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COMPUTATIONAL METHOD AND DESIGN OF A PACKED BED DIFFUSION TOWER FOR THE DESALINATION OF SEAWATER

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ABSTRACT

In a recent study, Klausner et al. [1] have described a diffusion driven process for desalinating seawater at low temperatures. The main advantage of the diffusion driven desalination (DDD) process is that low thermodynamic availability waste heat may be used to drive the process. When low pressure condensing steam from a 100 MW power plant supplies the heat to drive the DDD process, a fresh water production rate of 20 million gallons per day is feasible. This paper describes the computational procedure used to size the diffusion tower for a specified throughput.

Keywords: desalination, diffusion tower, packed bed, heat and mass transfer.

INTRODUCTION

Desalination is achieved by spraying heated saline water over a packed bed in a diffusion tower and low humidity air is blown through the packed bed from the bottom. As the falling liquid film of saline water forms over the packing material it contacts a turbulent low humidity air stream. Mass transfer principles govern the evaporation of liquid water and humidification of the air stream. When operating at design conditions, the air stream should be fully saturated (100% relative humidity) when exiting the diffusion tower. The humidified air stream is discharged to a direct contact condenser for fresh water production.

In order to achieve a high fresh water production yield from the DDD process, it is necessary to utilize a diffusion tower that operates according to design conditions. In addition, the primary energy consumption is the energy required to operate the forced draft blowers, which pump air through the system, and water pumps. Therefore, it is desirable to optimize the design of the diffusion tower such that the pressure drop across the diffusion tower is minimized. The design process consists of identifying the thermodynamic states of the air and water entering the diffusion tower and the desired states discharging the diffusion tower. With specification of the tower diameter, packing material configuration, and the liquid and air flow rates entering the tower, an appropriate heat and mass transfer analysis is used to compute the required height of the diffusion tower to achieve the desired discharge thermodynamic states.

ANALYSIS

This work will describe the heat and mass transfer formulation and solution procedure required to design and optimize the DDD process diffusion tower. The first and most widely used formulation to compute the heat and mass transfer associated with air/water systems is that due to Merkel [2], which was used to analyze cooling towers. Merkel's analysis contains two restrictive assumptions: 1) the water loss by evaporation of water is negligible and 2) the Lewis number is unity. 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 diffusion tower is to maximize the evaporation of water for desalination purposes. The current formulation is based on a two-fluid film model in which conservation equations for mass and energy are applied to a differential control volume. Three differential equations result: 1) mass transfer equation, 2) energy equation for the liquid film, and 3) energy equation for the air/vapor mixture. These equations are simplified so that only gradients in the direction of the tower height are included. Therefore, closure correlations are required. Correlations for the gas side mass transfer coefficient, gas side heat transfer coefficient, and liquid side heat transfer coefficient are used to close the set of three coupled ordinary differential equations. These three differential equations are solved using a finite difference marching technique and are used to evaluate the required tower height needed to achieve the design outlet conditions. Once the tower height is calculated, a standard correlation is used to compute the air pressure drop across the packed bed. The mass transfer coefficients associated with film flow in packed towers has been widely investigated. The most widely used and perhaps most reliable correlations are those due to Onda et al. [3]. Onda's correlations are used in the present study. Heat transfer coefficients for air/water film flow in packed towers have not been as widely investigated and reliable correlations presented in dimensionless form are not available. Both McAdams et al. [4] and Huang and Fair [5] measured air/water heat transfer coefficients in packed towers but their results were presented in dimensional form and their generality is questionable.

RESULTS

For this work, the heat and mass transfer analogy is used to compute the heat transfer coefficients: $\frac{Nu_L}{\Pr_L{}^{1/2}} = \frac{Sh_L}{Sc_L{}^{1/2}}$ for the liquid side and $\frac{Nu_G}{\Pr_G{}^{1/3}} = \frac{Sh_G}{Sc_G{}^{1/3}}$ for the gas side. Accordingly, the heat transfer coefficients are computed from, $h_L = k_L\left(\rho_L C_{pL}\frac{\kappa_L}{D_L}\right)^{1/2}$ and

$$h_G = k_G\left(\rho_G C_{pG}\right)^{1/3}\left(\frac{\kappa_G}{D_G}\right)^{2/3},$$

where h is the heat transfer coefficient, k is the mass transfer coefficient, ρ is the density, C_p is the specific heat, κ is the thermal conductivity, D is the diffusion coefficient, and the subscripts L and G respectively refer to the liquid and gas. The mass transfer coefficients are computed from Onda's correlation. When comparing with the data of Huang and Fair (1989) to the predicted heat transfer coefficient on the gas side, the agreement is good, but the liquid side heat transfer coefficient is over-predicted. However, since the gas side heat transfer controls the thermal resistance, the error in the overall heat transfer coefficient is small. The development of a generalized method for predicting the heat transfer through packed towers is an area that deserves further consideration.

For an inlet water temperature of 60° C and an inlet air temperature of 25° C, Fig. 1 shows the required diffusion tower height for different air to water mass flow ratios and varying water inlet mass flux. The tower height is computed such that the maximum possible humidity ratio leaves the diffusion tower. As the water inlet mass flux increases, the required diffusion tower height increases almost proportionally. This computation is for a tower diameter of 15 m. The diffusion tower should be designed such that the pumping power is minimized for a design throughput. Typically for distillation applications, the required tower height to diameter ratio is of order one.

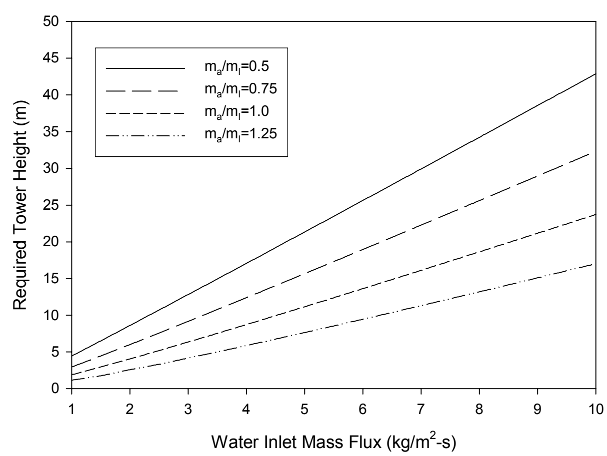

Figure 1. Required tower height for water inlet mass flux (60° C water inlet temperature)

For a water mass flux of 5 kg/m^2-s and air to water flow ratio of 1, the required diffusion tower height is 11.2 m. Figure 2 shows the computed liquid temperature, air temperature, and humidity ratio variation through the diffusion tower. A mass flux of 5 kg/m^2-s through a 15 m diameter diffusion tower corresponds to a water throughput of approximately 20 million gallons per day. With an outlet humidity ratio of approximately 0.10, a production rate of 2 million gallons of fresh water would result.

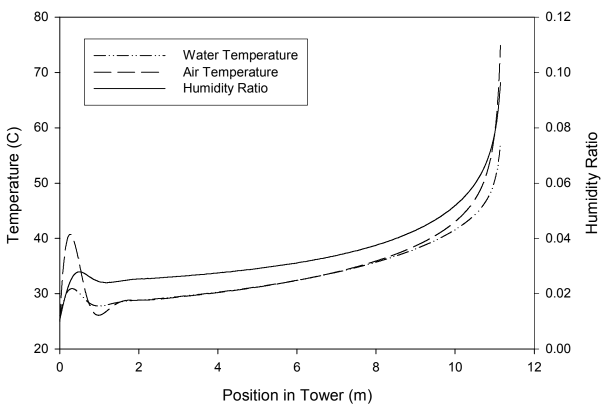

Figure 2. Temperature and humidity ratio profiles through the diffusion tower (5 kg/m^2-s inlet water mass flux)

The very nonlinear variation of temperature and humidity is a result of the complex interaction between heat and mass transfer in the tower. The non-monotonic behavior exhibited at the entrance to the tower has not been reported in previous investigations and requires experimental validation.

Future work will focus on computing the pressure losses through the diffusion tower and finding the operating condition that will minimize the energy to pump the fluid through the system and achieve a desired evaporation rate.

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