studied: (1) the side walls of the solar still were painted white color, (2) cover cooling by sprinkler arrangement, and (3) Cu_2O nanoparticles in the basin. The results showed that the fully modified solar still gave a productivity of 4,000 mL/m^2/d relative to the conventional solar still of 2,900 mL/m^2/d. Rufuss et al. [72] experimentally studied TiO_2, CuO, and graphene oxidenanoparticles with PCM. The result concluded that the CuO nanoparticles with PCM gave the maximum yield of 5.28 L/m^2/d.

Abhivav and Kumar [73] experimentally investigated an SSSS with Al_2O_3 nanofluids in the basin. The nanoparticles were synthesized in the laboratory and used at 0.1%, 0.5%, 1.0%, and 1.5% concentration in water. The result concluded that Al_2O_3 nanofluids in the basin enhanced the productivity by 20%. Navale et al. [74] experimentally tested the masonry solar still (solar still made of bricks, sand, and cement) for brackish water distillation. Two different types of nanofluids namely Al_2O_3 and CuO were analyzed at 0.1%, 0.2%, and 0.3% concentration. The CuO nanofluid with 0.3% concentration enhanced the distillate productivity by 89.42%, while the Al_2O_3 nanofluid at 0.3% concentration enhanced the productivity by 45.19%.

Kabeel et al. [75] performed experiments on SSSSs with Cu_2O nanoparticles (Fig. 11). Two identical solar stills were fabricated and the effect of CuO nanoparticles in the same climatic conditions was tested. The fabricated area of each solar still was 0.5 m^2. The weight concentration of the Cu_2O ranged from 10% to 40% in black paint and applied to the inner surface of the basin. It was revealed that adding the nanoparticles in the black paint enhanced the solar still performance by 25%. The increase of temperature in the basin transferred more heat to the water, causing an increase in evaporative heat transfer.

Sain and Kumawat [76] have done experiments on a solar still with Al_2O_3 nanoparticles. The nanoparticles were mixed with black paint and coated on the basin of the SSSS for freshwater yield enhancement. The area of the solar still was 1 m^2. The experiment was conducted with 1, 2, and 3 cm water depths. The size of the Al_2O_3 nanoparticles was in the range of 50–100 nm. The overall results concluded that the mixed Al_2O_3 nanoparticles in the paint with 1 cm water depth enhanced the productivity by 38.65%.

Sharshir et al. [77] studied the performance of a SSSS using nanofluids and glass cover cooling as shown in Fig. 12. The graphite and Copper Oxide (CuO) microflakes with different concentrations (0.125%–2%), three different water depths (0.25–5 cm) and different flow rates (1–12 kg/h) were studied. The thermal conductivity of the graphite and CuO was 129 and 76 W/m K. Three identical solar stills were designed and constructed with an area of 0.25 m^2 each. The graphite microflakes gave the highest efficiency of 49% partly because the thermal conductivity of the graphite is higher than CuO. At the same time, the density of the graphite (1.2 g/cm^3) is less than CuO (6.4 g/cm^3) nanoparticles. So the graphite nanoparticles were more suspended and distributed over the water in the basin. The graphite nanoparticles absorbed more energy from the sun and transferred the heat into the water. The water temperature increased and enhanced the freshwater productivity.

Chen et al. [78] investigated Silicon-Carbide (SiC) nanofluids in saline water to enhance the stability and thermal conductivity. The result concluded that the SiC nanofluids enhanced the thermal conductivity by 6% at 0.4% volume concentration. Gnanadeson et al. [79–80] experimentally studied the SSSS with multiwalled carbon nanotubes (MWCNTs). The MWCNTs were prepared by the chemical vapor deposition (CVD) method at the laboratory scale. The nanofluids in the water enhanced the heat transfer rate and increased the evaporation rate in the SSSS.

Abdelal and Taamneh [81] experimentally studied the pyramid solar still with graphene and CNT in the basin. The dimensions of the pyramid solar still basin were 0.70 × 0.70 m. The weight concentrations were carbon fabrics (such as fibers) 2.5%, graphene 2.5%, CNT 2.5%, and CNT 5%. They concluded that 5% weight concentration of CNT enhanced the system productivity by 30% as shown in Fig. 13.

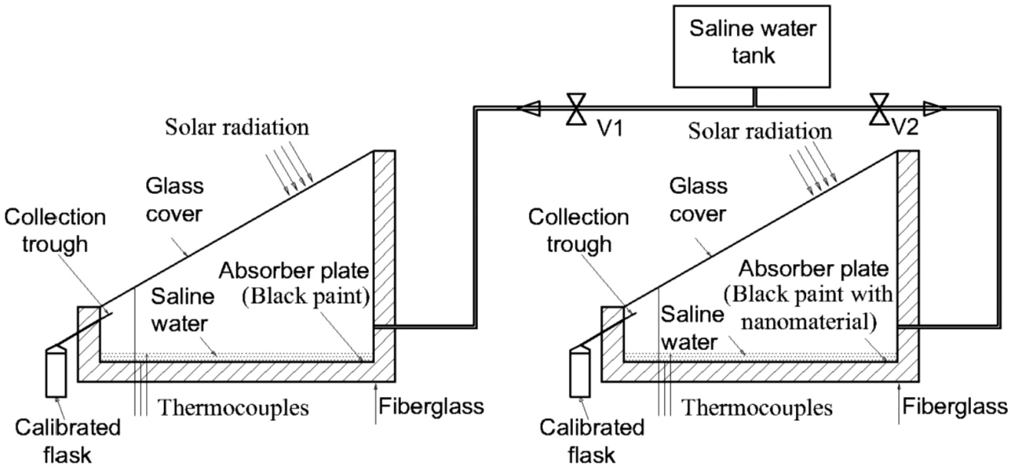

Fig. 11. Schematic view of solar still with nanomaterial [75].

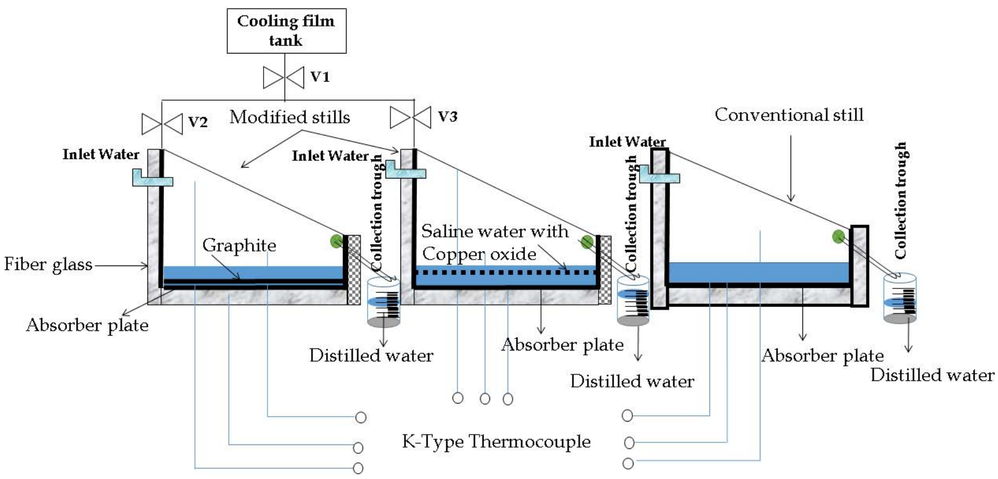

Fig. 12. SSSS with graphite microflakes and nanomaterial [77].

Elfasakhany [82] studied Cu-paraffin wax (PW) nanocomposites in the SSSS as shown in Fig. 14. The results concluded that the Cu-PW nanocomposites enhanced the system performance by 5%. Chen et al. [83] experimentally studied Fe_3O_4 dispersing MWCNTs in a solar still for greater solar energy absorption and to enhance the heat transfer. They found that the 0.04 wt% of MWCNTs nanofluids was absorbing 100% solar energy. The result concluded that the efficiency of the solar still with 0.04 wt% was 76.65% and without MWCNTs was 24.91%.

Methre and Easwaramoorthy [84] analyzed the Al_2O_3 – paraffin wax nanocomposites for freshwater improvement (see Fig. 14). The weight concentrations were 2 wt% Al_2O_3 and 4 wt% Al_2O_3. Three modes of operation were performed: case (1) with paraffin wax, case (2) PW–2 wt% Al_2O_3, and case (3) PW–4 wt% Al_2O_3. The results concluded that higher weight concentrations (4 wt% Al_2O_3) performed better than other experiments.

Chaichan and Kazem [85] conducted experiments in an SSSS with nanocomposites in the basin. The nanocomposites used were PW-aluminum powder in the distiller. They discovered that the nanocomposites augment the system productivity by 21.19% under Bagdad, Iraq climatic conditions during January 2013. Rajasekar and Easwaramoorthy [86] studied the mixture of Al_2O_3 nanoparticles with paraffin wax in the solar still. Two identical solar stills were constructed and tested in the same climatic conditions. Two modes of operation tested: (1) solar still with mixture of Al_2O_3 with paraffin wax and (2) solar still with paraffin wax alone. The experimental results reveal that Al_2O_3 with paraffin wax composites gave a higher efficiency of 45% than paraffin wax alone (38%). The various nanofluids and their thermal conductivity, volume concentrations are shown in Table. 1.

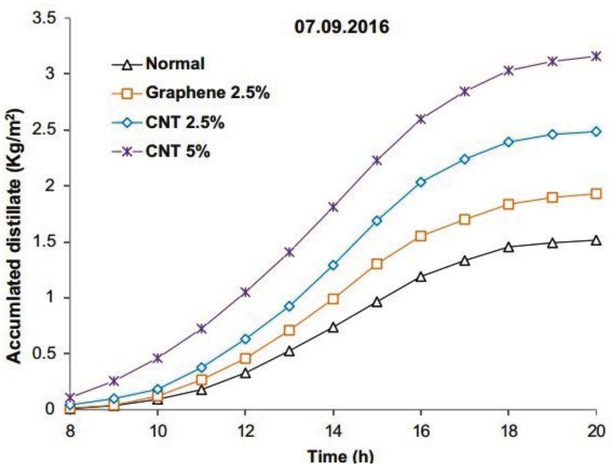

Fig. 13. Graphical view of pyramid solar still productivity [81].

Fig. 14. Pictorial view of paraffin wax and Cu nanopowder [84].

5. Application of nanoparticles in solar stills – an overview

Nanofluids consist of suspended of solid particles in the nanometer range and their thermal conductivity is higher than the base fluid [87,88]. The nanoparticles collide under stationery conditions evaluated by Keblinski et al. [89]. The heat transfer in a nanofluid depends upon size of the nanoparticle, volume concentration, and pH of the solution [54]. Sahota and Tiwari [59] studied Al_2O_3, TiO_2, and CuO water based nanoparticles in a DSSS. Their results concluded that an increase in volume concentration slightly affects the temperature difference between the water and glass where condensation occurs (ΔT) as shown in Fig. 15. Kabeel et al. [64] studied Al_2O_3 and Cu_2O water-based nanofluids in an SSSS. They varied the concentrations from 0.02% to 0.2%. They found that there is no marked increase in productivity beyond 0.16% (see Fig. 10(b)). Mahian et al. [66] experimentally studied a solar still with SiO_2 and Cu water-based nanofluids. They found that the increase of volume concentration (for high concentrations) (Fig. 16) and particle size (Fig. 17) of nanoparticles decrease the productivity and this phenomenon agreed with Sahota and Tiwari [59]. A survey of research papers focusing on the physics at the molecular level of nanofluids agreed. The important findings are: (1) the particle-particle and particle-molecule interactions

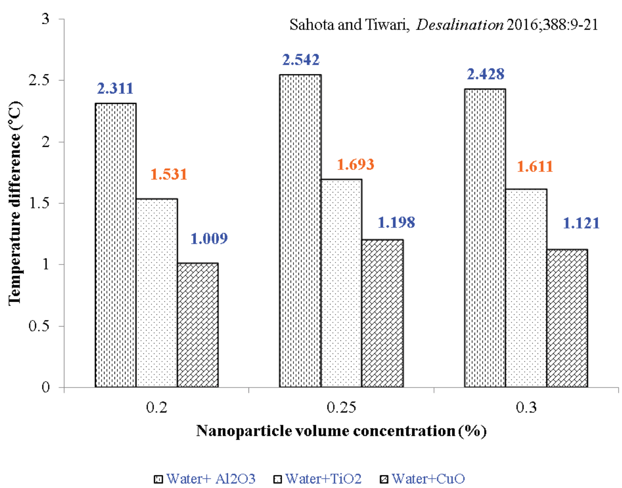

Fig. 15. Graphical view of temperature difference with respect to volume concentration [59].

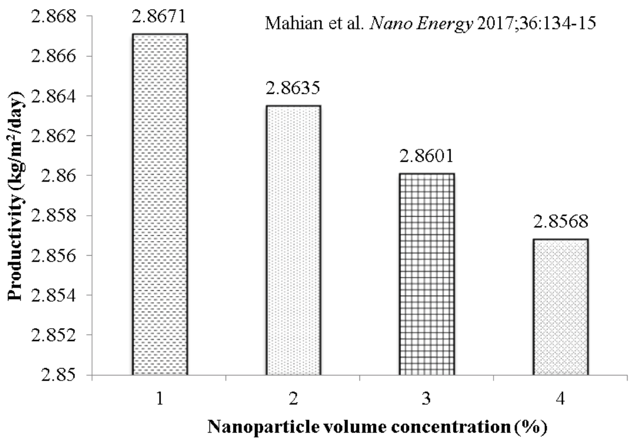

Fig. 16. Graphical view of productivity with respect to volume concentration [66].

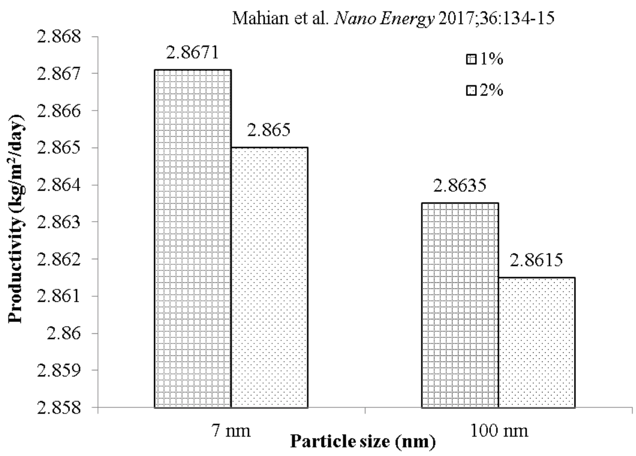

Fig. 17. Graphical view of productivity with respect to particle size [66].

play a significant role in enhancing the thermal conductivity of the nanofluids, (2) the smaller the nanoparticle size, the better the thermal conductivity, and (3) nanofluids have high thermal conductivities at low nanoparticle concentrations. By adding nanoparticles, initially, the conductivity of nanofluid will increase for a certain volume concentration. Further increase in volume concentration of nanoparticles will decrease the thermal conductivity of nanofluid (0.2%–4%). It is recommended that future work examine sets of experiments to find the optimum particle concentration for maximum thermal conductivity (or minimum cost of pure water).

6. Conclusion

In this review, thermal conductivity enhancement through different types of nanoparticles in solar stills is discussed. The high thermal conductivity of the nanoparticles interacts with their base fluid to enhance output of the distiller. A key takeaway from the above research findings is that the increase in the thermal conductivity of the nanofluid is not directly proportional to the concentration of the nanoparticle. Instead, the effect saturates. In terms of distilled water productivity, increasing nanoparticle concentration first increases output; but then at very high concentrations, output actually falls. It should be noted that the higher the concentration of the nanoparticles in the fluid, the more serious the problem of settling will be. The following conclusions can be drawn:

- Nanoparticles, when added to black paint for the basin, enhance the yield.
- The thermal conductivity of the nanofluid depends on the size and volume concentration of the nanoparticles in the base fluid.
- The smaller the nanoparticle size, the better the thermal conductivity of the nanofluid is at the same volume concentration.
- The still output attains a maximum at relatively low nanoparticle concentrations.
- MWCNTs, SiC, Cu, graphite flakes, Cu_2O, and Al_2O_3 nanoparticles have enhanced the productivity as well as system thermal efficiency.

Symbols

C	—	Specific heat capacity
D, d	—	Diameter, m
k	—	Thermal conductivity, W/m K
k_B	—	Stefan–Boltzmann's constant = 5.67 × 10^{-8} W/m²/K⁴
M	—	Molecular weight of the base fluid, kg/mol
N	—	Avogadro number
P	—	Nanoparticle
T	—	Temperature, °C

Greek

ρ	—	Mass density, kg/m³
ϕ	—	Volume fraction/nanomaterial concentration
μ	—	Dynamic viscosity, kg/m/s
ΔT	—	Temperature difference

Subscripts

bf	—	Base fluid
g	—	Glass cover
nf	—	Nanofluid
w	—	Water
p	—	Particle

Abbreviation

BF	—	Base fluid
CNT	—	Carbon nanotube
CVD	—	Chemical vapor deposition
DSSS	—	Double slope solar still
FE-SEM	—	Field emission-scanning electron microscope
FPC	—	Flat plate collector

MWCNT	—	Multiwalled carbon nanotube
NF	—	Nanofluid
NP	—	Nanoparticle
PCM	—	Phase change material
PTC	—	Parabolic trough collector
PV	—	Photovoltaic
PW	—	Paraffin wax
SSSS	—	Single slope solar still
TSS	—	Tubular solar still

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