

# Heat Transfer in Bubble Columns

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

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

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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<sup>3</sup>·K) with gas flow rate and the volumetric mass transfer coefficient ( $kGa$ ) in the range 0,35-7,49 kmol/m<sup>3</sup>·s·atm.

## Prijenos topline u mjehurastim stupcima

Izvorno znanstveni članak

Mjehurasti stupci su dodir 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 okolišne 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<sup>3</sup>·K) s protokom zraka i volumetričkim koeficijentom prijenosa mase u području 0,35 – 7,39 kmol/(m<sup>3</sup>·s·atm)

## 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

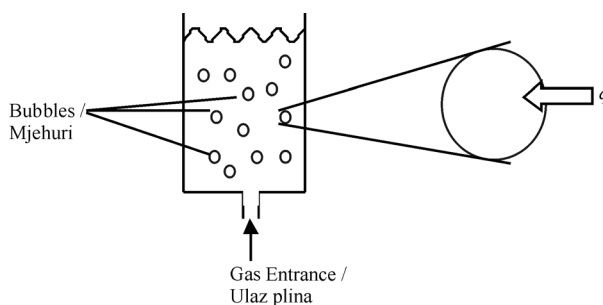
**Symbols/Oznake**

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

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;

$$q = G \cdot dH_y \tag{1}$$

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,

$$q_b = N_A M_A \lambda_o a S dz \tag{4}$$

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;

$$q_b = k_G P_T \frac{M_B}{M_A} (Y_i - Y) M_A \lambda_o a S dz \tag{9}$$

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

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

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

$$G \cdot dH_y = \{h_G a(T_i - T_G) + k_G a P_T M_B \lambda_o (Y_i - Y)\} S dz \tag{11}$$

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.

$$G \cdot dH_y = \{C_s (T_i - T_G) + \lambda_o (Y_i - Y)\} k_G a P_T M_B S dz \tag{13}$$

$$G \cdot dH_y = \{[C_s (T_i - T_o) + \lambda_o \cdot Y_i] - [C_s (T_G - T_o) + \lambda_o Y]\} \cdot k_G a P_T M_B S dz \tag{14}$$

$$G \cdot dH_y = k_G a P_T M_B (H_{yi} - H_y) S dz \tag{15}$$

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

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

If assumptions are considered;

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

$$H_{yi} = H_y \Big|_{T_i=T_L} \tag{18}$$

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

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;

$$q = G \cdot dH_y = k_y a M_B (H_{yi} - H_y) S dz \tag{28}$$

or,

$$(H_{y_i} - H_y) = \frac{q}{k_y a M_B S dz}, \quad (29)$$

For liquid phase;

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

or in terms of specific liquid enthalpy,

$$(H_x - H_i) = \frac{q}{(h_x a / C p_x) S dz}. \quad (31)$$

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

$$(H_x - H_y) = \frac{q}{s \cdot dz} \frac{1}{M_A} \left[ \frac{1}{k_y a} + \frac{C p_x M_B}{h_x a} \right], \quad (32)$$

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

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

$$q = K_y a M_B (H_x - H_y) s \cdot dz, \quad (34)$$

$$G \cdot dH_y = K_y a M_B (H_x - H_y) s \cdot dz, \quad (35)$$

$$\int_{H_{y,in}}^{H_{y,out}} \frac{dH_y}{(H_x - H_y)} = \frac{K_y a M_B}{G / s} \int_0^{Z_T} dz, \quad (36)$$

and upon integration one can get

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

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

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,

$$u_G S_C \varepsilon_g (\rho \cdot C p_G + C \cdot C p_{vap}) dT_G = h_G a (T_L - T_G) S_C dz. \quad (39)$$

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

$$\frac{T_L - T_{Gi}}{T_L - T_{Gf}} = \exp \left\{ \frac{(h_G a) Z_T}{u_G \varepsilon_g (\rho \cdot C p_G + C \cdot C p_{vap})} \right\}. \quad (40)$$

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

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

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

$$h_G a = \frac{-u_G \varepsilon_g (\rho \cdot C p_G + C \cdot C p_{vap})}{Z_T} \ln \left( \frac{T_L - T_{Gf}}{T_L - T_{Gi}} \right), \quad (42)$$

Using the definitions of

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

the equation takes the following form,

$$h_G a = \frac{-u_G \varepsilon_g (\rho \cdot C p_G + C \cdot C p_{vap})}{Z_T} \ln(1 - E_t), \quad (44)$$

### 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.

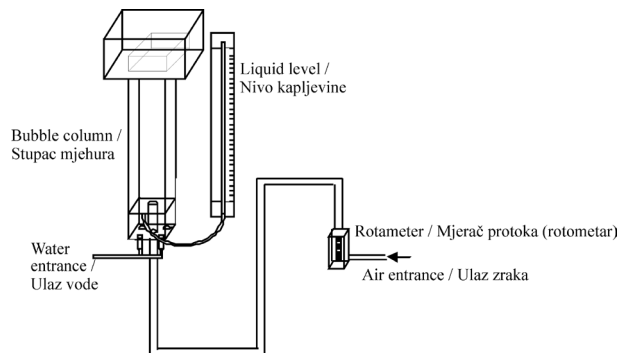


Figure 2. Experimental setup

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 ( $h_g$ ) and volumetric mass transfer coefficient ( $k_g$ ). 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];

$$\epsilon_g = 0,877U_g^{0,67} \tag{45}$$

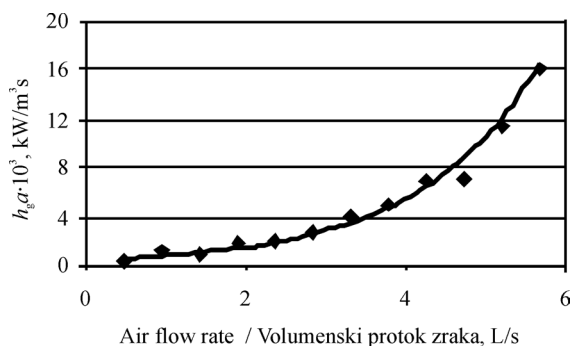


Figure 3. Variation of volumetric gas phase heat transfer coefficient with air flow rate

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

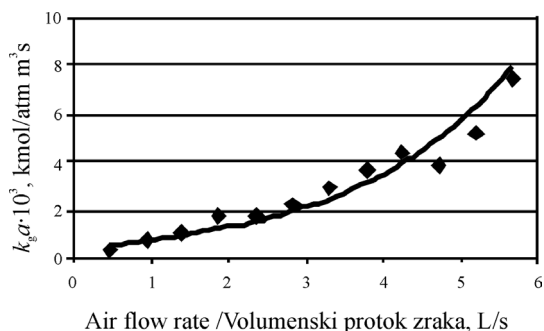


Figure 4. Variation of individual gas phase mass transfer coefficient with air flow rate

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.  $K_y a$ , 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.

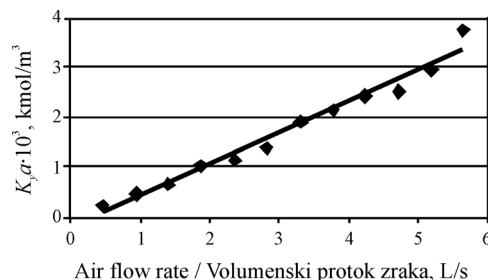


Figure 5. Variation of gas phase overall heat transfer coefficient with air flow rate

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.

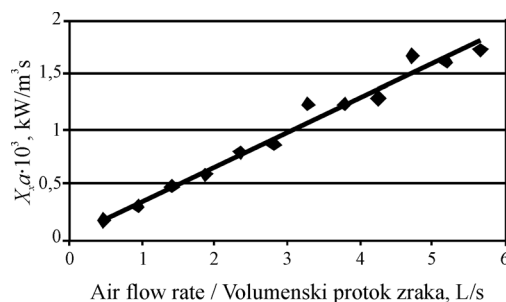


Figure 6. Variation of volumetric liquid phase heat transfer coefficient with air flow rate

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.

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