CODEN STJSAO ISSN 0562-1887
ZX470/1475 UDK 66.021.4

Heat Transfer in Bubble Columns

Bekir Zühtü UYSAL, Özkan Murat DOĞAN, Duygu UYSAL **and** ***Serdar DEMIR***

Gazi University, Faculty of Engineering, Department of Chemical Engineering and Clean Energy Research and Application Center, (CERAC-TEMENAR), Maltepe, 06570 Ankara, **Turkey**

bzuysal@gazi.edu.tr

Original scientific paper

Bubble columns are gas-liquid contactors often used in industry. Although they are used primarily for mass transfer purpose, since gas and liquid phases are fed to the column at different temperatures, direct contact heat transfer becomes important as well. This research is about the heat transfer characteristics of bubble columns. Experiments were carried out using a plexiglass column with dimensions 160x160x1180 mm. Water was first put into the column to the height of 1 m and heated to the desired temperature, and then experiments were performed by introducing ambient air to the column and recording the variation in temperature of water and inlet and outlet air temperatures and humidities. Models developed for the convective heat transfer from the liquid interface to the gas in the bubble were used together with the experimental data to determine the heat and mass transfer coefficients. The volumetric heat transfer coefficient (hGa) was found to vary over the range 0,3-16 kW/(m^3·K) with gas flow rate and the volumetric mass transfer coefficient (kGa) in the range 0,35-7,49 kmol/m^3·s·atm.

Prijenos topline u mjehurastim stupcima

Izvornoznanstveni članak

Mjehurasti stupci su dodiri između plina i kapljevine koji se često koriste u industriji.. Iako ih se primarno koristi s ciljem prijenosa mase, budući da se plinska i kapljevita faza razdvajaju u stupce pri različitim temperaturama. tada njihov izravni dodir postaje važan za prijenos topline.. Ovo se istraživanje bavi karakteristikama prijenosa topline mjehurastih stupaca. Eksperimenti su napravljeni koriste cilindar od plexiglasa dimenzija 160x160x1180 mm. U cilindar je prvo ulivena voda do visine od 1 m i koja je zagrijavana do željene temperature, nakon čega se u tu vodu uvodio zrak okolišnje temperature, pri čemu se mjerila promjena temperature vode, kai i ulazna i izlazna vlažnost zraka. Modeli razvijeni za konvektivni prijenos topline sa slobodne površine kapljevine na mjehur su korišteni zajedno sa eksperimentalnim podacima za određivanje koeficijenata prijenosa topline i mase.. Iznađeno je da je volumetrički koeficijent prijenosa topline varirao u području 0.3-16 kW/(m^3·K) s protokom zraka i volumetričkim koeficijentom prijenosa mase u području 0.35 – 7,39 kmol/(m^3·s·atm)

Keywords
Bubble column
Heat transfer
Mass transfer

Ključne riječi
Mjehurasti stupac
Prijenos mase
Prijenos topline

Received (primljeno): 2009-11-30
Accepted (prihvaćeno): 2010-08-20

1. Introduction

Bubble columns have a significant field of application in absorption processes or as liquid-gas reactors in chemical, biochemical and energy technologies. They have two-phase systems involving gas and liquid or three-phase systems involving gas, liquid and solid phases. Although the general objective of usage of bubble columns is to create a medium for reaction or mass transfer, due to the temperature difference between phases, direct-contact heat transfer occurs simultaneously and this case must be considered in modeling. There are plenty of researches done to observe the heat transfer between two-phase or three-phase and wall or an immersed surface [6]. But, the researches about heat transfer between phases are very few [5, 7]. In this work, a path similar to humidification [9] and direct-contact evaporation [2, 5] processes was been developed in order to determine the analytical model of direct-contact heat transfer and with the experimental data, the heat transfer coefficient between phases and mass transfer coefficient have also been determined.

2. Heat transfer in bubble columns

A simple demonstration of the model is shown in Figure 1. This model is used to determine the heat transfer

Symbols/Oznake

a	- interphase area, m^2/m^3 - međufazna površina
C	- density of water in air leaving the column, kg/m^3 - gustoća vode u zraku koji napušta stupac
C_s	- heat capacity of humid air, kJ/(kg·K) - specifični toplinski kapacitet vlažnog zraka
E_t	- dimensionless number, $\Delta T_G/(T_L-T_{Gi})$ - bezdimenzijski broj
G	- gas flow rate, kg dry air/s - maseni protok suhog zraka
h_g	- heat transfer coefficient, $kW/(m^3 \cdot K)$ - koeficijent prijenosa topline
$h_g a$	- volumetric heat transfer coefficient, $kW/(m^3 \cdot K)$ - volumetrički koeficijent prijenosa topline
H_G	- height of transfer unit, m - visina prijenosne jedinice
H_X	- liquid enthalpy, J/kg water - specifična entalpija kapljevite vode
H_y	- gas enthalpy, J/kg dry air - specifična entalpija suhog zraka
k_g	- gas phase mass transfer coefficient, $kmol/(atm \cdot m^2 \cdot s)$ - koeficijent prijenosa mase plinske faze
$k_g a$	- gas phase volumetric mass transfer coefficient, $kmol/(atm \cdot m^3 \cdot s)$ - volumetrički koeficijent prijenosa mase plinske faze
k_y	- gas phase mass transfer coefficient, $kmol/m^2 \cdot s$ - koeficijent prijenosa mase plinske faze
K_y	- gas phase overall mass transfer coefficient, $kmol/(m^2 \cdot s)$ - ukupni koeficijent prijenosa mase olinske faze
M_A	- molecular weight of water, kg/kmol - molarna masa vode
M_B	- molecular wight of air, kg/kmol - molarna masa zraka
N_A	- molar flux, $kmol/(m^2 \cdot s)$ - gustoća količinskog toka
N_G	- number of transfer unit - broj prijenosnih jedinica
P_T	- total pressure - ukupni tlak
q_c	- convective heat flux, kW/m^2 - konvektivna gustoća toplinskog toka
q_b	- heat flux corresponding to latnet heat, kW/m^2 - gustoća toplinskog toka koja odgovara latentnoj toplini
S	- surface area of air bubble, m^2 - površina mjehura
T_i, T_L	- water temperature, K - temperature vode
T_{Gi}	- temperature of gas at the exit of column, K - temperatura plina na ulazu u stupac
T_{Gf}	- temperature of gas at the exit of column, K - temperatura plina na izlazu iz stupca
y	- gas phase molar ratio - molni udio plinske faze
Z_T	- total column height, m - ukupna visina stupca
λ_o	- latent heat, kJ/kg - latentna toplina

coefficient used in the calculation of direct-contact heat transfer between gas and liquid in bubble columns. Herein, a bubble can be chosen representatively and a heat transfer model can be developed based on this bubble.

At first, the following assumptions can be done;

- Batch bubble column is used.
- The heat transfer resistance at the liquid phase is neglected. [1]
- The value of liquid phase heat transfer coefficient is assumed to be very high. [3]
- The interphase temperature is assumed to be equal to liquid temperature.
- The temperature is assumed to be constant during the stay of bubble in the column. [5]

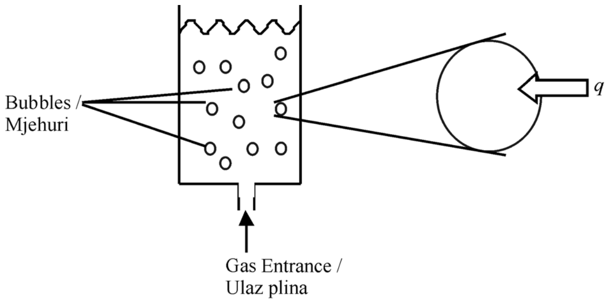

Figure 1. Schematic demonstration of bubble column

Slika 1. Shematski prikaz stupca mjehura

By choosing a control volume element with a height “dz” in the column shown in Figure 1, equation of energy considering the heat transfer from hot liquid to bubble phase can be written as follows;

$$q = G \cdot dHy\,. \tag{1}$$

Some part of the heat transferred to bubble is transferred convectively from interphase to bubble gas, and the other part of this heat is used to evaporate some of the water molecules at the interphase thus increasing the humidity of bubble gas.

$$q = q_c + q_b\,. \tag{2}$$

Convective heat flux can be written as follows.

$$q_c = \{h_G a(T_i - T_G)\}\,. \tag{3}$$

The heat flux corresponding to the latent heat used for the evaporation of water is,

$$q_b = N_A M_A \lambda_o a S\mathrm{d}z\,. \tag{4}$$

By using the definition of mass transfer flux, the expression of molar ratio related to humidity, the relation between the mass transfer coefficients;

$$N_A = k_y (y_i - y), \tag{5}$$

$$y = \frac{Y / M_A}{(Y / M_A) + 1 / M_B} \cong \frac{Y \cdot M_B}{M_A}, \tag{6}$$

$$k_y = k_G P_T, \tag{7}$$

the expression for mass transfer flux can be written as;

$$N_A = k_G P_T \frac{M_A}{M_B}(Y_i - Y)\,. \tag{8}$$

When Equation (8) is used, Equation (4) would be;

$$q_b = k_G P_T \frac{M_B}{M_A}(Y_i - Y) M_A \lambda_o a S\mathrm{d}z\,. \tag{9}$$

If Equation (3) and (9) is substituted into Equation (2),

$$q = \{h_G a(T_i - T_G) + k_G a M_B P_T \lambda_o (Y_i - Y)\} S \cdot \mathrm{d}z, \tag{10}$$

is obtained. By using this expression and Equation (1), the following equation is obtained.

$$G \cdot \mathrm{d}H_y = \{h_G a(T_i - T_G) + k_G a P_T M_B \lambda_o (Y_i - Y)\} S\mathrm{d}z\,. \tag{11}$$

Here, using the humid heat capacity,

$$C_s = \frac{h_G}{k_y \cdot M_B} = \frac{h_G a}{k_y a M_B} = \frac{h_G a}{k_G a P_T M_B}, \tag{12}$$

the equation is reduced to the following.

$$G \cdot \mathrm{d}H_y = \{C_s (T_i - T_G) + \lambda_o (Y_i - Y)\} k_G a P_T M_B S\mathrm{d}z, \tag{13}$$

$$G \cdot \mathrm{d}H_y = \{[C_s (T_i - T_o) + \lambda_o \cdot Y_i] - [C_s (T_G - T_o) + \lambda_o Y]\} \cdot k_G a P_T M_B S\mathrm{d}z, \tag{14}$$

$$G \cdot \mathrm{d}H_y = k_G a P_T M_B (H_{yi} - H_y) S\mathrm{d}z\,. \tag{15}$$

This expression can be integrated between the column inlet and exit.

$$\int_{H_{y,in}}^{H_{y,out}} \frac{dH_y}{(H_{yi} - H_y)} = \frac{k_G a P_T M_B s}{G} \int_0^{z_T} \mathrm{d}z\,. \tag{16}$$

If assumptions are considered;

$$T_i \cong \mathrm{T_L}, \tag{17}$$

$$\mathrm{H_{yi}} = H_y\big|_{T_i = \mathrm{T_L}}, \tag{18}$$

$$\mathrm{T_L} = \text{constant, and therefore } \mathrm{H_{yi}} = \text{constant}, \tag{19}$$

integration gives the following result.

$$Z_T = \frac{G / s}{k_G a P_T M_B} \ln\left(\frac{H_{yi} - H_{y,in}}{H_{yi} - H_{y,out}}\right). \tag{20}$$

This can be rephrased as the well known expression stating that the height of the column is the product of the height of transfer unit and the number of transfer units.

$$Z_T = H_G N_G\,. \tag{21}$$

Writing explicitly at the interphase,

$$H_{yi} = H_y\big|_{T_i = T_L} = C_s (T_L - T_o) + d_o Y_s, \tag{22}$$

$$T_o = 0^\circ C, \tag{23}$$

$$Y_i \cong Y_s, \tag{24}$$

$$C_s = 1005 + 1880 Y_s, \tag{25}$$

and gas enthalpies at the inlet and exit would be written as follows,

$$H_{y,in} = C_s (T_{G,in} - T_o) + \lambda_o Y_{in}, \tag{26}$$

$$H_{y,out} = C_s (T_{G,out} - T_o) + \lambda_o Y_{out}\,. \tag{27}$$

The humidity values at the entrance and at the exit can be determined experimentally and used in these equations.

If $T_i = T_L$ assumption (Equation 17) is not made, modeling can be done as follows.

For gas phase;

$$q = G \cdot \mathrm{d}H_y = k_y a M_B (H_{yi} - H_y) S\mathrm{d}z, \tag{28}$$

or,

$$(H_{yi} - H_y) = \frac{q}{k_y a M_B S \mathrm{d}z}, \qquad (29)$$

For liquid phase;

$$q = \mathrm{d}(LH_x) = h_x a (T_x - T_{xi}) S \cdot \mathrm{d}z, \qquad (30)$$

or in terms of specific liquid enthalpy,

$$(H_x - H_i) = \frac{q}{(h_x a / Cp_x) S \mathrm{d}z}. \qquad (31)$$

By summing up Equations (29) and (31),

$$(H_x - H_y) = \frac{q}{s \cdot \mathrm{d}z} \frac{1}{M_A} \left[\frac{1}{k_y a} + \frac{Cp_x M_B}{h_x a} \right], \qquad (32)$$

the above equation is obtained. By using the definition of volume based overall mass transfer coefficient,

$$\frac{1}{K_y a} = \left[\frac{1}{k_y a} + \frac{Cp_x M_B}{h_x a} \right], \qquad (33)$$

$$q = K_y a M_B (H_x - H_y) s \cdot \mathrm{d}z, \qquad (34)$$

$$G \cdot \mathrm{d}H_y = K_y a M_B (H_x - H_y) s \cdot \mathrm{d}z, \qquad (35)$$

$$\int_{H_{y,in}}^{H_{y,out}} \frac{\mathrm{d}H_y}{(H_x - H_y)} = \frac{K_y a M_B}{G / s} \int_0^{Z_T} \mathrm{d}z, \qquad (36)$$

and upon integration one can get

$$Z_T = \frac{G / s}{K_y a M_B} \ln\left(\frac{H_x - H_{y,in}}{H_x - H_{y,out}} \right), \qquad (37)$$

$$Z_T = H_{OG} N_{OG}. \qquad (38)$$

In the case when the mass transfer is negligibly small, the following approach can be followed. If it is considered that the heat transferred from liquid to gas phase through the interphase is used to increase the temperature of gas rising up through the column in the form of bubbles, the heat balance can be written as,

$$u_G S_C \varepsilon_g (\rho \cdot Cp_G + C \cdot Cp_{vap}) \mathrm{d}T_G = h_G a (T_L - T_G) S_C \mathrm{d}z. \qquad (39)$$

The integration of this expression along the entire height of column gives the following.

$$\frac{T_L - T_{Gi}}{T_L - T_{Gf}} = \exp\{ \frac{(h_G a) Z_T}{u_G \varepsilon_g (\rho \cdot Cp_G + C \cdot Cp_{vap})} \}. \qquad (40)$$

When the left-hand side of this expression is reorganized,

$$\frac{(T_L - T_{Gi}) - (T_L - T_{Gf})}{(T_L - T_{Gf})} = \frac{(T_{Gi} - T_{Gf})}{(T_L - T_{Gf})} = \frac{\Delta T_G}{(T_L - T_{Gf})}, \qquad (41)$$

an expression for for $(h_G a)$ is obtained.

$$h_g a = \frac{-u_G \varepsilon_g (\rho \cdot Cp_G + C \cdot Cp_{vap})}{Z_T} \ln\left(\frac{T_L - T_{Gf}}{T_L - T_{Gi}} \right), \qquad (42)$$

Using the definitions of

$$E_t = \frac{\Delta T_G}{T_L - T_{Gi}} \quad \text{or} \quad (1 - E_t) = \frac{T_L - T_{Gf}}{T_L - T_{Gi}}, \qquad (43)$$

the equation takes the following form,

$$h_g a = \frac{-u_G \varepsilon_g (\rho \cdot Cp_G + C \cdot Cp_{vap})}{Z_T} \ln(1 - E_t), \qquad (44)$$

3. Experimental

Experiments were carried out in a plexiglass column, shown in Figure 2, which had the dimensions of 16x16x118 cm. Water entered the column at the bottom through four nozzles. Gas was introduced co-currently through one nozzle.

Firstly, the column was filled with water up to the level of 100 cm. The experiment was performed as batch system. With the help of a heater immersed into the water, water was initially heated and then gas was let into the column.

Regarding the durability of plexiglass, the water was heated up to maximum 40 °C. The flow rate of air in column was changed between 28 and 340 L/min. With the thermocouples at the top and middle of plexiglass column, temperature measurement was done throughout the experiment.

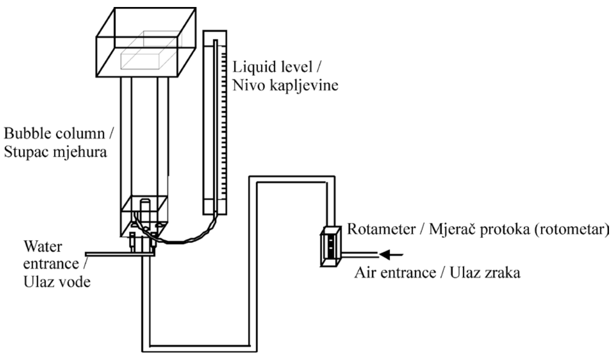

Figure 2. Experimental setup
Slika2. Eksperimentalni uređaj

4. Results and discussion

The experimental data, obtained in the experiments performed using the method explained above, were used to evaluate the volumetric heat transfer coefficient ($h_g a$) and volumetric mass transfer coefficient ($k_g a$). Their graphs are drawn in Figure 3 and 4 to show their dependencies on the air flow rate. Gas phase holdup was estimated with the following equation, obtained at similar operating conditions [4];

$$\varepsilon_{\mathrm{g}} = 0,877 U_{\mathrm{g}}^{0,67}. \tag{45}$$

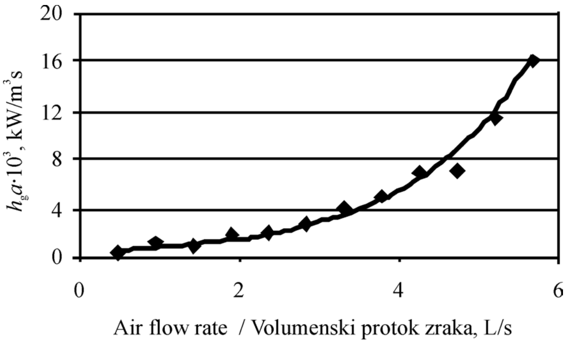

Figure 3. Variation of volumetric gas phase heat transfer coefficient with air flow rate

Slika 3. Ovisnost volumetričkog koeficijenta prijenosa topline o volumenskom protoku zraka

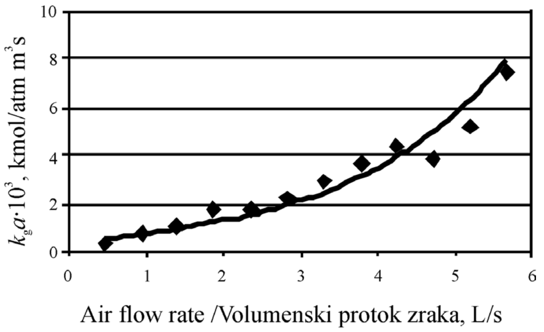

Figure 4. Variation of individual gas phase mass transfer coefficient with air flow rate

Slika 4. Ovisnost koeficijenta prijenosa mase pojedinačne plinske faze o volumenskom protoku zraka

As seen in Figures 3 and 4, as the air flow rate increases, the gas phase volumetric heat transfer coefficient and the gas phase volumetric mass transfer coefficient also increase. This is an expected result. With the increasing gas rate, both the turbulence inside the column and number of bubbles formed the increase. These two factors make volumetric heat and mass transfer coefficients increase.

The change in overall mass transfer coefficient with different gas rates is shown in Figure 5. K_ya, defined with Equation 33, expresses the reciprocal of the sum of gas and liquid side individual resistances. It increases with a higher gas rate at a slower rate than individual coefficients as expected.

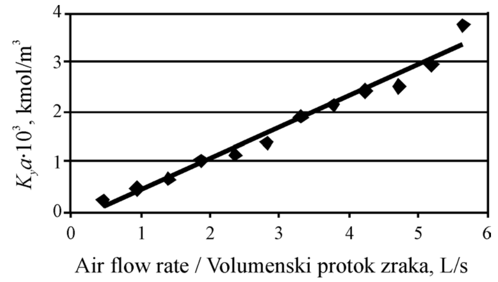

Figure 5. Variation of gas phase overall heat transfer coefficient with air flow rate

Slika 5. Ovisnost ukupnog koeficijenta prijenosa topline na strani plinske faze o volumenskom protoku zraka

With the experimental data given in Figure 5 and Equation 32, liquid side individual heat transfer coefficient can also be calculated. The results are shown in Figure 6.

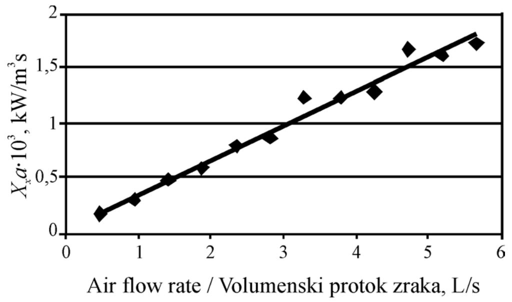

Figure 6. Variation of volumetric liquid phase heat transfer coefficient with air flow rate

Slika 6. Ovisnost volumetričkog koeficijenta prijenosa topline na strani kapljevite faze o volumenskom protoku zraka

The comparison of Figure 5 and 6 is interesting; both of them show linear change with gas rate. This shows the inevitable and profound effects of the liquid side individual resistances on the overall transfer coefficient.

5. Conclusions

Simultaneous heat and mass transfer phenomena were modeled for bubble columns involving direct contact between gas and liquid phases and volumetric heat and mass transfer coefficients were calculated by using the heat transfer experimental data. Use of the volumetric transfer coefficients as presented in this paper is easier and more practical in design calculations. The assessment of the results leads to the conclusion that the magnitude of the resistance at the liquid side has a significant effect on the overall transfer coefficient.

REFERENCES

[1] ALABOWSKII, A. N.: *Thermal Interaction at the Gas-Liquid Interface in an Apparatus with an Immersed Burner*, Inz. Fiz. Zhurn., 22 (1972), 117-122.

[2] BHARATAN, D.: *Direct Contact Evaporation, in Direct Contact Heat Transfe*, F. Kreith and R. F. Boehm, ed., *Hemisphere Pub. Corp.*, New York, 1988.

[3] BIRD, R.B.; STEWART, W.E. and LIGHTFOOT, E.N.: *Transport Phenomena (2nd Ed.), J. Wiley & Sons*, New York, 2007.

[4] DEMIREL, S, A.; ÇULHA, F. F. AR and UYSAL, B. Z.: *İki ve Üç Fazlı Taşkın Yataklarda Gaz Tutulması ve Kütle Transferi*, *UKMK-1 Kongre Bildiri Kitabı*, Ed. A. Tiryaki, 1. Cilt, s. 104, Ankara, 1994 (in Turkish).

[5] GUY, C.; CARREAU, P.J. and PARIS, J.: *Heat and Mass Transfer Between Bubbles and a Liquid*, Can. J Chem. Eng., 70 (1992), 55-60.

[6] HULET, C. CLEMENT, P.; TOCHON, P.; SCHWEICH, D.; DROMARD, N. and ANFRAY, J.: *Literature Review on Heat Transfer in Two- and Three Phase Bubble Columns*, Int. Jr. Chem. Reac. Engrg., 7 (2009), 1-94.

[7] KREITH, F. and BOEHM, R.F.: *Direct Contact Heat Transfer*, *Hemisphere Pub. Corp.*, New York, 1988.

[8] SIDEMAN, S.: *Direct Contact Heat Transfer Between Immiscible Liquids*, Adv. Chem. Eng., 6 (1966), 207-286.

[9] TREYBAL, R. E.: *Mass Transfer Operations*, *McGraw Hill*, New York, 1980.