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A review on flash evaporation desalination

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ABSTRACT

Desalination is the process used to get the pure water from saline/brackish water to meet the water crises demand. Thermal desalination processes are mainly used for the mass production in industrial units. Flash evaporation is one of the main thermal desalination process used in industries. It has an opportunity to utilize this concept to develop the small-scale plant and domestic applications. This paper attempts to review the factors that affect the flash evaporation desalination process and discuss the performance of the different configurations.

Keywords: Solar desalination; Flash evaporation; Multi-stage flash evaporation; Review

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1. Introduction

Water is one of the most essential sources for living things to survive. The demand for good quality water is continuously rising owing to the rise in the population, intense agricultural practice, industrialization and overall rise in living standards. Water is one of the most abundant resources on earth, occupying three-fourths of the planet's surface. About 97% of the earth's water is saltwater in the oceans and the remaining 3% is fresh water contained in the polar region (in the form of ice), ground water, rivers and lakes, which supply most of the water for the human and animal needs. Less than 1% fresh water is within human reach. Nature itself provides most of the required fresh water, way through hydrological cycle.

Desalination of sea or brackish water is the method used currently to produce drinking water [1]. The distillation of sea or brackish water can be achieved by utilizing a thermal energy source. Such thermal energy [2] could be obtained from a conventional fossil fuel resource, nuclear energy or from a non-conventional energy sources such as solar and biomass.

Desalination process can be classified into two categories based on the consumption of energy namely, thermal and non-thermal process. Under non-thermal energy, the system can be classified as membrane desalination, reverse osmosis, etc. These plants required high electrical energy. In thermal energy processes, multi-stage flash distillation (MSF), multiple-effect distillation, vapour-compression, flash evaporation and solar thermal desalination.

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A detailed review on active solar distillation is conducted by Sampathkumar et al. [1]. Kalidasa Murugavel et al. [2] made a review on passive-type solar stills. Velmurugan and Srithar [3] reviewed the different factors affecting the productivity of solar still. Rajaseenivasan et al. [4] reviewed the different factors affecting the performance of the multi-effect solar still. Ali et al. [5] reviewed the techno economical analysis on indirect solar desalination. A review on solar-assisted sea water desalination was conducted by Li et al. [6]. The above literature shows, there is no particular review on flash evaporation desalination. Thus, this paper purely focuses a review on flash evaporation-based desalination and the parameters affecting the system.

2. Flash evaporation

Flash evaporation is the process of converting the saturated liquid to vapour by sudden reduction in the surrounding pressure of liquid in a chamber. It immediately becomes as vapour from liquid to regain the equilibrium condition. Under adiabatic condition, the vapour and its latent heat of vaporization at the expenses of the surrounding liquid and both the vapour and the residual liquid cool to the saturation temperature at the reduced pressure. This process is commonly used in distillation processes, such as in water desalination, and in energy conversion and storage processes for steam production.

2.1. Pool and spray flash evaporation

In pool flash evaporation, certain amount of fluid is filled and sealed in airtight chamber and connected with the vacuum tank. A vacuum pump is provided with the chamber to produce vacuum inside the system. The flash is produced in the system with the help of reducing the pressure and increasing the temperature of the chamber and liquid. In the case of spray-type, water is sprayed through a nozzle into the vacuum chamber.

2.2. Depth of pool

Kim and Lior's [14] investigation shows critical initial pool depth at which non-equilibrium temperature difference changes sign from positive at smaller depths to negative at larger depths. Saury et al. [16] result shows that for the same initial temperature and pressure, equilibrium state is reached slower when the initial water level increases.

2.3. Single-stage flash evaporation

Single-stage flash evaporation is a process that occurs in a single chamber and the flashed steam is used for the further processes. It may be pool evaporation or spray evaporation.

2.4. Multi-stage flash evaporation

In general, multi-stage process is a series of single-stage flash evaporators. In this the flashing occurs in multiple stages by the heat exchangers.

3. Parameters control the process of flash evaporation

The following are the important parameters which affects the performance of the flash evaporation process. They are non-equilibrium fraction (NEF), degree of super heat, operating pressure of flash chamber, pool depth and spray nozzle.

3.1. Non-equilibrium fraction (NEF)

NEF is also called as non-equilibrium allowance by some authors. Miyatake et al. [7,8] introduced a non-dimensional number, NEF to measure the degree of completion for flash, and found that higher superheat or lower water film height led flash to take place faster and evaporate more sufficiently. This number characterized the evolution of temperature during the flashing phenomenon.

$$\mathrm{NEF}\ (t) = \frac{T(t) - T(\mathrm{e})}{T_\mathrm{o} - T_\mathrm{e}} \tag{1}$$

where T_o is the initial bulk-average temperature of the water, prior to flashing, $T(t)$ is the bulk-average temperature of the water at time t after flashing commenced and T_e is the equilibrium temperature after flashing practically ceased, corresponding to the equilibrium saturation pressure at that time, in the experiments equal to the measured vapour temperature T_v.

Saury et al. [9] result shows NEF at the initial flashing period decreases with the initial pressure. Also they reported as, NEF fluctuates significantly for small superheats and sometimes negative values are obtained. Junjie et al. [10] studied experimentally the heat and mass transfer properties of static/circulatory flash evaporation, i.e. NEF, evaporated mass and heat transfer coefficient. The heat transfer coefficient was redefined as average heat flux released from unit volume of water film under unit superheat. The results indicated that this coefficient has a time-dependent function and a peak value existed at its evolution vs. time.

Zhang et al. [11] investigated the NEF performance of NaCl solution using a circulatory flash evaporation system. Two methods were considered to calculate the NEF, one uses the saturate temperature of pure water as benchmark and the other uses the saturate temperature of NaCl solution considering boiling point elevation (BPE). Result shows that NEF considering BPE was more reasonable to reveal the essence of NaCl solution circulatory flash evaporation.

3.2. Superheat

Superheat is the important parameter in flashing operation, flashing takes place when the liquid's temperature exceeds a certain degree of superheat. As stated earlier, when the surrounding liquid conditions suddenly vary and become lower than its saturation condition. At such a deviation as a sudden pressure drop, the liquid at initial equilibrium becomes superheated, and the entire energy cannot be restricted in the liquid as sensible heat and the excess is converted into latent heat of vaporization. The temperature of the liquid decrease quickly towards the equilibrium value, so that the degree of superheat can be defined as [12].

$$\Delta T_{\mathrm{sup}} = T_{\mathrm{in}} - T_{\mathrm{sat}} \tag{2}$$

They concluded that as increase in degree of superheat leads to an increase in the flashing vapour by certain quantity as well as flashing efficiency [12]. Miyatake et al. [7,8] studied the flash evaporation in pools with the initial temperature of 40, 60 and 80°C and superheats of 2.5–5.5°C. Saury et al. [9] investigated the flash evaporation phenomenon of a water film, with the variation of superheats ranging from 1 to 35 K and initial temperature of 30–75°C. They obtained a correlation between the water mass evaporated by flashing and the superheat. Junjie et al. [10] result also confirms that mass of evaporation increases with the rising of superheat. Gopalakrishna et al. [13] investigated both degassed fresh water and a degassed 3.5% (by weight) aqueous NaCl solution in a vessel of 152 mm diameter, at water depths of 165, 305 and 457 mm, at initial temperatures from 25 to 80°C and initial superheats of 0.5–10°C. Kim and Lior [14] studied the performance of pool flash evaporation process in a 152 mm diameter chamber with initial water temperatures of 40–80°C, and superheats of 2–7°C. Peterson et al. [15] investigated the liquid flashing evaporation with sudden depressurization. Liquid superheats up to 5.7°C and sub cooling as much as 9.2°C below saturation were noted.

3.3. Operating pressure

Operating pressure is the main parameter which controls the whole process of flash evaporation. Miyatake et al. [7,8] studied the equilibrium pressure range as 74–463 mbar. Saury et al. [9] conducted the experiments with pressure in the range of 50 and 200 mbar, and it shows NEF in the initial flashing period decreases with the initial pressure. They also found that, the final flashed mass is a decreasing function of pressure and an increasing one of the initial temperature. Peterson et al. [15] varied the pressure in the range of 11.4–27.0 kPa in their experiment and conclude as, at low pressure drops normal evaporation takes place. If the change in pressure is large enough, flashing occurs.

3.4. Operating temperature

Miyatake et al. [17] extend their investigation by varying the inlet temperature of jet from 40 to 80°C. The result shows, at lower liquid temperatures the spray flash evaporation still has higher evaporation performance and extremely faster evaporation rate than the flash evaporation occurring in other systems.

3.5. Flashing efficiency (η)

The efficiency of the spray flash evaporation is known as the ratio between the steam generation rates to the maximum steam generation rate or it is defined as the ratio of the amount of actual evaporation to that of the theoretical evaporation [18].

$$\eta = \frac{(T_{\mathrm{in}} - T_{\mathrm{out}})}{(T_{\mathrm{in}} - T_{\mathrm{sat}})} \tag{3}$$

El-Fiqi et al. [18] carried out the experimental work on the flashing process using fresh liquid by varying the initial temperature ranging between 40 and 70°C, vacuum ranging between 60 and 250 mbar and feed flow rate ranging between 4 and 15 kg/h. Result shows the flashing efficiency and the amount of the flashed vapour increase depends on the decrease in the water level inside the flash chamber.

3.6. Nozzle diameter

Miyatake et al. [19] experimentally studied the performance of the spray flash desalination in a superheated water jet injected in the low-pressure vapour zone. They investigated the effects of superheat, flow rate and nozzle diameter on spray flashing at an inlet temperature of 60°C. The nozzles used were made of glass tube, and had internal diameters of 3.46, 5.02 and 8.15 mm. Mutair and Ikegami [20] experimentally studied the performance of the spray flash evaporation (Fig. 1) by varying the nozzle diameter in the range of 54.4, 81.3 and 107 mm.

4. General investigation on single-stage flash evaporation

Ikegami et al. [21] made a comparison study on spray flash desalination process with the direction of injection with the variation of liquid temperature and mean velocity. They observed that, the upward jet method needs a shorter distance to complete the flash evaporation than the downward jet method. Thus, the upward jet method has more possibility of making the spray flash desalination system more compact and efficient. Muthunayagam et al. [22] theoretically and experimentally studied the performance of the vaporization of saline water at low temperatures and reduced pressures (Fig. 2). Temperature in the range of 26–32°C and the vacuum pressures between 10 and 18 mm mercury. They observed that almost 4% at the lower range of vacuum pressures and the upper range of temperatures and matches very closely with the predictions.

Mutair and Ikegami [23] experimentally studied the characteristics of flash evaporation from superheated water jets for desalination. Hou et al. [24] investigated a low-temperature distillation coupled with spray evaporation. Effects of nozzle water feed rate, heating air temperature, heating air flow rate, distillate column water feed rate and vacuum degree were investigated. They concluded as the water productivity of the whole system can reach 1.2 kg/h with recovery rate over 95%. Darwish et al. [25] experimentally investigated the flashing unit operation and studied the effect of the flow rate, liquid inlet temperature, fluid level in the flashing chamber and the flashing ranges. They concluded that the efficiency increased with the increase in the liquid inlet temperature, the flashing range and the chamber length (within the experimental

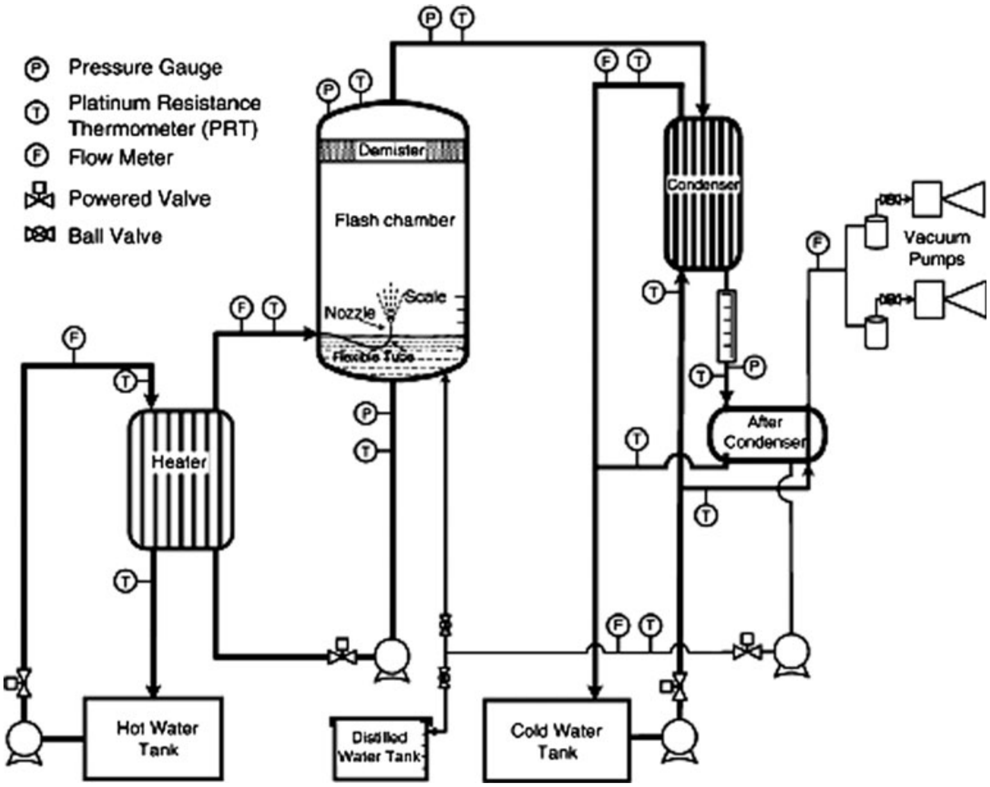

Fig. 1. Schematic diagram of the experimental plant [20].

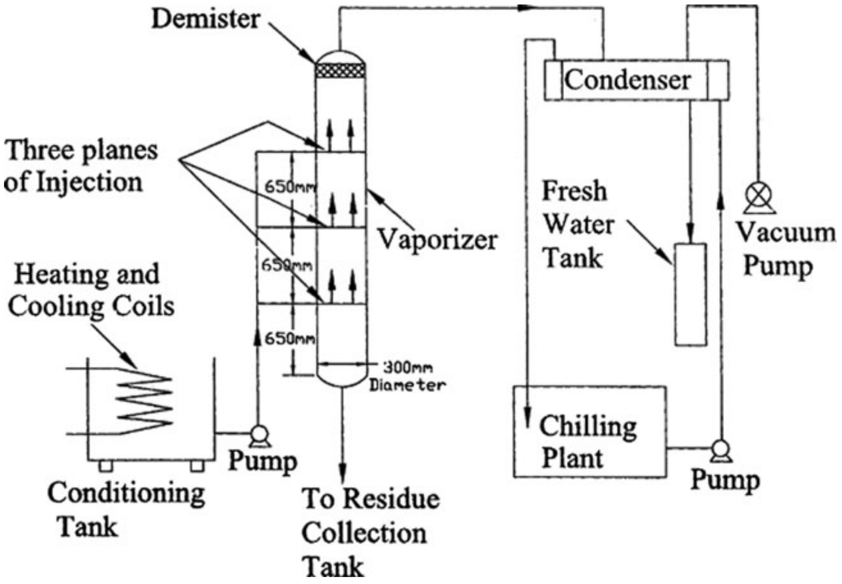

Fig. 2. Schematic diagram of the pilot plant [22].

range used). Also efficiency decreased with the increase in the flow rate and liquid level in the flash chamber.

5. Multi-stage flash evaporation

Alatiqi et al. [26] investigated the dynamic behaviour of a multi-stage flash water desalination system with a capacity of 4,546 m^3/d. It contains the 19 flashing stages, which include 16 in the heat recovery and 3 in the heat rejection section. Experiments were conducted in a scaled-down stage of a multi-stage flash evaporator at about 100˚C to examine the effects of electrolytically generated hydrogen bubbles on flash evaporation by Lior and Nishiyama [27].

Alhazmy [28] investigated the multi-stage flash desalination plant with brine-feed mixing and cooling. The larger the drop in the temperature of the mixture the larger the improvement will be in both yield and performance ratio. An improvement in the yield by 1.184% can be achieved for every 1˚C reduction in plant bottom temperature. Baig et al. [29] evaluated the performance of the once-through MSF system (Fig. 3). The result shows that brine side heat exchanger fouling has a significant effect in decreasing the overall heat transfer coefficient, which reduces the production rate as the fouling increases with time. Hosseini et al. [30] conducted a thermoeconomic analysis with reliability consideration of a combined power and multi-stage flash desalination plant.

Hybrid desalination processes including MSF and RO systems was investigated by Marcovecchio et al. [31] (Fig. 4). The vapour pressure in each of these stages was prohibited so that the heated brine enter reach chamber at the proper temperature and pressure (each lower than the preceding stage) to cause immediate and aggressive boiling/evaporation. The RO system is made of four major parts: the high pressure pumps (HPP), the first and the second stage of reverse osmosis and the energy recovery system (ERS). The stream is treated chemically before it enters to the RO system. Then, the stream passes directly to the HPP. Part of the power for the pumps is supplied by the ERS, and the rest is provided by an exterior source.

6. Single-stage flash evaporation with flat plate collector

Joseph et al. [32] investigated the performance of the single-stage solar desalination system for domestic applications (Fig. 5). This system used a solar flat plate collector with the area of 2 m^2 to heat the water, and the flash evaporator was used. A maximum distillate yield of 8.5 l/d was obtained with this system for 2 m^2 collector area.

7. Humidification–dehumidification (HDH) with flash evaporation

Kabeel and El-Said [33] made a comparison study amongst different configurations of the hybrid solar-powered desalination system. They examined the four different configuration of HDH with single-stage flashing system. They concluded as the

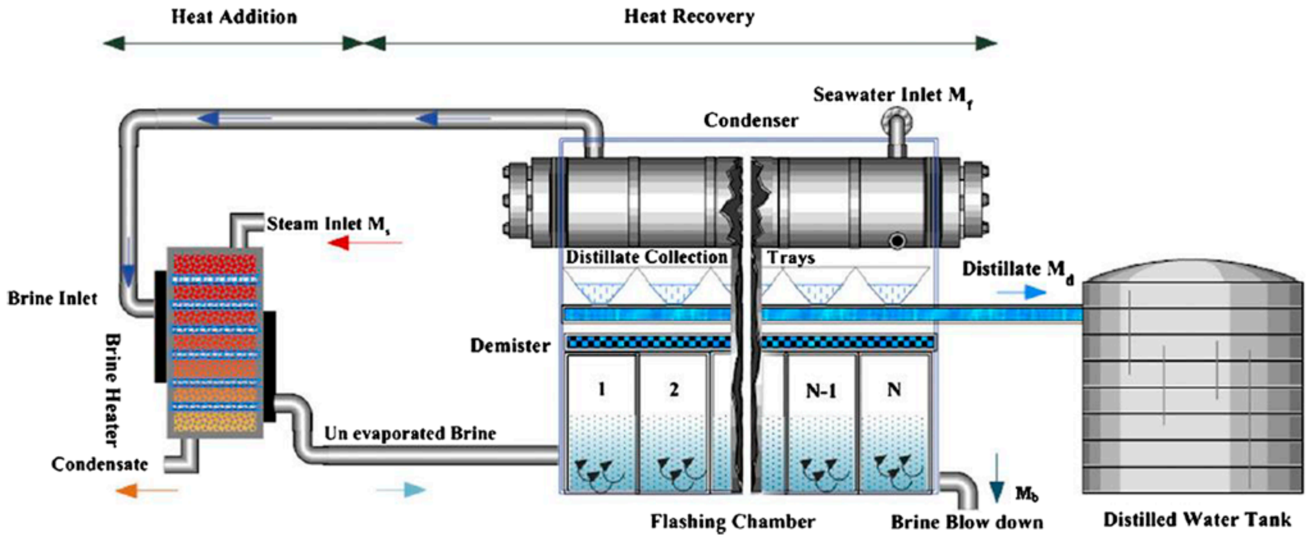

Fig. 3. A process description of a once-through MSF process [29].

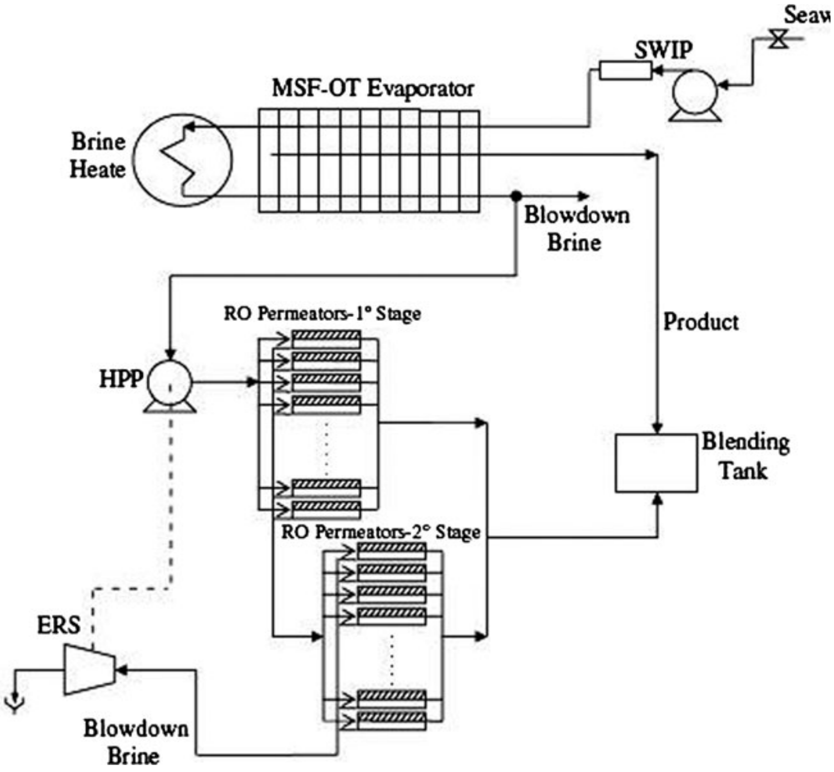

Fig. 4. Hybrid MSF-RO desalination system [31].

maximum productivity of 89.31 l/d and the gained output ratio (GOR) value of 10.2 was obtained.

Kabeel and El-Said [34,35] numerically and experimentally investigated the performance of the air humidification–dehumidification and water flashing evaporation (Fig. 6). The result shows the proposed system's daily water production up to 11.14 kg/m^2/d and the GOR of the system reaches 4.5. Also the trend of air solar heater collecting area

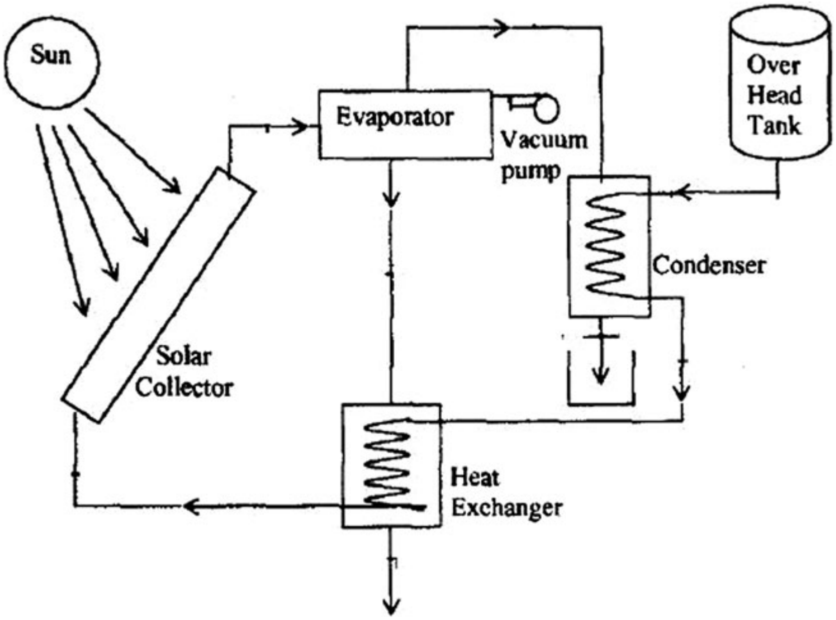

Fig. 5. Schematic diagram of the single-stage solar desalination system [32].

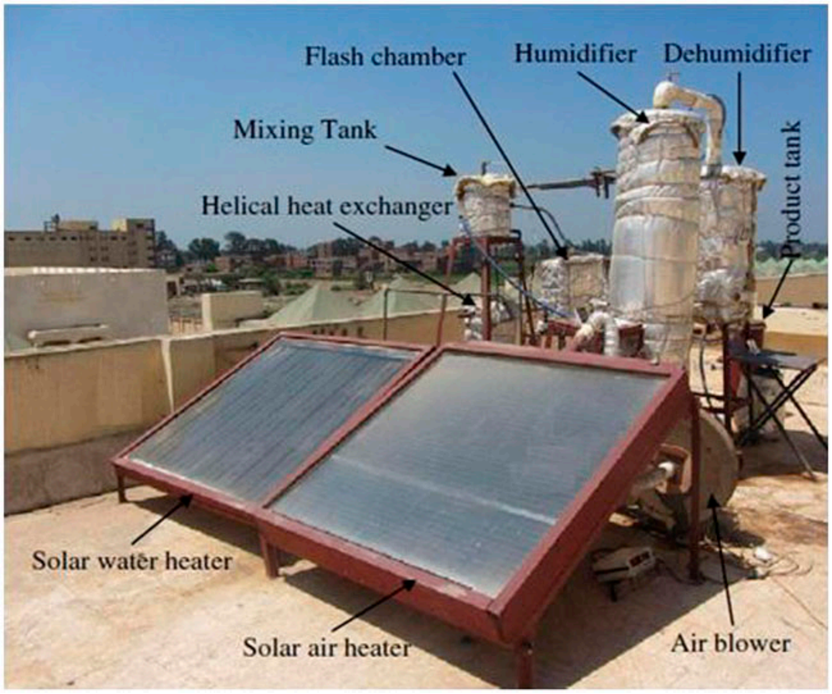

Fig. 6. HDH–SSF experimental set-up photo [35].

variation showed a pronounced increase in the fresh water productivity than that of the water solar heater collecting area variation. The experimental result shows the maximum productivity of the system reached 41.8 kg/d according to test and operation conditions.

Kabeel et al. [36] carried out an economic analysis of a small-scale hybrid air HDH–SSF (humidification and dehumidification water flashing evaporation) desalination plant. The study shows the estimated cost of the generated potable water by the hybrid system was 8.6 US$/m^3, while that value was reached 9.74 $/m^3 for the separated system. Also, the produced water costs decrease with increasing both the collecting area of the solar water heater and the plant lifetime.

8. Solar still with flash evaporation

Arslan [37] estimated the water production and still efficiency for different types of active solar stills in certain locations and proper modifications in the system designs were also made and compared on daily yields and daily still efficiencies. They observed the greatest daily yield of 12.37 l, which was obtained from the circular box solar still unit and the highest overall daily still efficiency, which is about 68.1%, in that of the active solar stills.

El-Zahaby et al. [38] studied the augmentation of solar still performance using flash evaporation. They used a stepped solar still integrated with hot water storage tank and two electrical air heaters and flash chamber. The inlet temperature of the impure water was 40–60˚C. They conclude as increasing the inlet impure water temperature leads to a decrease in the flashing vapour (productivity), and so the system efficiency.

Table 1
Comparison of different flash evaporation desalination system

S. no	Type of system	Parameters discussed	Results	Remarks	Refs.
1	Single-stage flash evaporation	Nozzle water feed rate, heating air temperature, heating air flow rate, distillate column water feed rate and vacuum degree	Distillate output of 5.5 kg/m^2 h is obtained and the gained output ratio (GOR) of 1.7 is obtained	Increasing the hot air flow rate improves the productivity and recovery rate, but thermal efficiency of the process is reduced	[24]
		Varying the water flow rate, liquid inlet temperature, liquid level in flashing chamber and flashing range	Presence of baffles, increasing the chamber length and increase in flashing range enhances the thermal efficiency	Efficiency of the system is increased with the increase in liquid inlet temperature As well as increasing the flow rate and liquid level resulted in the decrease in efficiency	[25]
2	Multi-stage flash evaporation (19 stages and capacity of 4,546 m^3/day)	Pressure, temperature, and flow rate of the heating steam; the pressure of the vacuum ejector; and flow rates of the brine recycle, make-up seawater, and cooling seawater	Increase in the heating steam temperature or pressure resulted in increasing the system temperature, which increased the flashing rate or the net product flow rate	The brine recycle flow rate had a very strong effect on the system performance where its increase resulted in a reduction in the brine level in the last stage and a reduction of the system temperature	[26]
3	Single-stage flash evaporation with flat plate collector	Solar irradiation and vacuum pressure	Maximum distillate yield of 8.5 l/d is obtained with collector area of 2 m^2	Efficiency of plant is varied from 15 to 26% for the variation in beam solar radiation from 400 to 900 W/m^2	[32]
4	HDH with flash evaporation	Solar radiation, feed water mass flow rate, inlet cooling water temperature, mass flow rate of cooling water and nanoparticle volume fraction	This system produces the maximum distillate amount of 41.8 kg/d	Performance ratio of SSF unit is varied between 0.32 and 1.4 and flashing ranges between 3 and 9˚C.	[35]
5	Solar still with flash evaporation	Inlet water temperature and solar radiation	The production rate reaches the maximum of 54.48 l/m^2/d with thermal efficiency of 50.026%	Increasing the inlet impure water temperature leads to a decrease in the flashing vapour (productivity), and so the system efficiency	[38]

9. Summary and recommendation future work

After making a detailed review of various flash evaporation processes, the following conclusions are inferred from the above discussion on (Table 1). (i) NEF, degree of superheat, operating pressure and temperature, pool depth, spray velocity and nozzle diameter are to be considered for designing the system, (ii) superheat and operating pressure are the parameters that control the evaporation rate of the system, (iii) hybrid systems are more advantageous and further studies need to design economically, (iv) stand alone flash evaporation systems to be designed for the people in remote areas, (v) investigations to be extend to design low-cost flash evaporators with minimum maintenance, (vi) analysis to be done with flash evaporation integrated with concentric collectors and (vii) studies to be done with flash evaporation integrated with stored thermal energy for off time production.

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