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Experimental Analysis of Solar Driven Bubble Column Humidifier for Humidification-Dehumidification (HDH) Water Desalination System

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Abstract

Humidification-dehumidification (HDH) is a carrier gas based thermal technique, which is ideal as a small scale decentralized water desalination system. An innovative design approach is to use the bubble column humidifier to enhance the performance of the HDH water desalination system. Therefore, a novel bubble column humidifier is proposed which is operated through solar thermal energy as the main source of energy input. The overall objective of this work is to develop and test the novel bubble column humidifier to identify the optimum performance operating conditions for its possible integration with a dehumidifier. The design of the bubble column humidifier is optimized in terms of perforated plate geometric features to reduce the overall pressure drop in the system. The study addresses the relation between the air pressure variation with water column height and air superficial velocity varies. The proposed bubble column humidifier is integrated with Fresnel lens to increase the water temperature as it enters the humidifier. The influence of water temperature on the vapor density is investigated at different air superficial velocities. Results indicate that the vapor density in the bubble column humidifier is significantly increased with the increase in the water temperature and air superficial velocity. One major advantages of this proposed humidifier is its ability to have a direct solar thermal heating. Subsequently, it can be located in remote areas.

Keywords: *solar thermal energy, water desalination, HDH systems, bubble column humidifier, Fresnel lens*

1. Introduction

The fresh water is the essence of life and its scarcity is the most threatening concern for mankind. The problem is more severe in developing countries where the population growth projection is much higher as compared to developed countries (Fiorenza et al., 2003). The rapid population growth resulted in higher fresh water demands for domestic and agriculture sectors 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. Given the fact that the population on earth continues to increase and industrial growth shows no signs of slowing down, it is expected that the number of people affected by clean water scarcity will escalate four times over the next 25 years (Miller, 2003). To alleviate the worries of the existing and approaching fresh water crisis, the answer for water sustainability may lie in developing the decentralized small scale water desalination system.

Solar humidification-dehumidification (HDH) is an appropriate choice for decentralized small scale water desalination system, especially in remote regions where inexpensive land and abundant solar radiations are available. The challenge is to come up with an efficient, reliable, and cost effective design approach to explore the true potential of the HDH water desalination systems. Several studies are available that explore HDH as an effective means of seawater desalination. However, the main focus of these studies is to improve the dehumidification process of the HDH system and very less attention is given towards the improvement of humidification process.

Humidification is one of the fundamental processes in the solar HDH water desalination system. There are many devices which can be used for the humidification purpose. These devices include spray tower, wetted wall tower,

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packed bed tower, and bubble column (Treybal, 1980). The aim of all these devices is to raise the humidity of the air by diffusion of water into unsaturated air stream. This diffusion process is caused by the concentration difference between the water vapor in the air and air-water interface.

Several studies considered using spray tower as a humidification device in theair HDH system. In the spray tower, water is sprayed in the form of droplets that falls under the force of gravity. Air is injected from the bottom to come in a direct contact with the falling water droplets in a counterflow arrangement. These type of devices have low humidification effectiveness due to the low water holdup. Other limitations include the use of mist eliminators which are 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. Younis et al. (1993), Ben-Amara et al. (2004), and Orfi et al. (2004) used spray tower as a humidification device and studied the effect of water-to-air mass flow rate ratio on the humidification efficiency. They varied the water-to-air mass flow rate ratio while keeping the absolute humidity and inlet water temperature constant. Moreover, the sprayed water temperature (60 ˚C) was kept less than the inlet air temperature (80 ˚C). The results showed that the absolute outlet humidity increased with increasing the amount of sprayed water to a certain level. However, further increase in the quantity of water initiated the air cooling and condensation of water vapor in the air. This process resulted in the decrease of absolute humidity although the outlet air is always saturated. This implies that air heated HDH cycle provides maximum air humidity at an optimum water-to-air mass flow rate ratio. Therefore, use of the multi stage air heated HDH system increases the production of fresh water.

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. Wallis and Aull (1999) used polypropylene made vertically hanging fleeces for their wetted wall humidifier. The thin film of the heated water was distributed and trickled downward along the inner perimeter of the fleeces to form a wetted surface. The dry air streamed upwards and came out saturated at the outlet of the humidifier. Orfi et al. (2004) employed an improved heat and mass exchange design for a wetted wall humidifier. In their design, the water flowing velocity was reduced for better heat and mass exchange. The reduction in water flow velocity was ensured by covering the wooden vertical wetted walls with a cotton wick. The wooden vertical walls were always kept wet using capillary force. This design improvement ensued higher humidifier performance and claimed to achieve around 100 % humidification efficiency.

The packed bed tower is a widely practiced humidification device in the HDH water desalination system owing to its better performance. It is similar to the spray towers in which water is sprayed in the form of droplets that fall under the force of gravity. However, in the packed bed tower, the packing material is used to improve the humidification efficiency. The use of packing material makes the water droplets more dispersed which increases the area and time of contact between both water and air. However, this improvement leads to a higher pressure drop in the packed bed humidifier. Tab. 1 shows different packing materials. Several factors affect the choice of the packing materials and their heat and mass transfer, e.g. pressure drop, durability, cost, and quality of water. Development of packing materials in the HDH systems were reported by Mirsky and Bauthier (1993) and the performance of different packing materials in such systems were investigated by Aull and Krell (2000). Wallis and Aull (1999) showed a gradual change of fills types in packed bed towers. Introduction of film fills caused a tremendous change by providing higher thermal performance by reducing pressure drop and increasing water to air contact area. However, older splash type fill packing is being used because all these benefits are lost pertaining to high fouling potential.

1.1 Bubble Column humidifier

An innovative design approach is to use the bubble column as a humidification device for a HDH water desalination system. The choice of a bubble column as a humidifier has been inspired due to the higher rate of heat and mass transfer in the liquid-gas dispersion. In this humidifier configuration, air is passed through perforated plates to form bubbles in the hot water column. As the air bubbles propagate through the hot water column, simultaneous heat and mass transfer take place where air becomes hot and humid at the outlet of the humidifier. Heat transfer to the liquid-gas diffusion has been studied by many researchers who suggested different models to analyze the effect of heat transfer coefficient on different system parameters. Kobel et.al (1958) showed that the liquid properties and gas velocity have the main impact on the heat transfer coefficient. Kast (1962) studied the effect of rising a bubble in the fluid and indicated 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 sucks the fluid radially. The fast radial exchange flow due to uprising bubble results in a capacitive heat transfer. The flow around rising bubble and air humidification in the bubble column humidifier is illustrated in Fig. 1.

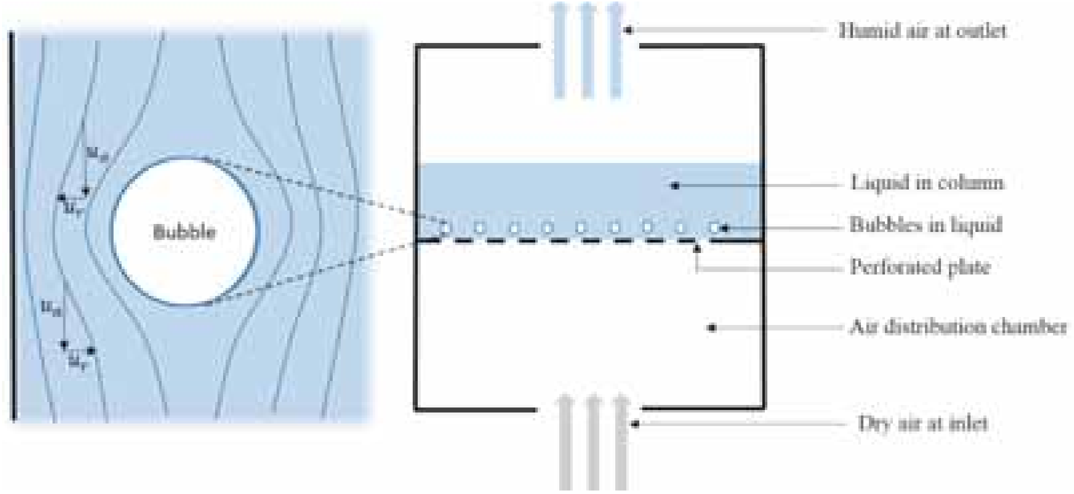

Fig. 1: Flow around rising bubble and air humidification in bubble column humidifier.

The higher rate of heat and mass transfer in a bubble column inspired the researchers to extensively practice these devices as multiphase reactor in chemical process like fisher-tropsch process, in metallurgical and many biomedical applications. However, the use of bubble column humidifier in HDH water desalination is very limited and there are very few studies that investigate the bubble column as a humidifier for HDH water desalination system. El-Agouz and Abugderah (2008) carried out an experimental investigation of a single stage bubble column humidifier. An evaporator column of 500 mm x 250 mm 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. 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. Their results specified that the performance of the bubble column humidifier is considerably affected by the inlet air velocity and the inlet water temperature. The air inlet temperature has a small influence on the vapor content difference in the air. The highest efficiency achieved for the bubble column 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, open area ratio, and water column height were not considered in this study. El-Agouz (2010) performed another experimental study to analyze the effect of water column height, water column temperature, and air flow rate on the performance of bubble column humidifier. The effect of water column height on the efficiency of the bubble column humidifier was not significant. However, the performance of bubble column humidifier was increased with the increase in the water column temperature and air flow rate. The maximum efficiency achieved for the bubble column humidifier was reported as 98 % at air flow rate of 14 kg/hr and water temperature of 85 °C.

Zhang et al. (2011) performed an experiment on a single stage bubble column humidifier to analyze the effect of air flow rate and water level on the pressure drop and the relative humidity of air. A cylindrical column of 198 mm diameter was used as an evaporator chamber in their experiment. A sieve plate of 8 mm thickness having 91 holes of 1 mm diameter was used as sparger. Their experimental work aimed to achieve higher water vapor in the air 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 the 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 aforementioned experimental investigation of the bubble column humidifier, water is heated by an electric heater that limits the use of these devices in remote areas where electricity availability is scarce. Therefore, a novel bubble column humidifier is proposed that is operated through solar thermal energy as the main source of energy input. In this novel humidifier, the absorber plate and bubble column were incorporated in a single frame design, as shown in Fig. 2. The absorber plate was painted black and titled to an angle equal to the latitude of Dhahran to absorb the maximum solar radiations. This design improvement has the following advantages:

- The tilted absorber plate acts as a sloped surface to create a thin film of water over the absorber plate. The minimum water depth over the absorber plate leads to better heat transfer and higher water temperature is achieved at the exit of absorber plate. It also results in minimum pressure drop in the air-side.
- The hot humid air at the exit of bubble column further passed over the thin film of hot water flowing over absorber plate to absorb more moisture and higher vapor contents are achieved at the exit of humidifier.

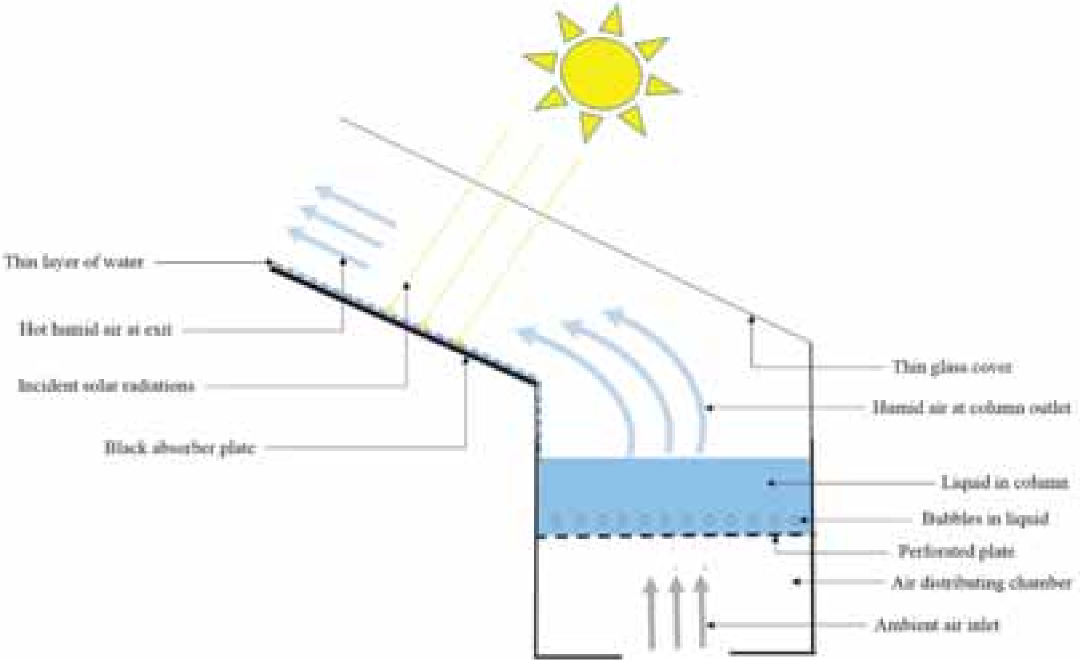

Fig. 2: Bubble column humidifier incorporated with absorber plate.

The overall objective of this work is to develop and test a new humidifier design to identify the optimum operating conditions for possible integration with a dehumidifier. Consequently, an improved HDH performance design is obtained. One major advantage of this proposed humidifier is its ability to have direct solar thermal heating. Subsequently, it can be located in remote areas.

2. Experimental Setup

A laboratory scale setup for the proposed bubble column humidifier was designed and built as shown in Fig. 3. The frame of the experimental setup was constructed of 100 mm thick Plexiglas sheet. Plexiglas is a transparent thermoplastic material that has a thermal conductivity of 0.19 W/m.K. The use of such transparent material is advantageous in a sense that it allows the observer to see what is happening inside the unit while performing the experiment. Another advantage of using the Plexiglas is its low thermal conductivity that reduces the heat loses from the system. Plexiglas sheet was also used to build the bubble column of 300 mm x 300 mm cross section and 400 mm height. A perforated plate was used as a sparger to form the bubbles in a pool of hot water in the bubble column. The perforated plate is made of a 2 mm thick black acrylic Plexiglas 300 mm x 300 mm in cross section. The perforated plate splits the bubble column into lower and upper compartments. Air ~~was~~ introduced by a 400 W adjustable blower to the lower compartment of the bubble column through a 25 mm diameter CPVC pipe. The lower compartment of the bubble column is 300 mm high. It was used to distribute the air stream uniformly through the perforated plate. The upper compartment of the bubble column is 100 mm high. It was used as a pool for hot water. Water level in the pool was measured and controlled.

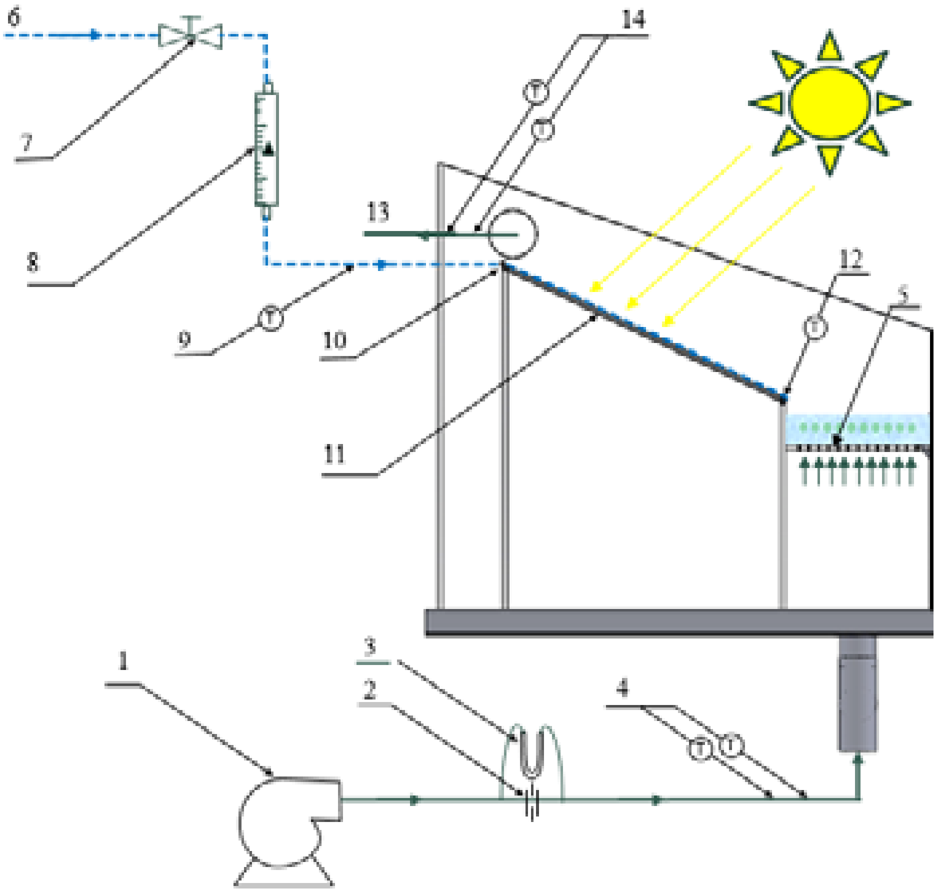

Fig. 3: Schematic diagram of experimental setup.

(1) Air blower, (2) Orifice meter, (3) Manometer, (4, 9, 12, 14) Thermocouples, (5) Perforated plate, (6) Water supply, (7) Throttle valve, (8) Rotameter, (10) Humidifier water inlet, (11) Absorber plate, (13) Humidifier air outlet

The experiment starts by blowing air using the air blower (1). The reason for blowing air first is that if the water flows first, it will penetrate down through the perforated plates (5). The blower is adjustable for the desired volumetric flow rate of the air stream that is measured by an orifice meter (2) connected to a manometer (3) to measure the pressure drop across the orifice plate and hence calculate air flow rate. The air dry-bulb / wet-bulb temperatures are measured by K-type thermocouples (4) before the air stream is admitted into the humidifier. Water supply (6) valve is then opened. The volumetric flow rate of the water was measured by a rotameter (8) adjusted to the desired value by a throttle valve (7). Water temperature is measured by a thermocouple (9) before entering the humidifier (10). A water film is distributed evenly over the black absorber plate (11) and flows by gravity. Water temperature increases as it flows over the absorber plate that is heated by solar radiations. Water temperature is measured at the exit of the absorber plate using thermocouples (12). Hot water then moves to a the bubble column chamber where air is passed through the perforated plate to form bubbles in the pool of the hot water. As the air bubbles propagate through the hot water column, simultaneous heat and mass transfer take place such that air is heated and humidified till it reaches the exit of the humidifier (13). Dry-bulb / wet-bulb temperatures of the hot and humid air are recorded using thermocouples (14) at the exit of the humidifier.

3. Data acquisition system

A data acquisition consisting of two NI 9213 thermocouple input modules installed in a NI cDAQ-9178 USB chassis is connected to a computer. Thermocouples measurements are displayed and stored using a Labview program. Real-time processed thermocouple readings are measured every 2 seconds and the average temperatures of every 5 minutes were recorded using the developed Labview program.

3.1 Instrumentation

K-type thermocouples were used to measure water temperature as well as air dry-bulb/wet-bulb temperatures. The volumetric flow rate of the water was measured by using FL5000 series rotameter of OMEGA. The volumetric flow rate of air is measured by an orifice meter connected to a manometer to read the pressure drop across the orifice plate. The orifice meter is designed and installed according to the ISO 5167 benchmark design recommendations. Solar radiation is measured using a handheld pyranometer. The measurement devices along with their range and accuracy are summarized in Tab. 1.

Tab. 1: Measurement devices along with their range and accuracy.

Properties	Instruments	Range	Accuracy
Temperature	NI cDAQ-9178, K-Type thermocouple	-267 – 316 °C	± 0.1 °C
Relative humidity		0 - 100 % RH	± 0.1 % RH
Pressure	U-Tube manometer	0.1 - 50 cm H_2O	± 1 mm
Water flow rate	Rotameter	1 - 7 LPM	± 5 % of full scale
Water column height	Graduate level	0.1 - 20 cm	± 1 mm
Air superficial velocity	Orifice meter	10-50 cm/s	± 1 cm/s
Solar radiations	Pyranometer	0-2000 W/m2	± 5 % of full scale

Thermocouple probes are calibrated before installing them in the experimental setup. Errors in the measurement devices is calculated as the ratio of the device least count to the minimum value of the output measured by that instrument. The uncertainty in the measurements is calculated as the root sum square of the fixed error of the instrumentation and the random error observed during different measurements. The resulting uncertainties are ± 0.79 cm/s and ± 0.93 % in the air superficial velocity and vapor density, respectively.

4. Results and Discussion

4.1 Influence of geometry of the perforated plate

The optimum design consideration of the perforated plate is an important aspect in the experimental investigation of the bubble column humidifier. In the design of the perforated plate, the perforations geometric configuration should be optimized to reduce air pressure drop. Another important aspect in the perforated design is to avoid water leakage through the perforations. Keeping in mind the aforementioned aspects, three different perforated plates were designed and tested to analyze the effect of perforation geometry on the performance of the bubble column humidifier. The geometric features of the three spargers used during the experimental work are listed in Tab. 2.

Tab. 2: Geometric features of different designs of perforated plate tested during experimentation.

	Number of holes	Hole Diameter (mm)	Pitch size (mm)	Open Area Ratio (%)
Design 1	105	3	25	0.77
Design 2	105	2	25	0.33
Design 3	149	2	20	0.49

Three different designs of perforated plates were tested at different air superficial velocities. Results are shown in Fig. 4. The minimum pressure drop is achieved using design 1 due to the bigger hole diameter and higher open area ratio compared to the other two designs. However, water leakage was observed from the perforations during the experiments that showed that this design is not useful. To overcome the problem of the water leakage, design 2 was tested with the same number of holes as in design 1 but the hole diameter was reduced from 3 mm to 2 mm. Design 2 was successful in preventing water leakage from the perforations but the pressure drop was high. The high pressure drop is due to the low open area ratio in design 2. Therefore, design 3 was tested with 149 holes with 2 mm-hole diameter. The higher number of holes increased the open area ratio and reduced the pressure drop compared to design 2. Moreover, no leakage was observed with design 3 during the experiment. Therefore, design 3 was selected as the best choice for our experimental setup. The perforated plate dimensions and hole geometry of design 3 are shown in Fig. 4. The perforated plate is 300 mm x 300 mm in cross section and it consists of 149 holes, 2 mm-diameter each. The holes are made in equilateral triangular configuration where the distance between any two adjacent holes is 20 mm. The holes are distributed 40 mm away from the boundary of the perforated plate to avoid the shear stresses near the wall of the bubble column.

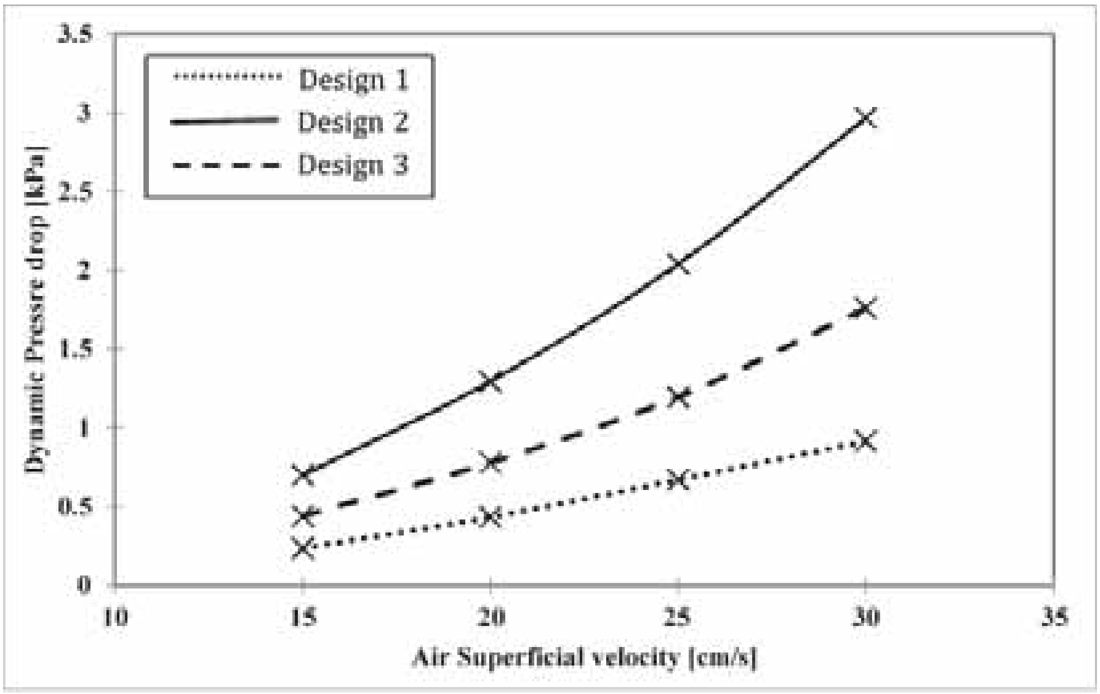

Fig. 4: Influence of air superficial velocity on the dynamic pressure drop under different design considerations of perforated plate.

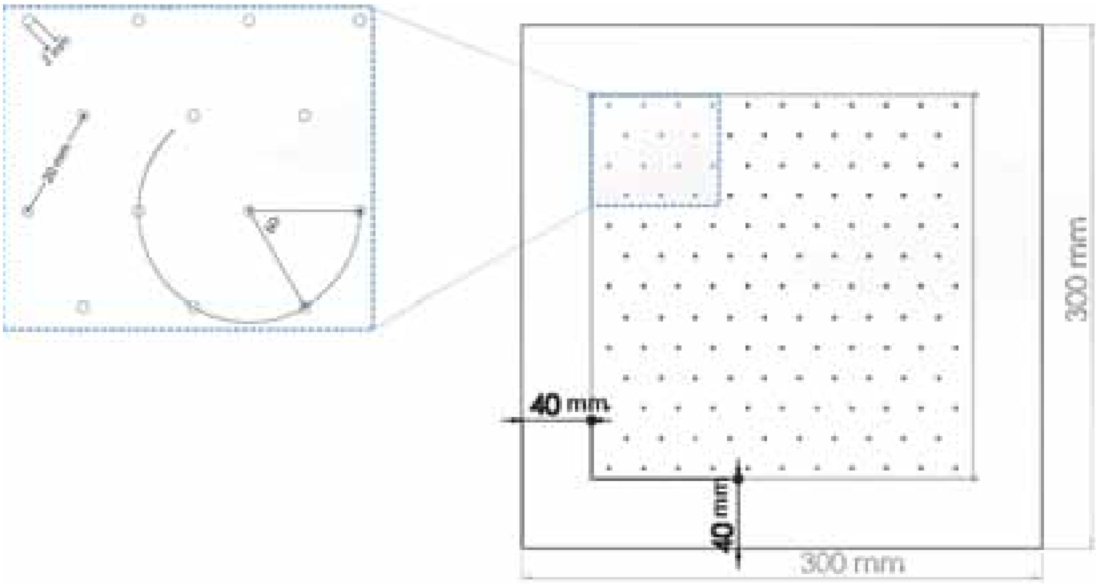

Fig. 5: Dimensioning and geometric features of the selected perforated plate.

Figure 6 shows the effect of water column height on the total air pressure drop at different air superficial velocities. The figure shows that the minimum pressure drop is attained at the lowest water column height of 1 cm and with 15 cm/s air superficial velocity. Increasing water column height to 3 cm and then to 5 cm while keeping the air superficial velocity at 15 cm/s results in a significant increase in the pressure drop. Furthermore, the air superficial velocity at 15 cm/s is not sufficient to completely overcome the static pressure head of the 5 cm water column height such that some water leaked through the perforations. Therefore, air superficial velocity at 15 cm/s is not taken into consideration for further investigations. The maximum pressure drop is monitored with a higher air superficial velocity of 30 cm/s. On contrary to the air superficial velocity of 15 cm/s, there is a slight increase in the pressure drop at higher water column heights.

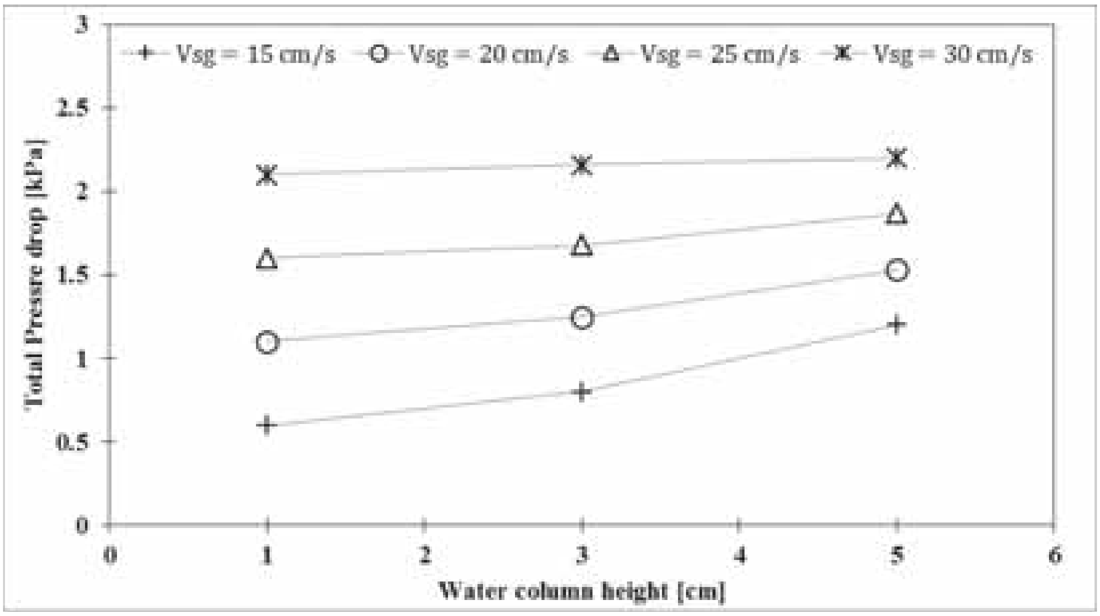

Fig. 6: Effect of water column height on the total pressure drop at different air superficial velocities.

4.2 Influence of water temperature

The major advantage of the proposed humidifier is its ability to have direct solar thermal heating for water flowing through the humidifier, the day round performance of the system was tested under climatic conditions of Dhahran, Saudi Arabia. The system was operated with and without Fresnel lens from 7 am to 5 pm in the month of June. The system performance without and with Fresnel lens was analyzed in terms of vapor density (absolute humidity) of the moist air at the exit of humidifier. Fig. 7 shows the solar heat flux, air and water inlet temperatures, and the water temperature after passing over absorber plate with and without the use of Fresnel lens. It can be seen that the solar radiation and ambient air temperature increases in the morning hours, reaching their maximum values around mid-day, and then decrease in the afternoon. Water temperature followed the same trend since it is directly influenced by the solar radiations. The black absorber plate was heated by solar radiation. Accordingly, water temperature was increased as it flows over the absorber plate. A higher water temperature was achieved by using Fresnel lens that concentrates the solar radiations on the absorber plate and, consequently, heats the water to a higher temperature.

Since the core objective of the bubble column humidifier is to effectively humidify the air, the day round performance of the proposed design is analyzed in terms of the vapor density in the moist air at the exit of humidifier. The influence of water temperature on the vapor density was investigated at different air superficial velocities. The results of the proposed design without and with Fresnel lens are presented in Fig. 8 and Fig. 9, respectively. Results indicate that the vapor density (Air humidity) in the humidifier is strongly influenced by the amount of the heat received by flowing water over the hot absorber plate. The integration of Fresnel lens increased the concentration of solar radiation on the absorber plate and heated the water to a higher temperature. The increase in the water temperature enhanced the ability of air to absorb more moisture and, consequently, higher humidity ratio is achieved at the outlet of humidifier. The increase in air superficial velocity also contributed significantly in increasing the vapor density in the moist air at the exit of humidifier. The increase in vapor density with the increase in air superficial velocity is attributed to the rise in velocity of comparatively bigger air bubbles. Moreover, the number of air bubbles increases with the increase in air superficial velocity and, consequently, provides higher interfacial area for better heat and mass transfer.

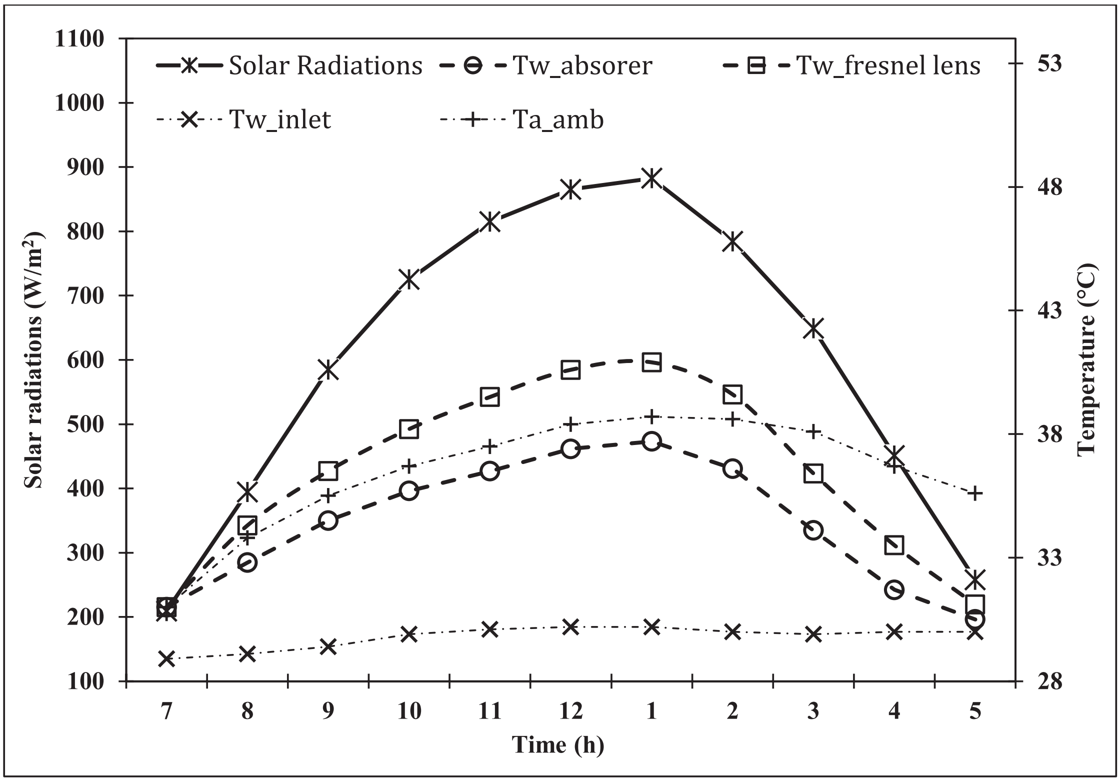

Fig. 7: The influence of solar radiations on the water temperature in the bubble column humidifier.

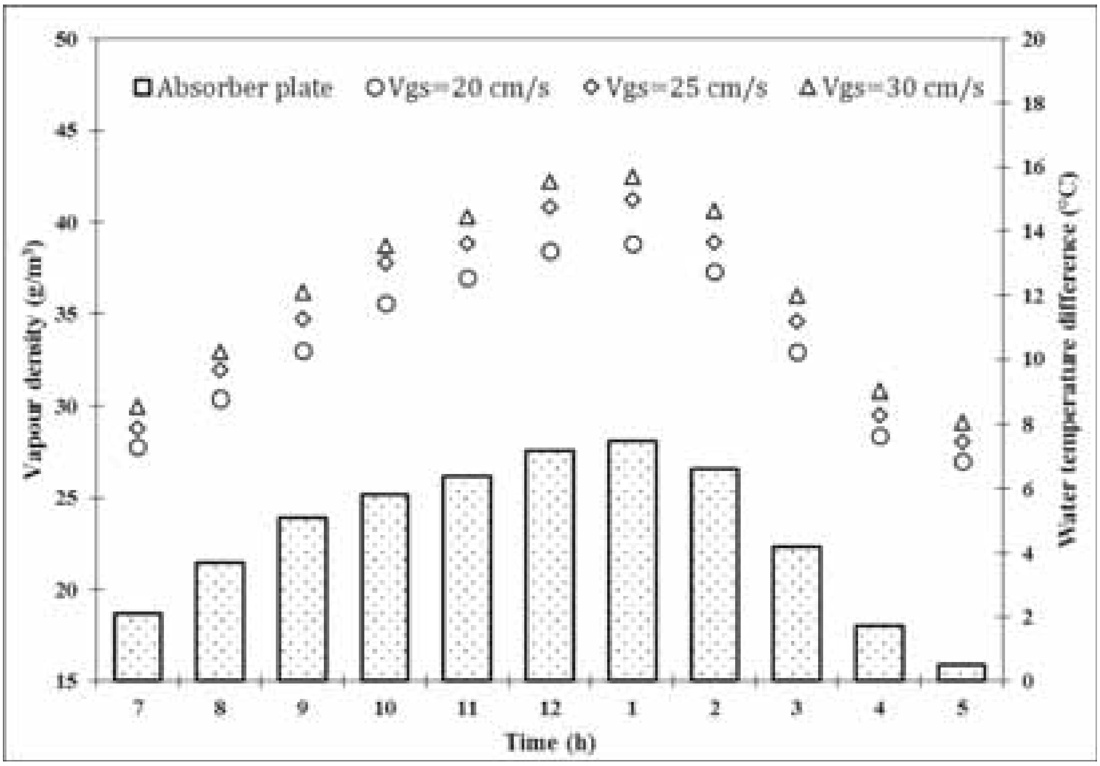

Fig. 8: Influence of water temperature and air superficial velocity on the vapor density in the moist air at the exit of humidifier.

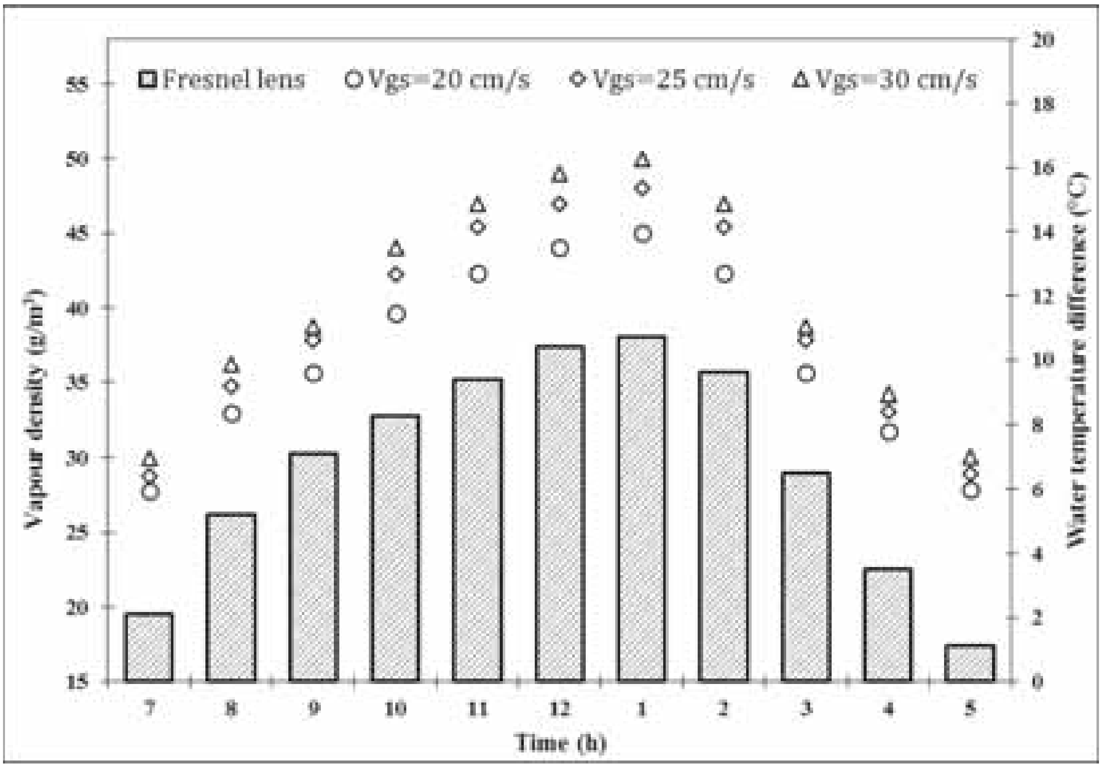

Fig. 9: Fresnel lens integration in the proposed design to increase the vapor density in the moist air at the exit of humidifier.

5. Conclusions

- The use of the bubble column humidification is an attractive option for solar humidification-dehumidification (HDH) water desalination systems. Therefore, a novel bubble column humidifier was developed and tested to identify the optimum performance operating conditions for its possible integration with a dehumidifier. One major advantage of this proposed humidifier is its ability to have a direct solar thermal heating. Subsequently, it can be located in remote areas.
- The optimum design for the perforated plate is an important aspect in the experimental investigation of bubble column humidifier. Different design configurations of the perforated plate were tested in order to achieve the lower pressure drop in the system. Findings revealed that the minimum pressure drop was experienced at a lower water column height and a lower air superficial velocity. However, the water column height and air superficial velocity should be optimized according to the geometry of the perforated plate in order to avoid water leakage through the perforations.
- The proposed design of the bubble column humidifier was integrated with the Fresnel lens in order to achieve a higher water temperature. The influence of water temperature on the vapor density was investigated at different air superficial velocities. Results indicate that the vapor density in the bubble column humidifier was significantly increased with the increase in water temperature and air superficial velocity. The increase in water temperature enhanced the ability of air to absorb more moisture and consequently higher vapor density was achieved at the outlet of bubble column humidifier.

6. Acknowledgments

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7. References

Amara, M. B., Houcine, I., Guizani, A., & Mâalej, M. (2004). Experimental study of a multiple-effect humidification solar desalination technique. Desalination, 170(3), 209-221.

Aull, R.J., & Krell, T. (2000). Design Features of Cross-Fluted Film Fill and Their Effect on Thermal Performance. CTI Journal, 21(2), 12-33.

Degaleesan, S., Dudukovic, M. and Pan, Y. (2001), Experimental study of gas-induced liquid-flow structures in bubble columns. AIChE J., 47: 1913–1931.

El-Agouz, S. A., & Abugderah, M. (2008). Experimental analysis of humidification process by air passing through seawater. Energy Conversion and Management, 49(12), 3698-3703.

El-Agouz, S. A. (2010). Desalination based on humidification–dehumidification by air bubbles passing through brackish water. Chemical Engineering Journal,165(2), 413-419.

Fiorenza, G., Sharma, V.K., & Braccio, G., 2003. Techno-economic evaluation of a solar powered water desalination plant. Energy Conversion and Management, 44, 2217-2240.

Kast, W. (1962). Analyse des wärmeübergangs in blasensäulen. International Journal of Heat and Mass Transfer, 5, 329-336.

Kolbel, H., Siemes, W., Maas, R., & Muller, K. (1958). Wärmeübergang an Blasensäulen. Chemie Ingenieur Technik, 30, 400-404. English translation: Heat transfer in bubble columns. Retrieved from http://www.fischer-tropsch.org/DOE/DOE_reports/89012412/de89012412_toc.htm.

Miller, J. E. (2003). Review of water resources and desalination technologies. Sandia National Labs Unlimited Release Report SAND-2003-0800.

Mirsky, G.R., & Bauthier, J. (1993). Evolution of Cooling Tower Fill. CTI Journal, 14(1), 12-19.

Müller-Holst, H., Engelhardt, M., Herve, M., & Schölkopf, W. (1998). Solar thermal seawater desalination systems for decentralised use. Renewable Energy, 14(1), 311-318.

Orfi, J., Laplante, M., Marmouch, H., Galanis, N., Benhamou, B., Nasrallah, S. B., & Nguyen, C. T. (2004). Experimental and theoretical study of a humidification-dehumidification water desalination system using solar energy. Desalination, 168, 151-159.

Treybal, R.E., 1980. Mass Transfer Operation, McGraw-Hill, NewYork.

Wallis, J.S., & Aull, R.J. (1999). Improving Cooling Tower Performance. Hydrocarbon Engineering, 92-95.

Younis, M. A., Darwish, M. A., & Juwayhel, F. (1993). Experimental and theoretical study of a humidification-dehumidification desalting system. Desalination, 94(1), 11-24.

Zhang, L., Cheng, G., & Gao, S. (2011). Experimental study on air bubbling humidification. Desalination and Water Treatment, 29(1-3), 258-263.