Modeling and Simulation of Multistage Humidification and Dehumidification Desalination Plant Using Solar Energy

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Abstract

The aim of this research was to develop a detailed mechanistic model that can be used for decision making in the design of humidification-dehumidification (HDH) desalination systems in order to minimise cost and time. In developing the model an individual raschig ring within a column was considered as control volume so as to establish relationships of all parameters influencing the mass transfer process using appropriate mathematical equations. The model was then simulated using gPROMS software with a second order centred finite difference discretisation method. Results show that convective mass transfer rate decays exponentially as the moist air passes along the column length. It also decreases with an increase in diameter of the packing rings. From simulation results an economical length of column and packing sizes of 40 cm and 6-8 mm respectively were recommended for an experimental HDH rig.

Keywords: Humidification, Dehumidification, Simulation, Desalination, Solar.

1. Introduction

A rapid growth in population, industrialisation and urbanisation is causing fresh water shortage in many areas around the globe. On the other hand, 97% of total water on earth has high level of salinity leaving only 3% as fresh water suitable for human consumption (Kucera, 2014). This necessitates the development of cheap desalination systems powered by renewable energy. Multistage humidification and dehumidification desalination using solar energy is a viable process for remote and arid areas with severe shortage of fresh water. The process is suitable because of its' simplicity, abundance of solar energy and moderate operating costs compared to conventional desalination processes.

Development of effective and efficient systems for the Humidification-Dehumidification (HDH) desalination process is both costly and time consuming. However, the application of properly tested and well proven models, can enable simulation and performance evaluation of these systems virtually, prior to fabrication of real system thus minimising design cost and time. To a large extent empirical models have been used by various investigators to study the performance of HDH systems. Although they give an insight about an overall performance, these models do not suffice completely in design process because they offer little information about internal processes of the system. They give information about interrelation between output and input variables of the system but little or no information about internal processes such as heat and mass transfer. This may lead to inappropriate design decisions that are expensive and probably difficult to correct at a later stage of fabricating the hardware prototype (Murray-Smith, 2012).

Therefore, the objective of this research is to develop and simulate a mechanistic model (that is developed on bases of the internal processes) for analysing virtually the structure and performance of the HDH systems prior to fabrication. This model is tested and refined using data obtained from a prototype of HDH system fabricated in the laboratory whereby glass raschig rings are used as packing material for its humidifier column. Moreover, the refined model is used to investigate the influence of important parameters on production rate of the process. These are packing size and length of column from which the economical sizes are recommended.

2. Model description

Figure 1 is a flow configuration in the humidifiers' column of the HDH plant. Raschig rings of random orientation are packed in a cylindrical column of diameter D to form a bed of height L. Air enters the column at the bottom with a flat velocity profile, flows through the packing and leaves the column at the top while saline water flows in the opposite direction. Figure 1 also shows the details of individual ring with internal radius (r) or diameter D_r and length (l). If a water film, on internal surface area of the ring (A_s), flowing downward is in contact with stream of air flowing upward at velocity (u_m) then mass transfer by convection will occur. A concentration boundary layer will develop due to difference in concentration of water vapour molecules at the surface ($C_{A,s}$) and upstream air ($C_{A,m}$). The rate of mass transfer (n_A) will depend on the magnitude of convection mass transfer coefficient ($\bar{h}_m$) along the surface. As mass transfer occurs, the net effect will be the variation of the mean vapour density ($\rho_{A,m}$) with length of the ring toward a direction indicated by numbers 1 and 2.

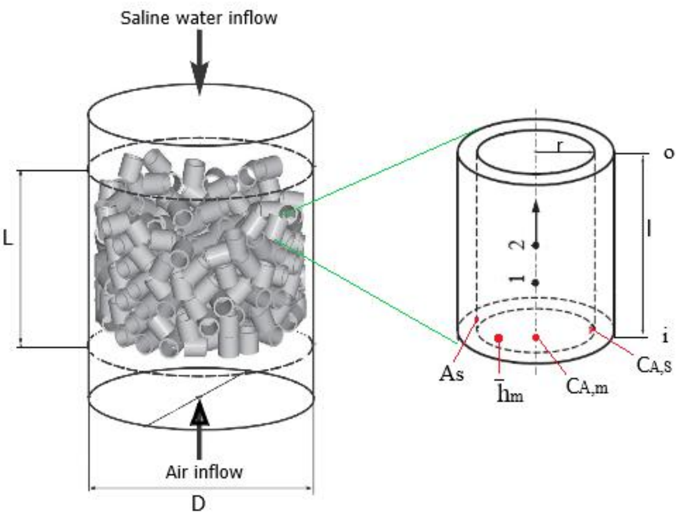

Figure 1: Flow configuration in the humidifiers' column of the HDH plant

The mass flow rate of species A (water vapour molecules) in a ring of arbitrary cross section area (A_c) is defined as

$$\dot{m}_A = \rho_{A,m} u_m A_c \quad (1)$$

where $\rho_{A,m}$ is the mean vapour density and u_m the mean vapour velocity

The mass density and molar concentration are related through the species molecular weight as

$$\rho_A = M_A C_A \quad (2)$$

For an ideal gas the mass density of constituent species is related to the corresponding partial pressure through the ideal gas law

$$\rho_A = \frac{P_{A,sat}}{RT} \quad (3)$$

where $P_{A,sat}$ is saturation pressure at a given temperature (T) and R the gas constant

The local mass flux of species A from the surface may be computed from

$$n_A^{"} = \bar{h}_m(\rho_{A,s} - \rho_{A,m}) \quad (4)$$

Equation 4 can be modified to get an expression for total rate of species transfer within a ring as

$$n_A = \bar{h}_m A_s \Delta\rho_{A,lm} \quad (5)$$

where the log mean concentration difference is defined as

$$\Delta\rho_{A,lm} = \frac{\Delta\rho_{A,o} - \Delta\rho_{A,i}}{ln\left(\frac{\Delta\rho_{A,o}}{\Delta\rho_{A,i}}\right)} \quad (6)$$

and $\Delta\rho_A = \rho_{A,s} - \rho_{A,m}$

By applying conservation of species A to a control volume about the ring, the total rate of species transfer may also be expressed as

$$n_A = \frac{\dot{m}}{\rho}(\rho_{A,o} - \rho_{A,i}) \quad (7)$$

where ρ and $\dot{m}$ are the total mass density and flow rate respectively

Moreover, equations 5 and 7 can be combined to get a general equation that characterises the variation of mean vapour density along the length l from the ring entrance (i) expressed as (Bergman, et al., 2011)

$$\frac{\rho_{A,s} - \rho_{A,m(l)}}{\rho_{A,s} - \rho_{A,m,i}} = exp\left(-\frac{\bar{h}_m \rho D_r}{\dot{m}} l\right) \quad (8)$$

The convection mass transfer coefficient may be obtained from an appropriate correlation defined as

$$\overline{Sh}_D = \bar{h}_m \frac{D_r}{D_{AB}} \quad (9)$$

in which $\overline{Sh}_D$ is the Sherwood number and D_{AB} the binary diffusion coefficient
The correlation defined in equation 9 is useful if the value of Sherwood number is known. This can be estimated from an equation proposed by (Kakac, et al., 2014).

$$\overline{Sh}_D = 3.66 + \frac{0.0668\left(\frac{D_r}{l}\right) R_{eD} S_c}{1 + 0.04\left[\left(\frac{D_r}{l}\right) R_{eD} S_c\right]^{\frac{2}{3}}} \quad (10)$$

These model equations were simulated using a general PROcess Modelling System (gPROMs) software for an entire tube length L and Diameter D. For the simulation the discretisation method used was a second order Centered Finite Difference Method (CFDM). Simulation results are shown in Figures 2 and 3.

Table 1: Parameters used in simulation

Parameter	Value	Unit	Parameter	Value	Unit
D	0.15	m	$P_{sat,i}$	3169	Pa
D_r	0.008	m	$P_{sat,s}$	9593	Pa
D_{AB}	26×10^{-6}	m^2/s	R	8.314	m^3-Pa/mol-K
L	1	m	Sh	4.31	
$\dot{m}$	0.001	kg/s	$T_{m,i}$	298	K
P_{atm}	101325	Pa	T_s	318	K

3. Results and discussion

In this study a mechanistic model was developed on basis of the mass transfer process in the humidifier column of the HDH system as shown by equations 1 to 10. The refined model was then used to investigate how the length of column and diameter of raschig rings (as packing material) influences the mass transfer rate of a process.

Figure 2 shows results for an investigation on variation of vapour content in moist air with length of column using the developed model. It shows that, the water vapour flow rate is levelling off along the column length. These results were in agreement

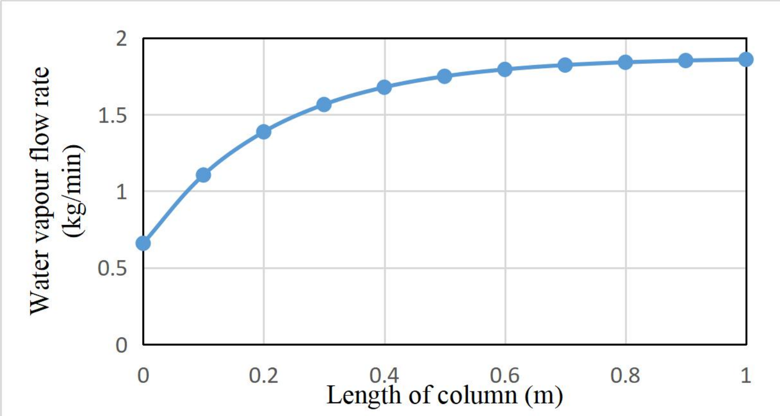

Figure 2: Variation of vapour content in moist air with length of column

with previous findings (Strigle, 1994 and Billet, 1995) that demonstrated about an influence of the packed towers' height on extraction efficiency and selection of an optimum height. Bergman, et al (2011) also demonstrated that the driving force for mass transfer is usually concentration gradient between two points. This force decays exponentially as the moist air approaches saturation conditions when moves along the column, and so does the convective mass transfer rate.

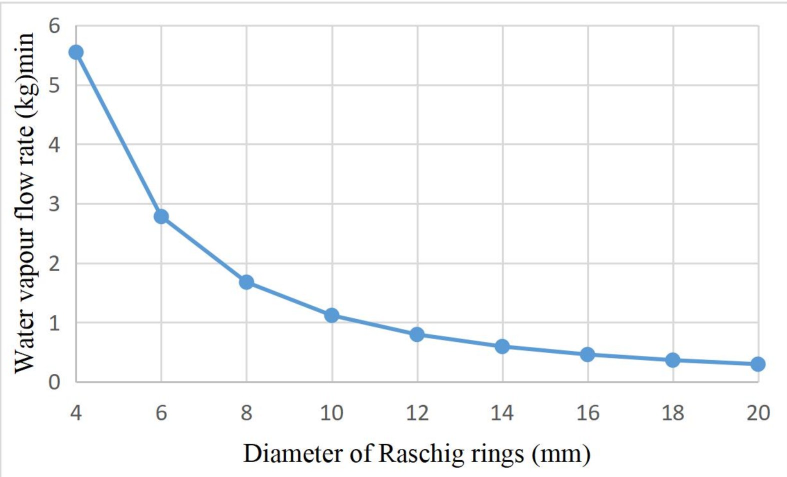

Figure 3: Variation of outlet vapour content in moist air with diameter of raschig rings

The diameter of raschig rings also has a significant effect on the convective mass transfer in the humidifier as shown in Figure 3. This figure shows that convective mass transfer within a column decays exponentially with increasing diameter of the rings because the voidage decreases with decreasing ring size and hence greater contact area between the air and water streams. This finding is also in agreement with other studies (Sinnott, 2005 and Towler & Sinnott, 2013) that have demonstrated small diameters of circular rings or pipes favours high values of convective mass transfer coefficient and consequently the convective mass transfer.

In general, the model developed in this research offers more details about the system and process parameter which are crucial for making decision during the design of the HDH systems. This is an advantage of mechanistic models over widely reported empirical models (Hermosillo, et al., 2012; Soufari, et al., 2009 and Nawayseh, et al., 1999) that only give relationships of system properties (i.e enthalpy, vapour content and temperature) at the inlet and outlet points without an insight for the internal processes. For example, using Figures 2 and 3, the economic length and diameter for the column and ring respectively can be specified. By considering the negative effect of pressure drop (Billet, 1995) and risks of flooding effects (Strigle, 1994) the column length of 40 cm and ring diameter between 6 – 8 mm are recommended for this system.

4. Conclusion

Mechanistic models make it possible to simulate and analyse theoretically the structure and performance of the HDH systems prior to fabrication. These models have proven to give more details about the internal processes and system parameters than empirical models. Application of the developed model in design of the HDH plant enabled the economical length of the column and packing size to be determined. For the HDH plant under design the recommended column length is 40 cm while diameter for raschig rings is between 6-8 mm. Moreover, simulation results of the system behaviour are in good agreement with those described by other authors who have studied the behaviour of packed columns.

The results of this research demonstrate the potential of detailed models for minimising cost and time in designing HDH systems. They enable appropriate design decisions to be made through virtual analysis and therefore prevent errors that are expensive and probably difficult to correct at a later stage during fabrication of the hardware.

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