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Mathematical modeling and sensibility analysis of a solar humidification-dehumidification desalination system considering saturated air

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ABSTRACT

Due to factors such as global warming, population growth and environment degradation, access to drinking water has become a problem in many regions of the planet, specially where the weather is dry. Solar desalination by humidification-dehumidification is a method whose energy source is clean and renewable, and is an interesting alternative to purifying salt or brackish water for human consumption. Modeling works of this system may be divided in two groups: those that consider saturated air in the whole system and the ones that do not adopt this consideration and describe mass transfer. In this work, a mathematical model considering saturation was developed to describe a process based in literature. Four model parameters were estimated by minimization of the sum of squared residuals for experimental temperature values throughout the equipment. The proposed model contains fewer parameters than the model described in literature, which does not consider saturated air. The deviance related to temperature experimental data has the same order as the experimental error. The error related to distillate production was more than 48% reduced, if compared to the literature model. After the validation of the model, a sensibility analysis was made regarding input and project parameters in relation to distillate production. The increase of absorbed heat in the solar collector, the increase of humidifier height and the reduction of seawater mass flow rate were the most significant factors to increase the distillate flow rate. On the other hand, environment temperature variation had little significance in distillate production.

1. Introduction

The lack of fresh water is a problem that has progressively worsened over the years. Due to factors such as anthropological degradation of the environment, global warming and population growth, regions which once had plenty of water for its inhabitants are having difficulties to supply them. It is estimated that in 2025 1.8 billion people will inhabit in regions with water shortage and two thirds of global population may live in conditions in which the demand for water is greater than the availability (Eliasson, 2015). In Brazil, besides the northeast region, which traditionally suffers with drought, other regions have suffered with water shortage. The state of Espírito Santo reported many water crimes in the drought period of 2016 (Fernandes, 2016), while the north and west regions of the state of Rio Grande do Sul have suffered from water shortage in such a way that researchers proposed air dehumidification as a source of fresh water (Henker et al., 2014).

A well-developed alternative is to get fresh water from seawater or brackish water desalination. Traditional processes like multiple effect distillation, multistage flash distillation, and reverse osmosis have showed to be effective in a large scale production. However, these processes normally consume fossil fuels which aggravate the greenhouse effect; thus contributing to intensify fresh water shortage. Besides, they are not economically viable for isolated regions where the demand is low and decentralized (Xiong et al., 2006).

Solar desalination by humidification-dehumidification (HDH) is an interesting alternative to supply this demand. This process is simple, has a reasonable cost for moderated production, and its energy source is clean, renewable and abundant in many places (Xiong et al., 2006).

A lot of HDH variations were proposed in order to increase process efficiency: operation in a continuous contact column (dewvaporation tower) (Hamieh et al., 2000; Xiong et al., 2006; Hamieh et al., 2001), variable pressure operation (Narayan et al., 2011) and “humidification compression” (Ghalavand et al., 2014), pulsed inlet water regime (El-Shazly et al., 2012), use of a phase change material as an energy deposit (Summers et al., 2012), water or air extraction of a component to inject into the other (Miller and Lienhard, 2013) and multiple insertions (Muthusamy and Srithar, 2015), HDH outflow seawater used to heat inlet water in the process (Hernández et al., 2014), multi-stage

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Nomenclature

A	cross-section area (m^2)
a	specific superficial heat transfer area ($m^2\,m^{-3}$)
C_p	specific heat capacity ($J\,kg^{-1}\,K^{-1}$)
$\dot{D}$	distillate mass flow rate ($kg\,s^{-1}$)
$\dot{G}$	dry air mass flow rate ($kg\,s^{-1}$)
h	specific enthalpy ($J\,kg^{-1}$)
Δh_{vap}	latent heat of vaporization ($J\,kg^{-1}$)
$\dot{L}$	seawater mass flow rate ($kg\,s^{-1}$)
M	molar mass ($kg\,mol^{-1}$)
P	cross-section perimeter (m)
p^*	vapor pressure (kPa)
p_t	total pressure (kPa)
$\dot{Q}$	heat transfer rate (W)
R	universal gas constant ($J\,kg^{-1}\,K^{-1}$)
T	temperature (K)
U	global heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
Y	gas humidity (kg water vapor/kg dry air)
z	column height (m)

Subscript

1	condenser seawater inlet
2	condenser seawater outlet
3	humidifier seawater inlet
4	humidifier seawater outlet
5	humidifier air inlet
6	humidifier air outlet
a	air
b	brine
c	condenser
d	distillate
h	humidifier
g	gas
l	loss
s	solar collector
t	heat transfer
v	water vapor
w	liquid water

operation (Zamen et al., 2014), water preheated during half period and operation just in the second period of the day (Hamed et al., 2015), use of HDH seawater outflow to feed a solar still (Sharshir et al., 2016), cooling photovoltaic modules with air, increasing their efficiency and recovering thermal energy to supply the HDH (Giwa et al., 2016), multi-effect operation with a strategy to maintain high temperature in all effects (Wu et al., 2016), multi-effect operation with a Fresnel lens solar concentrator as the energy source (Wu et al., 2017).

Mathematical models were developed for this process. A significant group of authors have considered that saturated air leaves the condenser, so that mass transfer modeling is only made in the humidifier (Ahmed et al., 2017; El-Shazly et al., 2012; Hamed et al., 2015; Hermosillo et al., 2012; Moumouh et al., 2016; Muthusamy and Srithar, 2015; Nematollahi et al., 2013; Rajaseenivasan and Srithar, 2017; Sharshir et al., 2016; Xiong et al., 2006). In this case, since air reaches the dew point in the condenser and some vapor is condensed, the assumption of liquid-vapor equilibrium is made, so that saturated air leaves the column. Some authors propose more complex models, which describes mass transfer in both columns (Eslamimanesh and Hatamipour, 2009; Soufari et al., 2009; Wu et al., 2016), while others consider that air leaves each column with 90% of relative humidity (Sharqawy et al., 2014; Zubair et al., 2017). Finally, some authors consider that saturated air leaves both columns (Ashrafizadeh and Amidpour, 2012; Farid et al., 2002; Giwa et al., 2016; Nafey et al., 2004; Nawayseh et al., 1999). In this case, besides the consideration of satured air leaving the condenser due to vapor condensation, it is considered that the mass transfer superficial area in the humidifier is sufficiently large so that it leaves the column saturated. According to Farid et al. (2002), experimental data verified this consideration.

Hermosillo et al. (2012) proposed a mathematical model that assume saturated air only at the condenser exit, and has five parameters. The authors calculated the parameter values for each experimental point, as a mass and energy balance resolution, along with the mass transfer equation. The parameter estimation of the model consisted in calculating the mean of the values obtained for each experimental point. A similar procedure was made by Hamed et al. (2015).

In the present work, the consideration of saturated air leaving both columns was made. This assumption simplifies the model, since it reduces the number of estimated parameters and prevent the need to estimate the mass transfer coefficient and the mass transfer superficial area. The humidifier mass transfer superficial area depends on the wetting of the superficial area, since mass transfer requires an interface gas-liquid. On the other hand, the humidifier heat transfer superficial area depends only on the substratum superficial area, as the liquid phase can also transfer heat to the substratum, and the substratum can further transfer the heat to the gas phase. Therefore, if the superficial area is not completely wet, the mass transfer superficial area is lower than the heat transfer superficial area and it is difficult to the measured. Besides, mathematical models with fewer parameters are more robust in extrapolations and are less likely to memorize experimental error, which may happen when the model has many parameters and little experimental data is available.

The objective of the present work is the proposal of a mathematical model for the HDH from mass and energy balance and experimental data reported by Hermosillo et al. (2012). Saturated air is assumed in both column exits and the model has four parameters, which are estimated by an optimization problem based on the sum of the squared residuals. Besides the development and validation of the model, another objective of this work is a sensibility analysis of input and project parameters in relation to distillate production.

2. Process description

The process of solar desalination by humidification-dehumidification consists of three basic equipment: a condenser (or dehumidifier), a humidifier, and a solar collector. Fig. 1 shows a fluxogram of a closed-air open-water process. Seawater (or brackish water) enters the condenser at temperature T_1 and is partially heated until T_2 by warm and humid air from the humidifier. The water at T_2 enters the solar collector and is heated until T_3. Seawater enters the top of the humidifier and gets in contact with cold air, fed in the column at temperature T_5. The water heats the air and is partially evaporated, and the brine flows out at the bottom of the column. The warm and humid air that leaves the humidifier at temperature T_6 and feeds the condenser, closing its cycle. The humidity condenses in the condenser and is the product of the process (Farid et al., 2002; Hermosillo et al., 2012; Hamed et al., 2015). The process is operated at forced convection, so that air passes through a compressor or a fan after leaving the condenser.

3. Calculation of relevant functions

The mathematical model considered the system in three parts: humidifier, condenser and solar collector. The reference temperature adopted was $T_{ref} = 298.15$ K. Processes with a solar collector are transient along all day, since irradiance changes with time. However, the experimental data from Hermosillo et al. (2012) used to estimate