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Experimental performance of bubble column humidifier and dehumidifier under varying pressure

Huicheng Liu [a], Mostafa H. Sharqawy [b,*]

[a] *Department of Mechanical Engineering, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia*
[b] *School of Engineering, University of Guelph, Guelph, Ontario N1G 2W1, Canada*

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ABSTRACT

The performance of bubble column humidifier and dehumidifier is investigated experimentally under sub-atmospheric pressures for the humidifier and elevated pressures for the dehumidifier. The bubble columns examined are of 10 cm diameter and 25 cm height. They are equipped with internal cooling and heating coils and the air is sparged through perforated plates at its bottom. The pressure tested in the humidifier ranges from 7 psia (0.48 bar) to 15 psia (1.03 bar), while the pressure tested in the dehumidifier ranges from 15 psia (1.03 bar) to 30 psia (2.07 bar). In addition, the water level in the bubble columns and the superficial velocity were varied in the range of 5–7 cm and 2–20 cm/s respectively. The performance was evaluated by measuring the total heat transfer rate and the effectiveness. Moreover, the experimental values of the mass transfer coefficient are presented as a function of the superficial velocity and pressure. The results show that operating the bubble column humidifier at sub-atmospheric pressure enhances the total heat transfer by about 35% and the effectiveness by about 7.1%. However, operating the dehumidifier at elevated pressures, results in higher heat transfer rate by about 27% but lower effectiveness by about 3.2%. It was demonstrated that the liquid height in the column has no significant effect on the performance however; the superficial velocity increases both the heat transfer and effectiveness for the humidifier and dehumidifier. Moreover, a modified effectiveness-number of transfer units (*ε-NTU*) model for counter flow cooling tower was found to agree well with the experimental results of the effectiveness and *NTU*. The *ε-NTU* model is an effective approach to analyze the performance of bubble column humidifier and dehumidifier.

1. Introduction

Desalination is a process which produces fresh water from saline or brackish water. It is a reliable, economic and sustainable technical solution to the global water scarcity. With the increasing demand of fresh water in remote communities, a number of small-scale desalination systems have been investigated specifically for its energy efficiency, economic feasibility, and environmental aspects. Humidification–Dehumidification (HDH) desalination technology is a thermal desalination process which is adaptable for small or large scale fresh water production. HDH process is based on the principle of humidifying a gas by saline water then dehumidifying it at a lower temperature. The fresh water is the condensate resulting from the dehumidification process. The HDH system is composed mainly of a humidifier, a dehumidifier, and a heater for heating either the carrier gas or the water. The efficiency of the HDH desalination system depends mainly on the performance of the humidifier and dehumidifier.

Convectional humidifier and dehumidifier such as packed-bed and finned-tube heat exchanger have been investigated in previous studies [1–3]. These equipment have very low heat and mass transfer coefficients and require large volume; hence, high capital cost. For instance, in packed-bed humidifiers, the specific surface area of the mass transfer process (surface-area-to-volume ratio) depends on the type of the fill which is either film or splash type, constructed or unconstructed packing. In all types the specific surface area is very low which requires large packing volume. On the other hand, finned-tube heat exchanger dehumidifiers have very low condensation heat transfer coefficient of the air–vapor mixture due to the large amount of non-condensable gases. This requires large surface area of tubes and fins which consequently increase pressure drop inside the tubes and on the gas side. Therefore, some attentions are now paid to bubble columns to be utilized as humidifiers and dehumidifiers in HDH desalination system. In bubble columns, the carrier gas is dispersed into a liquid column to form

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* Corresponding author. Tel.: +1 (519) 824 4120x58973.
E-mail address: melsharq@uoguelph.ca (M.H. Sharqawy).

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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)
d_b	bubble diameter (m)
d_o	perforated plate orifices diameter (m)
g	gravitational acceleration (m/s^2)
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)
P	pressure (bar)
$\dot{q}$	rate of heat transfer (W)
T	temperature (°C)
V_c	volume of liquid in bubble column (m^3)
V_g	superficial velocity (m/s)
z	coordinate (–)

Greek symbols

ϵ	gas holdup (–)
ε	effectiveness (–)
ρ	density (kg/m^3)
σ	surface tension (N/m)
ω	humidity ratio ($kg_{vapor}/kg_{dry\text{-}air}$)

Subscripts

a	air
$c1$	static liquid in bubble column
$c2$	aerated liquid in bubble column
da	dry air
i	inlet
lat	latent
o	outlet
s	saturated
w	water inside the coil

Dimensionless groups

GOR	gain output ratio (–)
HCR	heat capacity ratio (–)
NTU	number of transfer units ($(h_d a V_c)/\dot{m}_a$)

small bubbles instead of direct contact with solid surface. The enormous number of small bubbles results in a large interfacial surface area and enhanced heat and mass transfer processes hence small equipment volume.

There are few studies which proposed using bubble columns in HDH desalination systems. Vlachogiannis et al. [4] studied a HDH system which uses a combination of bubbles generation and mechanical vapor compression. In their experimental apparatus, air is dispersed as bubbles through a porous plate at the bottom of a saline water column in an evaporation chamber where it is humidified. The exit humid air flows to a compressor where it is pressurized and heated. Then, the air flows through an air distributor connected to 25 vertical tubes where condensation occurs on the internal surface of the tubes. After that, the air flows back to the evaporation chamber to form a closed-loop air cycle. Their experimental measurements show that increasing the saline water temperature will increase the fresh water production and decrease the compressor energy consumption.

El-Agouz and Abugderah [5] investigated experimentally the performance of a bubble column humidification process. The performance was evaluated by measuring the humidification efficiency (defined as the actual difference of the humidity ratio to the maximum difference) under varying operating conditions. An air supply pipe with 32 holes of 10 mm diameter each was submerged into the hot water column of an evaporation chamber. The results showed that, the humidification efficiency increases with the increase of the water column temperature, air inlet temperature, and the air velocity. El-Agouz [6] further investigated a complete HDH system which was mainly equipped with an air compressor, two shell-and-tube heat exchangers served as a dehumidifier, and a bubble column humidifier. The bubble column humidifier had a $40 \times 30\,cm^2$ cross-sectional area and 125 cm height where air enters through a perforated pipe drilled with 44 holes of 15 mm diameter each. The measurements were conducted under air flow rate up to 14 kg/h (equivalent to a superficial velocity of 2.8 cm/s), water temperature in the range of 50–90 °C, and water column height in the range of 20–60 cm. It was found that both of the humidifier efficiency and the fresh water productivity increase with the air flow rate and water temperature, but are slightly affected by the water column height.

Bubble columns could contain a heating or a cooling coil to provide the heat needed for the humidification process or extract the heat released from the dehumidification process. Different from this configuration, Ghazal et al. [7] presented a bubble column humidifier combined with a flat-plate solar collector where the solar collector was filled with water and air was sparged from a copper pipe at its bottom. The copper pipe had a diameter of 1.3 cm, a length of 60 cm, and many holes of 2 mm diameter on its side. It was found that the relative humidity of exit air is nearly 100% and the humidification efficiency (based on absolute humidity ratio) is above 90%. It was demonstrated that the direct contact system of air–water bubble column is feasible and efficient for the humidification process.

Narayan et al. [8] studied a bubble column dehumidifier of $30 \times 30\,cm^2$ which had a perforated plate at its bottom. It was found that increasing the superficial velocity increases the total heat flux significantly while the liquid height in the bubble column has a negligible effect on the total heat flux. It was further claimed that the liquid height has no effect on the system performance until it is reduced to several millimeters. Similarly, Tow and Lienhard [9] investigated the performance of a bubble column dehumidifier of $28 \times 28\,cm^2$ area and 36 cm height and has a perforated plate and copper coil internally installed. For air flow rate in the range of 1.5–2.5 L/s (equivalent to superficial velocity of 1.9–3.2 cm/s), the heat flux increases almost linearly with the air flow rate. Moreover, parallel-flow effectiveness was proposed as the ratio of the actual heat transfer rate to the maximum heat transfer rate assuming the outlet temperatures of air and water streams equal to the column liquid temperature. Using their effectiveness definition, they demonstrated that the effectiveness decreases with the air flow rate (or superficial velocity). On the other hand, it was found that the effectiveness is independent on the column liquid height if it is higher than 4 cm.

The operating conditions of the HDH system such as mass flow rates, temperature, pressure, and effectiveness of the humidifier and dehumidifier; have great impact on the overall performance of the system and the gain output ratio (*GOR*) which is the enthalpy of vaporization of the produced fresh water per unit energy added. It was demonstrated by Narayan et al. [10] that the HDH system performance could be improved if it works under variable pressure condition. This means that the humidifier works at sub-