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The effect of plate corrugation on the wetting performance of plate heat exchanger for desalination

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ABSTRACT

Latest market trends in seawater desalination show a marked shift towards the multiple effect distillation (MED) process. This is mainly due to the advantages the MED process has over the multi-stage flashing (MSF) process, such as lower energy consumption and higher water recovery ratio. The MED process is expected to gain bigger shares in thermal-based desalination installations in the coming years; and with more technological advancements, the unit cost of MED-product water is expected to become competitive and more attractive in comparison with today's relatively low-cost and viable reverse osmosis (RO) desalination technology. The MED process can be divided into two categories depending on the type of heat exchanger technology employed, that is, shell and tube heat exchangers (STHE) and plate heat exchangers (PHE). The falling film horizontal tube heat exchanger is the most widely used configuration of the STHE technology employed in MED seawater desalination today. However, a new trend is emerging where the PHE technology is establishing presence in the MED desalination applications. PHE technology has significant advantages due to its superior heat transfer performance and the ability to pack fairly large heat transfer surface area in the most compact volume. Employing PHE technology in the MED process is considered a major step in the intensification process of MED for seawater desalination, which has been one of the major focus areas of research under the strategic plan of the Water Research Center (WRC) at the Kuwait Institute for Scientific Research (KISR). The study was unique since there is information gap on PHE technology in the MED desalination applications. This hydrodynamic parametric study was performed at atmospheric pressure and ambient temperature, and was used to obtain the optimum and safe surface wetting. For fixed nozzle type and clearance, three plate cassettes of different corrugations were tested with four different flowrates and four different temperatures.

Keywords: Modeling; Testing; Evaporation; Nozzle; Corrugations; Wetting; Design; Distillation; Heat exchanger

1. Introduction

Plate heat exchanger (PHE) technology is establishing presence in the multiple effect distillation (MED) applications [1–3]. PHE devices consist of stacks of preformed corrugated metallic plates, which are pressed together in a frame with the edges sealed by means of compressible gaskets; thus, forming a series of interconnected narrow passages through which different fluids can flow through unrestricted passages. In comparison with conventional shell and tube heat

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exchanger (STHE) technology, PHE technology has significant advantages due to its superior heat transfer performance and ability to pack fairly large heat transfer surface area in the most compact volume. The heat transfer rate in PHE can be up to 180% higher than that of STHE, which means that PHE systems can have much smaller heat transfer surface area packed in much smaller volume; thus, the footprint is only a fraction of its STHE equal capacity [3]. PHE systems exhibit rapid response to variations in process operating conditions, particularly variations in the fluids temperatures. This is because the gaps between the plates contain relatively smaller fluid volume, where fluid is constantly moving with no place for stagnation that often causes hot spots. Moreover, PHE systems are more flexible and highly adaptive to changes and modifications in the industrial processes. PHE modules can be added or removed while number of passes and combinations of corrugation patterns can be rearranged easily for optimal performance for almost any given situation. PHE systems are relatively easy to maintain and clean since the plates can be manufactured using corrosion/chemical resistant materials and the plate cassettes can be formed, assembled, or sealed together by pressed or glued gaskets.

Employing PHE technology in the MED process is considered a major step in the MED process intensification for seawater desalination, which has been one of the major focus areas of research under the strategic plan of the Water Research Center (WRC) at the Kuwait Institute for Scientific Research (KISR). Therefore, this study was initiated to serve as a platform for further development and deployment of the PHE-MED technology in Kuwait.

2. Literature review

A quick literature review shows limited publications related to developments of the PHE technology in seawater desalination during the past several years. Successful attempts have been made to construct MED units for seawater desalination applications based on PHE technology. Examples are the Alfa Laval construction of PHE-MED units in Saudi Arabia, in Pakistan, aboard ships, etc. In fact, the first attempt to construct PHE-MED units was made by Alfa Laval Technologies [4]. As per Tonner et al. [5], pressed plates with falling film configuration is the latest development in thermal desalination technology in which a patterned distribution system was achieved, providing greater control of the fluid distribution and wetting of the plates surfaces at low velocities.

Two of the most important values that affect the design and performance of the PHE are the heat transfer coefficient and pressure drop. Although these parameters have been investigated several times extensively for many years and by many researchers [6–18], a general correlation that covers all the geometrical parameters of PHE could not be found due to the wide range of these parameters. Moreover, regulating the number of passes of each of the streams in the PHE with the appropriate selection of the corrugation pattern of the plates, especially the angle of corrugations inclination to the plate's longitudinal axis, usually have a big influence on the thermal and hydraulic performance of the PHE device. This is due to the effect of this angle, chevron angle, on the friction factor and Nusselt number which has been discussed by many investigators [19–22]. Another important factor to be considered, which has an influence on the hydrodynamic and thermal performance of the PHE devices is the shape of corrugations, for example, trapezoidal or sinusoidal [23,24]. The shapes of the plate corrugations have a big effect on the flow velocity of the fluids flowing inside the channels between the plates. The heat transfer coefficient usually increases due to the high turbulence of the fluids but at the same time the pressure drop increases too, which will accordingly increase the pumping power.

For an optimal design of a PHE, mathematical modeling should be considered for the main features of thermal and hydraulic performance of PHE. Taking into consideration the type of plates, number of plates with different corrugations and number of passes of streams in the mathematical model will help in providing solutions to estimate the lowest heat transfer area for the proposed PHE device.

To have an optimal design for a PHE device with a specific plate type and the same heat transfer area, the spacing between plates should be regulated [9]. Optimal configuration of a PHE should yield a device with a much reduced number of channels; pass arrangement, relative locations of the different feed and outlet connections. Sensitivity analysis could be applied to obtain the influence of other parameters such as pressure drop, plate type or plate capacity on the obtained solution instead of deriving a mathematical model that is a function of all of the configuration parameters, which was found to be not possible [7].

When designing a PHE device for evaporation and condensation purposes, it was found that using the evaporation and condensation temperatures as design parameters are more effective than using other parameters such as heating capacities where they will be more sensitive to the heat transfer coefficient deceptive variations [10]. Although computational fluid dynamics (CFD) modeling of PHE can provide temperature and velocity distributions without the need to collect extensive experimental data, it is usually of limited use in the cases of large number of plates with complex geometries [25].

Giurgiu et al. compared two different models of PHE with mini channels using CFD to study the effect of geometric characteristics including inclination angles on the heat transfer process intensification [26]. The studied parameters included distributions of temperature, velocity and convection coefficient along the mini channel. Results from experimental measurements confirmed that larger angles caused better heat transfer performance. Wang et al. attempted the use of simulation CFD software to simulate real situations of hot and cold liquid water flows in chevron-type PHE systems [27]. The simulation was based on a 3-D model aiming to improve heat transfer performance and design optimization in terms of parameters such as angle, depth, and pitch of the plate corrugation. Two other interesting publications also used CFD; the first by Chein et al. [28], who studied the relationship between mass flux on one hand and the temperature distribution and pressure drop on the other hand. The influence of corrugation angle on these parameters and on the heat transfer performance was explained while CFD results were shown to agree with experimental data. The second by Al-Zahrani et al. [29], who investigated the heat transfer characteristics in sinusoidal corrugation PHE for single phase flow (water-water) and two-phase flow (air-water) in counter arrangement. The impacts of Reynolds number (Re) and Prandtel number (Pr) were investigated and the CFD results showed positive correlation between Nusselt number (Nu) and Re and negative correlation between Re and the isothermal fanning friction factor (f). Lushchik et al. [30] and Aboul Khail and Erişen [31] published results of independent studies that used numerical modeling to investigate heat transfer enhancements in PHE with special geometries and demonstrated advantages of suggested modifications such as a diffuser channel vs. a constant cross-section channel. Persson [32] presented a patent on double wall type PHE, which can improve the fluids' heat transfer and reduce the pressure losses, and is also leak-proof. Jangid [33] reviewed the latest research works on the PHE technology and reported some of the important details on the design and heat transfer enhancement in these systems. The review also introduced some new correlations for evaporation heat transfer coefficient and friction factor, which can be applied to various system pressure conditions and plate chevron angles.

3. Methodology

The study involved the design and construction of a bench-scale test unit; exhaustive hydrodynamic, thermodynamic and heat transfer testing; data interpretation and analysis leading to the development of a roadmap for a more comprehensive pilot-scale study, which is an essential step in the actual implementation of solar-driven PHE-MED technology on a commercial scale. To keep the process as simple as possible and the cost of the unit low, it was decided that the unit should be constructed in two parts. One part is to serve the hydrodynamic parametric study, which needs to be performed at atmospheric pressure. This part to allow testing using one plate cassette and a spray nozzle distribution system at a time. A circulating pump was used for flow circulation. Three different spray nozzle distribution assemblies and three plate corrugation configurations (e.g., sinusoidal, trapezoidal and oval) of stainless steel have been constructed and tested, allowing one combination of these at a time (Fig. 1). In addition, close control over the clearance between the spray nozzle assembly and the plate was provided through a simple mechanism. Control over water flow rate and temperature was used to allow variations in flow characteristics in terms of Re and Ka numbers. This arrangement was used to determine how and the extent of any of these parameters can affect the plate's surface wetting rate. The main parameters in this hydrodynamic parametric study included the variables that could yield the correlation between Re and Ka numbers, which represent reliably the exact flow conditions for appropriate plate surface wetting for different plate configurations and different spray nozzle distribution arrangements [34].

To understand the hydrodynamics of the liquid falling film distribution over different plate corrugations, hydrodynamic parametric study was performed at atmospheric pressure and ambient temperature, and was used to obtain the optimum and safe surface wetting (Fig. 2). For fixed nozzle type and clearance, three plate cassettes of different corrugations were tested with four different flowrates and four different temperatures. At least 16 data points on Re-Ka curve for each plate was obtained. This was achieved by varying the flow rate and the temperature four times each. Varying the temperature resulted in different water viscosity and surface tension properties.

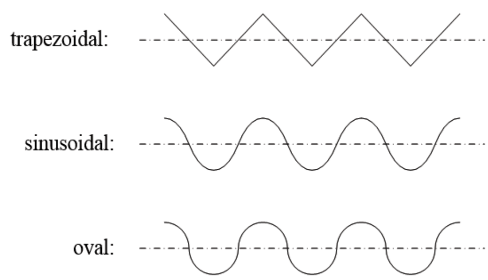


Fig. 1. Schematic view of the three different corrugations.

Fig. 2. Hydrodynamic testing unit.

The feed flowrate percent was increased from 85% to 120% of flow corresponding to the plate heat transfer area, where 85% provide performance data for under-wetting of the plates, 100% for base design wetting of the plates and 115%–120% provide performance data for over-wetting of the plates.

Moreover, four feed temperatures were examined, each one represents a certain situation in the MED plant, 50°C for lower end effects in common commercial MED plants, 60°C for augmentation with MSF and waste heat and solar thermal desalination applications, 70°C for base design top brine temperature (TBT), which is the most common for commercial MED plants and 80°C for higher TBT with possibility of nano filtration (NF) pre-treatment to expand operating range and number of effects.

4. Results and discussion

Fig. 3 represents the Re-Ka curve achieved by varying the flow rate and the temperature four times each. The two main equations used in the calculation are as follows:

$$\text{For Kapitza: } Ka = \frac{\eta^4 \cdot g}{\rho \cdot \sigma^3} \text{ for Reynold: } Re = \frac{\dot{M}_f}{2w \cdot \eta}$$

where ϱ is water density in kg/m^3; η is water viscosity in kg/m·s; δ is surface tension in N/m; w is width of the plate in m; and M_f is the mass flow rate in kg/s.

The width of the plate cassette remained constant, but the corrugations of the plate were different. Re-Ka curve was used to recognize the minimum wetting rate for safe wetting conditions for each plate. Since Kapitza number depends only on physical properties such as viscosity and surface tension of the falling film water, where the width of the plates is the same, this curve can be used for each set of plates operating under the same conditions of flow and temperature. Using different seawater concentration feeds requires different Re-Ka curve for each concentration. Moreover, calculating feed and brine for each plate and plotting the results on the provided Re-Ka curve helped obtain the safe wetting rate for the plate and consistency of the film (no risk of breaking films), and that is when the feed and brine results are consistent around the fitting curve.

4.1. Effect of main variables

One plate cassettes material was used in the investigation constructed of stainless-steel alloy. Three plate configurations have been tested (sinusoidal, trapezoidal, and oval) under different feed flowrate and temperature. Wetting percentage values were calculated using mesh calculation technique for each plate to find specifically dry and wet spots and calculate the wetting percentages. Fig. 4a–d illustrate the behavior of wetting obtained using stainless steel cassettes with the three configurations described above and at temperatures of 50°C, 60°C, 70°C, and 80°C with four selected flowrates representing 85%, 100%, 115%, and 120% of plate heat transfer area.

Temperature of 50°C represents lower end effects in common commercial MED plants. It was found that the cassette with oval corrugations provided the highest wetting percentages, always higher than 90%, compared to the sinusoidal and trapezoidal cassettes especially at lower feed flowrates. The minimum wetting percentages for the cassettes with oval corrugation occurred at the lowest feed flowrate of 84 L/h that represented 85% of flowrate for under-wetting of the plates followed by the cassettes with trapezoidal and sinusoidal corrugations, respectively. As the feed flowrates increased in value, the difference in wetting percentages between the three types of cassettes decreased especially between the oval and sinusoidal cassettes, where the wetting percentages values became approximately the same for flowrates higher than 100% and above, which represents base design wetting of the plates and over-wetting of the plates, respectively.

In other words, for the lower end effects in commercial MED plants and when the operating temperatures are near 50°C, it is recommended to use plate cassettes with oval corrugation especially when under wetting of plates is expected. While using plate cassettes with either oval or sinusoidal corrugations will make no difference if operating under base design conditions or even the over wetting conditions. Therefore, for the safest operation and full wetting requirements for lower end effects in commercial MED plants and when the operating temperatures are near 50°C it is suggested to use plate cassettes with oval or sinusoidal corrugations at flowrates higher than the base design conditions, that is, 115%–120%.

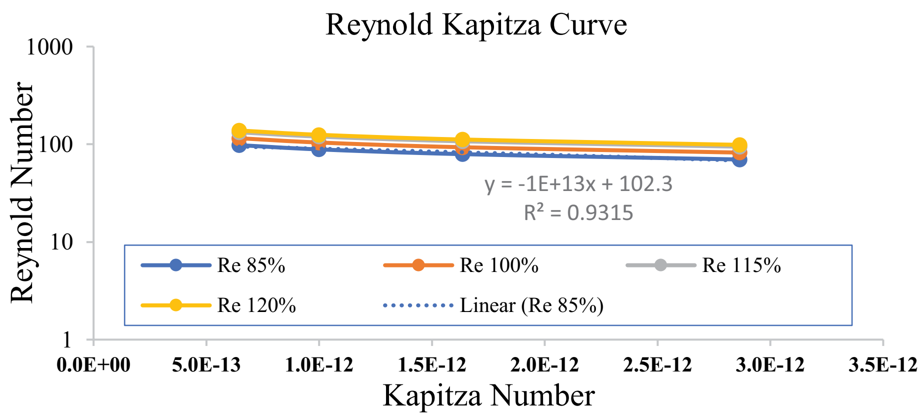


Fig. 3. Re-Ka curve obtained for the 16 points at different flowrates and temperatures.

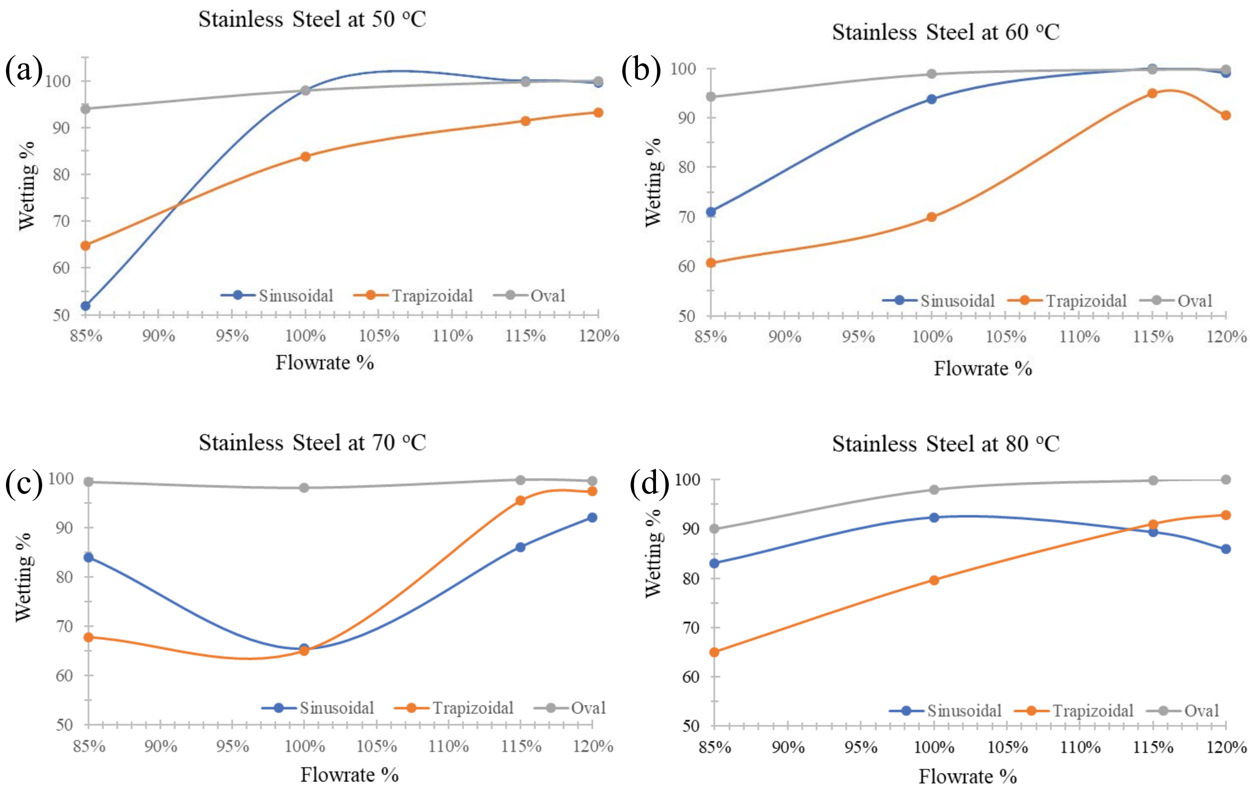


Fig. 4. Wetting % vs. flowrate for stainless steel with different corrugations at temperature different temperatures.

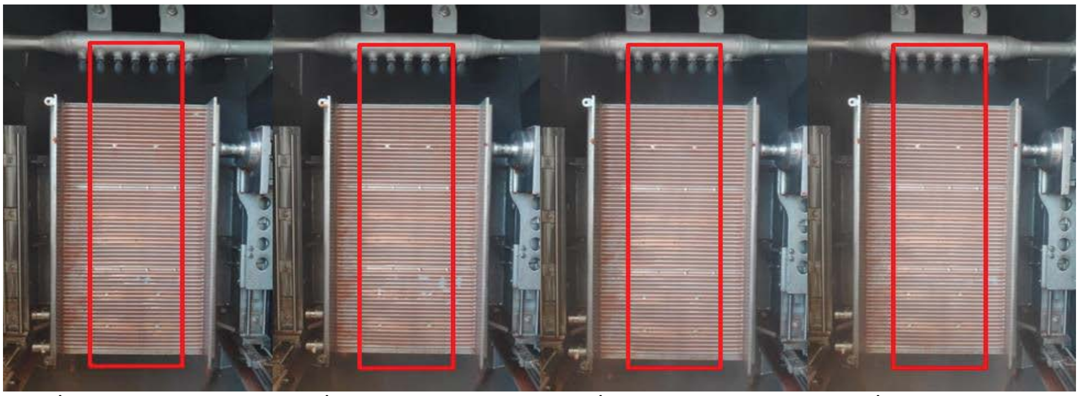
Temperature of 60°C represents augmentation with MSF and waste heat and solar thermal desalination applications. The cassette with oval corrugations provided the highest wetting percentages, always higher than 94%, compared to the sinusoidal and trapezoidal cassettes especially at lower feed flowrates. The minimum wetting percentages for the cassettes with oval corrugation occurred at the lowest feed flowrate of 84 L/h that represented 85% of flowrate for under-wetting of the plates followed by the cassettes with sinusoidal and trapezoidal corrugations, respectively. The small fluctuation in the wetting percentage for the oval corrugation is an indication that flowrate has minimum effect when using oval corrugated cassettes. As the feed flowrates increased in value, the difference in wetting percentages between the oval and sinusoidal corrugation cassettes decreased, where the wetting percentages values became approximately the same for flowrates higher than 100% and above, which represents base design wetting of the plates and over-wetting of the plates, respectively.

In other words, for augmentation with MSF and waste heat and solar thermal desalination applications with commercial MED plants and when the operating temperatures are around 60°C, it is suggested to use plate cassettes with oval corrugation especially when under wetting of plates is expected. While using plate cassettes with sinusoidal corrugations make no difference if operating under over wetting conditions. The plate cassettes with trapezoidal corrugation provided the lowest values of wetting percentages of 60% with the highest value of 95% at higher flowrates of 118%. Hence, for the safest operation and full wetting requirements for augmentation with MSF and waste heat and solar thermal desalination applications with commercial MED plants and when the operating temperatures are around 60°C, it is recommended to use plate cassettes with oval corrugations or sinusoidal corrugations at flowrates higher than the base design conditions, that is, (115%–120%).

Temperature of 70°C represents base design top brine temperature (TBT), which is the most common for commercial MED plants. The cassette with oval corrugations provided the highest and more stable wetting percentages, always higher than 99.1%, compared to the sinusoidal and trapezoidal cassettes. The minimum wetting percentages for the cassettes with oval corrugation occurred at the lowest feed flowrate of 84 L/h that represented 85% of flowrate for under-wetting of the plates followed by the cassettes with trapezoidal and sinusoidal corrugations, respectively. As the feed flowrates increased in value, the difference in wetting percentages between the three types of cassettes decreases especially between the oval and trapezoidal cassettes at high flowrates above 100%.

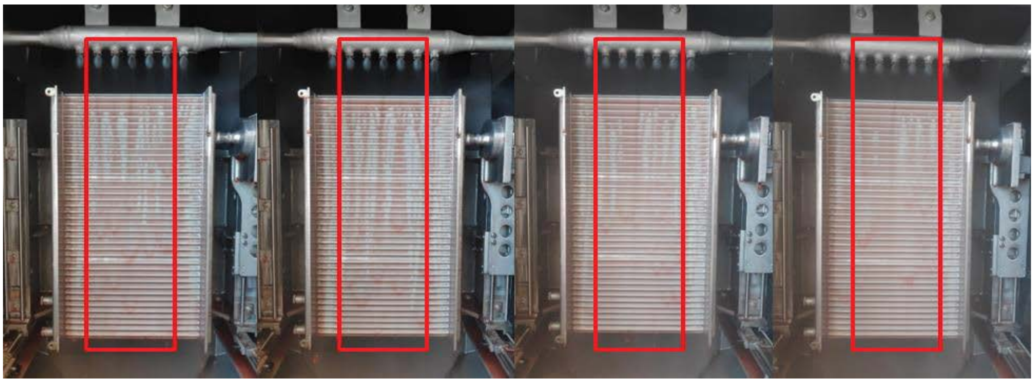
For base design top brine temperature (TBT) of 70°C, which is considered the most common for commercial MED plants, it is suggested to use plate cassettes with oval corrugation especially when under wetting of plates is expected. While using plate cassettes with either sinusoidal or trapezoidal corrugations provide low wetting percentages even under high flowrate conditions for over wetting. Therefore, for the safest operation and full wetting requirements for base design top brine temperature (TBT), which is the most common for commercial MED plants when the operating temperatures are 70°C it is required to use plate cassettes with oval corrugations at any value of flowrates. Figs. 5–7 represent view samples of the experimental results at 70°C for the three corrugations.

Temperature of 80°C represents higher TBT with possibility of nanofiltration (NF) pre-treatment to expand operating range and number of effects. The cassette with oval corrugations provided the highest wetting percentages,



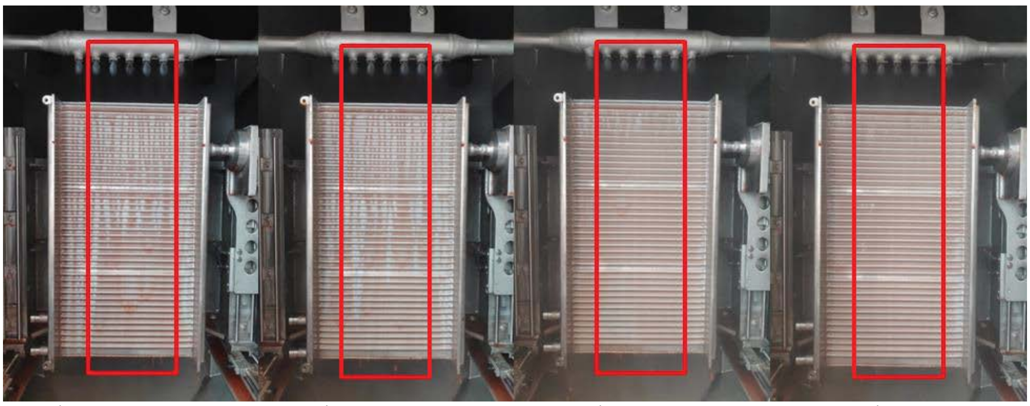
(a) $\dot{M}_f$ = 78 l/h 85%. (b) $\dot{M}_f$ = 92 l/h 100%. (c) $\dot{M}_f$ = 106 l/h 115%. (d) $\dot{M}_f$ = 111 l/h 120%.

Fig. 5. Effect of changing flowrate on wetting of the plates with oval corrugation at temperature of 70°C.



(a) $\dot{M}_f$ = 78 l/h 85%. (b) $\dot{M}_f$ = 92 l/h 100%. (c) $\dot{M}_f$ = 106 l/h 115%. (d) $\dot{M}_f$ = 111 l/h 120%.

Fig. 6. Effect of changing flowrate on wetting of the plates with sinusoidal corrugation at temperature of 70°C.



(a) $\dot{M}_f$ = 78 l/h 85%. (b) $\dot{M}_f$ = 92 l/h 100%. (c) $\dot{M}_f$ = 106 l/h 115%. (d) $\dot{M}_f$ = 111 l/h 120%.

Fig. 7. Effect of changing flowrate on wetting of the plates with trapezoidal corrugation at temperature of 70°C.

always higher than 90%, compared to the sinusoidal and trapezoidal cassettes. The minimum wetting percentages for the cassettes with oval corrugation occurred at the lowest feed flowrate of 84 L/h that represented 85% of flowrate for under-wetting of the plates followed by the cassettes with sinusoidal and trapezoidal corrugations, respectively. As the feed flowrates increased in value, the difference in wetting percentages between the three types of cassettes remained approximately the same at flow rates lower than 103% then this difference decreased at higher flowrates.

Hence, for commercial MED plants with higher TBT of 80°C with possibility of nanofiltration (NF) pre-treatment to expand operating range and number of effects, it is better to use plate cassettes with oval corrugation especially when under wetting of plates is expected. While using plate cassettes with either sinusoidal or trapezoidal corrugations will provide low wetting percentages even under high flowrate conditions for over wetting, with the highest value of 93% for trapezoidal corrugations with flowrate of 120%. Therefore, for the safest operation wetting requirements for higher TBT of 80°C with possibility of nanofiltration (NF) pre-treatment to expand operating range and number of effects for commercial MED plants, it is recommended to use plate cassettes with oval corrugations.

5. Conclusions

In conclusion, plate cassettes with oval corrugation provided the safest wetting compared to trapezoidal and sinusoidal. The wetting percentages for the plate cassettes with oval corrugation was always stable and higher than 90% despite the temperature or feed flow values. On the other hand, wetting percentages for the plate cassettes with sinusoidal or trapezoidal corrugations fluctuated in the range between 50 and 100%. The wetting percentages for the plate cassettes with sinusoidal corrugations depended mainly on the values of the temperatures more than the values of the feed flowrate with the highest wetting values obtained mainly at temperatures 60°C and below, while the wetting percentages for the plate cassettes with trapezoidal corrugation depended mainly on the values of the flowrate more than the values of temperature with the highest wetting values obtained with flowrates of 115%–120%.

As a result, the plate cassettes with oval corrugations are recommended to be used for the commercial MED plants for safest wetting values. If plate cassettes with sinusoidal corrugations are to be used for commercial MED plants, the TBT should not exceed 60°C and the flowrate is to be as high as 115%–120%, which will be suitable for augmentation with MSF and waste heat and solar thermal desalination applications.

If plate cassettes with trapezoidal corrugations are to be used for Commercial MED plants, the feed flowrate should be as high as 115% and above for over wetting of the plates despite the temperature value.

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