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Desalination of salty water using vacuum spray dryer driven by solar energy

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HIGHLIGHTS

- Theoretical analysis for desalination under reduced pressure aided by solar energy,
- New approach and design for a solar-aided desalination system under reduced pressure,
- New approach and design for solar energy collector using spherical-shaped system,
- Recycled latent heat of evaporation, waste heat from the vacuum pump, heat collected from the solar panels and droplet colour were considered in the theoretical analysis.

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ABSTRACT

This paper addresses evaporation under vacuum condition with the aid from solar energy and the recovered waste heat from the vacuum pump. It is a preliminary attempt to design an innovative solar-based evaporation system under vacuum. The design details, equipment required, theoretical background and work methodology are covered in this article. Theoretically, based on the energy provided by the sun during the day, the production rate of pure water can be around 15 kg/m^2/day. Assumptions were made for the worst case scenario where only 30% of the latent heat of evaporation is recycled and the ability of the dark droplet to absorb sun energy is around 50%. Both the waste heat from the pump and the heat collected from the photovoltaic (PV) panels are proposed to raise the temperature of the inlet water to the system to its boiling point at the selected reduced pressure.

1. Introduction

Water and energy are fundamental necessities for life on Earth and to sustain the modern world. In many parts of the world, the control and exploitation of water and energy has driven economic development. In many other places there are shortages in fresh water and energy supplies. Drinking water of acceptable quality has become a scarce commodity not to mention unevenly distributed geographically worldwide [14,24]. The World Health Organization (WHO) has estimated that lack access to drinking water may be an issue for more than a billion people [15]. The vast majority of these people are from undeveloped countries and/or living in rural areas where there is low population density. In remote locations it is very difficult and costly to install conventional clean water solutions, [25]. In many countries where there are shortages of clean and fresh water, there are many other water resources that have potential to be transformed. Such resources seawater, brackish/saline or contaminated groundwater, and coal seam gas water [26]. These kinds of water require an innovative technique of treatment that uses sustainable and low cost energy to produce clean water.

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Desalination of saline water is known to be one of the most sustainable alternative solutions to provide fresh water. This resource can play a significant role in socioeconomic development in many developing countries such as Africa, Pacific Asia and countries in the Middle East [16] and Latin America. Desalination is a process in which saline water is separated into two parts: one that has a low concentration of dissolved salts (fresh water), and the other which has a much higher concentration of dissolved salts than the original feed water (brine concentrate), [27]. Reverse Osmosis (RO), a conventional desalination technology, produces brine (70–55% of intake flow) depending of feed water quality; the dissolved salt concentration of the brine varies from 50 to 75 g/L resulting in a much higher density than seawater (Hamawand et al., 2013). Desalination of salty water/seawater is expensive, mostly because of the energy required [17]. However, desalination is a growing field around the world where the needs for drinkable water are crucial [2]. All conventional seawater desalination techniques such as RO, thermal distillation such as multi stage flash (MSF), electro-dialysis, or their combinations consume a large amount of energy and they do not recover the salt eventually. These techniques may also cause air pollution due to the large consumption of energy derived from fossil fuels [19,20]. Furthermore, the brine remains from these processes are huge and represent another potential environmental problem [18]. There is a potential for using algae to clean the water after amending it with some chemicals, however this has not been carried out experimentally [11]. Therefore, the utilization of renewable energy can be considered as one of energy sources of seawater desalination [3,5,17].

A complete separation of salt from salty water is something that cannot be achieved by many of the conventional methods. One conventional, most efficient and reliable method for complete separation is evaporation. Evaporation of water at atmospheric pressure requires large amounts of energy to raise the water temperature to the boiling point. In addition, at atmospheric pressure the evaporation rate is slow unless more vigorous heat is supplied. This problem can be overcome by carrying out the evaporation under reduced pressure where water can be evaporated at temperatures below its atmospheric pressure boiling point. Water evaporation under reduced pressure is energy efficient according to the laws of thermodynamics, and can be driven by low-grade thermal energy sources such as solar heat or process waste heat. While the evaporation under reduced pressure will accelerate the evaporation rate, one must be concerned with potential freezing problems [4]. Heat is required for water droplets to evaporate, heat is provided from the surrounding. Without supplemental heat there is a risk that the equipment parts get chilled and the remaining droplets freeze [1]. Carey et al. [21] conducted experiments under contract to NASA related to evaporation of water under vacuum. The set up consisted of 0.6 m^3 environmental vacuum chamber and a 250 mL beaker with 25 mL of liquid water at a temperature of 20 °C. The liquid took approximately 150 min to evaporate under reduced pressure of 0.38 kPa. In this experiment no external heat was provided neither to the liquid or the chamber.

Valuable information on desalination of seawater using solar energy has been reported, however, the desalination of sea water using vacuum spray dryer has not been fully elucidated. This study presents an innovative design for evaporation of water using renewable energy from the sun and recycles the latent heat of evaporation. Also the waste heat from the pumps and collected heat from PV panels that provide the pump with electricity are suggested as another source of energy [7,8].

2. Theory

Water such as concentrated salty water produced from other desalination processes such as RO process, brackish/saline groundwater and/or seawater can be sprayed inside a double walled glass column (evaporation column) exposed to sun light, Fig. 1. The double walled column will retain the heat inside the column and allow a full exposure to sun light. The column will be operated under reduced pressure to lower the water boiling point temperature. The generated vapour will condense on the chilled column (condensation column) attached to the double glassing evaporation column as shown in Fig. 1. This will allow the recovery of the energy (latent heat of evaporation) used to evaporate the water. After evaporating the water, the salt will end up at the bottom of the double walled column as pure dry salt.

A dark water soluble dye will be dissolved in the salty water before being introduced to the system to enhance its absorption of the sun light. Sunlight reflected or absorbed sunlight by an aerosol depends primarily on the composition and colour of the particles dissolved in it. In general, bright-coloured/translucent particles tend to reflect radiation in all directions and darker aerosols can absorb significant amounts of light [12]. Dark blue to black surfaces can absorb solar radiation to an approximate fraction of 0.8 to 0.9 of the incident radiation. A study by Gary et al. [13], showed that dispersed carbon black dust of size <0.1 μm can absorb solar energy as high as 5124.4 J/g/s (2×10^{10} cal Ib^{-1} per 10 h).

The heat required for the evaporation of the water droplets can be supplied/recovered from the following sources and sections in the process (Fig. 1); sun light, double walled insulated glassing effect, black colour effect, heat generated by the vacuum pump, heat collected from the PV panels and latent heat recovered from the generated vapour. The pump can run on solar energy using solar PV cells.

The evaporation process will be carried out under reduced pressure, in other words, this means that there will be a very small amount of air in the column. The water droplet will be released very close to the one of the opposite walls inside the middle column, to be specific it will be released next to the wall which is farther away from the sun light. This will create a smaller laminar sub-layer at that wall and will result in a higher heat transfer coefficient in comparison to the opposite wall. The fast falling of the droplet next to the wall will produce vortices (in the evaporated vapour) and turbulence which lead to reduction of the laminar sub-layer thickness, Fig. 2.

Water evaporates at a specific temperature at a specific pressure, in this design there will be three zones. The first zone is the double wall glassing that faces the sun light, the pressure inside this endclosed column will be above the atmospheric and the temperature is the highest among the whole system because it is facing the sun light. The second zone is the middle column, the pressure is below atmospheric and the temperature is almost as the same as or slightly lower than room temperature (depending on the number of droplets evaporated). The lower temperature is due to proximity of the vacuum pump and droplet evaporation. This zone can also be maintained at higher than the droplet boiling point temperature (under vacuum) if the number of the droplets is maintained in balance with the energy introduced to the system. The last zone is the vapour channel, the evaporated water from the droplets in the middle column now transports to the outside driven by the vacuum pump. The pressure inside this zone is the same as the middle column and the temperature is the lowest among the whole system. Inside this channel condensation may happen because the space available is smaller than the middle column and it is closer to the droplet. The space available inside the middle column is high enough to maintain almost constant temperature. The front side is exposed to sun light while, the other side of the wall where the vapour is transport driven by the vacuum pump has lower space which makes the change in temperature more possible, and furthermore is furthest away from the sun light.

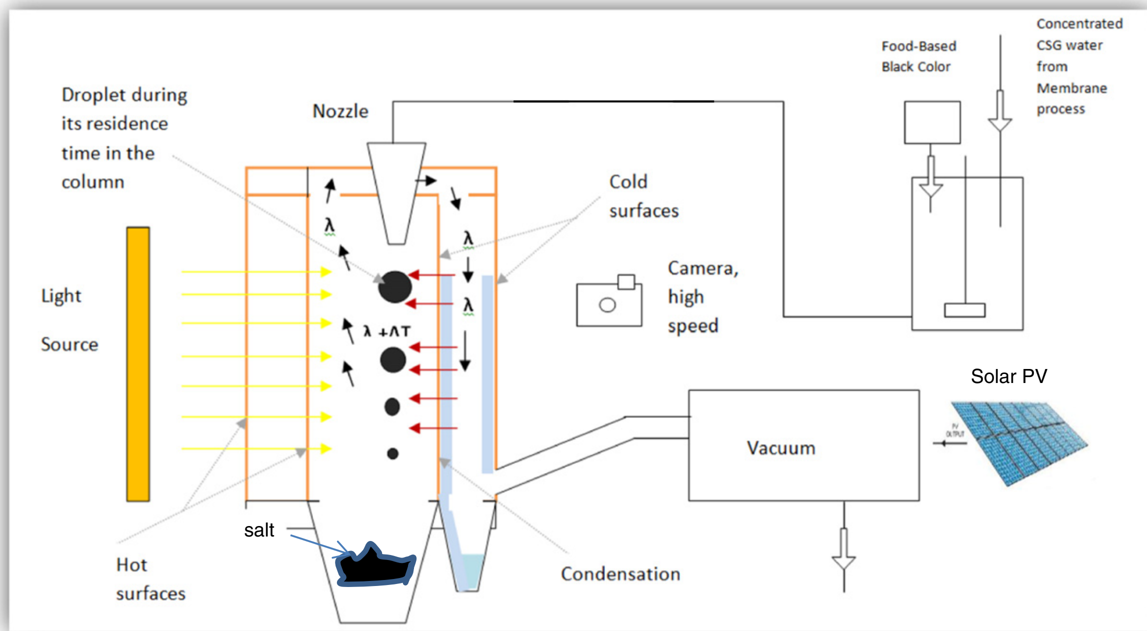

Fig. 1. A schematic diagram of the proposed laboratory setting for the crystallization system under vacuum, double glassing column.

3. Mathematical model

When a free water surface is in contact with pure vapour, the equilibrium rate of molecule transfer from vapour phase to the liquid or from the liquid phase to the vapour is given by kinetic theory of gases. When the system is not at equilibrium, the net rate of evaporation or condensation per unit droplet surface area is governed by modified Hertz-Knudsen equation [10,28], first proposed by Alty 1931 [29]. Maa [29], studied the evaporation rate of different solvents including water. This study by Maa showed that there is little or no resistance of molecules crossing the vapour-liquid interface. This means that the evaporation coefficient is unity and can be represented by the Eq. (1), below, which estimates the rate of evaporation from the water droplet:

$$-\rho_w \cdot \frac{d\bar{r}}{dt} = \sqrt{\frac{M_w}{2 \cdot \pi \cdot R_g}} \cdot \left[\frac{P_{sat(T_d)}}{\sqrt{T_d}} - \frac{P_{med}}{\sqrt{T_{med}}}\right] \tag{1}$$

where,

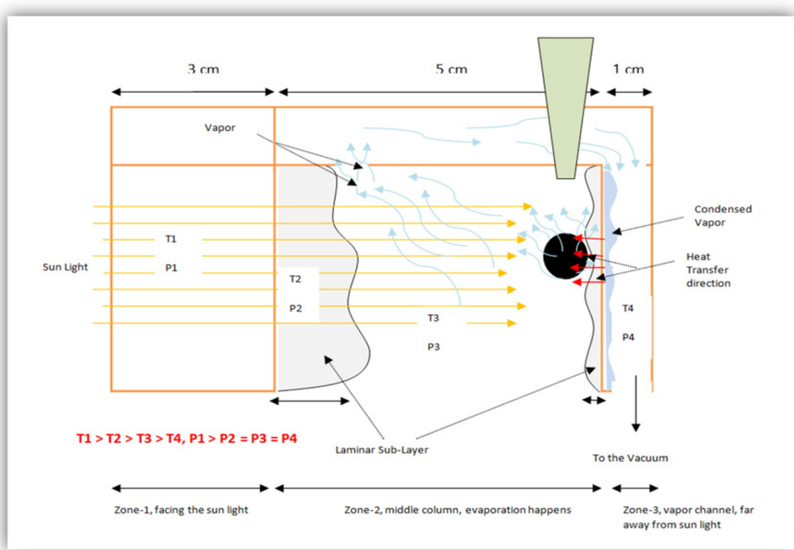

Fig. 2. A schematic diagram of a small portion of the single column spray evaporator, theory explanation.

P_{med} is the operation pressure of the evaporation medium (kPa),
$P_{sat(T_d)}$ is the saturation vapour pressure of water at droplet surface temperature (kPa),
M_w is the molecular weight of water (kg/mol),
R_g is the universal gas constant (J/mol·K),
T_d is the droplet temperature (K),
T_{med} is the evaporation medium temperature (K),
r is the droplet radius (m), and
ρ_w is the water density (kg/m^3).

Eq. (1) presents the rate of evaporation from the water droplet as a function of its radius (dr/dt), if condensation happens then the radius of the droplet will increase otherwise it will decrease. In case the droplet presented at its boiling point temperature, initial condensation, or in other words increase in the droplet radius can be neglected.

The saturation vapour pressure of water at the droplet's surface can be given using Antoine's equation (Eq. (2)) where temperature is in °C and pressure is in kPa;

$$LnP_{sat(T_p)} = 16.387 - 3885.7/(T_d + 230.17) \tag{2}$$

Ln refers to the natural logarithm. Using numerical method, finite difference Euler's method, Eqs. (1) and (2) can be rewritten as Eqs. (3) and (4), respectively;

$$\overline{r}_{(i+1)} = \overline{r}_{(i)} - \frac{\Delta t}{\rho_w}\sqrt{\frac{M_w}{2\cdot\pi\cdot R_g}}\cdot\left[\frac{P_{sat(T_d)}}{\sqrt{T_d}} - \frac{P_{med}}{\sqrt{T_{med}}}\right] \tag{3}$$

where $\overline{r}_{(i+1)}$ represents the radius of the droplet after a very small interval of time (Δt) and $\overline{r}_{(i)}$ represents the initial radius.

$$LnP_{sat(T_d)} = 16.387 - 3885.7/(T_d + 230.17) \tag{4}$$

Eqs. (3) and (4) can be used to predict the time interval required for the entire droplet to evaporate and the rate the droplet evaporates. The rate of evaporation of the droplet is calculated from the change in the radius of the droplet. The radius of the water receding front is an indication for the amount of water evaporated from the droplet's surface.

These equations assume that the droplet is entering the system at the temperature of evaporation (depending on the system's pressure) which means neglecting initial condensation is applicable. By introducing the waste heat from the vacuum pump, recycled latent heat of evaporation and heat collected from the PV panels, it is possible to introduce the droplet to the system at its boiling point to avoid initial condensation phenomenon. The temperature of the droplet will remain constant at its boiling point due to continuous evaporation while provided with sufficient heat. Also, the saturation vapour pressure of the water droplet will be constant based on Eq. (4). Furthermore, the vacuum pump is assumed to be efficient and is able to keep the pressure inside the system constant.

The evaporation will be dominated by the heat transfer from the medium (mostly vapour) to the droplet plus that received directly from the sun via radiation. For simplicity, at steady state conditions, the medium receives energy from the sun which is transferred to the droplet; the temperature of the medium is assumed to be constant and slightly above the droplet temperature due to losing its heat to the droplet via convection. Based on this assumption, the amount of water evaporated is calculated to maintain these conditions in the system.

4. Simple scenario

Assume low vacuum pressure of 6.9 KPa, this means that the droplet needs to enter the system at 38.7 °C to start evaporating instantly (no initial condensation).

The maximum amount of energy received from the sun in ideal circumstances is 1000 W/m^2. Fig. 3 shows the energy received from the sun per square meter on a clear day. The energy varies between 100 and 1000 W/m^2 depending on time of day. The data for the actual energy received which is provided by the sun on a clear day was retrieved from a book by Stine and Geyer [9], Fig. 3.

In this simple case, the recycled latent heat was not included in the calculation which otherwise would enhance the system efficiency. The waste heat from the pump has been assumed to provide heat for the droplet before entering the system to increase its temperature to the boiling point along with piping system connected to the solar PV panel if required. In this scenario, the system (medium, surroundings) the temperature is assumed to be constant at 38.7 + 5 °C (this is a reasonable assumption under clear day and direct contact with the sun light) and the extra temperature (heat) gained from the sun will be

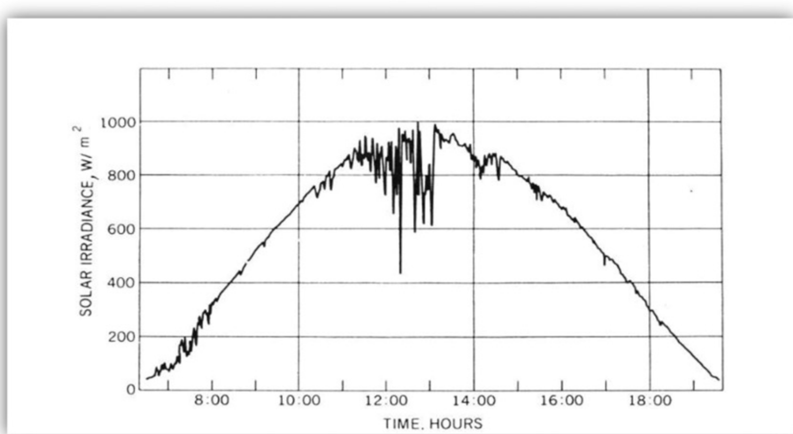

Fig. 3. An example of irradiance for a mostly clear day on a horizontal surface in Greenbelt, MD [30]: global solar radiation for the day was 27.1 MJ/m^2 [9].

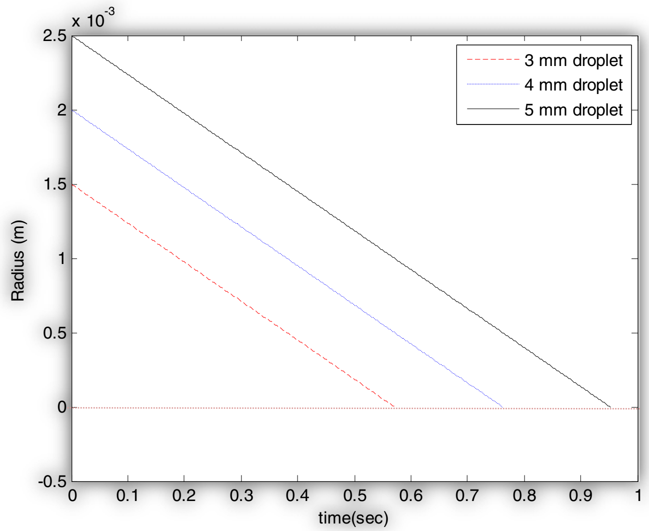

Fig. 4. Time required for evaporating a water droplet (3, 4 and 5 mm diameter) under reduced pressure.

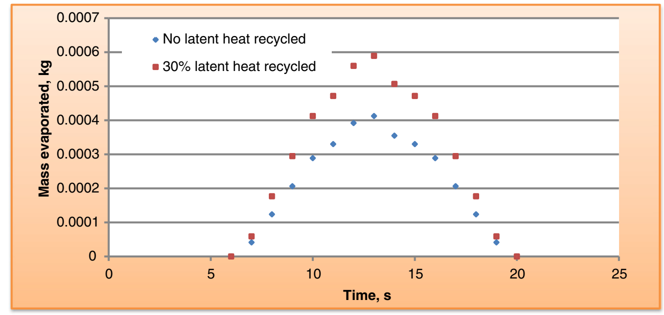

Fig. 5. Mass of water that can be evaporated per second during different times of the day without and with 30% of the latent heat recycled.

used to evaporate the droplets. For a droplet of 3 mm diameter (0.014 g weight), the model shows that it takes approximately 0.6 s to evaporate (Fig. 4) the droplet. Furthermore, the height of the system required to accommodate the 0.6 s time required for evaporation the droplets was estimated. Based on the speed the droplet travels to reach the base of the system, 3 m height column is required.

The results in Fig. 4 show that in order to evaporate one droplet every 0.6 s, it is required to raise the temperature of the input water to 38.7 °C and the temperature of the medium (mostly vapour) where the droplet travel to 38.7 + 5 °C. It is assumed that the initial temperature of the water and the medium is 20 °C. The energy required to raise the temperature of the water to 38.7 °C is; $m \times Cp \times \Delta T = 0.00001413\ \text{kg} \times 4.18\ \text{kJ/kg·K} \times (38.7 - 20)\ \text{K} = 1.104\ \text{J}$. As mentioned previously the calculation is for 1 m^2 area exposed to sun light; in case the depth of the evaporation compartment is 0.3 m then the volume occupied is 0.3 m^3. However, since the system is under vacuum, continuous vapour is produced which also gains energy from the sun and the walls of the compartment which later transfers to the droplet. The specific heat of water vapour at 43.7 °C is 1.871 kJ/kg·K and the density at standard conditions is 0.804 kg/m^3. To raise the temperature of the medium to 38.7 + 5 °C; $m \times Cp \times \Delta T = (0.804 \times 0.3)\ \text{kg} \times 1.871\ \text{kJ/kg·K} \times ((38.7 + 5) - 20)\ \text{K} = 10.7\ \text{J}$ of energy is required. The total amount of energy required to maintain the system at the condition assumed is 11.8 J for evaporating one droplet each 0.6 s. The sun provides an average 579 J/s (27.1 MJ/m^2/-day (13 h)) and the latent heat of evaporation required is 34.25 J (2424 KJ/kg × 0.01413 × 10^{-3} kg) for each droplet each 0.6 s. Also, in 0.6 s, the water droplet mixed with dark colour is able to absorb 43.4 J [5124.4 J/g/s (energy absorbed by 1 g black carbon) × 0.01413 g (droplet mass) × 0.6 s]. This gain of energy confirms the possibility of providing the droplet with enough energy to evaporate even only from the direct irradiation to the droplet. Based on the data above, the mass of water that can be evaporated in this system was calculated.

In this case the droplet obtains 10.7 J from the medium/recycled latent heat/pump waste heat and/or the pipes connected to the solar system. And 23.55 J (53% of the 43.4 J) absorbed directly from the sun; the number of droplets that can be evaporated is around 16.9 droplets (579/34.25) and the amount evaporated in one day (13 h) is 11.2 kg/m^2/day (16.9 × 0.00001413 kg × 13 h × 3600 s). In case 30% of the latent heat of evaporation has been recycled then 24.15 droplets (579/(34.25 × 0.7)) can be evaporated and total amount of 15.9 kg per day is obtained. Fig. 5 shows the distribution of the mass of water that can be evaporated per second during the day from 0600 to 2000. The maximum mass of water that can be evaporated is around 4 g and 6 g which occurs around 0100 (middle of the day) when the maximum energy received from the sun (1000 W/m^2) for both cases, respectively.

In case that the temperature of the inlet water to the system rises above 38.7 °C and/or the temperature of the medium rises above 38.7 + 5 °C then the time required for evaporation will reduce, see Fig. 65. A high temperature condition will not impact the amount of water evaporated because the received energy from the sun per second is the same as the previous case. It is very important then to balance the energy received from the sun (plus the recycled latent heat and waste energy) with the droplet size and the time of evaporation to avoid freezing the system.

5. Methodology, challenges and feasibility

5.1. Methodology

The experimental evaluation will be carried out as following;

- Empty column evaluation: estimate the heat accumulation in a one square meter area system with time.
- The water can be heated to a variety of temperatures prior to spreading in the spray column; this will help to indicate the optimum temperature of the water and at the same time help to evaluate the efficiency of using the waste heat from the vacuum pump.
- The variables that should be considered in regards to the droplet will be: size, colour, residence time, temperature and salt concentration.
- Measure the temperature inside the system at different heights and widths.
- Wall temperatures inside and outside of the system, in addition to the outdoor temperature.
- Measure the moisture content of the solid salt produced.

5.2. Sensors and equipment

The equipment required for building a lab-scale system includes the following;

- Temperature sensors to monitor the temperature of the water inlet, water produced, salt produced and inside the chamber. Also, sensors to monitor the intensity of energy received from the sun.
- Vacuum pumps are able to maintain a constant and consistent reduced pressure up to 99.99% vacuum and high suction rates of up to 1200 m^3/h is possible [22].

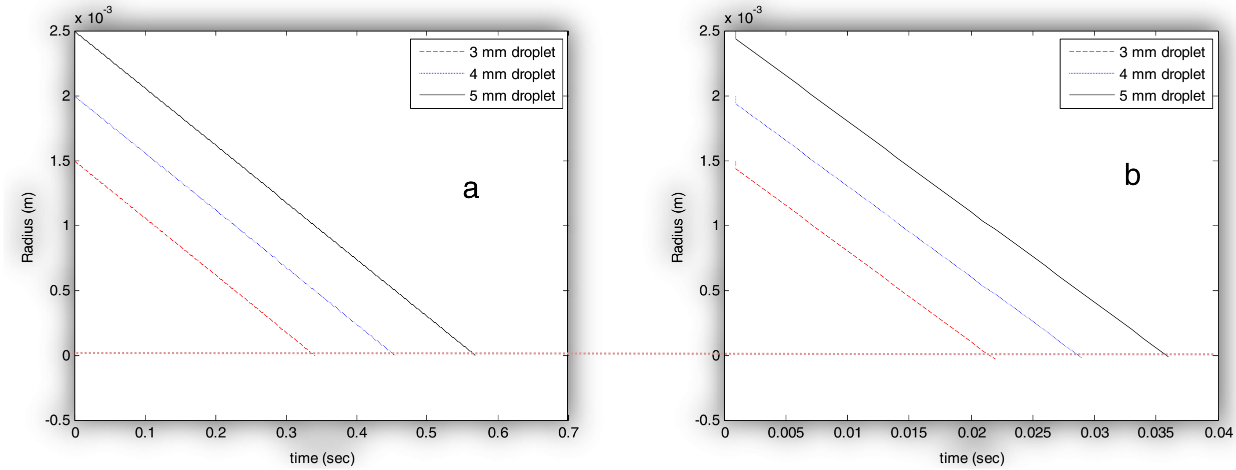

Fig. 6. Droplet radius decrease with time for: (a) where temperature of the medium increased by 10 °C instead of 5 °C and droplet temperature is at 38.7 °C and (b) where temperature of the droplet increased by 5 °C above boiling point and medium temperature is at 38.7 °C.

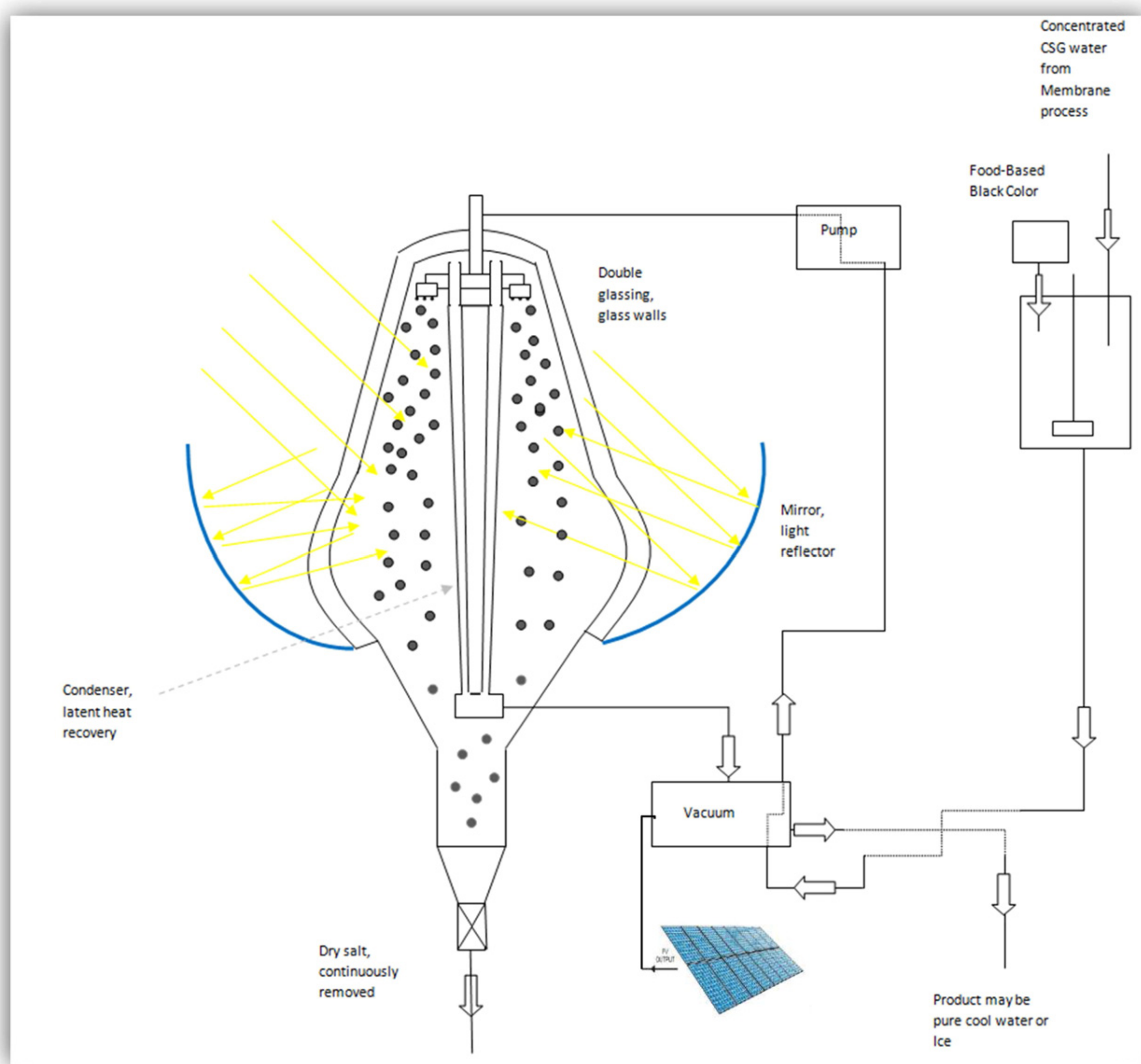

Fig. 7. A schematic diagram for the proposed prototype setting for the evaporation system under vacuum, large-scale setting.

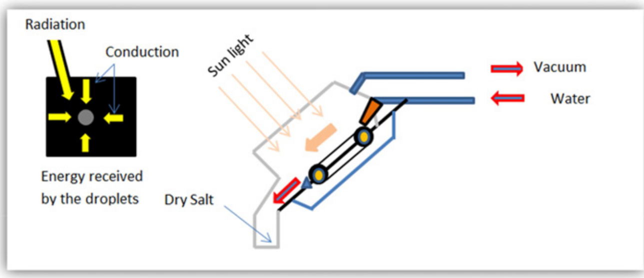

Fig. 8. Another design option.

- The operation is at a low range vacuum condition. Vacuum ranges are categorized as following: 3300–100,000 Pa low, 0.1–3300 pa medium and 0.0001–0.1 Pa high [23].
- Vacuum pumps such as Rotary Piston Mechanical Pump, Oil Sealed Mechanical Pump, and Sorption Pump can be used to generate low vacuum conditions [23].
- Thermal and high speed camera to monitor the temperature of the droplet and its diameter while traveling through the system.
- Monitor the waste heat collected from the vacuum pump and the collected heat by the heat exchanger attached to the solar panel.

5.3. Challenges

- The nozzle should be very fast in spraying the droplet to avoid evaporation at its tip. This may block the nozzle either by the remaining salt after evaporation of the water or the droplet may freeze at its tip.
- Multi droplets system, it will be limited to a specific droplets number per cubic unit of space; exceeding this limit may lead to exhaustion of the heat in that specific space and may lead to freezing the entire system.
- The nozzle can be designed to release droplet at a specific reduced pressure. Reduced pressure in the device can be kept at a specific value but above that required for the nozzle to function. A pulse vacuuming can be introduced to reduce the pressure in the device to that required for the nozzle to function in order to release and control the time and amount of the droplets release.

5.4. Feasibility

- For a concentrated salty water of 50% dissolved salt, the ability of water treatment will be doubled (half of the amount is required to be evaporated).
- For more efficient use of the sun energy the amount of water produced per day may be increased.
- Including the recycled latent heat of evaporation, waste heat from the pump and the droplet colour effect will all contribute in enhancing the system efficiency.

Fig. 7 shows a schematic diagram of an industrial scale system where multi droplets are spread. Based on this design, two products can be recovered cold pure water and pure coloured salt.

6. Other design option

The other design option is a rotating black coloured conveyer where the droplet sprayed over and travels instead of traveling in the vacuum (mostly vapour). In this case the entire surface will collect the energy from the sun and will be transferred to the droplet by conduction. The droplet will travel from one end of the conveyer

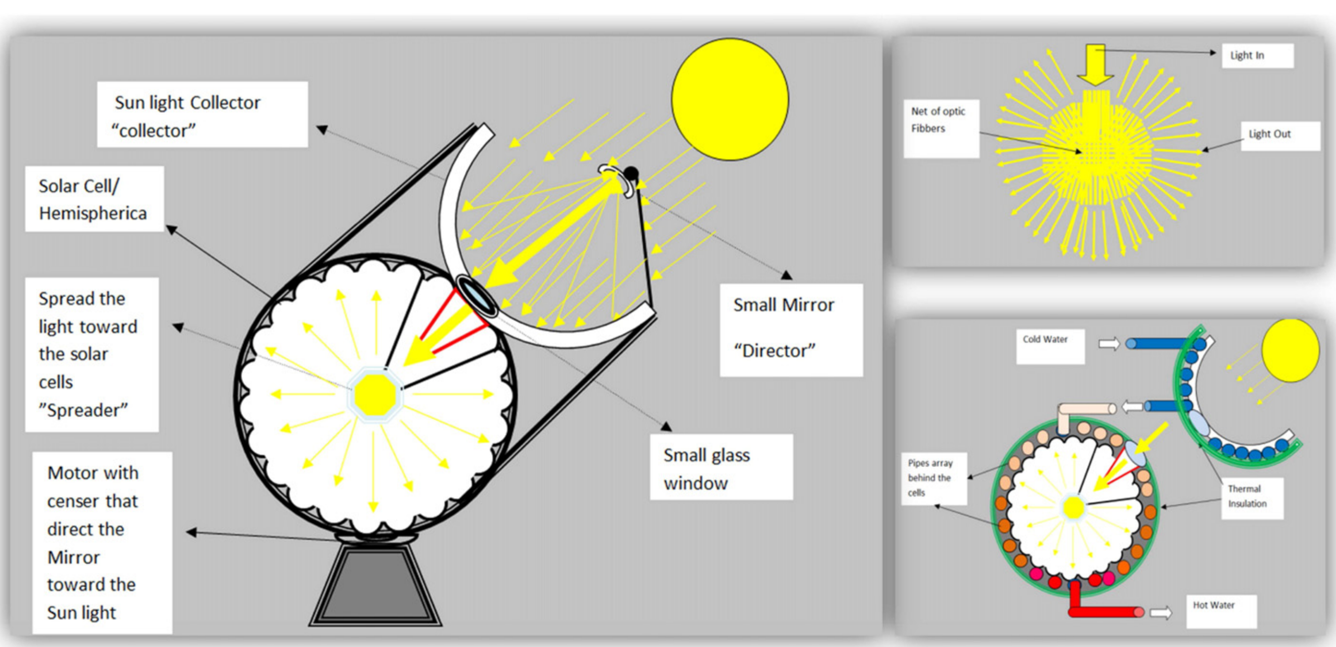

Fig. 9. Spherical shape light (energy) trapping system, to the left the entire system, right top is the fibre optic spreader and the right bottom is the pipes implemented to collect the heat accumulated in the system.

to the other end where the dry salt can be collected by scrapping (Fig. 8).

7. Innovative system for harvesting solar energy

Another option for the design of the system is a spherical closed environment. This system can be used to trap the sun light inside the system. In case the system used for evaporation, mirrors attached to the inside of the spherical shaped system (Fig. 9) are capable of reflecting the energy without losing it for more efficient energy collection and more efficient evaporation.

In case the spherical system is used for collecting heat and electricity, the system should covered with PV cells, this new shape allows more exposed surface to the sun light with less footprint occupied. The solar cells are protected against the weather disturbance and make better use of the light.

Simple calculation of the Spherical Solar Cell system;

The internal surface area for a sphere with diameter of 1.0 m

$$S.A = 4\pi r^2 = 4\pi(0.05\ \ \mathrm{m})^2 = \pi = 3.14\ \ \mathrm{m}^2$$

Number of small hemisphere with diameter of 0.1 m spread on 1 m diameter of the big entire sphere (1 m diameter) is (each hemisphere will occupy an area equivalent to an area occupied by a circle with 0.1 m);

$$No = 3.14\ \ \mathrm{m}^2/\pi(0.05)^2\mathrm{m}^2 = 400$$

Surface area created by a half sphere of 0.1 m diameter $= 2\pi(0.05)^2\ \ \mathrm{m}^2 = 1.57\times10^{-2}\ \ \mathrm{m}^2$

Surface area created by the 400 small half sphere $= 400\times1.57\times10^{-2}\mathrm{m}^2 = 6.28\ \ \mathrm{m}^2$

A complete closed sphere will:

- Protect the surface of the silicon cells from the weather condition
- Possibility of using a rough surface for more light absorbent, uncovered cells/very low reflection of light
- Creates 6.3 m^2 for each 1 m^2 of footprint
- Higher intensity of light inside the globe
- No escape of light entering the sphere
- Easy to control and direct toward the sun light
- Thermal energy production via heat exchanger placed inside the sphere (Fig. 9), this also help to cool the cells.

The system includes placing a large elliptical shaped sun light collector at the top of the sphere and then focuses it to the inside of the sphere. A light spreader placed in the middle of the sphere will be required to spread the light inside the sphere space.

The energy provided by the sun during a clear day (Fig. 7) is around 27.1 MJ/day/m^2. If 50% this energy trapped in the spherical system, then the amount of water that can be introduced to the vacuum evaporator at 100 °C can be around 40.5 kg/day or this can be at lower amount but with higher temperature. This water first will be circulated in the spherical system (Fig. 8) to collect the energy from the sun and it is based on 1 m^2 surface area available for collecting the sun energy;

$$\{27.1\ \mathrm{MJ/day} \times 50\% = m \times Cp \times \Delta T \\ = \mathrm{m\ kg/day} \times 4.182\ \mathrm{kJ/kg/K} \times (100-20)\ \mathrm{K} = 40.5\ \mathrm{kg/day}$$

This spherical collector will eliminate the initial condensation phenomena in the vacuum system and at the same time provides extra energy to the vacuum system. Also, the solar panel inside the sphere will provide electricity to drive the vacuum pump.

8. Conclusions

To conclude, the innovative approach and design presented in this article shows a promising potential of more efficient use of solar desalination when combined with vacuum action and waste heat/latent heat/solar heat recycling. PV cells can be used to drive the vacuum pump in the system. Around 15 kg/m^2/day of pure water can be produced in addition to by-product salt. Spherical closed system that is capable of trapping sun light will have a better efficiency than an open design to collect the heat and electricity from the sun light. In the vacuum system, it is very important to keep balance between the received energy from the sun, recycled latent heat, waste heat from the pump and the heat collected from PV panel with the droplet size, number and speed of traveling.

Acknowledgement

The authors would like to thank Professor David Buttsworth (USQ/Australia) for his valuable advice and help to achieve this work.

Appendix

MATLAB program used to generate the data in Figs. 4 and 6.

```
%% System conditions
% vacuum pressure, medium pressure
Pm=6900; % pa
% droplet boiling point, droplet temperature
DT=311.7; % K
% Saturation vapour pressure of water at droplet surface temperature
Psat=1000*exp(16.387-(3885.7/((DT-273)+230.17))); % pa
% medium temperature, assumed 5 degree above the boiling point
MT=DT+5; % K
%% droplet radius
for i=1:1:3
Dr(i)=0.001 + i/2000;
% droplet surface area
Dsa(i)=4*pi*Dr(i)^2; % m2
% Droplet volume
Dv(i)=(4/3)*pi*Dr(i)^3; %m3
% Droplet mass
Dm(i)=Dv(i)*row; % kg
end
%%
% j=0;
% selected delta time
delt(1)=0.001; % m
% Selected droplet radius
r(1)=Dr(1); % m
for j=1:1:600
delt(j+1)=j*delt(1);
%Radius of the droplet as function of time in seconds
r(j+1)=r(j)-(delt(1)/row)*((WMWt/(2*pi*Rg))^0.5)*((Psat/(DT)^0.5)-
(Pm/(MT)^0.5)); % m
M(j,:)=[j,delt(j),r(j)];
if(r(j)<0)
    break;
end
end

r(1)=Dr(2); % m
for j=1:1:800
delt(j+1)=j*delt(1);
%Radius of the droplet as function of time in seconds
r(j+1)=r(j)-(delt(1)/row)*((WMWt/(2*pi*Rg))^0.5)*((Psat/(DT)^0.5)-
(Pm/(MT)^0.5)); % m
N(j,:)=[j,delt(j),r(j)];
if(r(j)<0)
    break;
end
end

r(1)=Dr(3); % m
for j=1:1:1000
delt(j+1)=j*delt(1);
%Radius of the droplet as function of time in seconds
r(j+1)=r(j)-(delt(1)/row)*((WMWt/(2*pi*Rg))^0.5)*((Psat/(DT)^0.5)-
(Pm/(MT)^0.5)); % m
O(j,:)=[j,delt(j),r(j)];
if(r(j)<0)
    break;
end
end

plot(M(:,2),M(:,3),'r--');xlabel('time(sec)'),ylabel('Radius (m)')
hold on
plot(N(:,2),N(:,3),'b:');xlabel('time(sec)'),ylabel('Radius (m)')
hold on
plot(O(:,2),O(:,3),'black');xlabel('time(sec)'),ylabel('Radius (m)')
legend('3 mm droplet','4 mm droplet','5 mm droplet')
hold off
```

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