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USING OF NANOTECHNOLOGY CONCEPT TO ENHANCE THE PERFORMANCE OF SOLAR STILLS - RECENT ADVANCES AND OVERVIEW

AHMED KADHIM HUSSEIN[1], LIOUA KOLSI[2,3], OBAI YOUNIS[4,5,*], DONG LI[6], HAFIZ MUHAMMAD ALI[7], MASOUD AFRAND[8,9]

[1]College of Engineering -Mechanical Engineering Department - University of Babylon - Babylon City - Hilla -Iraq
[2]College of Engineering, Mechanical Engineering Department, Hail University, Hail City, Saudi Arabia
[3]Ecole Nationale d'Ingenieurs de Monastir, Unite de Metrologie et des Systemes Energetiques, Monastir, 5000, Tunisia
[4] College of Engineering at Wadi Addwaser, Mechanical Engineering Department, Prince Sattam Bin Abdulaziz University, Wadi Addwaser, Saudi Arabia
[5]Faculty of Engineering, Department of Mechanical Engineering, University of Khartoum, Khartoum, Sudan
[6]School of Architecture and Civil Engineering, Northeast Petroleum University, Fazhan Lu Street , Daqing 163318 , China
[7]Mechanical Engineering Department, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia
[8]Laboratory of Magnetism and Magnetic Materials, Advanced Institute of Materials Science, Ton Duc Thang University, Ho Chi Minh City, Vietnam
[9]Faculty of Applied Sciences, Ton Duc Thang University, Ho Chi Minh City, Vietnam

Abstract

This comprehensive literature review provides a rich overview of the most recent progress related to the utilization of the nanofluid in various types of the solar stills. This review considers a wide range of theoretical, experimental and numerical research papers related with the nanofluid utilization in the single-slope, double slope, solar still integrated with a condenser, hybrid and other limited types of the solar stills. To make the paper more useful to the readers in its subject, the authors give also a panoramic view about the water distillation process, distillation techniques and present a detailed survey about the most published review papers up to date in the distillation techniques and the solar stills. A fruitful summary and discussion of most important conclusions which are deduced from the previous works are presented in tables (Tables 1-6) to provide the interested researchers with a good road map about the capability of the nanofluid in enhancing the performance of different types of the solar stills and guides them to start new lines of the research in this subject. It was found that the water - nanoparticle mixture tends to increase the solar still productivity. From the other hand, more investigations on effect of utilizing the nanotechnology in solar still are required.

Keywords: Literature review, Renewable energy, Nanotechnology, Solar still, Water distillation.

1. Introduction

Water is considered as one of the most important natural resources that plays a crucial role in developing nation's economy. It covers about 70 % of the Earth's surface and it is classified into a sea and fresh water. Clean water is the basic component for the life continuity over the Earth planet and it is very essential for economy, agriculture, domestic and industrial applications. One of the major challenges nowadays is how can get a fresh and healthy water in a reasonable cost especially in the under developed and developing countries or in regions where the water quality is not in a good nature, water demand is very high and the solar energy is highly available like in the Arabian Peninsula.

It is important to mention that in the world around 97 % of the water in the ocean and it is of course salty, around 2 % of the water is stored as glaciers and icebergs in the polar region, that leaves us with only 1 % of fresh water (on the Earth surface or underground) available for different human, animal and plantation needs [1]. Although this very small ratio is believed to be enough to satisfy the needs of all different kinds of life and vegetation on our planet. But, this amount of the available fresh water is reducing day by day, while its utilization is increasing dramatically due to the fast and uncontrolled increasing in the number of the population (daily typical amount of drinking water is 5 L per person per day), climate change, improved living standards, pollution of water sources and the huge economic cycle. In addition, the fresh water sources are disproportionately spread on the earth and many countries suffer from water shortage problem.

In fact, the freshwater demand was increased dramatically from 75 to 100 L per day in the twentieth century. From the other side, the lack of the fresh drinking water is the main reason of the most severe diseases, which face the humankind, and unfortunately, around four million people die yearly due to diseases those related to water like diarrhoea, cholera, typhoid, guinea worm disease and shortage of good quality potable water. For example, in India about one million children die yearly due to drinking contaminated water and living in unhealthy conditions [2]. Moreover, it is estimated that more than one billion people on the earth have no access to the clean fresh water [3]. By the year of 2030, it is estimated that 50 % of the world population will suffer from the water scarcity.

Recently, more than one third of the African country's population are suffering high water stress. Therefore, it is very necessary to search about other methods to produce the fresh water locally by desalinate saline water. This can be achieved by using renewable energy sources such as the solar energy. Solar distillation is one of the best available ways to satisfy efficiently this mission.

The current literature review presents a rich overview about the current progress related to the application of the nanotechnology in different types of the solar stills. Research reviewed including theoretical, numerical and experimental up to date works related with the nanofluid applications in various types of the solar stills. This paper gives also a panoramic view about the water distillation process, distillation techniques and presents a detailed survey about the most published review papers up to date in the distillation techniques. The most important conclusions which are deduced from the previous works are reviewed and summarized carefully in Tables 1-6.

1.1. Nanofluid concept

The nanofluid is presented for the very first time in 1995 by Choi [4], nanofluids are simply defined as a mixture of nanoparticles of solid metallic or metallic oxide nanoparticles with base fluids like oil, water and ethylene glycol. Nanofluids present a new generation of advanced fluids that enhance heat transfer due to their enhanced thermal properties, therefore they have been used in many different industrial and engineering applications. These applications include Heat Exchangers, nuclear reactors, electronic cooling system and radiators, solar absorption and biomedical fields [5]. During the first decade of nanofluids, the primary interest of researchers was to determine the thermo physical properties of nanofluids such as density, thermal conductivity, heat transfer coefficient and thermal heat capacity [6]. Nanofluids are known for their high values of thermal conductivity and good properties of radiation absorption. For instance, the value thermal conductivity at the room temperature for individual multi-walled carbon nanotubes (MWCNTs) is greater than 3000 W/mK [7]. The nanoparticles size is very tiny; normally it ranges from 1 to 100 nm [8]. Adding large solid particles (more than 100 nm) to the base fluids is not recommended as would cause many drawbacks such as [9]: -

- Sedimentation due to the instability of the mixtures.
- High costs as a direct result of the high pumping power that is required to pump the large solid particles.
- Erosion of Channel walls and increment of pressure drop as a direct result of the large quantities of solid particles.
- Valves and pumps clogging.

All the above-mentioned drawbacks can be efficiently solved by utilizing the nanofluid, the utilization of nanofluids will provide the system with the following advantages [10]: -

- Enhancement of heat transfer characteristics due to higher values of effective thermal conductivity.
- The small size makes it much easier to be fluidized in the base fluids and thus it can move with relatively higher velocities inside solid blocks.
- The surface area to volume ratio is relatively large (typically more than 100 m^2/g), as well as large dimension-dependent physical properties and low values of kinetic energy.
- Nanofluid slows down the settling process of micro or millimetre sized particles.
- The thermos physical properties can easily be adjusted to suite different kind of industrial and engineering application by changing particle concentrations [11].
- In comparison to normal fluids while maintaining the heat transfer rate, nanofluids would require less pumping power [12].
- The problem of associated negative effects such as clogging of valves and fouling of pipes is resolved by using nanofluids as they can easy pass through pumps and pipes.
- Increasing surface area between particle and fluid which results in higher transfer rates.

- The transverse temperature gradient of the fluid is flattened due to the dispersion of nanoparticles.
- Nanfluid has the capacity to store large quantities of heat due to the small size of nanoparticles, this leads to high thermal capacity [13].

However, Nanotechnology is defined as the science branch that deals with nanofluids, it introduces a new hot research area to study and investigate these new types of fluids [14]. For more information with regards to the characterization and applications of nanofluids, interested readers can refer to the recent reviews by Hussein et al. [15, 16], Muhammad et al. [17], Hussein [18, 19] and Ahmed et al. [20].

2. Introduction to the Distillation Process.

In general, the distillation is a very old energy intensive method which is utilized for more than hundred years in land-based plants and by the crew of the sailing ships to get the drinking water in the open sea. In desalination process, the thermal energy evaporates brackish or saline water from the basin, as a result, water steam is collected on the cover which is then condensed as a final product, leaving all salts, inorganic and organic components and microbes behind it. Recently, cost of water distillation by the classical methods is increasing too much due to the high expensive modern technologies and high prices of the required fuel to produce the electrical energy which is used to run this process. The most remarkable merits of the distillation process are that it requires relatively low temperature up to 120 ºC this is easily provided from the solar energy or other sources of renewable free energy. Desalination process is one of the major key solutions for clean water shortage [21, 22].

3. Distillation Techniques.

Water desalination can be performed by many different methods. These methods are summarized below-

- Multi-Effect Distillation (MED): This method involving the concept of the phase change. The evaporation process in this method occurs by energy transfer between a film of condensing and the evaporation of falling film without boiling. Therefore, MED consists of some evaporator effects which is essential for the vapor generation as well as extraction of distillate water [23]. One of the advantages of this method is the use of low temperature heating steam which is typically ranges from 60 to 90°C [24]**.** A good example of the solar desalination plant which worked depending on this technique is located in Abu Dhabi (U.A.E.). This plant produces the pure water with a capacity of 80 m^3/day (annual average value). A sketch of this plant is shown in Fig. 1 as given by El-Nashar [25].
- Reverse Osmosis (RO): This method has much popularity during the last two decades which based on the membrane operations and nowadays takes about 60 % of all the desalination activities around the world. It is a pressure- driven membrane process where the high pressure drives the saline water to pass through a special membrane that only allows the molecules of water to pass selectively while preventing the dissolved salts. When using (RO) method for water purification, the feed water is pressurized on one side of a semi-

permeable membrane. To initiate they reverse osmotic water flow, the pressure of the water must be greater than the osmotic one. Since the membrane is selected to be highly permeable to the water, but not to the dissolved solutes, only the pure water will be able to cross through the membrane, this water is known as product water. Some disadvantages are associated with this method such as: problem of the severe fouling that occurs in the membrane, heavy gauge piping, complexity of pump sets, and maintenance demands. While the main benefit of (RO) is its low energy consumption. For more information with regards to the reverse osmosis, the readers can be referred to the comprehensive review by Gullinkala et al. [26].

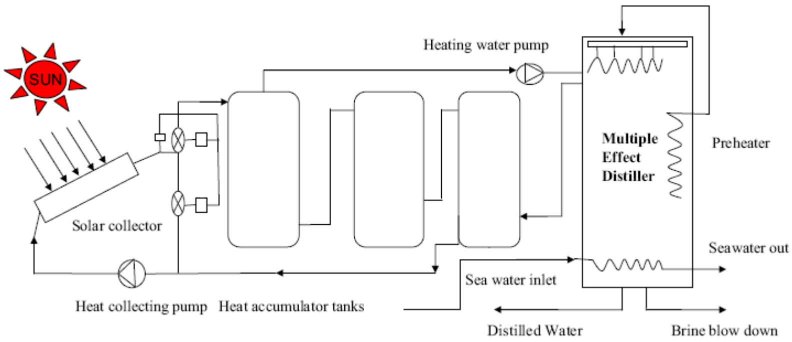

Fig. 1. Abu Dhabi solar desalination plant (El-Nashar [25]).

- Forward Osmosis (FO): This method achieved more attention in many industrial and engineering applications like treatment of wastewater, food processing and pharmaceutical applications. It is considered as one of the pressure-driven membrane processes. This technology has many important advantages such as the very low hydraulic pressure, low energy demand, low fouling propensity, easy cleaning, low costs, high salt rejection and the high-water flux. In (FO) method, the gradient of osmotic pressure is used to drive the water through the semi-permeable membrane from the feed solution side to the draw solution side. For further details about the forward osmosis, interested readers can refer to the review given by Zhao et al. [27].
- Membrane Distillation (MD): This thermally - driven technology filters the water by the use of a porous and hydrophobic membranes, these membranes are fully permeable to the water vapor but not liquid water [28]. It was introduced for the first time by Bodel in 1963, he patented the vapor diffusion through silicone rubber for distillation of saline water. It depends on the separation of non-volatile components from aqueous feed streams at a temperature below 100 °C. The membrane used in this method is made from hydrophobic polymers with pore sizes on the order of micrometres. The temperature across the porous membrane is not constant, the feed side has relatively high temperature and high salinity while the other side is kept at relatively low temperature. The temperature gradient across the membrane results in a vapor pressure gradient which drives the water vapor to cross through the membrane and then it is collected or condensed to a pure water. This allows the vapours to pass only and retains all the solid or non-volatile contaminants (i.e., salt) on another side. So, the water produced is theoretically

100 % pure from these components. This method can be used for potable water production from the sea or the brackish water and its efficiency depends highly on the membrane and module design together with the thermal management process. Also, it can be used for the waste (sewage) water treatment. Figure 2 shows a three-dimensional sketch of the membrane desalination water plant Drioli et al. [29]. It is also useful to mention that (MD) technique can be coupled with the solar collector for cost reduction of the distillation process as presented in Fig. 3, Wang et al. [30]

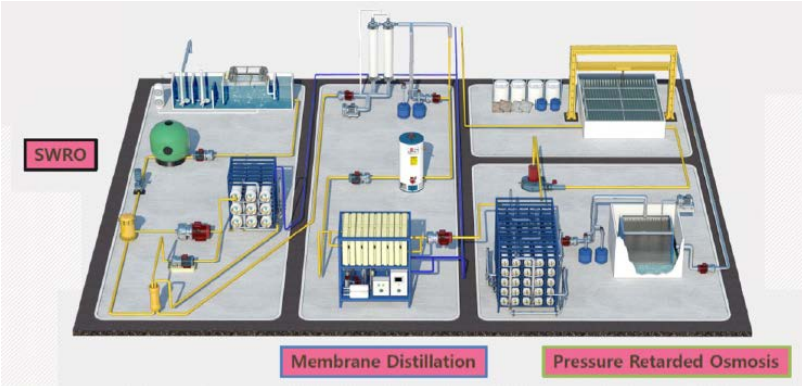

Fig. 2. Three- dimensional sketch of the membrane desalination water plant (Drioli et al. [29]).

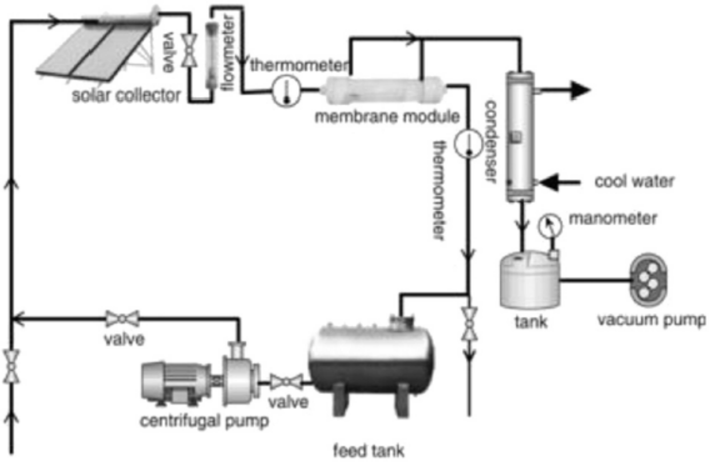

Fig. 3. Flow diagram of solar-heated MD system (Wang et al. [30]).

In general, there are eight different modes of this technique and can be noted as [31-34]: -

- Direct Contact Membrane Distillation (DCMD)
- Air Gap Membrane Distillation (AGMD)
- Sweeping Gas Membrane Distillation (SGMD)
- Vacuum Membrane Distillation (VMD)

- Material Gap Membrane Distillation (MGMD)
- Multi-Effect Membrane Distillation (MEMD)
- Vacuum-Multi-Effect Membrane Distillation (V-MEMD)
- Permeate Gap Membrane Distillation (PGMD)

For further details about the membrane distillation technique, readers can be referred to the comprehensive overviews by Drioli et al. [29] and Abu-Zeid et al. [35] respectively.

- Electro Dialysis (ED): this is a membrane process which does not include a phase change. This method is most suitable for the desalination of the brackish water and where neither the control of microbial nor the elimination of organic matter are significant. In this method, the water passes through a pair of special membranes and an electric field is subjected perpendicularly to these membranes. Only dissolved salts are allowed to pass through the membranes while water does not.
- Vapor Compression Distillation (VCD): in this kind of processes, the water vapor from the boiled water is adiabatically compressed and then superheated. This superheated vapor is then cooled down to the saturation temperature and condensed at a constant pressure. The process is driven by the mechanical energy and involves a phase change.
- Multistage Flash Distillation (MSF): This is a thermally driven method which involving a phase change. It consists of many different stages. In all stages, the feed water is preheated by the condensed steam. By dividing the total temperature difference into a big number of stages, the system approaches ideal total latent heat recovery. In this method, the vapor is generated through flashing due to sudden pressure drop of the next stage. Therefore, the operation of this method requires pressure gradients in the plant.
- Freeze Desalination (FD): In this method of desalination the sea water is undergoing cooling process of which the final water temperature is below its freezing point, as a result of this low temperature the ice crystals of the clean water start to form on the still surface. There are three types of the freeze desalination which are the direct contact freeze desalination, indirect contact freeze desalination and the vacuum operated freeze desalination [36].
- Desalination by Pervaporation (PV): This method is a very efficient approach to produce the clean water from salt water, this process is characterized by high rejection of salt and the ability to deal with high-salinity solutions. It has many practical applications such as the separation of liquid mixtures and separation of anhydrous organic mixtures. For (PV) desalination, the mechanism of transportation depends on the hydrogen-bonding, ion-dipole interactions and/or ion-ion interactions between the feed salt solutions and membranes with different chemistry and structure. For more details about the desalination by pervaporation, one can return to the detailed literature review by Wang et al. [37].
- Solar Distillation (SD): this is a very energy efficient method since it uses only the free solar energy. It is useful to refer that all the above described water treatment processes, consume high energy in order to extract a portion of clean water [38, 39]. The system is fed by salt water, the output of the system consists of two steams, pure potable water and wastewater with high

concentration of salt. Taking the thermodynamic limits into account, the production of a small amount of fresh water as 1.0 m^3 would approximately consumes energy of 0.71 kWh [40]. Also, it is estimated that 10,000 ton of oil per year is needed to produce 1000 m^3 of the clean water on daily basis. Using solar energy in desalination process is considered as one of the most promising application of renewable energy. This method is also intensive and environment friendly water purification technique [41]. Since, it reduces the emitted amount of greenhouse gas to the environment.

The solar distillation can be summarized as the vapours production above the liquids surface, using winds to transport the vapours, air-vapor mixture cooling, condensation and precipitation. This natural process is typically copied on a small scale in basin type solar stills. Solar distillation is a very complicated process that involves both heat and mass transfer. It can be used very efficiently in rural and desert areas where it is expensive to install water pipelines and the water supply by trucks is also unreliable and costly expensive [42]. From the other hand, the water distillation by the above-mentioned methods are not efficient due to their low - production of the fresh water, pollution due to using the fossil fuel and their high energy cost [43]. From the historical point of view, it was thought theoretically that Nicolo Ghezzi from Italy in 1742 was the first person who recommended the solar distillation device. But the first actual solar distillation device in the world was built in Chile, city of Las Salinas in 1872 by Charles Wilson. The overall area of the still was 4700 m^2, it consists of 64 water basins [44]. This pioneering design was considered the basic for most kinds of stills built since that time. For further information with regards to solar distillation, interested readers can refer to the review papers by Malik et al. [45] and Tiwari et al. [46].

There are also another distillation methods such as ion exchange, capacitive deionization, natural vacuum desalination, adsorption desalination, thin-film distillation, sea water greenhouse technology and ozone activated carbon filtration.

4. Review Papers Related with the Distillation Techniques.

Lawson and Lloyd [47] presented a comprehensive review about the membrane distillation. They explained its terminology, fundamental concepts, membrane properties, transport phenomena, module design, practical applications together with the historical review of its developments. El-Bourawi et al. [48] presented a detailed review of the membrane distillation process. They introduced in their review an introductory guide which explained the sequences of the different steps that should be followed to fulfill the requirements for (MD) in an industrial application. They concluded that the (MD) process had some major barriers such as the design of membrane and module, membrane pore wetting, low permeate flow rate, flux decay and economic costs. Al-Khudhiri et al. [49] reviewed in details the (MD) process including the membrane configuration and its characteristics, membrane modules, heat and mass transport mechanisms, thermal efficiency, fouling and the effects of operating parameters. They concluded that the effect of the high concentration solution on the heat and mass transfer mechanisms was not examined well. Gullinkala et al. [26] presented a review about the reverse osmosis (RO) and membrane distillation (MD) techniques. They presented various advantages of using (MD) technique, some of these advantages are given below: -

- Relatively low operating pressure and temperature in comparison with other conventional distillation processes.
- Compact modules.
- Energy saving due to its ability to use the available free energy sources.
- Mist elimination.
- The problem of corrosion could be easily solved by using plastic equipment.
- Smaller plant footprint due to the reduced vapor space.
- Lower capital costs than conventional distillation processes.
- Easy remote control and automation.
- Friendly to the environment.
- More fouling resistant than (RO) technique.
- Theoretically, 100 % salt elimination is granted
- Wide range of selectivity for membrane mechanical properties.
- It is not necessary to vaporize the entire flow.

Also, they refereed that the (MD) technique can be utilized in many fields such as: -

- Clean and freshwater production from brackish or sea water.
- Blood concentration.
- Extraction of diluted ethanol from aqueous solutions or from fermentation broths.
- Concentration of juice, grape juice, milk, sugar, and gelatine solutions.
- Organic materials elimination from the drinking water.
- Treatment of both water and wastewater.
- Recovery of valuable components, and treatment of radioactive wastes.

Wenten [50] reviewed the applications of (RO), its advantages, limitations, challenges and perspective of its membranes. They referred that the improvement in this technology including the unconventional membrane material, module and process design, and the energy recovery. Drioli et al. [29] summarized the developments and perspectives of the membrane distillation technique from the viewpoints of membrane fabrication, heat and mass transfer, non-traditional fouling, module fabrication and applications. Advantages and disadvantages of various models of (MD) technique were also highlighted. They mentioned that (MD) technique could be conducted at relatively low temperatures (less than 70 °C) and driven by low temperature difference (20 °C). Also, they referred that the concentration polarization has no significant effect on the process driving force and as a direct result, this process yields higher concentrations and recovery factors in comparison to (RO) technique. Abu-Zeid et al. [35] comprehensively reviewed the vacuum membrane distillation (VMD) technique with respect to its merits, demerits, various applications and its connection to the solar energy field. They referred that (VMD) technique has many advantages such as: -

- Energy saving membrane separation technology.
- Capability of utilizing renewable energy for preheating of feed solution.

- Excellent technique to produce the fresh water in regions which have a plenty of sea water and a high solar radiation.
- Easy to use by ship's crew which spend a long time in the sea for fishing purposes.
- Reasonable cost and high permeate flux for recovery of aroma compounds
- Less heat loss by the conduction.
- Relatively thin thermal and concentration boundary layers are developed on the membrane permeate side.
- Thermal polarization is very low.

While its disadvantages can be summarized as: -

- Membrane pore wetting and fouling are high.
- It is relatively difficult to recover the heat loss.
- The choices volatile components are very limited.
- Vacuum pump and external condenser are necessary.

They concluded that (VMD) technique could be used to resolve the issue of freshwater deficiency and energy crisis facing the world, if the water recovery and thermal efficiency were increased.

Hitsov et al. [51] carried out a literature review about the mathematical modelling of the membrane distillation technique. Different models for the heat and mass transport in the water channels of the module as well as inside the porous membranes were reviewed in detail. They suggested that more efforts must be done related with the recent mass transfer models of (MD) such as the ballistic transport and structural network models. They recommended also that the surface diffusion phenomena which occurred inside the membrane must be included in the (MD) modelling. Warsinger et al. [52] surveyed the published papers about the scaling and the membrane fouling which occurred in (MD) technique. Their survey included the physical, thermal and flow conditions that affected on the fouling, mechanisms of fouling, fouling differences by sources of water, system design, effects of operating parameters, prevention, cleaning in addition to the membrane damage. They suggested that the hydrophobic nature of the membrane, the maximum pore size and the low feed pressure in the (MD) process were necessary to reduce the scaling effect on the membrane surface. They summarized the factors that influenced the scaling problem in (MD) by the temperature, dissolved gases and water sources respectively. They concluded that the most important scaling and fouling effects on (MD) operating parameters are:-

- The quality of Wetting and permeate water is changed.
- Permeate flow rate is reduced.
- The temperature and concentration polarization are increased.
- Membrane damage and chemical degradation.

Tijing et al. [53] reviewed several foulants and fouling mechanisms of (MD) process with their possible mitigation and control techniques. The membrane fouling causes adverse effect on the overall performance of (MD) process. They referred that the membrane fouling led to some serious problems such as: -

- Down time.

- Extra cleaning.
- Further increasing in the costs of the energy consumption.
- Early membrane replacement.

From the other hand, they indicated in their review some factors which caused the membrane fouling, some of these factors are given below: -

- Poor long-term hydrophobicity of the material.
- Membrane damage and degradation.
- The membrane is very thin.
- Existence of inorganic and colloidal materials.
- Existence of organic macro-molecules and microorganisms in the feed water.

Goh et al. [54] presented a review about current trends in membranes and membrane processes for desalination. They highlighted some of the latest remarkable achievements of the innovative unconventional membrane materials together with the membrane processes for the water solution. They concluded that the introduction of nanomaterials during the membrane formation made favorable changes in the membrane morphology and its performance. Ashoor et al. [55] presented a review about recent applications of the direct contact membrane distillation (DCMD). The basics of this technique and its governing equations were explained also. They mentioned that this technique had a strong potential to treat the waste produced from oil and gas industries. They suggested that the future research should focus on the ability of reducing the (DCMD) membrane wetting by improving the membrane hydrophobicity and pore geometry. Tiwari et al. [56] reviewed briefly the research works on passive and active solar distillation systems. Their review includes water sources, water demand, potable water availability, purification methods in addition to the historical background. Also, they explained the principle and the classifications of the solar distillation systems together with their economic evaluation. They mentioned that merits of the solar distillation technique are summarized as: -

- Very efficient for polluted water disinfection. As it is well known that on sunny days the temperature of the water reaches high values resulting in killing all pathogenic bacteria.
- Low maintenance and high economical.
- Skilled workers are not necessary.
- Don't required a specific area, since it can be installed at any region.
- The cost of the energy required represents a very small ratio in comparison to the total cost of the distillation process. Since it uses the free and clean solar energy.
- The size of the solar distillation unit is small compared with another distillation techniques.
- Friendly to the environment.
- Very useful technique for rural areas.

Ranjan and Kaushik [57] presented a comprehensive review about thermodynamic models for the energy and exergy analysis based on the fundamental heat transfer correlations available in the literature for the simple basin type solar stills. They concluded that the cost of the desalination process decreased when the efficiency of the solar still increased. They highlighted also, the research findings of the techno-economic and regular economic analysis related to solar distillation. Moreover, they referred that the city of Abu Dhabi was constructed about twenty - two eco-friendly solar desalination plants. These plants generated a daily rate of 6600 gallons of potable water and 1050 kWh of green energy. For water desalination process cost reduction, the authors recommended the following steps:

- Optimum utilization of the solar energy.
- Design modifications like the combining or integrating of two or more solar devices to increase both productivity and efficiency at economical cost.
- Minimizing the irreversibility's (exergy destruction) associated with the desalination process.
- Reducing the size of system.

Li et al. [58] discussed in their review many solar desalination research activities. They mentioned that additional research are required to study the solar / fossil fuel hybrid systems, mainly the heat loss of decentralized thermal power systems for water and power co-generation. Since, this subject led to reduction of the fuel consumption and overcome the intermittence of the solar energy. Reif and Alhalabi [59] reviewed the technical challenges and potential opportunities of the solar desalination including the advanced techniques for the energy-recovery. They concluded that the most promising energy efficient solar desalination system is the direct solar desalination systems that uses solar thermal collectors. Sharon and Reddy [60] reviewed the integration of renewable energy sources with many different water desalination units, with special emphasis given to the solar energy.

They mentioned that the solar energy had the capability to make the desalination industry greener and desalination industries will be benefited by any further developments in solar thermal collectors and PV panels. Pugsley et al. [61] reviewed briefly the literature about the global applicability of the solar desalination technologies and examined both the economic and environmental feasibility. They suggested a rank scoring system which quantified the applicability of solar desalination based on objective measures of the water scarcity, water stress, the local availability of saline feed water, and solar insolation levels. They concluded that in countries with a relatively low solar insolation such as UK and Japan, it was useful to use the wind or wave energy to drive desalination plants instead of utilizing the solar energy. Pandey et al. [62] reviewed the present status of the solar desalination. They mentioned that there were various factors to improve the solar still efficiency like the material of the basin, transmissivity of the glass cover and maximum concentration of solar radiations on the condensing cover. Very recently, Chandrashekara and Yadav [63] reviewed and discussed various direct and indirect solar thermal desalination methods. They suggested that the indirect methods were more suitable for desalination systems of medium and large scale, while for small scale desalination systems the direct methods employing the solar stills were preferred. Another review paper related with the solar desalination were prepared by Delyannis and Delyannis [64] and Tiwari and Sahota [65]. Furthermore, there are an additional excellent review papers which deal with the water desalination by using various renewable energy sources. Examples of these papers include Kalogirou [66], Eltawil et al. [67], Al-Karaghouli et al. [68], Gude et al. [69], El-Ghonemy [70] and Ghaffour et al. [71].

The papers used to review investigations about the distillation techniques are presented in Table 1.

Table 1. Summary of review papers about the distillation techniques.

Reference	No. of papers	Year	Methods	Remarks
Lawson and Lloyd [47]	87	1997	Membrane distillation	• This method is characterized by high rejection and low operating temperatures.
El-Bourawi et al. [48]	168	2006	Membrane distillation	• (MD) had some major barriers such as membrane and module design, membrane pore wetting, low permeate flow rate, flux decay and economic costs.
Al-Khudhiri et al. [49]	125	2012	Membrane distillation	• Energy consumption of (MD) and operating parameters effect require more investigations.
Gullinkala et al. [26]	45	2010	1- Reverse osmosis 2- Membrane distillation	• More efforts must be done to improve distillation techniques by using membrane coatings and increasing the competition between manufacturers to reduce some advantages such as membrane wetting and its high cost.
Wenten [50]	171	2016	Reverse osmosis	• Large capacity plant required large size of (RO) element.
Zhao et al. [27]	227	2012	Forward osmosis	• (FO) had many advantages such as consumes low energy, low fouling propensity, easy cleaning, low costs and high salt rejection.
Drioli et al. [29]	198	2015	Membrane distillation	• (MD) technique requires relatively low temperatures typically lower than 70 °C and driven by low temperature difference (20 °C).

				• Has the capability to solve freshwater scarcity and energy shortage, if water recovery and thermal efficiency were increased.
Abu-Zeid et al. [35]	155	2015	Vacuum membrane distillation	• Has the capability to solve freshwater scarcity and energy shortage, if water recovery and thermal efficiency were increased.
Hitsov et al. [51]	95	2015	Membrane distillation.	• Surface diffusion phenomena which occurred inside membrane must be included in (MD) modelling.
Warsinger et al. [52]	153	2015	Membrane distillation.	• Scaling and fouling effects on (MD) operating parameters are summarized as: - 1. The quality of Wetting and permeate water is changed. 2. Permeate flow rate is reduced. 3. The temperature and concentration polarization are increased. 4. The membrane is damaged and the chemical degradation took place.
Tijing et al. [53]	256	2015	Membrane distillation.	• Fouling led to some problems such as: - 1. Down time. 2. Extra cleaning. 3. Further increasing in costs of energy consumption. 4. Early membrane replacement.
Goh et al. [54]	184	2016	Membrane distillation.	• Properties of desalination membranes were dramatically improved by using nanomaterials or

				membrane surface modifications.
Ashoor et al. [55]	185	2016	Direct contact membrane distillation	• Sustainability of (DCMD) technique was improved, when it was integrated with hybrid systems and renewable energy.
Wang et al. [37]	101	2016	Desalination by pervaporatio n	• Efficiency was improved by reducing concentration polarization in both sides of membrane.
Tiwari et al. [56]	84	2003	Solar distillation	• Advantages of solar distillation are: - 1. Very efficient for polluted water disinfection. 2. Low maintenance. 3. Skilled workers are not necessary. 4. Don't required a specific area. 5. Low cost. 6. Small size
Ranjan and Kaushik [57]	94	2013	Solar distillation	• Cost of desalinated water were reduced by the following steps: - 1. Optimum utilization of solar energy. 2. Design modifications. 3. Reduction in irreversibility's. 4. Reducing size of system.
Li et al. [58]	292	2013	Solar distillation	• Solar / fossil hybrid desalination systems were more economical and could overcome solar energy intermittence.
Reif and Alhalabi [59]	146	2015	Solar distillation	• Favorable locations for solar desalination include North and East Africa, Middle East, Southern Europe, Western South America, Australia, Northern Mexico and South-West USA.

Sharon and Reddy [60]	236	2015	Solar distillation	• Solar energy driven desalination units could cut off carbon emissions.
Pugsley et al. [61]	91	2016	Solar distillation	• Solar desalination could be applied efficiently in Middle East, North and East Africa, India, China, USA, Mexico, Pakistan, South Africa, East Australia and Namibia.
Pandey et al. [62]	54	2016	Solar distillation	• Efficiency of solar still was improved by improving basin material, transmissivity of glass cover and maximum concentration of solar radiations on condensing cover.
Chandrasheka and Yadav [63]	138	2017	Solar distillation	• Solar humidification and dehumidification desalination was still a developing technology at laboratory scale and not yet commercialized yet.
Kalogirou [66]	278	2005	Distillation by renewable energies	• Large units were more attractive for distillation processes, as the rate of heat loss is minimized.
Eltawil et al. [67]	119	2009	Distillation by renewable energies	• Wind power is more economical than PV. • Geothermal energy was suitable for different desalination processes at reasonable cost.
Al-Karaghouli et al. [68]	19	2009	Distillation by renewable energies	• Solar desalination was economical for small desalination units up to 10 m^3/day.
Gude et al. [69]	114	2010	Distillation by renewable energies	• Selection of suitable renewable energy source for desalination depended on plant size, feed water salinity, remoteness, availability of grid electricity, technical infrastructure and type of local renewable energy resource.

El-Ghonemy [70]	33	2012	Distillation by renewable energies	• Solar distillation was suitable for seawater desalination. • Integration of renewable energies in desalination was increasingly attractive.
Ghaffour et al. [71]	69	2014	Distillation by renewable energies	• Combined solar and geothermal energies were efficient for water desalination in KSA.

5. Merits of Utilizing the Nanofluid in the Solar Stills.

Nanofluids have lot of merits in comparison to normal base fluids this make them more effective they are used in solar stills. The most significant advantages of nanofluids are given below [18, 72-74]: -

- Nanoparticles are easy to change its shape, material and size, which makes them very efficient in maximizing the solar energy absorption and minimizing the emittance.
- The thermal conductivity of the nanofluid is much higher than the base fluid and hence, the efficiency and the productivity of the solar stills are significantly increased.
- The ability to reduce surface temperature by the usage of nanofluids, this temperature reduction will directly contribute in improving the solar still performance.
- The scattering and absorption of the incident solar radiation were highly improved by using nanofluids.
- Nanofluid helps in increasing the desired output temperature and the productivity of the system. While, in the conventional still, this would require larger areas for heat transfer which leads to increase both the cost and size of the still.
- A significant reduction of the convection and radiation heat losses can be achieved by using the nanofluid in the still basin.

6. Applications of Nanofluid in the Single Basin Single Slope Solar Still.

Gnanadason et al. [75] examined the vacuum single basin solar still under conditions of water and CNT-water nanofluid. The condensation rate on the cooler surface was greatly improved due to the higher rate of evaporation. In their design, the pressure inside the distillation chamber was reduced by using a simple vacuum It was found that the productivity of the still using nanofluid was increased highly with time compared with the still using the base water only as presented in Fig. 4. Gnanadason et al. [76] experimentally studied the effects of carbon nanotubes (CNTs) addition to the water inside a modified vacuum single basin solar still (Fig. 5). As a conclusion they stated that adding nanofluid to the still basin tends to increase its efficiency by about 50 %. It was found that the still productivity was increased when the depth of the water level and the salt concentration were considered minimum.

Gnanadason et al. [77] examined theoretically and experimentally the performance of a single basin solar still by using the base water and CNT-water nanofluid. The solar still used in their work was consisted of an Aluminum basin with a total area of (1 × 1 m^2) with a maximum height of 50 mm and 2 mm thickness. In order to be able to reduce the vapor leakage, silicon sealant is used to seal the cover tightly. The basin was fitted by 10 mm diameter pipes. One for feeding the basin with the brackish water, while the other pipe is used to flush the brackish water out from it. A condensate channel was designed along the lower edges of the glass cover to collect the distillate output and carry it outside the still. It was found that using of nanofluid in the basin surface was increased the still efficiency by about 60 %. They compared the water collection for both water and nanofluid solar stills and found that the still using nanofluid had a higher distillate output as presented in Fig. 6.

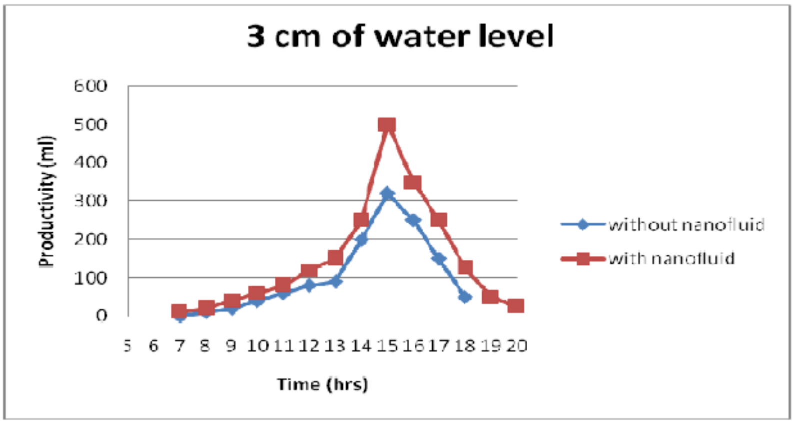

Fig. 4. Relationship between the productivity and time with and without using CNT-water nanofluid (Gnanadason et al. [75])

Fig. 5. The modified vacuum single basin solar still (Gnanadason et al. [76]).

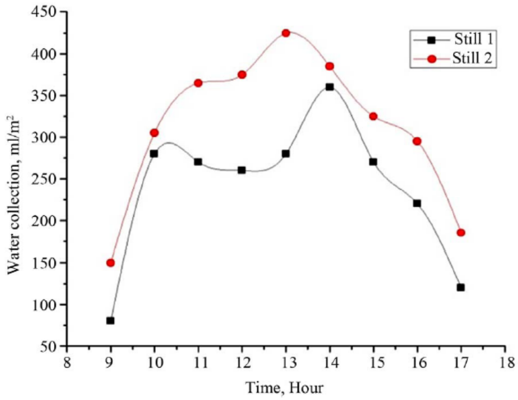

Fig. 6. Relationship between the water collection and time with and without using CNT-water nanofluid (Gnanadason et al. [77]).

They computed the solar still efficiency from the below given equation: -

$$\eta = \frac{\sum m_w \times h_{fg}}{\sum A_s \times I} \quad (1)$$

Panitapu et al. [78] used the Titanium oxide as a nanomaterial in the single basin single slope solar still to improve both productivity and efficiency. They reported that the basin temperature was increased highly with time by using nanofluid in comparison with its value by using the water only as shown in Fig. 7. Moreover, they concluded also that using nanofluid in the basin of the still led to increase the water temperature as well as the inside and outside glass cover temperatures. Elango et al. [79] presented an experimental work to compare the performance of a single basin single slope solar still in the same location and radiation conditions with and without water nanofluids. Four types nanofluids were utilized as a basin fluid including respectively ZnO/water, Al_2O_3/water, Fe_2O_3/water and SnO_2/water. Two identical experimental model stills having the same basin area (Fig. 8) were fabricated and tested with water and different nanofluids simultaneously.

They reported that the still filled with Al_2O_3/water nanofluid indicated a higher production (29.95 %), while stills filled with SnO_2/water and ZnO/water nanofluids gave 18.63 % and 12.67 % respectively more than the still filled with the ordinary water (Fig. 9). They concluded that nanofluids developed more temperature difference between the basin fluid and the glass cover which increased the productivity of the still. Shankar et al. [80] conducted experimental work to investigate the effect of colour and Al_2O_3 nanoparticles on the efficiency of two different kinds of a single slope solar still. They painted the sidewalls of one still by a white colour and added Al_2O_3 nano particles to its basin water. While the sidewalls of the second still was painted by a black colour and filled with the water only. The base of both stills were painted in black. Both stills were placed facing towards south, so that solar light incidents continuously during the sunshine. They indicated that adding the Al_2O_3 nanoparticles to the water increased its rate of evaporation and played as a heat storage medium for water evaporation after the sunset. Also, they concluded that the still with a white colour and nanoparticles had a higher hourly efficiency than the other one as presented in Fig. 10.

Sain and Kumawat [81] conducted an experimental work to examine the possibility of enhancing the productivity of the single slope solar still by utilizing Al_2O_3 nano-particles together with the black paint of the inner bottom surface of the still. Their results showed that the productivity and the efficiency of the still were increased by about 38.09 % and 12.18 % respectively when nano-particles with black paint were used at a water depth of 0.01 m. Gupta et al. [82] Conducted an experimental investigating to enhance the productivity and efficiency of a single slope solar still with white painted sidewalls by using CuO nanoparticles. They performed their experiments at water depth of 5 and 10 cm. Another similar black painted sidewall still was fabricated also for the purpose of comparison. It was found that white painted sidewalls reduced the heat loss to the environment and increased the productivity of the still by increasing the condensation. This increasing was 22.4 % and 30 % higher than the still filled by the water only at water depths of 5 and 10 cm respectively. They calculated the efficiency of the solar still from the following equation: -

$$\eta = \frac{Q \times h}{A \times I_d} \quad (2)$$

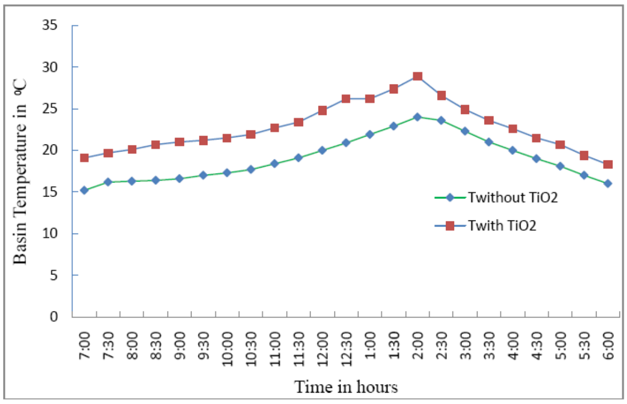

Fig. 7. Temporal variation of basin temperature with and without using TiO_2-water nanofluid (Panitapu et al. [78]).

Fig. 8. Photograph of the single basin single slope solar still (Elango et al. [79]).

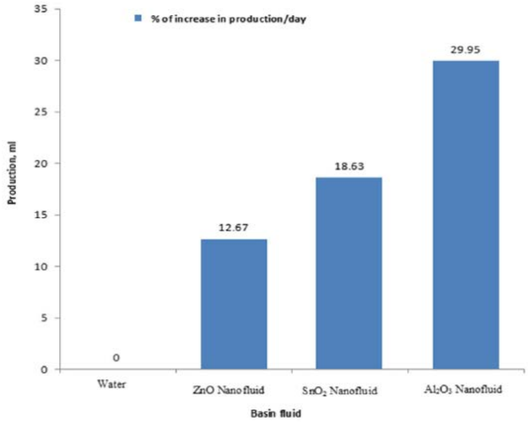

Fig. 9. Percentage increasing in production of nanofluid compared with water (Elango et al. [79]).

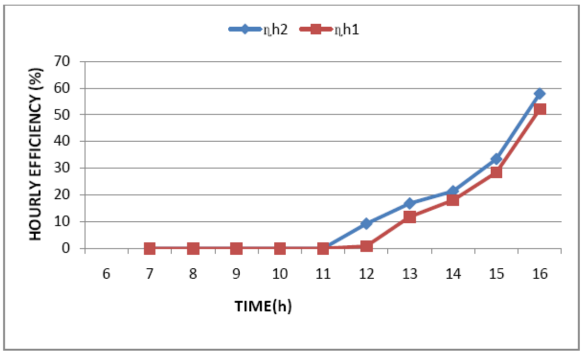

Fig. 10. Variation in hourly efficiency for white sidewalls and nano particles still (blue) and black sidewalls and water only still (red) (Shankar et al. [80]).

Sharshir et al. [83] modified the performance of a conventional solar still by utilizing flake graphite nanoparticles (FGN), phase change material (PCM) and the glass film cooling (Fig. 11). They observed that the productivity was increased by about 73.8 % in comparison to the conventional still with the utilization of the three previous modifications together. Also, it was observed that the enhancement in the distillate productivity was increased by 13 % when the saline water depth decreased from 2 to 0.5 cm. Very recently, Sharshir et al. [84] experimentally studied the performance of the conventional solar still by utilizing the graphite and copper oxide micro-flakes with different concentrations, different basin water depths and different film cooling flow rates. As a Conclusion, the productivity of the solar still was increased by 44.91 % when copper oxide was used, while for graphite micro-flakes it was increased by 53.95 % compared to the conventional solar still (without micro-flakes). This increasing was observed by using the glass cooling at a brine water depth of 0.5 cm and a concentration of 1 %. It was found that the productivity increased with increasing the particles concentration for both micro-flakes as shown in Fig. 12.

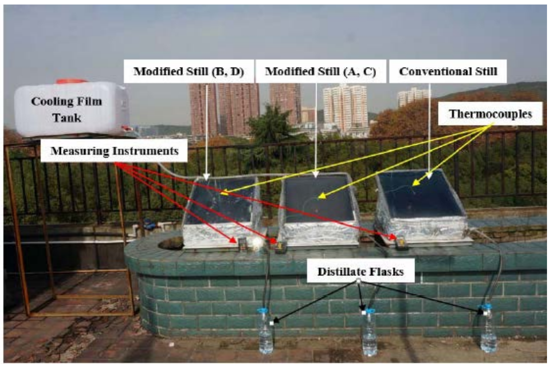

Fig. 11. Photograph of the modified single basin solar stills (Sharshir et al. [83]).

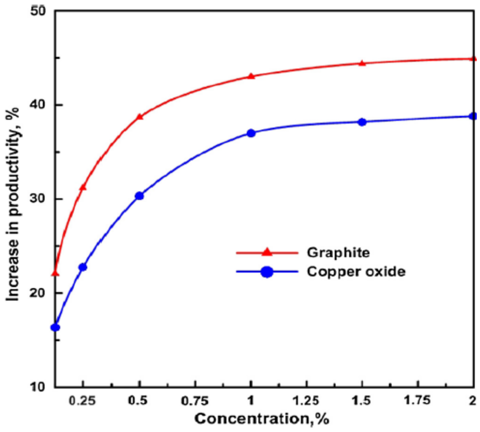

Fig. 12. Variation of productivity with concentrations for graphite and copper oxide micro-flakes (Sharshir et al. [84]).

The summary of reference used in the investigation of nanofluid in a single basin single slope solar still is given in Table 2.

Table 2. Summary of investigations of nanofluid in a single basin single slope solar still.

Model	Reference	Year	Nanofluid Type	Results and remarks
Experimental	Gnanadason et al. [75]	2011	CNT- water	• Using of nanofluid in the basin increased the temperature of the water and evaporation rate of the still. • Productivity of the still using nanofluid was highly increased

				with time compared with the still using the water only.
Experimental	Gnanadason et al. [76]	2012	CNT- water	• Nanofluid in a solar still was increased its productivity and efficiency. • Productivity increased when water level depth and salt concentration were minimum.
Experimental and Theoretical	Gnanadason et al. [77]	2013	CNT- water	• Using of nanofluid in the basin surface was increased the still efficiency by about 60 %. • Productivity was higher for still using nanofluid in compared with that using water.
Experimental	Panitapu et al. [78]	2014	TiO_2-water	• Nanofluid increased basin, water, inside and outside glass cover temperatures with respect to time.
Experimental	Elango et al. [79]	2015	ZnO-water Al_2O_3-water Fe_2O_3-water SnO_2-water	• Nanofluid with higher thermal conductivity absorbed more radiation in comparison with water. • Nanofluid developed higher temperature difference between basin fluid and glass cover. • Payback period of nanofluid was only 2.85 years. • Al_2O_3/water nanofluid indicated a higher production (29.95 %).
Experimental	Shankar et al. [80]	2015	Al_2O_3-water	• Productivity of solar still with a white colour and nano particles was 25 %

				more than the still with a black colour and water only. • White painted sidewalls reflected solar light to water and increased its rate of evaporation.
Experimental	Sain and Kumawat [81]	2015	Al_2O_3-water	• Nano-particles together with black paint increased productivity and efficiency of solar still.
Experimental	Gupta et al. [82]	2016	CuO-water	• Nanoparticles mixed with basin water increased the evaporation rate. • Nanoparticles increased still productivity at night by releasing their stored energy to water. • Nanoparticles increased productivity by 22.4 % and 30 % at water depths of 5 and 10 cm respectively.
Experimental	Sharshir et al. [83]	2017	FGN-water	• Productivity was enhanced by about 73.8 % by using flake graphite nanoparticles, PCM and glass film cooling.
Experimental	Sharshir et al. [84]	2017	Graphite - water Copper oxide - water	• When water flowed over glass cover, productivity improved by 47.80 % and 57.60 % by using copper oxide and graphite particles, respectively. • Productivity increased with increasing particles concentration for both micro-flakes.

7. Applications of Nanofluid in the Single Basin Double Slope Solar Still.

Sahota and Tiwari [85] presented a theoretical study to investigate the effect of Al_2O_3 nanoparticles on the performance of the passive double slope solar still for three different concentrations (0.04 %, 0.08 % and 0.12 %). Two different values of water mass were used in their study (35 and 80 kg). The results indicated that the daily yield obtained from the basin filled with the nanofluid increased with increasing the nanoparticle concentration. Moreover, they observed as shown in (Fig. 13) a good improvement in the daily yield when the nanofluid was used compared with using the water only. Sahota and Tiwari [86] analytically examined the effect of different nanoparticles (Al_2O_3, TiO_2 and CuO) on the performance of the passive double slope solar still for three different concentrations (0.2 %, 0.25 % and 0.3 %).

It was seen in Fig. 14 that Al_2O_3 -water nanofluid gave the highest still productivity compared with other types of the nanofluid. Also, they observed that the productivity of all types of the nanofluid was greater than that of the water only. As a conclusion they reported that nanofluids increased both the thermal energy and exergy efficiencies of the still. Very recently, Sahota et al. [87] studied theoretically the energy matrices, enviroeconomic and exergoeconomic analyses of the passive double slope solar still filled with Al_2O_3, TiO_2 and CuO -water based nanofluids. The results referred that the optimal range of the basin fluid mass was $20 \leq M_w \leq 40$ kg. While, the optimized values of Al_2O_3, TiO_2 and CuO nanoparticles were in the range of $0.143\ \% \leq \phi \leq 0.272\ \%$; $0.059\ \% \leq \phi \leq 0.187\ \%$ and $0.044\% \leq \phi \leq 0.153\ \%$ respectively. They reported that the maximum annual productivity, energy, and exergy were noticed for Al_2O_3-water nanofluid.

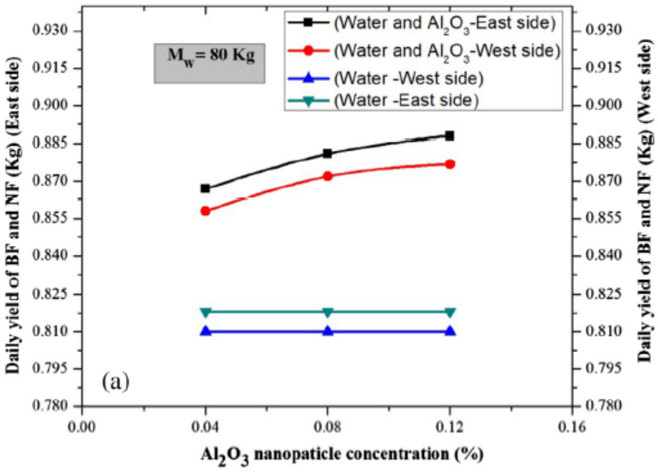

Fig. 13. Variation of daily yield obtained from base and nanofluids against nanoparticles concentration for water mass of 80 kg (Sahota and Tiwari [85]).

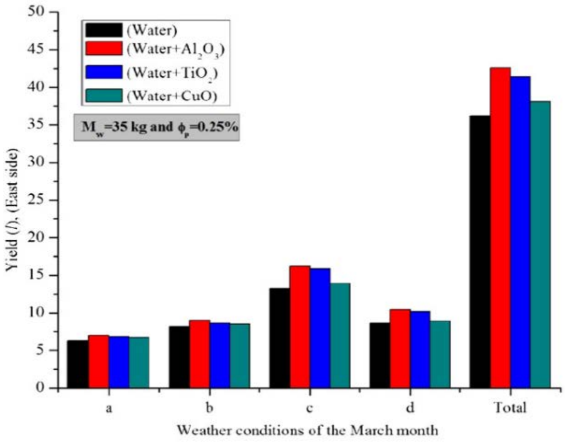

Fig. 14. Variation of the productivity (yield) obtained from base and nanofluids at different weather conditions (Sahota and Tiwari [86]).

Table 3 summarizes the investigations of nanofluid in a single basin double slope solar still.

Table 3. Summary of investigations of nanofluid in a single basin double slope solar still.

Mean of study	Reference	Year	Nanofluid Type	Remarks
Theoretical	Sahota and Tiwari [85]	2016	Al_2O_3-water	• Daily yield increased with increasing nanoparticle concentration in the water. • Daily yield increased at 0.12 % concentration by about 12.2 % and 8.4 % for 35 and 80 kg respectively in comparison with using water.
Theoretical	Sahota and Tiwari [86]	2016	Al_2O_3-water TiO_2-water CuO-water	• Thermal energy and exergy efficiencies were improved by using nanofluid compared with water only. • Al_2O_3 -water nanofluid gave the highest productivity compared with another types of nanofluid.
Theoretical	Sahota et al. [87]	2017	CuO -water Al_2O_3 -water TiO_2-water	• Concentration of nanoparticles and mass of base and nanofluids depended on climatic conditions. • Maximum annual productivity, energy, and exergy were noticed for Al_2O_3-water nanofluid.

8. Applications of Nanofluid in the Solar Still Integrated with an External or Internal Condenser.

Kabeel et al. [88, 89] attempted experimentally to enhance the solar still productivity by integrating the still with an external condenser under the Egyptian conditions by using Al_2O_3-water nanofluid. Two different basin stills were constructed in order to be used for solar desalination system performance testing and comparison. One of them was the conventional type and the other was the modified basin still which is presented in Fig. 15. It was found that the evaporation and condensation rates were increased by utilizing a small power consumption fan worked with photovoltaic solar panels. Thier results indicated that integrating the external condenser with the solar still basin increased the distillate water yield by 53.22 %.

While, using nanofluid increased the productivity of this type of stills by about 116 %. Kabeel et al. [90] focused experimentally on increasing the distilled productivity of the solar still by integrating it with an external condenser by using Al_2O_3-water and Cu_2O-water nanofluids. The system performance was investigated at various nanoparticles concentrations ($0.02 \leq \varphi \leq 0.2$) in the basin water with and without using a vacuum fan. As presented in Fig. 16, their results showed that using Cu_2O -water and Al_2O_3-water nanofluids increased the distilled productivity by 133.64 % and 125 % respectively when a vacuum fan was used.

While it was increased by 93.87 % and 88.97 % without using it. Moreover, they observed an increment in the productivity of distilled water when the nanoparticles concentrations in the water for both types of nanofluids is increased. Very recently, Kabeel et al. [91] numerically investigated the solar still integrated with an external condenser. In their study they used different nanoparticles concentrations ($0.02 \leq \varphi \leq 0.3$ %) under a low-pressure condition. It was found that the daily efficiency of the still with operating the fan was 84.16 % and 73.85 % by utilizing Cu_2O and Al_2O_3 nanoparticles respectively as shown in Fig. 17. While it was about 33 % for the conventional still filled with the water only.

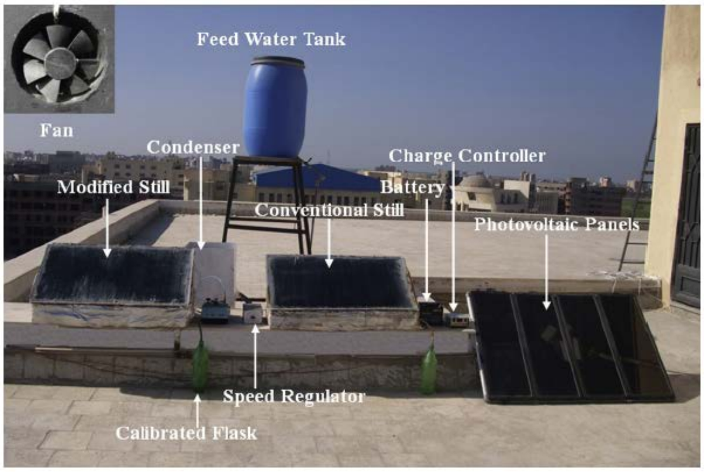

Fig. 15. Photograph of the two conventional and modified solar stills (Kabeel et al. [88, 89]).

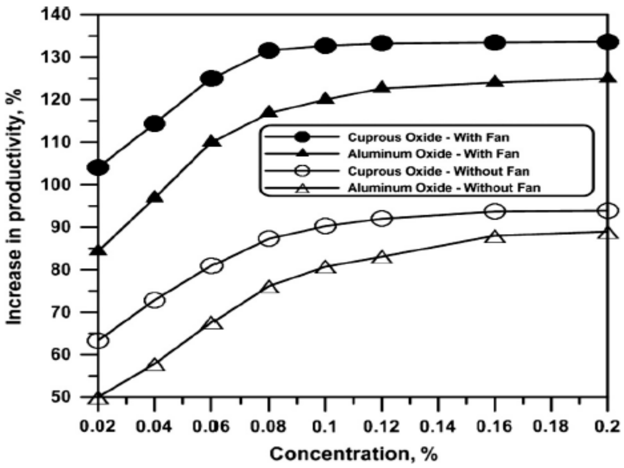

Fig. 16. Comparison of increment in productivity by nanofluids with and without using a vacuum fan (Kabeel et al. [90]).

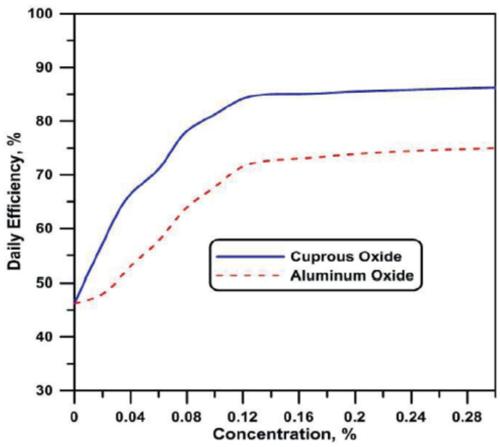

Fig. 17. Daily efficiency variation by using nanoparticles at different concentrations with using a fan (Kabeel et al. [91]).

A summary of the studies used for the investigations of nanofluid in the solar still integrated with an external or internal condense is presented in Table 4.

Table 4. Summary of investigations of nanofluid in the solar still integrated with an external or internal condenser.

Mean of study	Reference	Year	Nanofluid Type	Remarks
Experimental (external condenser)	Kabeel et al. [88] Kabeel et al. [89]	2013 and 2014	Al_2O_3-water	• Nanofluid exhibited high evaporation rate compared with water.

				• Nanofluid improved the water productivity by about 116 %. • Nanofluid was reduced the convection heat loss from basin to glass cover. • 53.22 % increment in distillate output due to the external condensers.
Experimental (external condenser)	Kabeel et al. [90]	2014	Al_2O_3-water Cu_2O -water	• Still productivity was improved by using a vacuum fan, external condenser and nanofluids. • Still productivity was increased by about 133.64 % by using a vacuum fan and Cu_2O-water nanofluid.
Numerical (external condenser)	Kabeel et al. [91]	2017	Al_2O_3-water Cu_2O -water	• Distillate productivity of still increased by using nanofluids and providing a low pressure.

9. Applications of Nanofluid in the Hybrid Solar Still.

Sahota et al. [92] used the characteristic equation to perform an analytical study on the effect of CuO, Al_2O_3 and TiO_2-water based nanofluids on the performance of the double slope solar still integrated with photovoltaic thermal flat plate collectors and operated under two different systems (i.e., with and without a helical heat exchanger). The results indicated that for two considered systems, the productivity of the still was higher for CuO-water nanofluid as presented in (Fig. 18). They concluded that the characteristic equation showed that the improved instantaneous thermal energy efficiency of both systems of nanofluids were higher than the base fluid.

Sahota and Tiwari [93] introduced a complete cost analysis (energy matrices, exergoeconomic and enviroeconomic analysis) of the hybrid double slope solar still loaded with CuO, Al_2O_3 and TiO_2-water based nanofluids integrated with photovoltaic thermal flat plate collectors and operated under two different systems (i.e., with and without a helical heat exchanger). Many parameters were optimized such as the thermal energy, exergy and productivity.

The results showed that the best annual performance was noticed for the still operated without a heat exchanger. Very recently, Mahian et al. [94] performed an experimental and theoretical investigation on the effect of SiO_2 and Cu nanoparticles on the performance of a solar still fitted with a heat exchanger installed in its basin. Three important parameters were investigated in their study (i.e., energy efficiency, exergy efficiency and freshwater yield). The experiments were carried out using different nanoparticle volume fractions ($0.5 \leq \phi \leq 2$ %), two different sizes of nanoparticles (7 and 40 nm), two depths of water in the basin (4 and 8 cm), and three volume flow rates of nanofluids (3, 4 and 5 l/min) during various weather conditions. Their results indicated that usage of heat exchanger increased the still productivity more than two times when inlet temperatures were high (i.e., 70 °C). As a conclusion, they stated that SiO_2-water nanofluid enhanced the evaporation rate of the still when the temperature was high. While Cu-water nanofluid enhanced it when the temperature was low as shown in Fig. 19.

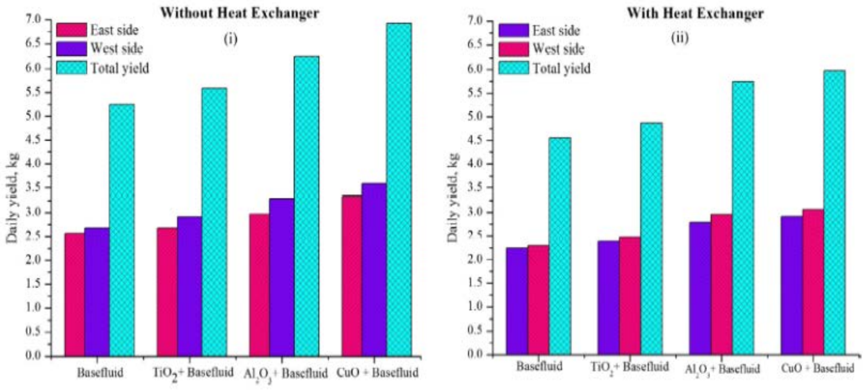

Fig. 18. Variations of daily yield (east side, west side and total) without and with using a heat exchanger for both base and nanofluids (Sahota et al. [92]).

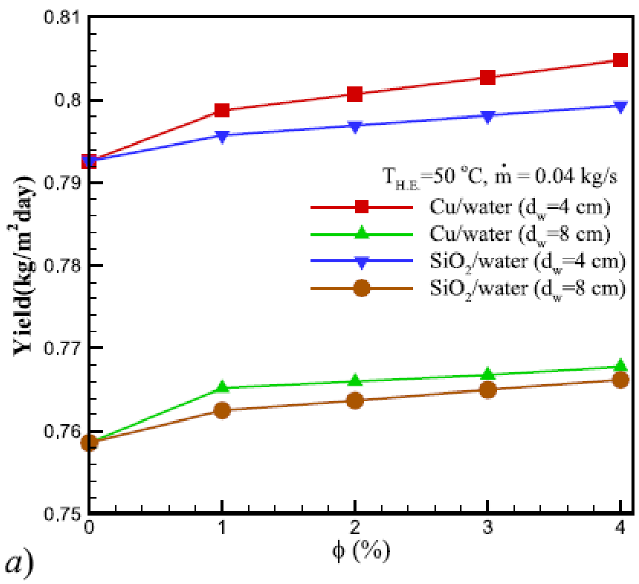

Fig. 19. Variation of yield with nanoparticle volume fractions for various nanofluids and water depth (Mahian et al. [94]).

Table 5 shows a summary for the studies used in the investigations of nanofluid in the hybrid solar still.

Table 5. Summary of investigations of nanofluid in the hybrid solar still.

Mean of study	Reference	Year	Nanofluid Type	Remarks
Theoretical	Sahota et al. [92]	2017	CuO -water Al_2O_3 -water TiO_2-water	• Productivity of still without a heat exchanger was better than with using it. • Maximum productivity was observed for CuO-water nanofluid.
Theoretical	Sahota and Tiwari [93]	2017	CuO -water Al_2O_3 -water TiO_2-water	• CuO-water nanofluid gave a better performance for stills operated with and without a heat exchanger. • Energy matrices were improved significantly by using nanofluids.
Experimental and Theoretical	Mahian et al. [94]	2017	SiO_2-water Cu-water	• Using nanofluids in heat exchanger enhanced still performance about 10 % at temperatures below than 60 °C. • Evaporation rate of solar still was influenced by Brownian motion of nanoparticles.

10. Applications of Nanofluid in Other Types of Solar Stills.

Omara et al. [95] experimentally investigated the effect of using Al_2O_3-water and Cu_2O-water nanofluids, patterns of the liner corrugated, double layer wick material, internal reflecting mirrors and induced vacuum on the yield of conventional and corrugated wick solar stills (Fig. 20). The second still was consisted from corrugated wick absorbers, and integrated with an external condenser to examine its performance. It was found that the productivity of corrugated wick solar still with internal mirrors, external condenser and filled with Al_2O_3-water nanofluid is about 255 % higher than that of the conventional still, when saline water depth is kept at 1 cm. Navale et al. [96] conducted experimental work to study the effect of the nanofluid on the performance of the masonic solar still. Two types of nanoparticles (Al_2O_3 and CuO) were used at 0.1 %, 0.2 % and 0.3 % concentration. According to their results, the maximum increase in productivity was 89.42 % for CuO-water nanofluid (Fig. 21) and 45.19 % for Al_2O_3-water nanofluid. This increase in the productivity was observed at 0.3% nanoparticles concentration.

Fig. 20. Photograph of the two conventional and corrugated wick solar stills (Omara et al. [95]).

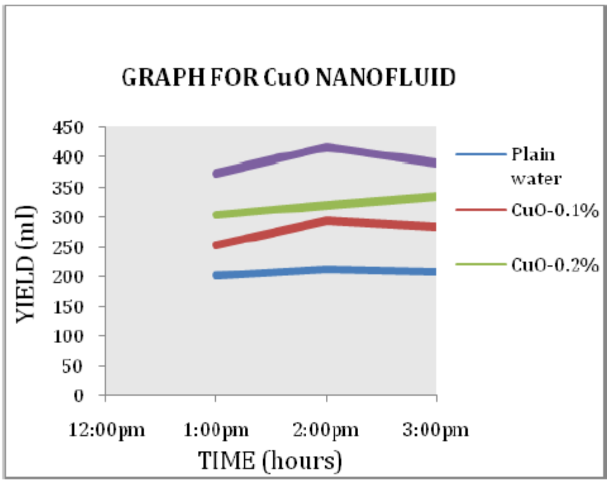

Fig. 21. Variation in productivity of the masonic solar still for different concentrations of CuO-water nanofluid and water only (Navale et al. [96]).

The investigations of nanofluid in other solar stills is summarized in Table 6.

Table 6. Summary of investigations of nanofluid in other solar stills.

Mean of study	Reference	Year	Nanofluid / Still Type	Results and remarks
Experimental	Omara et al. [95]	2015	Al_2O_3-water Cu_2O-water Corrugated wick solar still	• The integration of external condenser with corrugated still increased the distilled water by 180 % at a saline water depth of 1 cm. • Productivity of corrugated wick still with internal mirrors,

				external condenser and filled with Cu_2O-water nanofluid reached 285 % over the conventional still, at a saline water depth of 1 cm.
Experimental	Navale et al. [96]	2016	Al_2O_3 - water CuO - water Masonic solar still	• Productivity was improved by 89.42 % and 45.19 % when CuO-water and Al_2O_3-water were utilized respectively. • Nanofluid improved the evaporation inside the still.

11. Conclusions

This paper presents a widespread overview of latest improvements related to the nanofluid applications in different types of the solar stills. The presented and discussed results give a fruitful source of references for improving the solar still performance by the using the nanotechnology concept. Below is a summary of the most important conclusions: -

- According to the reviewed papers, uniform dispersion of the nanoparticles in the base fluid results in solar absorption enhancement, as well as increasing both the productivity and the efficiency of the solar still.
- Mixing of nanoparticles with the basin water tends to increase its thermal conductivity, water temperature and coefficient of convective heat transfer and as direct result the evaporation rate also increases. Since, the nanoparticles work as a heat storage material and provide a sufficient energy to the water and increase the still productivity at night.
- It is recommended to use a wiper mounted at the still basin to avoid settling of nanoparticles.
- It is essential to choose the suitable nanoparticles volume fraction.
- It is possible to increase the productivity of the solar still from 50 to 70 % by mixing nanoparticles in the water.
- Further efforts are required to investigate the reliability of utilizing nanofluids in solar stills from economical and environmental perspectives.
- Distilled productivity was increased with increasing the nanoparticles concentrations.
- Nanofluid has the ability to absorb directly the solar radiation due to the excellent matching between its optical absorption spectrum and the solar radiation spectrum.
- Using of nanofluid in the single-slope basin solar still increases its efficiency by about 60 %. Moreover, a significant improvement occurs in its distillate output when a nanofluid is used.

- More efforts should focus on developing a non-toxic and low cost nanoparticles to cut costs of nanofluid based solar still.
- More efforts and research work are needed to study the effect of nanoparticles sedimentation on the performance of solar stills.
- More efforts are required to study of using hybrid-nanofluids or PCM-nanoparticles on the productivity of solar stills.
- More efforts are required to investigate the advantages of the usage of nanofluids in order to develop the performance of many special designs of solar stills, to author's knowledge, no paper exists up to date considers this issue.

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Nomenclatures

A	Area of the glass surface of the solar still, m^2
A_s	Area of the basin, m^2
h	Latent heat of vaporization, MJ/s
h_{fg}	Latent heat of vaporization, kJ/s
I	Intensity of solar radiation, W/ m^2
I_d	Average daily solar radiation, MJ/ m^2
M_w	Mass of the water in the basin of the solar still, kg
m_w	Mass flow rate of collected distilled water, kg/s
Q	Daily output volume of water, L

Greek Symbols

ϕ	Nanoparticles volume fraction
η	Thermal efficiency of the solar still

Abbreviations

AGMD	Air Gap Membrane Distillation
CNT	Carbon Nanotubes
DCMD	Direct Contact Membrane Distillation
ED	Electro Dialysis.
FD	Freeze Desalination
FGN	Flake Graphite Nanoparticles
FO	Forward Osmosis
MD	Membrane Distillation.
MED	Multi-Effect Distillation
MSF	Multistage Flash Distillation
PCM	Phase Change Material
PV	Pervaporation
RO	Reverse Osmosis.

SD	Solar Distillation
SGMD	Sweeping Gas Membrane Distillation
VCD	Vapor Compression Distillation
VMD	Vacuum Membrane Distillation

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