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Research Paper

A continuous desalination system using humidification – dehumidification and a solar still with an evacuated solar water heater

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HIGHLIGHTS

- The different water mass flow rate on HDH is investigated.
- Enhancement of the gain output ratio of the desalination unit.
- Enhancing the thermal performance of the desalination unit with reusing rejected water from HDH.

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ABSTRACT

A continuous solar still (SS) integrated with a solar humidification–dehumidification (HDH) is investigated. An evacuated solar water collector is utilized in the HDH. The idea of closed-air and open-water cycles is considered as the operating principle of HDH process. The different water mass flow rates (1.5, 2, 2.5 and 3 L/min) of HDH is investigated. To avoid a large water loss during HDH desalination, a SS is fed with the exit warm water from HDH during day and night time. Therefore, the productivity of the SS with exit warm water from HDH is greater than that of the conventional solar still (CSS) by approximately 242% and the gain output ratio (GOR) is increased by about 39%. The daily water productions of the CSS, SS with exit warm water from HDH, HDH unit and continuous solar desalination unit are 3.9, 13, 24 and 37 L/day, respectively.

1. Introduction

Everything in the world, either for society or personal using, needs water. Unfortunately, only less than 0.1% of the existing water covering 71% of the earth's surface is accessible potable water [1]. Improving the effectiveness and efficiency of water purification technology is considered by many as perhaps the main challenge of the 21st century [2]. Therefore, intensive efforts are underway throughout the world to avert this looming crisis with conservation of the existing limited freshwater supply and conversion of the abundantly available seawater through various desalting technologies.

Humidification–dehumidification (HDH) desalination is a simple technology that is similar to rain cycle and has the possibility to carry out with solar heating [3,4]. The various system configurations of HDH, operating and meteorological conditions of a solar distillation system have been investigated in details [5,6]

Hamed et al. [7] investigated mathematically and experimentally a solar HDH system. They got high productivity of about 22 L/day due to preheating. The exergy analysis of HDH unit has been afforded [8]. The collector has lowest exergy efficiency and HDH process has lower exergy efficiency but the exit warm water from HDH has great exergy loss. Many improvements can be made on HDH process. Three ways were proposed to enhance freshwater yield per square meter area of collector. The first way depends on increasing both exergy and energy efficiencies and that is, to take measures for extra amount of energy and extra exergy. The second way is to enhance the flow of HDH process in order to gain a high-energy recover rate and the gain output ratio (GOR). Finally, the third way is based on reusing the exit warm water to get freshwater.

Zhani [9] has used the solar energy to generate a desalinate water depending on the HDH principle. Yıldırım and Solmuş [10]

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Nomenclature

a	specific area of evaporator, m^2/m^3
A	area of SS, m^2
A_C	external area of condenser surface, m^2
A_{cond}	evaporator area of heat transfer, m^2
A_E	external area of evaporator, m^2
Cp	heat capacity, J/kg °C
Cp_a	heat capacity of air, 1.009 kJ/kg °C
Cp_v	heat capacity of vapor, 1.88 kJ/kg °C
Cp_w	heat capacity of liquid water, 4.193 kJ/kg °C
Cp_b	heat capacity of liquid water brine assume = 4.193 kJ/kg °C
e	correction factor for cross-flow heat and mass transfer
H_a	enthalpy of saturated air, kJ/kg
H_{aci}	condenser inlet air enthalpy, kJ/kg
H_{ace}	condenser exit air enthalpy kJ/kg
H_{ahi}	humidifier inlet air enthalpy, kJ/kg
H_{ahe}	humidifier exit air enthalpy, kJ/kg
h_{fg}	evaporation and condensation latent heat of, kJ/kg
h_{bw}	convection heat transfer coefficient between the basin and water, W/m^2 °C
h_{ca}	convection heat transfer coefficient with the ambient, W/m^2 °C
h_{cw}	convection heat transfer coefficient between the water and glazier, W/m^2 °C
h_{fgss}	latent heat of vaporization for SS, J/kg
$I(t)$	solar insolation normal to glazier s cover, W/m^2
m	mass, L
m_a	air mass flow rate, kg/s
m_d	rate of desalinated water for HDH, kg/h
mw	water flow rate, kg/min
m_{re}	rejected water from HDH, L
m_{dss}	rate of mass evaporation, L/s
P_{am}	atmospheric pressure, kPa
P_g	water vapor pressure at glass temperature, Pa
P_w	water vapor pressure at water temperature, Pa
P_{db}	water vapor pressure at the dry bulb temperature, kPa
P_{st}	saturation pressure, kPa
T_{ace}	air temperature at condenser exit, °C
T_{aci}	air temperature at condenser inlet, °C
T_{amb}	ambient temperature, °C
T_{avgC}	average temperature in the condenser, °C
T_{avgE}	average temperature in the, evaporator, °C
T_{wce}	water temperature at condenser exit, °C
T_{whe}	water temperature at humidifier exit, °C
T_{whi}	water temperature at humidifier inlet, °C
U	heat loss coefficient from basin and sides to ambient, W/m^2 K
U_{cond}	over coefficient of heat transfer at condenser, J/m^2 s °C
U_{LC}	over all heat loss coefficient for condenser, J/m^2 s °C
U_{LE}	over all heat loss coefficient of evaporator, J/m^2 s °C
V	evaporator volume, m^3
V_a	wind velocity, m/s
W_{ace}	humidity ratio at condenser exit, kg_v/kg_a
W_{aci}	humidity ratio at condenser inlet, kg_v/kg_a
W_{ahe}	humidity ratio at humidifier exit, kg_v/kg_a
W_{ahi}	humidity ratio at humidifier inlet, kg_v/kg_a
W_{ast}	humidity ratio at saturation, kg_v/kg_a
Q_{bw}	heat transfer from basin to water in basin, W
Q_{cg}	heat transfer from glass to ambient, W
Q_{cw}	heat transfer from water in basin to glass, W
Q_e	heat transfer due to evaporation, W
Q_{loss}	heat transfer from basin to ambient, W
Q_{mw}	energy needed to heat makeup water to water basin temperature, W
Q_{rg}	radiation heat transfers from glass to ambient, W
Q_{rw}	radiation heat transfers from water in basin to glazier, W
T	temperature, °C

Greek letters

α	absorption coefficient
ε	emissivity coefficient
σ	Stefan–Boltzmann constant, $W/m^2 K^4$

Subscripts

a	air
b	basin
g	glass
sky	sky
w	basin water

examined theoretically the performance of a solar HDH unit with different configurations such as water heating only, air heating only and water–air heating. Hou and Zhang [11] studied the hybrid multi effect HDH and the conventional type. The GOR was improved by 2–3.

The amount of condensed water in SS depends on the glass–water temperature difference. Increasing this difference increases the circulation of air inside the SS which is the main reason to increase the productivity in desalination process. Regenerative SS [12], double glasses [13] and triple-basin SS [14] were investigated. Preheating is a method for increasing the SS yield. The collector increases the thermal energy given to the saline water of the SS [15–17]

Yadav [18] evaluated the performance of a SS connected with a collector using the forced circulation and thermosyphon modes. In case of forced circulation style, the system gave approximately 5–10% greater production than that of thermosyphon mode whereas; 30–35% improvement was obtained with simple SS. The water depth strongly influences the SS productivity [19–22].

The principal components of the SS system were also presented and compared. According to energy analysis, using continuous solar desalination process aims at enhancement the freshwater output per square meter area of solar collector. Evacuated tube solar collector is involved in the desalination system to heat entering water to the humidifier and the exit warm water from HDH process is reused to feed SS during the day and night time.

The objective of this work is to improve the performance of HDH and SS by using exit warm water from HDH. The operation involves two steps. In the first theoretical and experimental step, HDH system operates from 13 pm to 18 pm and the exit warm water from the humidifier bottom with high temperature of about 66–75 °C moves to an insulated tank. In the second (theoretical) step, the stored water in the insulated tank feeds the single stage SS at high temperature (assumed T_w = 70 °C). The exit warm water from HDH is of high temperature enough to feed water to SS during 24 h (change all water in the still basin every hour by warm water).

The contributions of this work are:

1. Increasing the output of the continuous system compared to HDH and CSS separately by using the exit warm water from HDH to feed CSS.
2. Increasing the thermal performance of the continuous system compared to HDH and CSS separately.