Desalination 369 (2015) 165–174

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Theoretical and experimental investigation of humidification process in supersaturated state

M. Zamen [a,b], M. Amidpour [c,*], N. Rezakhani [a]

[a] Iranian Research and Development Center for Chemical Industries (ACECR), Karaj, Iran
[b] Department of Mechanical Engineering, Shahrood University, Shahrood, Iran
[c] Department of Mechanical Engineering, K.N. Toosi University of Technology, Tehran, Iran

HIGHLIGHTS

- Humidification process in a cross flow packed bed was studied.
- The model was developed in both states of unsaturated and supersaturated air.
- Empirical data confirm the ability of the model in prediction of outlet conditions.
- Effective parameters on growth of supersaturated (SS) zone were studied.
- Mist formation in SS zone has a significant effect on outlet air temperature.

ARTICLE INFO

Article history:
Received 4 December 2014
Received in revised form 1 May 2015
Accepted 5 May 2015
Available online 16 May 2015

Keywords:
Humidification process
Packed bed
Supersaturated air
Mist formation
HD desalination

ABSTRACT

In this paper, humidification process over a cross flow packed bed with an open air cycle is studied and a precision model is presented. Initial results show that air may become saturated with water vapor before leaving the packed bed. In this case excess water vapor condenses as mist in air stream that often is called supersaturated state. So the model was developed for both unsaturated and supersaturated states to predict accurately the outlet condition of the air and water streams. Then the model was validated by using experimental results obtained from an experimental facility. Comparison of the theoretical and experimental results confirms the ability of the supersaturated model at prediction of outlet condition of air and water streams. Effective parameters on development of supersaturated zone were studied. The proposed model can be used in designing HD desalination units and results better prediction of outlet condition of humidification process.

1. Introduction

The packed column is well known as an efficient device for gas–liquid direct contact heat and mass transfer such as absorption, stripping, distillation, humidification and dehumidification. In this study, humidification process will be considered as a heat and mass transfer process between a pure liquid and an insoluble gas. This process can be used for air cooling, water cooling, air humidification and air heating. One of the recent applications for packed bed is simultaneously heating and humidifying the air in order to use it in humidification–dehumidification (HD) desalination units.

HD desalinator applies humidification/dehumidification processes to produce fresh water of brackish and sea water in low capacity decentralized plants. Many researches have been done in the nineties and afterwards on HD desalinators and some pilot plants are constructed and tested that most of them use solar energy as heating source (Al-hallaj et al. [1], Ben Bacha et al. [2], Orif et al. [3], Soufari et al. [4], Yuan et al. [5]). Also, some theoretical studies for performance enhancement of the process have been done. Hou [6] and Zamen et al. [7] evaluated the multistage process that can reduce the thermal energy consumption of the process and reduce the investment cost of solar collectors. McGovern et al. [8] investigated the effect of air extraction–injection on the performance and energy recovery of a HD system through developing the saturation curve and pinch methodology. Some studies tried to use direct contact dehumidification instead of film condensation method [9,10]. In all cases, packed column was used for humidification and in some other cases were used for dehumidification process. Likewise, different methods were used for the process simulation.

The most widely used model to estimate the heat and mass transfer associated with air/water evaporating systems is based on the Merkel

* Corresponding author.
E-mail address: Amidpour@kntu.ac.ir (M. Amidpour).

http://dx.doi.org/10.1016/j.desal.2015.05.004
0011-9164/

method [11], which is used to analyze cooling towers. The critical simplifying assumptions of Merkel's method are the following.

- The Lewis factor relating heat and mass transfer is equal to 1.
- The air exiting the packed bed is saturated with water vapor and it is characterized only by its enthalpy.
- The reduction of water flow rate by evaporation is neglected in the energy balance. This energy balance simplification has a greater influence at elevated ambient temperatures.

Merkel's analysis is known to under-predict the required cooling tower volume and is not useful for the current analysis since the purpose of the humidification process is to maximize the evaporation of water for desalination. Poppe and Rogener [12] do not assume the simplifying assumptions of Merkel that result in prediction of values of evaporated water flow rate and water content of the exiting air. Klopper and Kroger [13] derivate the heat and mass transfer equations for packed bed in wet-cooling towers based on Poppe's method in both unsaturated and supersaturated air condition. They concluded that Poppe's method can accurately estimate the state of the outlet air that is important in HD desalination process.

As noted above Poppe's and Merkel's methods give good results in the simulation of cooling towers. Olander's method [14] is the most common method which is applied in HD desalination process modeling [2–4,9,15,16]. In both Poppe's and Olander's methods a film of the water is considered in contact with the air in a small element of the packed bed. Both of them are the same in the concept but Poppe's method uses the enthalpy parameter in main equations that lead to three complex equations in the form of the 1st order differential equations and uses algebraic equations for calculation of enthalpy. But Olander's method directly uses multiple of temperature and specific heat capacity of the moist air that leads to some simple differential equations.

In recent studies, authors [16] utilizing humidification/dehumidification process in an open channel for sea water desalination by using solar energy is investigated. The earliest modeling results show that according to the air travel distance in the packed bed and inlet conditions of air and water, air may become saturated with water vapor prior to its exit from the packed bed and result in supersaturated state formation in packed bed. Klopper and Kroger [13] presented a complete model which contains unsaturated and supersaturated states for cooling towers based on Poppe's method analysis. But it has not been considered in literature for Olander's method and especially for HD desalination units.

So in this paper, humidification process in an open air cycle is modeled based on Olander's method in unsaturated and supersaturated states. Then the model is validated by using experimental results obtained from an experimental facility.

2. Mathematical modeling

2.1. Governing equations in unsaturated state

The model is developed for direct contact humidification process that is shown in Fig. 1. The hot water is distributed on top of a packed bed while air is horizontally blown through the bed. Falling water forms a thin film on the packed bed surface area that is in contact with the air stream. Energy transfer from hot water to air by a combination of convective heat transfer due to the temperature difference between water and air and the latent heat transfer due to absolute humidity difference between water/air interface and air stream. Therefore, during this process the temperature of water decreases and temperature and humidity of air stream increase. In this section, it is supposed that the air is in unsaturated state during the process.

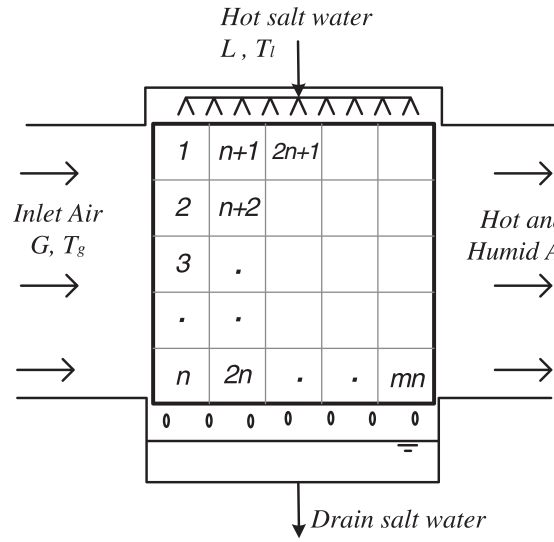

Fig. 1. Grid elements of packed bed in humidifier.

The mathematical analysis based on mass and energy balance equations is used to model this system. First, some assumptions should be considered in modeling.

- The process is done under adiabatic conditions.
- The pressure is constant during the process and is equal to ambient pressure.

Based on the aforementioned assumptions, the packed bed is divided to some smaller elements which are shown in Fig. 1. Each element will be small enough that the air and water properties supposed to be constant within the element and also following the assumptions could be used in modeling streams in any element.

- Temperature and humidity of air stream (T_g, ω) in any element change only in the horizontal direction (in air flow direction).
- Water temperature and flow rate (T_L, L) in any element change only in the vertical direction (water flow direction).

As schematically shown in Fig. 2 air and water streams pass adjacent to each other separated with interface area. If *dv* denotes the volume of

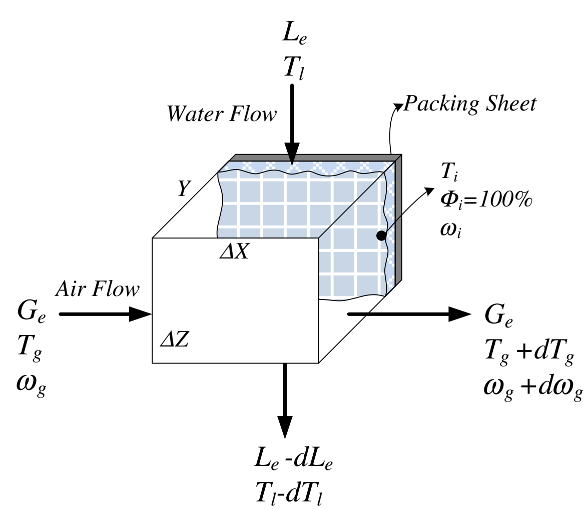

Fig. 2. A small element of humidifier.