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The effect of pressure on the performance of bubble column dehumidifier

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ABSTRACT

Many experimental and theoretical studies have been conducted on bubble columns to improve its performance. Most of these studies assumed operating under atmospheric pressure condition and neglected the gas-side resistance. In this work, the effect of the pressure on the dehumidification process in bubble column dehumidifier is investigated experimentally under varying operating conditions. The measurements were conducted at absolute pressures in the range of 1–2 bars, superficial velocity range of 2–18 cm/s, and column height range of 3–7 cm. A model is developed for the relationship between the bubble column effectiveness and the number of transfer units which combines the influence of the heat and mass transfer processes. In addition, a semi-empirical model is adopted and modified for the gas-side mass transfer coefficient to capture the effect of the pressure. The model correlates Sherwood number with Reynolds number, Schmidt number, and the density ratio of air and water vapor. It is found that the total heat transfer rate and the effectiveness of the bubble column dehumidifier both increase with the superficial velocity. However, the heat transfer rises and the effectiveness decreases with the pressure. The column height is found to insignificantly affect the heat transfer and the effectiveness. The developed models predict the total heat transfer rate and the bubble column effectiveness with a maximum deviation of 2% from the experimental measurements. The results suggest that operating a bubble column dehumidifier under higher pressure will result in a larger size to compensate for the decrease occurs in the effectiveness.

1. Introduction

Bubble column reactor is a device where a gas is sparged in the form of bubbles into a column of liquid or a liquid–solid mixture. They are considered as multiphase reactors wherein simultaneous heat and mass transfer occurs between the gas bubbles and the liquid in the column. Bubble columns are heavily used in many chemical, petrochemical, biochemical, and metallurgical industries. Recently, some investigators [1–4] proposed to use bubble columns in humidification dehumidification (HDH) desalination systems. HDH is a promising thermal desalination method which uses air as a carrier gas to desalinate saline water. In the HDH process, hot-humid air leaves a humidifier almost saturated with water vapor, and then the water vapor condenses and releases its latent heat in a dehumidifier. Bubble columns could be used in HDH systems as humidifiers, dehumidifiers, or both since they have great advantages of reducing the size required for humidification or dehumidification process due to the large contact area and the low thermal resistances [1,2].

El-Agouz and Abugderah [3] conducted experimental studies on a bubble column humidifier to evaluate the influence of varying the operating conditions on the vapor content in the humidified air and the humidification efficiency. The bubble column humidifier consisted of a chamber with an air supply pipe connected and located at its bottom. The pipe has 32 injection holes drilled at the pipe end and each hole has a diameter of 10 mm. It was found that when the water temperature in the bubble column reached 75 °C, the vapor content of the outlet air increased by 222 g_w/kg_s. Later El-Agouz [4] studied experimentally a complete HDH system which was set by adding two shell-and-tube heat exchangers as dehumidifier connected to a bubble column humidifier and an air compressor. He measured the humidifier effectiveness (or efficiency, as defined by the ratio of actual to maximum vapor content difference) and fresh water production. The measurements were taken at air flow rate up to 14 kg/h, water temperature of 50–90 °C, and water height in the bubble column of 20–60 cm. It was found that both the humidifier efficiency and the fresh water production increase with the air flow rate and

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Nomenclature

a	specific area (surface area per unit volume), m^{-1}
A_c	cross-sectional area of bubble column, m^2
c_p	specific heat at constant pressure, J/(kg K)
D	diffusion coefficient, m^2/s
d_b	bubble diameter, m
d_o	perforated plate orifices diameter, m
g	gravitational acceleration, m/s^2
h	convective heat transfer coefficient, W/(m^2 K)
h_d	convective mass transfer coefficient, kg/(m^2 s)
H	height, m
i	specific enthalpy, J/kg
i_{fg}	enthalpy of vaporization, J/kg
$\dot{m}$	mass flow rate, kg/s
$n_{0\text{-}3}$	correlation coefficients in Eq. (17), –
P	pressure, Pa
$\dot{q}$	rate of heat transfer, W
R	thermal resistance, K/W
T	temperature, °C
$\dot{V}$	volumetric flow rate, m^3/s
V	volume, m^3
V_g	superficial velocity, m/s
z	coordinate, –

Greek symbols

ϵ	gas holdup, –
ε	effectiveness, –
μ	dynamic viscosity, kg/(m s)
ρ	density, kg/m^3
ω	humidity ratio, kg_{vapor}/kg_{air}

Subscripts

a	air
c	liquid in bubble column
$c1$	initial liquid height
$c2$	aerated liquid height
f	saturated liquid
g	saturated vapor
i	inlet
lat	latent
m	measured
o	outlet
r	ratio
sc	saturated at column temperature
sen	sensible
v	water vapor

Dimensionless groups

GOR	gain output ratio, –
Le_f	Lewis factor, $h/(h_d C_{pa})$
NTU	number of transfer units, $(h_d a V_c)/\dot{m}_a$
Re	Reynolds number, $(\rho_a V_g d_b)/\mu_a$
Sc	Schmidt number, $\mu_a/(\rho_a D)$
Sh	Sherwood number, $(h_d d_b)/(\rho_v D)$

water temperature, while slightly affected by the water height in the bubble column.

In a bubble column dehumidifier, vapor carried by the air bubbles condenses on the interfacial area between the bubble surface and the cold liquid in the column. The latent heat of vaporization is recovered by a coolant flows inside a cooling coil immersed in the bubble column. Narayan et al. [1] presented a theoretical and experimental investigation of bubble column dehumidifier. They proposed a thermal resistance model involved some remarkable thermal resistances associated with the different temperatures. Narayan et al. [1] determined the heat and mass transfer between the entering air and liquid in the column by the sensible and latent heat resistances. In addition, they considered the thermal resistances inside and outside the cooling coil due to convection heat transfer. To estimate the mass transfer coefficient at the air side and the liquid side of the bubble–liquid interface, they referred to the theory of surface renewal constructed by Higbie [5] and derived an expression for the surface renewal time (or contact time) by assuming a characteristic length and velocity scale. They conducted experiments on two bubble columns of 30 cm × 30 cm × 46 cm dimensions for each column, with a superficial velocity range of 4–8 cm/s and bubble diameter range of 4–6 mm. One of the bubble columns was used as a humidifier, where the supplied air was passed through a perforated plate upward into hot water. The other one was used as a dehumidifier with similar perforated plate where hot-humid air was passed through a cold water column. Their results showed that high superficial velocity and low bubble diameter are favorable to the heat transfer while the column height has no effect on the total heat transfer. The measured heat transfer rates were higher than those achieved in existing state-of-the-art dehumidifiers by an order of magnitude.

Tow and Lienhard [2] simplified the thermal network model proposed by Narayan et al. [1] in which the gas-side resistance was neglected. They assumed that the thermal resistance inside the air bubbles should be regarded as zero under perfect mixing conditions [6]. Their modified thermal resistance model included only the heat transfers inside and outside the cooling coil. The convection heat transfer coefficient inside the coil was calculated based on the correction for laminar flow in curved tubes [7], and the heat transfer coefficient outside the coil was calculated using Deckwer's correlation [8] for gas/liquid dispersion to immersed coil. Tow and Lienhard [2] measured the effectiveness of the bubble column dehumidifier at superficial velocity range of 1.9–3.2 cm/s, water height in the bubble column of 4–20 cm, and air inlet temperature of 40–60 °C. It was found that increasing the superficial velocity and inlet air temperature led to a decrease in the effectiveness and an increase in the heat flux. In addition, the water height in the bubble column slightly affects the dehumidifier performance which is consistent with previous research [1].

Bubble columns are usually operated at non-atmospheric conditions in industrial applications [9]. However, almost all HDH systems utilizing bubble columns [1–4] were experimentally investigated at atmospheric pressure. Ghalawand et al. [10] studied theoretically a variable pressure HDH system with a packed-bed humidifier working at 1 bar and a flash drum dehumidifier working at 3 bars. A compressor was used to increase the pressure and temperature of the humid air after the humidifier and a throttling valve was used to reduce the pressure after the dehumidifier in a closed-air cycle. The gain output ratio (GOR) which is the ratio of the latent heat of vaporization of the fresh water produced to the total energy input by the compressor was calculated to be 2.07. Higher GOR (>1) indicates that the HDH system working under elevated dehumidifier pressure is efficient. It was reported [11] that the single pressure HDH system has a limited thermal performance where a maximum GOR value of 4.5 was experimentally achieved [12]. Narayan et al. [13] explained three disadvantages of the single pressure HDH systems which are (1) low humidity ratio at