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# Design and development of an air humidifier using finite difference method for a solar desalination plant

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**Abstract.** Humidifier is an important component in air humidification-dehumidification desalination plant for fresh water production. Liquid to air flow rate ratio is optimization is reported for an industrial cooling towers but for an air humidifier it is not addressed. The current work is focused on the design and analysis of an air humidifier for solar desalination plant to maximize the yield with better humidification, using finite difference method (FDM). The outlet conditions of air from the humidifier are theoretically predicted by FDM with the given inlet conditions, which will be further used in the design calculation of the humidifier. Hot water to air flow rate ratio and inlet hot water temperature are identified as key operating parameters to evaluate the humidifier performance. The maximum and optimal values of mass flow rate ratio of water to air are found to be 2.15 and 1.5 respectively using packing function and Merkel Integral. The height of humidifier is constrained to 1.5 m and the diameter of the humidifier is found as 0.28m. The performance of humidifier and outlet conditions of air are simulated using FDM and compared with experimental results. The obtained results are within an agreeable range of deviation.

## 1. Introduction

Desalination (or desalinization) is the process of removing dissolved salts and minerals from water. Desalinated water has purity higher than that required for normal drinking purposes; hence it is of great use for both domestic and industrial purposes. Abdel-Salem et al., [1] investigated experimentally the influence of inlet air and water temperatures, water to air flow ratio to the humidifier on fresh water production. They observed that an increase system productivity with at high air and water temperatures to the humidifier. Nawayseh et al., [2] developed a simulation model and proved air humidification-dehumidification (HDH) desalination as an efficient and sustainable technology for fresh water generation using solar energy. Yanniotis and Xerodemas [3] performed experimental and computational fluid dynamics (CFD) studies on spray and pad humidifiers. Comparative experimental and CFD results gives better evaporation with pad humidifier with 300 mm pad thickness for high air to water flow ratios. Detailed design and analysis was carried out by Ettouney [4] on different layouts of humidification dehumidification desalination process and concluded that accumulation of air in a condenser is to be taken care by proper design of the dehumidification unit. Yamalı and Solmus [5] studied the performance of the HDH desalination system consists of a humidifier with four plastic in series as a packing material. The experiments were



conducted by varying different parameters and the experimental observations are in an agreeable range with theoretical results. Marmouch et al. [6] studied the influence of humidifier theoretically and experimentally on fresh water production. They developed a theoretical model based on heat and mass transfer characteristics and developed correlations for humidifier characteristics with water to air ratio for different inlet water temperature.

Amer et al., [7] examine the theoretical and experimental investigations on a HDH desalination system consists of a humidifier for air humidification with gunny bag cloth, poly vinyl chloride and wooden slates. A maximum yield of 5.8 lit/hr of fresh water is observed for a wooden slates packing in humidifier with forced air circulation. Hermosillo et al., [8] carried out theoretical and experimental studies on a HDH desalination system by using treated cellulose paper as a packing material in humidifier which will provide more area for water evaporation. The developed model results are compared with experimental results which are in agreeable range. Chiranjeevi and Srinivas [9, 11, 13, 15] studied the influence of different operating parameters on the performance of an integrated solar desalination plant theoretically and experimentally. They conducted experiments with PVC sheets as packing material in the humidifier and observed an increased air humidification at high temperatures and high flow rates of hot water and results in increased fresh water yield. Kabeel et al. [10] carried out experimental studies on a solar driven HDH desalination system using forced and natural air circulation. They used cellulose paper as the packing material in the humidifier with different holes size and concluded that 5 mm holes size configuration gives more wetted area and hence higher productivity. Xu et al. [12] studied the performance of a humidifier for a humid air turbine with corrugated ceramic foam as packing material. The experimental results shows 93% increase in specific surface area and increased heat and mass transfer performance. Raj et al. [14] evaluated the performance of humidifier in a solar HDH desalination plant with PVC packing with honeycomb structure in humidifier. It is observed that a maximum effectiveness of 0.75 at air flow rate 0.55 m<sup>3</sup>/s and 150 LPH of hot water to the humidifier.

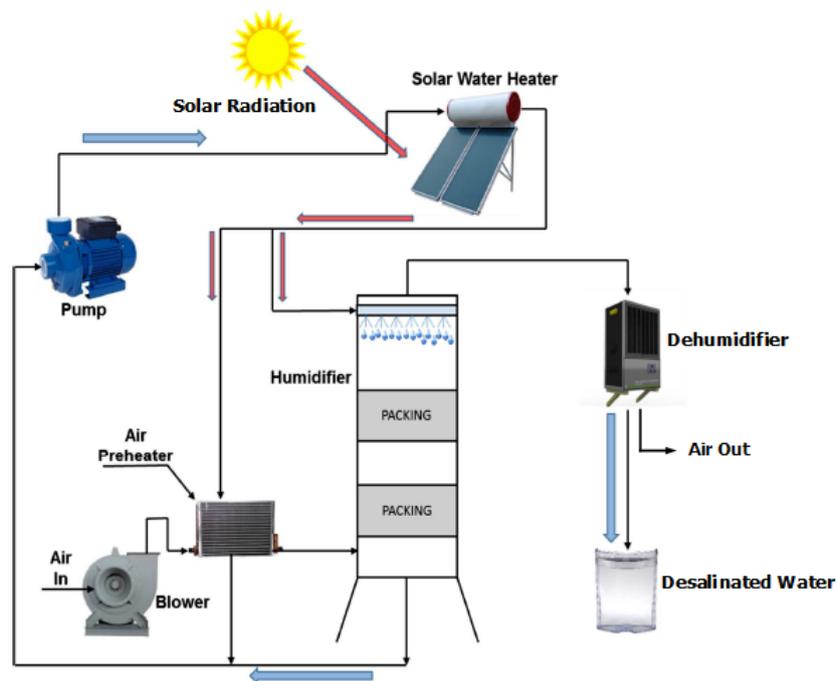
Many researchers investigated the performance of humidifier theoretically and experimentally with different packing materials. The literature shows that humidifier is a key component in the HDH desalination technique which will influence the fresh water yield. In the above mentioned HDH desalination techniques water and air both are not heated for the desalination process. Increase in water temperature as well as air temperature provides effective sensible heat transfer from the water to air. Solar Water Heater (SWH) is used to heat the water. Air pre heater is used to increase the air temperature. The literature shows many of the researchers designed the humidifier based on heat and mass transfer characteristics. In the proposed HDH system Finite Difference Method (FDM) is used in the design of a humidifier. FDM is a simple technique in which the total height of the humidifier is divided as equal layers and exit conditions of each layer is found by FDM and given them as input conditions for the next layer of the humidifier. Outlet conditions obtained for the last layer by FDM is compared with experimental observations.

## 2. Methodology

Air humidifier is an important component in an HDH desalination plant. The present study is focused on design and optimization of a humidifier for a desalination plant by using FDM. The obtained results are compared with experimental observations for different temperatures of hot water. The other components in the plant are a blower, an air preheater and dehumidifier which are not focused in the present work. The following section briefs the working principle of a HDH desalination plant.

**Fig. 1** is the schematic of the line diagram with different components of a solar HDH desalination plant. Atmospheric air is pumped into the air preheater on the annulus side to heat with hot water from a solar water heater. Air preheating increases its temperature and decreases the relative humidity which will enhance the moisture absorbing capacity of the air in the humidifier. The hot air is then enters at the bottom of a vertical column cylindrical humidifier get heated further and humidified with the hot water sprayed at the top. Air passes through the two layers of honeycomb structured PVC packing inside the vertical column humidifier and gets heated and humidified. The packing material is

kept inside the humidifier to provide more surface area for hot water which will enhance the heat and mass transfer between hot water and air. In the process of humidification light weight water particles get evaporated and moved along with the air circulated, heavier water particles will not evaporate and will be collected at the bottom of humidifier. High temperature humid air is then enters the dehumidifier and is dehumidified and cooled by rejecting heat to the cold water circulated or can be to the atmospheric air. Cooling and dehumidification in dehumidifier results in condensing the water vapour present in the humid air which results in fresh water. The cooled air from the dehumidifier is left to the atmosphere or it may recirculate for the next cycle. Hot water is generated with a solar water heater and cooled hot water from the air preheater and rejected brine at the bottom of humidifier is recirculated with a pump to the solar water heater.



**Figure 1.** Schematic of solar humidification dehumidification desalination plant.

### 2.1 Experimental setup development and procedure

**Fig.2** shows the photograph of experimental setup with main components of humidification dehumidification desalination plant. As shown in **Fig.2**, atmospheric air is sent by the blower in to the annulus of the air preheater for heating with hot water circulated on tube side of air preheater. Air preheater is a concentric tubular heat exchanger made of stainless steel material with a provision of passing hot water through tube side and air through the annulus side. The purpose of pre heating air is to decrease the relative humidity of the air which will help in absorbing moisture from the water quickly. The hot air is then sent at the bottom of the humidifier and passes through the two stages of PVC packing and gets heated further and humidified. The PVC packing provides more surface contact area between water and air so that air can gain as much heat and moisture as possible for the given conditions. A Humidifier is a vertical cylinder made of stainless steel with two stages of PVC packing kept inside for better heat and mass transfer between water and air. Hot water is sprayed at the top section through the nozzles provided and the brine is exited at the bottom of humidifier. An opening is provided at the bottom to enter heated air from air preheater and after heating humidification it is left at the top of humidifier. The hot humid air leaving from the humidifier is then enters into shell side of the dehumidifier, where it rejects the heat to the normal cooling water circulated from an over head tank. The cooling and dehumidification of hot humid air in the dehumidifier with cooling water results in condensation of water vapor and air cooling. Condensate is the fresh water produced from the

process of HDH is collected at the bottom of dehumidifier is removed periodically and the cooled air is exited at the bottom of dehumidifier. Dehumidifier is a shell and tube heat exchanger, shell is made of an acrylic tube and tube is from stainless steel tube bent into many as per the design. Baffles are provided in the heat exchanger on shell side to provide better fluid flow pattern for humid air and hence increased heat transfer rates. An opening is provided at the top of dehumidifier to enter hot humid air and two openings are provided at the bottom for fresh water exit and cooled air exit. Cold water flow to the tube side of the dehumidifier is regulated with a valve provided.

Experiments were conducted with a fixed flow rate of air at 15 m<sup>3</sup>/hr and normal circulating water to the dehumidifier. The flow rate of hot water from solar flat plate collector is kept constant for air preheater and is varied for humidifier. The process of humidification in humidifier is studied for different flow rates of water varied from 100 lit/hr to 200 lit/hr and different temperatures of hot water. The experimental observations were noted with the necessary measuring instruments kept at the inlet and exit of humidifier. Measured hot humid air temperature at the exit of humidifier is compared with the simulated value obtained from FDM.



**Figure 2.** Photograph of solar humidification dehumidification desalination plant.

**Fig. 3** is the photograph of the humidifier with a stainless steel shell tube having openings at the bottom and top for air entry and exit, for hot water entry and brine exit. Inside of the humidifier it is shown one layer of honeycomb structured PVC packing with a wire mesh for further splitting of sprayed water droplets.



**Figure 3.** Photograph of the humidifier with honeycomb PVC packing

The properties of atmospheric air and moist air calculate with the equations available in the literature [16].

Saturation vapour pressure is calculated based on the equation mentioned and is expressed in Pascals..

$$p_s = 610.78 \times \exp\left(\frac{t}{t+2383} \times 17.2694\right) \quad (1)$$

where,  $t$  is the air temperature in °C.

Relative Humidity ( $RH$ ) is the ratio of the actual water vapour pressure to the saturation water vapour pressure at the prevailing temperature, which is expressed as a percentage.

$$RH = p/p_s \quad (2)$$

Specific humidity is the ratio of mass of actual water vapour present in the air to the mass of dry air and is expressed as kg of water vapour to the kg of dry air and is represented by  $w$ .

$$w = 0.632 \times \left( \frac{p}{p - p_v} \right) \quad (3)$$

where,  $p$  is the total pressure and  $p_v$  is the vapor pressure.

Specific enthalpy of moist air is computed with the following equation,

$$h = c_p T_{db} + wh_v \quad (4)$$

where,  $c_p$  is specific heat of air and  $h_v$  is the specific enthalpy of water vapour.

Enthalpy of water vapour can be found by,

$$h_v = h_{dp} + 1.884(T_{db} - T_{dp}) \quad (5)$$

where,  $h_{dp}$  is the enthalpy of saturated vapour at dew point temperature,

$T_{db}$  dry bulb temperature and  $T_{dp}$  is the dew point temperature.

The formulations used for designing the humidifier by using finite difference method are available in the literature [17]. The enthalpy of air leaving the humidifier is found by doing energy balance between the sprayed hot water and the cold air. Water is entering in the humidifier from the top at a

higher enthalpy ( $h_{l,in}$ ) and leaving from the bottom at lower enthalpy ( $h_{l,out}$ ), as a result of drop in temperature. At the same time, air enters at a low enthalpy ( $h_{a,in}$ ), absorbs the moisture from packing and leaves as high enthalpy moist air ( $h_{a,out}$ ).

$$h_{a,out} = h_{a,in} + \frac{m_L}{m_a} C_{p,L} (T_{L,in} - T_{L,out}) \quad (6)$$

The enthalpy of inlet air remains constant, the outlet enthalpy is a function of mass flow ratio of water and air. In a graph, liquid enthalpy plotted against air enthalpy, we get a series of oblique lines with a common starting point (air inlet enthalpy is same). On the same plot, the saturation enthalpy ( $h_s$ ) of air is plotted for the corresponding inlet and outlet temperatures. The  $h_s$  line which cuts  $h_a$  line, gives us the maximum water to air mass flow ratio, corresponding to that  $h_a$  line.

The optimum water to air flow rate can be found by using Merkel integral method. Merkel Integral ( $I_m$ ) and packing function ( $I_p$ ) are both functions of water to air mass flow ratio, and can be plotted in the same diagram. For optimum condition, the two values must be equal, hence their intersection in the graph will give the required ratio for a given tower height. The tower height is to be assumed initially and plays a major role in fixing this value.

The Merkel integral is determined using British Standard Quadrature Method.

$$I_m = \int_{w,out}^{w,in} \frac{dh_l}{h_s - h_a} \quad (7)$$

It is proposed, the simplest assumption of taking ( $h_s - h_a$ ) as constant and equal to the average of the values of this quantity at the top and bottom of the humidifier.

$$(h_s - h_a) = \frac{(h_s - h_a)_{top} + (h_s - h_a)_{bottom}}{2} \quad (8)$$

Since, this cannot account for a nonlinear saturation curve. Thus, the other method is to take it as a mean of the values at 0.1, 0.4, 0.6 and 0.9 time the humidifier height. Thus, the final expression of the Merkel Integral is,

$$I_m = \frac{(h_{l,in} - h_{l,out})}{(h_s - h_a)} \quad (9)$$

where, ( $h_s - h_a$ ) is the average value for the total range of the tower.

The packing function is given by,

$$I_p = \frac{K_a V}{L} \quad (10)$$

where,  $K_a$  is the mass transfer coefficient in  $\text{kg}/\text{m}^2\text{s}$ ,

$V$  is the volume of the humidifier per unit cross sectional area in  $\text{m}^3/\text{m}^2$  and

$L$  is the mass flow rate of water in  $\text{kg}/\text{m}^3$ .

From the heat and mass transfer balance for the whole height of the humidifier the above equations can be written as,

$$\frac{K_a V}{L} = BZ \left[ \frac{m_{hw}}{m_{da}} \right]^{-y} \quad (11)$$

where,  $Z$  is the packing height and the constants values are  $B = 0.691$  and  $y = 0.69$  taken for corrugated plastic sheets.

In humidifier, the humidity of the outlet air is found of by finite difference method.

$$\Delta w = \frac{m_{hw}}{m_{da}} \Delta h_{hw} \frac{(w_s - w)}{(h_s - h_a)} \quad (12)$$

where,  $w_s$  and  $h_s$  are the specific humidity and enthalpy of saturated air at the local hot water temperature, and

$$\Delta h_{hw} = \frac{h_{hw, in} - h_{hw, out}}{n} \quad (13)$$

where,  $n$  is the number of elements considered in finite difference method.

The temperature and RH of humid air from the humidifier can be determined from specific humidity and enthalpy.

After knowing the mass ratio, The hot water demand in 1<sup>st</sup> humidifier,

$$m_{hw, humidifier} = \frac{m_a (h_{a, out} - h_{a, in})}{c_{p, hw} (T_{hw, in} - T_{hw, out})} \quad (14)$$

## 2.2 Error analysis

The experiments were conducted by varying different parameters which are measured with the following instruments. Thermocouples are used for measuring temperature of the fluids at different locations, digital humidity sensor for measuring relative humidity, anemometer for air velocity, rotameter for volume flow rate of water, measuring jar for fresh water production and pyranometer for solar radiation. **Table 1** lists the instruments different instruments used to measurement, accuracies and their standard uncertainty. Standard uncertainty is calculated by using the following formulae [15].

$$u = \frac{a}{\sqrt{3}} \quad (15)$$

**Table 1.** Details of instruments, accuracies, measuring range and standard uncertainty of experimental observations.

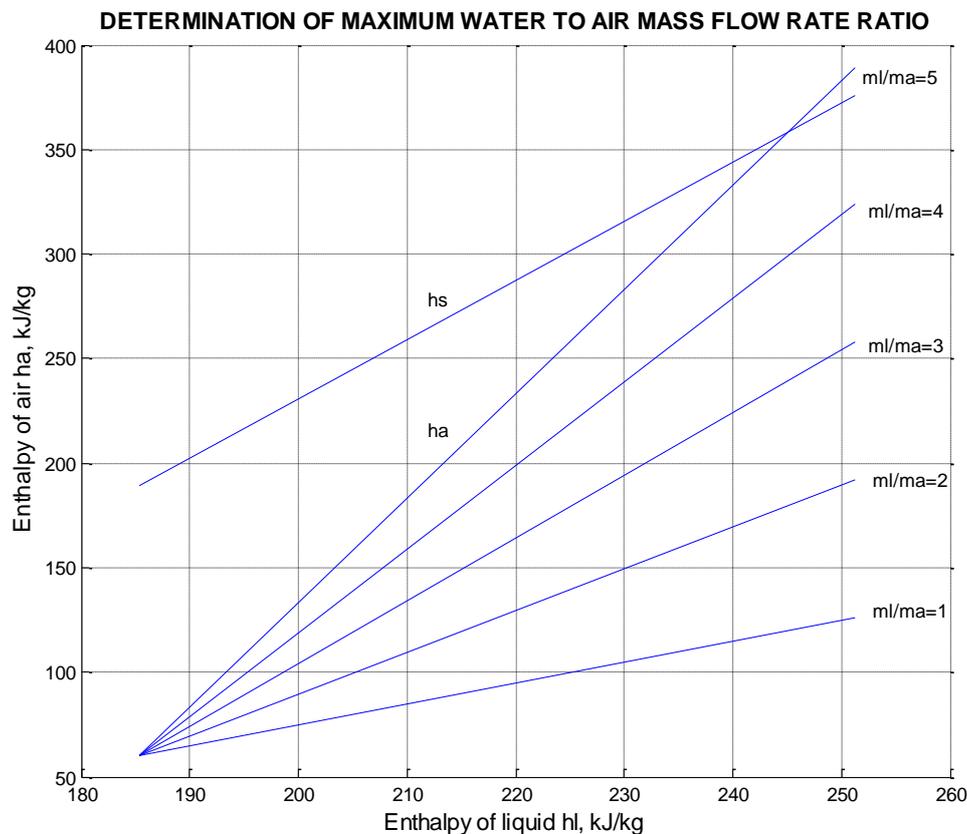
Sl. No.	Instrument	Accuracy	Range	Standard Uncertainty
1	Thermocouple	±0.5 °C	0-200 °C	0.288 °C
2	Digital humidity sensor	±3.5% RH	0-100% RH	2.02%
3	Anemometer	±0.2 m/s	0.4-30 m/s	0.115 m/s
4	Rotameter	±0.5 LPH	0-400 LPH	0.288 LPH
5	Pyranometer	±1 W/m <sup>2</sup>	0-2000 W/m <sup>2</sup>	0.577 W/m <sup>2</sup>

## 3. Results and Discussion

The degree of humidification of air depends on the inlet water temperature and inlet air relative humidity and its temperature and the surface area available for heat mass transfer from water. The hot water inlet temperature and water to air mass flow rate ratio have been identified as key operational parameters. These conditions can be varied to maximize the humidity of outlet air. Thermodynamic analysis of humidifier is done and the dependence of air enthalpy with respect to water enthalpy is studied for different flow rate ratios (**Fig.4**). Merkel Integral is a new parameter introduced for designing of cooling towers, which is used to determine optimum flow rate ratio (**Fig.5**). The unknown outlet air conditions, specific humidity, enthalpy and temperature, are predicted based on inlet conditions (**Fig.6**), using finite difference method. The results from this simulation are further used to determine the humidifier diameter. Different inlet conditions, water temperature and flow rate ratios are simulated and plotted against the outlet temperature and specific humidity for the study of trend variations of these properties and the humidifier performance (**Fig.7** and **Fig.8**). An experimental study was done to verify the results obtained from simulation with the observation from the HDH desalination plant. The variation trend of outlet air temperature with inlet water temperature is studied

(**Fig.9**) and is then compared with theoretical outlet air temperature (**Fig.10**). The air pre-heating and humidification processes are plotted on a simplified psychrometric chart to study the deviation of actual process with some of the experimental readings (**Fig.11**).

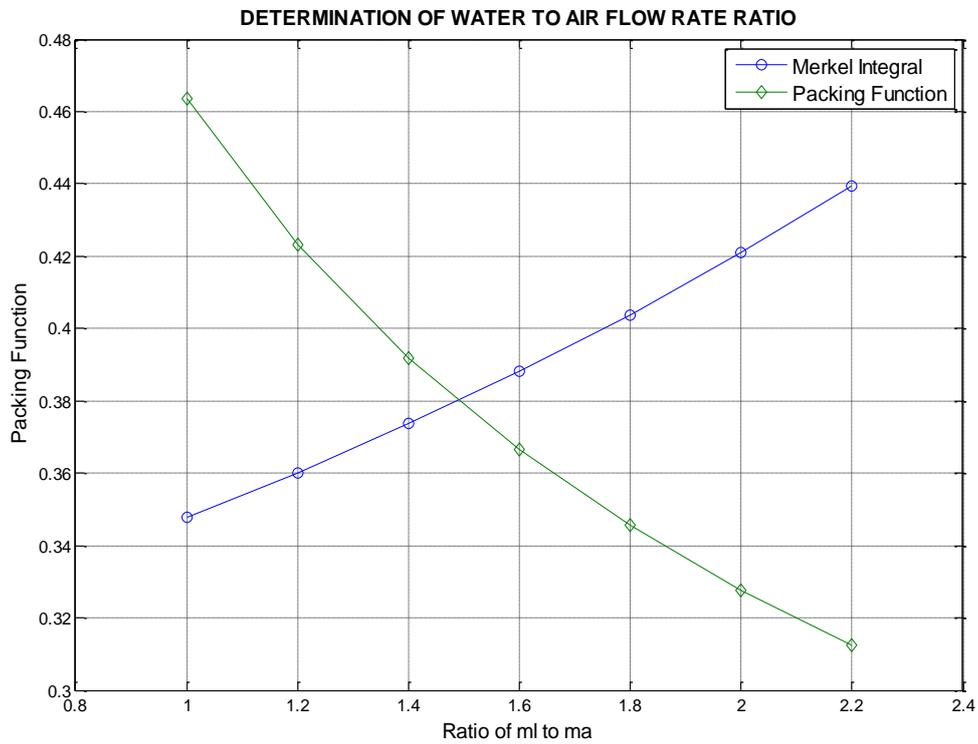
**Fig.4** shows the variation of air enthalpy with respect to water enthalpy. The point of inlet of water is the point of air outlet and vice versa. Since the water is losing its temperature and getting cooled, its enthalpy is decreasing. Simultaneously, as the air is undergoing heating and humidification process, it gains enthalpy. A series of oblique lines are obtained for different flow rate ratios. The saturation enthalpy line for air is plotted in the same graph. This line determines the maximum flow rate ratio which can be used for a particular set of inlet conditions



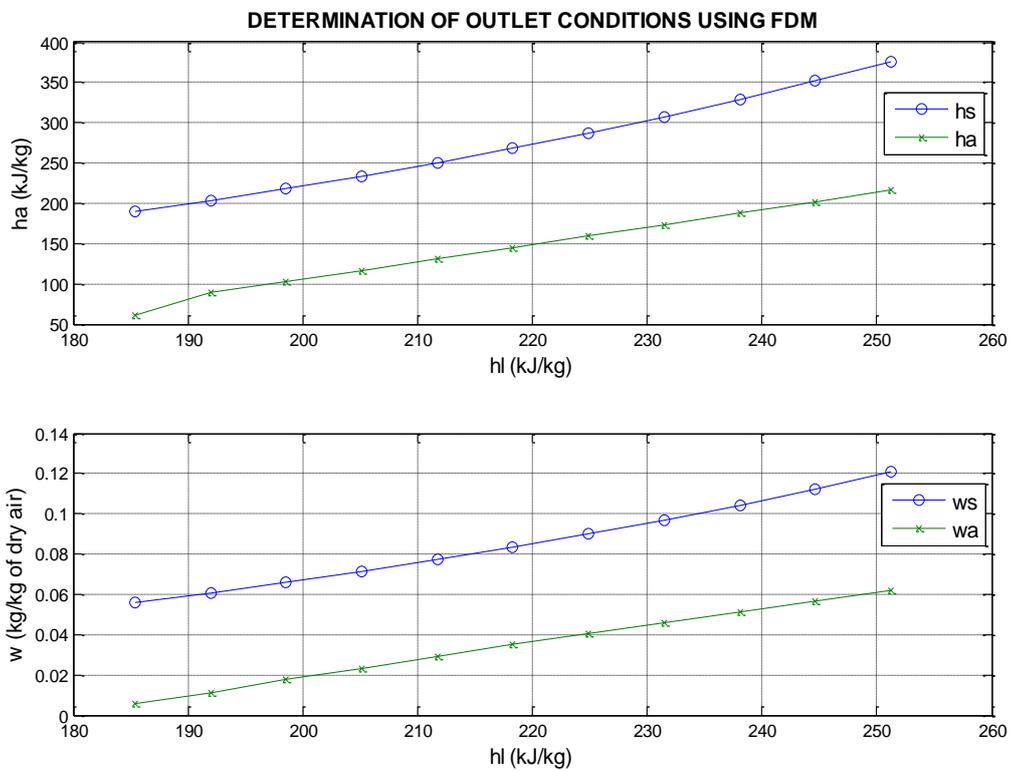
**Fig.4** Liquid enthalpy versus air enthalpy plot

**Fig. 5** shows the variation of Merkel Integral and packing function for different water to air mass flow ratio. The intersection point of these two curves gives the optimum mass flow ratio of water and air. The height of humidifier, which is an assumption based on design constraints of the plant, is an important factor in the determination of Merkel Integral.

Finite difference method is the mathematical tool used to determine the outlet conditions based inlet theoretically. **Fig.6** shows a plot between water enthalpy and outlet air enthalpy and outlet air specific humidity. The water enthalpy is known at both inlet and outlet of the humidifier and the saturation enthalpy is determined from the psychrometric chart. From these two values, the outlet enthalpy of air is predicted. Similarly, for specific humidity, first saturation values are determined and then simulated for outlet conditions.

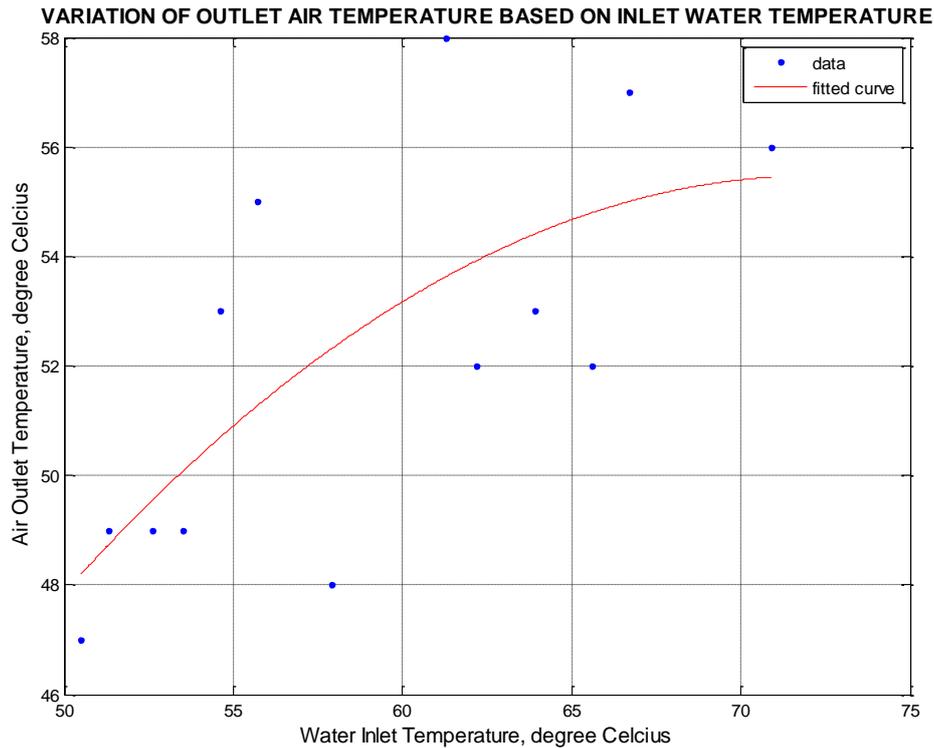


**Figure 5.** Ratio of water to air flow rate versus packing function plot



**Figure 6.** Variation of air enthalpy and specific humidity with water enthalpy

From the observations made from experimentation, the variation of outlet air temperature with respect to inlet water temperature was plotted in **Fig.7**. It was observed that the best fit curve was of second degree polynomial function. As the inlet water temperature increases beyond a particular value, the air temperature will tend to become constant. Hence, it is concluded that, experimentally, the humidifier system works best only up to a certain temperature of inlet water. Very high temperature water will not ensure maximum humidification.

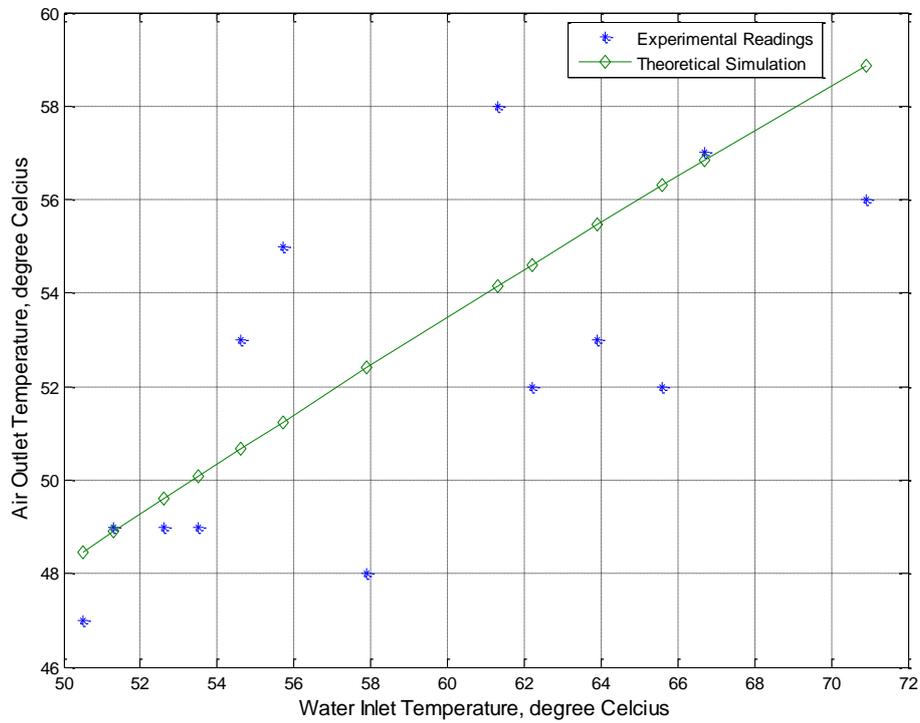


**Figure 7.** Experimental Results for outlet air temperature

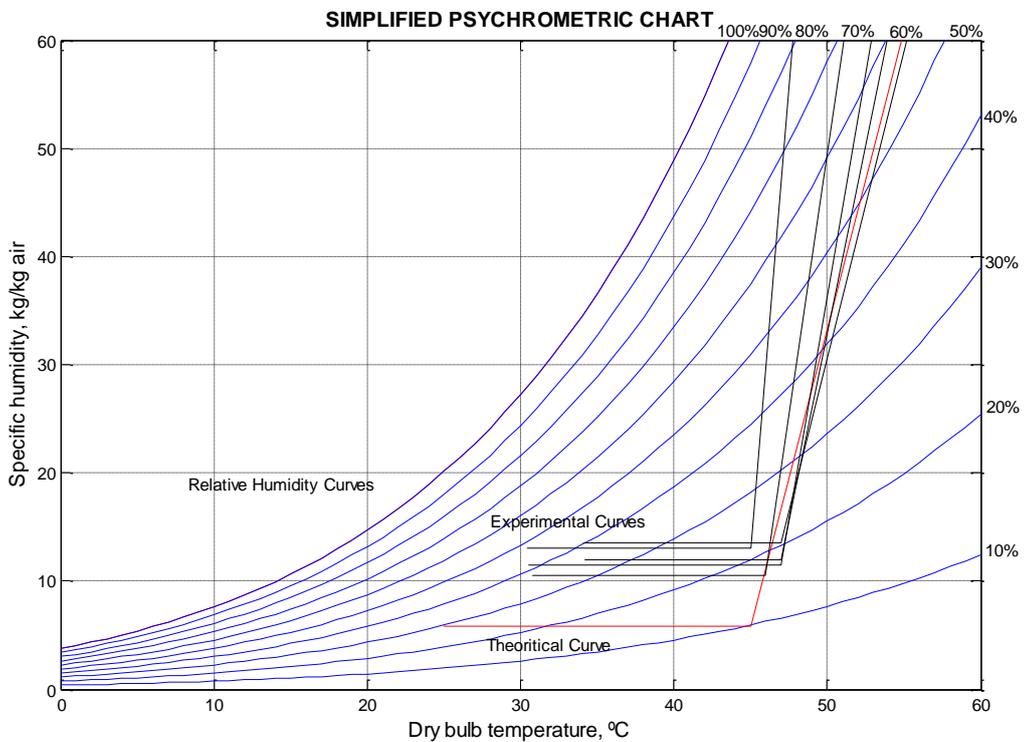
**Fig.8** shows the theoretically predicted air outlet temperature and experimental observations. This graph shows the extent of deviation in experimental results when compared with simulations. These deviations are a result from numerous air and water leakages in the plant and other errors encountered in taking the experimental readings.

**Fig.9** shows heating and humidification processes, on a simplified psychrometric chart, in air pre-heater and humidifier, respectively. The horizontal lines show heating process which is done to reduce the relative humidity of air to be sent to humidifier. The specific humidity remains constant though. The oblique lines represent humidification process where both relative and specific humidity increase. The graph shows one theoretical curve on which the design calculations are based and a few experimental curves for reference.

**COMPARISON OF EXPERIMENTAL AND THEORETICAL VALUES OF OUTLET AIR TEMPERATURE**



**Figure 8.** Experimental Results compared with simulated values for outlet air temperature



**Figure 9.** Comparison of Theoretical and Experimental values of humidification process

Air outlet temperature predicted from the developed FDM model and the experimental observations are tabulated in **Table 2** for different inlet hot water temperature at a flow rate of 150 LPH. The percentage deviation of the simulated value with experimental value is calculated and it is in the agreeable range. So the proposed method of FDM can be recommend for an air humidifier for a HDH desalination or humid air turbine plants.

**Table 2.** Comparison of Experimental and Theoretical Outlet Air Temperature

S. No.	Water Inlet Temperature, °C	Air Outlet Temperature, °C		
		Experimental value	Simulated value	Deviation, %
1	70.9	56	58.8654	4.86
2	66.7	57	56.8513	- 0.26
3	65.6	52	56.3109	7.65
4	63.9	53	55.4658	4.44
5	62.2	52	54.6094	4.78
6	61.3	58	54.1516	- 7.11
7	57.9	48	52.3982	8.39
8	55.7	55	51.2454	- 7.33
9	54.6	53	50.664	- 4.61
10	53.5	49	50.0794	2.15
11	52.6	49	49.5987	1.21
12	51.3	49	48.9001	- 0.20
13	50.5	47	48.4676	3.028

#### 4. Conclusions

Design, modelling and simulation using FDM, experimental analysis is carried out on a humidifier in the solar HDH desalination plant. An analogy is discussed between the working principle and performance of cooling tower and humidifier. Hence the design of humidifier system is based on the design procedure for a typical cooling tower.

In this work, based on the availability of space and the requirements of the desalination plant, the height of humidifier is constrained to 1.5 m. Initial assumptions like water inlet and outlet temperatures, and inlet conditions of air are the parameters required to determine the optimum water to air mass flow rate ratio required to obtain the maximum yield. Using simulations it was found to be 2.15. This optimum ratio is further used to predict the outlet conditions at the humidifier exit using Finite Difference Method. Using the simulated outlet conditions and the maximum pressure drop across humidifier ends, the diameter was determined to be 0.28 m. Further, experimental values from the actual plant setup were recorded and compared with the simulated theoretical values. These were found to be within the acceptable range of error. Temperature versus specific humidity plots for experimental and simulated values show similar trend on a simplified psychrometric chart. An analysis of the outlet air conditions like temperature and specific humidity based of inlet water temperature was shown. These graphs may be used to obtain the desired output by varying the inlet conditions.

#### Nomenclature

#### Symbols

h	specific enthalpy, kJ/kg
m	mass flow rate, kg/s
n	packing function constant
p	pressure, Pa
t	temperature, K
v	velocity of air at the exit of dehumidifier, m/s
w	specific humidity of air, kg of water vapor/kg dry air
B	packing function constant
K	mass transfer coefficient, kg/m <sup>2</sup> s
L	mass flow rate of water, kg/m <sup>3</sup>
S	total cross section area, m <sup>2</sup>
V	volume per unit cross sectional area, m <sup>3</sup> /m <sup>2</sup>
Z	tower height, m
$\Delta w$	change in specific humidity

**Suffix**

a	air
l	liquid
m	Merkel Integral
p	packing function
s	saturation state
w	water

**Acronyms and abbreviations**

DBT	Dry Bulb Temperature
FDM	Finite Difference Method
HDH	Humidification-Dehumidification Method
LPH	Liters Per Hour
RH	Relative Humidity

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