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The effect of air flow on solar stills performance: a review

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ABSTRACT

Following the decline in rainfall in most countries, especially in arid zones, the urge for desalination to compensate water crises has increased. Water has always been vital to our lives. Given the fact that the amount of sanitary water available is low, we have to discover methods for water desalination on Earth. One of these methods is the use of solar stills for desalinating the brackish water. However, low production of available desalination plants necessitates finding ways to increase their output. Recently, this area has attracted a great deal of scientific attention. There are several methods to augment the water production in solar stills, one of which is the betterment of solar stills via airflow. The present study aimed to introduce different solar stills employing airflow in their structures. This research demonstrated that solar stills would have a better performance if they benefited from airflow.

Keywords: Solar still; Active; Passive; Desalination; Air flow; Water production; Efficiency

1. Introduction

The volume of water on the floor is steady in a closed circular closed orbit. Consumable water on Earth for different uses (agriculture, industry, and drinking water) accounts for only 3% of the total amount of water [1,2], three quarters of which are in the polar ice caps and out of reach for humans [3–5]. The United Nations General Assembly has notified that water is inaccessible to half of the population in the developing countries. In addition, 75% of human illnesses stem from water shortage [6]. World Health Organization (WHO) has warned that 80% of human-induced diseases are directly associated with water [7,8]. If safe water is available to all humans, infant mortality caused by many diseases (diarrhea) will be substantially reduced [9,10]. Societies need adequate water to supply energy, drinking water, and food. Nowadays, global demand for food production is gradually increasing at very high rates [11]; for instance, agriculture consumes about 70% of all the available water [12,13]. Despite these shortcomings, scientists have suggested that the desalination of seawater can help overcome the crisis [14]. There are several methods for desalination of water, a number of which require high-tech technologies and high energy consumption and are suitable for cities with central purification facilities [15]. However, there are also some simpler alternatives that can be applied individually in homes and the countryside. One option would be the use of solar distillation in warm and dry areas where solar energy is free and abundant [16–18]. This method is easily operated and low-cost; nonetheless, water production via solar desalination is low [15]. Therefore, airflow is employed to promote the stills and enhance freshwater production. According to studies, the methods applying

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this strategy function as follows: heating the basin via water heaters, air bubble technique, airflow in wicker desalination, airflow in multi-effect desalination, use of a fan and condenser to create forced discharge flow, simultaneous use of a fan and thermoelectric in desalination structure, use of a solar chimney, and use of airflow for glass cooling. There are also several studies on the efficacy of wind velocity and air temperature in solar desalination systems. The most important objective of this research was the recognition of practical methods of yield promotion in solar stills via airflow. In this paper, diverse methods of applying airflow in the structure of solar stills were described. Fig. 1 demonstrates multiple designs of solar stills in which airflow is utilized.

2. Mechanisms of heat and mass transfer in conventional solar stills

In this paper, the effect of airflow on the performance of different types of solar stills was reviewed. The heat transfer coefficient between air and still surfaces has a key role in the performance of solar stills. Therefore, in this section, the equations of this coefficient are presented for the categories of solar stills classified in Fig. 1.

The convective heat transfer coefficient between the air and glass cover for a solar still is as follows [19–21]:

$$h_{c,g-a} = 5.7 + 3.8 \times V_{\text{wind}} \tag{1}$$

where V_{wind} is the wind velocity.

For a solar still with air bubbling technique, the volumetric heat transfer coefficient between air and water is as follows [22]:

$$h_g a_s = \frac{G C_{p,\text{air}} \left(T_{\text{air,out}} - T_{\text{air,in}}\right)}{Z \cdot \text{LMTD}} \tag{2}$$

where LMTD is the logarithmic mean temperature difference between air and water, G is the airflow rate, and Z is the water level.

For a solar still integrated with a solar air collector, the heat transfer coefficient between the airflow and the channel is related to the Reynolds number as follows [23]:

if Re < 2,300

$$h_c = \left(k_f / D_h\right)\left(5.4 + \frac{\left(0.0019\left(\text{Re}\,\text{Pr}\,D_h / L_g\right)^{1.71}\right)}{\left(1 + 0.00563\left(\text{Re}\,\text{Pr}\,D_h / L_g\right)\right)^{1.71}}\right) \tag{3}$$

if 2,300 < Re < 6,000

$$h_c = \left(k_f / D_h\right)\left(0.116\,\text{Re}^{0.67} - 125\,\text{Pr}^{0.33}\right)\left(1 + \left(D_h / L_g\right)^{2/3}\left(0.17\right)^{0.14}\right) \tag{4}$$

if Re > 6,000

$$h_c = \left(k_f / D_h\right)\left(0.018\,\text{Re}^{0.08}\,\text{Pr}^{0.4}\right) \tag{5}$$

where Pr is the Prandtl number, L_g is the length of the glass cover, and D_h is the hydraulic diameter of the air channel.

3. Different methods of using airflow in solar stills

There are two kinds of solar stills, namely active and passive modes [9,10,24,25]. In passive modes, only solar energy enters the basin without any intermediaries, thereby heating the water inside [15,26,27]. Nevertheless, in active modes, in addition to the solar radiation, the energy enters the still from a separate device (solar collectors, heat pipe, photovoltaic panels) to augment the yield [28,29]. Fig. 2 illustrates different types of active and passive solar stills.

4. Different methods of using airflow in a single-effect active solar still

4.1. Heating the basin water with solar air collector (using solar energy for heating the air)

Solar air collector has been employed by researchers to raise the water temperature and heat transfer coefficients in the solar distillation systems [22]. The most simple air collector has a channel in which the air flows between the absorber and backplate [30–32]. Once the sunlight shines to the collector, the rays are transmitted from the glass to the absorber, thereby heating the air [33]. Several researchers have combined air collectors with solar stills to augment the efficiency.

Azari et al. [34] conducted an experimental study on a solar still integrated with a v-grooved solar air collector and reported the enviroeconomic and exergoeconomic parameters as shown in Fig. 3. They compared the results with a conventional still and the area in both stills was 0.4 m^2 and the air collector area was 0.5 m^2. The hot air from the solar air collector entered the bottom channel of the still to increase the basin water temperature. The annual yield of the modified and conventional solar stills were respectively 898.81 and 333.06 kg/m^2. They concluded that the yield in the hybrid still increased by 170% compared with that of the conventional solar still.

Kabeel et al. [12] coupled a still with an air heater and applied PCM to raise the distillation rate. They designed some holes on copper tubes to distribute the hot air bubbles from air collector to the basin water. The water production rose by about 108% in comparison with the common solar still. The freshwater yield was 9.36 L/m^2 d for the designed solar still.

Abdullah [13] studied a solar still connected to an air collector (Fig. 4). The traditional solar still and the system in the study were compared. Therein, the hot air from the collector was transferred into the stepped basin to heat the water. With the flow of air, the system showed higher productivity than the conventional type. The water production of the system was 6.3 L/m^2 d. The yield increased by 85%. A cover-cooling method and an air collector were simultaneously employed. The yield rose by 112% compared with the conventional type. Fig. 4 portrays the aforementioned system.

To increase the desalination production rate, higher temperature difference between evaporation and distillation surfaces is an important factor [35,36]. Therefore, the basin water temperature should increase or the glass cover temperature should decrease. Both of these methods affect the other one. Ladouy and Khabbazi [15] applied instantaneous heating to raise the air temperature in a triangular

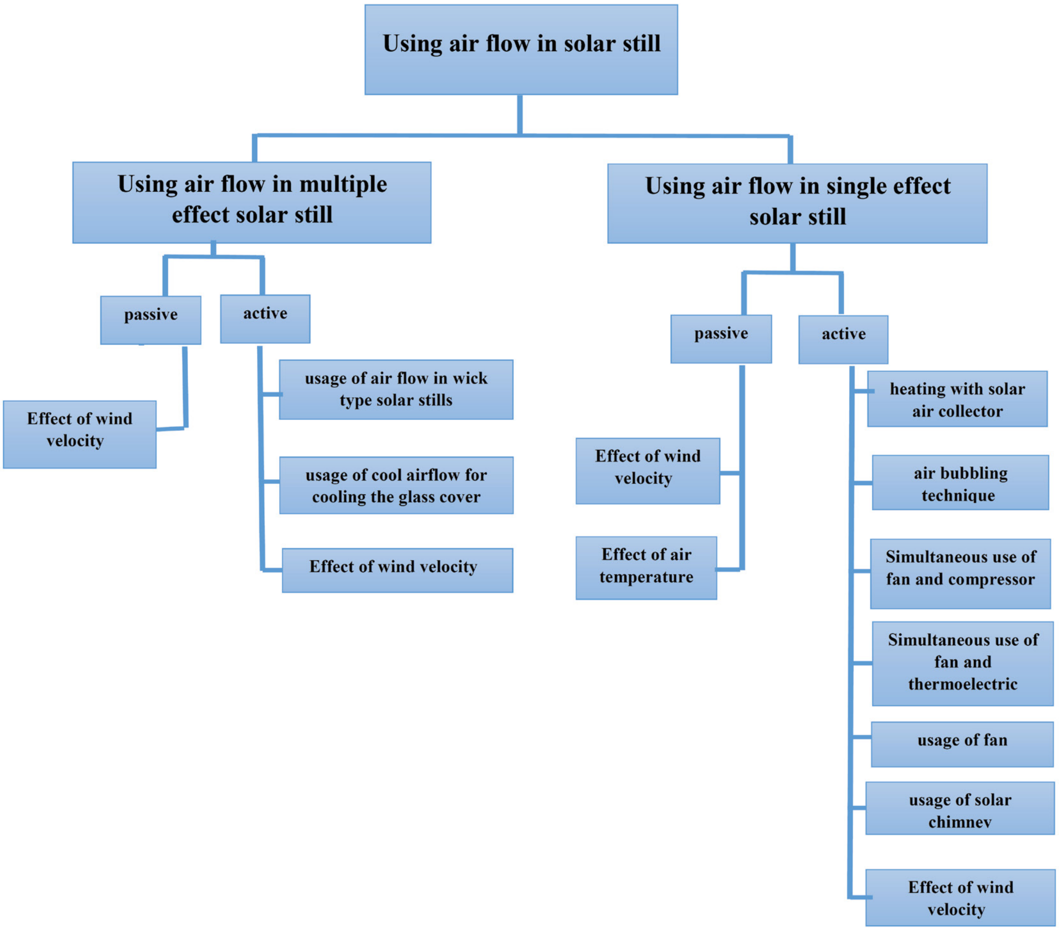

Fig. 1. Classification of different methods of using airflow in solar stills.

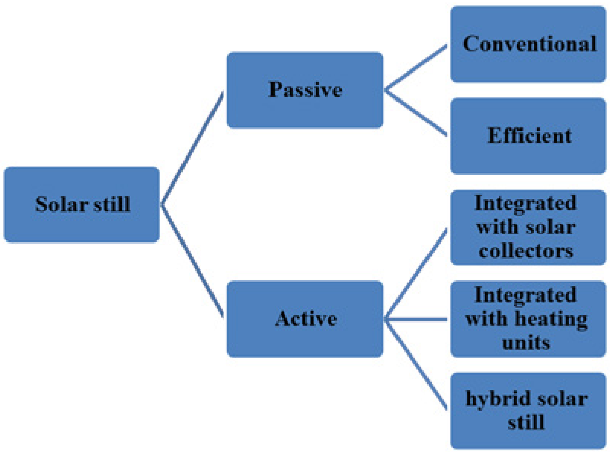

Fig. 2. Classification of different solar stills.

desalination system. The method includes air heating without raising the temperature of cold surfaces in the still. They employed an electric heat exchanger with PV panel to increase the water temperature with discontinuous method. Three types of heating modes (10, 20 and 45 s) were utilized in 15-min time intervals for the discontinuous heating method. The 20-s mode was regarded as the best time period in their experiments. In comparison with other methods without any air heating, the results revealed that through the use of this heating method with air, the efficiency was improved by 5%. The increase in desalination rate was also about 19%.

El-Zahaby et al. [16] studied a solar still with stepped basin connected with a water sprinkler system. They implemented electrical air heaters to distribute hot air under the solar still. They investigated different water flow rates and motor speeds. They also studied the effect of brackish water temperature and power consumption on the system performance. Under the most optimum conditions, the yield was 54.48 L/m^2 d and the thermal efficiency was 50%. The yield was increased because of using two air heaters.

Eltawil and Omara [26] designed a solar still attached with some instruments, such as a water heater and a solar air heater. In their experiment, they linked the solar still with an air collector and a condenser. In another experiment, hot water-atomized unit and air collector and condenser were attached to the solar still. For coupling the air collector with still, hot and dry air was first suctioned from the air collector and entered the solar still. Afterwards, the air bubbles were formed and split on the water in the basin. The velocity of hot airflow was about 0.7 m/s. The hot air circulation increased the heat transfer

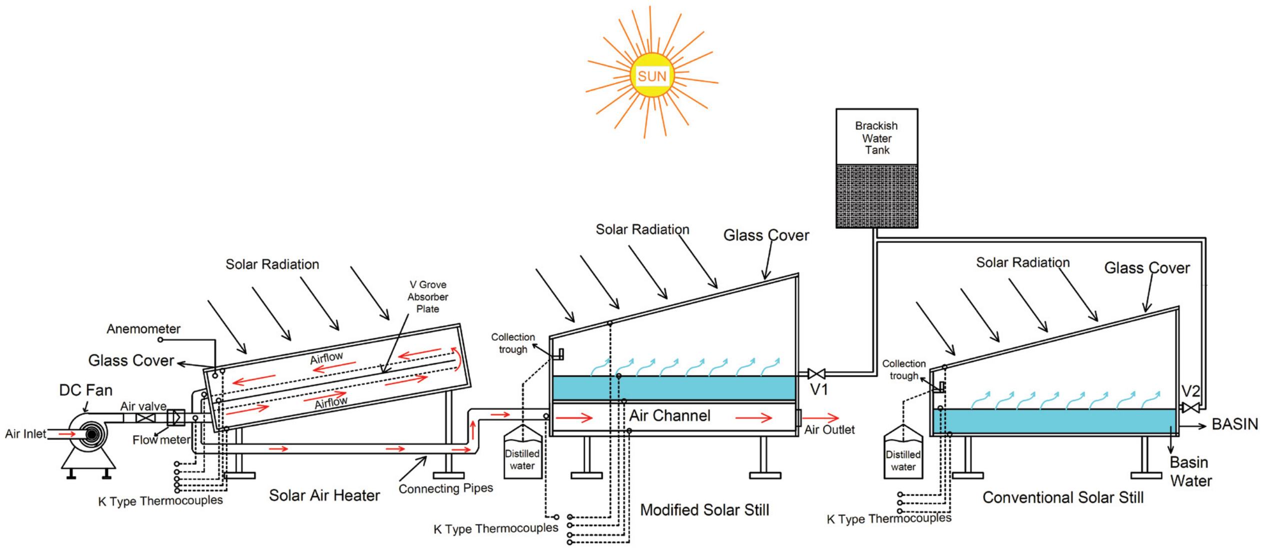

Fig. 3. Sketch of solar still integrated with solar air collector [34].

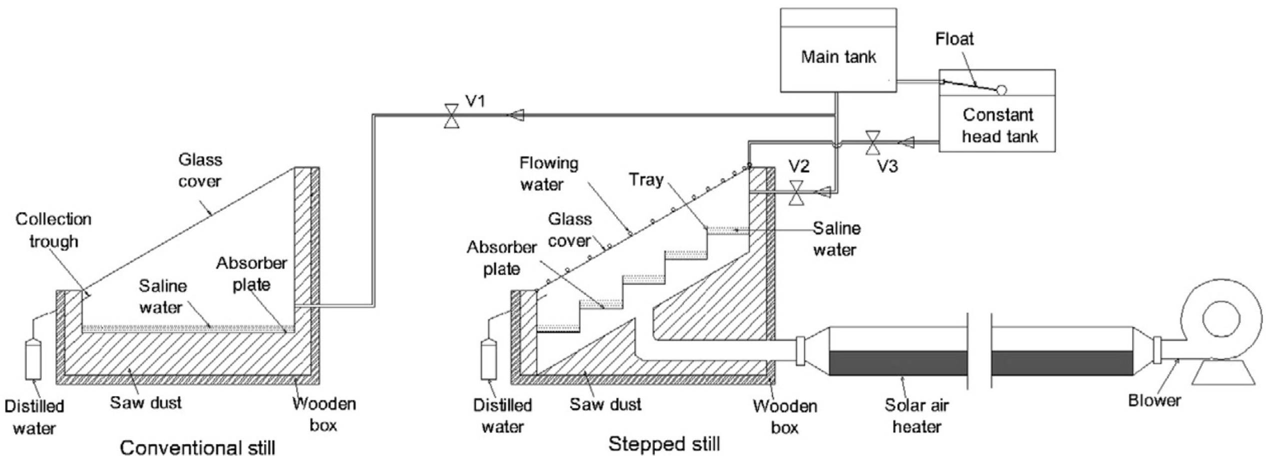

Fig. 4. Diagram of a solar still attached with an air heater [13] (Reprinted with permission from Elsevier).

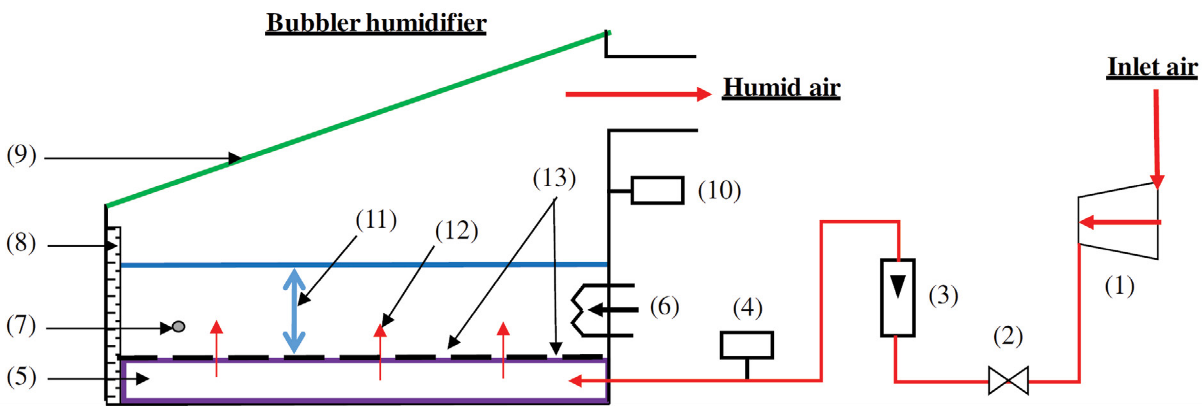

Fig. 5. Diagram of the experimental system [22] (Reprinted with permission from Elsevier).

in the still. The percentages of improvement in the yield, once the solar still was integrated with the hot water-atomized unit and hot air and condenser were 148% with 29%, respectively.

If an air collector is employed to heat the basin water, hot air can be used for other purposes, such as drying agricultural products or in air conditioning systems. It is worth noting that an increase in the water temperature with hot airflow should not reduce the temperature difference between hot and cold surfaces in a solar still since the amount of production and efficiency of the still will decrease. To prevent this phenomenon, different methods can be used for cooling the glass cover.

4.2. Air bubbling technique

Creation of air bubbles in the water is a method for enhancing the vaporization rate. Pandey [29] conducted certain experiments on the effects of air bubbles on the operation of solar desalination systems. He carried out four types of tests to find the best solution for improving the still performance. These methods were as follows: the ambient air bubbling, bubbling of ambient air that was dried with $CaCl_2$ traps, the simultaneous bubbling of dry air and glass cooling, and glass cover cooling only at last. For drying the ambient air, he placed the $CaCl_2$ traps between the air pump and the still. Applying dry air bubbling technique was on account of the increment in the water absorption capacity with air bubbles. The glass was cooled by passing water through it. The results illustrated that the highest yield of about 47.5% belonged to the simultaneous bubbling of dry ambient air and glass cooling.

Halima et al. [22] designed a mechanism creating air bubbles in the water. They installed a plate with some holes at the basin, distributing the air in the water, as in Fig. 5. The effect of airflow rate and water depth was examined in their work. They also studied the heat and mass transfer coefficients in the still. They compared their system with a common solar still. The findings demonstrated that the bubbler basin had a higher efficiency. The highest water production rate was 14 Lm^2/h for the basin water temperature of 70°C.

Porta-Gándara et al. [37] studied a simple solar still with air bubbling technique experimentally. They simulated the system via a computer program and compared the experimental and theoretical results. They utilized a PV panel to supply the electric power of the air pump and defined a factor to show the effect of air bubbling method. A 12% increase was observed in the yield for this type of system, which is depicted in Fig. 6.

In the air bubbling technique, air bubbles cause perturbation on the surface of the basin water, increasing the mass transfer coefficient and consequently the rate of water evaporation. In this method, the cost required to set up the system to create air bubbles and the rate of increase in water production must be proportional.

4.3. Simultaneous use of fan and condenser

To increase the freshwater production, it is essential to take out the heat from the condensation surface of a solar still. Some researchers have implemented both fan and external condenser in the structure of solar stills. The fan removes the steam from the still and leads it toward the condenser. Bhardwaj et al. [38] shed light on the effect of plastic channels on the desalination rate of the solar stills. In addition, they checked the efficacy of placing a fan inside and outside the still and even evaporation cooling on the distillation rate. They concluded that the simultaneous use of evaporation cooling and an external fan was more suitable than the use of a fan in the still. The efficiency of the still was 32.3% when using an outside fan.

Kumar et al. [39] studied the result of agitation and external condensation on a solar still efficiency. The still was equipped with a shaft connected to a DC motor as a motive and a condenser and an exhaust fan. The fan and the condenser raised the air circulation and vapor condensation. Once the steam was extracted by the fan, the glass temperature

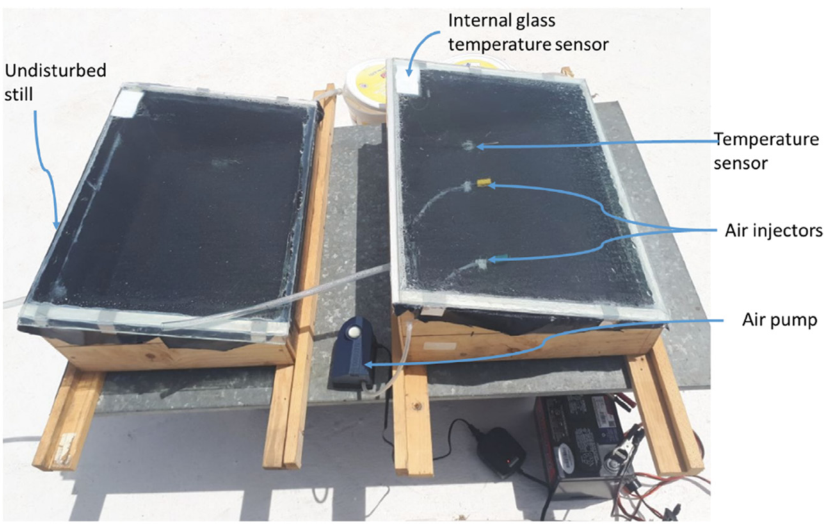

Fig. 6. Solar still with air bubbling technique [37] (Reprinted with permission from Elsevier).

was lowered, resulting in a higher condensation value. The solar still enhancement regarding condensation rate was 39.49% on account of air circulation. Yeh and Chen [40] found energy balance equations for a solar still by employing air flowing through it. The steam was directly evaporated by the preheated air stream, entered the condenser, and was cooled by the fan, as shown in Fig. 7. Significant improvements in the production were observed once water vapor was directly drained out of the still via the flow of air. Wind velocity and the airflow rate were the studied parameters affecting the water production rate. Employing a fan and a condenser, the efficiency reached 60%.

Rahim [41] coupled a solar still with a condenser and a fan. Therein, vapor was distilled before touching the glass. The copper tubes were held under the water tank and operated as a condenser. The vapor was removed from the still via a fan and entered into the tubes. This system made it possible to control the temperature difference among the cool and hot surfaces. This temperature difference enhanced the production. Without using a fan or a condenser, the output was 19.41%, but after applying this technique, the efficiency reached 29.55%. Certain parameters, such as air temperature and air velocity, were investigated in order to find the best conditions.

Nijegorodov et al. [42] described the governing equations of the traditional solar stills. They proposed that it was better to consider a condenser for water vapor condensation and to apply the latent heat of evaporation to preheat the water in the still. They used a fan to take out the vapor via the condenser. They proposed PV panels to supply the electrical power of the fan (Fig. 8). With a 100-W exhaust fan and a condenser, they obtained about 1 L/m^{2}h of freshwater whereas in the conventional type, the yield was only 0.4 L/m^{2}h.

Kabeel et al. [43] investigated the efficacy of a condenser using nanoparticles on the desalination yield in a still and the effect of water vaporization at different speeds of a fan. They studied the freshwater output in different speeds of the fan. Owing to airflow, the water generation increased. Using nanofluids, when composed with a fan and a condenser, improved the yield of the still by 116%. Cost analyses were performed for both conventional and designed solar stills. The cost of 1 L of freshwater using the modified solar still was $0.05.

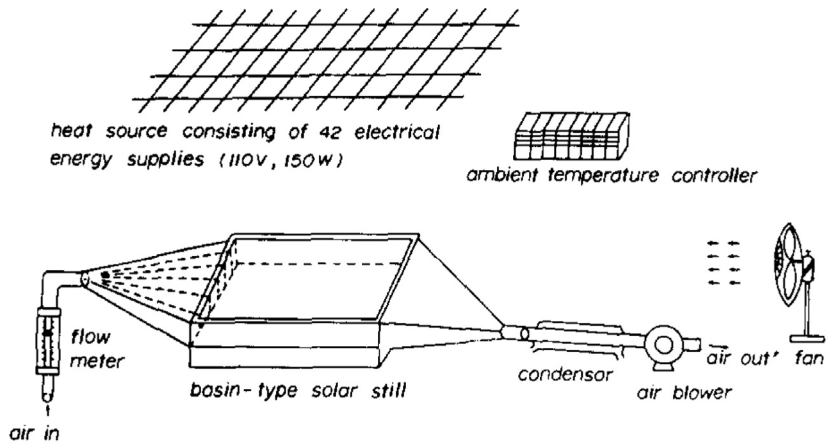

Fig. 7. Solar desalination unit with airflow [40] (Reprinted with permission from Elsevier).

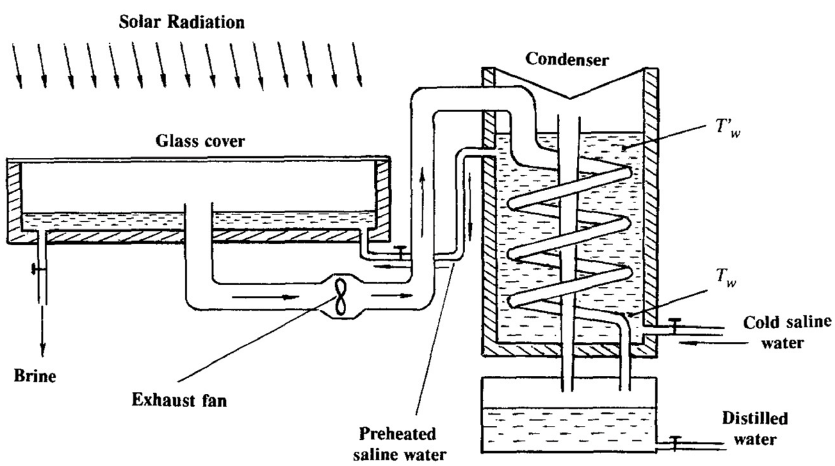

Fig. 8. Schematic view of the system [42] (Reprinted with permission from Elsevier).

El-Samadony et al. [44], examined a stepped solar still. They linked reflectors, a condenser, and a fan to the still. They also utilized a fan for removing the vapor from the basin. The output was great owing to the fan letting the air flow via the still and raising the vaporization rate. The productivity in the solar still with a reflector, a condenser, and an air suction fan was 165% higher than that of a usual one. They calculated the cost of water production with solar stills, which was \$0.036/L of that with the designed still.

Hassan et al. [45] studied four different types of active solar stills and compared their performances by evaluating the exergy, energy, enviroeconimic parameters, and exergoeconomic parameters. In one of their designs, they replaced the backplate of the solar still with a heat sink and integrated the still with a solar collector and a condenser and fan with air-cooling flow. The experimental setup is illustrated in Fig. 9. The output of this distillation system was 9.11 L/m^{2}d. The energy and exergy efficiency of the system were respectively 18.7% and 1.332%. The cost of water per liter was \$0.021138 L.

Using a fan and a condenser, the fan increases the heat transfer rate since it causes forced air flow in the system. In addition, the evaporation rate increases with the reduction in the pressure inside the solar still by removing non-condensable gases from the still to the condenser.

4.4. Using thermoelectric and fan

When using thermoelectric and fan, the fan is utilized to create airflow for cooling the thermoelectric modules. Thermoelectric modules can be applied in two different ways for basin water heating or glass cover cooling purposes. Rahbar and Esfahani [46] designed a new desalination unit, applying thermoelectric modules, a heat pipe, and a fan in its structure. Employing the fan, the temperature difference between the thermoelectric module and the inclined wall of still was created. The airstream produced by the fan cooled the heat pipe and thermoelectric. The thermoelectric module also served to cool down the glass cover, thereby increasing the freshwater. They investigated the effect of wind velocity, ambient temperature, and solar radiation on the performance of the still through several experiments. The annual yield of their designed solar still was 180 L/m^2. The cost of one litter of water was \$/0.18 L/m^2.

Proceeding the previous work, Rahbar et al. [47] studied a portable solar still with three thermoelectric modules and three fans installed on it. Thermoelectric modules were cooled via airflow using three fans outside the still (Fig. 10). The desalination rate was 0.5 L when the solar intensity was 25,500 J/m^2. A 3.2% increase was observed in water output because of using thermoelectric.

In another study, Rahbar et al. [48] conducted an exergy analysis for a solar still with thermoelectric heating modules. A Plexiglas sheet was employed to build the basin. In their design, four thermoelectric modules were installed to preheat the water and four fans to circulate airflow for cooling thermoelectric modules. They evaluated the energy and exergy efficiencies. Exergy efficiency was enhanced by time and the highest exergy rate was 25%. Cost analysis showed that the cost of one liter of the produced water was \$0.1422 L/m^2 in their design.

4.5. Using a fan

The forced convection flow is applied to cool the desalination plant when a fan is used. In these methods, photovoltaic modules can be employed to supply the required power. Air flow rate is a highly influential parameter in the water production of solar stills and should be considered within a reasonable range. The result of utilizing a fan on the quantity of yield in solar still was reviewed by Al-Garni [49]. Several experiments were carried out to check the temperature of different parts of the still and output of the system in different fan speeds. It was concluded that a slight decline in the temperature of the glass and water was caused when the airflow speed changed from 7 to 9 m/s via a fan. The still yield decreased by 4%–8%.

Fig. 9. Solar still with a heat sink integrated with a solar collector and a condenser and fan with an air-cooling flow [45] (Reprinted with permission from Elsevier).

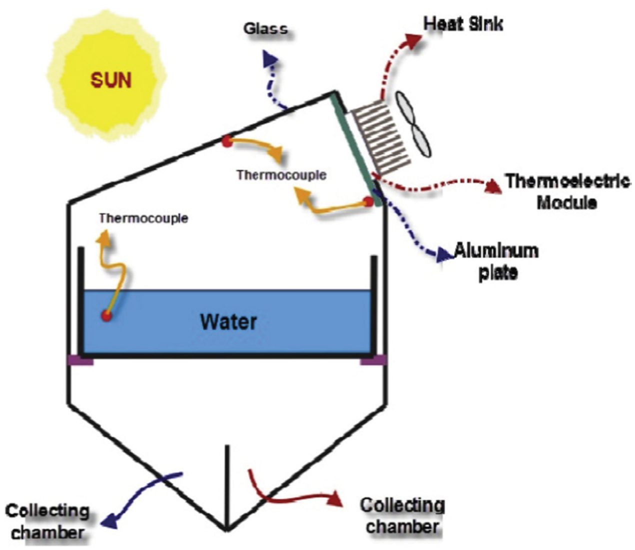

Fig. 10. Experimental view of the solar still [47] (Reprinted with permission from Elsevier).

To examine the forced convection effect on the pyramid-shaped solar still efficiency, Taamneh and Taamneh [50] installed a fan functioning through photovoltaic solar panels on the glass in order to create airflow in the still (Fig. 11). The fan caused turbulence in the air containing water vapor above the saline water, removing it from its surface. As the water vapor was removed faster from the water surface, the evaporation rate increased by 25%.

Suneesh et al. [51] studied a v-shaped solar still. They evaluated the yield of the solar still via airflow on the glass. With cotton gauze cover and airflow, the yield rate reached 4.6 L/m^{2}d. Two fans were implemented and the velocity of airflow was 4.5 m/s. Cost analysis was also conducted in their research; for the system with airflow, the cost of water production was $0.028 kg. Fig. 12 exhibits the system.

The air motion effect in the still was experimentally investigated by Ali [52]. Therein, three types of experiments were performed with the following methods: first, with a non-insulated air channel with a fan, secondly, with an air channel with a fan, and thirdly, as a conventional solar still. The output was 55.6% higher than the third one while we had a fan and non-insulated air channel. The air circulation created by the fan reduced the surface tension of the water and increased the vaporization.

Fig. 11. Photo of pyramid solar distiller unit [50] (Reprinted with permission from Elsevier).

The influence of forced convection in a solar still via a mathematical model under a computer program was examined by Ali [53]. He first modelled a simple solar still theoretically and then investigated the airflow effect in his model. Accordingly, air circulation augmented the yield through the heat and mass transfer coefficients. There was a 30% enhancement in the output through the air-vapor mixture motion.

4.6. Using a solar chimney to create air circulation

In the method using a solar chimney, the air flow inside the basin causes water vapor to escape from the solar still to the plenum chamber. It then flows into the copper pipes cooled by water and condenses. In this method, when the temperature difference in the solar chimney decreases, the Buoyancy pressure difference and the density rate also decrease. Refalo et al. [54] investigated the integration of a solar chimney and a solar still (Fig. 13). They compared the yield and temperature of different parts in simple and chimney distillation systems. The chimney effect increased the vaporization by the airflow. The studied solar still employed the solar chimney that was a passive airflow generator. A solar chimney able to create air circulation enhanced the heat transfer, and as a result, the vaporization. The efficiency was enhanced by 8.8% and the water output was 5.1 L/m^{2}d.

5. Employing airflow in multi-effect active solar stills

5.1. Using air flow in wick type solar stills

In wick type solar stills, the wick is applied to amend the vaporization rate. There are several types of wick desalination units with different mechanisms, within some of which the airflow has been used for the betterment of the system. Mink et al. [55] studied a wick type solar still and utilized airflow. In their system, the brackish water first came to the lower channel through a spiral conduit and floated into the wick on a channel. The ambient air, after entering the upper channel and being warmed by the sun, absorbed and saturated the vapor and then entered the lower channel and was condensed into a spiral conduit. Finally, the produced water entered the water tank. The water in the spiral tube was preheated by the latent heat of air condensation on the spiral conduit. Applying this system, there will be a three-fold raise in

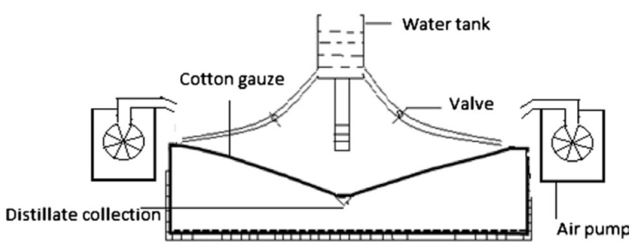

Fig. 12. View of the "V" type solar still with two fans [51] (Reprinted with permission from Elsevier).

the vaporization rate. The required electric energy for the system was evaluated. They investigated the relationship between airflow rate and input water. They extracted a diagram for the output water and airflow rate in the system and found that with airflow increment until 2 m^3/h, the yield increased to 1.1 L/m^2h and then it was decreased.

Tanaka [56] investigated a wick type still with vertical and tilted parts linked to each other (Fig. 14). The vertical multi-effect still had a thin air gap among its parts. The air gaps in both stills, saturated with moisture, were connected. Thus, water vapor was transferred between the vertical and tilted parts. In this work, the vapor was taken away from the wicks by airflow and condensed on the glass of both stills. Thus, the yield increased. Energy balance equations were extracted. The output freshwater was 19.2 kg/m^2 d.

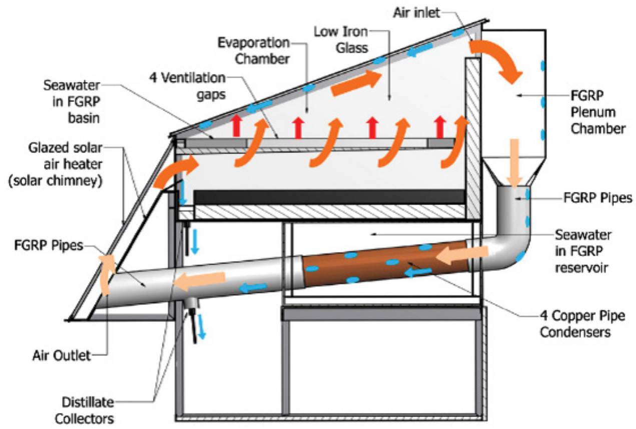

Fig. 13. Schematic diagram of solar distiller with solar chimney and condenser [54] (Reprinted with permission from Elsevier).

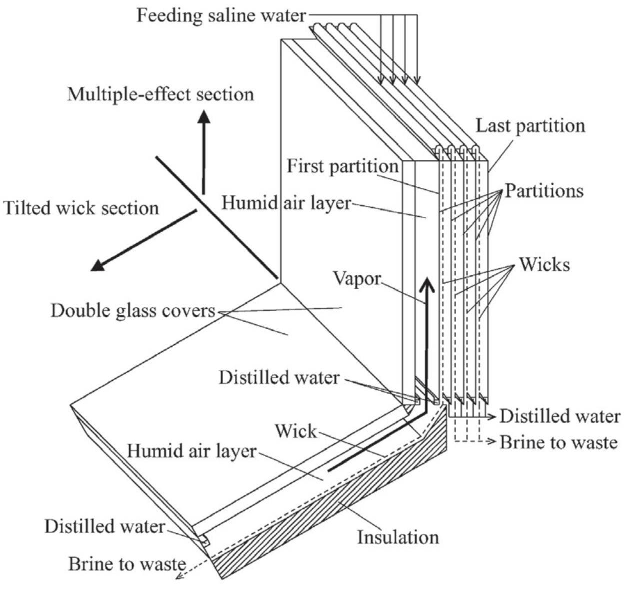

Fig. 14. Schematic diagram of the wicked and multi-effect stills that were connected to each other [56] (Reprinted with permission from Elsevier).

Yeh and Chen [57] extracted energy balance equations for a wick type solar still with airflow through the second stage (Fig. 15). According to their study, the efficiency could increase by removing the vapor with airflow from the still. The produced water was respectively 0.071 and 0.027 kg/m^2 h for the first and second effects of the still, when the solar radiation was 180 $kcal/m^2$ h.

Kaushal et al. [58], revealed the differences between a common type and a wick type solar still equipped with heat recovery system. Accordingly, the water content was high because of heat transmission through humid air. The high temperatures of float wick surface and airflow increased the heat flux through multi-effect solar still. They studied the temperature of the different parts of the still, efficiency, and output of the distillation system. This system achieved 21% of enhancement in water output.

Briefly, in wick type solar stills, the ambient air enters the still and passes through the wicks and becomes hot and saturated. After passing through the solar still, it loses its heat and its water vapor condenses. This type of still can be utilized vertically and horizontally or as a combination of both. It should be noted that the cost of these stills is lower owing to their simple structure and that they are not combined with other devices, such as solar collectors.

5.2. Applying cool air flow for cooling the glass cover

The stimulating factor for desalination technology is the temperature difference among evaporating and condensing zones [59,60]. Researchers have investigated various designs to reach this aim. In several papers, airflow was applied to cool the glass. In the case of using cool air flow for cooling the glass cover, air is applied to cool the glass cover. In this method, an air blower is used to flow the air into the chamber in contact with the glass cover and thus cool the glass. The water performance for cooling is better than that of air on account of the high specific heat of water relative to air.

Arunkumar et al. [61] investigated tubular solar still with airflow over its cover (Fig. 16). Solar radiation was reflected via a concentrator and then absorbed with an

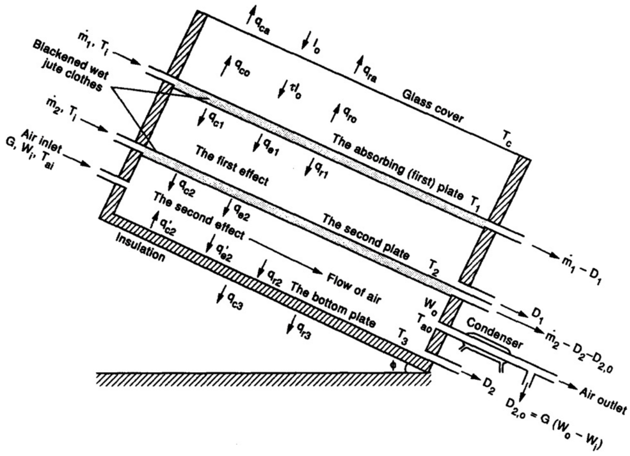

Fig. 15. A wick-type solar distiller with air flow via the unit [57] (Reprinted with permission from Elsevier).

absorber. An air blower was utilized to blow the air inside the tube around the cover at a constant rate of 4.5 m/s. Primarily, the experiments were performed without cooling fluid flow. Afterwards, tests were conducted to study the operation improvement with airflow (at 4.5 m/s) as a cooling fluid. With cooling airflow, the production increased by 49% and reached 3.05. They compared the results concerning the freshwater production rate when the air and water were selected as the cooling flow. They concluded that the performance of water was better than that of air owing to the higher specific heat capacity of water.

5.3. Multi-effect solar still with air flow through the last effect

If the vapor in the still is directly evacuated by the airflow, there is a great rise in the desalination yield. The energy balance for the upward-type and double-effect solar distiller with airflow through the second-effect unit was obtained by Yeh and Chen [63]. The airflow, created via a fan through the second effect of still, extracted the water vapor from it. Water, produced from the first effect unit, was collected in a trough. The water vapor was removed through airflow from the second effect and was collected in a condenser as extra freshwater. The energy balance equations were extracted for the still. The yield was more than the downward-type unit. They proposed two factors for determination of how much the water vapor was saturated.

In another research, Yeh and Ho [63] reviewed a multi-effect desalination unit. The air was flown in the last effect; thus, the vapor was removed and condensed rapidly in the condenser. A great improvement was created in the rate of freshwater production by removing steam from the last-effect unit by airflow. They found about the energy balance equations for the system and compared the theoretical and experimental results. Water output was 0.363 kcal/m^{2}h on irradiation of 547 kcal/m^2 h.

Fig. 16. Pictorial view of tubular solar still [62] (Reprinted with permission from Elsevier).

5.4. Effect of wind velocity on the performance of solar stills

Numerous parameters affect the distillation yield in solar stills, including wind speed [64–66]. Castillo-Téllez et al. [67] studied the air velocity role on the output yield, temperature distribution, and efficiency in a solar still. To analyze the role of air speed, a wind tunnel with transparent plastic material was made on the glass cover, according to Fig. 17. Different ranges of air speed created in the wind tunnel were produced via three fans. The still was examined at various air velocities. The system had a good performance in the air velocities up to 5.5 m/s and then there was a downward trend. The best speed range for air was found to be 3.5 m/s. The efficiency of the still was 58% in this range of the airflow velocity.

Nafey et al. [68] developed a general equation for the distillation rate in a solar still. In their formula, wind speed is an important factor in water production.

$$P_d = -1.39 + 0.894H_d + 0.033t_a - 0.017V - 0.008\theta - 1.2\left(\frac{\delta}{l}\right) \tag{6}$$

where P_d is the wind speed and V is the water productivity.

Mahian and Kianifar [69] checked the wind velocity on a pyramidal shape solar still. They discovered that with the increase in wind velocity up to 10 m/s the desalination yield rose rapidly. Since the enhancement in the wind velocity created a superior temperature difference among the water and the glass, the rate of vaporization increased. At wind speeds above 10 m/s, the water temperature decreased leading to less production. The yield was 3.5 L/d when the wind speed was 5 m/s. They prepared a mathematical model for the system and compared the theoretical and experimental results. They investigated the effect of Reynolds number and thickness of the insulation in addition to wind velocity.

Al-Hinai [70] indicated that wind speed is a more important factor than air temperature in surface distillation.

Fig. 17. A double-glass desalination unit with wind tunnel [67] (Reprinted with permission from Elsevier).

Raising the wind velocity from 1 to 3 m/s results in an 8% increase in freshwater output. The enhancement in the wind velocity can reduce glass temperature, and finally results in more output. Several researchers have studied the effect of wind speed on the desalination performance. Their results have revealed that wind speed is a very important parameter in the performance of solar stills. At higher speeds, the rate of water production is reduced due to the decrease in basin water temperature and at lower speeds, the production will still be low due to the high glass temperature. Therefore, wind speed should be in a proportional range to increase production. Table 1 represents the comparison between water production rates in different types of solar stills.

In Table 1, different solar stills are classified according to the classification mentioned in Fig. 1. The results obtained from Table 1 are as follows:

- Among the solar stills in the first category (heating the basin water with solar air collector), the highest water production belonged to a single-effect solar still integrated with a double-pass solar air collector, which was about 9.36 L/m^2 d in Tanta, Egypt;
- The maximum amount of the production in the second category (air bubbling) was related to a single-slope solar still, which was about 6.137 L/m^2 d in La Paz, BCS, Mexico;
- For the third category (simultaneous use of fan and condenser), the highest production was observed in a solar still with forced air cooling and a production of about 9.11 L/m^2 d in Sohag, Egypt was the most efficient still;
- In the fourth category (simultaneous use of fan and thermoelectric), a double-slope solar still in Semnan, Iran, whose production was about 3 L/m^2 d, had the most production;
- For the solar stills in the fifth category (using a fan), the highest water production was related to a single-effect single-basin solar still in Tehran, Iran, which was about 5.2 L/m^2 d;
- In the sixth category (using airflow in wick type solar stills), the highest production belonged to a multi-effect solar still in Patiala, India with a 5.9-L/m^2 d production rate;
- For the effect of wind velocity on the performance of solar stills (category 7), the production of a single-slope solar still in Suez Gulf, Egypt, which was about 6.5 L/m^2 d, was the highest amount of water yield.

Since the intensity of solar radiation is one of the most important factors affecting the performance of solar stills, the range of solar radiation for each case is presented in Table 1. As can be seen, in most cases, the minimum solar radiation is 5 W/m^2 while the maximum one is 1,000 W/m^2. In addition, other factors, such as ambient air temperature, humidity of airflow, and the season of testing (summer or winter), affect the performance of the system. Owing to the high intensity of sunlight and less humidity in the hot seasons, the system will have a better efficiency. Faster evaporation does not occur on sunny days just because of more heat, but because the sunny days are drier and the relative humidity is lower, the evaporation rate will be higher.

By comparing the amount of water production between all the items compared in Table 1, it can be seen that a single-effect solar still integrated with a double-pass solar air heater had the highest water production, in Tanta, Egypt, which was 9.36 L/m^2 d; it is classified in the first category in Fig. 1.

It could be observed that the water production rate is directly concerned with temperature difference between hot and cold sides of solar stills. It means that with the increase in the temperature difference between water and glass, the yield will be enhanced. Therefore, by choosing different methods, such as applying hot air flow to heat the basin water and cooling the glass cover simultaneously, the enhancement in the water production could be seen.

Accordingly, it was observed that the use of air flow to improve the performance of solar stills is very effective and increases water production in these systems. Moreover, the use of airflow to promote the solar still in rural areas of developing countries, where solar energy is free and abundant, is efficient. Since, in some areas, it is required to use hot air for solar dryers and building heating, a system that can produce drinking water and hot air for dryers and space heating simultaneously is of great value.

It is worth noting that PCM is also used in this type of solar stills so that the system could have night production; this factor plays a great role in increasing the water production. The material of the basin is also very effective in the water production rate. The higher heat transfer coefficient of the plate is used as the absorber in the still; the more heat enters the water in the basin, the better will be the performance of the system. As mentioned previously, in this type of still, the absorber material is copper metal, which is also effective in boosting its performance. The other still with a high production rate, which was coupled with a parabolic trough solar collector and heat sink condenser with forced air cooling, in Sohag, Egypt, was 9.11 L/m^2 d; it was classified in the third category in Fig. 1. It could be observed that radiation changes in the range of 200–1,000 W/m^2 and the experiments were performed in summer. In this system, owing to the use of solar collector, the basin water temperature increased and on account of the forced convection of

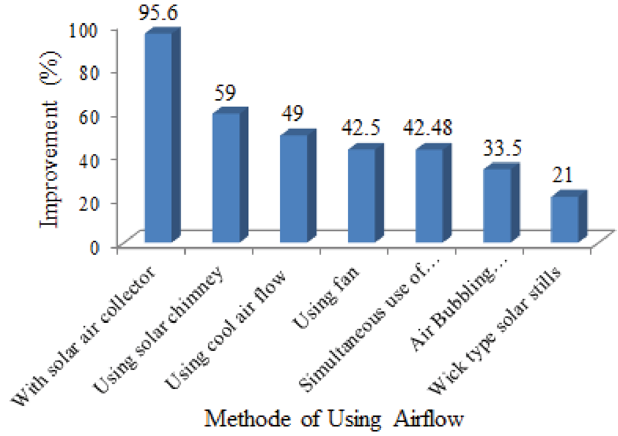

Fig. 18. The percentage of improvement applying different methods using airflow in solar stills.

Table 1
Comparison of yield for different types of solar stills

Author	References	Location	Type of solar still	Categorization	Description	Average yield ($L/m^2/d$)	Range of solar intensity (W/m^2)
Azari et al.	[34]	Zanjan, Iran	Single slope active solar still	Heating the basin water with solar air collector	A double passes solar air collector integrated with modified solar still	2.46	200–1,000
Kabeel et al.	[12]	Tanta, Egypt	Single effect active solar still	Heating the basin water with solar air collector	A double passes solar air collector coupled with modified solar still, with (PCM)	9.36	200–1,050
Abdullah	[13]	Tanta, Egypt	Single effect, stepped, active solar still	Heating the basin water with solar air collector	Stepped solar still coupled with a solar air-heater	6.3	50–1,000
Ladouy and Khabbazi	[15]	Morroco	Single effect, triangular, active solar still	Heating the basin water with solar air collector	Using impulse heating method to increase the air temperature in a triangular solar still	4.44	***
El-Zahaby et al.	[16]	Tanta, Egypt	Single effect, stepped, active solar still	Heating the basin water with solar air collector	Step-wise solar still coupled with a spray water system and two air heaters	6.6	50–800
Eltawil and Omara	[26]	Kafrelsheikh, Egypt	Single effect, single slope, basin type solar still	Heating the basin water with solar air collector	Hybrid of solar still with condenser and air collectors	5	50–1,000
Pandey	[29]	New Delhi, India	Single effect, Single slope, basin solar still	Air bubbling technique	Simultaneous bubbling of dry ambient air in the basin water and glass cover cooling	1.981	***
Porta-Gándara et al.	[37]	La Paz, BCS, Mexico	Single slope basin type solar still by perturbing the water surface of the still	Air bubbling technique	Perturbation by the injection of air bubbles into the basin	6.137	830–920
Bhardwaj et al.	[38]	Netherlands	Single effect, inflatable plastic solar still with passive condenser	Simultaneous use of fan and condenser	Effect of placing an external fan, internal fan and evaporation cooling on distillation rate	2.13	***

(Continued)

Table 1 Continued

Author	References	Location	Type of solar still	Categorization	Description	Average yield ($L/m^2/d$)	Range of solar intensity (W/m^2)
Kumar et al.	[39]	Tamil Nadu, India	Single effect, single basin single slope solar still	Simultaneous use of fan and condenser	A shaft coupled with a dc motor and exhaust fan used for agitating of water and extracting vapor to external condenser	2.667	5–800
Rahim	[41]	Bahrain	Single effect, horizontal solar desalination still	Simultaneous use of fan and condenser	Basin type solar still with an external condenser and a fan	2.5	***
Kabeel et al.	[43]	Kafrelsheikh,Egypt	Single effect, single basin solar still	Simultaneous use of fan and condenser	Circulation of air in the still and the absence of non-condensing gases	8.5	200–900
El-Samadony et al.	[44]	Kafrelsheikh,Egypt	Single effect, stepped solar still	Simultaneous use of fan and condenser	Stepped solar still with internal and external reflectors and an external condenser and fan	5.5	5–1,000
Hassan et al.	[45]	Sohag, Egypt	Solar still coupled with a parabolic trough solar collector and heat sink condenser with forced air cooling	Simultaneous use of fan and condenser	Solar still with a heat sink and integrated the still with a solar collector and a condenser and fan with air cooling flow	9.11	200–1,000
Rahbar and Esfahani	[46]	Semnan, Iran	Portable thermoelectric solar still	Simultaneous use of fan and thermoelectric	Thermoelectric module, a heat pipe and a fan was used to improve the temperature difference	0.3	50–600
Rahbar et al.	[47]	Semnan, Iran	Single effect, portable asymmetrical solar still	Simultaneous use of fan and thermoelectric	Portable solar still composed with three thermoelectric modules and three fans	3	250–1,000
Rahbar et al.	[48]	Semnan, Iran	Single effect, double slope solar still	Simultaneous use of fan and thermoelectric	Double slope solar still equipped by thermoelectric heating modules and fans	1.8	5–1,000
Al-Garni	[49]	Dhahran, Saudi Arabia	Single effect, double slope solar still	Using fan	Using an external fan in a double slope solar still	2.03	***
Taamneh and Taamneh	[50]	Tafila, Saudi Arabia	Single effect, pyramid-shaped solar still	Using fan	A pyramid shaped solar still with a fan that works	3.14	200–1,000
Suneesh et al.	[51]	Tamil Nadu, India	Single effect, "V" type solar still	Using fan	A v-shaped solar still, that there was a cotton gauze cover on top of it with two fans	4.6	200–1,000

(Continued)

Table 1 Continued

Author	References	Location	Type of solar still	Categorization	Description	Average yield ($L/m^2/d$)	Range of solar intensity (W/m^2)
Ali	[53]	Tehran, Iran	Single effect, single basin solar still	Using fan	Three types of experiments were done with a non-insulated air channel with a fan, second, with an insulated air channel with a fan third, as a conventional solar still	5.2	***
Refalo et al.	[54]	Malta	Single effect	Using solar chimney to create air circulation	Chimney effect was used to produce airflow	5.1	***
Mink et al.	[55]	Bangkok, Thailand	Multiple effect active solar still	Usage air flow in wick type solar stills	Air flow, has flown through a blower on the second effect	1.6	***
Tanaka	[56]	Japan	Vertical multiple-effect diffusion solar still	Usage air flow in wick type solar stills	Combination of vertical multiple-effect diffusion solar still and tilted wick still in which the air flow was used to increase the efficiency	3.88	0–900
Kaushal et al.	[58]	Patiala, India	Multiple effect active solar still	Usage air flow in wick type solar stills	A floating wick basin type vertical multiple effect diffusion solar still with waste heat recovery	5.9	50–900
Arunkumar et al.	[61]	Coimbatore, India	Tubular solar water desalting system	Using cool air flow for cooling the glass cover	Innovative design of tubular solar still with a rectangular basin	1.5	100–1,000
Castillo-Téllez et al.	[67]	Temixco, Morelos State, Mexico	Double slope solar still	Effect of wind velocity on the performance of solar still	Placing a transparent wind tunnel on the solar still external cover	3.04	100–800
Nafey et al.	[68]	Suez Gulf, Egypt	Single slope solar still	Effect of wind velocity on the performance of solar still	A general equation to predict the daily production of single slop solar still was developed	6.5	0–1,000
Mahian and Kianifar	[69]	Mashhad, Iran	Single basin pyramidal shaped solar still	Effect of wind velocity on the performance of solar still	Effect of wind speed on a single basin pyramidal shaped solar still was studied	5.5	***
Al-Hinai	[70]	Sultanate, Oman	Basin type solar still	Effect of wind velocity on the performance of solar still	A mathematical model proposed to predict the productivity of a simple solar still and the wind velocity is researched	4.15	***

Table 2
The percentage of improvement of water production for different types of solar stills over conventional ones

Author	References	Categorization	Improvement over the conventional one (%)
Azari et al.	[34]	Heating the basin water with solar air collector	170
Kabeel et al.	[12]	Heating the basin water with solar air collector	109
Abdullah	[13]	Heating the basin water with solar air collector	85
Ladouy and Khabbazi	[15]	Heating the basin water with solar air collector	19
Eltawil and Omara	[26]	Heating the basin water with solar air collector	60
Pandey	[29]	Air bubbling technique	33.5
Bhardwaj et al.	[38]	Simultaneous use of fan and condenser	25
Kumar et al.	[39]	Simultaneous use of fan and condenser	39.49
Rahim	[41]	Simultaneous use of fan and condenser	53.2
Kabeel et al.	[43]	Simultaneous use of fan and condenser	53.22
El-Samadony et al.	[44]	Simultaneous use of fan and condenser	66
Hassan et al.	[45]	Simultaneous use of fan and condenser	18
Al-Garni	[49]	Using fan	8
Taamneh and Taamneh	[50]	Using fan	25
Suneesh et al.	[51]	Using fan	39
Ali	[53]	Using fan	60
Refalo et al.	[54]	Using solar chimney to create air circulation	59
Kaushal et al.	[58]	Using air flow in wick type solar stills	21
Arunkumar et al.	[61]	Using cool air flow for cooling the glass cover	49
Mahian and Kianifar	[69]	Effect of wind velocity on the performance of solar still	56

airflow by the fan, the temperature difference between the glass and the water augmented; thus, the still will have a better performance.

The single effect, single basin solar still in Kafrelsheikh, Egypt, which is 8.5 L/m^2 d, is also a high-performance still. In this system, the range of solar radiation is 200–900 W/m^2 and the basin is made of galvanized iron, and a fan along with a condenser are used simultaneously to increase the efficiency of the system. The increase in water production rate was 53.2% compared to that in the conventional one.

The amount of water production in active solar stills with airflow in their structures is compared with conventional ones in Table 2, which shows the importance of using air flow in the structure of solar stills. It is obvious that the water production rate in active types is more than that in passive ones. Moreover, for each type of solar stills classified according to Fig. 1, the average percentage of improvement in water production rate is represented in Fig. 18. As can be seen, for the method of heating the basin water with solar air collector, the rate of water production increased by an average of 95.6% compared to that in the conventional type. The lowest percentage belongs to the method using airflow in wick type stills, which is 21%.

As mentioned above, the amount of the water produced in solar stills with airflow in their structure is higher than that in conventional ones; nevertheless, there are certain disadvantages employing these systems, which must be considered. For example, to operate the fan installed in the inlet of the air heater, it is necessary to provide energy for the fan, which will reduce the efficiency of the system and increase the costs. Furthermore, in cases where PV panels were used to supply electricity, the cost of the system increased; thus, economic analysis of the system should be performed and its cost-effectiveness should be verified.

Based on the literature cited in the manuscript, in some cases, the length of the collector used to heat the air is too long, which is why they cannot be used everywhere.

In some cases, controlling the speed of motor is required to adjust the wind speed and airflow rate blown into the solar still. In these cases, skilled expert supply is required. However, it is highly challenging in rural areas.

If the amount of airflow used is not adjusted properly, the glass cover may become hotter instead of being cooled, or the basin water may become colder and water production may decrease. Accordingly, it is necessary to choose the best type of system. Additionally, the prevailing conditions must be taken into account.

6. Future scope

This paper demonstrated that the effect of airflow on desalination efficiency is of particular importance. Therefore, the followings could be suggested for future research in this regard:

- Due to the fact that the amount of the water produced in active solar stills is more than that in passive types, a more detailed study about the effect of airflow on active solar stills should be conducted with further focus.
- Investigating the effect of the speed and temperature of airflow and also mass flow rate of air used for cooling the glass cover could be recommended.

- Surveys could be conducted on the effect of various flow rates of hot air entering the basin by changing the dimensions and number of the holes on the absorber plate to create air bubbles.
- Study on the effect of airflow on solar stills with nanofluids seems to be necessary.
- Employing airflow between the glass covers of a double-glazing solar still for cooling the glass cover should be investigated.

7. Conclusions

Based on the above discussions on the review about airflow effect on solar stills performance, the following results were obtained:

- To enhance the output of desalination, a great temperature difference among the evaporation and distillation surfaces is necessary;
- By using air collectors, the water output will be higher in solar stills;
- The result of simultaneous bubbling of dry ambient air in the water and glass cooling is the great yield in solar stills;
- If water vapor drains out of the basin via the flow of air, the output will be further;
- Increasing the mass transfer coefficient based on forced convection has a main effect on increasing the yield;
- By using both fan and condenser, the air flow and vapor condensation will increase;
- The highest exergy rate in a solar still with a fan and thermoelectric heating modules was 25%;
- As the vapor is removed faster with a fan from the water surface, the vaporization will be better;
- Because of air stream in the basin created with the fan, the surface tension of the water diminishes and the vaporization will increase;
- By removing the water vapor by airflow from the last-effect unit in wick type solar stills, the freshwater production would be enhanced;
- Because of the high temperature of wick surface and air flow in wick type solar stills, the heat flux through the still will be better;
- The solar still with a solar chimney raises the water output more than that in usual type stills because of the chimney effect producing airflow and evacuating vapor from the still;
- At a speed of about 5.5 m/s, the operation of solar stills will be better. Afterwards, it decreases at higher levels;
- Wind speed should be in a suitable range to increase the water production.

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