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Humidification–dehumidification desalination system driven by geothermal energy

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ABSTRACT

The work presented in this paper focuses on desalinating sea water system using a humidification–dehumidification process as it is supplied with water heated by geothermal energy as clean and renewable natural resources of energy. Computer simulation of the behavior under various working conditions of the desalination system was carried out to predict the variations of key output. Such variables include the ratio of sea water mass flow rate related to air mass flow rate, cooling water temperature difference across the condenser, geothermal source inlet temperatures to the heat exchanger and the amount of produced distilled water. To validate the computer program, a comparison between the experimental and theoretical results was conducted, and a good agreement had been obtained. The result showed that, the optimum value of the ratio between sea water mass flow rate to air mass flow rate was found to be in the range of 1.5 to 2.5. Improvement in the fresh water productivity at the optimum ratio of sea water mass flow rate to the air flow rate was observed by increasing both the geothermal source inlet temperature and the cooling water temperature difference across the condenser.

1. Introduction

Earth is a water-rich planet, which is fortunate because water is key to man's progress. It is essential for agricultural and industrial growth and is required to support growing urban populations.

Most of the countries in the Middle East are arid, and they are facing great challenges due to limited water resources and aridity. Desalination seems to be the most suitable solution. Desalination of sea water and brackish water has been given high priority as a source of water for domestic, industrial and agricultural applications in this region [1]. Standard desalination techniques such as multi-stage flash, multi-effect, vapor compression and reverse osmosis are expensive technologies especially when driven by conventional energy sources. Additionally, the geothermal energy is environmentally advantageous energy source which produces far less air pollution than fossil-fuel sources. The life of a geothermal resource may be prolonged by re-injecting the waste fluid which is the most common method of disposal.

Geothermal energy as one of the renewable energy resources represents an alternative source of energy, which provide many advantages compared to conventional energy produced from fossil fuel [2]. Most desalination thermal process is performed at relatively low temperature. Consequently low enthalpy geothermal energy is gradually emerging as successful renewable energy source of producing fresh water with great advantages [3,4].

Akpinara and Hepbasli [5] studied the exergetic performance of the geothermal heat pump systems installed in Turkey based on the actual operation data. They found that the geothermal thermal application is suitable for the developing countries as an available source of energy. This is due to their higher energy utilization efficiencies than those of both conventional heating and cooling systems.

Manologloua et al. [6] presented the socio-economic impacts of a geothermal desalination plant on the island of Milos (Greece), which suffers from lack of water.

Several comparative studies on the different renewable energy sources that are used for desalination of brackish and sea water are published [7–9]. Tzen and Morris [7] and Rodriguez [8] found that geothermal energy is suitable for different desalination processes at reasonable cost wherever a proper geothermal source is available. One of the main advantages is that no energy storage is required.

Many workers have studied the humidification–dehumidification desalination system (HDDS) for different low temperature energy sources (solar, geothermal, PV systems, etc.). Bourouni et al. [10] presented and analyzed the operation and performance of different HDDS plants worldwide. They recommended that HDDS installations can be used for the low temperature part of classical distillers, this is to avoid effects of vacuum in which distillers have to function.

A new sea water solar HDDS was described by Chafik [11]. Nafey et al. [12,13] investigated theoretically and experimentally the solar HDDS system. The results showed that the productivity of the unit is strongly influenced by the air flow rate, cooling water flow rate and total solar

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energy incident through the day. Recently, Orfi et al. [14,15] proved theoretically that the daily production of fresh water by solar HDDS system depends on the ratio between the salt water and the air mass flow rates.

More recently, Yamal and Solmus [16] designed a theoretical model to simulate the solar HDDS system based on the idea of closed water and open air cycles. They found that the system productivity increased by about 8%. Four configurations are analyzed for the air humidification–dehumidification water desalination system by Ettouney [17]. Al-Enezi et al. [18] experimentally evaluated the desalination process characteristics as a function of the flow rate of the water and air streams, the temperature of the water stream and the temperature of the cooling water.

The previous studies of the HDDS focused on the use of solar energy as renewable source to drive the desalinating sea water system. This is because energy cost is one of the most important elements in determining the cost of water production from desalination plants.

The present work concerns with the use of the geothermal energy, at low enthalpy, as a heat source for the HDDS. Also included are design guide lines for the proposed desalinating sea water system.

2. Geothermal desalination system

The selection of the appropriate renewable energy/desalination technology depends on a number of factors. These include, plant size, feed water salinity, remoteness, availability of grid electricity, technical infrastructure and the type and potential of the local renewable energy resource. Among the several possible combinations of desalination and renewable energy technologies, some seem to be more promising in terms of techno-economic feasibility than others. However, their applicability strongly depends on the local availability of renewable energy sources and the quality of water to be desalinated.

Geothermal sources were classified according to their reservoir enthalpy/temperatures as low (<100 °C), medium (100–150 °C) and high temperature (>150 °C).

For water production, geothermal energy plays an important role as a source of energy for low enthalpy/temperature desalination systems.

In the phase-change or thermal processes, the distillation of sea water is achieved by utilizing a thermal energy source, normally at temperature around 100 °C. Thus, for humidification–dehumidification sea water desalination system low temperature geothermal energy source is suitable.

In the present work, it is assumed that the operating behavior of a desalination system driven by geothermal energy is in a steady state case. The most promising system equations, boundary conditions, and optimum working conditions are conducted via computer program. The computed results of the program had been validated and compared with the experimental results. The influences of some special arrangement features of the desalination unit from the thermodynamic, heat and mass transfer are significantly considered.

3. Experimental apparatus and measurement techniques

The main objective of the experimental test facility is to validate the different simulated heat and mass transfer processes in the simulation model. The humidification–dehumidification desalination system with geothermal heat source test facility is shown in Fig. 1.

The system operates at atmospheric pressure in which air is used as a carrier for vapor. The hot water is injected to the top of the humidifier tower equipped with packed bed to increase the contact surface and therefore improve the humidification rate.

The air is firstly heated in an air-preheater and is then passed through the backed bed to meet the sprayed hot water and becomes moist or saturated at point (3). The air is discharged to the humidification tower using an air blower and the air flow rate is controlled by a by-pass and control valves. Hot and saturated air flows toward the dehumidifier (condensation tower), then it condenses as it comes into contact with the cold condensation cooling water coils to remove the water moisture from the carrier air to obtain the distilled fresh water.

Digital temperature/humidity measuring instrument (Testo 625, K-type temperature sensor) is used to measure each point of the air temperature and relative humidity at each point of the system. This is done with an accuracy of ±2% RH and the air temperature measurement with an accuracy of ±0.5 °C. The temperature of the hot water, sprayed water, and cooling water are measured using K-type thermocouples, with an accuracy of 0.1 °C.

Each of air, hot water and sprayed heated water flow rates was measured using a glass Rotameter (KDG memory) fitted with each circuit, as shown in Fig. 1. The accuracy of the measured quantity of each is about 1% of the measured value.

To estimate the uncertainty of the heat and mass transfer rate, the mathematical method of the root mean square was applied [19]. The uncertainty is determined by the square root of the sum of the squares of the uncertainties of the separated terms. Substituting the individual expected uncertainties of the measured quantities into the main equation yields to the uncertainty in the heat and mass transfer quantity, not exceed ±4.59%.

A set of experiments were conducted with different operating conditions including water to air mass flow rates (varied from 1.5 to 2.5), different inlet temperatures to the heat exchanger from the heating source (varied from 60 to 90 °C). During the experiments, air temperature and humidity of the air were measured after the steady state conditions. The heating water temperatures were also measured for the whole system.

4. Theoretical model description

The mathematical model was developed according to the energy and mass balance equations for each process in the cycle. It mainly includes heat exchanger energy balance, humidification process, dehumidification process and the system boundary conditions. The system is assumed to be adiabatic (no heat losses). The system is also working under the atmospheric pressure. It is assumed to be working under steady state conditions. The sea water properties are assumed to be equal to the fresh water properties. The psychometric conditions of the air had been calculated referred to ASHRAE standard properties [20]. The following equations below describe the mathematical formulation of the model.

4.1. Heat exchanger energy balance equation

The heat exchanger type is shell and tube with counter flow between the geothermal hot water and the sea water. The energy equation of the heat exchanger is as follows;

$$\dot{Q}_{\mathrm{g}} = \dot{Q}_{\mathrm{s}} = \dot{Q}_{\mathrm{HTgs}}. \tag{1}$$

This equation yields to;

$$\dot{m}_{\mathrm{g}} c_{\mathrm{p}} (t_{\mathrm{gi}} - t_{\mathrm{go}}) = \dot{m}_{\mathrm{s}} c_{\mathrm{p}} (t_{\mathrm{so}} - t_{\mathrm{si}}) = UA_{\mathrm{HT}} \Delta\theta_{m}. \tag{2}$$

4.2. Air preheater energy balance equation

The air preheater is used to heat the inlet air to the humidifier, the energy balance leads to the next equation;

$$\dot{Q}_{\mathrm{a}} = \dot{m}_{\mathrm{a}} c_{\mathrm{p}} (t_{\mathrm{a2}} - t_{\mathrm{a1}}) = UA_{\mathrm{HT}} \Delta\theta_{\mathrm{m}}. \tag{3}$$