A concise review on the role of nanoparticles upon the productivity of solar desalination systems

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Abstract:

In recent years, nanofluids have been widely used to improve the performance of various energy systems due to their favourable thermo-physical and optical characteristics. In particular, solar distillation systems, as an affordable and reliable technique to provide freshwater, have benefited from nanofluid technology. This article performs a review of literature on the implementation of nanofluid technology in active and passive solar distillation systems. The progress made and the existing challenges are discussed and some conclusions and suggestions are made for future research. The review indicates that the daily productivities of solar distillation systems enhance by using nanofluid and increasing the volume fraction of nanoparticles. However, long-term operational stability and life cycle assessment remain critical issues. These factors should be considered for future research in this field.

Keywords: Solar distillation systems; Nanotechnology; Desalination; Active and passive solar desalination.

Nomenclature

E	energy (J/kg)
F	force (N)
g	gravitational acceleration (m/s^2)
k	thermal conductivity ($W/m.^oC$)
p	Pressure (Pa)
S_h	energy source term ($Kg/m.s$)
S_α	mass source term ($Kg/m^3.s$)
t	time (s)
T	temperature (^oC)
V	velocity (m/s)

Subscripts/superscripts

eff	effective
i	i^{th} phase
v	vapor

Greek symbols

α	volume/void fraction (-)
μ	dynamic viscosity ($kg/m.s$)
ρ	density of the fluid (kg/m^3)
φ	solid volume fraction of nanoparticles (-)

Abbreviations

CFD	Computational fluid dynamics
VOF	Volume of fluid

1. Introduction

The shortage of freshwater is rapidly being converted into a critical issue in many parts of the world. Such crisis significantly hurts industrial and agricultural sectors and adversely influences human life. Although about 75% of the earth is covered with water, just 0.014% of that is usable directly for the human. Indeed, most of the water on the planet is stored as salt sea water (up to 97.5% of the global water) [1]. This figure clearly reflects the massive importance of distillation systems. Electrodialysis and reverse osmosis are two common techniques to distillate saltwater. In electrodialysis, salt ions can be transported from one solution through ion-exchange membranes towards the other one through using an electrical potential difference [2]. A schematic view of this system is shown in Fig. 1. An external electrical potential difference is used between two end-electrodes to create an ionic current inside the membrane. Consequently, the feed flow is desalinated inside alternating ducts, and the concentrate and diluate are gathered.

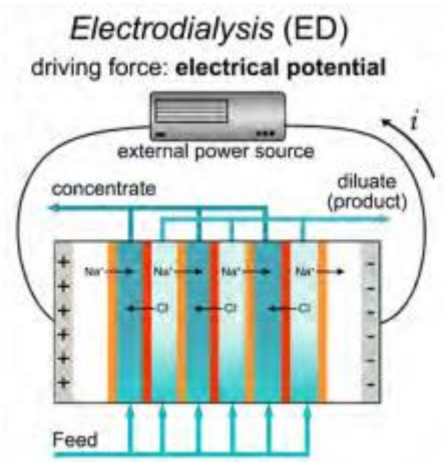


Fig. 1. A schematic view of electrodialysis system [2]

In reverse osmosis, semipermeable membranes are employed to eliminate molecules, ions, and larger particles from saline water [3]. A schematic view of a reverse osmosis system is shown in Fig. 2. In this system, a pressure is applied to overcome osmotic pressure.

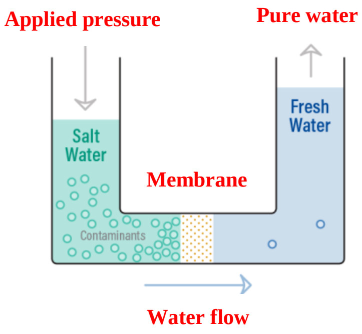


Fig. 2. A schematic view of a reverse osmosis system

The high costs of construction, repair, and maintenance and also the need for electrical power consumption are some disadvantages of electrodialysis and reverse osmosis techniques. Moreover, the high capacity of these methods makes them unsuitable for the regions with disperse population. Solar distillation systems are a promising alternative for these applications. In solar distillation systems, solar energy is used to heat and evaporate water that at the same time is separated from impurities and salt. After evaporation, the vapour is condensed to collect the distilled water. A schematic view of a double slope solar still is disclosed in Fig. 3. Solar beam transmits through a clear glass cover and transfers to the water surface in salt water basin. The water evaporates and thermal energy transfers between the glass and salt water surface by convection, evaporation, and radiation. The vapour condenses on the inner surface of the glass releasing its latent heat of vaporisation. The condensed water drips down the internal surface of the cover due to the gravity and can be gathered in internal gutters [4].

Fig. 3. A schematic view of a double slope solar still [5]

Low costs of construction, repair, and maintenance, simplicity, portability, and use of solar energy resources are some advantages of solar distillation systems. Conventional solar distillation systems have a low capacity and large size, which occupied a large space. Researchers used different passive and active techniques to overcome the disadvantages and improve the efficiencies of these devices [5-9].

Manikandan et al. [10] reviewed the potentials of wick materials to enhance the productivity of solar stills. They recommended the wick materials as leading and economic materials to improve the productivity of solar stills. Their review also showed that the floating wick type solar still has the maximum productivity amongst all existing wick type solar stills. Note that floating wick material in the basin of solar still causes suction of water as a result of capillary action. Thus, the upward surface of wick material is always moist and this increases the evaporation rate. Kabeel et al. [11] reviewed the potentials of condenser for improving the productivity of solar stills. This review showed that supplying further region for condensation enhances the condensation rate and also improves the evaporation rate in the still. Figure 4 discloses a schematic view of a single slope solar still with external condenser. In this design, a vacuum fan is installed on the side wall of the solar still and the output of this fan can be guided towards the external condenser to provide more distilled water.

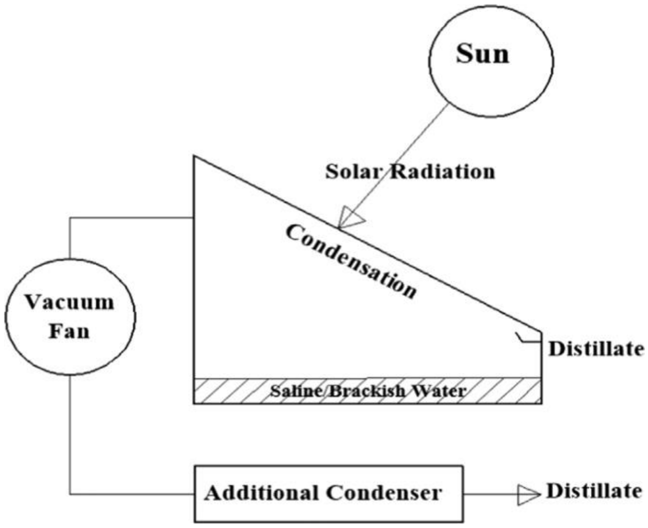


Fig. 4. A schematic view of a single slope solar still with external condenser [11]

Sathyamurthy et al. [12] performed a literature review on the integration of solar still with solar collectors to enhance the production of freshwater. They reported that the combination of solar stills and solar collectors enhances the production of freshwater by about 36%. A schematic view of a single slope solar still with a flat plate collector is discloses in Fig. 5. In this figure the flat plate collector is used to heat the water and assists with the evaporation process.

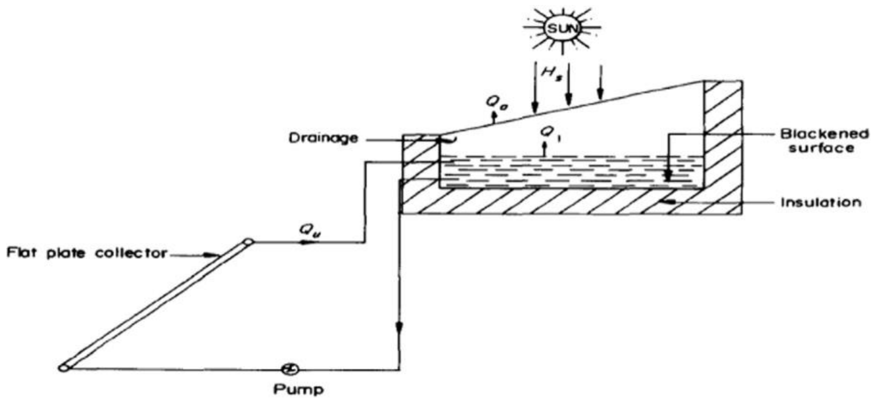


Fig. 5. A schematic view of a single slope solar still with a flat plate collector [13]

Omara et al. [14] reviewed the methods for cooling glass cover of solar stills. Their review indicated that using this method has a potential for reducing the temperature of glass cover in the range of 6 to 20 °C and that it can enhance the productivity and performance up to

20% and 15.5%, respectively. Figure 6 shows a schematic view of a single slope solar still with water flowing above the glass as a cooling film.

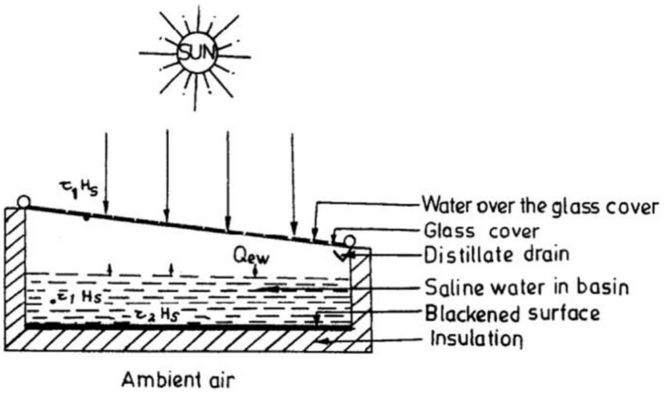


Fig. 6. A schematic view of a single slope solar still with water flowing above the glass as a cooling film [15]

Shukla et al. [16] reviewed the applications of latent heat energy storage materials. They stated that there are a considerable number of investigations on the numerical simulations and laboratory experiments in this field. However, there are a small number of studies on evaluating the system in the actual climatic conditions. Omara et al. [17] reviewed the solar stills equipped with reflectors. Reflectors can be used to improve the solar radiation directed to the basin of the still. They recommended these devices as a highly attractive and inexpensive modification for enhancing the productivity of the solar still. Figure 7 discloses a schematic view of a single slope solar still equipped with internal and external reflectors.

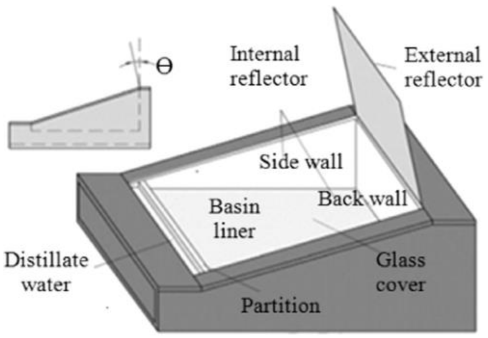


Fig. 7. A schematic view of a single slope solar still with internal and external reflectors [18]

Over the last two decades, nanoparticles and nanofluids have opened a new window to enhance the efficiencies of various thermal systems [19-34]. Due to the promising characteristics of nanofluids, some researchers used them to improve the performance of different solar systems. Mahian et al. [35] performed a literature review on the potentials of nanofluids in solar systems. They concluded that using nanofluids in solar collectors is affordable and environmentally friendly as they lead to the reduction of CO_2 emissions by fuel consumption. Subsequently, Kasaeian et al. [36] performed another literature review in this field. Their review indicated that a large value of thermal conductivity of nanofluid causes performance enhancement in solar systems. However, a large value of nanoparticle concentration does not always enhance the performance of these systems. The preceding reviews did not consider the solar desalination systems as a solar still. This article performs a comprehensive review on the role of nanoparticles on the productivity of solar desalination systems. The progress made and the existing challenges facing this method are discussed and some conclusions and suggestions are made for future research. Further, the numerical modelling of nanofluid solar still by volume of fluid model is explained briefly in a dedicated section.

2. Mathematical modelling of nanofluid solar still

Generally, experimental works are costly and time consuming. Hence, it is often required to employ an affordable and fast method to predict the performance of solar desalination systems. Computational fluid dynamics (CFD) provides an opportunity to achieve this goal. Previously, researchers used moist air model to simulate a solar still [6, 37-39]. This model considers all regions of the still as a moist air and condensation and evaporation processes are not modelled in solar still. For an actual solar still, there is a two-phase flow with a liquid-vapour phase change process. However, volume of fluid model has the capability to simulate the two-phase flow in the solar still where the change in joint surface between the two phases is important. This model has the ability to follow the interface between liquid and vapour phases and simulate the phase change during condensation and evaporation processes [40]. The mathematical modelling of nanofluid solar still by this model is explained briefly in this section.

2.1. Governing equations

Volume of fluid (VOF) model offered by Hirt and Nichols [41] can be used to simulate the two-phase flow with evaporation and condensation processes in solar stills. In VOF, it is required to calculate the volume fraction of each phase in any cell of geometry. The summation of the volume fraction for vapor or liquid phase in a cell must be one:

$$\sum_{i=1}^{n_{phase}} \alpha_i = 1 \tag{1}$$

In this equation, α_i is the volume fraction of the i^{th} phase.

The thermo-physical properties of a two-phase flow in any cell can be calculated by using the mean quantities of phases, weighted by their pertinent volume fractions. For example, viscosity of a liquid-vapour two-phase nanofluid flow is defined as [40]:

$$\mu = \alpha_v \mu_v + (1-\alpha_v)\mu_{eff} \tag{2}$$

In this equation, α_v is the volume fraction of the vapor phase. Further, μ_{eff} and μ_v are viscosities of nanofluid as the liquid and vapor phase, respectively.

A single phase method can be employed to calculate the effective properties of nanofluid as Albojamal and Vafai [42] reported that this method is able to predict nanofluids properties within an acceptable range of accuracy. The effective properties of nanofluid can be found in the work of Bovand et al. [43]. Other properties of vapour-liquid two-phase flow can be calculated by using a similar procedure.

The following continuity equation for the volume fraction of both phases should be solved to track the interface between them:

$$\frac{\partial \alpha_i}{\partial t} + V\nabla.\alpha_i = \frac{S_{\alpha i}}{\rho_i} \tag{3}$$

In this equation, ρ_i denotes the density for the i^{th} phase. In addition, t and V indicate time and velocity, respectively. Mass exchange between the two phases during condensation and evaporation processes in still is taken into account by adding the source term of $S_{\alpha i}$ in the above equation.

A single momentum equation can be used for all over the geometry. The velocity obtained by solving this equation can be shared amongst the phases. This equation is:

$$\left[\frac{\partial}{\partial t}(\rho V) + \nabla.(\rho VV)\right] = -\nabla p + \nabla.\left[\mu_{eff}(\nabla V + \nabla V')\right] + \rho g + F \tag{4}$$

In Eq. 4, p and F are pressure and surface tension forces at the interface between the liquid and vapour phases [44], respectively. The gravity term in Eq. 4 enables the model to reproduce the natural convection in the still.

Finally, the temperature field can be obtained by solving an energy equation. The energy equation is:

$$\frac{\partial}{\partial t}(\rho E) + \nabla.\left[V(\rho E + p)\right] = \nabla.(k\nabla T) + S_h \tag{5}$$

In this equation, k indicates the thermal conductivity. Note that energy (E) and temperatures (T) are employed with mass-averaged form as follows:

$$E = \frac{\sum_{i=1}^{n_{phase}} \alpha_i \rho_i E_i}{\sum_{i=1}^{n_{phase}} \alpha_i \rho_i} \tag{6}$$

The heat transfer during evaporation and condensation processes is taken into account by adding the source term of S_h in energy equation.

It should be clarified that the velocity components at all walls of the solar still are zero due to the no-slip condition. Constant temperature applies on the glass cover and bottom wall as phase change processes occur on them. Finally, thermal insulated boundary condition can be used for the lateral walls to minimize heat losses from solar still.

3. Applications of nanoparticles in solar stills

Nanoparticles, or nanoscale solid particles, can be suspended in a liquid to boost the heat transfer charactristics and evaporative rate of a liquid. Generally, nanofluids have distinctive physical properties to those of the base liquid. Amongst them is their large thermal conductivity [45-48] and higher values of solar intensity absorptivity [49]. The thermal and optical characteristics of nanoparticles are dependent upon various factors including their thermo-physical properties (e.g. thermal conductivity, specific heat, and viscosity) [50], shape, size, and solid volume fraction of nanoparticles [51,52]. Due to these characteristics, some researchers investigated the potentials of various types of nanoparticles to improve the productivity of solar stills. Table 1 presents some date about the thermal conductivity and cost of various nanoparticles. These data were presented by Elango et al. [53]. As shown in this table, although some nanoparticles have an excellent thermal conductivity their cost is rather high and hence they are not affordable for the use in the solar stills. As a result, the nanoparticles with large thermal conductivity and sensible cost are more suitable.

Table 1: The thermal conductivity and cost of various nanoparticles [53]

No.	Nanopowders	Thermal conductivity (W/m° K)	Quantity	Cost (Rs)[1]
1	Aluminum Oxide (Al_2O_3)	40	25 g	2000
2	Zinc Oxide (ZnO)	29	100 g	1500
3	Tin Oxide (SnO_2)	36	25 g	1500

[1] Indian rupee

4	Iron Oxide (Fe_2O_3)	7	25 g	1750
5	Gold nanopowder (Au)	315	1 g	35029
6	Titanium Dioxide (TiO_2)	8.5	100 g	12859
7	Copper Oxide (CuO)	76	5 g	3111
8	Carbon nanotubes	3000-6000	250 mg	19521
9	Zirconium (IV) Oxide (ZrO_2)	2	100 ml	10611
10	Silicon nitride (Si_3N_4)	29-30	25 g	11434
11	Boron nitride (BN)	30-33	50 g	4911
12	Aluminum nitride (AlN)	140-180	50 g	5193
13	Diamond nanopowder (C)	900	1 g	8755
14	Silver nanopowder (Ag)	424	5 g	12917

3.1. Solar still enhanced only with nanoparticle

This section reviews the solar desalination systems that are enhanced only with nanoparticles. Elango et al. [53] evaluated the potentials of various nanoparticles to improve the productivity of a solar still. Their nanoparticles were Al_2O_3, ZnO, and SnO_2. The percentage enhancements in the productivity of the solar still by using these nanoparticles in comparison with pure water (without adding nanoparticles) are disclosed in Fig. 8.

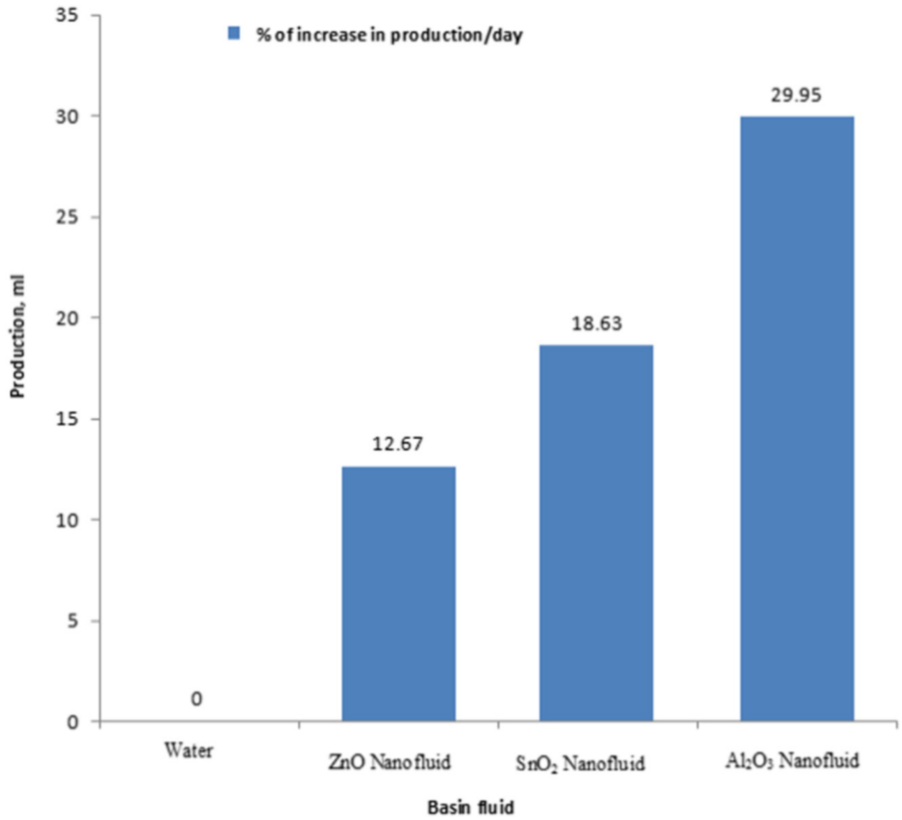


Fig. 8. The percentage enhancements in the productivity of the solar still by using nanoparticles reported by [53] in comparison with the base fluid (without using nanoparticles)

Sahota and Tiwari [54] investigated analytically the effects of Al_2O_3 nanoparticle on the efficiency of a solar still. They considered two masses containing 35 kg and 80 kg, respectively for basefluid. Figure 9 shows the procedures of their analytical work. BF, NF, DSSS, and HTC in this figure indicates the base fluid, nanofluid, double slope solar still, and heat transfer coefficient, respectively. Further, the thermo-physical properties of the base fluid and nanofluid are presented in tables 2-4. Their analysis showed that the productivity of solar still can be improved by about 12.2% and 8.4% through using Al_2O_3 nanoparticles with solid volume fraction of 0.12% in water with masses of 35 and 80 kg, respectively in comparison with the case without using nanofluid. Also, their results showed that the daily productivity enhances as the solid volume fraction of nanoparticles increases.

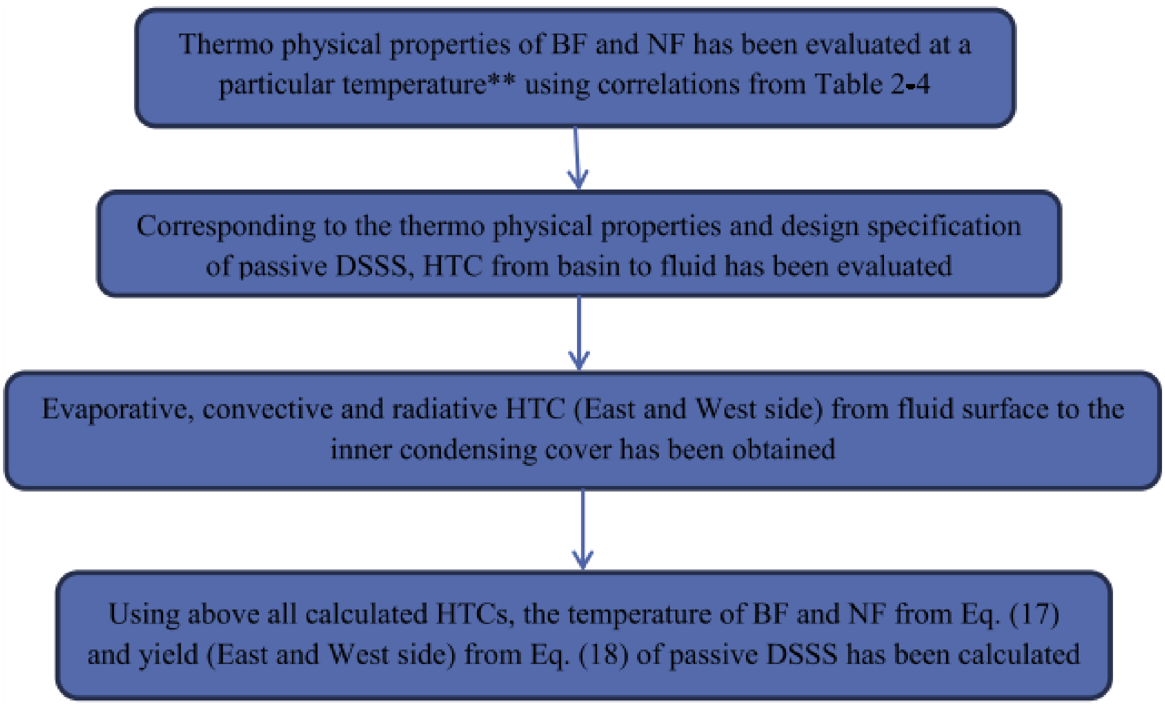


Fig. 9. The procedures of the analytical work presented by Sahota and Tiwari [54]

Sahota and Tiwari [55,56] repeated this analysis by considering three nanoparticles containing Al_2O_3, CuO, and TiO_2 nanoparticles. Figure 10 discloses the productivities of double slope solar still enhanced by different nanoparticles used by Sahota and Tiwari [55] for the east and west sides of the system. The nanoparticle concentration and water mass are 0.25% and 35kg, respectively. As shown in this figure, the productivity achieved by the east side of double slope solar still is marginally higher in comparison to that of the west side.

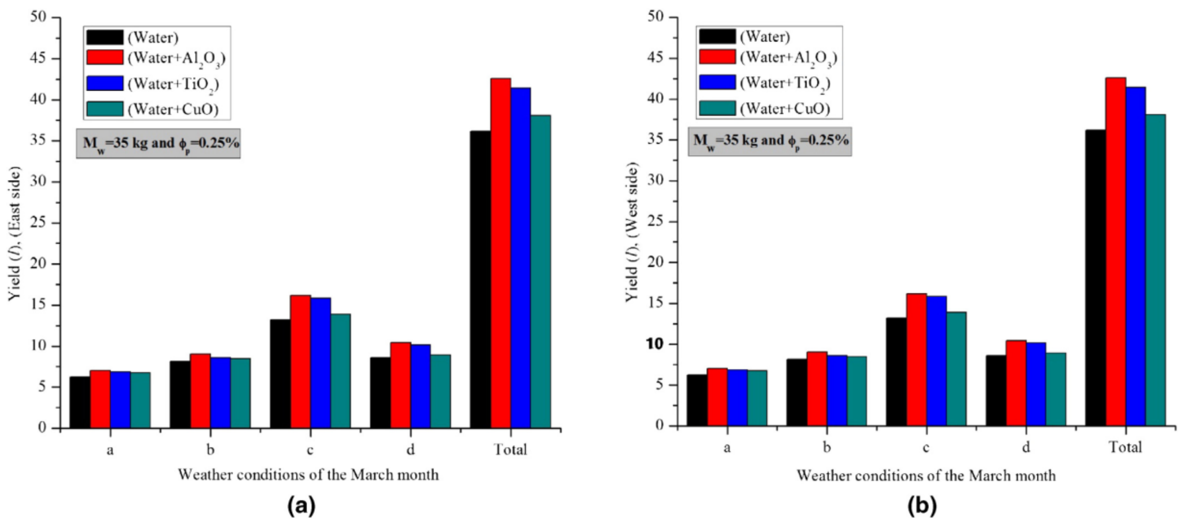


Fig. 10. The productivities of double slope solar still enhanced by different nanoparticles reported by Sahota and Tiwari [55] for the east and west sides.

Sahota and Tiwari [56] found that the optimized concentration of nanoparticles is a function of the climatic conditions including the ambient temperature and solar radiation intensity. In a recent study Sahota and Tiwari [57] used Al_2O_3, CuO, and TiO_2 nanoparticles in a double slope solar still. They calculated the annual energy, exergy, and productivity of this still. Sahota and Tiwari [57] observed considerable improvements in different parameters by using these nanoparticles. The improvements in still by nanoparticles in comparison with the case of base fluid are presented in Table 2. Sahota and Tiwari [57] found that the exergy of the solar still increases by employing the nanoparticles.

Table 2: Improvements of enhanced still by nanoparticles in comparison with the case of base fluid [57]

	Al_2O_3	CuO	TiO_2
Productivity	16.1%	5.25%	10.38%
Energy	26.76%	12.96%	19.36%
Exergy	37.77%	11.99%	25.55%

Chen et al. [58] evaluated experimentally the potential usage of SiC nanoparticles in a solar distillation system. They recommended this type of nanofluid as a good option for solar distillation systems as it has efficient thermal characteristics, excellent stability, and small luminousness. They showed that the thermal conductivity of seawater with SiC nanoparticles is improved by about 5.2% in comparison with the base fluid. Kabeel et al. [59] coated the absorber plate of solar still the black Cu_2O nanoparticles. They used the nanoparticles to enhance the heat transfer rate and salty water temperature. Their findings indicated that employing Cu_2O nanoparticles enhances the productivity of still by about 16% and 25% in comparison with the conventional solar still for solid volume fractions of 10% and 40%, respectively. Taamneh [60] used VOF model to investigate the effects of zeolite particles on the efficiency of a three dimensional pyramid solar still. They compared the numerical results by experimental ones to evaluate the accuracy of their model. Figure 11 shows the result of velocity vectors at the central section of the pyramid still for the case of base fluid (without particle). As shown in this figure, there is a recirculating vortex within the still. This vortex is generated as the result of natural convection in the still. The vapour and thermal energy are transferred between water and glass surfaces due to the circulation of this vortex. Figure 12 shows the variations of experimental and numerical productivities with particle concentration. As shown in this figure, the productivity enhances by using zeolite particles in the still. Further, there is a good agreement between the experimental and numerical results.

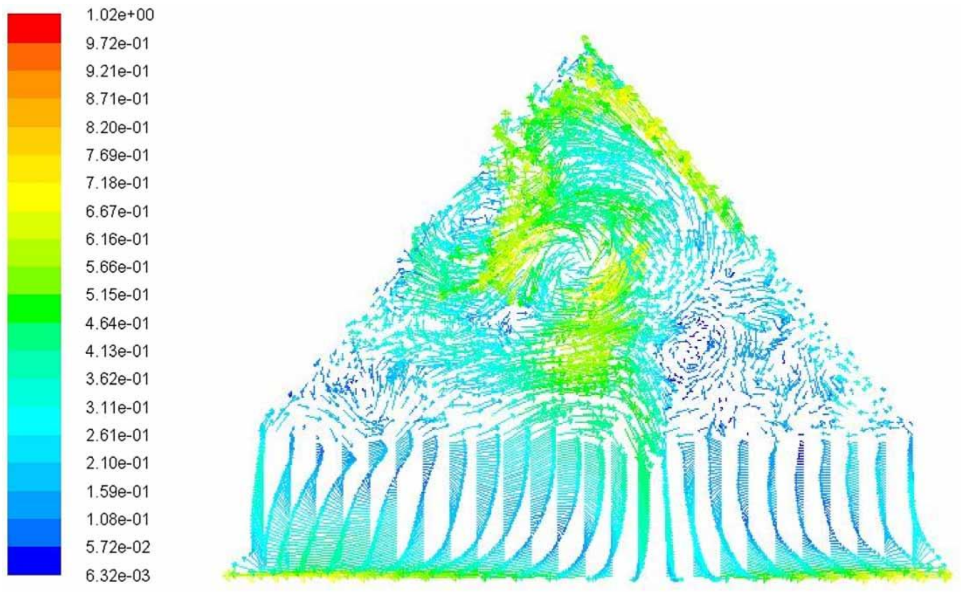


Fig. 11. Velocity vectors at the central section of the still for the case of base fluid (without particle) presented by Taamneh [60]

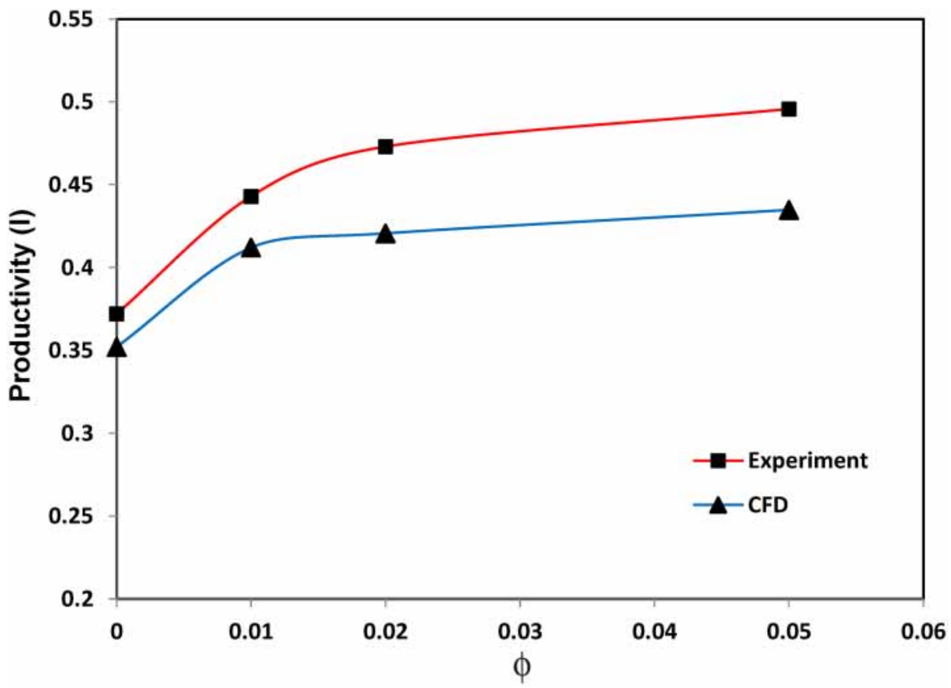


Fig. 12. Variations of the experimental and numerical productivities with the particle concentration presented by Taamneh [60]

Rashidi et al. [61] simulated the nanofluid flow in a two-dimensional single slope solar still by VOF model. They also performed an entropy generation analysis on this problem. These authors used Al_2O_3 nanoparticles and reported that the productivity of solar still enhances by about 25% through increasing the nanoparticle concentration in the range of 0 to 5%. Figure 13 discloses the frictional and thermal irreversibilities contours for two nanoparticle concentrations taken from Rashidi et al. [61]. The unit of frictional and thermal irreversibilities in these contours is $W/m^3.K$. It should be stated that the thermal and frictional entropy generations are irreversibilities, which commonly take place during fluid flow and heat transfer processes. These irreversibilities affect the performance of the system, therefore, it is important to calculate and minimize them. The frictional and thermal entropy generations are defined based on the second law of thermodynamic and can be evaluated through calculating the velocity and temperature derivatives. For more information about them, the readers are referred to the seminal textbook of Bejan [62]. It can be seen that from this figure, the bottom and top walls of the solar still have the maximum frictional and thermal irreversibilities, while the irreversibilities are negligible at the centre of the still. It should be noted that the velocity and temperature gradients are intense at the walls due to the heat transfer and phase change near the walls of the still, which lead to an increase in the irreversibilities. This figure further shows that the frictional and thermal irreversibilities increase by using the nanofluid in comparison with the case of pure fluid (without using nanofluid). It should be stated that the thermal energy and vapour mass are transferred between liquid surface and glass cover of a solar still due to the natural convection. This natural convection is induced by the buoyancy forces generated due to the temperature difference between the liquid and glass cover. Such forces become stronger through increasing the temperature difference. Generally, nanofluids have a smaller heat capacity in comparison with water. This indicates that nanofluids absorb the solar energy quicker and thus can be heated faster in comparison with water. As a result, the rates of evaporation and natural convection are strengthened by adding nanoparticles and this improves the heat and mass transports between the water and glass surfaces. This causes the existence of larger velocity and temperature gradients around the bottom and top walls as a result of the formation of thinner velocity and thermal boundary layers. It is evident that the existence of a larger velocity and temperature gradients increase the frictional and thermal entropy generations.

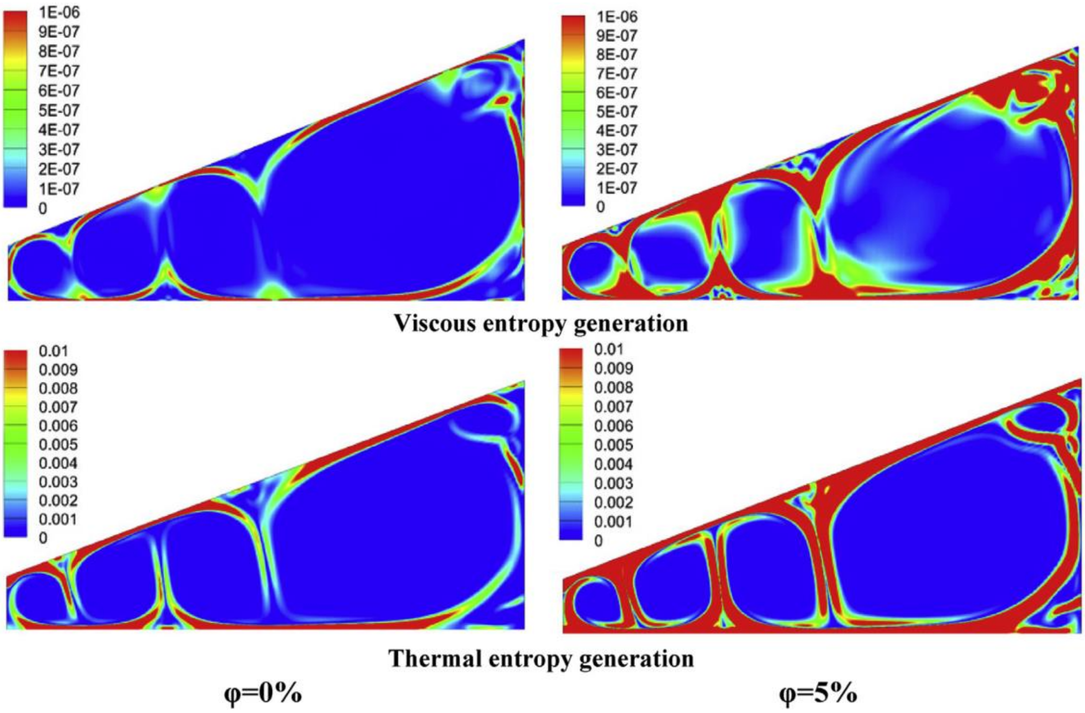


Fig. 13. Frictional and thermal irreversibilities contours for two values of nanoparticle concentration presented by Rashidi et al. [61]

Rashidi et al. [63] repeated this analysis for a cascade solar still. This revealed that, in general, the distance between evaporating and condensing surfaces (water and glass cover surfaces) decreases by using a cascade solar still. Thus, the vapour transfers faster to condensing surface through using a cascade solar still. Rashidi et al. [63] found that the productivity of solar still improves by about 22% when Al_2O_3 nanoparticle concentration increases in the range of 0 to 5%. Figure 14 shows that the liquid and vapour fractions inside the cascade solar still of Rashidi et al. [63] during times for two values of nanoparticle concentration. These contours are on the basis of a VOF modelling. As discussed earlier, the VOF model has an ability to simulate evaporation and condensation phenomena inside the solar still. As inferred from this contour, at the first time (t=0 sec), there is only a liquid layer inside the solar still. However, the vapour appears for the next times as the volume fraction of the vapour phase is increased. This vapour is transferred to the glass surface due to the natural convection and buoyancy force generated as a result of temperature difference between the water and glass surfaces in the still. This figure further shows that the evaporation and condensation rates improve by adding the nanoparticles inside the still.

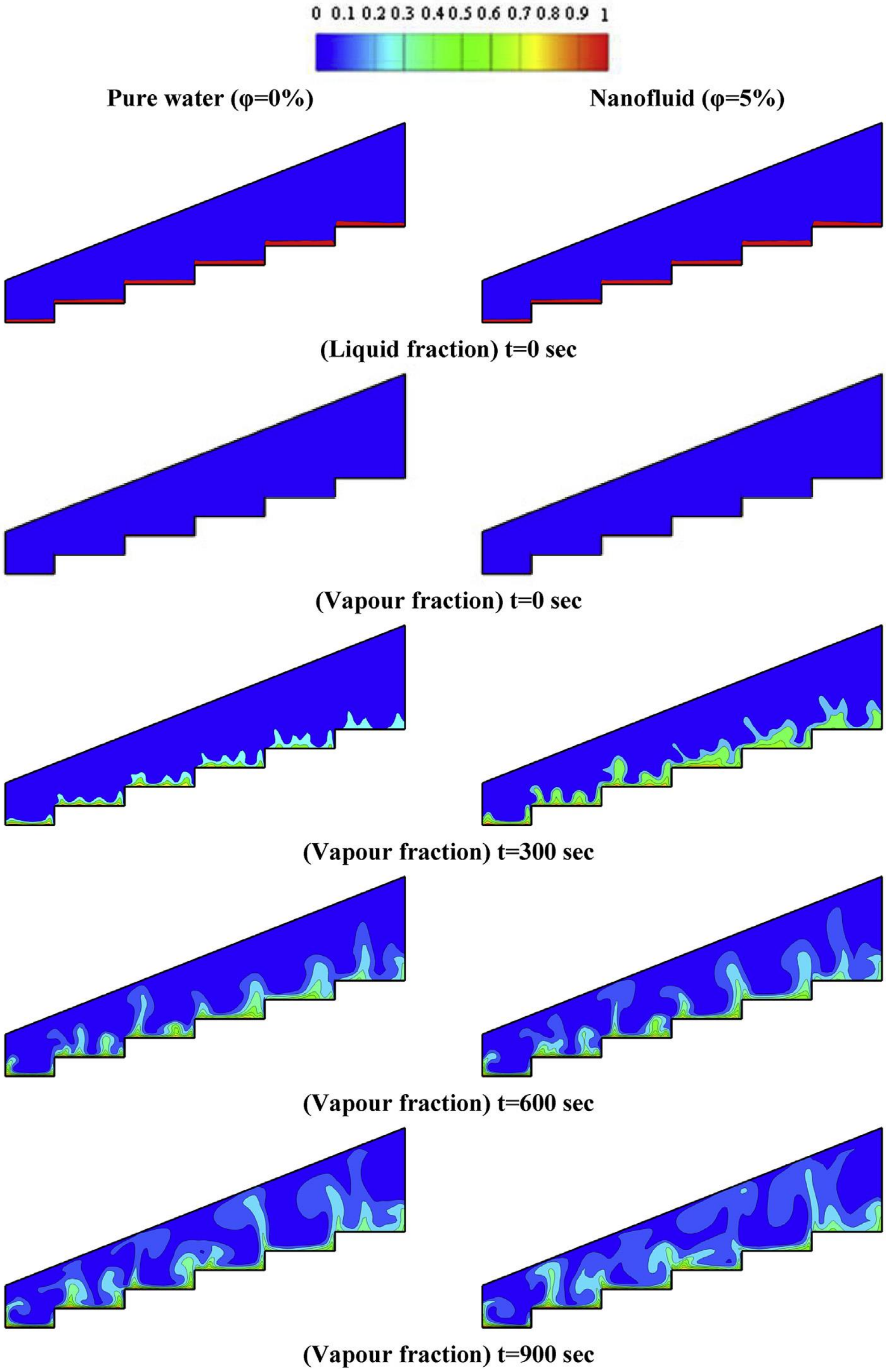


Fig. 14. Temporal evolution of liquid and vapour fractions in a cascade solar still for two values of nanoparticle concentration presented by Rashidi et al. [63]

Table 3 summarizes the studies on the application of nanoparticles for the productivity enhancement of solar desalination systems.

Table 3: Articles on the application of nanoparticles for the productivity enhancement of solar desalination systems

Authors	Type of research	Type of solar still	Type of nanoparticle	Concentration of nanoparticle (%)	size of nanoparticle
Elango et al. [53]	Experimental	Single slope	Al_2O_3, ZnO, and SnO_2	0.05 and 0.1	Al_2O_3-0.05% (394.7nm) Al_2O_3-0.1% (245.1nm) ZnO-0.05% (16nm) ZnO-0.1% (9.3nm) SnO_2-0.05% (114.5nm) SnO_2-0.1% (115.9nm)
Sahota and Tiwari [54]	Analytical	Double slope	Al_2O_3	0.04, 0.08, and 0.12	20nm
Sahota and Tiwari [55]	Analytical	Double slope	Al_2O_3, CuO, and TiO_2	0.2, 0.25, and 0.3	20nm
Sahota and Tiwari [56]	Analytical	Double slope	Al_2O_3 and TiO_2	0.04, 0.08, and 0.12	20nm
Taamneh [60]	Numerical	Pyramid	Zeolite	1 to 5	0.25 μm
Kabeel et al. [59]	Experimental	Single slope	Cu_2O	10 to 40	10-14nm
Chen et al. [58]	Experimental	Solar distillation system	SiC	0.04-1	30nm
Sahota and Tiwari [57]	Analytical	Double slope	Al_2O_3, CuO, and TiO_2	0.25	20nm
Rashidi et al. [61]	Numerical	Single slope	Al_2O_3	1 to 5	60nm
Rashidi et al. [63]	Numerical	Cascade	Al_2O_3	1 to 5	60nm

3.2. Combination of nanoparticles and other techniques in solar desalination systems

Some researchers combined the technique of adding nanoparticles with the other methods to achieve a higher productivity in the solar stills. Kabeel et al. [64] enhanced the efficiency of the solar still by adding nanoparticle and providing vacuum. The nanoparticles were Al_2O_3 and Cu_2O. They used vacuum fan to improve the condensation rate. A view of their experimental setup is disclosed in Fig. 15. Kabeel et al. concluded that employing Cu_2O

improves the productivity of the solar still by about 133.64% and 93.87% for the cases of with and without the fan, respectively. These enhancements were by about 125.0% and 88.97% for the case of Al_2O_3. Further, their cost analysis showed that the costs of producing one litre of pure water, when employing Cu_2O, are about 0.035$ and 0.045$ for the cases with and without the fan, respectively. These costs were about 0.038$ and 0.051$ for the case of Al_2O_3, while for the conventional still this cost was about 0.048$.

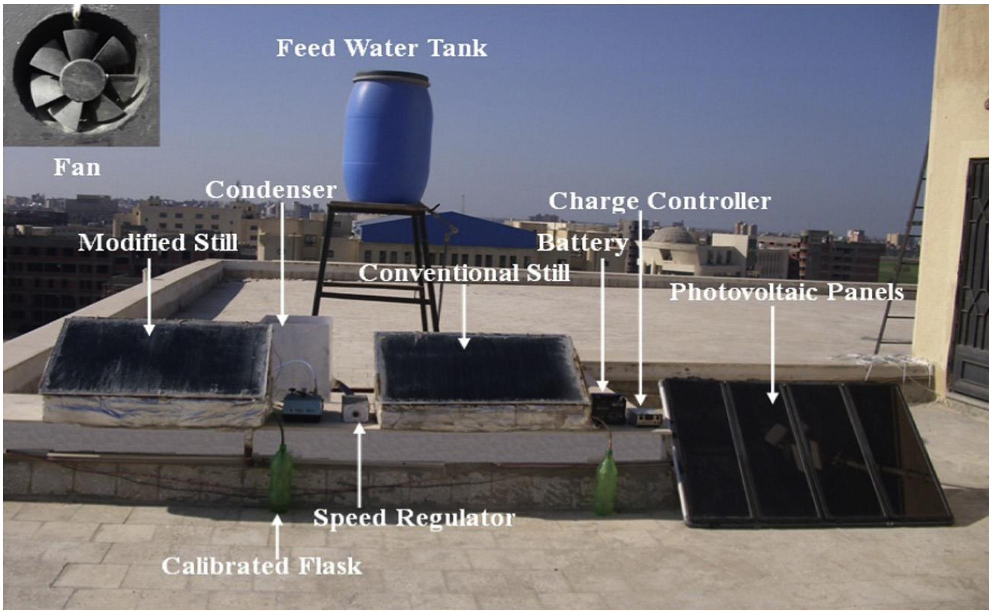


Fig. 15. The experimental setup of Kabeel et al. [64]

In another investigation, Kabeel et al. [65] used simultaneously the external condenser and Al_2O_3 nanoparticles to improve the efficiency of a solar still in an experimental work. They installed a vacuum fan at the side wall of the solar still and the output of this fan is guided towards the external condenser to provide more distilled water. They found that the productivity of the still improves by about 53.2% through using the external condenser, while it enhances by about 116% by combined usage of nanofluid and the external condenser. Recently, Kabeel et al. [66] investigated analytically the potentials of external condenser and nanofluid to enhance the efficiency of a solar still. The schematic diagram of their solar still is disclosed in Fig. 16. Note that the fan is used in their system to provide a greater evaporation rate and smaller values of pressure inside the basin still. Further, wetted air is guided towards the condenser to produce more pure water. They used Al_2O_3 and Cu_2O nanoparticles and recorded the daily performance of 84.16% for enhanced solar still by Cu_2O nanoparticles and fan, while the daily performance of enhanced solar still by Al_2O_3 nanoparticle and fan was about 73.85%. Importantly, the daily performance of the conventional solar still was only about 34%.

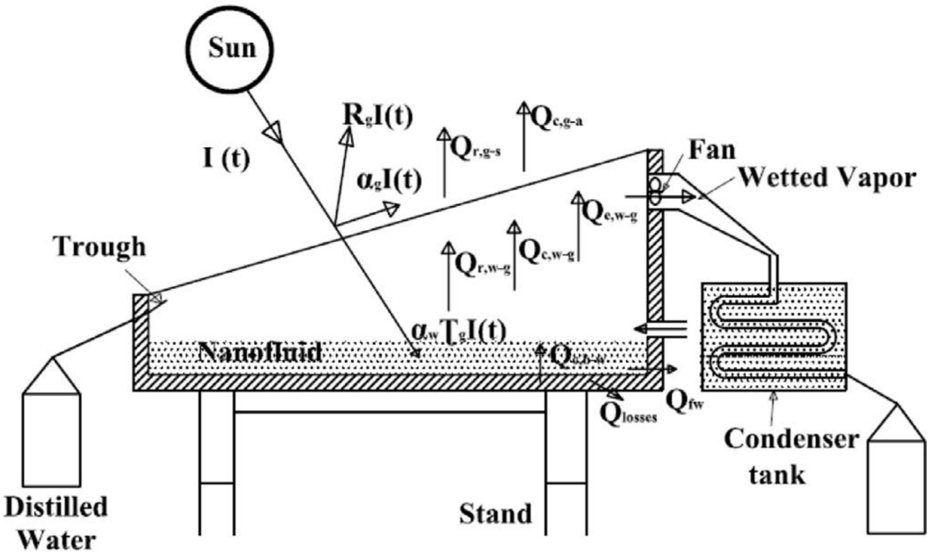


Fig. 16. The schematic diagram of the solar still proposed by Kabeel et al. [66]

Sharshir et al. [67] improved the efficiency of the solar still by combined usage of nanoparticles and glass cover cooling. They used C and CuO as the nanoparticles and film flow as the glass cover cooling. The experimental setup of Sharshir et al. [67] is shown in Fig. 17. They recorded the daily performances of 47.80% and 57.60% when employing CuO and C nanoparticles, respectively along with the usage of glass cover cooling, while the daily performance of the conventional still was 30%. Also, they recorded the daily performances of 38% and 40% when employing CuO and C, respectively, without the usage of glass cover cooling.

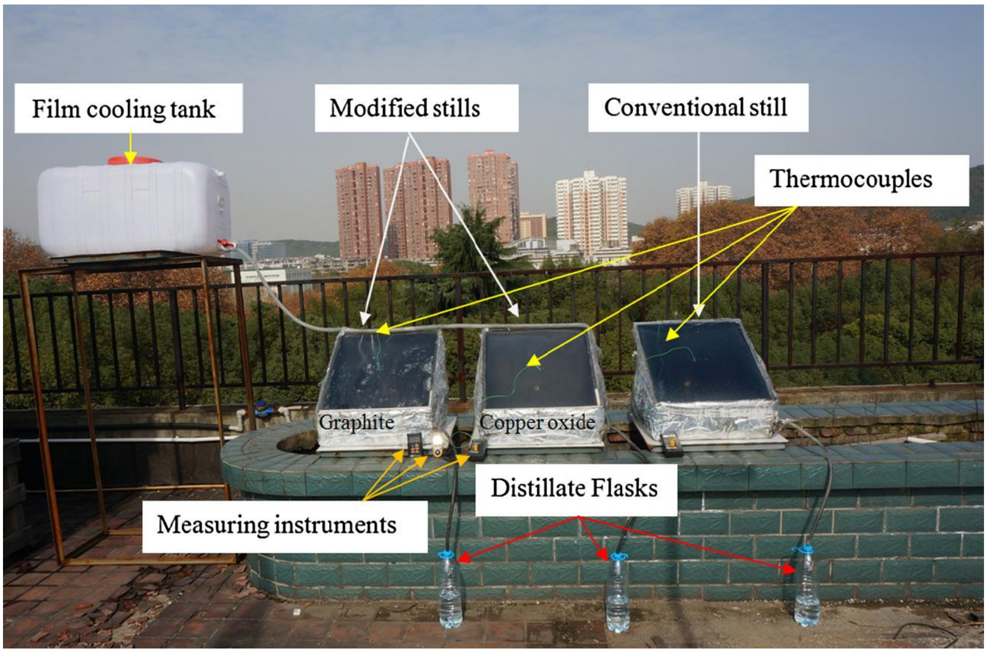


Fig. 17. The experimental setup of Sharshir et al. [67]

El-Said et al. [68] coupled a nanofluid solar heater with a hybrid desalination system to achieve a higher productivity. This unit consisted of a two stage humidification–dehumidification unit and an evaporation unit. They used a nanofluid solar water heater in the evaporation unit to increase the evaporation rate. These authors found that the amount of pure water generation increases and the cost of generated pure water decreases by using the nanofluid in the solar water heater of the evaporation unit. They concluded that the performance of solar water heater is affected by nanoparticle concentration. Mahian et al. [69] used simultaneously nanofluids and solar collector to improve the productivity of a solar still equipped with a heat exchanger. Their experimental setup is shown in Fig. 18. After receiving thermal energy of solar collector, nanofluid flows through the heat exchanger mounted in the solar still basin to exchange the thermal energy with salty water. Accordingly, the energy of solar collector is transferred to the salty water by the heat exchanger. They used both Cu and SiO_2 nanoparticles. At lower temperatures (e.g. <50 °C), adding Cu nanoparticles was observed to be more efficient for improving the evaporation in the still comparing with those of SiO_2. However, for larger temperatures (70°C) SiO_2

particles have the larger values of evaporation rate in comparison with Cu nanoparticles. For larger temperatures (70°C), the maximum improvement in evaporation rate is about 1%. Moreover, they concluded that adding nanoparticles with smaller diameter is more efficient in the solar still.

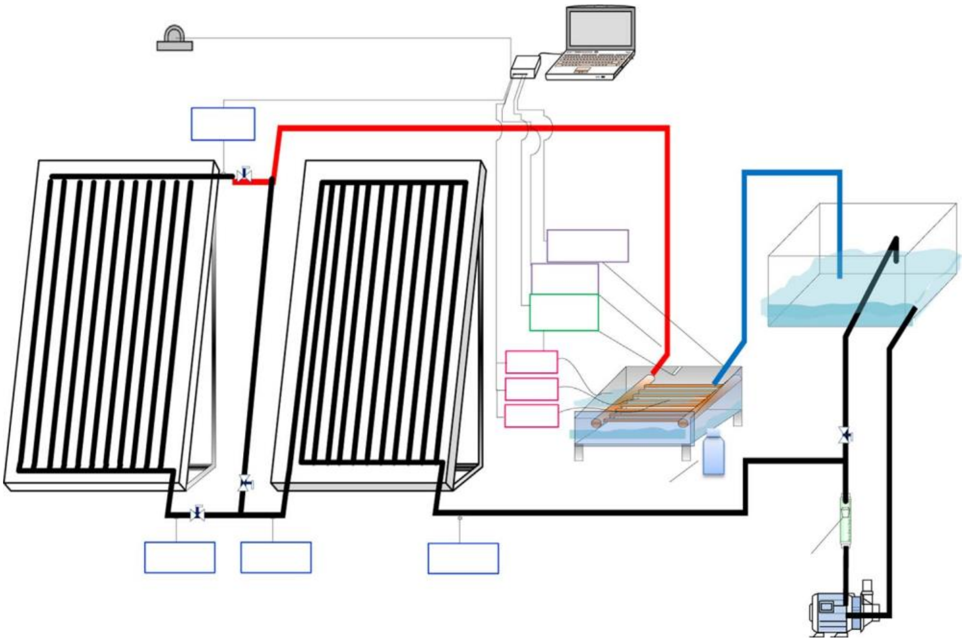
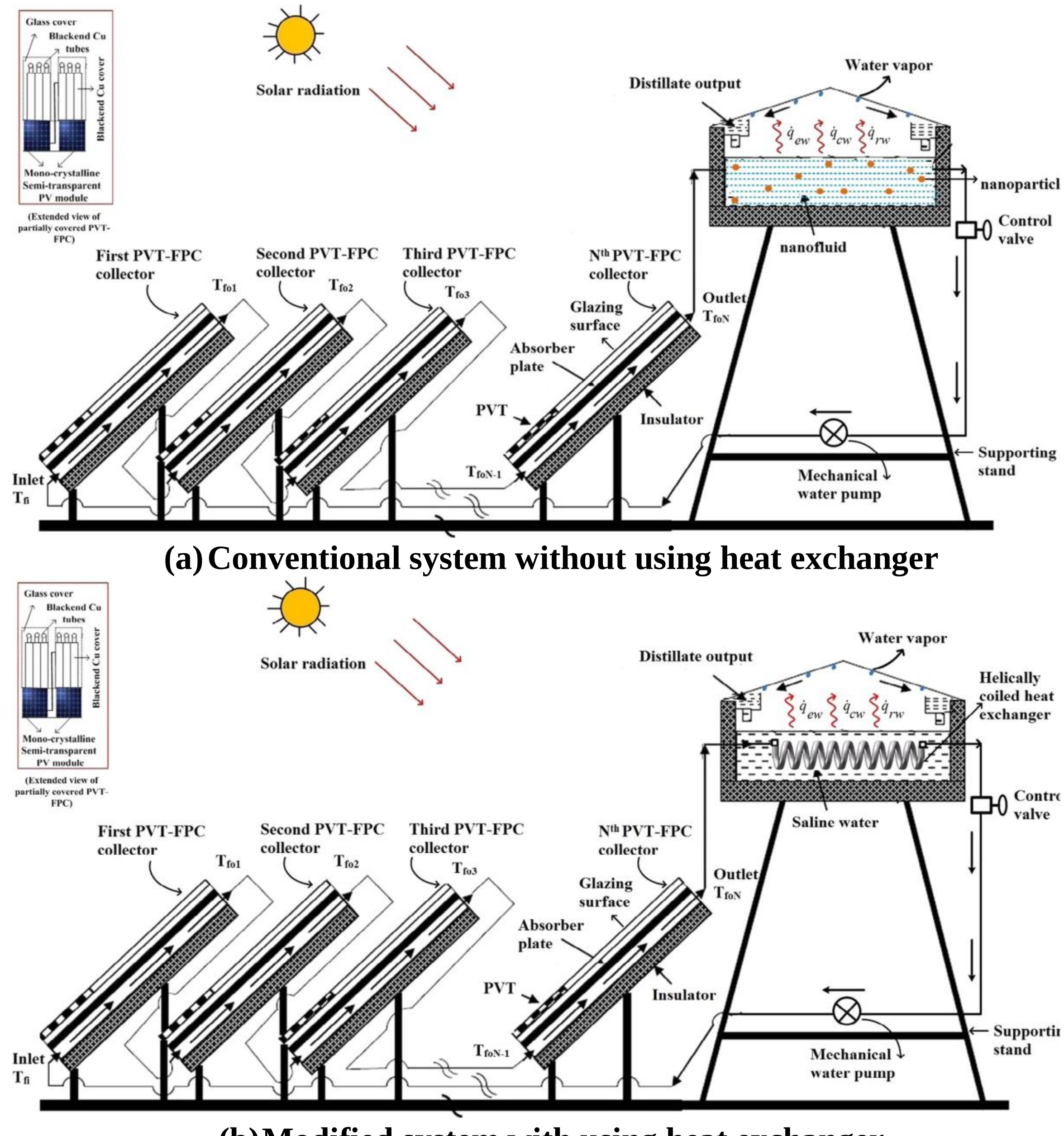


Fig. 18. The experimental setup of Mahian et al. [69]

Sahota et al. [70] coupled a nanofluid solar still with a helically coiled heat exchanger. They compared their design with the conventional system. The schematic views of their systems are shown in Fig. 19. Some collectors are used in both systems to preheat the salt water in the basin of the solar still. A helically coiled heat exchanger is used in the basin of modified system to transfer the thermal energy into the basin water. They reported that the productivity of conventional system without using heat exchanger enhances by about 32%, 19.23%, and 6.7% through using CuO, Al_2O_3, and TiO_2 nanoparticles in comparison with case of base fluid. However, these enhancements in the productivity of the modified system with using heat exchanger were about 31.49%, 26.4%, and 7.26% by using CuO, Al_2O_3, and TiO_2 nanoparticles.



(a) Conventional system without using heat exchanger

(b) Modified system with using heat exchanger

Fig. 19. Schematic views of the systems analysed by Sahota et al. [70]

In another investigation, Sahota et al. [71] repeated this analysis and performed the exergoeconomic and enviroeconomic analyses for this problem. They used CuO and Al_2O_3 nanoparticles. Their enviroeconomic analyses were based on the amount of carbon dioxide reduction by using a renewable energy system and encourage to employ the maximum amount possible of renewable energy. They found that the amount of carbon dioxide reduction increases by using nanofluids in both systems a and b (with and without using helically coiled heat exchanger). Shanmugan et al. [72] improved the productivity of a solar still by Al_2O_3 nanoparticles and phase change material. They achieved to efficiency of 59.14% by combined usage of nanoparticles and phase change material. Sharshir et al. [73] combined three techniques containing usages of flake graphite nanoparticles, phase change material, and film cooling in a solar still. They improved the productivity by about 73.8% by combining these techniques in comparison with the conventional still.

Table 4 summarizes the studies on combined application of nanoparticles and another technique for the productivity enhancement of solar desalination systems.

Table 4: Articles on combined application of nanoparticles and another technique for the productivity enhancement of solar desalination systems

Authors	**Type of research**	**Type of solar still**	**Type of nanoparticle**	**Concentration of nanoparticle (%)**	**size of nanoparticle**
Kabeel et al. [64]	Experimental	Single slope	Al_2O_3 and Cu_2O	0.02 to 0.2	10-14nm
Kabeel et al. [65]	Experimental	Single slope	Al_2O_3	<0.2	----
Sahota and Tiwari [70]	Analytical	Double slope	Al_2O_3, CuO, and TiO_2	0.044 to 0.263	20nm
Sahota and Tiwari [71]	Analytical	Double slope	Al_2O_3, CuO, and TiO_2	0.04 to 0.14	20nm
Kabeel et al. [66]	Analytical	Single slope	Al_2O_3 and Cu_2O	0.02 to 0.3	10-14nm
Sharshir et al. [67]	Experimental	Single slope	CuO and C	1	CuO (1 μm) C (1.2–1.3 μm)
Sharshir et al. [73]	Experimental	Single slope	Flake graphite	0.5	100nm
El-Said et al. [68]	Theoretical	Hybrid desalination system	Al_2O_3	1, 2, and 3	30nm
Mahian et al. [69]	Experimental/theoretical	Single slope	Cu and SiO_2	1 to 4	7, 40, and 100 nm
Shanmugan et al. [72]	Experimental	Single slope	Al_2O_3	----	50nm

4. Conclusions and suggestions for future studies

This paper reviewed the literature on the role of nanoparticles on the productivity of solar desalination systems. Both active and passive solar distillation systems were included.

Further, the mathematical modelling of nanofluid solar still by VOF model was explained briefly. The main results of this review and some suggestions for future studies are as follows.

4.1. Conclusions

- The daily productivity enhances as the solid volume fraction of nanoparticles increases.
- The exergy of the solar still increases by employing the nanoparticles.
- VOF model can be used to simulate solar stills numerically. This model has the ability to follow the interface between liquid and vapour phases and simulate the phase change during condensation and evaporation processes.
- SiC nanoparticles are an attractive option for solar distillation systems as they have good thermal characteristics, excellent stability, and small luminousness.
- The bottom and top walls of the solar still have the maximum frictional and thermal irreversibilities, while the irreversibilities are negligible at the centre of the still.
- The amount of carbon dioxide reduction increases by using nanofluids.
- The technique of using nanoparticle can be combined with other passive and active techniques in solar stills to achieve higher productivities.

4.1. Suggestions for future studies

Some suggestions are made as a direction of the future research in this section.

- The production of solar stills can be used directly by human. Accordingly, the safety of nanoparticles for human health should be taken into account before using these materials. Complications of this system should be cleared.
- The overall productivity enhancement by nanoparticles should be examined for different climate zones to achieve a more comprehensive data about this technique.

- Long-term operational stability and life cycle assessment are critical issues. These factors should be considered for future research in this field.
- Conduction of numerical and mathematical modelling and obtaining some correlations for estimations of productivity and heat transfer coefficients for these systems are very useful in predicting the system performance.
- Most of investigations in this field are performed for single and double slope solar stills. Other types of solar stills such as pyramid, sun tracing, semi-sphere, and cascade types need more attentions.

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