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Experimental analysis of augmented desalination by cooling integration

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Abstract

This work evaluates a two-stage humidification-dehumidification (HDH) process for combined air cooling and desalination for fresh water production from salt water experimentally. A pilot scale plant is designed and constructed with 16 m^2 solar collector area for salt water heating. The operational parameters identified are hot saline water supply to humidifiers and it's temperature. The saline water is heated in a solar water heater (SWH) and supplied to the two humidifiers and air preheaters. Main performance parameters i.e. desalinated water generation, cooling effect and energy utilization factor (EUF) of the plant is studied in the light of hot water inlet temperature and its flow rate. It is observed that a maximum of 2.5 LPH of fresh water is produced at a water and air flow rates of 300 LPH and 10 m^3/hr respectively. At low inlet water temperatures the resulted cooling effect is more compared with high temperatures and an average of 120 W of cooling effect is produced. The energy utilization factor (EUF) of combined two stage desalination and cooling plant is more compared with individual single stage plants and an average value of 0.4 is attained for combined plant. On overall basis, maximum possible water flow rate in humidifier and also high temperatures are recommended to yield more desalination output.

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Keywords: desalination; humidification; dehumification; cooling effect.

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1. Introduction

In past recent years energy conservation and management became a major research area. A lot of research has been done on using renewable energy sources as energy source. Solar energy is major renewable energy source which falls on earth and return back unused is used to get hot water for humidification. Many researchers are looking for systems which can utilize low temperature sources with renewable energy. The proposed plant produces distilled water and cooled air for room cooling with a nominal electric power input for running auxiliary units. Humidification can be done by hot water spray and dehumidification by circulating water, atmospheric air and chilled water. This makes the plant less dependent on electricity, which is ideal for hot places where sun radiation is high and having water scarcity.

Nomenclature

EUF	energy utilization factor
h	specific enthalpy, kJ/kg of dry air
m	mass flow rate, kg/s
Q	heat, kW
W	work, kW

Suffix

APH	air preheater
chw	chilled water
da	dry air
ds	double stage
dw	desalinated water
fg	latent heat
fs	first stage
ss	second stage
hw	hot water

The process of air humidification-dehumidification (HDH) is based on the natural water cycle. This technique is studied and applied by many researchers due to low temperature energy (solar, geothermal, waste heat) use, simplicity, low cost and less payback period. HDH is a best suitable choice for producing fresh water when the demand is decentralized. Orfi et al.[1] did theoretical study on solar desalination system using HDH technique and showed an optimum water to air mass ratio ranges from 1.6 to 2.2 for a maximum yield of 0.05 grams of fresh water per unit kg of dry air. Chiranjeevi and Srinivas [2] developed a model for parametric study of a combined two stage HDH desalination plant integrated with cooling system. Yamli and Solmus [3] did experiment on humidification and dehumidification (HDH) process and concluded that with increase in mass flow rate of the air fresh water productivity remains same. Prakash Narayan et al. [4] constructed and carried out on a pilot scale HDH unit and validated the design models developed. Further the optimization of heat and mass exchange devises have been studied with the experimental data. Dai and Zhang [5] have investigated the performance of a solar desalination system experimentally. It is found that the performance of the system is strongly depends on the salt water temperature of inlet to the humidifier, the mass flow rate and the mass flow rate of air. Farhad et.al. [6] conducted an experimental and theoretical energy and exergy analysis of a solar desalination system consisting of a solar collector and a humidification tower. The developed model is validated against the experimental data, an effective design of a humidification tower can be designed from the results. Orfi et al. [7] conducted an experiment on a water desalination system using solar energy and compared the results with the mathematical model. The results show that there exists an optimum mass flow rate ratio corresponding to a maximum fresh water production. Zamen et al. [8] designed, constructed and conducted experiments on a two-stage pilot plant. Experimental results show that the productivity can be increased by 20% compared with single stage unit. Mehrgoo and Amidpour [9] used the Lagrangian multipliers and genetic algorithm (GA) methods to optimize the production rate in HDH system subject

to global constraint (fixed volume). Kabeel and El-Said [10] developed a laboratory experiment for a hybrid solar desalination system consisting of a HDH and single stage flashing evaporation using solar air heater and solar water heater (SWH) and obtained a good agreement between simulated and measured variations for water production and performance ratio. Chang et al. [11] developed the performance characteristics of multi-effect HDH system with the use of packed porous plastic balls and finned heat exchangers. Kang et al. [12] also simulated two stage multi-effect HDH desalination plant with nine equations and nine parameters. By varying different parameters experiments were conducted and compared with the simulation results to validate the developed models. Yıldırım and Solmus [13] extended their work with the use of fourth order Runge–Kutta method for mathematical modelling of HDH system using solar air heater and solar water. Nada et al. [14] designed and constructed a test rig of HDH desalination plant to study the performance under different operating parameters.
Hamed et al. [15] investigated the HDH plant theoretically and experimentally with solar water heating system. They proved that the highest desalination yield is in the afternoon time of operation. Chiranjeevi and Srinivas [16] developed a pilot plant and analysed the experimental results with simulation results on a combined two stage humidification-dehumidification desalination and cooling plant. Li et al. [17] conducted an experiment on HDH pilot plant with solar air heaters using vacuum tubes with air heating and cold water spray into hot air for humidification.

The literature published indicates that most of the researchers focussed on desalination systems and integrated desalination and cooling systems were not focussed much. In the present work the main objective is to conduct experiments for different flow rates and temperatures of saline water to prove the feasibility of possible increase in desalination yield with added cooling benefit.

2. Methodology

Thermodynamic design is carried out on two stage desalination and cooling and developed an experimental integrated pilot plant. It is tested experimentally to highlight the dual benefits of increased desalination yield with an addition of air cooling. In present work an open air closed water (OACW) arrangement of HDH system is designed and constructed.

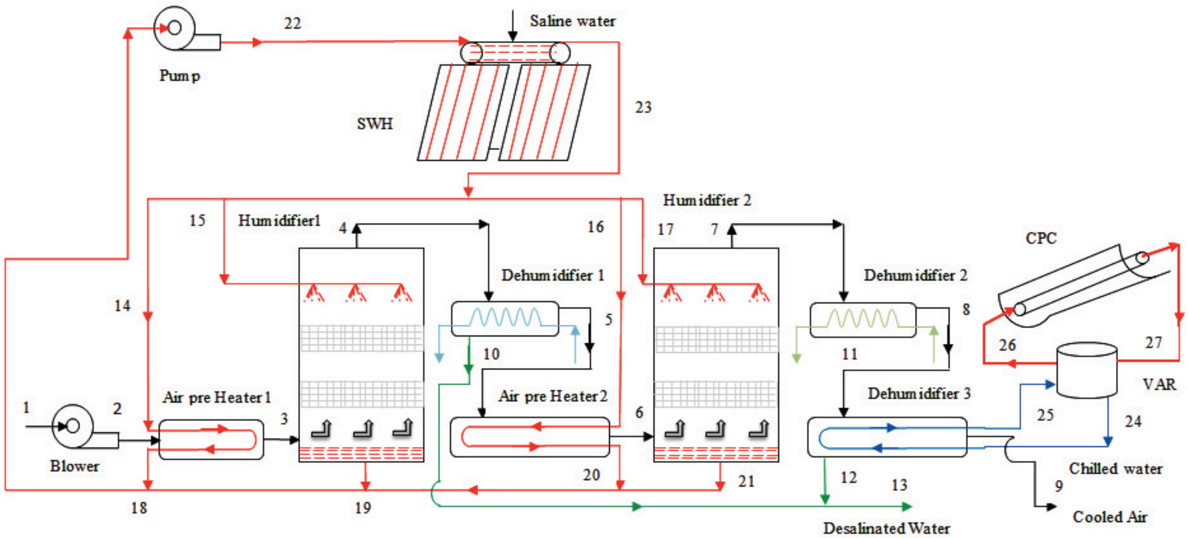

Fig.1. Line diagram of two stage desalination and cooling plant.

Fig.1. shows a schematic layout of the proposed two stage OACW tow stage HDH desalination and cooling plant using solar thermal supply. The air is supplied to the desalination plant from a blower (1-2) or alternately solar air expander can be used from the air turbine without the use of blower. The first stage desalination consists of 1st air

pre heater (APH) (2-3), 1st humidifier (3-4), and 1st dehumidifier (4-5). Similarly the second stage desalination plant has 2nd APH (5-6), 2nd humidifier (6-7), 2nd dehumidifier (7-8), and 3rd dehumidifier (8-9). APH is a concentric tubular heat exchanger located at the inlet of humidifier to increase the humidification capacity of the air. Humidifier is a vertical cylindrical container connected with hot water inlet, outlet and air inlet, and outlet pipes. Two layers of inner plastic packing is kept inside the humidifier to increase the contact between hot water and air. First stage dehumidifier is a shell and tube heat exchanger in which humid air condenses y rejecting latent heat to circulating water. In second stage the humid air is condensed in the 2nd dehumidifier (plate finned heat exchanger) by rejecting heat to air by natural convection and the subsequent condensation of humid air takes place in 3rd dehumidifier (shell and tube heat exchanger) by rejecting heat to chilled water. The condensation of humid air in second stage by air cooling decreases the cooling load on chilled water in the 3rd dehumidifier and hence reduced size of the water cooler. The desalinated water is collected at points 10 and 13 from first and second stage respectively. The cooled air by chilled water in 3rd dehumidifier is below the room temperature, so it can be used for room air conditioning.

Vapour absorption refrigeration (VAR) plant (24-27) is designed and constructed for generating chilled water. This plant works on the principle of absorption of refrigerant (ammonia) into absorbent (water) at low temperature and low pressure by rejecting heat to air or water and separation of refrigerant and absorbent at high temperature and high pressure by the latent heat addition. A solution pump circulates the working fluid and creates the high pressure in the vapour generator [18]. But the study of VAR plant is beyond the scope of current study.

Fig. 2. Experimental setup of two stage HDH desalination and cooling plant.

Photograph of combined two stage HDH desalination and cooling plant experimental test set up is shown in Fig.2. Saline water is heated indirectly with glycol-water mixture in SWH, installed on the rooftop of the laboratory. The advantage with indirect type heating of saline water saves the SWH from corrosion and increases the life. The hot water is supplied to two air preheaters and two humidifiers connected in parallel mode which ensures the same temperature of hot water for all four components. The air is supplied to the first stage HDH plant from an air turbine passes through APH increases the temperature without changing in specific humidity (SH) resulting in moisture absorbing capacity. In the 1st humidifier, hot water is sprayed at the top over the plastic packing, collected at the bottom and drained to the water collecting tank for recirculation to SWH. Heated Air from 1st APH enters the bottom of 1st humidifier and gains moisture from the thin film of hot water flow down the packing by evaporation. The packing provides more contact area between hot water and air with an increase in residence time resulting in high relative humidity (RH). The plastic packing arranged in humidifiers is a honey comb structure and lain in two layers. The RH and SH levels of air increases in the humidification process. The heated humid air is then enters the top of 1st dehumidifier is cooled with circulating water supplied at ambient conditions. As described dehumidifier is a vertical shell and tube heat exchanger having tubes to flow water and baffles were arranged on shell side to direct the humid air on to the outer surface of tubes. At the bottom of the dehumidifier, a space is provided to collect the desalinated water periodically through a drain valve. The dehumidified air flows from the 1st dehumidifier to the 2nd APH for the second stage processes. Individual flow control valves are provided to the main water pipe line coming from SWH to vary the flow control in two APH and two humidifiers. For current study volume flow rate of air is fixed and mass flow rate of hot water is varied. In the second stage approximately similar process takes place in 2nd APH and 2nd humidifier. The second stage dehumidification process starts in air cooled plate finned heat exchanger and 3rd dehumidifier by chilled water. The 3rd dehumidifier is also a vertical shell and tube heat exchanger similar to the 1st dehumidifier. The air coming from the 3rd dehumidifier is cooled below the atmospheric temperature, so it can be used for room air conditioning. To visualize the dehumidification process, 1st and 3rd dehumidifiers are enclosed in cylindrical acrylic pipes. APHs, humidifiers and chilled water pipe lines are insulated to minimize the heat losses or gain. A standby water cooler operated by 0.5 hp hermitically sealed compressor is used for the generation of chilled water. For circulating the hot saline water between SWH and desalination plant 1 hp centrifugal pump is used. A 0.5 hp piston pump is used for the circulation of chilled water from water cooler to the 3rd dehumidifier. As mentioned before the air for the desalination plant is taken from solar air expander, which is beyond the scope of the current study. All the components are assembled and erected over a 1.5 m high stand for easy collection of hot water, circulating water, chilled water and desalinated water in appropriate containers. Air leakages are arrested properly by placing the gas cuts at the flanged joints.

Experiments are conducted on the proposed plant by controlling the hot water supply to humidifiers and hot water inlet temperature to desalination plant. A fixed mass flow rate of air 10 m^3/h is maintained during the experimentation. The hot water flow rate to the two humidifiers is maintained same with independent flow control valves located at the inlet of humidifiers. The temperature of the hot water supplied to APHs and humidifiers is same as the hot water is supplied from the same SWH. The hot water flow rate (1150 LPH) to APHs, normal circulating water flow rate (310 LPH) to 1st dehumidifier and chilled water flow rate (125 LPH) to 3rd dehumidifier are fixed during the experimentation. The hot water pump is switched on after closing the vent valve in SWH for closed loop circulation of hot water. Once the hot water circulated to the desalination plant and sufficient water gets stored at the bottom of humidifiers, air is supplied gradually to the desalination plant. The plant is allowed to reach steady state and the initial desalinated water level in the collecting column is noted separately for the two stages. Air temperatures and water temperatures at the inlet and outlet of each component are measured using thermo-couples. Air flow rate and water flow rates are noted from the respective rotameters. Humidifiers pressure is noted from the bourdon tube pressure gauges. The RH values of air at different stages are measured by digital humid meters.

Thermo-physical properties of wet air and water are taken from standard thermodynamic relations. Desalinated water is directly measured from the experimentation at an interval of 20 minutes and converted them to ml/hr.

The amount of energy contained by desalinated water is,

$$Q_{dw} = m_{dw} h_{fa}. \quad (1)$$

The cooling effect from the plant is calculated with simple energy equation.

$$Q_{cooling} = m_{da}(h_{ambient} - h_9). \quad (2)$$

The performance of the desalination plant is solved with energy utilization factor (EUF) for first stage, second stage and combined desalination cycle.

The EUF of the first stage without cooling effect,

$$EUF_{fs\ cycle} = \frac{m_{fs\ desalination} h_{fg}}{Q_{APH,\ 1} + Q_{humdifier,\ 1} + W_{pump,\ hw}}. \quad (3)$$

The EUF of the second stage with cooling effect,

$$EUF_{ss\ cycle} = \frac{(m_{ss\ desalination} h_{fg}) + Q_{cooling}}{Q_{APH,\ 2} + Q_{humdifier,\ 2} + W_{pump,\ hw} + W_{cooler} + W_{pump,\ chw}}. \quad (4)$$

The EUF of the double stage pant with cooling effect,

$$EUF_{ds\ cycle} = \frac{(m_{ds\ desalination} h_{fg}) + Q_{cooling}}{Q_{APH,\ 1} + Q_{humdifier,\ 1} + Q_{APH,\ 2} + Q_{humdifier,\ 2} + W_{pump,\ hw} + W_{cooler} + W_{pump,\ chw}}. \quad (5)$$

3. Results and discussions

The key process variations identified are hot saline water flow rate in humidifiers and its inlet temperature to desalination plant. Separate flow control valves are used to control the hot fluid flow into the two humidifiers. Whereas hot water flow rate to two APHs, circulating water flow rate in 1st dehumidifier and chilled water flow rate in 3rd dehumidifier are kept constant. The hot water temperature is followed with the change in solar radiation. The overall plant performance can be assed with desalination yield, cooling effect and EUF of the plant.

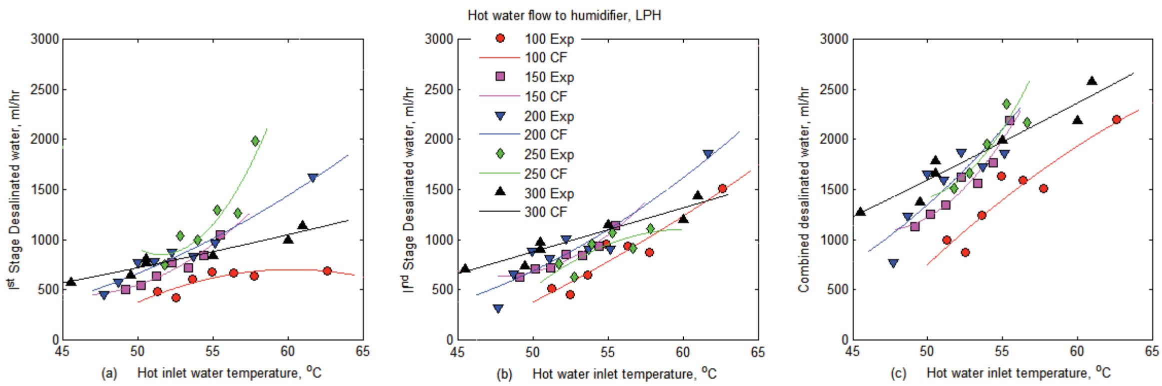

Fig. 3. Desalinated water (a) the 1st stage, (b) the 2nd stage, and (c) combined two stage from experimentation.

Fig.3. presents the role of hot water flow rate in humidifiers and its inlet temperature on desalination yield from experimentation and the corresponding second order curve fit. The results shown are (a) the first stage desalination, (b) the second stage desalination, and (c) the combined two stage desalination. The first stage desalination is by circulating water supplied at ambient temperature and the second stage desalination is by atmospheric air followed by chilled water cooling. The desalinated water yield is increased from Fig.3a to Fig. 3b with the proposed concept of cooling integration. In addition to the increased desalination yield, extra cooling benefit is resulted from second stage. In the first stage, water yield changed from 0.4 to 1.3 LPH per 10 m^3/hr flow of air. For the same quantity of air in the second stage a desalination yield changed from 0.5 to 1.5 LPH. The combined two stage plant yield a maximum of 2.5 LPH per 10 m^3/hr of air, which is an equivalent of 250 mL/m^3 of air. From the figure it is also noticed that at lower flow rates though the temperature of hot water is increased there is not significant change in desalination yield in first stage. Whereas in second stage the desalination yield increases with increase inlet hot

water temperature for low hot water flow rates. This may be because in second stage the humid air cooled by chilled water to temperatures below atmosphere, so that desalination takes place below atmospheric temperature.

The influence of hot water flow rate to the humidifiers and its temperature on the desalination and cooling effect is shown in Fig. 4. The cooling effect maintained in the range of 50 W to 150 W for an air flow of 10 m^3/hr with 45 to 65 °C of humidifier hot water inlet temperature range. A maximum of 150 W cooling effect is observed for 250 LPH at 57 °C of hot water temperature. It is observed that the cooling effect is maximum at
lower flow rates of water compared with high flow rates of water. This is because at low water flow rates humidification is less and hence the cooling load shared for desalination less resulting in more cooling effect. It is suggested an optimum cooling effect can be obtained at a hot water flow rate of 200 LPH and 55 °C at 10
m^3/hr of air flow rate. A high desalination output results less cooling effect due to more cooling absorbed by desalinated water.

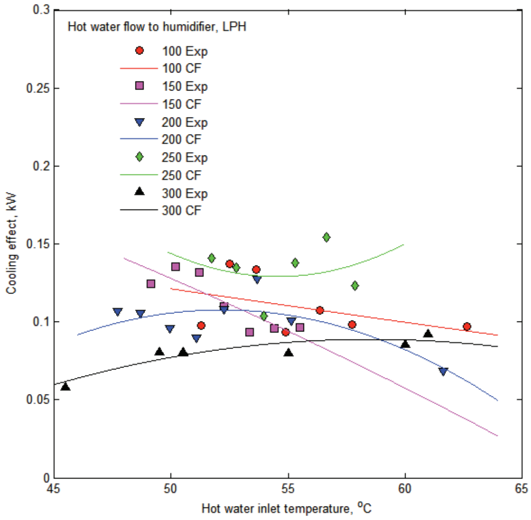

Fig. 4. Influence of hot water flow to humidifiers and its temperature on the desalination and cooling effect.

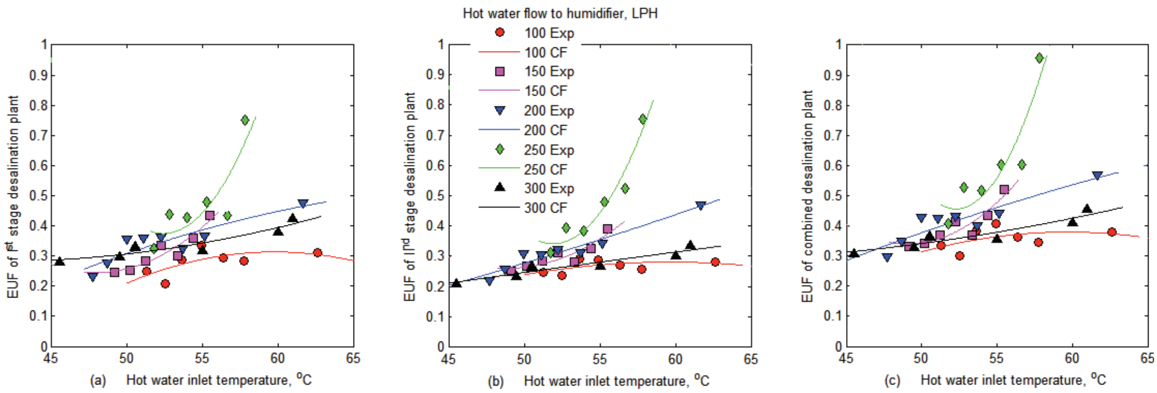

Fig. 5. Influence of EUF with respect to hot water flow rate and its inlet temperature

The effect of EUF with the changes in hot water inlet temperature and hot water flow rate for the (a) first stage, (b) the second stage and (c) the combined desalination and cooling plant is shown in the Fig. 5. In the first stage plant only desalinated water is obtained as output, where as in second stage both cooling and desalinated water are obtained as output. In the combined plant first and second stage desalinated water along with cooling effect in second stage is obtained as output. Hence the EUF for the first stage is high compared to EUF in second stage due to usage of chilled water pump and cooler. But in the combined plant the overall EUF is high due to desalinated water out from the first stage without any extra energy input for hot water pumping. An average value of 0.35, 0.3 and 0.4 EUF are obtained for the first, second stage and combined desalination cooling plant respectively. It is also observed that the EUF is increased with respect to hot water inlet temperature and a higher EUF is observed for higher water flow rates.

4. Conclusions

The performance of first, second stage and combined cooling and desalination plant are studied experimentally by varying the input parameters of hot water flow rate and its inlet temperature for a fixed air flow rate. The operating temperature of 55 °C and 250 LPH of hot water flow rate are suggested to yield maximum output both in single and combined cooling and desalination plant. Maximum desalination output of 2.5 LPH is obtained at 60 °C of hot water temperature with 300 LPH of inlet hot water flow for an air flow rate of 10 m^3/hr and approximately 150 W of cooling effect is produced. An average EUF of 0.4 is obtained for the proposed combined cooling and desalination plant. The plan has an advantage of operating desalination plant single stage and combined desalination and cooling, with an additional cooling effect which can used for air conditioning application.

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