Parametric study of a two stage humidification dehumidification desalination plant

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ABSTRACT

Air humidification and dehumidification (HDH) desalination is viewed as a promising technology for small scale standalone water production applications. The process has several attractive features, which includes low operating temperatures, ability to combine with sustainable energy sources and requirements with low level technical features. In this work, parametric sensitivity of an integrated two stages HDH desalination and cooling plant is studied. Solar flat plate collectors and concentrated parabolic collector are used as a heat source for desalination plant and vapor absorption refrigeration (VAR) plant respectively. The sequence of operations carried out in the plant are first stage air preheating-humidification-dehumidification, second stage air preheating-humidification-dehumidification followed by chilled water cooling. The present work is aimed on the thermodynamic modeling for maximization of gained output ratio (GOR), energy utilization factor, fresh water production and production rate for different atmospheric conditions. The influence of hot water temperature and its mass flow rate, effectiveness of humidifier are studied on the plant performance for optimum operating conditions. GOR is increased at low atmospheric air temperature for increased hot water temperature, a maximum of 0.97 is achieved and a maximum EUF of 0.72 is observed at lower air temperature. The resulted fresh water is 42 kg/h at 60 kg/h mass flow of air with a water flow rate of 1100 kg/h. GOR increases with increase in effectiveness for low inlet air temperature whereas it decreases for higher inlet air temperatures.

KEY WORDS: Air, Humidification, Dehumidification, Desalination, Cooling effect.

1. INTRODUCTION

FRESH is an essential need for human and animal living. Rapid growth in industrialization and urbanization leads for decrease in vegetation and increase in the environmental pollution. It is very essential to look for low cost, environment friendly technologies to produce potable water. Solar desalination by air humidification dehumidification (HDH) is a proven cost effective technology with low payback period. This technique works on humidification of air with water and dehumidification of air by cold water or air resulting in desalinated water. In this work a detailed thermodynamic study is carried out to evaluate the thermal performance of a two stages solar desalination unit.

HDH method of desalination attracting many researchers due to its simple components, low cost, easy to operate at wide range of temperatures etc. Many systems functioning worldwide using low temperature sources like solar, geothermal with HDH technique are presented, analyzed and evaluated. Kabeel (2013), presented detailed review on different HDH desalination systems and concluded that it is a best choice to produce fresh water in decentralized locations where the total thermal energy required can be obtained from solar energy. Ettouney (2005), developed equations for thermal design of humidification dehumidification systems for different layouts to evaluate the performance for optimum operating conditions at minimum production cost. Prakash Narayan (2010), carried out theoretical cycle analysis on different HDH cycles for performance improvement. They proposed multi-extraction, multi-pressure and thermal vapour compression to get high gained output ratio (GOR) of 5 and above. Hou (2005), presented a method for performance optimization of solar HDH desalination process using pinch technology. This method proves to be a simple and efficient to find the optimum mass flow rate ratios of hot water and dry air for a given temperature of spraying hot water and cooling water flowing in the dehumidifier. El-Agouz (2010), investigated the influence of operating parameters on performance of a desalination system based on HDH method with air passing through hot seawater. A maximum fresh water production of 8.22 kg/h is observed from experiments at a water temperature of 86°C and an air flow rate of 14 kg/h.

Vlachogiannis (1999), carried out thermodynamic analysis on a new desalination concept of combining HDH and mechanical vapor compression. Preliminary experiments on a laboratory prototype proved the concept with successful operation of the system. Franchini and Perdichizzi (2014), developed a computer code for simulation of a HDH system operating at low temperature coupled with Li-Br absorption chiller. They designed and demonstrated an integrated cooling and desalination plant in which Li-Br absorption machine is driven by heat collected from solar collectors and the HDH system is driven by low temperature heat rejected by the chiller. Chiranjeevi (2014), and Srinivas (2015), carried out carried out thermodynamic study on a combined two stage HDH desalination and cooling plant coupled with aqua–ammonia based vapor absorption system. The experimental readings are compared with the simulation results, which are in an agreeable range. Zamen (2014), conducted experiments on a two stage solar HDH desalination pilot plant constructed in an arid area with 80 m^2 solar collector area. The plant experimental results show an increase in heat recovery in condensers and reduce investment cost. Dai and Zhang (2000), conducted experiments solar desalination unit and concluded that temperature, mass flow rate of salt water to humidifier, and the mass flow rate of air strongly influence the performance of the plant. The unit functioned well with a thermal efficiency of 80%. Narayan (2013), design and constructed a pilot scale HDH plant with a peak production capacity of 700 l/day. The experiments were carried out and the theories of HDH systems with or without mass extraction and injection are validated and optimization studies were carried. Karan (2010), carried out irreversibility analysis on humidification-dehumidification desalination cycles to minimise the specific entropy generation. It is also observed that, each cycle have one limiting component that cannot be substantially improved.

From the above cited literature it is found that thermodynamic study for optimum operating conditions were not carried out on a two stage HDH desalination system for maximum yield. Hence the objective of the present work is to analyze the performance of the two stage HDH cycle thermodynamically by varying different operating parameters. A thermodynamic simulation model is developed for finding optimum operating conditions for the proposed plant.

System description: Fig.1 shows the line diagram of the proposed two stages open air closed water (OACW) HDH desalination system. The thermodynamic state properties of the system are tabulated in Table 1 for the line diagram shown in Fig. 1. A blower is located at the inlet of desalination plant, forces the atmospheric air into the first stage air pre heater (2-3). The sensible heat is added to air indirectly in air pre heater by hot water (14) supplied from solar water heater (SWH) resulting in temperature rise and decrease in relative humidity (RH) without changing specific humidity (SH). The hot air then enters the first stage humidifier will pass through the wetted packing. As the temperature of hot water (15) is more than the inlet air (3), heating and humidification results in humidifier. The water temperature at the exit (19) of humidifier will decrease by latent loss to air. Air (4) gains the moisture from the hot water depending on the heat and mass transfer conditions in humidifier. The condition of air at the humidifier exit depends on the hot water temperature, spray characteristics and packing material. After heating and humidification the humid air enters into an air cooled dehumidifier (4-5) for the first stage desalination. The cooling and dehumidification in first stage dehumidifier results in condensed desalinated water (10) collected at point 13. This completes the first stage humidification dehumidification desalination. The processes sensible heating in second stage air pre heater (5-6), heating and humidification in second humidifier (6-7) and cooling and dehumidification in second dehumidifier (7-8) are repeated in the second stage desalination. To achieve more yield in desalination the air (8) coming from second dehumidifier is further cooled by chilled water (24) in dehumidifier 3 to state 9. The temperature of air at state 9 is less than atmosphere, so it will be further send for central air conditioning purpose. The chilled water (24-25) is generated in an aqua-ammonia vapor absorption refrigeration (VAR) system using solar energy. The low temperature water (18, 19, 20 and 21) collected is circulated back to solar water storage tank for reheating by a circulating water pump.

An indirect solar water heater is used to generate the hot water. Thermic fluid from the inner storage tank flows to the solar flat plate collectors gains the heat and transfers the same to hot water in the storage tank. The hot water is used for air preheating in air pre heaters and heating and humidification in humidifiers. The VAR plant considered is a single effect system having ammonia-water mixture as a working fluid. The heat required to generate ammonia vapor from ammonia-water mixture is given by a thermic fluid (26-27) circulated through a solar concentrated parabolic collector and a generator. The total energy supplied to the HDH plant is the sum of heat supply to air in air pre heaters and humidifiers, heat taken away by chilled water and electric power required to operate auxiliaries.

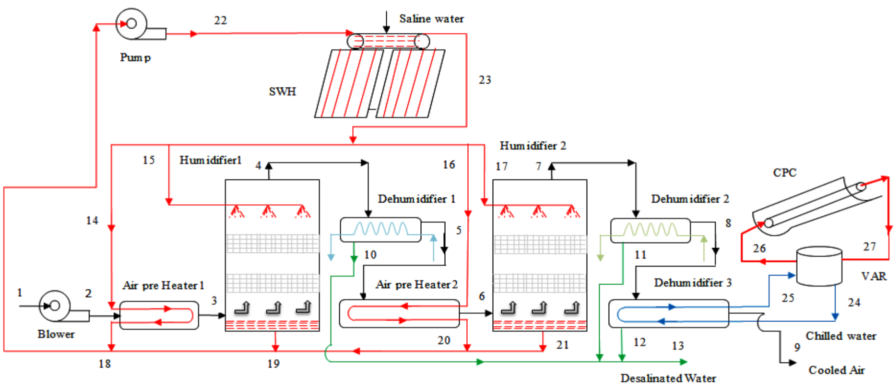

Fig.1. Line diagram of two stage desalination plant

The psychrometric processes takes place in different components of the plant is represented on a psychrometric chart for better understanding. For detailed understanding of the key processes sensible heating, heating-humidification and dehumidification in HDH plant are represented on a psychrometric chart as shown in Fig.2. The psychrometric processes represented in Fig.2are sensible heating (2-3) in first state air pre heater, heating and humidification (3-4) in first stage humidifier followed by dehumidification (4-5) in first stage dehumidifier. The second stage processes sensible heating (5-6), heating and humidification (6-7), dehumidification (7-8) and dehumidification by chilled water (8-9) are represented on the chart. From the chart it is clearly observed the advantage of air preheating for greater humidification as it decreases the sensible heat load in the humidification process in both the stages. From the chart an amount of 45 and 75 grams of water vapor can be condensed from first stage to second stage dehumidification process respectively.

Table.1. Properties of air at different states with reference to Fig. 1.

State	P, kPa	T, ˚C	RH, %	M, kg/h	SH, g/kg	H, kj/kg
1	101.33	30	50	60	13.36	64.31
2	141.85	32	62.47	60	13.36	66.37
3	137.85	70.4	9.13	60	13.36	105.92
4	129.85	78.08	95	76.81	293.59	855.45
5	125.85	36	100	56.64	30.95	115.66
6	121.85	70.4	18.2	60	30.95	152.21
7	113.85	78.08	95	79.66	358.64	1027.59
8	109.85	36	100	40.62	35.71	127.9
9	105.85	10	100	39.47	7.32	28.5

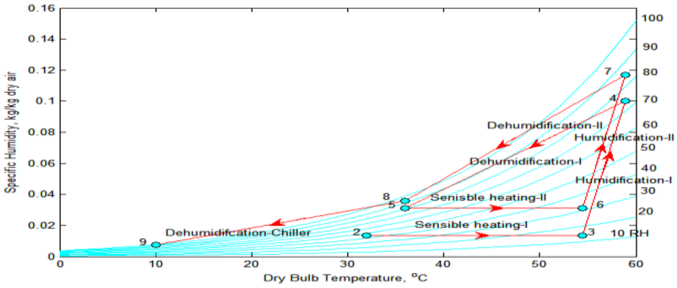

Fig.2. Psychrometric processes in desalination plant

System simulation: The following assumptions are made while carrying thermodynamic analysis. Thermal efficiency and effectiveness of humidifier and dehumidifier are assumed as 70 % and 80 % respectively. Atmospheric air at inlet of air is taken as 30°C, inlet hot water temperature 60°C to humidifier and air pre heaters, chilled water from VAR at 4ºC, terminal temperature difference (TTD) of 6°C at chiller. Yuan (2013), resulted 90-93 % RH at the exit of humidifier. The RH of air after humidification is 95% and 100% after the dehumidifier.

The properties of air at different conditions are determined from psychrometry. Following are the formulae developed for the first stage humidifier. The air outlet temperature (4 and 7) and water outlet temperatures (19 and 21) at humidifier are obtained from the effectiveness and efficiency of humidifier respectively.

The humidifier efficiency,

$$\eta_{humidifier} = \frac{T_{a,o} - T_{a,i}}{T_{w,i} - T_{a,i}}. \quad (1)$$

The humidifier effectiveness,

$$\varepsilon_{humidifier} = \frac{T_{w,i} - T_{w,o}}{T_{w,i} - T_{WBT}}. \quad (2)$$

The makeup water to be supplied at SWH,

$$m_{mw} = (\omega_4 - \omega_3)m_{da}. \quad (3)$$

From the energy balance in humidifier, the hot water required

$$m_{15} = \frac{m_{da}(h_4 - h_3 - h_{15}(\omega_4 - \omega_3))}{(h_{15} - h_{19})}. \quad (4)$$

The dry air flow rate at the inlet of humidifier,

$$m_3 = (1 + \omega_3)m_{da}. \quad (5)$$

Similarly, the wet air flow rate at the outlet of humidifier,

$$m_4 = m_3 + (\omega_4 - \omega_3)m_{da}. \quad (6)$$

The desalinated water after dehumidification in dehumidifier1,

$$m_{10} = (\omega_4 - \omega_5)m_{da}. \quad (7)$$

Above procedure is repeated for the second stage humidifier.

The desalinated water after dehumidification in dehumidifier2 and dehumidifier3 are,

$$m_{11} = (\omega_7 - \omega_8)m_{da}. \quad (8)$$

$$m_{12} = (\omega_8 - \omega_9)m_{da}. \quad (9)$$

From heat balance the chilled water required from VAR is,

$$m_{24} = \frac{m_{da}(h_8 - h_9)}{c_{p,ch.w}(h_{25} - h_{24})}. \quad (10)$$

The performance parameters of the plant are,

Equivalent heat of vaporization of desalinated water,

$$Q_{dw} = m_{13} \times 2504.9. \tag{11}$$

Cooling effect from air after dehumidifier3,

$$Q_{ce} = m_9(h_{amb} - h_9). \tag{12}$$

Net power supply to the plant,

$$W_{net,\ in} = W_{blower} + W_{ch\,water\ pump} + W_{SWH\,pump}. \tag{13}$$

Heat input,

$$Q_{in} = Q_{AH1} + Q_{HDF1} + Q_{AH2} + Q_{HDF2}. \tag{14}$$

Energy utilization factor (EUF),

$$EUF = \frac{(Q_{dw} + Q_{ce})}{(W_{net,in} + Q_{in})}. \tag{15}$$

Gained output ratio (GOR),

$$GOR = \frac{Q_{dw}}{Q_{in}}. \tag{16}$$

Production rate (PR),

$$PR = \frac{m_{dw}}{(m_{15} + m_{16})} \times 100. \tag{17}$$

Fresh water production (FWP),

$$FWP = m_{10} + m_{11} + m_{12}\,. \tag{18}$$

2. RESULTS AND DISCUSSION

The variation of gained output ratio, energy utilization factor, production rate and fresh water production by the hot water temperature, flow rate at different atmospheric air temperature are studied in detail. Humidifier is a key component in the plant influences the humidification rate. The influence of humidifier effectiveness on gained output ratio is studied against different hot water and air temperatures.

Fig.3 represents the variation of gained output ration and energy utilization factor with respect to hot water inlet temperature for different air inlet temperatures. Higher the inlet air temperature leads to a low heat addition in humidifier and hence high GOR. For low inlet air temperatures the heat added will be more and hence low GOR. It is clear from the Fig.3a that in winter season for low air temperature GOR is more for higher hot water inlet temperature. Also the variation of GOR for summer conditions is not much varied for different hot water inlet temperature. Its variation for different air inlet temperatures is low for high hot water temperatures is less for low hot water temperatures. From the Fig.3b air at low temperatures has ability to take more heat energy which is added in air pre heaters and humidifiers. Hence EUF is less for low inlet air temperatures compared with high inlet air temperatures.

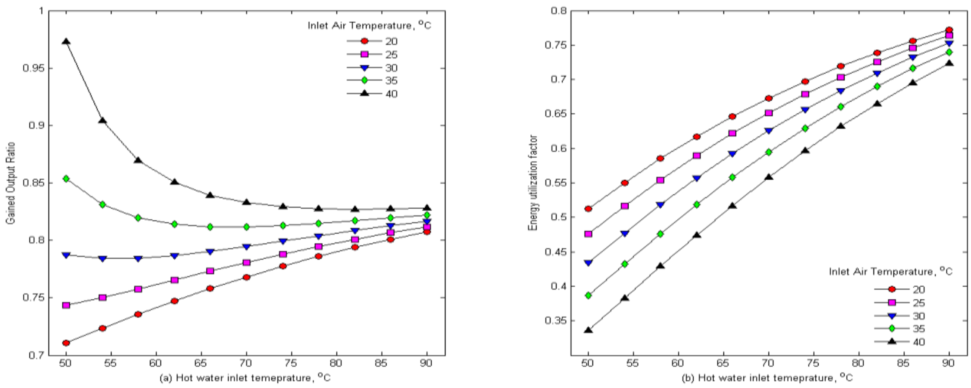

Fig.3. Gained output ratio, Energy utilization factor variation with hot water inlet temperature

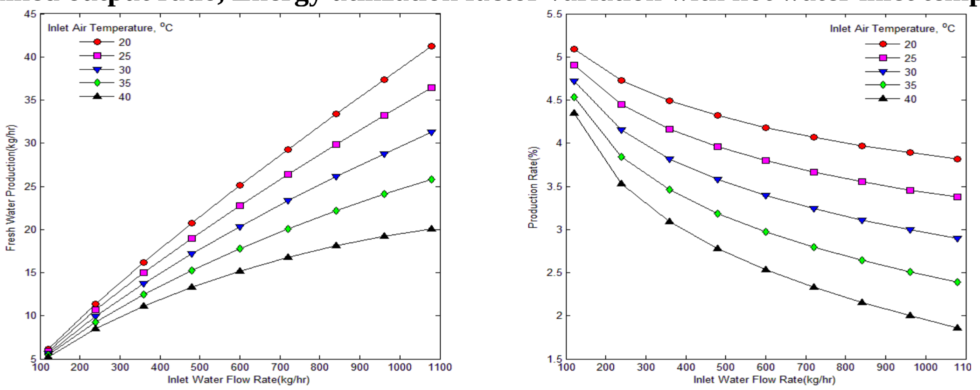

Fig.4. Study on the influence of hot water flow rate on fresh water production and production rate

Fig.4 shows variation of fresh water production and production rate for different flow rates of hot water with air supplied at different temperatures. Fresh water production with respect to inlet water flow rate for different inlet air temperature ranging from 20 – 40˚C for fixed hot water temperature of 60˚C and effectiveness of 0.8. Fig. 4a shows a decrease in fresh water production with increase in inlet air temperature, and maximum fresh water production achieved is 98 kg/hat an inlet air temperature of 20˚C and the hot water flow rate of 1100 kg/h. The production rate is also maximum for air inlet temperature of 20˚C as shown in the Fig.4b. Production rate decreases as with increase in inlet air temperature for an increase in hot water flow rate ranging from 0 – 1100 kg/h.

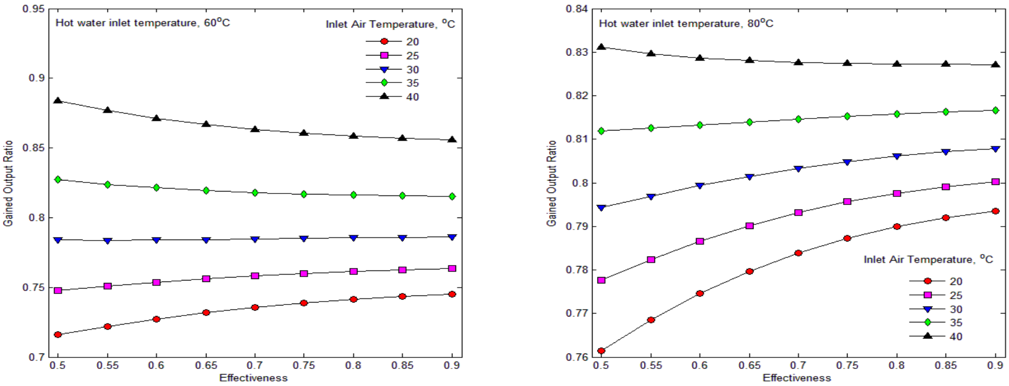

Fig.5.Variation of GOR with humidifier effectiveness at air temperatures of 60˚C and 80˚C

Fig.5 shows the variation of GOR with respect to humidifier effectiveness for different inlet air temperature range of 20 – 40˚C. At higher humidifier effectiveness helps in better humidification of inlet air supplied at low temperatures results in high desalination water. This will increase the GOR at low air temperatures, whereas at high inlet air temperatures GOR will decrease. The result shows that GOR increases for lower inlet air temperatures and for higher inlet air temperatures it decreases with increase in effectiveness for the hot water temperature of 60 and 80°C. It is observed from the Fig. 5that there is a slight increase in GOR for lower air inlet temperatures and it decreases at higher inlet air temperatures for hot water inlet temperature of 80˚C.

3. CONCLUSION

The parametric study is carried out on a two stage HDH system with a simulation code developed in MATLAB. The results gained output ratio, production ratio, fresh water production and energy utilization factor are studied for different hot water temperature and flow rate on different atmospheric air temperatures. Desalinated water is the main output from the proposed plant and air is cooled by chilled water at 4˚C in dehumidifier3 is coming can be used for air conditioning purpose. An increase in plant GOR at lower inlet air temperatures and slight decrease in GOR at higher inlet temperature is observed, this gives an optimum operating range for a given inlet air temperature. A maximum GOR of 0.97 is obtained for an air temperature of 20˚C at hot water temperature of 50˚C. A maximum EUF of 0.76 obtained for hot water temperature of 90˚C at an air temperature of 20˚C. Change in fresh water production is more compared to production rate change for increase hot water mass flow rate. A maximum of 42 kg/h of fresh water is produced from the plant for an inlet air temperature of 20˚C and hot water flow rate of 1080 kg/h. This study helps in choosing best operating conditions for the plant for given conditions of atmospheric air and hot water.

4. ACKNOWLEDGEMENT

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