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تحلية مياه البحر بالطاقة الشمسية: الأسباب الحقيقية لانخفاض إنتاجيتها

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الخلاصة

تعتبر التقنيات الحالية في تحلية المياه غالية الثمن بسبب احتياجها لقدر كبير من الطاقة الكهربية أو الحرارية من البترول. ولهذا فإن تحلية مياه البحر باستخدام الطاقة الشمسية تعتبر حلا قليل التكلفة لأزمة الطلب المتزايد على المياه. باستخدام التقنيات المتاحة حاليا فإن إنتاج المياه عن طريق السخانات الشمسية solar still لا تستخدم على المستوى الصناعي لأنها تعطي كميات قليلة من المياه العذبة، مقارنة بكمية المياه المنتجة عن طريق الغليان بالوقود أو التحلية بالأغشية. وتعتبر كمية الإنتاج القليلة للسخانات الشمسية هي السبب الرئيسي في عدم إمكانية استخدام السخانات الشمسية على المستوى الصناعي. ويعود هذا إلى حقيقة أن درجة الحرارة القصوى التي يمكن الوصول لها داخل السخان الشمسي قليلة، وبالتالي يكون معدل التبخر داخل السخان الشمسي قليلا. وتعتبر درجة الحرارة المنخفضة هي السبب الرئيسي في هذا العيب الخطير. وتؤدي درجة الحرارة المنخفضة إلى انخفاض انتقال الحرارة ومن ثم انخفاض معدل التبخر. الدراسة المقدمة هنا تحلل الأسباب التي تؤدي لانخفاض درجة الحرارة داخل السخان الشمسي، وتقترح بعض التعديلات لحل تلك المشكلة. تم ذلك عن طريق تقسيم السخان الشمسي إلى أربع أجزاء، وتحليل كل جزء بدقة على حدة لحل المشكلة الأساسية، ومن ثم إعطاء أقصى درجة حرارة ممكنة وأعلى معدل لانتقال درجات الحرارة داخل السخان الشمسي. بحل هذه المشكلة يمكن استخدام السخانات الشمسية في تحلية المياه على المستوى الصناعي.

Solar still; unrevealed facts and reasons causing its low productivity

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ABSTRACT

The current techniques for water desalination are relatively costly because of the high consumption of electrical power or fossil fuel. Desalination of seawater using solar energy is therefore, one of the ways to meet the growing water demand at low cost. With the technologies currently available, solar still fresh water production is not applied on large scales, mainly because the production rate of desalted water is very low, when compared with techniques using fossil fuels or membranes. The low production rate has been the main reason behind the lack of industrial usage of solar stills. As the maximum temperature, which can be reached within the solar still is not very high, the evaporation rate inside the solar still remains low. This low temperature is the main reason for such a massive disadvantage, resulting in a reduced heat transfer rate and slow vaporization process. The work reported herein aims at analyzing the reason(s) for solar still low productivity and suggesting design modifications to solve such a problem. This is done by dividing the solar still evaporation into four processes; then every process is thoroughly analyzed to solve the main problem, and provide the maximum temperature and heat transfer rate inside the solar still. With this problem solved, the use of solar stills in industry can become a possibility.

Keywords: Desalination; seawater distillation; solar still.

INTRODUCTION

Water shortage crises might lead to other crucial issues affecting health and resulting in environmental problems. Water is the most basic needed commodity on earth for human and other living species. Being an abundantly available natural resource, water covers almost three fourth of the earth's surface with less than one percent of fresh water source being actually within human reach (Shiklomanov,1998). Ever since seawater desalination was introduced as one of the ways to overcome water scarcity, humans continue to desalinate seawater. Using the latest technologies integrated to it, water desalination has become very important in today's world especially in arid areas such asthe Sahara, the Middle East and many more (Trieb & Müller-Steinhagen, 2008). Numerous seawater desalination plants have been developed over the last two decades. However, such desalination plants use the two most common technologies in desalination, i.e., thermal distillation and membrane separation (Howe, 1974; Buros *et al*., 1980; Bruggen, 2003) to increase the supply of desalted and potable water.

The prices of fossil fuel continue to be unstable becausethe sources of fossil fuel keep declining (Shafiee & Torpal, 2009). This, in addition to economic parameters such as inflation cause both the capital and operating costs of desalination plants using current technologies to become more costly. Use of renewable energy in desalination plants is expected to solve this fresh water production problem without causing any depletion of fossil fuels, hydrocarbon pollution and environmental degradation (Bhattacharyya, 2013). Solar energy has the greatest potential of all the sources of renewable energy as it is the most recommended alternative (Shiklomanov, 1997); this is because it is the most economic source of thermal energy. Despite being inexhaustible and universally available, the use of solar energy is however more economical than the use of fossil fuels especially in arid areas where fresh water is scarce, and other sources of energy are not available. Most areas facing water scarcity problems have minimal rain, which means almost continuous exposure to the sun for most of the year. Solar energy can be used either directly as thermal or can be converted to electrical energy by photo-voltaic (PV) conversion or via photo voltaic cells. Thus, solar distillation is classified into two categories known as passive and active solar distillation, as presented in Figure 1 (Shankar & Kumar, 2012).

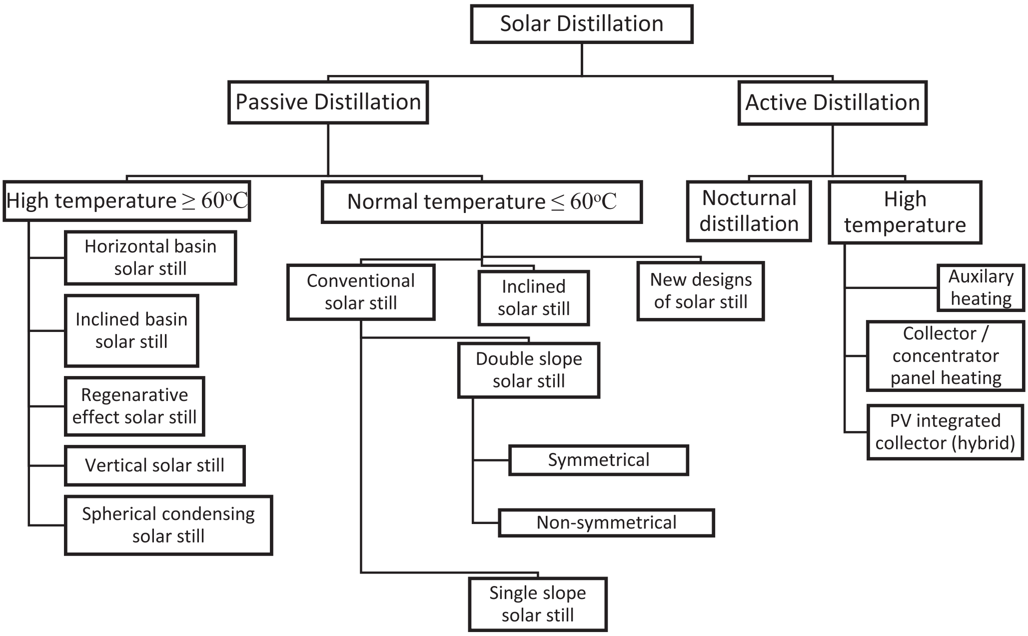

Fig.1. Two categories of the solar still (Shankar & Kumar, 2012).

Solar distillation, also known as the solar still, is a method that employs solar energy source to distill fresh water at a much lower production rate.Because of its low production, usually around 1 kg/m^2.hr (Al-Kharabsheh & Goswami, 2003), many improvements have been taken into consideration in order to enhance its efficiency. As per the authors' knowledge, highest value of efficiency is 50% (Al-Hamadani & Shukla, 2013). The efficiency value is calculated using the following equation (El-Bahi & Inan, 1999),

$$\eta(\%) = \frac{Q_e}{H_0} \qquad (1)$$

where (MJ/m^2/d) is the energy required to evaporate the specific daily yield and (MJ/m^2/d) is the measured total solar radiation fall upon the still surface of the evaporator. Modifications to the solar stills, which may include additional basin levels (also known as multiple effect solar still), condensers, solar collectors, reflectors, sun-tracking devices, and other modifications often show some increment in term of the still efficiency. However, none of these improvements was ever proven to be applicable in large-scale industrial desalination processes.

The objective of this research is to analyse the reason of the low fresh water productivity within solar stills. To do this analysis, the conventional solar still is separated into four processes, each process is analysed separately. As per the current knowledge available for the authors of this communication, this point was never discussed earlier. Finding out the reason of minimal fresh water production of the solar stills is an important step, as it is required in order to scale up solar stills to industrial levels, and using them in solving the water shortage crises in many places where fresh water is not easily accessible.

The solar still

A solar still operates similar to the natural hydrological cycle of evaporation and condensation. Normally, seawater is exposed to solar radiation, vaporizes and then condenses on the inclined glass or any transparent cover and collected in reservoir as desalted water (Tiwari *et al.*, 2003). Basically, solar stills are simple and have no moving parts and they can be used almost anywhere whereas the operation is straightforward and no special skill is required for its operation and maintenance (Tiwari *et al.*, 2003). Solar stills can range from simple setups made from common materials to more sophisticated apparatuses (Gnanadason *et al.*, 2012).

Despite being the simplest method, the solar still faces a major problem, its low productivitywhich is usually around 1 kg/m^2.hr (Al-Kharabsheh & Goswami, 2003). Several factors affecting the productivity of the solar still are solar intensity, wind velocity, ambient temperature, water-glass temperature difference, free surface area of water, absorber plate area, glass angle, the depth of water, and the temperature of inlet water (Velmurugan & Srithar, 2011; Tiwari *et al.,* 2003, Badran & Abu-Khader, 2007). However, parts of these factors are uncontrollable as they are meteorological parameters; those include solar intensity, wind velocity, ambient temperature and water-glass temperature difference, whereas the remaining parameters can be varied to enhance the productivity of the solar stills (Tarawneh, 2007; Phadatare & Verma, 2007; Nijmeh *et al*., 2005 and Kumar *et al*., 2008). In order to clarify the ideal needs of a solar still in a more comprehensive way, despite all the factors that affect the solar still, one can broadly group the relevant improvements required at respective areas as in Figure 2 a into four parts and label as P1, P2, P3 and P4 for process 1, 2, 3 and 4, respectively.

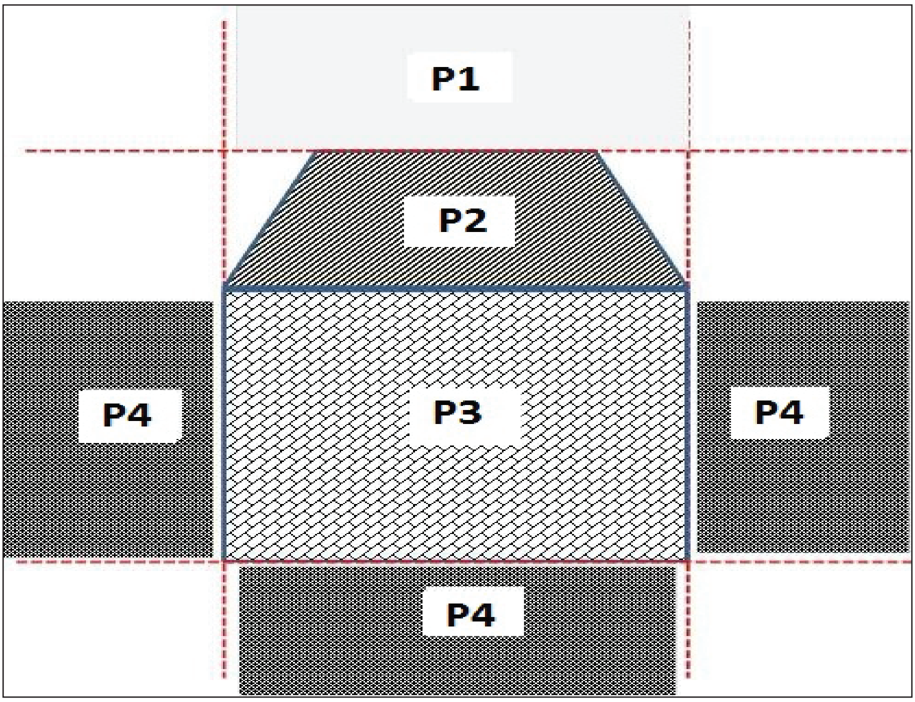

Fig.2. The distribution of the different processes inside and outside (with the surrounding) of the solar still

P1: Solar irradiation: from the sun to thesolar still unit

Process 1 (P1) is the part, where the flow of the heat energy in the form of solar radiation, takes place. In order for a solar still to operate at the highest possible efficiency, heat transfer by radiation should be at its maximum possible value, as radiation is the main heat source to vaporize the water (Murugavel & Srithar, 2011). Solar radiation, as mentioned earlier, is one of the renewable energy sources used in desalination and it is the main source for the desalination process discussed herein, within the solar still.

Although the earth’s atmosphere is largely transparent to the incoming solar radiation, not all of the sun’s energy that reaches the earth atmosphere makes it to the surface. Approximately, only 51% of the solar radiation is actually absorbed by earth’s surface, whereas 16% and 3% is absorbed by the ozone layer (stratospheric ozone and tropospheric water vapor and aerosols) and the clouds, respectively. The remaining 30% is eitherbackscattered by the air or reflected by both clouds and earth’s surface (Twidell & Weir, 2006; Iqbal, 1983) as illustrated in Figure 3 (Peixoto & Oort, 1992).

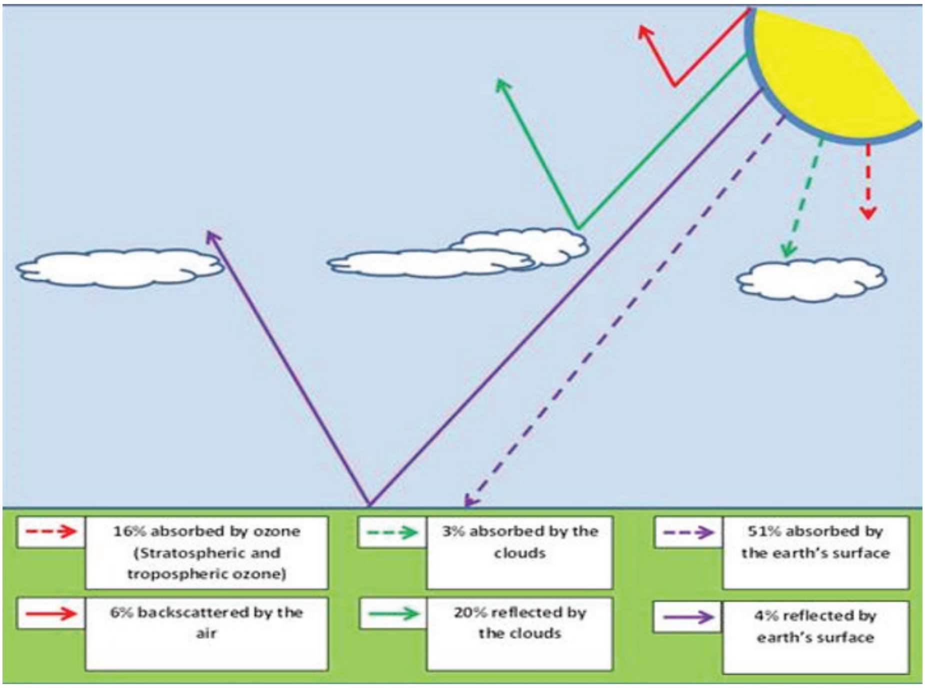

Fig.3. Tabulation of solar radiation (Peixoto & Oort, 1992)

Energy radiated from the sun consists of two components; namely, (i) one that comes directly from the sun known as direct solar radiation, and (ii) another that originates from the dispersion of direct solar radiation in the atmosphere, which is known as diffuse solar radiation (Paulescu *et al.*, 2013) . Since a fair proportion of solar radiation diffuses through different constituents in the atmosphere, the surface temperature of the earth is affected. Basically, the heat source for the solar still would be the total solar radiation received by the unit itself. The tendency of improving this part not only depends on additional equipment that will be introduced to the unit, but also it relies on the material and shape of the receiving surface. Many studies have addressed the variation of the shape of the solar still top cover; namely, the hemispherical shape, pyramid shape, parabolic shape, and a spherical shape, including the most common shape, single and double slope, where they are frequently discussed and investigated experimentally (Kabeel, 2008; Akash *et al*., 2000; Gad *et al*. 2011) due to their simplicity. Comparing results of different studies, changing the shape has no significant impact on evaporation rate. Difference in roof design allows different amounts of solar radiation received by the unit. Double slope solar still (DSS) is found to have better efficiency than single slope solar still (SSS) during summer time (Tiwari & Yadav, 1987). However, in colder weather the single slope solar still was found to have a higher efficiency (Tiwari & Yadav, 1987). A similar conclusion was reached (Madhlopa *et al.*, 2011), where it was foundthat the single slope solar still has better performance compared to the double slope solar slope. This is because of the back wall effect in single solar still that reflected most of solar radiation to the base of the still. In the same paper, the importance of the transmittance parameter in choosing the material of the still roof was also highlighted.

In spite of the shape, integration of additional devices to the unit was studied by many researchers. The most common device is the solar collector, as the name implies, collects heat by absorbing sunlight in the form of solar radiation, then releases the heat to the water after sunset, allowing continuous operation of the solar still (Rajesh & Bharath, 2009). Conventional solar still, also known as passive solar still, did not have any solar collector to store the solar energy, because it is the method that applies heat from the solar energy directly onto the seawater. Obviously, this could not preserve a continuous process of desalting seawater. To the contrary, an active solar still is a conventional solar still that is assisted by a thermal solar collector. The study (Rajesh & Bharath, 2009])shows that coupling the collector with a single basin still, increases the productivity by about 40-45% for bore-well water, seawater, and river water. This is strongly supported by another research (Rajaseenivasan *et al*., 2014), where it was concluded that, although the cost of setting up the solar still with solar collector is economically higher, yet throughout the year, with 60% enhanced production rate of the solar still with collector, compared to the conventional type, the total economic analysis shows that the cost of desalination by solar still with collector is lower than that for conventional solar still (Rajaseenivasan *et al*., 2014).

Apart from that, the upturn in solar still efficiency is also found in a solar concentrator. A solar concentrator is basically a device that concentrates the sunlight from a larger area to a smaller focus point, as the magnifying glass functions. Usually, a solar concentrator is used (Arunkumar *et al*., 2013) as an enhancer for the solar radiation received by the solar collector. The method of concentrating the sunlight is actually based on using either magnifying glasses or concave mirrors (Arunkumar *et al*., 2013). This is highly preferable to be applied in the solar still unit, as most lens do not cost much and they even increase the total amount of energy received; more than twice the actual amount received without it.

Many researchers studied the application of solar concentrator to the solar collector.It was found that in order for a solar concentrator to be preciselypositioned in the same direction of the sun rays, a solar tracker is needed (Bakos, 2006). A solar tracker is a sensing device that works by tracking the motion of the sun and gains a feedback that indicates the actual position of the sun in order to determine the solar collector focus position. Coupling a solar tracker with the lens or the mirror guarantees higher efficiency in heating the liquid water inside the solar still.

A solar tracker is needed, as it has higher accuracy in tracking the motion of the sun. It was found that a solar still coupled with a solar tracker has on average 22% increase in efficiency over the fixed solar still (Lee *et al.,* 2009). Therefore, the integrated devices (solar collector and solar tracker together) could concentrate the sun light more efficiently. A conventional fixed system might losesome of the sun light as the sun rays pass through. Thus, in order for a solar collector to operate with high efficacy, it can be clinched with a solar tracker. Alternatively, the solar concentrator focus can be tracked, and the motion path of the highest radiation spot can be determined. If the focus path is determined, it can completely eliminate the usage of the solar tracker, replacing it with something which is simpler, cheaper, and easier to deal with, especially in underdeveloped areas. The only disadvantage of this system is that it will be much localized, as the highest radiation spot path will change significantly by changing the latitude of the geographical location where the process takes place.

P2: The point solar radiation is received by the solar still – the seawater

The main objective of Process 2 (P2) is to allow heat to transfer from the point solar radiation reaching the surface of the unit, i.e., the glass wall of the solar still, to the seawater.The maximum possible amount of heat received by the unit should be transferred to the seawater inside. The main problem here, as known from the basics of heat transfer, is for this amount of heat to be transferred to the water. Therefore, there should be enough temperature difference between the water and the air within the solar still. However, with the currently available solar still technologies, the maximum temperature reached within the solar still is below the boiling point of water, which results in very low evaporation rates within solar stills.

Theoretically, the low temperature within the solar still results because the convective heat transfer occurs between the water surface and inclined transparent surface, which is normally of the glazing type. The heat transfer due to convection from the water surface to the glazing surface can be written as follows (Phadatare & Verma, 2007):

$$q_c = h_c(T_w - T_g) \tag{2}$$

Where q_c is the heat transfer coefficient for convection, $T_w$is the surface water temperature, T_g is the glazing surface temperature and h_c is the convective heat transfer calculated as follows (Phadatare & Verma, 2007):

$$h_{cw} = 0.884\left[\left(T_w - T_g\right) + \frac{\left(P_w - P_g\right)\left(T_w + 273\right)}{268.9\times10^3 - P_w}\right]^{\frac{1}{3}} \tag{3}$$

whereP_w is the saturation pressure at the basin water temperature, and Pg is the vapor pressure at the glazing surface temperature. Meanwhile, evaporative heat transfer is given as (Phadatare & Verma, 2007):

$$q_{ew} = h_{ew}(T_w - T_g) \tag{3}$$

where is calculated as follows (Phadatare & Verma, 2007):

$$h_{ew} = 16.273 \times 10^{-3} h_{cw}(P_w - P_g)/(T_w - T_g) \tag{4}$$

A sample calculation is given in the Appendix to the present communication.

Several techniques can be considered to improve the evaporation rate, such as preheating the seawater or adding a boiler to the unit. In case of preheating or adding a boiler, the heat that is transferred to the seawater has to be transferred throughout the whole seawater body (Abad *et al.*, 2013). This is different from the conventional solar still, where heat is transferred mostly only onto the surface of the seawater where evaporation takes place, thus significantly slowing down the vaporization process (Suneja & Tiwari, 1999).

In the case of conventional solar still, failure of heat distribution throughout the seawater causestemperature non-uniformity for each layer of the seawater (if not every molecule).Eventually, this will cause the point with highest temperature inside the seawater to be circulated until it reaches equilibrium with the surrounding temperature (Phadatare & Verma, 2007),so the average temperature of the seawater cannot be high enough for the water to vaporize at a high rate. This may be attributed to the depth of the seawater level, as concluded by (Phadatare & Verma, 2007). They reported that the lower the depth of seawater in the solar still, the higher the production rate, because the lower the depthof the seawater that needs to be heated up.

Preheating the seawater is the simplest solution for such an issue that could be thought of. This method is usually performed before the seawater enters the solar still. Technically, preheating is done to increase the temperature of the required raw material, in this case, seawater, so that the seawater that enter the solar still is at higher temperature and is ready to vaporize (Khalifa *et al.*, 1999). However, few documented resultsare available for similar techniques. Nevertheless, this method leads to higher operational cost for the solar still as preheating itself requires massive amounts of energy.In case of industrial scale operations, this will logically increase the operating cost of the process, which reduces or even nullify the main advantage of the solar still. Increasing the operating costs is also found to be the main drawback for the use of the boiler in the solar still (Abad *et al.*, 2013).

In order to clarify this problem with a numerical example, calculation details are provided in the appendix.Calculations done throughout this research work have shown that, in order to vaporize an amount of 10 kg of seawater within 10 hours, in a basin whose surface area is 1m^2, the glass temperature of the solar still should be relatively high, around 60^{o}C for 10 hours continuously. This requires the air temperature around the solar still to be higher than 60 ^{o}C for the whole distillation period.With this relatively high temperature requirement, it is easy to see why no solar still has ever produced desalted water at the rates produced by other processes. One of the flaws here is that raising the temperature inside the conventional solar still is carried out gradually and slowly. This obviously raises the legitimate question:How to reach this high temperature using only sun rays? More importantly, assume that a temperature higher than 100^{o}C can be reached inside the solar still; the whole body of the solar still should be made of materials which can tolerate such a high temperature.

How can the vaporization rate be increased without using external heating techniques? The most logical solution is to distribute the heat within the water body, driving the heat to the lower levels within the seawater basin. If done correctly, this should increase the rate of heating and consequently the rate of vaporization of the water within the solar still.

Seeing the low production problem as a result of the low temperature outside and inside the solar still is the most important conclusion for this publication. Experiments done throughout the course of this work helped to increase the water temperature and consequently the vaporization rate inside the solar still, using some simple techniques, which shall be topic for next publication. More importantly, increasing the temperature inside the solar still using only solar energy can move the solar still for the first time from small-scale production, to industrial scale production, making it a competitor for other techniques requiring either fossil fuel or electrical energy.

P3: The evaporation process

Process 3 (P3) is where the water vaporizes; physically it can be considered to take place at the water/air contact area.

Desalination rate increases significantly through distillation, as in the case of the solar distillation, boiling process is actually the main process that can give higher desalted water production rates than the evaporation process as it occurswithin a conventional solar still. Logically, the volume of the desalted water produced from the solar still would be small compared to other techniques using boiling, e.g., multi-stage flash distillation (MSF), which is why it is not a wise decision for industrial scale production (Qiblawey & Banat, 2008).

The main process in the conventional solar still is the evaporation. Evaporation is the process by which water changes from a liquid to a gas or vapor (Perlman, 2014b). A simple comparison between evaporation and boiling is written here. Evaporation is a process that balances the earth water cycle, and latent heat is necessary energy for evaporation to occur as it breaks the hydrogen bonds that hold water molecules together, so that water starts to boil. In evaporation, not all particles in the liquid are moving at the same speed. Unlike boiling, normally, evaporation will occur layer by layer starting from the surface and it usually consumes the internal energy of the liquid. Therefore, evaporation results in cooling, unless external heat is provided to the process. On the other hand, no cooling is observed during boiling. The faster molecules are likely to surpass the forces pulling them to the neighboring molecules, and as the particles at the surface of the liquid are only held in place by forces from the neighboring molecules besides and beneath them, they are easier to break away from the bulk. However, it takes more energy for the particles in the middle of the liquid as they have forces holding them on all sides making bond-breakage more energy consuming for such molecules.

Evaporation happens under almost any conditions, even at room temperature and atmospheric pressure. A body of water is made of a large number of water molecules, all going at different speeds. As the temperature increases, the average speeds of the molecules increase and more molecules have the required energy to fly off the surface (Perlman, 2014a). Consequently, the evaporation rate increases with temperature. Because the molecules have more kinetic energyat higher temperatures, more of them are likely to move faster and are able to escape from the bulk. Consequently, evaporation occurs more quickly at higher temperature (Perlman, 2014a). Since vapor molecules move faster in the gas phase, thus as the water vapor increases, more frequent collisions with the liquid surface occur, and the condensation rate increase. Eventually, the condensation rate will become equal to the evaporation rate, thus reaching equilibrium, where the water is evaporating and condensing at the same rate, and the amount of vapor in the empty space can no longer increase or decrease.

Thermodynamically, when a system is not in equilibrium, the system does not stop changing until it reaches equilibrium (Tosun, 2012). Thermodynamic equilibrium role can be shown in the case, where there is a low concentration of molecules in the vapor phase, and high concentration in the liquid phase, the movement of molecules from high concentration to low concentration will occur, seeking equilibrium. This is when evaporation takes place. In a liquid, the particles are moving quickly. Obviously, vaporization only occurs with the molecules at the surface of the substance. At the surface, some of the particles are able to escape into the air, while others do not have enough energy to escape and remain in the liquid phase.

At a glance, both evaporation and boiling might appear to be the same, because both represent a transition from the liquid phase to the gas phase. However, there are some important differences that help in making the distinction. Boiling happens only when the motion of molecules is fast enough to overcome the van der Waals' forces that hold them together, and it occurs uniformly all over the boiling liquid and it happens only when the temperature surrounding is above the boiling point of that substance (Geankoplis, 2003). Evaporation, on the other hand, occurs only at the surface of the liquid and might possibly occur at any temperature (most likely below the boiling point).In order to break the bond between two molecules, one molecule has to be moving fast enough to overcome the pull of the other, until it is far enough, as it can be concluded that the greater the space between the molecules becomes, the weaker the force is between them, which causes the bond (hydrogen bond in case of water) to diminish. This explains why boiling is a faster process than evaporation.

Apart from that, the surface area of the water is also one of the factors affecting the evaporation process in the solar still. It is expected that only a limited increase in yield is possible by increasing the evaporation area for a given amount of solar radiation reported (Kwatra,1996) through his simulation, where he simulated a solar still with enlarged evaporation area and as a result, an increase in the amount of the yield of 19.6% when the evaporation area was quadrupled. Later, in 2008, through another experiment (Kabeel, 2008), a concave weir was brought to the solar still with four glass cover surfaces in order to increase the amount of solar radiation falling on the evaporative surface and it is reported that the result has shown that the system's efficiency of that particular solar still is higher than the conventional type solar still.

The evaporation rate of the water in the solar still is directly proportional to the exposure area of the water. Thus the productivity of the solar still increases with the free surface area of the water in the basin. In a separate case study, in order to increase the surface area, sponges were used to increase the free surface area of the water in a solar still (Abu-Hijleh & Rababa'h, 2003). Sponges have capillaries throughout the whole body, which is why water is easily absorbed by the sponges, thus increasing the surface area over which water evaporation occurs. The same conclusion was made by other authors (Velmurugan *et al.*, 2008), which is that the productivity of the solar still increases, when the sponges are used in a single basin solar still and stepped solar still.

In contrast to that, the main reason of introducing the multiple effect solar still is to recover vapor latent heat, which then leads to the enhancement of both distillate productivity and thermal efficiency (Fernández & Chargoy, 1990; Schwarzer *et al.*, 2009; Adhikari *et al.*, 2000; Shatat & Mahkamov, 2010; Kalbasi & Esfahani, 2010; Xiong *et al.*, 2013; Abu-Jabal *et al.*, 2001) as understood from the multiple effect evaporator. Most of the researchers (Huang *et al.*, 2014; Schwarzer *et al.,*2001; Rajaseenivasana *et al.*, 2013) conclude that the technology of multiple effect solar improves the solar still water production, as it was found that fresh water production increases with increasing the number of stages. In multiple effect solar still, despite the number of effects, the gap between the effects is also important, as it determines whether the heat transfer could wisely occur or otherwise. The disadvantage of having additional basin effects to the solar still is that higher setup and upkeep expenses are required, compared to the conventional unit (Schwarzer *et al.,* 2001; Al-Karaghouli *et al.,* 2009).

Identically, with condenser, hybridization or integration of solar still is usually more complicated than other techniques. A typical passive solar still usually does not come with a condenser. Thus basically, the rate of desalination process depends on the rate of evaporation alone. Additionally, for vapor to remain inside the evaporator compartment within the solar still, it will reduce solar radiation to the basin and increase the partial pressure of vapor, impeding the evaporation of seawater. However, adding a condenser to the solar still can increase the rate of the desalination process, due to increment in the evaporation and condensation rates.

A passive solar still with a separate condenser in which the double slope solar still is divided was investigated (Madhlopa & Johnstone, 2009). Experiments included both evaporation and condensation processes, taking place at evaporator chamber and condenser chamber. Throughout the study, it was found that the vapor productivity was 62% higher than that of a conventional still. This is confirmed by other experiments (El-Bahi & Inan, 1999; Abu Hijleh, 1996; Rahim, 1995), where it was concluded that coupling the solar still with an outside condenser could increase the solar still productivity efficiency.Results show that with a properly designed condensation process of passing cooling water over the glass cover could increase the efficiency. On the other hand, a poor choice of the parameters would result in a reduction in still efficiency, which may be caused by the reduction in thermal energy reaching the glass roof because of the cooling water.

Additionally, when a solar still is integrated with a passive condenser, a fraction of the vapor will be purged into the condenser, which will then minimize the pressure inside the evaporator and the formation of vapor droplets on the inner glass surface. Consequently, the reflection and absorption of the solar radiation are decreased, hence more solar energy is transmitted to the water and the glass temperature is also reduced thus resulting in an overall improvement of the evaporation rate. Therefore, it is preferred to equip a conventional solar still with a condenser, in order to speed up the desalination rate, simultaneously allowing the seawater to vaporize at a lower temperature. Furthermore, from a thermodynamic perspective, seawater can be evaporated at lower pressure.By all means, the thermal efficiency of the still is vastly increasedinthe presence of a vacuum condenser comparedwith that in a conventional still.

Generally, when researchers look into enhancing the solar still, they are actually thinking of how to increase the heat transmitted to the unit so that more vaporization can occur. One point iscommonly overlooked:Is it possible for a solar still to vaporize the seawater at lower temperatures by manipulating other thermodynamic properties inside? Yes indeed, theoretically employing the low power vacuum pump solution (Kabeel & El-Agouz, 2011).

P4: Storing the heat

Process 4 (P4) is where the thermal energy can be stored, when there is lack of solar energy, i.e., during night time and cloudy periods. The main energy source of the solar still, as discussed earlier, is the solar energy which comes from the sun.This source is not available before sunrise or after sunset. Moreover, solar energy is intermittent in nature, and its intensity is dependent on the hour of the day and local weather conditions. Some methods have been introduced in order to have continuous access to thermal energy originally coming from the sun, even at night time or cloudy periods, one method is to incorporate heat storage system (Tabrizi & Sharak, 2010) where they integrated a basin solar still with a heat reservoir filled up with sand which gave positive results. Other technique employed to store the heat, using phase changing material (PCM), studied earlier.A considerable amount of heat stored within PCM during sunshine hours is enough to produce fresh water during night time (Naim & El Kawi, 2003), even thin layers of basin water leads to enhancement of still productivity especially during night period (Ramasamy & Sivaraman, 2013).

Basically, without heat storage (regardless active or passive), a solar still would not be able to operate due to absence of solar radiation. Heat storage prolongs the working time overnight, which will increase the total productivity. Generally, through a conventional solar still, the amount of seawater which can be vaporized at night depends on the depth of seawater as the heat is stored in the seawater body during daytime and release at night.

When it was first introduced, the solar still consisted only of simple materials.Back then it was mainly composed of a transparent surface, usually glass, as a cover, and a basin which could be from concrete or timber, the roof and the basin are the main body of the solar still. In case of keeping, or preserving, the heat stored, the choice of material has to be wisely done, as theoretically, material would assist in the heat storage process, especially for nocturnal use. Due to the extensive growth of research that has been done in materials of construction of solar stills, many types of new material have been introduced to the solar still to ensure the highest productivity rate possible.

Constructing a solar still can be divided into two major parts, i.e., roof and body. The criteria of choosing the material for the roof are that it must be transparent enough to be able to transmit the thermal components of the solar radiation to the seawater. This can be achieved with a roof surface that has low reflection. Many researchers (Kabeel & El-Agouz, 2011; Ghoneyem & Ileri, 1997; Murugavel *et al*., 2008) agree that glass is more suitable than plastic. However plastic is much cheaper. Meanwhile for the solar still body, despite being watertight it is preferable to use water resistant material as it will contain seawater, which is a corrosive substance. There are many successful experiments in earlier years (Srivastava *et al.*, 2014; Sengar *et al*., 2012), which proved certain suitable materials according to their advantageous properties, can be used for this unit such as fiber reinforced polymer (FRP) and galvanized iron (GI). Yet, none of all these findings conclude that their designs are comparative to fossils fuel based desalination unit. Basically, the bigger the scale of the plant, the more convinced material are required to be applied, thus, the cost will not simply be ignored. Therefore, if a standard low cost passive solar still are to be applied in the larger scale (which might happen only if the simple material as in the small scale is used), some other factors need to be entirely studied and modified, so that it is not similar to that small scale design such as operational factors.

CONCLUSIONS

The world can be considered nearly at its critical position in facing fresh water drought issues. The desalination industries involving membranes and thermal integrated systems succeeded in providing fresh water. However, such fresh water is obtained at high capital and maintenance costs. The shortage of fossil fuelsmay increase the costs of producing such fresh waters. Consequently, methods involving the use of alternative energy sources for producing fresh water become very attractive. Using a solar still appears to be a very viable method. Although its productivity is relatively low, certain improvements of the solar still have shown its success in increasing its efficiency which makes, it economically attractive.

The research work on improving desalination using the solar still is an ongoing process. Continuous new improvements arebeing introduced to the unit.However,the solar still has never been considered for industrial applications as the other currently used techniques. In order to use the unit in industry, it must be convincingly capable of vaporizing the seawater either at the same rate as current techniques or better. The only way to figure it out is through experiments resulting in high efficiency with low cost. The changes that are to be made to the solar still unit must be at the accurate spot, so that it could enhance the solar still's efficiency and improve the economic outcome of the process.Different studies were carried out in order to identify ways to improve the current solar still techniques. No significant change of the solar still efficiency could be made, except that shown by increasing the basin effect and integrating or hybridizing the solar still. In such a case, the process requires higher maintenance cost and becomes more complicated.

The main reason of the solar still's low productivity is the low temperature of seawater inside, leading to low evaporation rates inside the unit.Therefore, this is the first thing that needs to be improved. The main impact of the low temperature inside the solar still, as shown throughout the present work, is that the temperature is much lower than water boiling point. This results in the low rates of desalination, thus making the solar still a less popular desalination technique. As evaporation is not a fast process, it could not result in higher production rate of fresh water production. Moreover, technically, the only way for enhancing the evaporation rate results from integrating the still with a condenser, solar collector and multi-staging the evaporation process. However, incorporating a solar collector is relatively expensive, considering the cost of manufacturing the panels and that it requires large space for capturing the sun's energy, which will increase the overall cost of the process. In case of multistage evaporation, most of the cost will be that of the maintenance services required frequently as the different stageswill trap more salt and other impurities. In short, all these improvements, might replace the current techniques but at relatively higher cost. For these reasons, more investigation aiming at identifying changes and their expected outcomes needs to be carried out.

APPENDIX

Assume that ΔT=20ºC between water temperature (T_W) and glass temperature (T_g) where both T_W and T_g are assumed to be 60ºC and 40ºC respectively.The saturation pressure at the basin water temperature (P_W) and the vapor pressure at the glazing surface temperature (P_g) can be calculated as,

$$P_w = exp\left[25.31 - \frac{5144}{T_w+273}\right] \text{and} P_g = exp\left[25.31 - \frac{5144}{T_g+273}\right]$$

With value of $P_w = 19197.83\ Pa$ and $P_g = 7154.49\ Pa$

The heat transfer due to convection from the water surface to the glazing surface can be written as,

$$q_c = h_c(T_w - T_g)$$

Where q_c is the heat flux and h_c is the convective heat transfer coefficient calculated with the help of the following equation:

$$h_{cw} = 0.884\left[(T_w - T_g) + \frac{(P_w - P_g)(T_w + 273)}{268.9 \times 10^3 - P_w}\right]^{\frac{1}{3}}$$

Using the calculated pressure and temperature values in the above equations give the value of

$$h_{cw} = \frac{3.24W}{m^2K}$$

eanwhile, the evaporative heat transfer is given by,,

$$q_{ew} = h_{ew}(T_w - T_g)$$

where is calculated as follows:

$$h_{ew} = 16.273 \times 10^{-3} h_{cw}(P_w - P_g)/(T_w - T_g)$$

The values obtained from both equations are as follows: $h_{ew} = 31.75\ W/m^2K$ and $q_{ew} = 634.95\ W/m^2$

Eventually, the final efficiency can be obtained by the following equations:

$$\eta = \frac{q_{ew}}{I\ (t)}$$

With *I*is the total insolation of the sun that can be measured by pyranometer which commonly reads around 900-1100 W/m^2. Taking, the efficiency of a normal solar still is at 63.5%. Additionally, the yield can be calculated by,

$$\dot{m} = \frac{q_{ew}}{L}\ x\ 3600$$

Where L is the latent heat of vaporization of water, which has the value of 2264.76 kJ/kg. Therefore, the yield of a normal solar still is 1.0096kg/m^2/hr.

The foregoingfigure means that, even on a hot sunny day where the glass temperature may reach 60, a solar still with an area of 1 m^2 will produce only 1 kg/hr. A very small value indeed for such a relatively large area. Consequently, technical improvements must be introduced in order to increase that figure.

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