



MEASUREMENT OF HEAT AND MASS TRANSFER COEFFICIENTS IN A BUBBLE COLUMN

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ABSTRACT

Bubble columns are preferred in many chemical and biochemical processes for gas-liquid contacting due to their simplicity in design, operation and maintenance. Solids, in some operations, are introduced into the bubble column as a third phase to enhance heat and mass transfer inside the bubble column.

In this study, gas phase volumetric heat and mass transfer coefficients inside a bubble column employing a single gas nozzle were measured and the effect of adding the solid phase was investigated.

It was found that both the heat and mass transfer coefficient increased with an increase in the gas superficial velocity and were further enhanced by the addition of a suspended solid phase after a certain minimum superficial velocity (0.056 m/s) has been reached in the column. It was also found that increasing the solid concentration beyond 5 wt.% did not contribute to any further change in both coefficients. This agrees well with previously reported findings except for unresolved discrepancies in the effect of that on heat transfer coefficients.

Keywords: Two and three phase bubble column, Gas holdup, Heat and mass transfer coefficient.

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1. INTRODUCTION

Bubble column contactors with and without suspended solids, are often used for chemical processes (Stegeman et al., 1996). Slurry bubble column reactors provide benefits which have made them attractive for a number of industrial processes in the areas of syngas conversion to fuel and chemicals, heavy oil upgrading, environmental pollution control, and biotechnology (Lie and Prakash, 1997; Sotelo et al., 1994). The advantages of these contactors include the simplicity in their design, operation and maintenance, high heat and mass transfer rates, isothermal conditions, plug-free operation, and on-line catalyst addition and withdrawal.

It has been shown that the liquid side heat transfer resistance is negligible compared to the gas side resistance (Alabowskii, 1972). The outside heat transfer coefficient calculated using available correlations such as those proposed by Bird et al. (1960) or Sideman (1966) is very high. Thus, the temperature of the bubble interface can be considered equal to the temperature of the liquid. A transfer model, similar to that proposed for humidification (Trybal, 1980) or direct contact evaporation (Bharatan, 1988) was developed in this study for the case of a bubble moving in a uniform temperature liquid.

Previous investigations conducted to study the effect of introducing solids in the bubble column on heat transfer coefficient showed that the average heat transfer coefficient decreased with increasing solid concentration (Lie and Prakash, 1997; Saxena and Patel, 1991).

On the other hand, and as reported by many investigators (Sotelo et al., 1994; Karamanew et al., 1992; Vink et al., 1992; Favio et al., 1997; Anabtawi et al., 1991; Guy et al., 1992; Anabtawi and Uysal, 1992), the volumetric mass transfer coefficient increased as the concentration of solid was increased.

Key characteristics affecting the performance of bubble columns are the gas holdup and size distribution of bubbles. (Anabtawi et al., 1991; Nishikawa et al., 1976) have shown that a single nozzle can be employed to feed the gas phase and the nozzle's diameter has no profound effect on the gas holdup. These authors have further shown that the use of a single nozzle helps to obtain fine and almost mono sized bubbles. It has been also well established that the gas holdup increases with increasing gas rate (Anabtawi et al., 1991; Nishikawa et al., 1976; Hughmark, 1967; Kim et al., 1972; Akida and Yshida, 1973.; Hikiata et. al., 1980; Vatai and Tekici, 1989; Shetty et al., 1992; Das et al., 1992).

Introduction of solids as a third phase to the bubble columns may be required in many chemical and biochemical processes. Employing a two dimensional column and 1-mm sand particles, Anabtawi and Uysal (1992) have shown that the gas holdup increases with gas flow rate but decreases with solids concentration in the solids concentration range from 5 to 20%. Similar findings are also reported by other investigators (Lie and Prakash, 1997; Saxena and Patel, 1991; Juan and Morsi, 1999).

The purpose of this project was to investigate the effect of gas superficial velocity, solid concentration and static liquid height on gas holdup and heat and mass transfer coefficient in a bubble column. The investigation was carried out using air-water system and a cation resins of 0.1-mm average particle diameter, and 1.2 specific gravity as the solid phase.

2. THEORY

The following assumptions were made in deriving the models required to predict the heat and mass transfer coefficients in the bubble column:

- The liquid (water in this study) operates in a batch mode at a uniform temperature, T_L .
- Liquid side resistance to heat transfer is negligible, thus the heat transfer coefficient, h_L , is considered high (Alabowskii, 1972; Bird et al., 1960; Sideman, 1966).
- The temperature at the gas-liquid interface, $T_i = T_L$
- The time necessary for the liquid temperature to change by 1°C is much longer than the residence time of bubbles in the liquid. Therefore, it is assumed that bubbles move in a constant temperature liquid (Guy, C., et al., 1992).

The rate of heat transfer between liquid and gas, q , over a differential column height, dZ , is given by:

$$q = G dH_y \quad (1)$$

where G is the mass flow rate of air (kg dry air/s), and H_y is enthalpy of air (J/kg dry air)

Now, this heat is transferred from the hot liquid phase to the gas phase (bubbles) by convection, q_{conv} , and by the influx of water vapor in the gas phase, q_λ . Thus,

$$q = q_{\text{conv}} + q_\lambda, \quad (2)$$

where q_{conv} , and q_λ are expressed as follows:

$$q_{\text{conv}} = h_G a (T_i - T_G) S dZ, \quad (3)$$

$$q_\lambda = N_A M_A \lambda_o a S dZ, \quad (4)$$

$$N_A = k_y (y_{Ai} - y_A), \quad (5)$$

Where, h_G is the convective heat transfer coefficient in gas side, a is the specific gas-liquid interfacial area, T_i is the interfacial temperature, T_G is the temperature of gas (in the bubble, at a certain height in the column), S is the cross-sectional area of the column N_A molar flux of water vapor into the gas bubble, M_A is the molecular weight of the liquid, k_y is the mass

transfer coefficient in the bubble side based on mole fraction (kmol/m².s), λ_o is the latent heat of vaporization at T_i, y_A and y_{Ai} are the mole fractions of the liquid vapor in the bubble and at its interface with the liquid, respectively.

The relation between y_A and humidity **H** of the gas-liquid vapor mixture is:

$$y_A = \frac{H/M_A}{H/M_A + 1/M_B} \tag{6}$$

where M_B is the molecular weight of the gas. Since **H** can be considered relatively small, as an approximation:

$$y_A \approx \frac{HM_B}{M_A} \tag{7}$$

Substituting equations (7) into equation (5) and replacing k_y with k_G (k_y= k_GP_T), the mass transfer coefficient based on pressure (kmol /m².s.atm), yields:

$$N_A = k_G P_T \frac{M_B}{M_A} (H_i - H) , \tag{8}$$

where P_T is the total pressure.

Combining equations (1, 2, 3, 4, and 8) yields:

$$GdH_y = \{h_G a (T_i - T_G) + k_G a P_T M_B \lambda_o (H_i - H)\} SdZ \tag{9}$$

When the humid heat, c_s, expressed as:

$$c_s = \frac{h_G}{k_y M_B} \tag{10}$$

is substituted in equation (9), yields

$$G dH_y = [c_s (T_i - T_G) + \lambda_o (H_i - H)] k_G a P_T M_B S dZ, \tag{11}$$

Which can be written as

$$G dH_y = k_G a P_T M_B \{ [c_s(T_i - T_o) + \lambda_o H_i] - [c_s(T_G - T_o) + \lambda_o H] \} S dZ, \tag{12}$$

where T_o is a reference temperature. Equation (12) can be written in the following form:

$$G dH_y = k_G a P_T M_B (H_{yi} - H_y) S dZ, \quad (13)$$

where, $H_{yi} = c_s(T_i - T_o) + \lambda_o H_i$, and $H_y = c_s(T_G - T_o) + \lambda_o H$

Based on the assumption that $T_i = T_L = \text{constant}$ which implies that $H_{yi} = \text{constant}$, the variables of equation (13) can be separated and integrated to yield:

$$k_G a = \frac{G/S}{Z_T P_T M_B} \ln \frac{(H_{yi} - H_{yin})}{(H_{yi} - H_{yout})} \quad (14)$$

where Z_T is the bubble column height. For the air- water system employed in his study, the enthalpies of equation (14) can be calculated as follows

$$H_{yi} = H_y (\text{at } T_i = T_L) = c_s (T_L - T_o) + \lambda_o H_s,$$

where, $T_o = 0^\circ\text{C}$; $H_i = H_s$ (humidity of saturated air at T_L), and $c_s = 1005 + 1880H_s$

$$H_{yin} = c_s (T_{Gin} - T_o) + \lambda_o H_{in},$$

where, H_{in} is humidity of inlet gas, and $c_s = 1005 + 1880H_{in}$

$$H_{yout} = c_s (T_{Gout} - T_o) + \lambda_o H_{out},$$

where, H_{out} = humidity of outlet gas, and $c_s = 1005 + 1880H_{out}$

Thus, based on experimental data of T_{Gin} and T_{Gout} , H_{in} , and H_{out} , ($k_G a$) can be calculated from equation (14) at different operating conditions.

If it is assumed that the heat transfer due to liquid evaporation is negligible. In other words, in the absence of mass transfer, an energy balance over a differential section of the column would give:

$$U_G S \epsilon_G (\rho C_{pG} + c C_{p_{vap}}) dT_G = h_G a (T_L - T_G) S dZ \quad (15)$$

Since $T_L = \text{constant}$ during an experiment, equation (15) can be rearranged and integrated to yield the following equation:

$$\ln \frac{T_L - T_{Gout}}{T_L - T_{Gin}} = - \frac{h_G a Z_T}{U_G \epsilon_G (\rho C_{pG} + c C_{p_{vap}})} \quad (16)$$

Therefore:

Gas holdup, ε_G , can be determined experimentally using the following equation:

$$\varepsilon_G = \frac{Z_T - Z_0}{Z_0} \quad (17)$$

Where Z_0 and Z_T are the static and aerated liquid heights in the column, respectively.

3. EXPERIMENTATION

Experiments were conducted in a column of 0.15-m inside diameter and 1.52-m height (Figure 1). A silk screen was fitted 8 cm above the bottom of the column to hold the solids. A centrifugal pump was used to fill the column with water from a thermally controlled storage tank. Water filters, one at the inlet of tank and the other at the inlet of the column were used to ensure water purity. Air was introduced into the bottom of the column through a 6-mm nozzle. Air volumetric flow rate was measured using a rotameter. A one-way valve was installed after the rotameter to allow air to enter the column and prevent water backflow. Three thermocouples were arranged in equal distances inside the column to measure temperature along the column height. Humidity and temperature sensors were used to measure temperatures of air (T_i , T_{in} , and T_{out}), and relative humidity ($\%H_{in}$, $\%H_{out}$).

The solids used in gas-liquid-solid experiments were 0.1-mm cation resins of 1.2 specific gravity, manufactured by ROHS & HAAS.

In all experiments, the column was first filled with water at 55 °C to a certain level. The desired flow of air was then introduced into the column and the system was allowed to reach steady state for approximately 5 minutes. The water levels in the column, the inlet and outlet temperatures and humidity of air as well as the temperatures at various points in the column were measured at different gas flow rates ranging from 4×10^{-4} to 18×10^{-4} m³/s. This procedure was repeated at different static water levels (70 cm, 80 cm, 90 cm, 100 cm) and different solid concentrations (0, 5, 10, 15% by weight).

4. RESULTS AND DISCUSSION

Numerous studies have been carried out on multiple aspects of bubble columns. From these studies, it can be concluded that the important characteristics design parameters of this equipment are flow regime, bubble size distribution and bubble coalescence, gas holdup, gas liquid interfacial area, and mass and heat transfer coefficients.

Particular emphasis in the literature is given to the study of gas holdup and the volumetric mass transfer coefficient in the liquid side. It is established that both of these parameters

fundamentally depend on gas flow into the contactor, and on the physical properties of the liquid and gas.

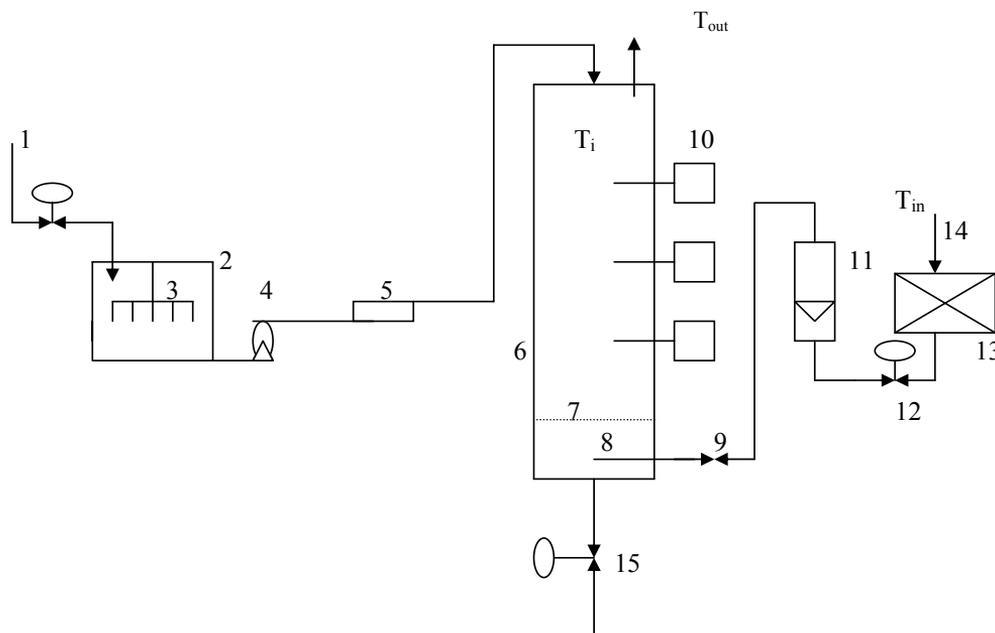


Figure (1) Schematic diagram of the experimental setup (1. Main line of water; 2 Cylindrical heating tank; 3. Electrical heaters; 4. Centrifugal pump; 5. Water filter; 6. Bubble column; 7. Silk screen; 8. Nozzle; 9. One way valve; 10. Thermocouples; 11. Flow meter; 12. Regulating valve; 13. Compressor; 14. Main line of air; 15. Drain valve).

The addition of a suspended solid phase to the column, further complicates the fluid dynamics of the system and affects the characteristics behavior of its design parameters such as gas holdup and the mass and heat transfer rates within the column. Previous investigations of these parameters show that gas holdup increases with increasing gas velocity. However, the dependence of gas holdup on superficial velocity varied from one study to another ranging from linear dependence of gas holdup on velocity down to a dependence of a power of about 0.47 of the superficial velocity. Numerous correlations have also been proposed, however, the difference among them are significant which can be attributed principally to the use of different diffuser systems and different ranges of the superficial velocity of gas.

4.1. Gas Holdup

Figure (2) shows a typical result found in this study for the effect of gas superficial velocity on gas holdup. This result is in full agreement with reported investigations on similar systems (Anabtawi et al., 1991; Nishikawa et al., 1976; Hughmark, 1967; Kim et al., 1972; Akida and

Yshida, 1973, Hikiata et. al., 1980; Vatai and Tekici, 1989; Shetty et al., 1992; Das et al., 1992) including the effect of the addition of a suspended solid to the column, which as shown in the figure results in a decrease in the gas holdup. It was observed that the presence of solid particles enhances bubble coalescence into larger bubbles. It was also observed that the bubble coalescence increased as gas velocity increased. The bubble coalescence rate is countered by bubble break up rate throughout the column height (Akita and Yoshida, 1974). Bubble size distribution and average bubble size through the column depend on the balance between the coalescence and breakup rate.

A typical variation of gas holdup with static liquid height up to a static liquid height of 1 m is shown in figure (3). The decrease in gas holdup with increasing static height for both the two and three phase system agrees with reported study on similar systems (Kodiak et al., 1984; Name et al., 1997).

4.2. Gas-phase Mass and heat Transfer Coefficients

Figure (4) shows typical results of the values of the volumetric mass transfer coefficient, k_{Ga} , as a function of the gas superficial velocity according to the transfer model proposed in this study, at different solid concentration in the column. These results show the strong dependence of the mass transfer coefficient on the gas velocity. These results also show that the presence of a suspended solid phase only begins to contribute to enhance the gas phase mass transfer coefficient after a certain minimum superficial gas velocity, necessary to maintain solid suspension in the liquid phase, has been reached in the column (≈ 0.056 m/s in the present system). Furthermore, these data also show that increasing the solid concentration in the column beyond 5 wt% does not contribute to any further change in the gas phase mass transfer. This finding is illustrated in Figure (5). In light of the proceeding discussion about the effect of the solid phase on the gas holdup, a plausible explanation for the increase in the mass transfer coefficient in the presence of the solid phase, which becomes more pronounced with an increase in the gas superficial velocity, is that the solid presence enhances the internal gas circulation in bubbles resulting in an appreciable increase in k values. However, it appears that the effect of the solid presence on this internal gas circulation within bubbles diminishes beyond a 5 wt. % of solid in the column.

Figure (6) shows typical results of the values of the volumetric heat transfer coefficient, h_{Ga} , as a function of gas superficial velocity according to the heat transfer model employed in this study. This figure illustrates a remarkable resemblance of the characteristics behavior of the heat transfer coefficient to that of the mass transfer in terms of their strong dependence on the gas superficial velocity and the effect of the presence of the solid phase on these coefficients.

5. CONCLUSIONS

The effect of superficial gas velocity and solid concentration on gas holdup and volumetric heat and mass transfer coefficients in a bubble column were investigated. Gas holdup

increases as superficial gas velocity increases but decreases with solid concentration. Both volumetric heat and mass transfer coefficient increased with superficial gas velocity. An addition of 5 wt. % of suspended solids into the bubble column enhanced both the volumetric heat and mass transfer coefficients. The increase in volumetric heat and mass transfer coefficient was observed when the superficial gas velocity was greater than 0.056 m/s. However, Further increase in suspended solids beyond 5 wt. % in the column did not contribute to any further change in the values of these coefficients. The results agree with the previous investigators finding except for unresolved discrepancies in the effect of that on heat transfer coefficients.

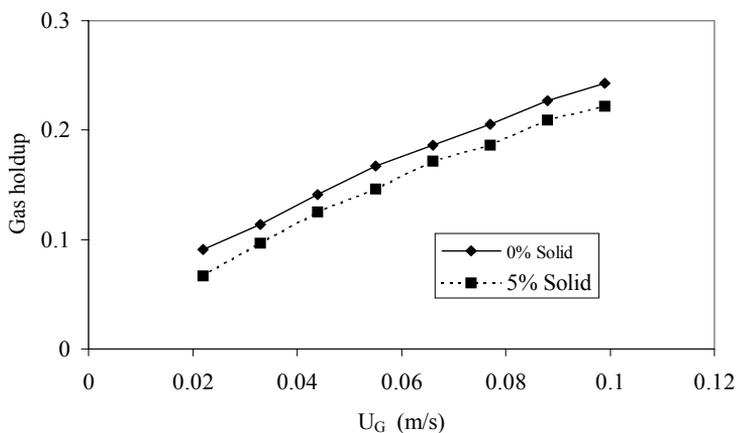


Figure (2) Effect of gas superficial velocity on gas holdup at $U_G = 0.077$ m/s and $Z_0 = 0.7$ m.

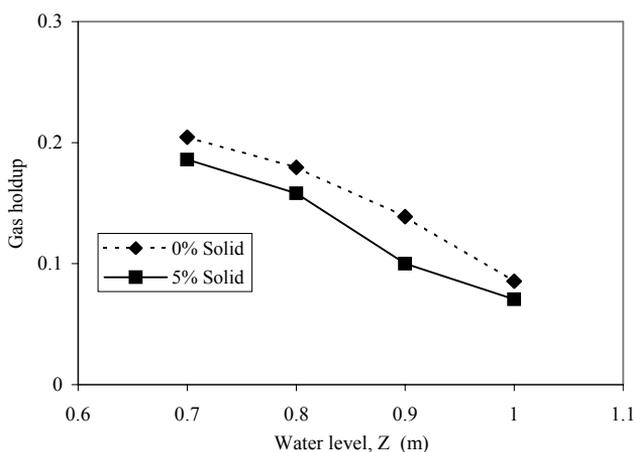


Figure (3) Variation of gas holdup with the static liquid height at $U_G = 0.077$ m/s.

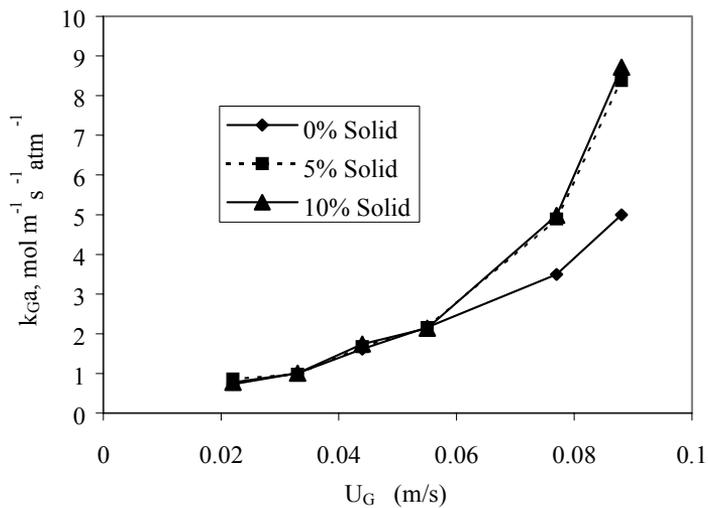


Figure (4) Effect of gas superficial on volumetric mass transfer coefficient at $Z_0 = 0.7m$.

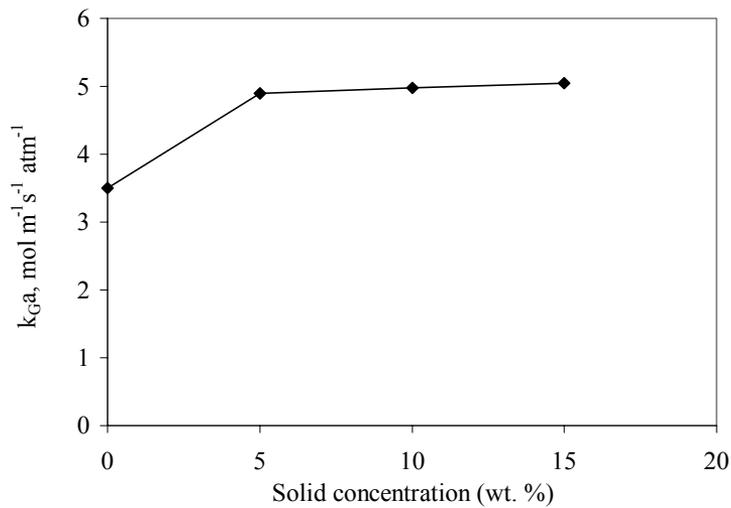


Figure (5) Effect of solid concentration on volumetric mass transfer coefficient ($U_G = 0.077$ m/s; $Z_0 = 0.7$ m)

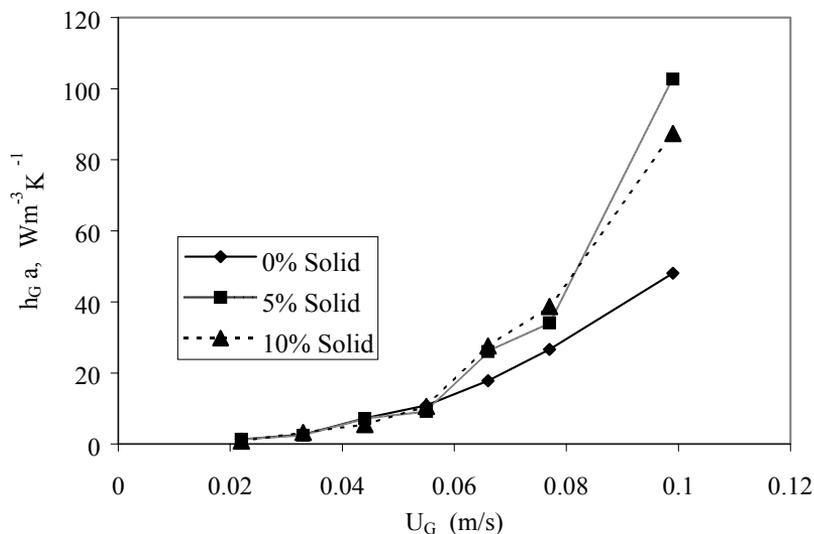


Figure (6) Effect of gas superficial velocity on Heat transfer coefficient at $Z_0 = 0.7\text{m}$.

SYMBOLS

- a specific gas-liquid interfacial area (m^{-1})
- C_{pG} specific heat of gas ($\text{J/kg dry air} \cdot \text{K}$)
- $C_{p,vap}$ specific heat of vapor ($\text{J/kg dry air} \cdot \text{K}$)
- D diameter of the column (m)
- h_{GA} heat transfer coefficient ($\text{W/m}^3 \cdot \text{K}$)
- H_{in} Inlet humidity (kg water/kg dry air)
- H_{out} outlet humidity (kg water/kg dry air)
- H_y enthalpy of gas at height y (J/kg dry air)
- H_{in} enthalpy of inlet air (J/kg dry air)
- H_{out} enthalpy of outlet air (J/kg dry air)
- G mass of dry air (kg dry air/s)
- k_{GA} volumetric mass transfer coefficient ($\text{mol/m} \cdot \text{s} \cdot \text{atm}$)
- M_B air molecular weight (kg/kg mol)
- Q volumetric flow rate (m^3/s)
- P_T total pressure (atm.)
- S cross sectional area (m^2)
- T_o reference temperature = 273 (K)
- T_i temperature at interface (K)
- T_{in} inlet gas temperature (K)

T_{out}	outlet gas temperature (K)
T_1	temperature at Z_1 (K)
T_2	temperature at Z_2 (K)
T_3	temperature at Z_3 (K)
U_G	superficial velocity (m/s)
Z_0	static height of water in the column (m)
Z_T	final height of water in the column (m)

Greek Letters

λ_0	latent heat of evaporation (kJ/kg).
ρ	density (kg/m ³)
ε_G	gas holdup

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