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Experimental and simulation studies on two stage humidification–dehumidification desalination and cooling plant

C. Chiranjeevi, T. Srinivas *

CO_2 Research and Green Technologies Centre, School of Mechanical and Building Sciences, VIT University, Vellore 632 014, India

HIGHLIGHTS

- Experimental demonstration of two stage desalination and cooling
- Use of chilled water for condensation of humid air
- Simulation of experimental results
- Comparative study on conventional condensation and improved condensation
- Improved design of proposed integrated plant

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ABSTRACT

Humidification–dehumidification (HDH) desalination is a simple and cost effective solution to convert the saline water into desalinated water. In current work, desalination yield has been augmented with two stage HDH integrated cooling plant. A pilot plant has been developed and analyzed with experimental and simulation studies. The identified operational variants are hot saline water supply to humidifiers and its inlet temperature. The saline water is heated in a solar water heater (SWH) and supplied to two humidifiers and two air preheaters. The simulated results developed for subsystems are validated with the experimental readings. Desalination yield is not satisfactory level at lower water temperature in the first stage plant but there is no such limitation in the second stage operation. Nearly 1.5 LPH of desalinated water is resulted at 15 m^3/h of air. The energy utilization factor (EUF) of two stage plant is concentrated at higher side compared to the single stage plant's EUF. The increased flow of saline water in humidifiers and its high temperature is favoring the desalination output but with a penalty in cooling effect.

1. Introduction

Currently, the ground water level is decreasing due to urbanization and increased water demand with population. Indian costal line is very long at east and west, and so there is a good potential and scope for desalination plants. Low grade energy can be used in humidification–dehumidification (HDH) cycle as a cost effective solution. The use of low grade heat for thermal desalination processes is relevant in energy conservation and plays a significant role in increasing the capacity to satisfy the future water demands [1]. It basically operates on water cycle principle of air humidification and condensation (dehumidification). In current work, double stage desalination with final air cooling by chilled water has been experimented and studied. Humidification can be done by hot water spray and dehumidification by circulating water, air cooling and chilled water.

Recently researchers are paying attention on HDH technology due to its attractive benefits such as simple, cost effective, low pack back, etc. Yamali and Solmus [2] compared the HDH experimental results with theoretical results and stated that the water condensation does not lie on saturation curve. Mehrgoo and Amidpour [3] used the Lagrange multipliers and genetic algorithm (GA) methods to optimize the production rate in HDH system subject to global constraint (fixed volume). Kabeel and El-Said [4] 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). Chang et al. [5] developed the performance characteristics of multi-effect HDH system with the use of packed porous plastic balls and finned heat exchangers. Kang et al. [6] also simulated two stage multi-effect HDH desalination plant with nine equations and nine parameters. Yıldırım and Solmus [7] extended their work with the use of fourth order Runge–Kutta method for mathematical modeling of HDH system using solar air heater and solar water. Nada et al. [8] designed and constructed a test rig of HDH desalination plant to study the performance under

* Corresponding author.

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different operating parameters. Hamed et al. [9] 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. Li et al. [10] conducted an experiment on HDH pilot plant with solar air heaters using vacuum tubes.

The literature search indicates that the combined desalination and cooling plant has not been focused much with experimental demonstration and study. The main objective of the current work is to conduct experimental and simulation study to prove the feasibility of possible increase in desalination yield with added cooling benefit. The current work is the extension of previously reported thermodynamic analysis and design results [11].

2. Methodology

An experimental pilot plant for two stage desalination plant integrated with cooling generation is developed after the thermodynamic work and design. It is tested experimentally to highlight the benefit of increased yield in desalination and additional cooling. Simulation study is conducted at the designed size of the plant and the theoretical results are validated with the experimental values.

Fig. 1 shows the schematic layout of two stage HDH desalination and cooling plant using solar thermal supply. The air is supplied to the desalination plant from a blower (1–2) or alternatively expanded air can be used from the air turbine without the use of a blower. The first stage desalination consists of 1st air preheater (APH) (2–3), 1st humidifier (3–4), and 1st dehumidifier (4–5). Similarly the second stage desalination plant has 2nd APH (7–8), 2nd humidifier (8–9), 2nd dehumidifier (9–10), and 3rd dehumidifier (10–11). APH is a concentric tube heat exchanger located at the inlet of humidifier to increase the humidification capacity of air. Humidifier is a vertical cylindrical container connected to hot water inlet, outlet and air inlet, and outlet pipes. It consists of two layers of inner plastic packing to increase the contact between hot water and air. The first stage desalination plant consists of 1st dehumidifier where humid air is condensed by rejecting heat to circulating water. The second stage desalination plant has two dehumidifiers viz. the 2nd dehumidifier and the 3rd dehumidifier. In the second stage, the humid air is condensed in the 2nd dehumidifier by rejecting heat to air by natural convection. The subsequent condensation of humid air is carried out in the 3rd dehumidifier by rejecting heat to chilled water. The condensation of humid air in the second stage by air cooling and chilled water cooling decreases the chilling water cooler size. Therefore the air cooled heat exchanger (2nd dehumidifier) shares the 3rd dehumidifier load and so decreases the chilled water demand. The desalinated water is collected at two points, 6 and 12 respectively from the first stage and the second stage operations. After the second stage, the air temperature is cooled below the room temperature. So it can be used for centralized air conditioning.

The vapor absorption refrigeration (VAR) plant (31–56) is beyond the scope of the current study. However VAR plant works on the principle of absorption of refrigerant (ammonia) into absorbent (water) at low temperature by rejecting heat to air or water and separation of refrigerant and absorbent at high temperature by the heat addition. The absorption and separation can be carried out at the absorber (low pressure) and boiler (high pressure) respectively by rejecting and heat supply. The solution pump circulates the working fluid and creates the high pressure in the boiler [12].

In earlier work, the combined two stage desalination and cooling plant has been analyzed thermodynamically with a focus on process conditions to select the optimized operational conditions without fixing the capacity of the plant. Thermodynamic optimization and analysis has been carried out with initial assumptions. It results the data of maximum performance and the related operational conditions. After selecting the process conditions, the system size (design) has been solved at the required capacity of desalinated water and cooling [11]. Therefore the size of a thermal system can be solved at the known performance, inlet and outlet conditions. Then it can be simulated at the given size (after the design and manufacturing) to find the outlet conditions and performance for the prediction of off-design conditions. The experimental and simulation results help in finding the operational difficulties in the experimentation and refine the product design.

Fig. 2 is the experimental image of two stage desalination and integrated cooling plant. Saline water is heated in SWH indirectly with glycol-water mixture, installed at the rooftop of the laboratory. The indirect heating of saline water or ground water saves the solar water heater from the corrosion and increases its life. The hot water is supplied to two APHs and two humidifiers in parallel pipe connections. The parallel connection of hot water to the four components supplies the same hot water to all the components. As indicated in the earlier section, the first stage desalination plant consists of a dehumidifier where air is condensed by heat rejection to circulating normal cooling water. The second stage desalination consists of two dehumidifiers i.e.

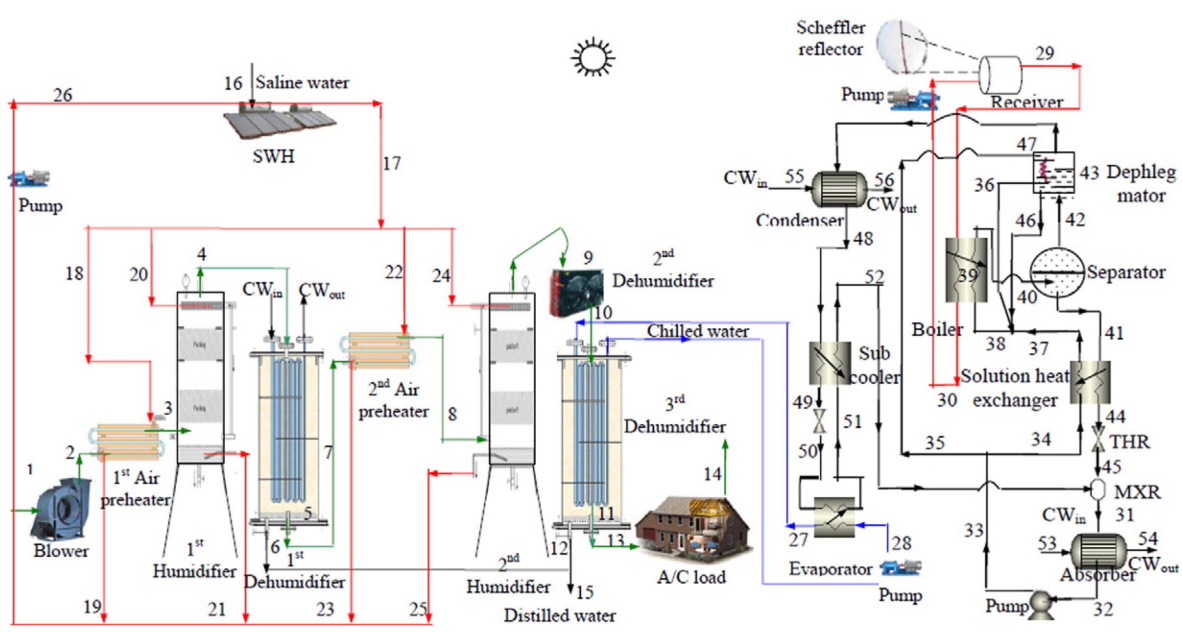

Fig. 1. Two stage desalination and cooling plant.