Mathematical Modeling of Bubbler Humidifier for Humidification-Dehumidification (HDH) Water Desalination System

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Abstract: - The scarcity of fresh water is an issue of high concern as most of the world population suffers from clean water shortage. One potential solution to tackle this issue is to develop efficient, reliable, and cost effective decentralized water desalination system to make the clean water accessible for most of the world population. Humidification-dehumidification (HDH) is a carrier gas based thermal technique that is ideal for a small scale decentralized water desalination system. An innovative design approach is to use the bubbler humidifier to enhance the performance of the HDH water desalination system. The aim of this work is to develop an analytical model for bubbler humidifier that can predict the heat and mass transfer without introducing any adjustable parameters. The effect of air inlet velocity, water column height, and perforated plate hole diameter on the heat and mass transfer is analyzed and engineering justifications are presented. Results indicate that the increase in air inlet velocity significantly enhance the heat and mass transfer coefficient. The increase in water column height and bubble diameters slightly decrease the total heat flux. The efficiency of humidifier in terms of water vapor contents in the air stream at the outlet of the humidifier is analyzed and findings showed that the increase in the temperature difference between the air and water stream increases the efficiency of the humidifier.

Keywords: - water desalination; HDH systems; direct contact heat and mass transfer; bubbler humidifier

1 Introduction

The fresh water scarcity, energy crisis, and climate change are the most intimidating concerns for mankind as it brought many disquiets like health, pollution, and environmental issues. The problem is more severe in developing countries where the population growth projection is much higher as compared to developed countries [1]. The increase in world population growth results in high demand for potable water that is predicted to be 6,900 billion m^3 by 2030. The existing supply of fresh water is 4,200 billion m^3 that is well below the projection of potable water demand [2]. The challenge is to provide sustainable solution to balance the potable water requirements by secure and affordable energy with the pressing issue of climate change.

Water is one of the most abundant resource present on earth. However, around 97.5 % of the earth water is saline, leaving behind approximately 2.5 % fresh water. Major part of the fresh water is hard to access as it is frozen as icecaps and glaciers. Therefore, very little quantity of fresh water is available to support our lives. However, rapid population growth have resulted in higher fresh water demand for domestic as well as agriculture sector to produce adequate quantities of food. While the fresh water demand is rising exponentially, the industrial revolution is making the fresh water scarcity situation more alarming by polluting the lakes and rivers by industrial waste. Keeping in mind the aforementioned concerns, the number of people affected by clean water scarcity are expected to escalate four times over the next 25 years [3].

Given the fact that the population on earth continues to increase and industrial growth shows no signs of slowing down, it is inevitable that conventional sources of freshwater are not sustainable. To alleviate this threatening drift and the apprehensions of the existing and approaching crisis, the answer for sustainability may lie in decentralized small scale water desalination.

2 Solar desalination

Solar distillation is an appropriate choice for decentralized small scale water desalination systems, especially in remote regions where inexpensive land and abundant solar radiation are available. Conventional solar still is one technique used to distill water. In this technique all functional processes for water desalination (solar absorption, evaporation, and condensation) occur within the single compartment as shown in fig. 1. The major disadvantage of solar still is its low efficiency. This type of solar distillation experiences very low productivity and requires relatively large landscape.

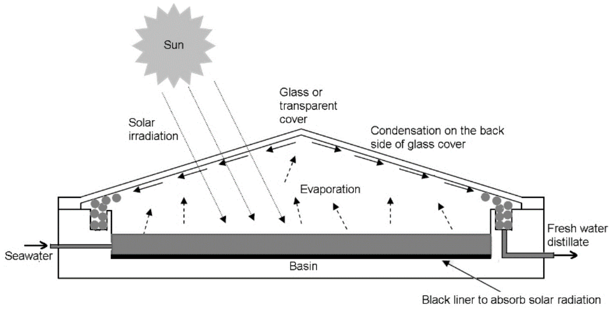

Fig. 1. Conventional solar still.

An improved technique is known as humidification-dehumidification (HDH) technique in which various functional processes (solar absorption, evaporation, and condensation) occur within a separate component as shown in fig. 2. These separate compartments are known as humidifier, dehumidifier, and external thermal energy source. In HDH process, the warm saline water comes in direct contact with unsaturated air in the humidifier. Consequently, air comes out hot and humid at the exit of the humidifier. Then, this humid air is passed through the dehumidifier to extract water out of the humidified air. Because of better control over condensation and evaporation processes, efficiency has been improved noticeably in HDH process as compared to solar still. Other advantages of HDH process include its simple, flexible and modular nature, ability to utilize waste heat resources and low grade energy, usage of low-cost construction materials, and moderate investment constraint.

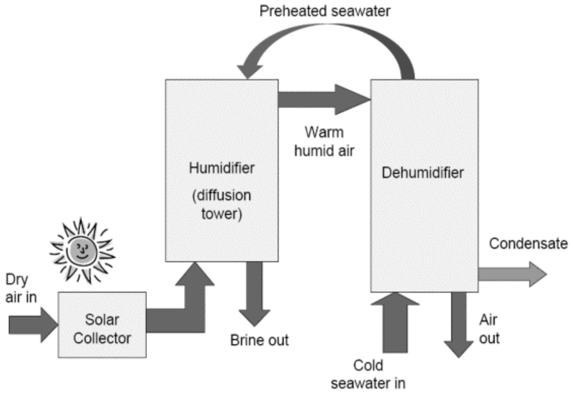

Fig. 2. Schematic of humidification-dehumidification (HDH) unit [4].

2.1 Heat and Mass Balances

By applying the principle of mass conservation, the mass flow rate of air always remain same throughout the system. Therefore,

$$\dot{m}_{a,i} = \dot{m}_{a,o} = \dot{m}_a \tag{1}$$

In the humidifier, hot saline water transfers the mass and heat to unsaturated air. The mass and energy balance of the humidifier is defined by the following equations:

Mass balance:

$$\dot{m}_{w,i} = \dot{m}_{w,o} + \dot{m}_a(\omega_{a,o} - \omega_{a,i}) \tag{2}$$

Energy balance:

$$\dot{m}_{w,i}h_{w,i} = \dot{m}_{w,o}h_{w,o} - \dot{m}_a\left(h_{a,i} - h_{a,o}\right) \tag{3}$$

In the dehumidifier, feed water only exchanges heat with hot humid air. No mass transfer take place to or from the feed water. Therefore, mass flow rate of the feed water is constant in dehumidifier and hence,

$$\dot{m}_{w,o} = \dot{m}_{w,i} \tag{4}$$

The hot humid air condensed in the dehumidifier to form the distilled water. The mass and energy balance of the dehumidifier is described by the following equations:

Mass balance:

$$\dot{m}_{fw} = \dot{m}_a(\omega_{a,i} - \omega_{a,o}) \tag{5}$$

Energy balance:

$$\begin{aligned}&\dot{m}_a\left(h_{a,i}\right) + \dot{m}_{w,i}(h_{w,i})\\ &= \dot{m}_a(\, h_{a,o}) + \dot{m}_{w,o}(h_{w,o}) + \dot{m}_{fw}h_{fw}\end{aligned} \tag{6}$$

3 Improvements in HDH Systems

Humidification-dehumidification (HDH) is a carrier gas based thermal technique that is ideal for small scale water desalination systems [5]. Several literature studies are available that explore HDH as an effective mean of seawater desalination. The main focus of the researchers in developing a small scale water desalination unit is to achieve efficient evaporation and condensation in these systems. Some of the early work includes those by El-Dessouky [6], Abdel-Salam et al. [7], Al-Hallaj et al. [8], Muller-Holst et al. [9], Bourouni et al. [10], and Xiong et al. [11]. In these studies conventional shell and tube heat exchangers were used as condensers for the dehumidification process. Film condensation over tubes is extremely inefficient as the process involves condensing water vapor out of air-water vapor mixture. The presence of air in water vapors is an issue of high concerns as it adversely affects the access of water vapors to the cold tube surface and results in a lower efficiency of an HDH system. To enhance the condensation in the presence of air, a direct contact condenser was used in a diffusion-driven desalination technology described by Klausner and co-workers at the University of Florida [12, 13]. The heat transfer coefficient is higher for the direct contact dehumidifier but the system heat recovery potential is less. Narayan et al. [14] proposed an innovative design approach to use a bubbler dehumidifier for efficient condensation. In their study, the moist air is mainly condensed in a pool of cold water instead of condensing on cold surface.

In the humidifier, air comes in contact with water and humidified. The aim of the humidifier is to increase the area and time of contact between the water and air. There are many devices that can be used for the humidification purpose. These devices include spray tower, wetted wall tower, packed bed tower, and bubble column.

In the spray tower, water is sprayed in the form of droplets that falls under the force of gravity. The air is injected from the bottom that comes in a direct contact with the falling water droplets. These type of devices have low humidification effectiveness due to the low water holdup. Other limitations include the use of mist eliminators that is essential to avoid the water entrainment in the air at the exit of the spray tower. Furthermore, the losses in the spray nozzles caused a high pressure drop in the water stream.

Wetted wall towers could also be used in an HDH system for air humidification purpose. In this type, thin water film flows downward on the inner perimeter to form a wetted surface along a tower length. The air stream can either flow upward or downward to have a direct contact with the falling water thin film. These towers have a higher humidification efficiency and a lower air side pressure drop as compared to other humidification towers. However, the water flow rate is restricted to a lower capacity due to the limitation of the thin film water flow only on the inner perimeter of the tower.

The packed bed tower is the widely practiced humidification device in the HDH water desalination system. It is similar to the spray towers in which the water is sprayed in the form of droplets that falls under the force of gravity. However, in the packed bed tower, packing material is used to improve the humidification efficiency. The use of packing material makes the water droplets more dispersed which increase the area and time of contact between the water and air. However, this improvement leads to a higher pressure drop in the packed bed humidifier.

3.1 Bubbler Humidifier

An innovative design approach is to use the bubbler humidifier. The choice of a bubbler humidifier has been inspired due to the higher rate of heat transfer in the liquid-gas dispersion. In this humidifier configuration, air is passed through perforated plate to form bubbles in hot water column. As the air bubbles propagate through hot water column, simultaneous heat and mass transfer take place and air comes out hot and humid at the outlet of humidifier. The bubbles formation increases the surface of contact, which leads to performance enhancement of the humidification process.

El-Agouz and Abugderah [15] carried out an experimental investigation of a single stage bubbler humidifier. An evaporator column of 500 mm x 250 mm square cross section was used in this experiment. The air stream is introduced by a 75 mm diameter PVC pipe having 32 holes of 10 mm diameter on both sides. The pipe was submerged in the water and acted as a sparger to form bubbles in the pool of water. In this study, they considered the effect of different operating parameters on the humidifier efficiency. These operating parameters include water inlet temperature, the air inlet temperature, and the air inlet velocity. The results specified that the performance of the bubbler humidifier is considerably affected by the inlet air velocity and inlet water temperature. The air inlet temperature has a small influence on vapor content difference in the air. The highest efficiency achieved for the bubbler humidifier was reported as 95 % with 222 gw/kga at 75 °C of air and water temperatures. Geometrical features such as the number of holes, holes diameter, column diameter, and water column height were not considered.

El-Agouz [16] performed another experimental study of a single stage bubbler humidifier. An evaporator column of 400 mm x 300 mm square cross section was used in this experiment. The air stream is introduced by a 75 mm diameter copper pipe having 44 holes of 15 mm diameter on the upper side. The pipe was submerged in the water and acted as a sparger to form bubbles in the pool of water. This experimental work aimed to analyze the effect of different operating parameters on the bubbler humidifier efficiency. These operating parameters include the water column height, the water column temperature, and the air flow rate. The results showed that the performance of bubbler humidifier is increased with the increase in water column temperature and air flow rate. The effect of water column height on the efficiency of the bubbler humidifier is not significant. The maximum efficiency achieved for the bubbler humidifier was reported as 98 % at air flow rate of 14 kg/hr and 85 °C of water temperatures.

Zhang et al. [17] performed the experiment on the single stage bubbler humidifier to analyze the effect of air flow rate and water level on the pressure drop and relative humidity of air. A cylindrical column of 198 mm diameter was used as an evaporator chamber in this experiment. A sieve plate of 8 mm thickness having 91 holes of 1 mm diameter was used as sparger. This experimental work aimed to achieve a higher water content at the exit of humidifier with less pressure drop and less blower power consumption. The results showed that the increase in the water level and air flow rate caused greater pressure drop and higher blower energy consumption. The moisture contents at the exit of the humidifier were increased with the increase of water and air temperatures. In the range of experimental operating conditions, the experimental results showed that the air reached 100 % relative humidity.

In all the experimental investigation of the bubbler humidifier [15-17], the humidification efficiency was evaluated by using the following equation:

$$\eta = \frac{\omega_o - \omega_i}{\omega_{o_{sat}} - \omega_i} \tag{7}$$

As the core objective of the direct contact humidifier is to attain higher vapor contents in the moist air at the outlet, the efficiency of the humidifier can be represented in terms of the humidity of moist air at its inlet and outlet states. However, this approach is not appropriate as the effect of water temperature is not taken into consideration. Narayan et al. [18] proved that an energy based effectiveness is a more suitable approach to evaluate the performance of heat and mass exchanger devices like humidifier. The effectiveness of direct contact heat and mass exchanger humidifier can be calculated by the expression proposed by Narayan et al., which is defined as

$$\epsilon_H = \frac{\Delta\dot{H}}{\Delta\dot{H}_{max}} \tag{8}$$

where $\Delta\dot{H}_{max}$ is defined separately for water and air stream. In the case of air passing through the hot water column, the ideal condition for air at the exit can be achieved when it is saturated at water inlet temperature. The effectiveness of humidifier in terms of air stream can be defined as

$$For\ \ \Delta\dot{H}_{max,w} > \Delta\dot{H}_{max,a}$$

$$\epsilon_H = \frac{h_{a,o} - h_{a,i}}{h_{a,o}^{ideal} - h_{a,i}} \tag{9}$$

where $h_{a,o}^{ideal}$ is calculated at water inlet temperature in the humidifier.

In the HDH desalination systems, bubbler humidifiers are not practiced for humidification purpose so far. There are very few studies that investigate the bubbler humidifier. Therefore, there is a need to explore the potential of bubbler humidifier as an efficient decentralized small scale water desalination system.

4 Theoretical modeling for bubbler column

In the bubbler column, air is passed through perforated plate to form bubbles in the hot water column as shown in fig. 3. As the air bubbles propagate through hot water column, simultaneous heat and mass transfer take place and air comes out hot and humid at the outlet of bubbler column.

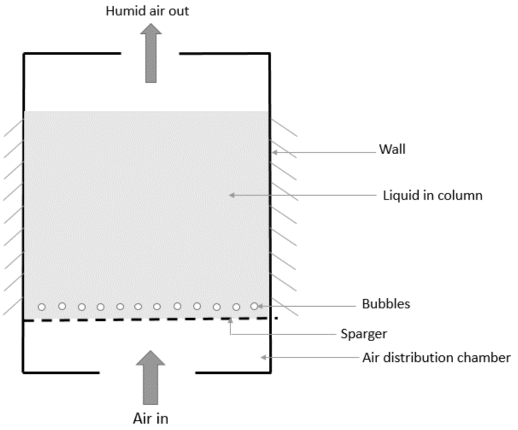

Fig. 3. Air humidification in bubbler column.

For the bubbler humidifier modeling, it is important to understate the mechanism of heat transfer in a bubbler column. Heat transfer to the liquid-gas diffusion is studied by many researcher and they suggested different models to analyze the effect of heat transfer coefficient on different parameters. Kobel et al. [19] studies showed that the liquid properties and gas velocity have the main impact on heat transfer coefficient. Kast [20] studied the effect of rising a bubble in the fluid and described that the fluid element in the front of the rising bubble moves toward the wall due to the radial momentum that it received by uprising the bubble. This radial momentum of the fluid breaks the boundary layer at the wall and the boundary layer assumption is not valid, especially in the case of high bubbles concentration. Conversely, the uprising bubble form a wake underneath it that sucks the fluid radially. The fast radial exchange flow due to uprising bubble results in a capacitive heat transfer. This mechanism is illustrated in fig. 4.

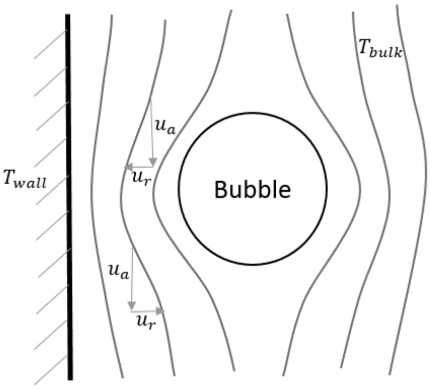

Fig. 4. Flow around rising bubble.

4.1 Mathematical Model

The mathematical modelling for a direct contact heat and mass transfer in the bubbler humidifier includes the following assumptions:

- The water in a bubbler column is at a uniform temperature, T_{bulk}.
- The liquid-gas interface in a water column experience the same temperature as the water bulk temperature.
- Bubbles experience a uniform temperature in the water column as the residence time of bubbles in water column is much lower than the required time to change the temperature of water.

The fluid will be in contact with the uprising bubble for a certain period of time. Hibbies Surface Renewal Theory explains the behavior of the uprising bubble with respect to time [21]. According to Hibbies Surface Renewal Theory, the mass is transported when it is in contact with water and the contact time (residence time) is equal roughly the same time required for the bubble to move one diameter further. Unsteady heat diffusion takes place adjacent to the surface in the fluid element that can be described as follow:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial^2 x} \tag{10}$$

This problem is defined by the boundary conditions that corresponds the temperature T as the wall temperature at x = 0 for all values of time, the bulk (column) temperature as starting temperature for all values of x, and bulk temperature for all values of time when x = ∞. The last condition requires the infinite depth of the fluid and very short time of contact.

$T=T_{wall}$	$x = 0$	$t \geq 0$
$T=T_{bulk}$	$x > 0$	$t = 0$
$T=T_{bulk}$	$x = \infty$	$t > 0$

Laplace transformation of equation (10) with boundary conditions results in instantaneous temperature profile that is used to get the following expression of heat flux:

$$q = \frac{2}{\sqrt{\pi}} \sqrt{\frac{k\rho C_p}{t}} (T_{wall} - T_{bulk}) \tag{11}$$

where, t is the renewal time calculated as

$$t = \frac{d_b}{V_c} \tag{12}$$

To calculate the surface renewal time, we need to evaluate the bubble diameter d_b and liquid circulation velocity V_c. The bubble diameter can be calculated by the following expression given by Miller DN [22]

$$d_b = \left\{ \frac{6\sigma d_o}{(\rho_l - \rho_g).\, g} \right\}^{1/3} \tag{12}$$

Liquid circulation velocity can be calculated by the following expression suggested by Field and Rahimi [23]

$$V_c = 1.36\{gH(V_g - \varepsilon V_b)\} \tag{13}$$

where, ε is the volumetric gas holdup that can be calculated as follow:

$$\varepsilon = \frac{V_g}{0.3 + 2V_g} \tag{14}$$

Bubble velocity V_b, can be calculated from the following expression based on Mendelson's wave equation [24]:

$$V_b = \sqrt{\frac{2\sigma}{\rho_l d_b} + \frac{g d_b}{2}} \tag{15}$$

4.2 Heat and Mass Transfer

A thermal resistance model that includes both heat and mass transfer associated with air humidification in the bubble column is shown in fig. 5.

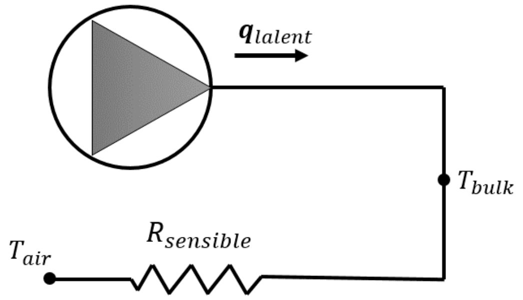

Fig. 5. Thermal resistance model for bubbler humidifier.

The two temperature nodes in the thermal resistance model represents the average air temperature of the bubbles (T_{air}) and the bulk temperature of the liquid column (T_{bulk}). Simultaneous heat and mass transfer is taking place between these two temperature nodes. The thermal resistance $R_{sensible}$ is responsible for the heat transfer and heat source q_{latent} symbolizes the mass transfer between the fluid and bubbles. The latent heat flux through diffusion of water vapors to bubbles and sensible heat flux via thermal resistance $R_{sensible}$ sum up to give overall heat flux *(q)* between the liquid and bubbles. It is defined as

$$q = q_{latent} + q_{sensible} \tag{16}$$

Heat flux due to evaporation is given by following equation

$$q_{latent} = j.h_{fg} \tag{17}$$

Where, j is the mass flux calculated as

$$j = \frac{\dot{m}_a}{A}(\omega_o - \omega_i) \tag{18}$$

The sensible heat flux ($q_{sensible}$) via thermal resistance $R_{sensible}$ is calculated as

$$q_{sensible} = \frac{T_{lmtd}}{R_{sensible}} \tag{19}$$

where, T_{lmtd} is the log mean temperature difference calculated as

$$T_{lmtd} = \frac{(T_{bulk} - T_{a,i}) - (T_{bulk} - T_{a,o})}{ln\left[\frac{(T_{bulk} - T_{a,i})}{(T_{bulk} - T_{a,o})}\right]} \tag{20}$$

$R_{sensible}$ is the thermal resistance associated with the sensible heat transfer from the liquid column to bubbles and can be calculated as

$$R_{sensible} = \frac{1}{h_t A} \tag{21}$$

where, h_t is the heat transfer coefficient linked with $R_{sensible}$ that can be calculated by introducing Lewis factor. Lewis factor linked the heat transfer to the mass transfer as follow:

$$h_t = Le_f(\rho c_p k_l)\frac{a_s vol}{A} \tag{21}$$

The area in the heat transfer coefficient expression is normalized by introducing specific interfacial area (a_s) of bubbles. The specific interfacial area (a_s),can be measured by the following expression presented by Miller DN [22]

$$a_s = \frac{6\varepsilon}{d_b} \tag{22}$$

Le_f is the Lewis factor calculated as

$$Le_f \cong Le^{2/3} \tag{23}$$

where, Le is Lewis number for air-water system and defined as

$$Le = \frac{\alpha}{D_{AB}} \tag{24}$$

k_l is the mass transfer coefficient linked with the latent heat and can be calculated as

$$\frac{1}{k_l} = \left(\frac{1}{k_{l,1}} + \frac{1}{k_{l,2}}\right)^{-1} \qquad (25)$$

where, $k_{l,1}$ and $k_{l,2}$ are mass transfer resistences that can be calculated by the expressions presented by Narayan et al. [14] which are defined as

$$k_{l,1} = \frac{D_{AB}}{d_b/2} \qquad (26)$$

$$k_{l,2} = \frac{2}{\sqrt{\pi}}\sqrt{\frac{D_{AB}}{t}} \qquad (27)$$

Where, t represents the surface renewal time that can be calculated as follow

$$t = \frac{d_b}{V_s} \qquad (28)$$

5 Results and Discussion

The aforementioned equations are simultaneously solved using Engineering Equation solver (EES). The effect of some important parameters that include air superficial velocity, water column height, and perforated plate hole diameter on heat and mass transfer is analyzed. The influence of air superficial velocity on the heat transfer coefficient at different water column height is presented in fig. 6. The results showed that the air superficial velocity strongly influence the heat transfer coefficient in the bubbler humidifier and heat transfer coefficient value increases as the air superficial velocity increases. The trend shows the remarkable resemblance with many researchers that investigate the effect of air superficial velocity on heat transfer coefficient in bubbler column [25, 26].

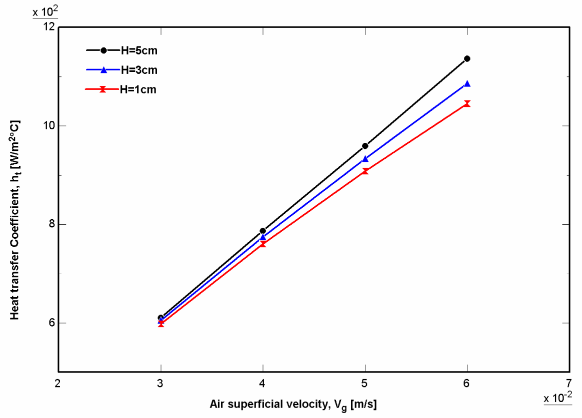

Fig. 6. Influence of air superficial velocity on heat transfer coefficient.

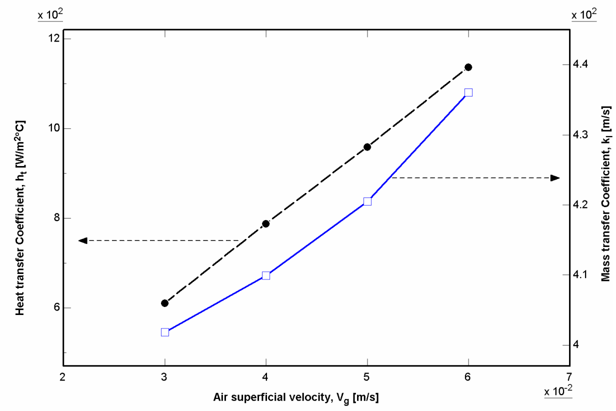

Fig. 7. Influence of air superficial velocity on heat and mass transfer coefficient.

In the heat transfer coefficient modeling, we introduced the Lewis factor that is used in governing equations of simultaneous heat and mass transfer. The influence of air superficial velocity on mass transfer coefficient is also analyzed along with the heat transfer coefficient and presented in fig. 7. Findings indicated that the increase in superficial velocity increases the mass transfer coefficient that is directly linked with the heat transfer coefficient via Lewis factor. Hence, both the heat and mass transfer coefficient are significantly increased as the air superficial velocity increases.

The water and air inlet temperature are important factors that need to be analyzed to evaluate the performance of the bubbler humidifier. The effect of temperature difference between water and air stream on the latent heat flux and sensible heat flux is presented in fig. 8. Findings showed that the increase in the temperature difference between water and air stream increases the sensible and latent heat flux.

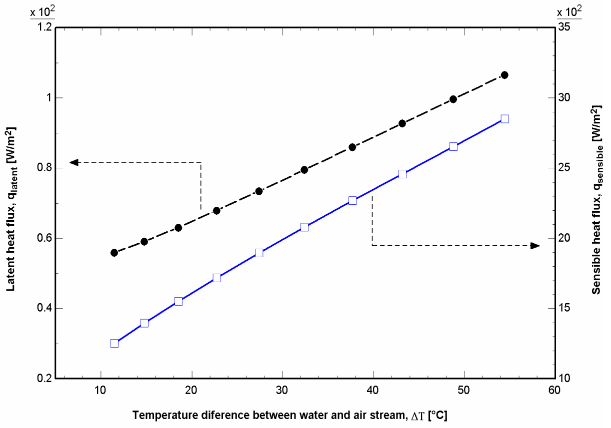

Fig. 8. Influence of temperature difference between water and air stream on latent and sensible heat flux.

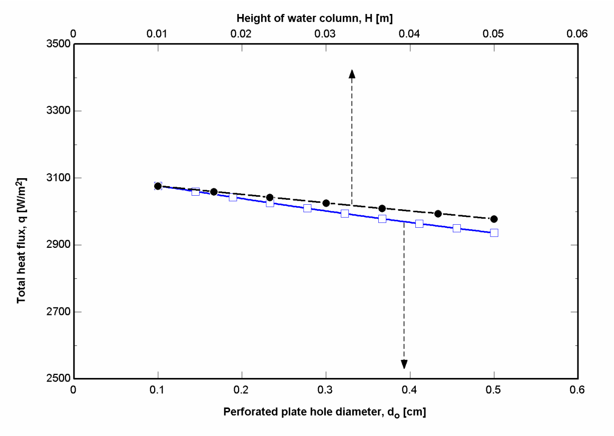

Fig. 9. Influence of perforated plate hole diameter and water column height on total heat flux.

The total heat flux in the bubbler humidifier is the sum of the sensible heat flux that is linked with heat transfer coefficient and latent heat flux that is linked with mass transfer coefficient. The effect of perforated plate hole diameter and water column height on total heat flux is shown in fig. 9. The results showed that the increase in perforated plate hole diameter and water column height slightly decreases the heat transfer coefficient. Although, the influence of the perforated plate hole diameter and liquid column height on the total heat flux is not much significant but it is worth mentioning their trends as they provides vital information in designing the bubbler humidification column.

The efficiency of the humidifier can be examined by the amount of water that the air can take with it while passing through the water column. To investigate the vapor content difference between the air inlet and outlet condition, the effect of increasing the temperature difference between water and air stream is analyzed and presented in fig. 10. The results shown in fig. 10 indicated that the difference in vapor content is higher for higher temperature difference. The trend is justifiable by the fact that by increasing the temperature difference between water and air stream, the ability of air to absorb the amount of water increases and consequently higher vapor content difference occurs. The result shows the resemblance with many researchers that investigate the effect of increase in water column temperature on the efficiency of bubbler humidifier [15, 17].

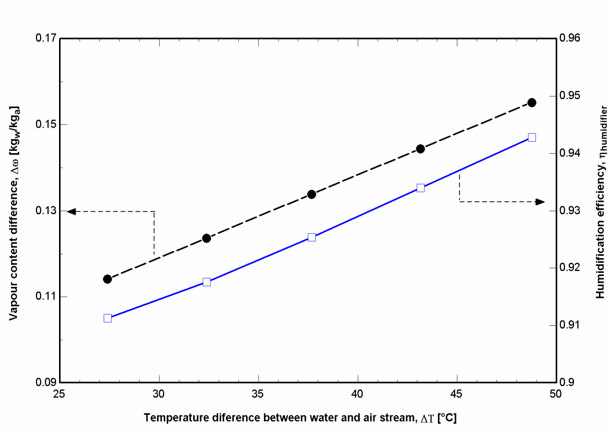

Fig. 10. Influence of temperature difference between water and air stream on humidification efficiency.

Conclusions

- Humidification-dehumidification (HDH) is a carrier gas based thermal technique that is ideal for a small scale decentralized water desalination system. An innovative design approach is to use the bubbler humidifier to enhance the performance of the HDH water desalination system.
- The analytical model of the direct contact heat and mass transfer bubbler humidifier was developed in this study. It can predict the heat and mass transfer without introducing any adjustable parameters. The current model is considered a good approximation for the experimental data.
- Findings indicate that the increase in air inlet velocity significantly enhance the heat transfer coefficient while the increase in the water column height and perforated plate hole diameter slightly decreases the heat transfer coefficient.
- The efficiency of humidifier in terms of the water vapor contents in the air stream at the outlet of humidifier is analyzed and results are indicative of increase in humidification efficiency with the increase in temperature difference between water and air stream.

Acknowledgments

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Nomenclature

a_s	specific interfacial area	$m^2\ m^{-3}$
c_p	specific heat capacity	$J\ kg^{-1}\ k^{-1}$
D_{AB}	diffusion coefficient	$m^2\ s^{-1}$
d_b	bubble diameter	m
d_o	hole diameter	cm

H	liquid column height	m
$\dot{H}$	enthalpy rate	W
h_a	specific enthalpy of air–vapor mixture	J kg^{-1}
h_{fg}	specific enthalpy of vaporization	J kg^{-1}
h_t	heat-transfer coefficient	W m^{-2} k^{-1}
j	mass flux	Kg m^2 s^{-1}
k	thermal conductivity	W m^{-1} k^{-1}
k_l	mass transfer coefficient	m s^{-1}
Le	Lewis number	-
l	length scale	m
$\dot{m}$	mass flow rate	Kg s^{-1}
q	total heat flux	W m^{-2}
q_{latent}	latent heat flux	W m^{-2}
$q_{sensible}$	sensible heat flux	W m^{-2}
$R_{sensible}$	thermal resistance for sensible heat	K m^2 W^{-1}
T_{air}	temperature of air	°C
T_{bulk}	bulk temperature of the liquid column	°C
T_{lmtd}	log mean temperature difference	°C
V_b	velocity of bubble	m s^{-1}
V_c	velocity of fluid circulation	m s^{-1}
Vg	superficial gas velocity	m s^{-1}
V_r	velocity in radial direction	m s^{-1}
vol	volume of liquid column	m^3

Greek symbols

α	thermal diffusivity	m^2 s^{-1}
Δ	change or difference	-
η	humidifier efficiency	-
ϵ	effectiveness	-
ε	volumetric gas holdup	-
ρ	density	kg m^{-3}
σ	surface tension	N m^{-1}
ω	specific humidity	kg$_w$ kg$_a$$^{-1}$

Subscripts

a	air
b	bulk
g	gas
H	humidifier
i	inlet
l	liquid
max	maximum
o	outlet
sat	saturated
w	water

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