Experimental and modeling studies of mass transfer and hydrodynamics in a packed bed absorption column for CO_2 – water system

Dario D. Balaban[1,2], Branislava G. Nikolovski[1], Mitar D. Perušić[2] and Goran S. Tadić[2]

[1]University of Novi Sad, Faculty of Technology Novi Sad, Bulevar cara Lazara 1, 21000 Novi Sad, Serbia
[2]University of East Sarajevo, Faculty of Technology Zvornik, Department of Process Engineering, Karakaj 1, 75400 Zvornik, Republic of Srpska, Bosnia and Herzegovina

Abstract

This paper presents research on hydrodynamics and mass transfer in a packed absorption column. Experimental data on dry column pressure drop, flooding point, and efficiency of absorption of CO_2 in water is obtained on a lab-scale absorption column packed with Raschig rings. Auxiliary parts of equipment together with chemical analyses provide simple monitoring and collecting the data. All obtained data were used to test different mathematical models for a given problem, *i.e.* for determination of the dry column pressure drop, flooding point and the overall gas transfer unit height. For dry column pressure drop, models developed primarily for packed columns described the data the best, with the Billet model generating a 6.54 % mean error, followed by Mackowiak and Stichlmair models. In flooding point calculations, empirical models were tested and models of Lobo, Leva and Takahshi gave the best results. Mass transfer (absorption) experiments gave expected results, since absorption efficiency increased with the increase in the liquid/gas flow rate ratio, *i.e.* with approaching the flooding point. The Onda's model was used to calculate partial mass transfer coefficients in liquid and gas phases based on which the height of the overall gas transfer unit was estimated and subsequently compared with the experimental data. Deviation of calculated and experimental results for the height of the overall gas transfer unit is in the expected range of 0-20 %, with mean value of 15.5 %. In conclusion, the available models for determination of the investigated hydrodynamics and mass transfer parameters in packed absorption columns gave adequate results in comparison to the experimental values.

Keywords: pressure drop; flooding; height of transfer unit.

Available on-line at the Journal web address: http://www.ache.org.rs/HI/

TECHNICAL PAPER

UDC: 542.745.1: 544.431.11: 543.272.62

Hem. Ind. **77(2)** 99-109 (2023)

1. INTRODUCTION

Absorption is one of the most important unit operations, primarily due to its application in flue gas cleaning, carbon capture and wastewater treatment. Mass transfer in absorption columns is usually enhanced by column packing, which increases the interphase surface area throughout the column. Proper design and evaluation of packed towers require accurate models to predict hydrodynamics and mass transfer coefficients [1].

The complex nature of the system (multiphase flow through a porous medium, short residence time, mass and heat transfers, flooding phenomenon) has led researchers to develop empirical and semi-empirical mathematical models, considering different parameters affecting the absorption process. Complete models are obtained by considering large databases of results of absorption experiments (geometry of the system, type of packing, flow rates, *etc.*) and fitting the data to the proposed model. This approach can result in models which are not suitable for most of absorption systems, mainly due to the lack of overall data for new absorption systems and geometries.

Since column packings can have complex geometries and different sizes, different approaches were used in modeling of the pressure drop across the column as well as the flooding phenomenon. The most common approach consists of

Corresponding authors: Dario D. Balaban, University of Novi Sad, Faculty of Technology Novi Sad, Bulevar cara Lazara 1, 21000 Novi Sad, Serbia
E-mail: dario.balaban@uns.ac.rs
Paper received: 20 January 2023; Paper accepted: 11 June 2023; Paper published: 27 June 2023.
https://doi.org/10.2298/HEMIND230120014B

fitting experimental data to proposed equations resulting in a series of empirical and semi-empirical models, which have been used for decades [2]. In recent times, researchers have taken a turn and began using machine learning [3], and especially computational fluid dynamics to model multiphase flow through porous media [4-9]. This approach has proven to provide more accurate results in assessment of pressure drop in packed columns.

In mass transfer modeling, general models for prediction of mass transfer coefficients are uncommon due to specific characteristics of each absorption system. Since the focus of the present research is on absorption of CO_2 in water, it is worth mentioning that several models can be found in literature for specific systems, usually for those which include common solvents like amines and sodium hydroxide [10-14]. Due to the complex nature of mass transfer in absorption columns, proper design and evaluation of columns require prior research on a lab-scale level for the specific system, providing complete information about mass transfer and hydrodynamics in the column.

The aim of this research was to conduct several types of experiments on a lab-scale packed column for absorption of CO_2 in water and to describe the obtained data with models available in literature. The main focus of experimental work was to obtain data for dry column pressure drop, flooding point, absorption efficiency, and height of the overall gas transfer unit. Also, since the CO_2-water system is rare in the industrial absorption applications, available data are scarce [15], so that the data obtained in these experiments could be used in further research and in more accurate model development.

2. MATERIALS AND METHODS

In order to investigate and analyze hydrodynamics and mass transfer, several types of experiments were performed on a lab-scale packed absorption column Armfield UOP7-MKII ("Armfield", England), Figure 1.

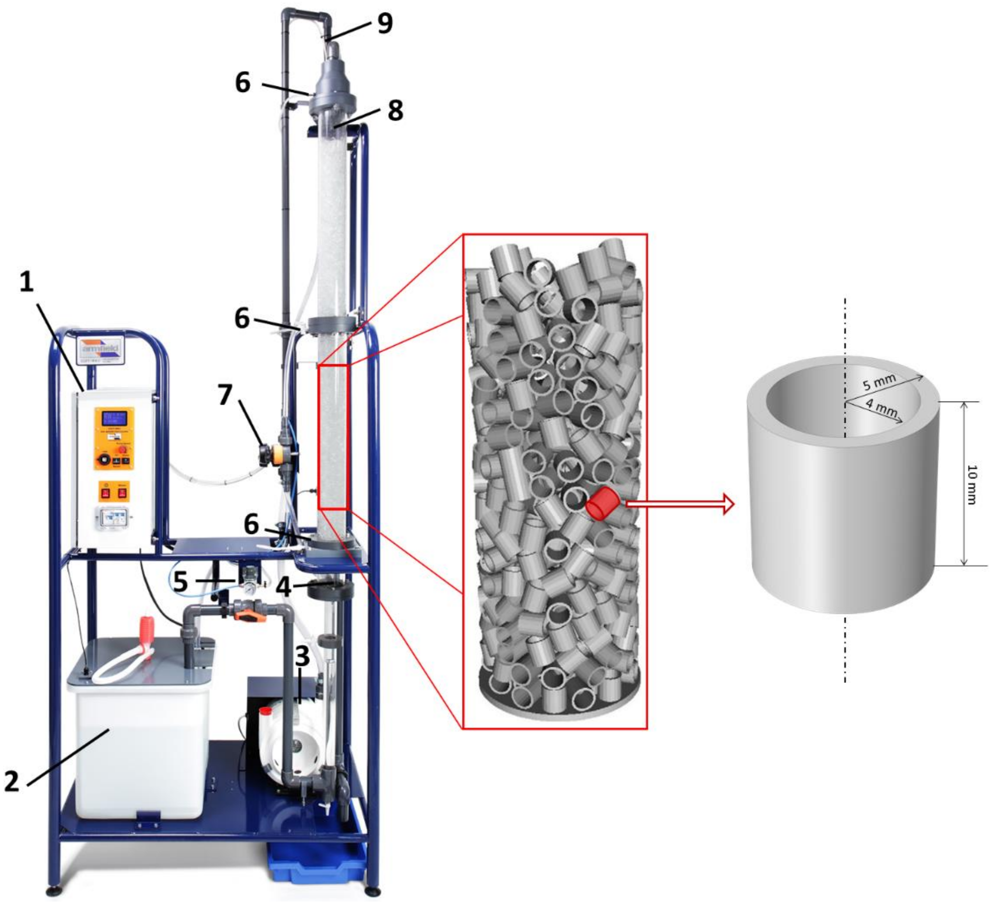

Figure 1. Armfield UOP7-MKII absorption unit system with packing; 1 –control console with a display, 2 – water tank with the pump, 3 – air compressor, 4 – gas mixture inlet, 5 – CO_2 flow control valve, 6 – pressure measurement points, 7 – water flow control valve, 8 – water inlet, 9 – gas mixture outlet [17]

This unit is designed for implementation of counter current CO_2/H_2O or CO_2/dilute NaOH absorption systems, and it features electronic instrumentation for measurement of fluid flow, temperature, CO_2 concentration and pressure drop through the column, as well as for control of liquid and gas flow rates and data logging. The column is made of clear acrylic and is packed in two stages with 10×10 mm glass Raschig rings (specific surface area of 440 m^2 m^{-3}). The height of each stage is approximately 0.58 m, with the column diameter of 0.08 m. Pressure measurement points are located at the base, center and top of the column, which enable calculation of pressure drops in the top and bottom stages. The concentration of CO_2 in the mixture with air at the top and at the bottom of the column is measured by electronic gas sensors, while electronic flow meters provide accurate measurements of liquid and gas flow rates. Liquid and gas temperature readings are obtained by thermistors in the liquid tank and at the inlet gas line. All data is sent to a connected PC, where real-time logging and subsequent data analyses can be performed. Tap water was used as the liquid phase, whereas ambient air and CO_2 from a pressure cylinder ("Messer", Bosnia and Herzegovina) represent the gas phase.

Experiments, as well as overall research, were divided in three stages: determination of dry pressure drop and column flooding (hydrodynamics) and absorption studies (mass transfer).

In dry pressure drop experiments, air flow rate was varied from 20 to 150 l min^{-1}, and pressure drop values for both stages of the column were measured. For modelling purposes, packed bed porosity was determined by the water displacement method, by measuring the total packed bed volume in one section and volume of water needed to completely fill the section.

In flooding experiments, water flow rate was varied from 2 to 8 l min^{-1}, and for each experiment air flow rate was increased until flooding occurred while collecting the data.

In absorption experiments, different combinations of flow rates were used, air flow rate was varied from 40 to 70 l min^{-1}, water flow rate from 1 to 5 l min^{-1}, and CO_2 flow rates used were 3 and 4 l min^{-1}. Air and CO_2 streams were mixed together before entering the bottom of the column. In order to obtain a complete mass balance, required for further calculations, CO_2 concentrations in liquid phase at the bottom and at the top of the column were determined by titration of the liquid samples with 0.0277 M NaOH ("Sineks Laboratory", Bosnia and Herzegovina), as recommended by the equipment supplier. Each analysis was performed three times. Based on the obtained results and known CO_2 concentration in the feed air-CO_2 mixture, the outlet CO_2 concentration is calculated according to the CO_2 mass balance for the entire column. Absorption experiments lasted until equilibrium was reached, verified by automatic plotting the outlet gas CO_2 concentration against time provided by the data logging software. When the outlet gas CO_2 concentration appeared to be constant in a 1 min interval, the experiment was completed.

2. 1. Mathematical model

Several equations and approaches were used to model the pressure drop in packed dry column: the Ergun equation, and the Billet, Mackowiak, Ozahi, Li and Stichlmair models. The equivalent diameter of the Raschig ring was calculated as a Sauter diameter (the diameter of a sphere with the same volume/surface area ratio as a particle of interest), according to the packing dimensions. The Ergun equation [18] was used for pressure drop calculations, Eq. (1), in the transition flow type through a porous medium:

$$\Delta P_{\mathrm{ergun}} = H_{\mathrm{c}} 150 \frac{\left(1-\varepsilon\right)^2}{\varepsilon^3} \frac{u_{\mathrm{v}} \mu_{\mathrm{v}}}{d_{\mathrm{p}}^{\ 2}} + H_{\mathrm{c}} 1.75 \frac{1-\varepsilon}{\varepsilon^3} \frac{\rho_{\mathrm{V}} \cdot u_{\mathrm{v}}^{\ 2}}{d_p} \tag{1}$$

The Billet model [19] takes into account free space available next to the wall of the column and uses a friction factor, which is a function of packing size and material, as shown in Eq. (2):

$$\Delta P_{\mathrm{Billet}} = H_{\mathrm{c}} \psi_0 \frac{a_t}{\varepsilon^3} \frac{F_{\mathrm{v}}}{2K} \tag{2}$$

The Mackowiak model [20] is similar to the Billet model, with the only difference in the friction factor which is here only a function of the modified Reynolds number, as shown in Eq. (3):

$$\Delta P_{\mathrm{Mackowiak}} = H_{\mathrm{c}} \psi_0 \frac{(1-\varepsilon)}{\varepsilon^3} \frac{F_{\mathrm{v}}^{\ 2}}{d_{\mathrm{p}} K} \tag{3}$$

Ozahi [21] has also developed a similar model, Eq. (4), with the friction factor being a function of the modified Reynolds number and packing sphericity:

$$\Delta P_{\text{Ozahi}} = H_c\left(\frac{276}{\text{Re}_o} + 1.76\psi^2\right)\frac{(1-\varepsilon)}{\varepsilon^3\psi^2}\frac{\rho_v u_v^2}{d_p} \tag{4}$$

The Li's model [22] represents a modified form of the Ergun equation, which takes into account the packing sphericity, as shown in Eq. (5):

$$\Delta P_{\text{Li}} = H_c 150\frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{u_v\mu_v}{\psi^2 d_p^2} + H_c 1.75\frac{1-\varepsilon}{\varepsilon^3}\frac{\rho_V u_v^2}{\psi d_p} \tag{5}$$

The Stichlmair model [23] is an empirical model, similar to the Mackowiak model, which takes into account the friction factor which is a function of the Reynolds number, as shown in Eq. (6):

$$\Delta P_{\text{Stichlmair}} = H_c 0.75 f_0 \frac{(1-\varepsilon)}{\varepsilon^{4.65}}\frac{\rho_v u_v^2}{d_p} \tag{6}$$

Many authors have developed mathematical models for prediction of gas flow rate at which flooding occurs in a packed column. Almost every available model is empirical, obtained from numerous experimental data. Hence, most of the models represent nonlinear correlations between nondimensional groups of parameters, for example, models of Sherwood [23], Lobo and Leva [2]. These models identify two key nondimensional groups of parameters, as shown in Eqs. (7) and (8):

$$X = \frac{u_L}{u_{\text{flood}}}\sqrt{\frac{\rho_L}{\rho_G}} \tag{7}$$

$$Y = \frac{u_{\text{flood}}^2}{g}\frac{\rho_v}{\rho_L}\frac{a_t}{\varepsilon^3}\mu_L^{0.2} \tag{8}$$

Also, all three models follow a similar form, Eq. (9):

$$\log(Y) = -a\log^2(X) - b\log(X) - c \tag{9}$$

Parameters a, b and c for these models are given in Table 1.

Table 1. Parameters in different flooding point correlations [2]

Model	*a*	*b*	*c*
Sherwood	0.2866	1.0997	1.6784
Lobo	0.252	1.041	1.732
Leva	0.27	1.076	1.705

Also, we have compared two additional models with the experimental data that is the Bertetti and Takahashi models [2], presented by Eqs. (10) and (11), respectively:

$$4.85\mu_L^{0.04}\left(\frac{\rho_V}{\rho_L}\right)^{0.33} u_{\text{flood}}^{0.67} + 4.1\mu_L^{0.1}u_L^{0.67} = \frac{6.4\varepsilon}{a_t^{0.33}} \tag{10}$$

$$\sqrt{u_{\text{flood}}}\left(\frac{\rho_v\mu_L^{0.2}a_t}{\rho_L\varepsilon^3 g}\right)^{0.25} + \sqrt{u_L}\left(\frac{\mu_L^{0.2}a_t}{\varepsilon^3 g}\right)^{0.25} = 0.552 \tag{11}$$

In mass transfer studies a series of absorption experiments was performed in which inlet and outlet CO_2 concentrations in both liquid in gas phases were determined. The obtained data can be used for comparisons with mathematical model predictions. Here, the Onda's model [24] was used, Eqs. (12) and (13), as its derivation was based on the data in line with the experimental absorption system and the packing type. The Onda's model allows for determination of partial mass transfer coefficients in gas and liquid phases *via* following relations, respectively:

$$\frac{k_{\mathrm{G}}}{a_{\mathrm{t}}}\frac{RT}{D_{\mathrm{V}}}=2\left(\frac{V}{a_{\mathrm{t}}\mu_{\mathrm{V}}}\right)^{0.7}\left(\frac{\mu_{\mathrm{V}}}{\rho_{\mathrm{V}}D_{\mathrm{V}}}\right)^{\frac{1}{3}}\left(a_{\mathrm{t}}d_{\mathrm{p}}\right)^{-2} \tag{12}$$

$$k_{\mathrm{L}}\left(\frac{\rho_{\mathrm{L}}}{\mu_{\mathrm{L}}g}\right)^{\frac{1}{3}}=0.0051\left(\frac{L}{a_{\mathrm{w}}\mu_{\mathrm{L}}}\right)^{\frac{2}{3}}\left(\frac{\mu_{\mathrm{L}}}{\rho_{\mathrm{L}}D_{\mathrm{L}}}\right)^{\frac{-1}{2}}\left(a_{\mathrm{t}}d_{\mathrm{p}}\right)^{0.4} \tag{13}$$

where a_{w} is the wetted specific surface area of the packing, which is calculated From Eq. (14):

$$\frac{a_{\mathrm{w}}}{a_{\mathrm{t}}}=1-\exp\left(-1.45\left(\frac{\sigma_{\mathrm{c}}}{\sigma_{\mathrm{L}}}\right)\left(\frac{L}{a_{\mathrm{t}}\mu_{\mathrm{L}}}\right)^{0.1}\left(\frac{L^2a_{\mathrm{t}}}{\rho_{\mathrm{L}}^2g}\right)^{-0.05}\left(\frac{L^2}{\rho_{\mathrm{L}}\sigma_{\mathrm{L}}a_{\mathrm{t}}}\right)^{0.2}\right) \tag{14}$$

Liquid and gas diffusivity values were adopted from the literature [24]. In order to model equilibrium phase compositions, the Henry's law was used, since only dilute solutions appeared through the column. The Henry's constant was calculated from the temperature dependence for the given system, as shown in Eq. (15):

$$\ln K_{\mathrm{H}}=a_1+\frac{b_1}{T_{\mathrm{abs}}}+c_1\ln(T_{\mathrm{abs}})+d_1T_{\mathrm{abs}} \tag{15}$$

with the constants a_1 = 159.865, b_1 = -8741.55, c_1 = -21.669 and d_1 = 0.00110259. The Henry's constant is then used to compute the equilibrium partial pressure and concentration of CO_2 in gas phase, Eq (16), which is necessary for determination of the equilibrium line slope, Eq (17).

$$Y_{\mathrm{CO_2}}^{*}=\frac{p_{\mathrm{CO_2}}^{*}}{p_{\mathrm{atm}}-p_{\mathrm{CO_2}}^{*}} \tag{16}$$

$$m=\frac{Y_{\mathrm{CO_2,in}}^{*}-Y_{\mathrm{CO_2,out}}^{*}}{X_{\mathrm{CO_2,out}}-X_{\mathrm{CO_2,in}}} \tag{17}$$

According to the *NTU* method, height of a packed column can be calculated by Eqs. (18) and (19):

$$Z = HTU \cdot NTU \tag{18}$$

$$Z = H_{\mathrm{OG}} \cdot N_{OG} \tag{19}$$

N_{OG} represents an overall number of gas phase transfer units and can be calculated numerically by the well-known Eq. (20):

$$N_{\mathrm{OG}}=\int_{Y_1}^{Y_2}\frac{dY}{Y_{\mathrm{CO_2}}-Y_{\mathrm{CO_2}}^{*}} \tag{20}$$

In this way, the experimental height of the overall gas phase transfer unit can be calculated (for a known height of the packed column), while heights of gas and liquid transfer units can be calculated from the obtained partial mass transfer coefficients, according to Eqs. (21) and (22):

$$H_{\mathrm{G}}=\frac{G_{\mathrm{m}}}{k_{\mathrm{G}}a_{\mathrm{w}}P} \tag{21}$$

$$H_{\mathrm{L}}=\frac{L_{\mathrm{m}}}{k_{\mathrm{L}}a_{\mathrm{w}}C_{\mathrm{T}}} \tag{22}$$

Finally, the value of the height of the overall gas transfer unit can be obtained from the slope of the equilibrium line, eq. (23):

$$H_{\mathrm{OG}}=H_{\mathrm{G}}+m\frac{G_{\mathrm{m}}}{L_{\mathrm{m}}}H_{\mathrm{L}} \tag{23}$$

This approach allows for indirect comparison of the used mathematical model and experimental results, through comparison of experimental and calculated heights of the overall gas transfer unit, eq. (23). For all experimental and calculated data, mean absolute percentage error (MAPE) was used as a measure of prediction accuracy.

3. RESULTS AND DISCUSSION

As stated in the experimental section, in pressure drop experiments the air flow rate was varied and pressure drops in the top and bottom parts of the packed column were logged. The obtained values were then summed, to provide the total pressure drop in the column, which was later compared to the values obtained by using different mathematical models. The experiments resulted in expected values, since the pressure drop through a porous media increased exponentially with the increase in gas flow rate. For a given range of air flow rates, the pressure drops were calculated by Eqs (1-6) and the obtained results are displayed in Figure 2.

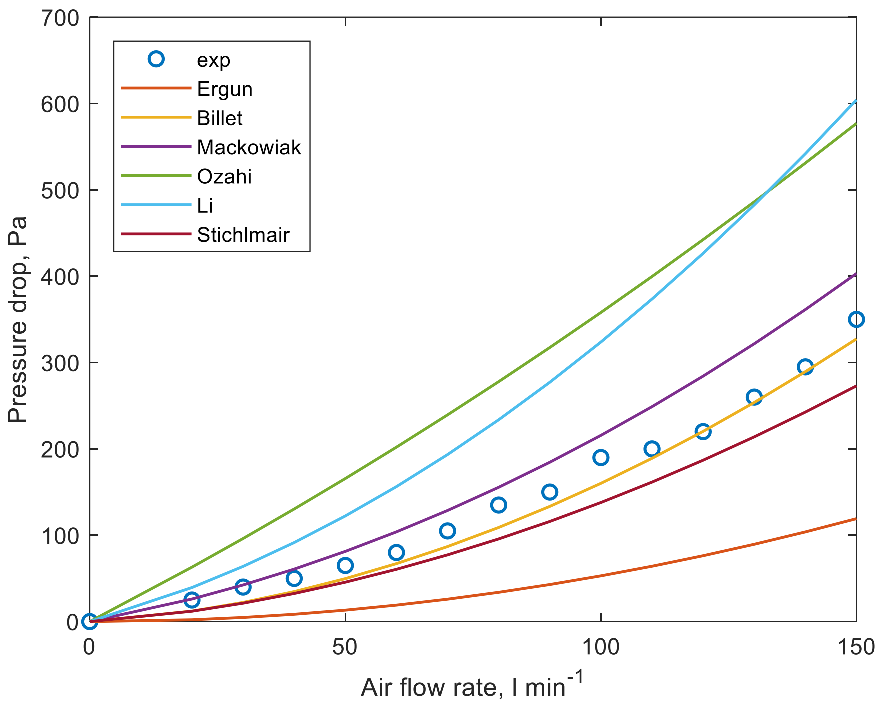

Figure 2. Pressure drop values for different air flow rates: experimental (symbols) and predicted values by different models (lines)

It can be concluded that the models that provided the best results are the models which were developed primarily for packed columns (*i.e*. the Billet, Mackowiak and Stichlmair models), with the MAPE values in the range of ±20 %. The Billet model gave the best approximation, since the obtained MAPE value was 6.5 %.

As stated in the experimental section, in flooding experiments, for a given water flow rate, the air flow rate varied until flooding in the column occurred (Table 2).

Table 2. Experimental air flow rate and superficial velocity at the flooding point for a given water flow rate

$\dot{V}_L$ / l min^{-1}	2	3	4	5	6	7	8
$\dot{V}_{flood}$ / l min^{-1}	190	140	106	75	57	45	35
$u_{flood,exp}$ / m s^{-1}	0.63	0.46	0.35	0.25	0.19	0.15	0.12

Different models were tested against the experimental data, mostly providing adequate results, since the mean percentage error did not differ much from values obtained in the original model development. MAPE values for all of the used models are shown in Table 3.

Table 3. MAPE values for different models in prediction of flooding points

Model	Bertetti	Lobo	Leva	Takahashi	Sherwood
MAPE, %	35.4	13.2	17.4	14.1	23.2

As stated before, models of Sherwood, Lobo and Leva were developed in a similar way, with the same nondimensional groups of parameters, only with different constants in the general equation (see Eq. 9). The obtained experimental values of *X* and *Y*, as well as model equations are displayed in Figure 3.

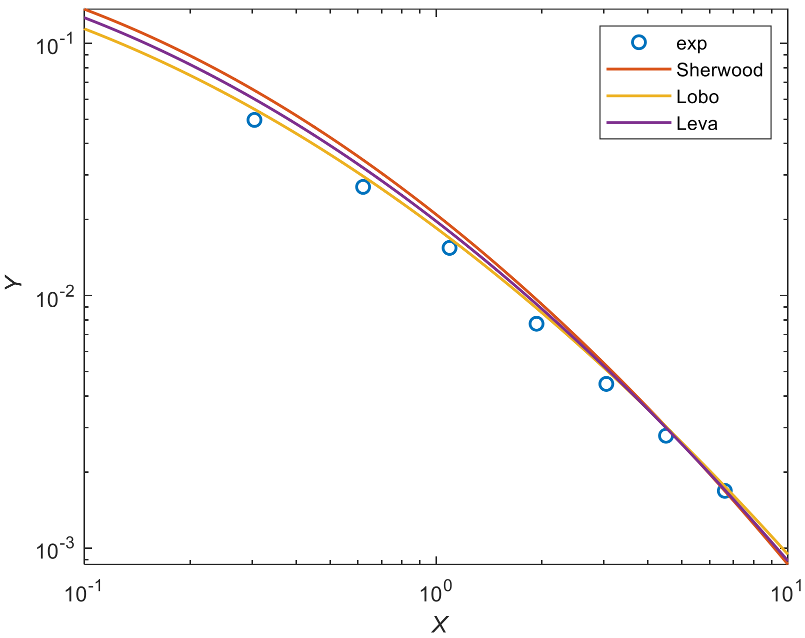

Figure 3. Experimental values (symbols) and predicted by mathematical models (lines, Eq. 9) of nondimensional groups of parameters (Eqs 7 and 8) for flooding points in the packed column

In mass transfer experiments, air, water and CO_2 flow rates were varied, while inlet and outlet CO_2 concentrations were measured and calculated, which allowed for determination of the absorption efficiency, *i.e*. percentage of absorbed CO_2 in each experiment. For constant air and CO_2 flow rates, the increase in water flow rate resulted in an increase in absorption efficiency, as the column system is approaching the flooding point. In every set of experiment, flooding data were used to determine the most preferable water flow rate for given conditions, since the highest absorption efficiency is usually at flow rates slightly below the flooding point. Results of individual experiments are shown in Figure 4.

The results follow linear trends with the highest efficiencies obtained at highest water flow rates. For constant water and CO_2 flow rates, the absorption efficiency decreases with the increase in air flow rate, which is in accordance with the column flooding approach theory.

Heights of the overall gas transfer unit were calculated according to Eqs. (19) and (20) for each experiment (labeled as $H_{OG,exp}$), while the calculated values by the Onda's method are labeled as $H_{OG,calc}$. For each experiment, those two values are compared in order to validate the model with the experimental data. The parity plot of calculated and experimental values of H_{OG} is shown in Figure 5.

It can be concluded that the used model overestimates values of partial mass transfer coefficients, since the calculated height of the overall gas transfer unit is lower than the experimental value. However, the calculation error is mostly in the range of 10-20 %, which is in accordance with model derivation in the original reference [24]. Also, it can be concluded that the error was lower for lower values of H_{OG}, *i.e*. for higher liquid/gas flow rate ratios. The average percentage error for all experiments is 15.5 %.

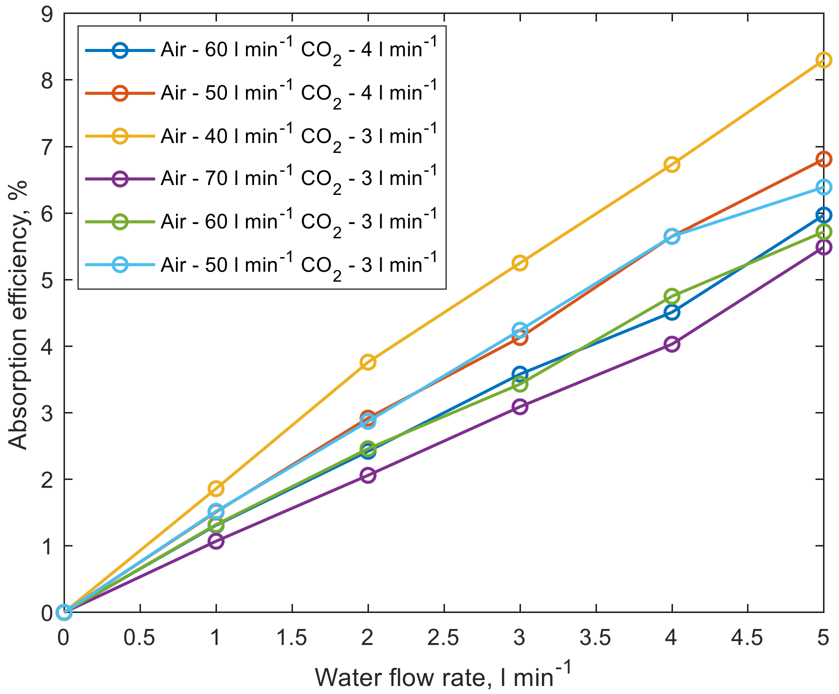

Figure 4. Absorption efficiency as a function of water flow rate for different gas phase compositions and flow rates

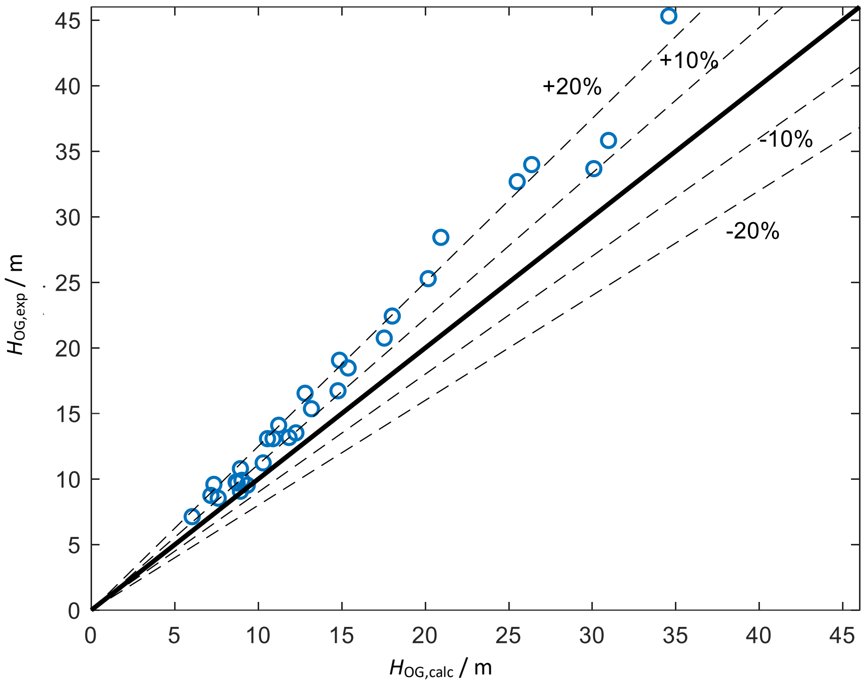

Figure 5. Parity plot for experimental and calculated heights of the overall gas transfer unit

4. CONCLUSION

Mathematical modelling of hydrodynamics and mass transfer in packed absorption columns is a complex procedure, since there are many parameters which can affect mass and momentum transfers in multiphase porous systems. Since absorption is one of the most important unit operations, many authors have developed models, both empirical and theoretical, that describe the mentioned phenomena. In order to provide more experimental data on absorption in packed columns and to model the obtained experimental results, a lab-scale absorption unit was used in the present work. This unit is particularly beneficial for demonstration of basic principles of absorption, flooding points, pressure drop, mass transfer and effectiveness of CO_2 absorption in water in packed columns. A series of experiments were conducted in order to obtain data for pressure drop across the column at various gas flow rates, flooding points at different flow rates and the absorption efficiency. For each set of experimental data, models found in literature were used in order to describe the obtained data. The Billet model proved to be the most suitable for prediction of dry column pressure drop with the MAPE value of ~6.5 %, which was slightly lower than those found for the models of Stichlmair and Mackowiak. Flooding points were evaluated by using several empirical models, and most of them (*i.e*. Lobo, Leva, Takahashi and Sherwood) gave adequate results, with the MAPE values in the range of 13-23 %, which is acceptable taking into account the complex phenomenon of column flooding. In mass transfer calculations, the Onda's model was used, describing well the obtained experimental results. The obtained results can be used for further investigation of CO_2 – water based packed bed absorption systems, as well as packed bed columns in general, since unconventional Raschig ring size was used as a packing.

5. NOMENCLATURE

a	Parameter in flooding correlation
a_1	Parameter in Henry's equation
a_t / m^2 m^{-3}	Specific surface area of a packing
a_w / m^2 m^{-3}	Wetted specific surface area of a packing
b	Parameter in flooding correlation
b_1	Parameter in Henry's equation
c	Parameter in flooding correlation
c_1	Parameter in Henry's equation
C_T / kmol m^{-3}	Total molar concentration
d_1	Parameter in Henry's equation
D_L / m^2 s^{-1}	Liquid diffusivity
d_p / m	Equivalent diameter of a packing
D_V / m^2 s^{-1}	Diffusivity in vapor
f_0	Friction factor
F_v / m s^{-1} (kg m^{-3})$^{0.5}$	Gas capacity factor
g / m s^{-2}	Gravitational constant
G_m / kmol m^{-2} s^{-1}	Molar flow rate of gas per unit area
H_c / m	Column height
H_G / m	Height of the gas phase transfer unit
H_L / m	Height of the liquid phase transfer unit
H_{OG} / m	Height of the overall gas phase transfer unit
H_{OL} / m	Height of the overall liquid phase transfer unit
HTU / m	Height of transfer unit
K	Wall factor
k_G / kmol m^{-2} s^{-1} Pa^{-1}	Gas film mass transfer coefficient
k_L / m s^{-1}	Liquid film mass transfer coefficient
L / kg m^{-2} s^{-1}	Mass flow rate of liquid per unit area
L_m / kmol m^{-2} s^{-1}	Molar flow rate of liquid per unit area
m	Slope of equilibrium line
N_{OG}	Number of overall gas phase transfer units
NTU	Number of transfer units
P / Pa	Total system pressure
p^* / Pa	Equilibrium partial pressure
R / J kmol^{-1} K^{-1}	Universal gas constant
Re_0	Modified Reynolds number
T / K	Temperature

T_{abs} / K	Absorption temperature
u_{flood} / m s^{-1}	Flooding velocity
u_L / m s^{-1}	Superficial liquid velocity
u_V / m s^{-1}	Superficial gas velocity
V / kg m^{-2} s^{-1}	Mass flow rate of gas per unit area
X	Nondimensional flooding number
X^* / kmol $kmol^{-1}$	Equilibrium liquid phase content (ratio)
X_{CO_2} / kmol $kmol^{-1}$	Liquid phase CO_2 content (ratio)
Y	Nondimensional flooding number
$Y^*_{CO_2}$ / kmol $kmol^{-1}$	Equilibrium gas phase CO_2 content (ratio)
Y_{CO_2} / kmol $kmol^{-1}$	Gas phase CO_2 content (ratio)
Z / m	Height of packed column

Greek letters

ε	Packed bed porosity
μ / Pa s	Dynamic viscosity
σ_L / N m^{-1}	Liquid surface tension
σ_c / N m-1	Critical surface tension
ρ / kg m^{-3}	Density
ψ	Particle sphericity
ψ_0	Drag coefficient

Acknowledgements: *The authors would like to acknowledge to the Ministry of Science, Technological Development and Innovation of the Republic of Serbia for the financial support, Project No. 451-03-47/2023-01/200134.*

REFERENCES

[1] Flagiello D, Parisi A, Lancia A, Di Natale F. A review on gas-liquid mass transfer coefficients in packed-bed columns. *ChemEngineering*. 2021; 5(3): 43. https://doi.org/10.3390/chemengineering5030043

[2] Piché S, Larachi F, Grandjean BPA. Flooding capacity in packed towers: Database, correlations, and analysis. *Ind Eng Chem Res.* 2001; 40(1): 47-487. https://doi.org/10.1021/ie000486s

[3] Shahsavand A, Derakhshan Fard F, Sotoudeh F. Application of artificial neural networks for simulation of experimental CO2 absorption data in a packed column. *J Nat Gas Sci Eng*. 2011; 3(3): 518-529. https://doi.org/10.1016/j.jngse.2011.05.001

[4] Marek M. CFD modelling of gas flow through a fixed bed of Raschig rings. *J Phys Conf Ser*. 2014; 530(1): 012016. https://doi.org/10.1088/1742-6596/530/1/012016

[5] Haroun Y, Raynal L. Use of Computational Fluid Dynamics for Absorption Packed Column Design. *Oil Gas Sci Technol.* 2016; 71(3): 43. https://doi.org/10.2516/ogst/2015027

[6] Basha OM, Wang R, Gamwo IK, Siefert NS, Morsi BI. Full-Scale CFD Modeling of Multiphase Flow Distribution in a Packed-bed Absorber with Structured Packing Mellapak 250Y. *Int J Chem React Eng.* 2020; 18(3): 1–17. https://doi.org/10.1515/ijcre-2019-0207

[7] Lu X, Xie P, Ingham DB, Ma L, Pourkashanian M. Modelling of CO_2 absorption in a rotating packed bed using an Eulerian porous media approach. *Chem Eng Sci.* 2019; 199: 302–318. https://doi.org/10.1016/j.ces.2019.01.029

[8] Dixon AG. COMSOL Multiphysics Simulation of 3D Single-phase Transport in a Random Packed Bed of Spheres. *Proc COMSOL Conf Bost.* 2014; 15261(2013): 15261.

[9] Marek M. Gas flow maldistribution in random packed beds of non-spherical particles – A CFD study. *Chem Eng Sci.* 2019; 197: 296–305. https://doi.org/10.1016/j.ces.2018.12.032

[10] Pan W, Galvin J, Huang WL, Xu Z, Sun X, Fan Z, Liu K. Device-scale CFD modeling of gas-liquid multiphase flow and amine absorption for CO_2 capture. *Greenh Gases Sci Technol.* 2018; 8(3): 603–620. https://doi.org/10.1002/ghg.1770

[11] Krauß M, Rzehak R. Reactive absorption of CO_2 in NaOH: An Euler-Euler simulation study. *Chem Eng Sci*. 2018; 181: 199-214. https://doi.org/10.1016/j.ces.2018.01.009

[12] Mores P, Scenna N, Mussati S. A rate based model of a packed column for CO_2 absorption using aqueous monoethanolamine solution. *Int J Greenh Gas Control.* 2012; 6: 21–36. https://doi.org/10.1016/j.ijggc.2011.10.012

[13] Tontiwachwuthikul P, Meisen A, Lim CJ. CO_2 absorption by NaOH, monoethanolamine and 2-amino-2-methyl-1-propanol solutions in a packed column. *Chem Eng Sci.* 1992; 47(2): 381–390. https://doi.org/10.1016/0009-2509(92)80028-B

[14] Lin SH, Shyu CT. Performance characteristics and modeling of carbon dioxide absorption by amines in a packed column. *Waste Manag.* 1999; 19(4): 255–262. https://doi.org/10.1016/S0956-053X(99)00135-X

[15] Ali S, Akhtar J. Hydrodynamics of Packed Bed Column: Study of the Column for the Absorption of CO_2 in Water and its Efficiency. *Mass Spectrom Purif Tech.* 2018; 04(01): 2–6. https://doi.org/10.4172/2469-9861.1000122

[16] Niegodajew P, Marek M. Analysis of orientation distribution in numerically generated random packings of Raschig rings in a cylindrical container. *Powder Technol.* 2016; 297: 193–201. https://doi.org/10.1016/j.powtec.2016.04.024

[17] Armfield. UOP7 MKII – Gas Absorption Column n.d. https://armfield.co.uk/product/uop7-mkii-gas-absorption-column/

[18] Reddy RK, Joshi JB. CFD modeling of pressure drop and drag coefficient in fixed and expanded beds. *Chem Eng Res Des.* 2008; 86(5): 444–453. https://doi.org/10.1016/j.cherd.2007.12.007

[19] Billet R, Schultes M. Modelling of Pressure Drop in Packed Columns. *Trans Znsr Chem Eng.* 1991; 14(6): 167–174. https://doi.org/10.1002/ceat.270140203

[20] Çarpinlioğlu MÖ, Özahi E. A simplified correlation for fixed bed pressure drop. *Powder Technol.* 2008; 187(1): 94–101. https://doi.org/10.1016/j.powtec.2008.01.027

[21] Ozahi E, Gundogdu MY, Carpinlioglu MÖ. A modification on Ergun's correlation for use in cylindrical packed beds with non-spherical particles. *Adv Powder Technol.* 2008; 19(4): 369–381. https://doi.org/10.1163/156855208X314985

[22] Li L, Ma W. Experimental Study on the Effective Particle Diameter of a Packed Bed with Non-Spherical Particles. *Transp Porous Media.* 2011; 89(1): 35–48. https://doi.org/10.1007/s11242-011-9757-2

[23] Stichlmair J, Bravo JL, Fair JR. General model for prediction of pressure drop and capacity of countercurrent gas/liquid packed columns. *Gas Sep Purif.* 1989; 3(1): 19–28. https://doi.org/10.1016/0950-4214(89)80016-7

[24] Onda K, Sada E, Murase Y. Liquid-side mass transfer coefficients in packed towers. *AIChE J.* 1959; 5(2): 235–9. https://doi.org/10.1002/aic.690050220

Eksperimentalna istraživanja i modelovanje prenosa mase i hidrodinamike u apsorpcionoj koloni sa punjenjem za sistem CO_2 – voda

Dario D. Balaban[1,2], Branislava G. Nikolovski[1], Mitar D. Perušić[2] i Goran S. Tadić[2]

[1]Univerzitet u Novom Sadu, Tehnološki fakultet Novi Sad, Bulevar cara Lazara 1, 21000 Novi Sad, Srbija

[2]Univerzitet u Istočnom Sarajevu, Tehnološki fakultetZvornik, Katedra za procesno inženjerstvo, Karakaj 1, 75400 Zvornik, Republika Srpska, Bosna i Hercegovina

(Stručni rad)

Izvod

U ovom radu predstavljeni su rezultati istraživanja o prenosu mase i hidrodinamici u apsorpcionoj koloni sa punjenjem. Eksperimentalno je ispitivana laboratorijska apsorpciona kolona sa Rašiigovim prstenovima i dobijeni su rezultati za pad pritiska, tačke plavljenja i efikasnost apsorpcije CO_2 u vodi. Prateća oprema uređaja i hemijske analize omogućile su jednostavno dobijanje i praćenje podataka. Svi dobijeni rezultati su korišteni za testiranje različitih matematičkih modela za dati problem, *tj.* za pad pritiska u suvoj koloni, za određivanje tačke plavljenja i visine prenosne jedinice u gasnoj fazi. Za pad pritiska u suvoj koloni, modeli primarno razvijeni za kolone sa punjenjem najbolje su opisali eksperimentalne podatke, gde je model Bileta (Billet) dao srednju grešku od ~6.5 %, a prate ga modeli Makovjaka (Mackowiak) i Štihlmera (Stichlmair). U proračunu tačke plavljenja testirani su empirijski modeli, od kojih su najbolje rezultate dali modeli Loboa (Lobo), Leva (Leva) i Takahašija (Takahashi). Eksperimenti prenosa mase (apsorpcije) su dali očekivane rezultate, s obzirom da se efikasnost apsorpcije povećavala sa porastom odnosa protoka tečnost/gas, tj. približavanjem tački plavljenja. Model Onde (Onda) je korišten za određivanje parcijalnih koeficijenata prenosa mase u tečnoj i gasnojfazi, na osnovu kojih je određena visina prenosne jedinice u gasnoj fazi i poređena sa eksperimentalnim podacima. Odstupanje izračunatih i eksperimentalnih rezultata za visinu prenosne jedinice je bilo u očekivanom rasponu od 0-20%, sa srednjom greškom od 15.5 %. Može se zaključiti da dostupni modeli za određivanje datih parametara hidrodinamike i prenosa mase u apsorpcionim kolonama sa punjenjem daju prihvatljive rezultate u poređenju sa eksperimentalno određenim vrednostima.

Ključne reči: pad pritiska; plavljenje; visina prenosne jedinice