SHU XU
YIKAI CHENG
and
DAPENG WU

Experimental studies on a solar integrated plate-fin desalination unit

A new single-effect plate-fin desalination unit which utilizes solar or waste energy has been developed. This patented process is applicable for seawater desalination using simple and modular technology. In order to demonstrate the performances of this new process, a laboratory unit was constructed. It is composed of five evaporation cell, condensation cell, and heating cell and cooling cell. In this unit, a relatively large fraction of latent and sensible heat of condensation along with brine is successfully recycled and utilized. Since the falling film evaporation and fins are use, the average distilled water production is 0.5 m^3/d. and the yield is about two times greater than that of a conventional single basin solar still with the same thermal energy input. The mean heat exchange coefficient between heating cell and evaporating film was around 2500 Wm-2K-1. The first result concerning the influence of the heating fluid temperature and the heating fluid flow rate are presented. Other factors which influence the freshwater yield are also discussed.

Keywords: *Solar, plate-fin, desalination system, evaporation ratio.*

1. Introduction

The lack of potable water is a big problem in many countries of the world where freshwater is becoming very scarce. Increasing amounts of fresh water will be required in the future as a result of enhanced living standards and the rise in population rates, together with the expansion of industrial and agricultural activities. Vast reserves of freshwater underlie the earth's surface, but much of it is too deep to access in an economically efficient manner. Additionally, people cannot drink seawater and it is also unsuitable for industrial and agricultural uses. By removing salt from the massive supply of seawater, desalination has emerged as an important source of freshwater. Desalination is mankind's earliest form of water treatment; it is still a popular treatment solution throughout the world today. Solar desalination is one of the most promising options for supplying potable water. Solar energy is renewable, consistently available in most geographic locations and free. A variety of solar desalination technologies has been developed over the years on the basis of thermal distillation, membrane separation, electro dialysis, etc. (Bruggen, 2013). It is well known that three processes MSF, RO, and multiple-effect distillation (MED) will be dominant and competitive in the future (Shammiri and Safar, 2009). The MED process is the oldest desalination method and is very efficient thermodynamically (Ophir and Lokiee, 2015). And low temperature multi effect distillation (LT-MED) is the most efficient thermal desalination processes currently in use. It incorporates technological advances which have in reliable, and economical, plants producing high purity product water.

Many solar MED devices of medium capacity powered by solar energy are built worldwide. Thomas (Nashar and Samad, 2010) reported that solar MED experiments in Kuwait experienced difficulties, operating under the variable conditions of solar insulation. Great success has been found with self-regulating solar MED. The solar MED-plant designed with 18 stack type stages were analyzed (Jabal, et al., 2010). Evacuated-tube solar collectors were used with water as heat carrying medium. The plant was able to desalt seawater of 560,000 ppm. The major problem was the maintenance of the pumps. The authors pointed out that the acid cleaning and silt removal were extremely necessary for better performance of the plant. G.F. Casini described the small-scale solar MED desalination plants (Casini, 2003). It was a simple prototype small scale solar desalination system based on solar MED principle intended for checking the design principles and operational features for the future plant. The solar desalination unit was a tower with series of flat trays for effects and used a flat plate solar collector with oil as a heating medium for thermal energy. Oil is circulated by natural convection between the solar collector and the first effect. A practical scale solar desalination system of three effects using only solar energy from solar collectors as the heat source. The solar unit was developed and manufactured by the Ebara Corporation and tested at the Al Azhar University in Gaza. The average production rate was in the range of 6-13 L/m^2/day.

In recent years, the solar MED plants can have horizontal, vertical, or submerged tubes. The size of solar LT-MED units

Messrs. Shu Xu, Yikai Cheng and Dapeng Wu, School of Mechanical Engineering, Huaihai Institute of Technology, Liangyungang, China. Email: xucan264001@126.com

has increased quickly. Two solar MED units in Sharjah, UAE have a capacity of 22,700m^3/day each (Bacha, et al., 2013). A design and demonstration module for the solar MED process exists for a 45,400 m^3/day unit (Bacha, et al., 2014). Most of the recent applications for the large solar MED plants have been in the Middle East (Bacha, et al., 2015). Although the number of solar MED plants is still relatively small compared to MSF plants, their numbers have been increasing. These multiple-effect processes almost exclusively used submerged tube designs. But there are some drawbacks and limitations in the aforementioned solar units. Desalination systems employing the distillation process have long since depended on basic shell and tube heat transfer technology. This basic form of heat transfer has been acceptable in the past, but as the economics of systems becomes more important, and as waters for desalination become more diverse, then the total cost aspect of the project becomes essential.

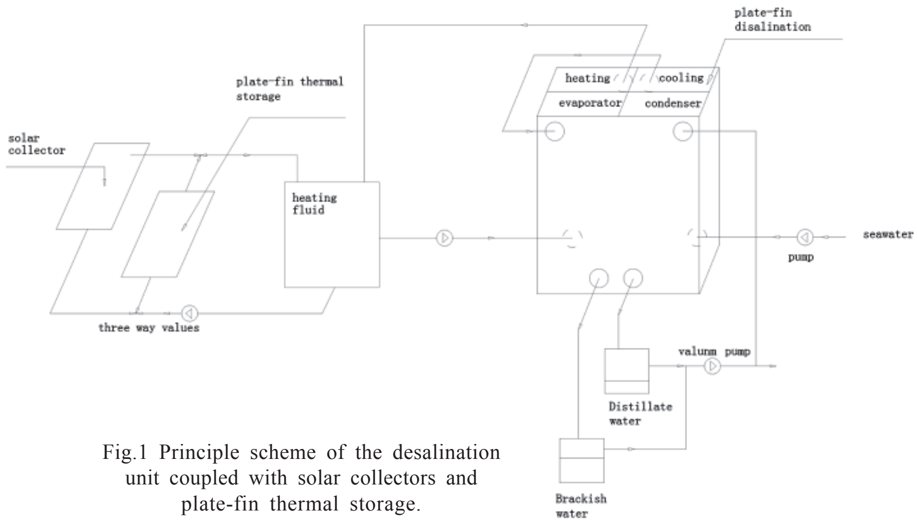

Fig.1 Principle scheme of the desalination unit coupled with solar collectors and plate-fin thermal storage.

In this paper, a new solar integrated plate-fin desalination unit is designed after comprehensive analysis of the advantages and shortcomings of the distillation techniques. This new configuration has several advantages never before available to any thermal desalination process. The use of plate-fin falling film (PFFF) leads to higher heat transfer coefficients due to the using of serrated fin. The PFFF system incorporates a patented distribution system, which provides greater control of fluid distribution and wetting of the surface as well as turbulent boundary layers promoted at low velocities due to the plate pattern. The experimental results of performance test of this unit are summarized.

2. Experimental

2.1 Operational principle of the new solar desalination system

The new solar desalination system consists of a solar unit, which provides the thermal energy, a plate-fin thermal storage and a desalination module that uses a new plate-fin desalination unit to treat the brackish water. The corresponding system scheme presented in Fig.1 is an illustration of the unit components. The solar unit mainly consists of a (1) integrated plate-fin desalination unit; (2) plate-fin thermal storage (PFTS); (3) flat plate collector field; (4) control unit, circulation pump and an electrically temperature controlled mixing valves (three-way valve).

Seawater is pumped into cooling cell to be preheated and then goes to evaporation cell. In the new desalination unit the evaporation/condensation cell is heated and cooled by the heating and cooling cells respectively. The heating of the evaporation cell is ensured by hot water (80°C) flowing upward along heating cells. The hot water is produced thanks to the solar unit. The cooling of the condensation cell is also ensured by seawater in cooling cell.

The control device of the solar unit regulates the whole desalination system. With the installation of the three-way valve, quasi steady-state conditions for the evaporation are guaranteed even during the daytime mode. If the temperature of the collector outlet exceeds the maximum temperature adjusted for the valve, some water will flow into plate-fin thermal storage. And plate-fin thermal storage begins to work. The phase change material (PCM) stores a large amount of heat during melting. When the temperature level of the collector outlet is lower than the minimum temperature of the evaporation, the PCM will release a large amount of heat during solidification. The supplementation of the system by a high temperature plate-fin thermal storage makes it possible to keep the temperature range and the volume flow at the evaporation chamber entrance over 24 hours at a certain level.

2.2 Description of the solar integrated plate-fin desalination unit

The material of plate-fin is stainless steel to prevent corrosion and its size is 1m (height)×0.5m (width)×3cm (thickness)

The Fig.2(a) is front side of integrated plate-fin desalination unit. The above two nozzles are seawater inlet and non-condensable gas extraction outlet. The lower two nozzles are for brine outlet and distilled water outlet.

Removing plate, we can see internal structure of evaporator and condenser, (Fig.3). In the evaporator, serrated fins are used and in horizontal mode. The seawater to be evaporated flows as a falling film along fins heated by hot water in the heating cell. Some sloped holes are machined in

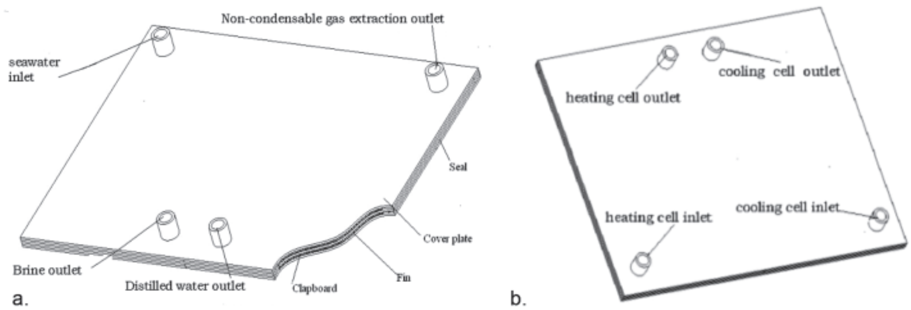

Fig.2 (a) Front and (b) Back front side of integrated plate-fin desalination unit

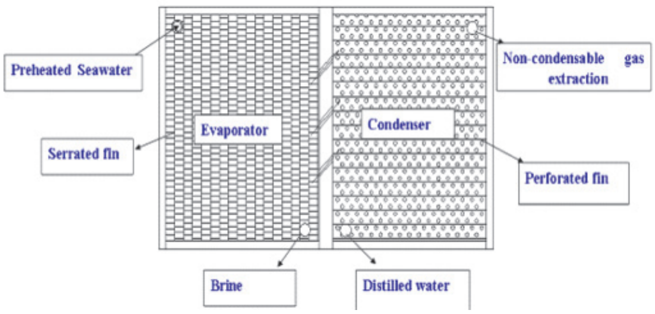

Fig.3 Internal structure of evaporator and condense in plate-fin desalination unit

the strip seal to ensure steam go into condenser thus reducing thermal losses and complex piping. Perforated fin are used and also in horizontal mode. The cooling of the condenser is ensured by cold seawater in the cooling cell.

The Fig.2(b) is the back side of integrated plate-fin desalination unit. The above two nozzles are for heating cell outlet and cooling cell outlet. The lower two nozzles are for heating cell outlet and cooling cell outlet. In the heating cell and cooling cell, serrated fins are both used.

2.3 Presentation of the single-effect laboratory unit

In order to optimize the design of the elementary cell and the operating conditions for the plate-fin desalination system, a laboratory prototype was constructed. The total weight of the process core is about 45kg and the size is 1m (height)× 0.5m (width)×3cm (thickness). It is supported by a stainless steel structure in order to enable gravity flow of brine and distillate to water boxes located under the pilot level.

The heating of the first evaporator is ensured by hot water with temperature lower than 80°C to avoid scaling. The primary heat source is an electrical heater composed of four electric resistances of 6 kW linked to a temperature control system within a tank. The cooling of the last condenser is ensured by fresh water coming from tap water.

The system operates in closed loop. The salted water (produced with tap water added with 35g NaCl/L) flows as a thin film on the plates, it is partially evaporated and the concentrated brine recovered at the bottom of each evaporation zone is sucked by a centrifugal pump and injected again at the top of each evaporation zone after mixing with make-up fresh water coming from the tank. The salted water enters on top of the evaporation cell, and water is distributed all along the plate thanks to a distribution system. Brine and distilled water flow by gravity and are collected at the bottom of the vapour cell and condensation cell. Both fluids go back to the salted water tank in order to maintain a constant salted water concentration. An electro-valve connected to a cooling coil is installed in order to maintain a constant temperature in the salted water tank. The system operates under vacuum produced by a vacuum pump. The experiment unit of plate-fin desalination system is shown in Fig.4, including absolute pressure sensor at the vacuum circuit, ten temperature sensors (thermocouples type K) at the inlet and the outlet of each fluid and four flow meters to measure all flow rates.

The studied parameters are as follows,

1. Heat carrier fluid flow rate (Qh) varying from 1.0 to3.2 m^3/h

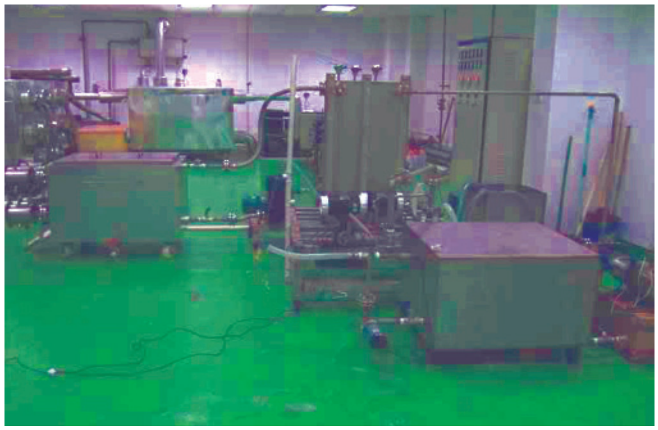

Fig.4 The experiment unit of plate-fin desalination system

2. Film flow rate (Qf) varying from 20 to 160 L/h
3. Cooling fluid flow rate (Qc) varying from 0.8 to 2.0 m^3/h

The pressure inside the vapour cell and condensation cell were maintained at 120 mbar, which corresponds to a boiling temperature of 50°C. The operating temperatures are well below the saturation limits of problematic sealants found in sea and most ground waters. The salted water used contains 36.5g of sodium chloride per liter.

3. Result and discussion

3.1 Influence of the evaporarion ratio

The indoor experiments were carried out continuously for about two months. The performance of the system was studied and the optimum operating conditions were researched.

The mass, momentum, and energy equations of the three-dimensional model are shown as follows:

Continuous equation:

$$\rho_i \frac{\partial u_i}{\partial x_i} = 0 \qquad ...\ 1$$

Momentum equation:

$$\frac{\partial}{\partial x_j}\left(u_i u_j\right) = \frac{\mu_i}{\rho_i}\nabla^2\left(u_i\right) - \frac{1}{\rho_i}\frac{\partial p}{\partial x_i} \qquad ...\ 2$$

Energy equation:

$$\rho_i \frac{\partial T_i}{\partial t} = \frac{\lambda_1}{c_p}\frac{\partial}{\partial x_j}\left(\frac{\partial T_i}{\partial x_j}\right) + S_T \qquad ...\ 3$$

The distilled water production measured with the single-effect unit ranged from 12 L/h to 22L/h, which is 0.28-0.53 m^3/d. The production capacity and the quality of the production are largely improved with reference to the traditional solar basin unit. Fig.5 presents the variation of the evaporation ratio τ with the heat carrier and film flow rates. The evaporation ratios are high. This is due to better film distribution and plate-fin; the evaporation ratio reached 50% for the lowest flow rate but in this case dry zones with salt deposit appeared. Then it is recommended to use a film flow rate between 50 and 100 L/h leading to evaporation ratios between 20 and 30%. Therefore, the modification of the pilot design: using of fins in the heating and cooling cells, and modification of the film distribution system, all improve production.

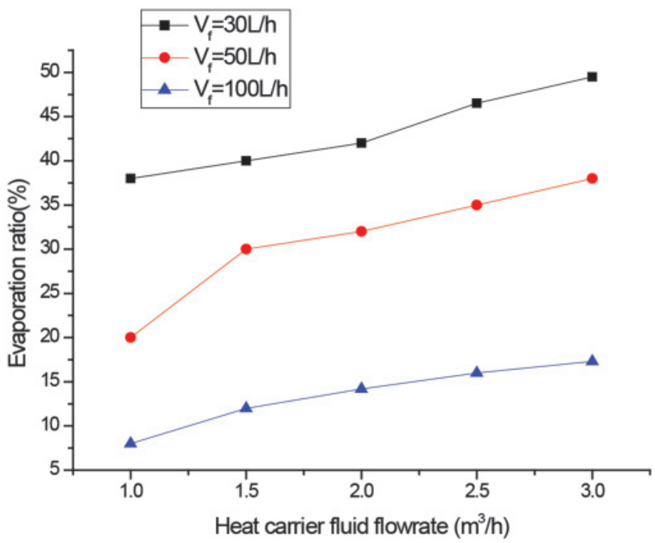

Fig.5 Variation of the evaporation ratio with heat carrier and film flow rates

3.2 Influence of operating temperature on the yield

The experimental results illustrate, Fig.6(a), that the operating temperature of the unit has great influence on the yield. The higher the operating temperature more will be the yield of the unit. Therefore, the unit has more advantages when it operates under high temperature conditions.

3.3. The steady-state performance ratio (PR) of the unit

The performance ratio of this unit is given by

$$PR = \frac{m_e h_{fg}}{Q} = \frac{m_e h_{fg}}{M_h C_P\left(T_1 - T_2\right)} \qquad ...\ 4$$

h_{fg} – Heat of vaporization of water (kJ/kg)

m_e – Yield of fresh water (kg/h)

Q – Total heat inputted into the unit (kJ)

M_h – Hot water flow rate (kg/h)

Experimental results illustrate that the performance ratio of this system is very good and generally reaches 78%. From experimental results, it is found that many factors influence PR, especially the hot water flow rate. The increase of the flow rate of hot water will increase the quantity of evaporated water, the temperature and the quantity of the brine which falls to the bottom of the evaporation cell will increase and decrease respectively at the same time. These are adverse to the condensation of the vapour in the condensation cell. Then the yield of distillate decreases. Experimental results also illustrate that the contribution of the yield of the still to PR of the unit is about 10–15%. The variation of PR with the operating temperature is shown in Fig.6(b). It is seen that PR increases with the increase of the operating temperature under the same conditions. It illustrates that the unit has more advantages in higher operating temperatures.

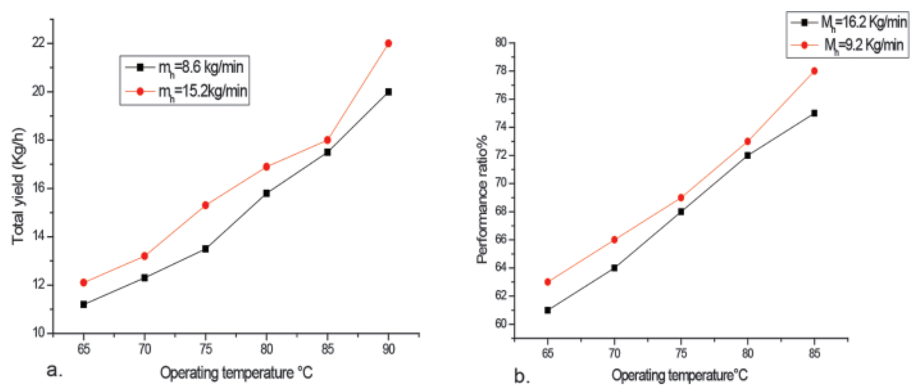

Fig.6 Variation curves of (a) total yield with operating temperature T under different operation conditions and (b) PR with the operating temperature.

4. Conclusion

The results obtained with the single-effect laboratory unit clearly demonstrate the feasibility of this process. It was specially shown that high-quality distilled water can be produced. In this system, a considerable fraction of latent and sensible heat is successfully recycled and utilized to preheat the brine and recycle air. A relative amount of latent heat is reused. The system can be directly operated with solar system or supplied with waste heat. Using of fins in each cell led to increased values of the overall heat exchange coefficients. These tests will allow us to complete the thermal study, particularly to evaluate the heat transfer coefficient between condensations and evaporation cells. It will then be possible to size an industrial unit.

Reference

1. Van der Bruggen B., (2013): Desalination by distillation by reverse osmosis-trends towards the future, *Membr*. Tech., 52(2), 6-9.
2. Al-Shammiri M., Safar M., (2009): Multiple-effect distillation plants: state of the art, *Desalination*,126 (3), 45-59.
3. Ophir A., Lokiee F., (2015): Advanced MED process for most economical sea water desalination, *Desalination*, 182 (3), 187-198.
4. El-Nashar A. and Samad M., (2010): The solar desalination plant in Abu Dhabi: 13 years performance and operation history, Renewable Energy, 14 (5), 263-274.
5. Abu-Jabal Moh'd, S. Kamiya I., Narasaki Y., (2010): Proving test for a solar-powered desalination system in Gaza-Palestine, *Desalination*, 137 (22), 1-6.
6. Casini G.F., (2003): The application of a high temperature scale control additive in a Middle East MSF plant, *Desalination*, 47 (4), 19-22.
7. Ben Bacha H., Bouzguenda M., Abid M.S. and Maalej A.Y., (2013): Modeling and simulation of a water desalination station with solar multiple condensation evaporation cycle technique, *Renewable Energy*, 18(5), 349-365.
8. Ben Bacha H., Bouzguenda M., Damak T., Abid M.S., Maalej A.Y., (2014): A study of a water desalination station using the SMCEC technique: production optimization. Renewable Energy, 21 (2), 523-536.
9. Ben Bacha H., Maalej A.Y., Ben Dhia H., Ulber I., Uchtmann H., Engelhardt M. and Krelle J., (2015): Perspectives of solar powered desalination with "SMCEC" technique, *Desalination*, 122 (19),177-183.