Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2021.26609

211 (2021) 60–68
January

Effect of spray nozzle orientations on the performance of the flash evaporator of LTTD desalination plant

D. Balaji[a,*], Raju Abraham[b]

National Institute of Ocean Technology, Ocean Structures NIOT Campus, Chennai, Tamil Nadu 600100, India, emails: dbalaji.niot@gov.in (D. Balaji), abraham@niot.res.in (R. Abraham)

Received 13 April 2020; Accepted 19 September 2020

ABSTRACT

This work discusses the influence of spray or feeder nozzle orientation on the production rate, non-equilibrium temperature difference (NETD), water quality, and flash efficiency of the evaporator of 100 m^3/d capacity low-temperature thermal desalination plant. To investigate this, the flash evaporator of the Kavaratti LTTD plant was taken for the study which is located at UT Lakshadweep Islands. This plant is being operated continuously for supplying potable drinking water to the local Island community. In the present work totally three different nozzle orientations (upward, downward, horizontal) were tested for the performance analysis of the flash evaporation. Experimental studies were conducted for different operating conditions and relevant data were collected for comparative analysis. It was observed that the orientation of the feeder or spray nozzle significantly influences the production rate, NETD, product water quality, and flash efficiency in the evaporator, and the mechanism responsible for variation in the performance of flash evaporation with respect to feeder orientation is also discussed. Upward nozzle delivers a good performance of up to 1.4 times the evaporation rate, 85%–90% flash efficiency, and lowest thermal loss (NETD) of 0.69°C to 0.75°C compared to horizontal and downward nozzle orientations. As far as product water quality is concerned, the downward-facing nozzle gives better quality or low salinity product water than the other two nozzle orientations.

Keywords: Flash evaporation; Spray nozzles; Non-equilibrium temperature difference (NETD); Flash efficiency; Nozzle orientation; LTTD plant

1. Introduction

Flash evaporation process is widely used in the fields like seawater desalination [1], national defense [2], health care [3,4], electronic industry [5], and aerospace [6]. According to Peterson et al. [7] the sudden change of the temperature behavior of the liquid happens, as a result of the flash evaporation not like the gradual reduction of the temperature as in the case of the simple evaporation. Ikegami et al. [8] carried out the experiment using straight top facing flow nozzles and found that quick evaporation occurs in the top facing nozzle than the downward-facing nozzles. Miyatake et al. [9], conducted studies for varying water depths like 100 and 200 mm in the chamber. They found that bubble nucleation and their growth is dominant in 100 water depth than 200 mm water depth water column inside the chamber. Bubble formation size increases with the decrease of the water depth of the pool inside the chamber. Miyatake et al. [10] proved that the flash evaporation rate through the nozzle is greater compare to the flow of liquid into the chamber like a river as in the case of multi-stage flash (MSF) evaporation. This is due to less disturbance caused to the flow of the liquid in the MSF plant.

Chen et al. [11] developed a theoretical model with key considerations given to droplet motion and droplet size distribution. This model is capable of accurately predicting

* Corresponding author.

the water productivity and thermal efficiency of existing spray evaporator under specific operating conditions. Using this model, the effect of several design parameters on system performance was studied. From their study, it was observed that smaller droplets enabled a faster evaporation process while higher initial droplet velocity promoted water productivity. Thermal utilization marginally changes with the degree of superheat.

Cai et al. [12] conducted their studies on spray flash evaporation of high pressure and high-temperature steam water test loop in order to study the evaporation in the tube leakage problems. Their study focused on the flash evaporation of the highly super-heated jet at a small injection rate. They also measured the parameter that influences the evaporation such as temperature and humidity of the region where the spray flash evaporation occurs. They also noted that the rate of injection of rate, the direction of the injection of the rate, injection pressure, and initial water temperature of the jet were influenced by the enhancement of the evaporation rate. They found that injection pressure guarantees the complete evaporation by atomization of the water spray.

Hosseini Araghi et al. [13] carried out an investigation on the performance of a new vacuum spray flash desalinator, a core component of the open water cycle in a discharge thermal energy combined desalination (DTECD) technology using theoretical and experimental techniques. They considered the feed water with 3.5 wt.% of NaCl and keep the inlet temperature range between 55°C and 75°C based on the low temperature utilized in the DTECD system. In order to design an efficient desalinator, physical aspects of the proposed vacuum spray flash evaporation (VSFE) should be studied. Thus, an experimental study was undertaken to verify the theoretical evaporation rate and centerline temperature data. They developed a CFD model for their proposed desalinator and implemented in the available package ANSYS FLUENT 16.2. They also compared some results with a thermodynamic model embedded in ASPEN/HYSY 8.0. They noted that the defined thermodynamic models based on vapor–liquid equilibrium in the Aspen and Fluent would predict the evaporation rate with the average errors of 5% and 17%, respectively. Droplet size, velocity, temperature, and concentration profiles are predicted and the underlying physics are discussed regarding the VSFE geometry.

Chen et al. [14] developed an experimental setup and mapped the temperature profiles of the sprayed water in the axial direction. They maintained low flow velocity conditions and observed the water jet shatters into droplets due to the flash atomization effect. Such a shattering phenomenon can be captured and quantified by a mathematical model based on droplet analysis. They used the developed model and translated the temperature profiles into the mean spray droplet diameters. They observed that the mean droplet diameters of the spray are several orders of magnitudes smaller than the nozzle diameter. Such fine droplets allow complete evaporation to be accomplished within 50 cm from the nozzle exit, enabling a compact evaporator design. Additionally, higher initial temperature differences and higher flow velocities reduce the mean droplet diameter to be smaller than 300 μm, and the corresponding vertical distance required to complete the evaporation process is shorter than 10 cm.

Cai et al. [15] conducted another study related to the flash evaporation using superheated upward and downward jets and observed their characteristics changes significantly. They developed a model based on the motion of the droplet and size variation of the droplet as well as its temperature. They developed models for both upward and downward jets and compared them by the previous experimental results and validated successfully. With these models, they could able to predict the evaporation rate, efficiency, and other parameters of the droplets in the superheated condition.

Gao et al. [16] indicated that the spray flash evaporation is an effective method of desalination which proportionately increases the specific surface area of the salty water by way of atomizing the water particles and improving the performance of the desalination plant. They focused on the explosive boiling phenomenon which occurs inside the superheated droplets on the heated surface. They conducted an experimental study on the distilled and 3.5 wt.% salty water in the sub-atmospheric conditions. From the experimental data, they observed that the nucleate site is located in the upper layer of a droplet because of the internal superheated liquid and Marangoni convection.

Fathinia et al. [17] aim to improve the performance of the spray flash evaporation as a key component of DTECD systems using a multi-nozzle head in various arrangements for the first time. They proposed two novel nozzle arrangements and compared with the conventional single nozzle. The injection of saline water inside the vacuum chamber was performed under various operating conditions including inlet flow rate, pressure injection, superheat degree, and salinity. They also observed droplet sizes and distribution and analyzed using shadowgraph imaging. A similar outcome was reached between the droplets measurement analysis and measured evaporation rate and gain output ratio which implied the most efficient arrangement. The proposed arrangement in which five nozzles are located in the farthest distance totally improved the efficiency of the system under various conditions up to a maximum of 28% compared to the conventional single nozzle for the same flow rate. In addition, it was found that the number of nozzles plays a more significant role than their arrangements for a certain pressure injection. Moreover, the optimized maximum superheat degree for the most efficient arrangement was found to be 19°C. These results provide a new fundamental understanding in the area of spray flash evaporation and reveal that increasing the number of nozzles and placing them in the farthest distance apart can improve the efficiency of the system.

As far as flash evaporation is concern it is very wild in nature. The temperature of the liquid decreases suddenly, marking the occurrence of the evaporation inside the chamber where the pressure is maintained at sub-atmospheric. The higher the temperature difference between the feedwater and the saturation temperature maintained inside the evaporator, the greater will be the flash evaporation rate for the given feedwater flow rate. The height of the water column standing inside the evaporator significantly affects the evaporation rate. As the water level increasing the hydrostatic pressure of the liquid also increases. Therefore the evaporation takes place only up to the depth of the liquid where the pressure equalizes with the surrounding saturation pressure. The liquid column below did not experience any evaporation due to the localized increase in pressure as a result of the hydrostatic head. In order to avoid this issue, flash spray nozzles are introduced in order to enhance the evaporation rate. The function of the spray nozzle is to increase the surface area of the sprayed water particle by way of reducing the liquid thickness so as to enhance the evaporation rate.

2. Description of the LTTD process

In the present study, three types of flash feeder nozzles are tested like vertical upward nozzle, horizontal nozzle, and downward-facing nozzle. Each of the nozzle orientations has its own way of influence the flash evaporation rate and the quality of the product water. As far as the LTTD desalination process is concerned the vacuum is maintained inside the flash evaporator using two-stage vacuum pumps. The vacuum is maintained at 27 kPa. The shell and tube condenser connected with the flash evaporator by means of vapor duct supposed to the same pressure. But due to the pressure drop in the vapor duct and condenser tubes inside the shell, the pressure drop increases to 2–4 kPa below the pressure maintained inside the evaporator. The vacuum suction flange starts from the condenser shell as shown in Fig. 1. Therefore pressure is lower on the condenser side than the flash evaporator side. The flash evaporated vapor from the evaporator goes to the condenser shell side through the demister pads via the vapor duct. Most of the seawater particle carry over in the vapor gets shredded in the demister pad and some of the water particles drop down due to its own weight because of agglomeration action. Only very few particles enter the condenser along with the water vapor.

Among the three nozzle orientations tested, the vertical upward nozzle projects supreme performance as far as flash evaporation rate, flash efficiency, and thermal loss are concerned whereas the downward-facing nozzle shows better water quality than the other two spray nozzle orientations. The mechanism that exists behind these concepts is discussed in detail in the present work.

3. Experimental methodology

Suitable experiments were carried out at Kavaratti LTTD for three different orientations of the feeder spray nozzle. The shape of the evaporator is rectangular in shape. A low vacuum of around 27 m bar (abs) was maintained inside the evaporator. Evaporator erected at a height of +13 m from the sea Chartered datum. Due to the barometric sealing height, no discharge pump is used. The area of the evaporator was measured to be around 8 m^2. The length and width of the evaporator are around 4 and 3 m respectively. The height of the evaporator is around 3 m. The demister pad is located at a height of 2.2 m from the bottom of the evaporator. The thickness of the demister pad is around 150 mm. A *C*-type demister pad is used for the experiment. The depth of the brine water at any time inside the evaporator varies between 0.2 and 0.3 m depending upon the feedwater flow rate. The operating temperature of the evaporator corresponding to saturation pressure is around 22.7°C. The temperature of the inlet feed water to the evaporator varies between 28.5°C and 30°C. The normalized liquid load corresponding to the chamber width of 3 m is 150 kg/s, which is the design point load of the evaporator. However, the measured liquid load or feedwater flow rate during the experiment varied between 100 and 140 kg/s. This could be due to the tide level variation in the sea environment when the flow rate readings were measured. The flow rate for all three nozzle orientations including the upward nozzle is varied between 100 and 140 kg/s only. No large scale water flow occurs in the experiment which limits the usage of the upward-facing nozzle. Three different nozzle orientations were tested in the experiment. This includes upward (Fig. 2a), horizontal (Fig. 2b), and downward orientation as shown in Fig. 2c. The height of the upward spout nozzle was around 0.15 m which was projected from a 0.3 m diameter horizontal intake feed water pipe that protruded into the evaporator.

There were around 16 nos of spout nozzles arranged evenly on either side of the intake feed water pipe as shown in Fig. 3. Two vacuum transmitters of the Honeywell model with an accuracy of ±0.5°C were used to measure the vacuum level. The insertion type flow meter of the E + H model with an accuracy of ±1 kg/s was used to measure the flow rate supplied to the evaporator. 13.5 kW submersible seawater pump of Grundfos make was used to pump raw seawater into the evaporator from the intake well. 26 kW submersible seawater pump of Grundfos make was used to pump deep sea cooling water into the tubes of the shell and tube condenser for condensing the water vapor from

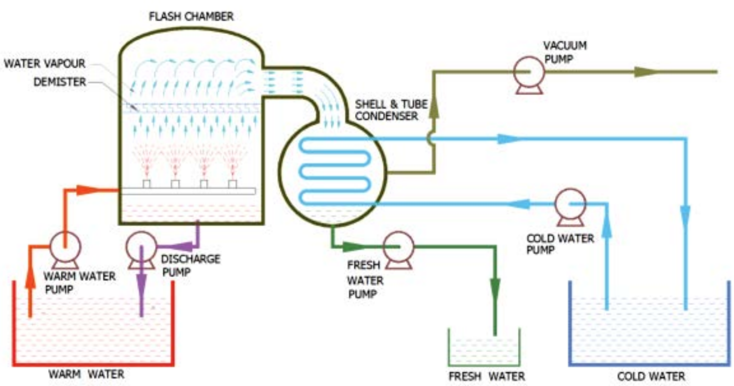

Fig. 1. Schematic diagram of the LTTD process.

Fig. 2. (a) Upward nozzle, (b) horizontal nozzle, and (c) downward nozzle.

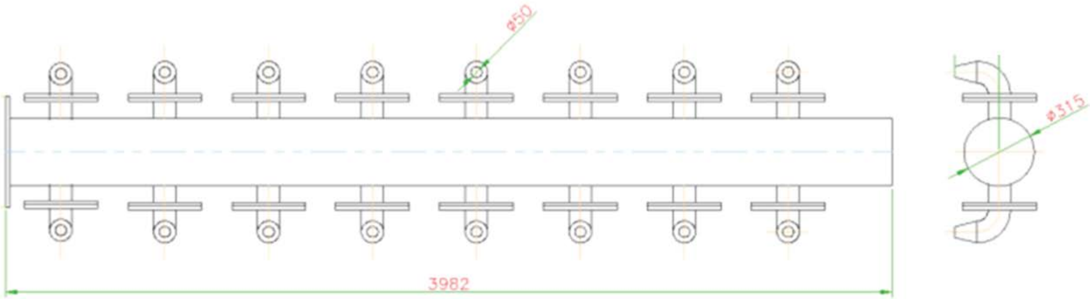

Fig. 3. Arrangements of nozzles in the main feeder pipe inside the evaporator.

the evaporator. The arrangement drawings of the upward nozzle, downward nozzle, horizontal nozzle, and flash evaporator picture are indicated in Figs. 4a–c and 5, respectively. The total length of the condenser was around 6 m with 1,250 nos of tubes. The flow of cooling water circulates in two-pass tubes. The diameter of the condenser shell was around 1.5 m with ¾ inch 90/10 cupro-nickel tubes of around 1 mm thick. Here also two vacuum transmitters of Honeywell model with an accuracy of ±0.5°C were used to measure vacuum inside the shell side and insertion type flow meters of E + H model with an accuracy of ±1 kg/s fixed one each at inlet and outlet pipeline of the condenser for measuring the intake and outlet cooling water temperature. During the experiment, no significant variation in the warm water pump power consumption was observed for different nozzle orientations.

The experimental procedure includes varying the warm water flow rate from 100 to a maximum of 140 kg/s that were discharged into the evaporator for varying nozzle orientation such as upward-facing, downward-facing, and horizontal facing nozzle and measuring the output parameters such as freshwater generation rate, intake seawater temperature, brine discharge temperature, saturation pressure and temperature of the evaporator corresponding to each nozzle configuration. With these input values, the performance of the evaporator was determined.

4. Mathematical models

4.1. Flash evaporator efficiency

$$\eta = \frac{\Delta T_{\text{actual}}}{\Delta T_{\text{sup}}} = \frac{\left(T_{\text{in}} - T_{\text{out}}\right)}{\left(T_{\text{in}} - T_{\text{sat}}\right)} \tag{1}$$

4.2. Non-equilibrium temperature difference or thermal loss

$$\text{NETD} = T_{\text{out}} - T_{\text{sat}} \tag{2}$$

where T_{sat} is the saturation temperature (K) and T_{out} is the brine discharge outlet water (K).

4.3. Flash efficiency model of Miyatake et al. [18]

$$\eta_{\text{flashing,Water}} = 1 - \left[1 + 1.5 \times \left(\Delta T_{\text{sup}} - 3.0\right)\right]^{-1} \tag{3}$$

$$\eta_{\text{flashing,Nacl}} = 1 - \left[1 + 2.5 \times \left(\Delta T_{\text{sup}} - 1.0\right)\right]^{-1} \tag{4}$$

The flash evaporator efficiency in Eq. (1) is used to determine how efficiently the flash evaporator is operating by taking the ratio of the actual heat ($T_{\text{in}} - T_{\text{out}}$) to the maximum heat ($T_{\text{in}} - T_{\text{sat}}$) that is thermodynamically possible. Non-equilibrium temperature difference (NETD) in Eq. (2) is otherwise called thermal loss. The warm water with intake temperature must reach the saturation temperature to maintain thermal equilibrium with the surrounding pressure before leaving the evaporator. But, due to the short residence time, there was a difference in temperature between the outlet brine temperature and saturation temperature. The difference in this temperature is not effectively utilized for conversion into vapor. This is called NETD or thermal loss. As far as Eqs. (3) and (4) are concerned, it was developed by Miyatake et al. [18]. These models were developed in a lab set-up in a controlled environment based on the large experimental data. These models were used in order to understand how close the measured value of the present experiment is matching

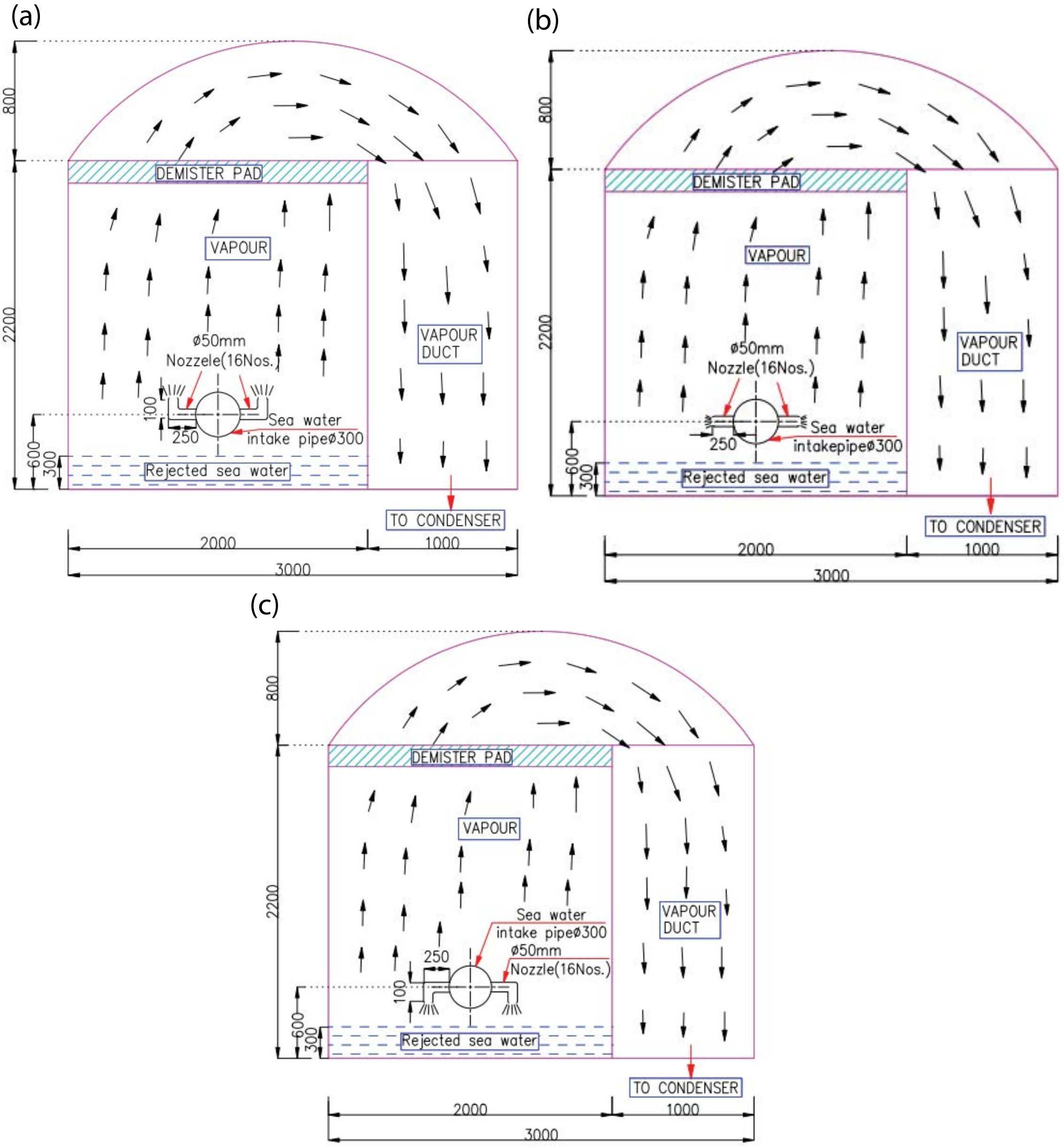

Fig. 4. (a) Upward nozzle, (b) horizontal nozzle, and (c) downward nozzle arrangement in the evaporator.

with the models that were widely used in the scientific community for validation of the results.

5. Results and discussions

5.1. Effect of the spray nozzle or feed nozzle orientation on NETD and flash efficiency

In order to find out the influence of nozzle on the flash evaporation of seawater, 3 different orientations of feeder nozzles such upward nozzle, horizontal nozzle, and downward nozzle of 0.075 m inner diameter were employed in the experiment. All these 3 nozzles experimented with feedwater flow rates that gradually increased from 100 to 140 kg/s and the corresponding value of NETD ($T_{wo} - T_{sat}$) was recorded and plotted in Fig. 6. Fig. 6 depicts that the downward nozzle recorded the highest NETD value ranging from 1.6°C to 1.1°C a decreasing trend followed closely by the horizontal nozzle which varies between 0.9°C and 0.8°C with a gradual increase in the warm water flow rate into the evaporator.

The lowest NETD value was recorded for the upward spout nozzle of the evaporator that varied between 0.75°C to 0.62°C. From this comparative study, it was understood that the upward nozzle produces the lowest thermal loss or NETD. Since the NETD values of the upward nozzle of evaporator were recorded lowest, it would be concluded that the upward nozzle utilizes the latent heat of evaporation better compare to other nozzles. This could be due to the fact that the duration that the splashed water exposed

Fig. 5. A view of the flash evaporator.

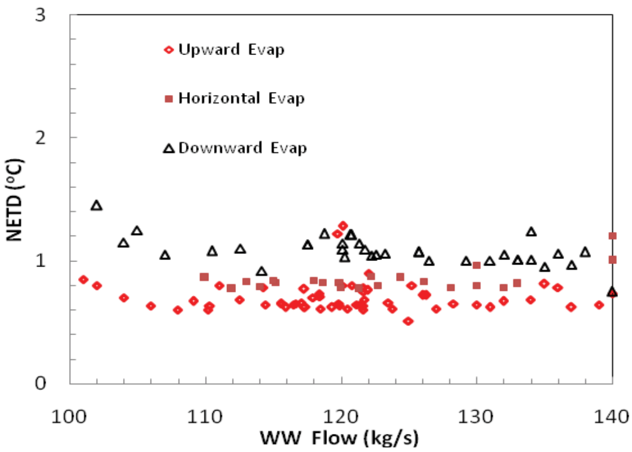

Fig. 6. Warm water flow vs. non-equilibrium temperature difference.

to the vacuum zone would have been much higher than the other nozzle orientations that would have hiked the latent heat release from the feed water, leads to the lowest NETD recorded in the experiment. The least NETD value was observed at the highest flow rate and it might be due to more height of splashed water jet which resulted in more duration the water exposed to vacuum. But literature reported that there was a hike in local liquid pressure when the jet column height increases [19]. This leads to delayed evaporation, but the introduction of the 0.075 m diameter nozzle might have reduced the water jet thickness comparatively to a certain amount even with increased column height. In addition to that, there was also a possibility that could have reduced the splashed water temperature further which would be the horizontal travel of the brine water inside the rectangular evaporator which is almost 4 m in length. The brine water that carries heat above the saturation temperature would be releasing heat until it travels inside the evaporator before reaching the exit nozzle. This might be adding to the extra evaporation at least to a certain extent and reduction in water temperature. It was noted that upward nozzle orientation gives 12.5% and 37.5% lower NETD values compare to the horizontal and downward nozzle orientations respectively.

The effect of feeder nozzle orientation on the flash efficiency in terms of warm water flow rate is depicted in Fig. 7. Most of the plots show an increasing trend with the increase in the flow rate. This was because the amount of vapor generation increases when the quantity of water inside the evaporator increases. The prediction of the flashing efficiency using the correlations suggested by Miyatake et al. [18] was compared with the experimentally measured results of the flashing efficiency of the different nozzle orientations for better understanding (Eqs. (3) and (4)). The upward nozzle of the evaporator showed the highest efficiency in the range that starts from 85% and went up to 92%. Next, the highest efficiency was displayed by the horizontal spout nozzle whose efficiency varied between 82% and 85%. However, this value fluctuates slightly between the flow rate 125 and 135 kg/s. This could be due to the fluctuation in the water flow caused by the water jet hitting on the walls of the evaporator. The lowest efficiency was shown by the downward nozzle of the rectangular evaporator. The efficiency of this configuration comes in the range of 77%–82%. The downward nozzle had the lowest residence time compare to horizontal and upward spout nozzles. The results of the Miyatake et al. [18] model for NaCl and water was determined and depicted in Fig. 7. The results were compared with the experimental values and observed that the model predicts the highest value in the range of 88% for NaCl and more than 93% for the water. The model developed by Miyatake et al. [18] did not include the effect of warm water flow but the super-heat of the liquid. Because of this reason, there was no variation in the trend of the curve plotted based on this model. The difference in the efficiency between each of the spout nozzle configuration was mainly due to the variation in the residence time for each of the spout nozzle orientation. The nozzle spout orientation which took more residence time obviously gives the highest flash efficiency. It was observed that upward nozzle orientation gives 4.7% and 7.1% higher efficiencies compared to the horizontal and downward nozzle orientations respectively and 2.4% lower than the Miyatake et al. [18] (NaCl) model and 6.6% lower than the Miyatake et al. [18] (H_2O) model.

5.2. Effect of spray or feedwater nozzle orientation on flash evaporation process and quality of product water

The heat load of the evaporator was determined for 3 different nozzle orientations and plotted in Fig. 8. Fig. 8 indicates that the upward spout nozzle generates more heat load compared to the remaining nozzle configurations in the range of 2,700 to 3,000 kW. This was due to the liberation of more latent heat from the splashed water which was exposed to the vacuum zone for a longer period due to increased residence time as a result of increased water jet velocity which was already discussed. The heat load of the horizontal nozzle orientation varies between 2,500 to 2,850 kW. Downward nozzle orientation indicates that heat load varies in the range of 2,400 to 2,800 kW. Fig. 8 also clearly indicates that with the increment in the

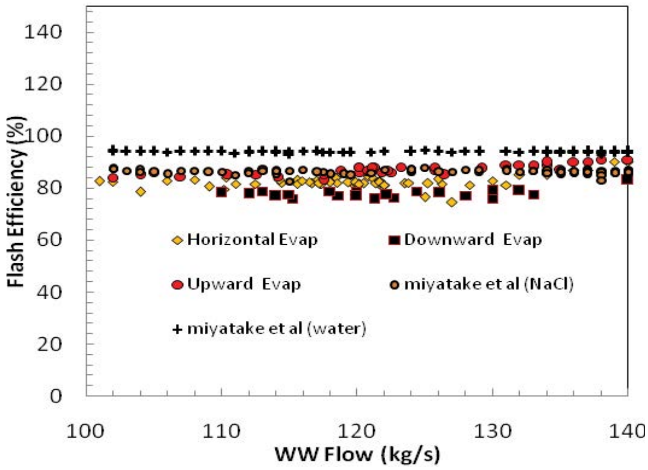

Fig. 7. Warm water flow rate vs. flash efficiency in the evaporator.

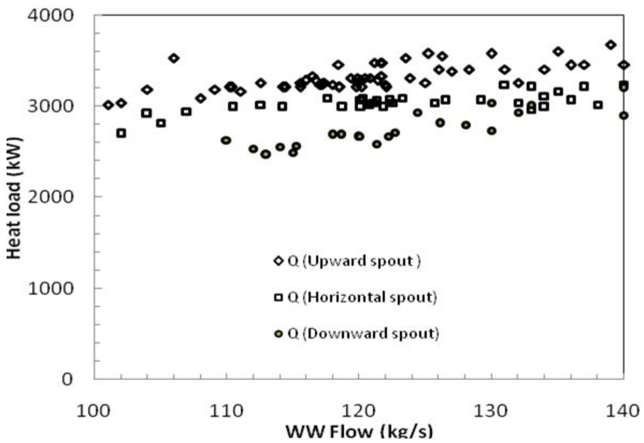

Fig. 8. Warm water flow rate vs. heat load of the evaporator.

warm water flow rate there was an increment in the heat load inside the evaporator. This was due to the fact that as the flow rate increased, the amount of water exposed to the vacuum zone was also increased; as a result, more water vapor generates and condensed to form freshwater in the condenser. However, due to the influence of the individual nozzle orientation, there was a variation in the heat load generated inside the evaporator. It was noted that the upward nozzle exhibits 13.3% and 23.6% higher heat load compared to the horizontal and downward nozzle orientation respectively for the same feedwater flow rate.

It is indicated in Fig. 9 that the increment in the warm water flow rate inside the evaporator leads to a decrease in the temperature drop of warm water across the evaporator. An increased drop in the temperature of the warm water was observed when less amount of water was exposed to the vacuum zone. As the flow rate decrease, the thickness of the splashed water also decreases, as a result, the surface of the liquid loses more temperature in order to attain the thermal equilibrium with the surrounding. This experimental study indicates that the highest temperature drop was observed in the upward nozzle compared to the

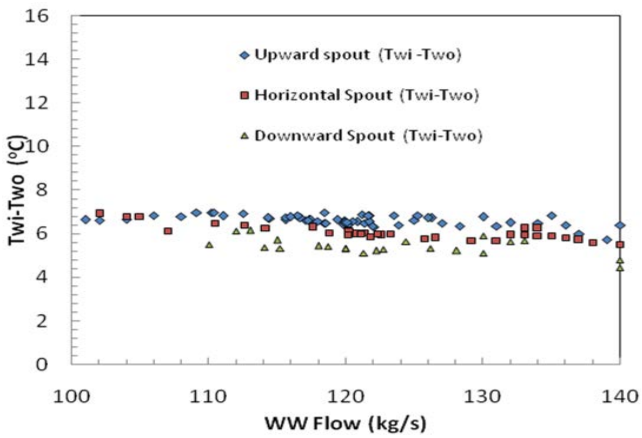

Fig. 9. Warm water flow vs. temperature drop of feed water across evaporator ($T_{wi} - T_{wo}$).

other nozzle orientations. It was already discussed that increased residence time and increased water jet velocity due to reduced spout nozzle lead to a reduction in thickness which in turn resulted in increased temperature drop across the evaporator. In the present study, the temperature drop was measured to be around 7.0°C for the lowest flow rate of around 102 kg/s for the upward nozzle, and this drop in temperature decreases to 5.9°C (average) as the flow rate increases to 140 kg/s. Similarly, for the horizontal nozzle, the value varies between 6.8°C to 5.9°C for the flow rate that varies between 100 to 140 kg/s. For the same flow rate range, the value varies between 5.75 to 4.9°C for the downward nozzle orientation. This could be due to the flow physics of the flashed water inside the evaporator. The water after splashing and losing temperature it falls into the brine water whose temperature was still greater than the saturation temperature by fewer degrees Celsius. Those water particles would undergo evaporation until it travels in the vacuum zone until it reaches the exit port. Because of this event, there was a further reduction in brine water temperature in the evaporator apart from losing temperature during flash evaporation. Experiments were conducted for different warm water flow rates and the corresponding mass of vapor generated or production rate in the evaporator for 3 different nozzle orientations were recorded and depicted in Fig. 10. Fig. 10 clearly indicates that as the warm water flow rate increases inside the evaporator the amount of vapor generation or production also increases. Fig. 10 also clearly indicates that the upward nozzle enhances the production rate by 1.4 times the production rate of downward-facing nozzle orientation and 1.2 times higher than the horizontal nozzle orientation. It is also indicated in Fig. 11 that as the warm water flow rate increases there was a corresponding increase in the salinity of the product water which means a decrement in the quality of potable water in terms of ppm. Fig. 11 also clearly indicates the influence of the feeder nozzle orientations on the quality of the product water. From Fig. 11 it is observed that the upward nozzle orientation gives the highest salinity because of the increased spray velocity which enables the water vapor to carry more water droplets and also the chances of bypassing the de-mister is

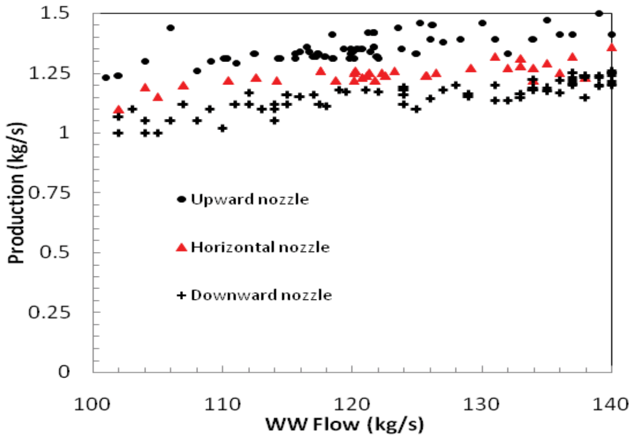

Fig. 10. Warm water flow rate vs. production rate.

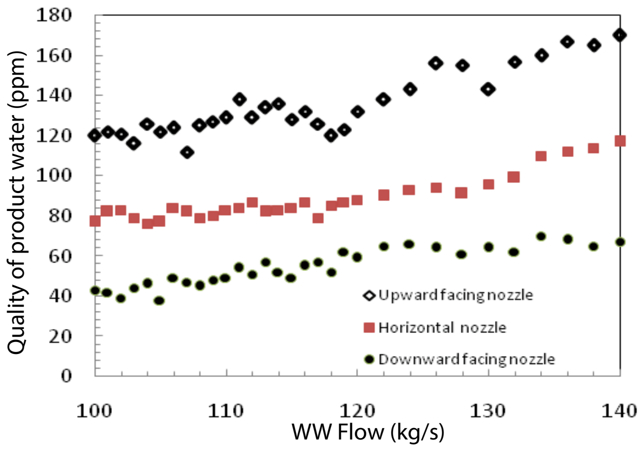

Fig. 11. Warm water flow rate vs. product water quality.

also higher on the downstream side of the de-mister when the vapor velocity is higher especially at a maximum flow rate of the feed water. While the downward-facing nozzle gives better quality than the upward and horizontal nozzle orientations. It is noted that the downward face nozzle orientation reduces the product water salinity by 2.4 times compared to an upward-facing nozzle and 1.6 times compared to the horizontal facing nozzle orientation.

In order to identify the reasonable accepted range of water quality corresponding to the chamber height with the consideration of the process efficiency, the present study indicates that the downward-facing nozzle gives the water quality in the range of 150–170 ppm, which is quite having more total dissolved solids in the product compared to the other two nozzle orientations with the minimum ppm of less than 500 ppm as suggested by standards available for drinking water quality. The downward-facing nozzle gives at least a closer range of water quality to meet the standards available for drinking water quality compared to the other remaining nozzle orientations, even though downward configuration exhibits a low generation of production rate. In the present study the chamber height up to the demister pad which decides the amount of salinity that entrains the demister is kept at 2.2 m from the base. The quality of the water could be controlled more efficiently by varying either the feeder height or demister elevation [20] for the given chamber height without much affecting the process efficiency.

6. Conclusion

A study was conducted to investigate the influence of feed water nozzles on the major factors of flashing phenomenon:

- Employing of upward nozzle enhances production rate by 1.2 times the horizontal nozzle orientation and 1.4 times the downward nozzle orientation.
- Also upward nozzle orientation projects 12.5% and 37.5% lesser NETD or thermal loss values compared to the horizontal and downward nozzle orientations respectively.
- Low NETD value or thermal loss was observed at high flow rates and low superheat values.
- The present study indicated that the highest flashing efficiency was observed in the range of 80 to 90% for the upward nozzle and the lowest efficiency (60%–65%) was observed for the downward nozzle.
- Upward nozzle orientation exhibits 4.7% and 7.1% higher efficiencies compared to the horizontal and downward nozzle orientations respectively.
- It was observed that upward nozzle exhibits 13.3% and 23.6% higher heat load compared to the horizontal and downward nozzle orientation respectively for the same feedwater flow rate.
- It was noticed that the downward face nozzle orientation decreases the product water salinity by 2.4 times compared to the upward-facing nozzle and 1.6 times compared to the horizontal facing nozzle orientation.

Symbols

M_f	—	Mass flow of feed water, kg/s
M_v	—	Mass flows of water vapor, kg/s
C_p	—	Specific heat capacity of seawater, kJ/kg K
h_{fg}	—	Latent heat of vaporization, kJ/kg
T_{in}	—	Feed water inlet temperature, K
T_{out}	—	Feed water outlet temperature, K
ΔT_{sup}	—	Superheat of the liquid, (K) ($T_{in} - T_{sat}$)
T_{sat}	—	Saturation temperature, K
ΔT_{actual}	—	Actual heat of the liquid, (K) ($T_{in} - T_{out}$)
P_{sat}	—	Saturation pressure, m bar, symbol
η	—	Flashing efficiency of evaporator, %
T	—	Intake seawater temperature, K
X	—	Salinity of the feed seawater, ppm

References

[1] S. Goto, Y. Yamamoto, T. Sugi, T. Yasunaga, Y. Ikegami, M. Nakamura, Construction of simulation model for spray flash desalination system, Electr. Eng. Jpn., 170 (2010) 9–17.

[2] J.-X. Wang, Y.-Z. Li, H.-S. Zhang, S.-N. Wang, Y.-F. Mao, Y.-N. Zhang, Y.-H. Liang, Investigation of a spray cooling system with two nozzles for space application, Appl. Therm. Eng., 89 (2015) 115–124.

[3] Z.-F. Zhou, B. Chen, R. Wang, G.-X. Wang, Comparative investigation on the spray characteristics and heat transfer dynamics of pulsed spray cooling with volatile cryogens, Exp. Therm Fluid Sci., 82 (2017) 189–197.
[4] J.-M. Tian, B. Chen, D. Li, Z.-F. Zhou, Transient spray cooling: similarity of dynamic heat flux for different cryogens, nozzles and substrates, Int. J. Heat Mass Transfer, 108 (2017) 561–571.
[5] W.-L. Cheng, W.-W. Zhang, S.-D. Shao, L.-J. Jiang, D.-L. Hong, Effects of inclination angle on plug-chip spray cooling in integrated enclosure, Appl. Therm. Eng., 91 (2015) 202–209.
[6] W.-L. Cheng, W.-W. Zhang, H. Chen, L. Hu, Spray cooling and flash evaporation cooling: the current development and application, Renewable Sustainable Energy Rev., 55 (2016) 614–628.
[7] R.J. Peterson, S.S. Grewal, M.M. El-Wakil, Investigations of liquid flashing and evaporation due to sudden depressurization, Int. J. Heat Mass Transfer, 27 (1984) 301–310.
[8] Y. Ikegami, H. Sasaki, T. Gouda, H. Uehara, Experimental study on a spray flash desalination (influence of the direction of injection), Desalination, 194 (2006) 81–89.
[9] O. Miyatake, K. Murakami, Y. Kawata, T. Fujii, Fundamental experiments with flash evaporation, Heat Transfer Jpn. Res., 2 (1973) 89–100.
[10] O. Miyatake, T. Tomimura, Y. Ide, T. Fujii, An experimental study of spray flash evaporation, Desalination, 36 (1981) 113–128.
[11] Q. Chen, K. Thu, T.D. Bui, Y. Li, K.C. Ng, K.J. Chua, Development of a model for spray evaporation based on droplet analysis, Desalination, 399 (2016) 69–77.
[12] B. Cai, Q. Zhang, Y. Jiang, H.F. Gu, H.J. Wang, Experimental study on spray flash evaporation under high temperature and pressure, Int. J. Heat Mass Transfer, 113 (2017) 1106–1115.
[13] A. Hosseini Araghi, M. Khiadani, M.H. Sadafi, K. Hooman, A numerical model and experimental verification for analyzing a new vacuum spray flash desalinator utilizing low grade energy, Desalination, 413 (2017) 109–118.
[14] Q. Chen, M. Kum Ja, Y. Li, K.J. Chua, Experimental and mathematical study of the spray flash evaporation phenomena, Appl. Therm. Eng., 130 (2018) 598–610.
[15] B. Cai, Q.Q. Wang, S.T. Yin, H.F. Gu, H.J. Wang, H.D. Zhen, L. Zhang, Energy analysis of spray flash evaporation from superheated upward jets, Appl. Therm. Eng., 148 (2019) 704–713.
[16] W.Z. Gao, J.Y. Qi, J.H. Zhang, G.M. Chen, D.W. Wu, An experimental study on explosive boiling of superheated droplets in vacuum spray flash evaporation, Int. J. Heat Mass Transfer, 144 (2019) 118552.
[17] F. Fathinia, Y.M. Al-Abdeli, M. Khiadani, Evaporation rates and temperature distributions in fine droplet flash evaporation sprays, Int. J. Therm. Sci., 145 (2019) 106037.
[18] O. Miyatake, Y. Koito, K. Tagawa, Y. Maruta, Transient characteristics and performance of a novel desalination system based on heat storage and spray flashing, Desalination, 137 (2001) 157–166.
[19] S. Mutair, Y. Ikegami, Experimental investigation on the characteristics of flash evaporation from superheated water jets for desalination, Desalination, 251 (2010) 103–111.
[20] D. Balaji, K. Jayaraj, S.V.S. Phani Kumar, M.V. Ramana Murthy, Water quality improvement studies in LTTD plant, Desal. Water Treat., 57 (2016) 24705–24715.