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An investigation into a laboratory scale bubble column humidification dehumidification desalination system powered by biomass energy

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ABSTRACT

This article describes a biomass powered bubble column humidification-dehumidification desalination system. This system mainly consists of a biomass stove, air heat exchanger, bubble column humidifier and dehumidifier. Saw dust briquettes are used as biomass fuel in the stove. First level of experiments are carried out in bubble column humidifier with ambient air supply to select the best water depth, bubble pipe hole diameter and water temperature. Experiments are conducted by integrating the humidifier with the dehumidifier. Air is sent to the humidifier with and without pre-heating. Preheating of air is carried out in the air heat exchanger by using the flue gas and flame from the combustion chamber. It is observed that the humidifier ability is augmented with the rise in water depth, water temperature, mass flow rate of air and cooling water flow rate, and reduction in bubble pipe hole diameter. It is found from Taguchi analysis that the water temperature dominates in controlling the humidifier performance compared to other parameters. Better specific humidity is recorded with a bubble pipe hole diameter of 1 mm, water depth of 170 mm and water temperature of 60 °C. Highest distillate of 6.1 kg/h and 3.5 kg/h is collected for the HDH desalination system with preheated air and direct air supply respectively. Recovery of waste heat using an air heat exchanger reduces the fuel consumption from 0.36 kg to 0.2 kg for producing 1 kg of distilled water. Lowest distilled water cost of 0.0133 US $/kg through preheated air supply and 0.0231 US $/kg through direct air supply is observed. A correlation is developed to estimate the mass transfer coefficient and it agrees with the maximum deviation of 9% from experimental results.

1. Introduction

Desalination is the emerging field in today's scenario that deals with purification of water from available water sources like saline water, brackish water or effluent. Based on the requirements, various desalination technologies have been developed. Humidification-dehumidification (HDH) desalination is one of the simplest methods of water purification that meets the small quantity water needs. An extensive review on the potential of solar humidification-dehumidification desalination was revealed that, additional research and development is needed to improve the efficiency and to reduce the capital cost of system [1]. Ability of a humidification-dehumidification desalination system was enhanced by using a double pass solar air heater [2]. Placing a parabolic trough solar air heater between the humidifier and dehumidifier of a desalination setup showed a better distilled water output [3].

A characteristic study on a humidification-dehumidification desalination system has shown that the distilled water productivity strongly depends on saline water inlet temperature, air flow rate, solar radiation and cooling water flow rate [4]. An experimental investigation on humidification dehumidification desalination was performed with evacuated tube solar air heater. The result shows that the evacuated tube collector improved the air temperature and thereby fresh water production rate [5]. An analysis done in a humidification-dehumidification desalination system by using the exhaust waste heat, achieved a gained output ratio of 2.44 [6]. Humidification-dehumidification desalination powered by a photovoltaic panel was tested in free and forced convective mode of air circulation. The evaporation rate was elevated in forced convective mode compared to free convection mode [7]. Mosleh et al. [8] developed a desalination device consisting of a parabolic trough collector, heat pipe and evacuated tube collector and achieved an efficiency of 65.2%. Rahbar et al. [9] investigated the ability of an asymmetrical solar still with thermoelectric modules and observed improved distillate output.

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Nomenclature

A	area, m^2
a	specific interfacial area, 1/m
c	heat capacity ratio
C	heat capacity rate, W/K
C_p	specific heat, J/kg K
d	difference
D_{AB}	diffusion coefficient, m^2/s
d_b	bubble diameter, m
d_o	hole diameter, m
E	enthalpy, J/kg
g	gravitational acceleration, m/s^2
GOR	gained output ratio
h	heat transfer coefficient, W/m^2 K
h_d	mass transfer coefficient, kg/m^2 s
h_{fg}	latent heat of evaporation, J/kg
i	interest rate, %
k	thermal conductivity, W/m K
L_e	Lewis factor
$\dot{m}$	mass flow rate, kg/s
n	life time of desalination system, years
N	number of transfer units
P	pressure, kPa
P_g	saturation pressure of water vapor, kPa
q	heat transfer rate, W
Re	Reynolds number
Sc	Schmidt number
T	temperature, K
t	thickness, m
U	overall heat transfer coefficient, W/m^2 K
u	uncertainty
V_g	superficial velocity, m/s
z	height of water in humidifier, m

Greek letters

ø	diameter, m
γ	kinematic viscosity, m^2/s
ε	effectiveness/gas holdup
η	efficiency
ρ	density, kg/m^3
σ	surface tension of water, N/m
φ	relative humidity
ω	specific humidity, kg of water vapour/kg of air

Subscript

1	air at humidifier inlet
2	air at humidifier outlet (Dehumidifier inlet)
3	air at dehumidifier outlet
4	cooling water inlet
5	cooling water outlet
a	air
cp	copper pipe
cw	cooling water
dw	distilled water
ha	humid air
in	inlet
l	liquid
lat	latent
max	maximum
min	minimum
out	outlet
r	ratio
sen	sensible
te	thermal energy
v	water vapor
w	water

Abbreviations

AMC	annual maintenance cost
AOC	annual operational cost
ASV	annual salvage value
CC	capital cost
CRF	capital recovery factor
FAC	fixed annual cost
S	salvage value
SFF	sinking fund factor
TAC	total annualized cost

Fresh water yield of a humidification-dehumidification desalination system was enhanced by using a solar parabolic trough concentrator [10]. A study reported that the water production cost of humidification-dehumidification desalination unit reduces with the increase in inlet humidifier air temperature [11]. Capacity of a closed air cycle humidification-dehumidification desalination system was augmented by increasing water flow rate, water temperature and air circulation [12]. A hybrid (HDH and flash evaporation) desalination technology, tested with a solar water heater containing nanofluids (Al_2O_3/H_2O), collected a fresh water yield of 41.8 kg/day [13]. A study concluded that the preheating of water had considerable effect on fresh water production capacity of humidification-dehumidification desalination [14]. Investigation on a humidification-dehumidification desalination unit with half perforated circular inserts in air heater section, showed a peak distillate output of 0.82 kg/h [15]. An energy and exergy analysis was performed in a packed bed HDH desalination system with various turbulators in air heater and dehumidifier. The result shows that the distillate rate was enhanced by 45% compared to conventional HDH desalination [16]. An exergetic analysis was conducted on a solar vacuum desalination, with an air cooled condenser by Ibrahim and Dincer [17]. The system reduced the basin heat loss by 75% and enhanced the exergy efficiency by 152% [17]. A thermoelectric cooler used in a portable HDH desalination setup collected an improved condensation rate by means of lowering the condensation surface temperature [18].

A bubble column humidifier was experimentally tested by varying the water depth and air velocity in humidifier. The bubble column humidifier produced a maximum specific humidity of 0.222 kg of water vapour per kg of air [19]. An electrically heated bubble column HDH desalination system, with varying range of water temperature collected a peak distillate output of 8.22 kg/h at 85 °C [20]. A solar flat plate humidifier, fabricated on the basis of bubble column principle, was tested with and without an external mirror. The study reported that the specific humidity increased with the presence of external mirror due to higher solar radiation accumulating in humidifier [21]. An experimental analysis was conducted on a solar bubble column HDH desalination system integrated with solar air heater [22]. It was found that the specific humidity of air increases with the rise in inlet temperatures of air and water at humidifier inlet. A comparative study on bubble column desalination was carried out by integrating the solar air heater and dual purpose solar collector. Consequence of the tests shows that the heating of both air and water in a dual purpose collector has superior effect, compared to heating of air alone in a solar air heater [23]. A packed bed HDH desalination integrated to a dual purpose solar collector was tested with and without turbulators in the solar collector field [24]. Presence of turbulators