Journal of Petroleum Research and Studies

Open Access
Vol. 14, No. 4, December 2024, pp. 75-93

P- ISSN: 2220-5381
E- ISSN: 2710-1096

DOI: http://doi.org/10.52716/jprs.v14i4.783

Effective Enhancement of CO_2 Mass Transfer in an Oscillatory Baffled Column: A Comparative Study

Omer I. Farhan[1], Harith N. Mohammed[2], Safaa M.R. Ahmed[2*]

[1]Petroleum and Gas Refining Engineering Department, College of Petroleum Processes Engineering, Tikrit University, Tikrit, Iraq.
[2]Chemical Engineering Department, College of Engineering, Tikrit University, Tikrit, Iraq.
[*]Corresponding Author E-mail: Safaamohamed@tu.edu.iq

Received 02/08/2023, Revised 02/10/2023, Accepted 05/10/2023, Published 22/12/2024

Abstract

CO_2-water mass transfer was studied in a multi-orifice oscillatory baffled column (OBC) operated in a semi-batch system (batch liquid phase and continuous gas phase). The effect of column configurations, oscillation conditions and gas flow rates, on CO_2 concentration ratio (C/C_o) in the gas phase, CO_2 concentration in water (g/l) and mass flux (g/m^2.min) were examined. The experiments were conducted over a wide range of oscillation condition expressed by modified oscillatory Reynolds number (Re'_o= 0-1450) and aeration rate, volume of gas per volume of liquid per minute, (*vvm* = 0-1). The inlet gas stream consists of 15% v/v CO_2 (the rest is N_2) used to simulate the emission of flue gas streams in industries. The results showed that the mass transfer enhancement increased with oscillation (frequency and amplitude) due to the improved mixing in the OBC. The OBC showed a higher enhancement in CO_2-water mass transfer than that obtained with a bubble column (BC) (smooth column without baffles and oscillation), and baffled column (without oscillation). The maximum enhancement of CO_2 mass flux achieved in the OBC was 10-fold over the BC at Re'_o = 1449 and *vvm*=0.8.

Keywords: GHGs, Gas-liquid system, mass transfer, oscillatory baffled column.

التعزيز الفعال لنقل كتلة ثاني أكسيد الكربون في عمود متذبذب محير: دراسة مقارنة

الخلاصة:

تمت دراسة نقل كتلة ثاني أكسيد الكربون إلى الماء في عمود مذبذب متعدد الفتحات (OBC) يعمل في نظام شبه الدفعة (طور سائل دفعي وطور غاز مستمر). تم اختبار تأثير نوع العمود ومعدلات تدفق الغاز الداخلي وظروف التذبذب على نسبة تركيز ثاني أكسيد الكربون في الطور الغازي وتركيز ثاني أكسيد الكربون في الماء وتدفق الكتلة. أجريت التجارب على مدى واسع من ظروف التذبذب المعبرعنها بعدد رينولدز المتذبذب المعدل (0-1450) ومعدل التهوية، حجم الغاز لكل حجم سائل في الدقيقة (0-1). يتكون تيار الغاز الداخل من 15٪ CO_2 v / v والباقي هو نيتروجين المستخدم لمحاكاة انبعاث تيارات غاز المداخن في الصناعات. أظهرت النتائج أن تعزيز نقل الكتلة يزداد مع التذبذب (التردد والسعة) بسبب تحسن الخلط في ال

Open Access
Vol. 14, No. 4, December 2024, pp. 75-93

P- ISSN: 2220-5381
E- ISSN: 2710-1096

OBC. أظهر OBC تحسينًا أعلى في نقل كتلة CO_2 في الماء أكثر من ذلك الذي تم الحصول عليه باستخدام عمود فقاعي (BC) (عمود أملس بدون حواجز وتذبذب)، وعمود بحواجز (بدون تذبذب). كان الحد الأقصى لتعزيز تدفق كتلة ثاني أكسيد الكربون الذي تم تحقيقه فيOBC هو 10 أضعاف اكثر من BC عند عدد رينولدز المتذبذب المعدل 1449 ومعدل حجم الغاز = 0.8.

1. Introduction:

Emission of greenhouse gases (GHGs) is one of the major challenges for all societies in the world [1]. Among all these greenhouse gases, carbon dioxide has the largest negative impact on the binary atmosphere for its massive emissions that result from burning fuels producing flue gases and causing global climate change [2]. In different industries that generate CO_2, the concentration of CO_2 in the flue gas stream will vary depending on the emission source, and generally it is diluted with nitrogen and water vapor. The concentration of carbon dioxide in the flue gas stream may be about 12-15 vol. % for coal fuel, 3-8 vols. % for natural gas fuel and about 20 vol. % for the cement production industry and 3-8 vols. % in refineries [3] [4].

Intensification of gas dissolution in liquid requires the production of microbubbles and reduced mass transfer resistance around the surface of the gas bubbles [5]. Conventional gas-liquid columns (for example, packed column, bubble column, and spray column) face several operating problems such as immersion, loading, foaming, and orientation with difficulty in scaling-up these columns [6]. In a particular case, bubble columns (BCs) present a poor mass transfer performance at large gas aeration rate (Q_{gas}) so the contact time is very short [5]. In addition, the complex flow structures, back mixing, and unexpected spike are the major drawbacks of BC [7].

Oscillatory baffled column (OBC) is a multi-stage mixing method that can efficiently intensify various multi-stage chemical and biological processes [8]. It is a regular column containing periodically spaced baffles with oscillatory flow generated by diaphragms, pistons, or bellows [9]. The interaction of the oscillatory flow with periodic contractions creates complex hydrodynamics with recirculating vortices, resulting in efficient mixing, improved mass and heat transfer, and compact geometry (i.e., low column length-to-diameter ratio) [10]. In addition, the mixing intensity can be changed by adjusting the oscillatory conditions (amplitude and frequency of oscillations [11].

Oscillating flow allows sensitive control of mixing and residence times and offers a solution to many problems of conventional flow columns. Importantly, the oscillation-enhanced mixing is independent of the net flow rate, and thus it is possible to achieve a high level of mixing at lower flow rates (longer residence times) and Reynolds numbers. In addition, the mixing quality can be guaranteed during scaling-up [12] [13]. An important advantage of OBC is increased gas

Open Access
Vol. 14, No. 4, December 2024, pp. 75-93

P- ISSN: 2220-5381
E- ISSN: 2710-1096

retention, and a more uniform distribution of shear rates in OBC resulting in a thinner liquid film. In addition, the oscillation causes the formation of smaller bubbles [14].

Various baffle geometries have been used in literature (for example, integral, central axial baffles, helical baffles wire wool baffles, single-orifice baffles, multi-orifice baffles and disc and doughnut baffles) which present different degrees of mixing [12]. However, in the special case of gas-liquid system, multi-orifice design is recommended due to the wider operating range under the bubbling flow regime, higher mass transfer rates and allowing for good control of bubble size [7][9].

Although several studies investigated the dissolution of gases such as O_2, O_3 and air in water using (OBC) [7] [8] [15]. The CO_2 dissolution in water using (OBC) has been poorly studied to date. Taslim et al. [16] used a pure stream of CO_2 with single orifice design. The results showed that a significant enhancement in mass transfer was achieved by OBC compared to that obtained by BC. Pereira et al.[5] had a concern about the bubble size distributions and scaling-down to very low superficial gas velocity (*vvm* = 0.01-0.1) when they studied dissolution of 5% v/v CO_2 in water using a multi-orifice baffled column. However, they did not focus strongly on the effect of the baffle geometry and oscillation conditions on the CO_2 dissolution.

The main aim of this study was to investigate the performance of OBC provided with multi orifices baffles design in enhancing the CO_2 mass transfer from the flue gas stream by increasing the dissolution of CO_2 in the liquid phase (water). This can be achieved through the objectives listed below:

- Study the solubility of carbon dioxide in water and compare the results with those obtained by bubble column.
- Study the ability of OBC to overcome the limitations of CO_2 mass transport over a wide range of fluctuation conditions.

1.1 Theory

The flow structure in OBCs is characterized by three dimensionless groups, the net flow Reynolds number (Re_n), oscillatory flow Reynolds number (Re_o) and Strouhal number (St) (Equations (1-3)) [10].

Open Access
Vol. 14, No. 4, December 2024, pp. 75-93

P- ISSN: 2220-5381
E- ISSN: 2710-1096

$$Re_n = \frac{\rho u_{net} D}{\mu} \quad (1)$$

$$Re_o = \frac{2\pi f x_o \rho D}{\mu} \quad (2)$$

$$St = \frac{D}{4\pi x_o} \quad (3)$$

Where: ρ is the fluid density (Kg/m^3), u_{net} is the net velocity (m/s), D is the column diameter (m), μ is the dynamic viscosity (pa.s), f is the frequency of oscillation (Hz), and x_o is the amplitude of oscillation (center-to-peak), m.

The net flow Reynolds number controls the flow pattern of the fluids and when the liquid phase is batch (no liquid enters or leaves the column) Re_n equal to zero [17]. Re_o describes the mixing intensity where the equation of Re_o is analog to that of Re_n, except u replaced by $2\pi f x_o$ (the maximum oscillation velocity (ms^{-1})) [18]. Strouhal number (St) describes the effective propagation of vortices in the baffle cavity [19]. Both equations of Re_o and St mentioned above do not include any parameter that influence the flow behavior such as the orifice diameter (d_o) and number of orifice (n) [20]. In addition, the flow pattern in the multi-orifice design differs from the single-orifice design in that the influence of the number of orifice (n), the orifice diameter (d_o), and the orifice free open area (α) on the OBC performance should be considered [9]. Therefore, Pereira et al. [5] proposed "dimensionally modified oscillatory numbers" (Equations (4-6)) to describe the effect of the above parameters.

$$Re'_o = \frac{2\pi f x_o \rho}{\mu} \frac{D}{\sqrt{n}} \sqrt{\frac{1-\alpha}{\alpha^2}} = Re_o \frac{1}{\sqrt{n}} \sqrt{\frac{1-\alpha}{\alpha^2}} \quad (4)$$

$$St' = \frac{D}{4\pi x_o} \frac{1}{\sqrt{n}} = St \frac{1}{\sqrt{n}} \quad (5)$$

$$\alpha = \frac{n d_o^2}{D^2} \quad (6)$$

Where, Re'_o is the modified Oscillatory Reynolds number, St' is the modified Strouhal number, α is free baffle open area, n is orifice number per baffle.

2. Experimental setup and procedure:

2.1 Experimental set up

Figures (1) and (2) illustrate a schematic diagram and a graphical image of the experimental setup respectively. The setup consists of a 41mm inner diameter (ID) and an acrylic column with a height of 980 mm. The column was placed vertically on an oscillator fixed at the bottom of the

Open Access
Vol. 14, No. 4, December 2024, pp. 75-93

P- ISSN: 2220-5381
E- ISSN: 2710-1096

column. The piston (oscillator) movement was controlled by a variable speed motor. The oscillation frequency was controlled by changing the motor speed while the oscillation amplitude (center-to-peak amplitude) was controlled by adjusting the off-center position of a rod connected with in a rotating wheel. The oscillator is able to provide fluid oscillation frequency (f) and center-to-peak amplitude (x_o) in the ranges 0 - 10 Hz and 0−10 mm respectively. The MOBC was equipped with multi-orifice baffles spaced equally (l_b) by 1.5 D. The baffles were printed using a 3D- printer. These baffles were designed to fit closely to the internal wall of the column. In order to support the set of the baffles, they were fixed periodically with two stainless steel rods (3 mm in diameter). The specifications of the columns and the baffles are listed in Table (1). The entire volume of the column was 1.3 L while the working volume (V_L) was fixed at 1 L. Distilled water was used as liquid phase media. The experiments were conducted in a semi-batch mode (batch liquid phase and continuous gas phase). The gas stream consists of 15% v/v CO_2 and 85% N_2 which was chosen to simulate the composition of the flue gas streams from industrial emission sources. The percentages of CO2 and gas flow rate (Qgas) were controlled by two calibrated gas rotameters (LZB-3WB, Darhor Co.). The gases were mixed using a three-way valve. The mixed gases flowed from the bottom to the column upward. All experiments were carried out at atmospheric pressure (the top end of column is open) and room temperature (~25 °C). Table (2) shows the experimental operating conditions.

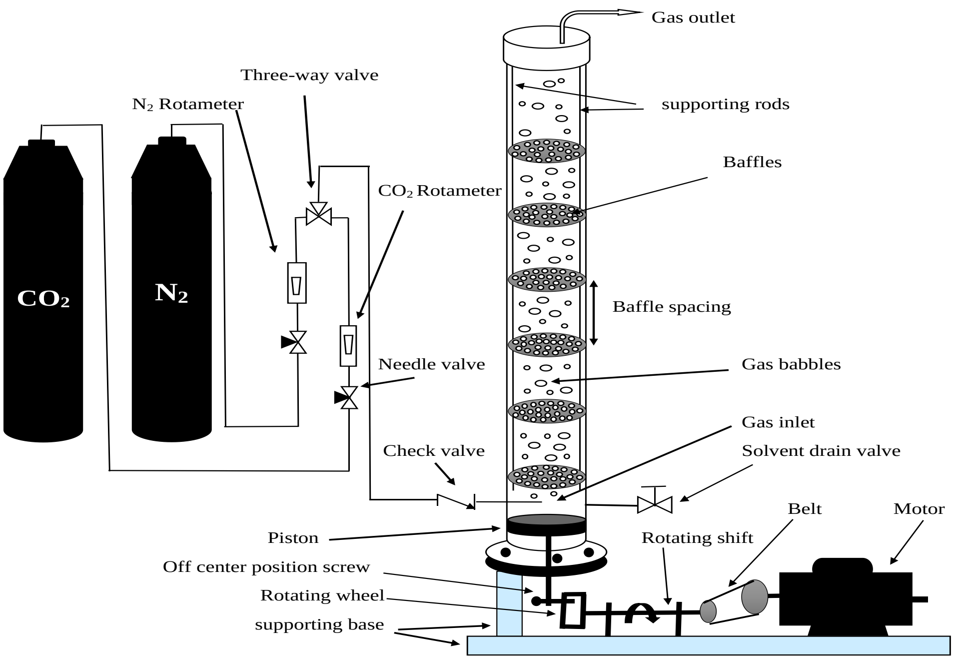

Fig. (1): A schematic diagram of the experimental setup

Open Access
Vol. 14, No. 4, December 2024, pp. 75-93
P- ISSN: 2220-5381
E- ISSN: 2710-1096

Table (1): Baffles specification

Baffles Design		
Number of orifices per baffle(n)	64	
Orifice diameter, mm	3	
Baffle thickness, mm	2	
Baffle open area, %	33	
Baffle spacing, mm	60	
Total no. of baffles inserted	12	
Construction material	ABS like Resin	

Fig. (2): Photo of the experimental setup

Table (2): Operating condition

Condition	Range
Oscillation frequency, f (Hz)	0 - 3
Time, t (min)	0-30
Oscillation amplitude, x_o (mm)	0-6
Aeration rate, vvm	0-1
Oscillatory Reynolds number, Re_o	0- 5000
Modified oscillatory Reynolds number, Re_o'	0-1450

Open Access
Vol. 14, No. 4, December 2024, pp. 75-93

P- ISSN: 2220-5381
E- ISSN: 2710-1096

The CO_2 mass transfer experiments were carried out in three column configurations: bubble column (BC) (unbaffled column and no oscillation), baffled column (without oscillation) and a multi-orifice oscillatory baffled column (MOBC) at different oscillation condition. A sparger was not used because of its negligible effect on MOBC efficiency as the flow and bubble size are dominated by oscillation [21][22]. Prior each run, the column was filled with distilled water and the gas volumetric flow rate was adjusted to the required value to achieve the required total flow rate of 15% v/v CO_2 / 85% N_2 mixture. Samples were taken within a specific interval (1-30 minutes).

2.2 CO_2 concentration analysis

The CO_2 concentrations in the output gas stream were measured using a calibrated gas chromatography (GC) instrument (GC-2030 Nexis, Shimadzu, Japan). A gas sampler was used to collect the samples for analysis. The GC was equipped with a TCD detector and Rt-q-BOND column (RESTEK, USA) with dimensions of 30 m length, 0.53 mm ID, and 20 µm thickness. 0.5 ml of the sample was injected into the GC by a specific gas syringe (A-2, Luer Lock, RESTEK, USA) with a split ratio of 10.0 where the carrier gas is Helium (He). The detector and injector temperatures were 250 ºC and 200 ºC respectively. The data were acquired and analyzed using a software (lab solution) provided by Shimadzu.

The concentration ratio of CO_2 (C/C_o) in the gas phase was calculated using eq. (7)

$$\frac{C}{C_o} = \frac{y_{CO2}^{out}}{y_{CO2}^{in}} \qquad (7)$$

Where:

(C/C_o) is the CO_2 concentration ratio in the gas phase, y_{CO2}^{in} is the volume fraction of CO_2 in the input gas stream, and y_{CO2}^{out} is the volume fraction of CO_2 in the output gas stream.

The the volumetric gas flow rates converted into mass rate and the difference between input and output CO_2 amounts which is the CO_2 dissolution in water (mass balance principles) and the CO_2 accumulate in water. The CO_2 concentration in water was plotted against running time producing a straight line where the slope of this line represents the absorption rate (g/l.min) then the mass flux calculated by eq. (8).

CO_2 mass flux= absorption rate * height of water in the column (8)

Open Access
Vol. 14, No. 4, December 2024, pp. 75-93

P- ISSN: 2220-5381
E- ISSN: 2710-1096

3. Results and Discussions:

The concentration ratio of CO_2 (C/C_o) in the gas phase, CO_2 concentration in water (g/l), and CO_2 mass flux (g/m^2.min) were calculated in three column designs: a bubble column (smooth column, no baffles and no oscillation), BC, a baffled column (without oscillation), and an oscillatory multi-orifice baffled column (MOBC) (with baffles and oscillation), to evaluate the performance of MOBC comparing its results with that obtained by the baffled and bubble columns.

3.1 Effect of column configuration on CO_2 mass transfer.

Figures (3 and 4) show the results of the CO_2 concentration ratio (C/C_o) in the three column designs BC, baffled column and OBC at the maximum oscillation condition (f =3 Hz, x_o=6 mm, Re'_o=1449), and vvm=0.6 (Q_{gas} =600 ml/min). In addition, Figure 4 shows the results of CO_2 concentration profiles in the three column designs at same condition.

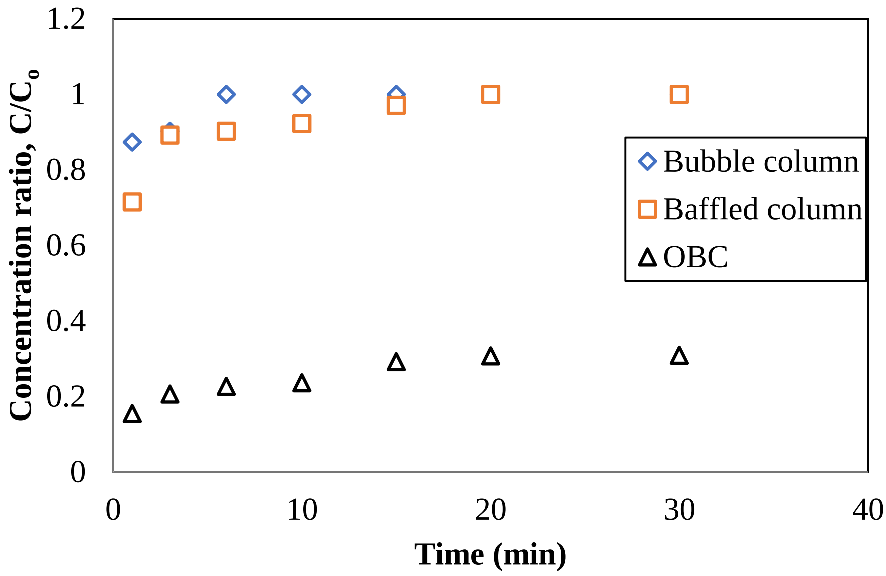

Fig. (3): The concentration ratio of CO_2 in gas phase (C/C_o) *vs* time at *vvm* =0.6 (Q_{gas} = 600 ml/min) and (for OBC, f = 3 Hz, x_o= 6 mm, Re'_o= 1449).

Open Access
Vol. 14, No. 4, December 2024, pp. 75-93

P- ISSN: 2220-5381
E- ISSN: 2710-1096

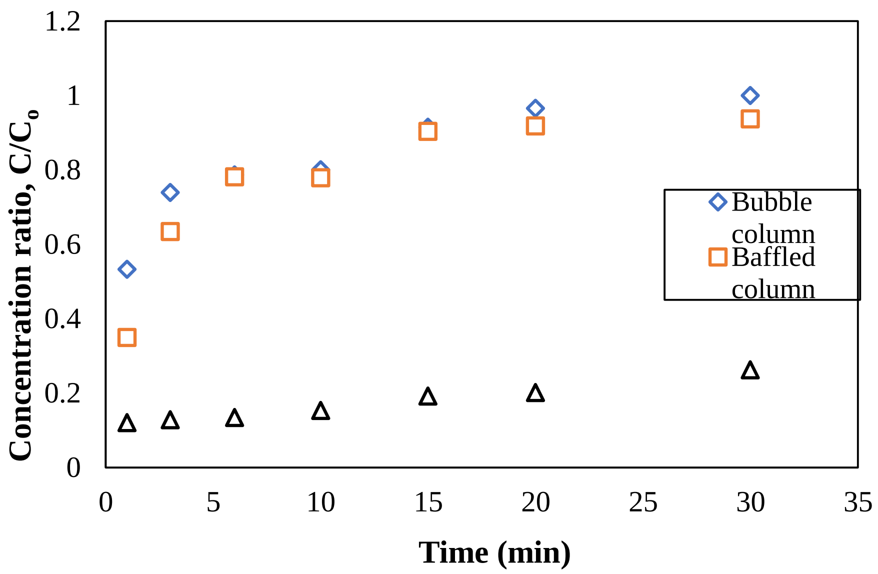

Fig. (4): The concentration ratio of CO_2 in gas phase (C/C_o) *vs* time at *f* = 3 Hz, x_o= 6 mm, Re'_o= 1449), and *vvm*=0.2 (Q_{gas} = 200 ml/min).

As can be seen from Figures 3 and 4, the concentration ratio (C/C_o) increased with time in the order: bubble column > baffled column > OBC. This means that OBC displays higher performance than the other column designs (smaller C/C_o). This is due to the double effect of fluid oscillation and the multi-orifice baffles which results in a significant increase in gas-liquid mass transfer rates. The max value of concentration ratio in the OBC is approximately 5.8 times smaller than that in the bubble column where the C/C_o decrease from 0.87 to 0.15, this decreasing in concentration ratio indicating that the CO_2 dissolution in water by OBC is higher. the (C/C_o) increased with time because the liquid phase (distilled water) becomes more loaded with CO_2, thus the gas-liquid driving force to mass transfer decreases and the CO_2 concentration in water increased.

Figures (5 and 6) show that the CO_2 concentration in water increases in the order OBC> baffled column> BC. This behavior agrees with results obtained by [14][15][16].

Open Access
Vol. 14, No. 4, December 2024, pp. 75-93

P- ISSN: 2220-5381
E- ISSN: 2710-1096

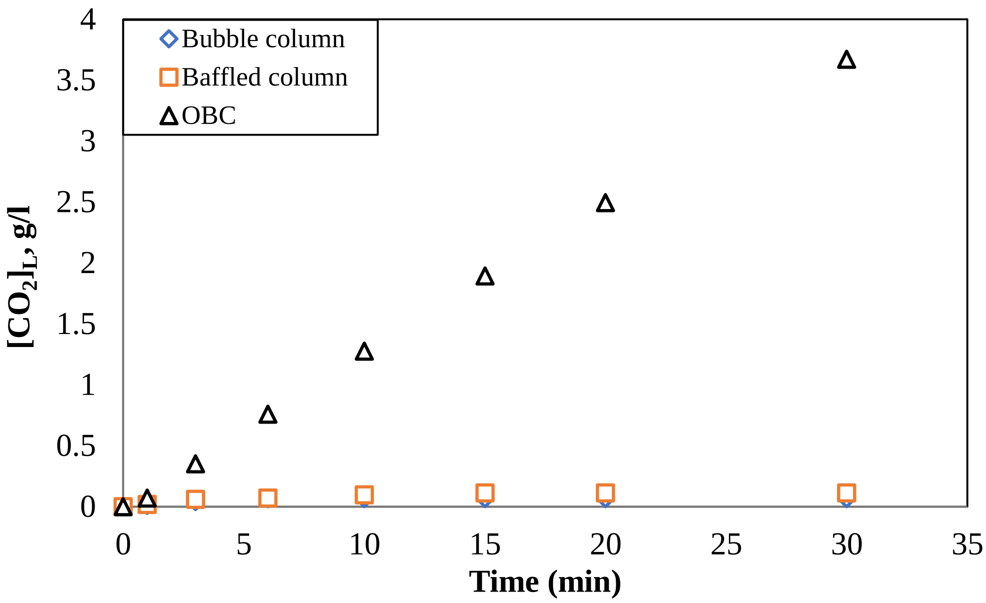

Fig. (5): CO_2 concentration in water *vs* time at *vvm* =0.6 (Q_{gas} = 600 ml/min) and (for OBC, f = 3 Hz, x_o= 6 mm, Re'_o= 1449).

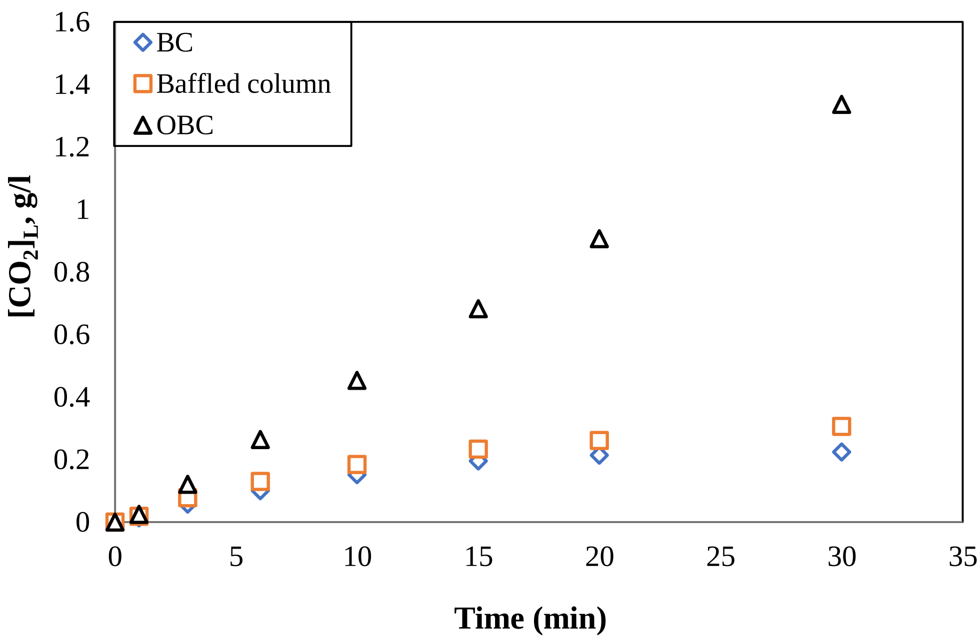

Fig. (6): CO_2 concentration in water *vs* time at f = 3 Hz, x_o= 6 mm, Re'_o= 1449, and *vvm*=0.2 (Q_{gas} = 200 ml/min).

Figures (3) to (6) revealed that the performance of BC and baffled column effective in dissolving CO_2 at time ≤ 10 minutes. At time >10, the concentration ratio becomes constant (~1), CO_2 concentration in water reached steady state due to the limitation of mass transfer where the amount of CO_2 that transferred from gas phase equals to the amount dissolved in liquid phase.

Open Access
Vol. 14, No. 4, December 2024, pp. 75-93
P- ISSN: 2220-5381
E- ISSN: 2710-1096

The increase in CO_2 concentration is due to the increase in CO_2 mass flow, where the mass flow was 9.424, 14.972 and 94.164 g/m^2.min for BC, baffled column and OBC, respectively. This behavior may be due to the high resistance of the liquid film around the gas bubble, the large bubble size, and the small gas retention in the BC and baffled column [5].

The motion of the bubbles was tracked and the gas and liquid flow pattern was followed using normal observation at different conditions. As observed, the OBC exhibited a higher bubbly flow (i.e. a homogenous flow with small, uniform bubbles dispersed across the column) than other designs, confirming the highest performance of the CO_2 dissolution. This confirms the high efficiency of OBC as the bubble size distribution plays a key role in gas-liquid mass transfer systems. It is often recommended to use a bubble flow pattern in order to obtain a high mass transfer rate even at low gas flow rate since small bubbles have a high contact area which results in increased transfer between phases [7]. The BC showed a small number of large bubbles (the diameter of the bubbles is approximately equal to the diameter of the column) moving in an S-shape along the column. However, the heterogeneous flow in the baffled column is caused by the tight coalescence of the bubbles [23].

3.2 Effect of oscillation on the CO_2 concentration ratio

Figure (7) shows the dependency of the CO_2 concentration ratio on the oscillation condition.

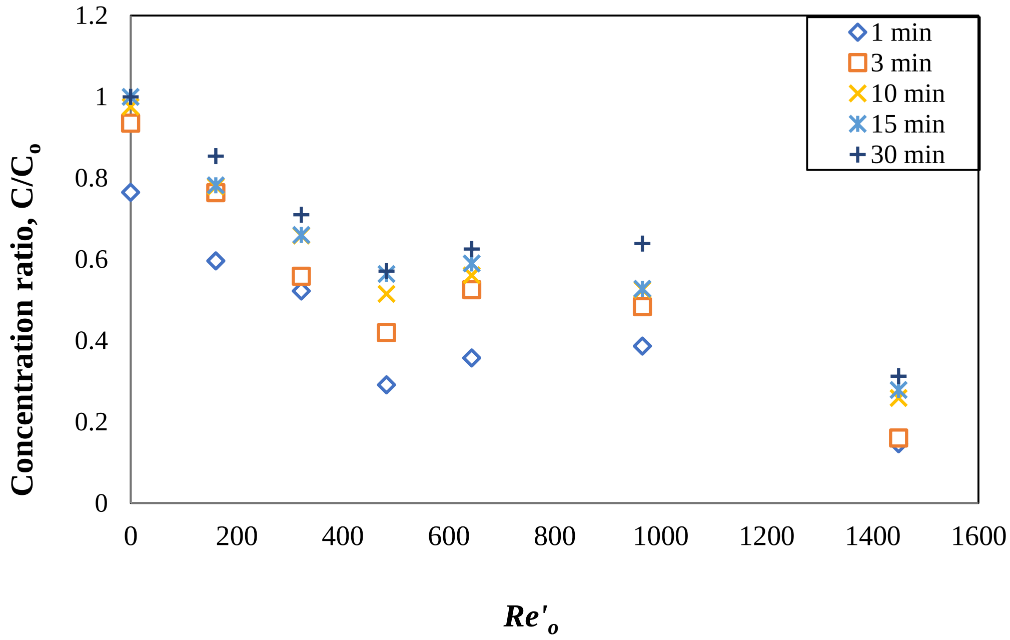

Fig. (7): Effect of Re'_o on CO_2 concentration ratio in the OBC at different times and at *vvm*=0.6.

Open Access
Vol. 14, No. 4, December 2024, pp. 75-93

P- ISSN: 2220-5381
E- ISSN: 2710-1096

It can be seen that the CO_2 concentration ratio decreased when Re'_o increased from 0 to 483. However, at Re'_o = 644 and 966 the effect of Re'_o on the concentration ratio becomes negligible. This behavior can be attributed to the individual effect of the oscillation parameters, f and x_o at Re'_o = 644 and Re'_o = 966 (for example, at f=1 Hz and x_o = 4mm, and f=2Hz and x_o = 2mm Re'_o has at the same value, however, it shows different effect on the flow pattern so the enhancement will be different).

3.3 Effect of oscillation on the CO_2 mass transfer.

Figures (8 and 9) show the dependency of the CO_2 concentration in water and CO_2 mass flux on the oscillation condition respectively.

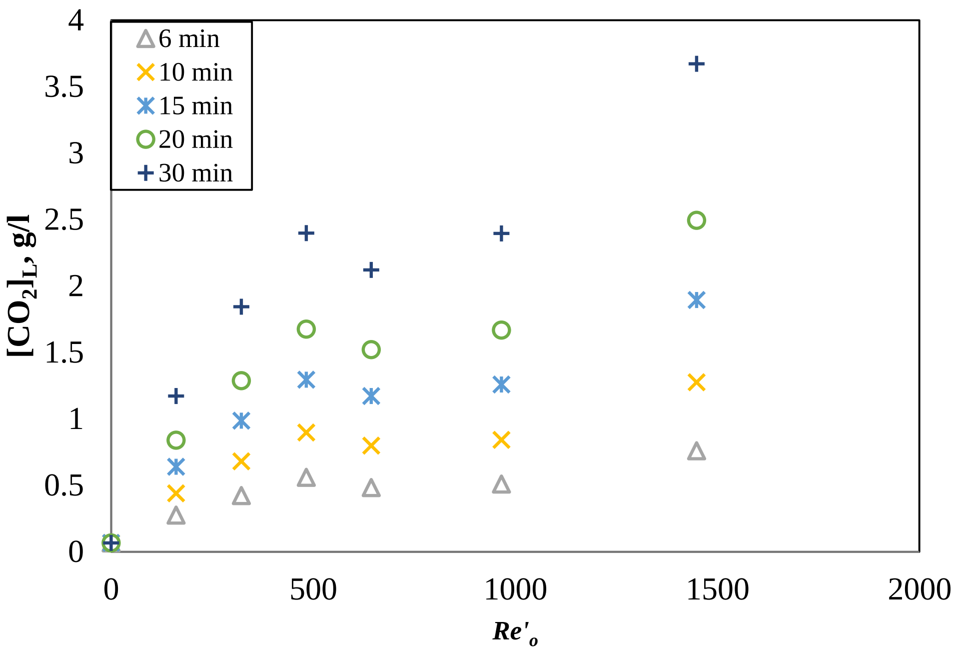

Fig. (8): Effect of Re'_o on CO_2 concentration in water at different times and at *vvm*=0.6.

It can be seen from Figure (8), that the CO_2 dissolution increased when Re'_o increased from 0 to 483. Hence, the CO_2 concentration in water increased with Re'_o at all times. However, the same fluctuation can be observed where Re'_o=699 give smaller CO_2 concentration than those obtained at Re'_o= 483. At higher values of Re'_o the CO_2 concentration changed significantly with time more than at lower values of Re'_o due to the enhancement obtained and continuity of dissolution. Figure (9) shows that at Re'_o< 500 the mass flux increases with Re'_o, however, at Re'_o= 644-966, the flux decreases with Re'_o due to same reason illustrated above and it seen clearly at higher *vvm*. The maximum enhancement was achieved at Re'_o=1449. This enhancement resulted due to

Open Access
Vol. 14, No. 4, December 2024, pp. 75-93

P- ISSN: 2220-5381
E- ISSN: 2710-1096

increasing the bubble break-up and gas hold-up as the interaction between the oscillation and the multi-orifice baffles increased [15] [21] [24].

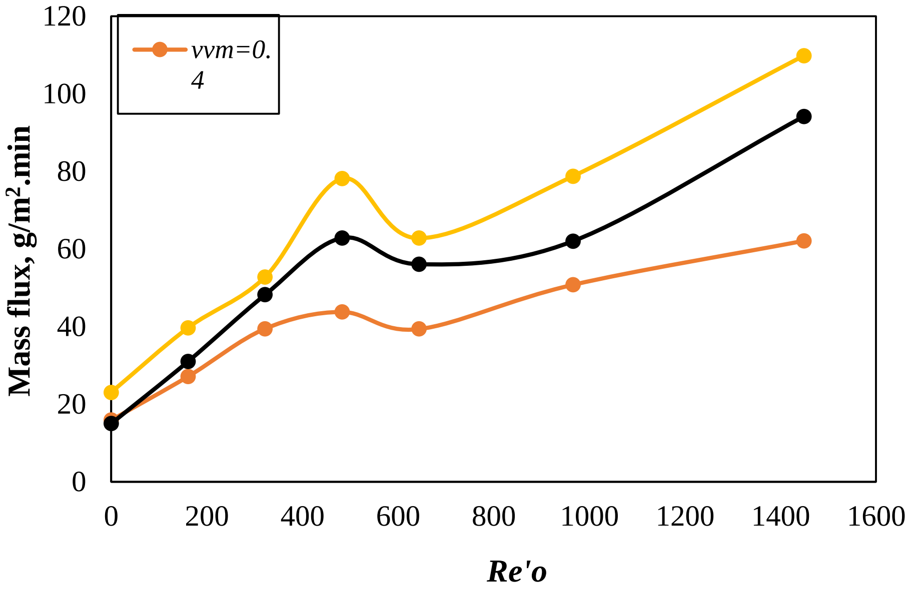

Fig. (9): Effect of Re'_o on the CO_2 mass flux (g/m^2.min) in the OBC at different *vvm*.

3.4 Effect of gas flow rate on the CO_2 mass transfer.

Figures (10) to (12) show the effect of the gas volumetric flow rate expressed in (*vvm*) term on the CO_2 concentration ratio (C/C_o) in the gas phase and CO_2 concentration in water at a range of Re'_o values.

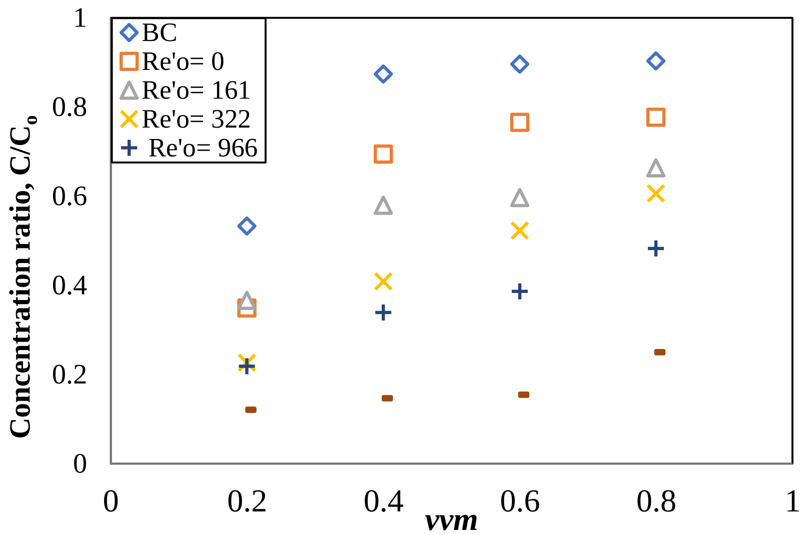

Fig. (10): Effect of the aeration rate (*vvm*) on the CO_2 concentration ratio in the three columns at different Re'_o values

Open Access
Vol. 14, No. 4, December 2024, pp. 75-93

P- ISSN: 2220-5381
E- ISSN: 2710-1096

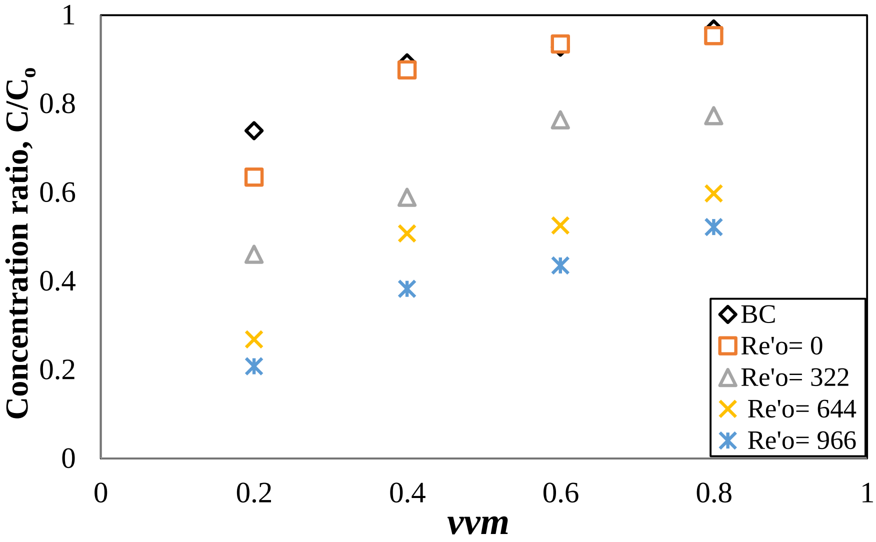

Fig. (11): The effect of the aeration rate (*vvm*) on the CO_2 concentration ratio at different Re'_o and 3 min

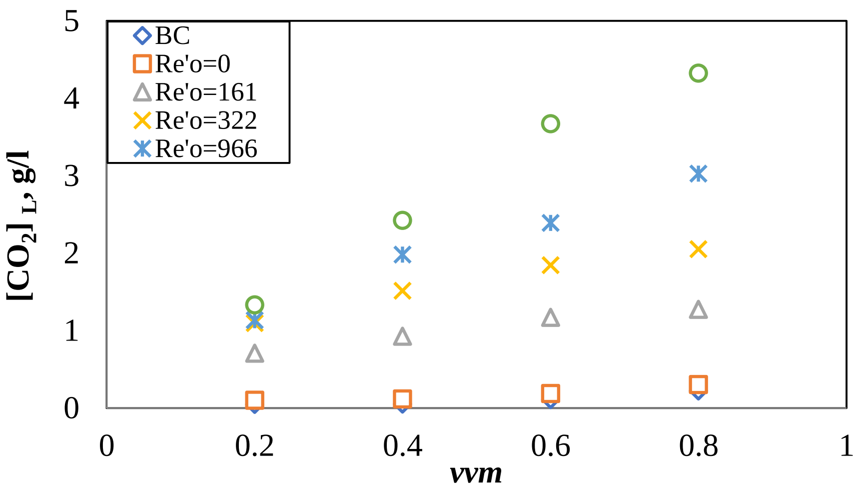

Fig. (12): Effect of the aeration rate (*vvm*) on the CO_2 concentration in water in the three columns at different Re'_o values

Figures (10) to (12) show similar trends where the CO_2 concentration ratio and CO_2 concentration in water increases with increasing *vvm*. This behavior is predictable, according to the definition of the aeration rate, at constant volume of liquid phase. An increase in *vvm* causing an increase in the population of bubbles, hence the contact area and gas holdup increase as well as the trapped bubbles in baffle zones increase [22]. In addition, an increase in *vvm* results in increasing the bubbles collision process hence the mass transfer rate increases [21]. This behavior occurred due to short bubble residence time, when *vvm* increases. In the other hand, an increase in *vvm* leads to increasing CO_2 amount (as CO_2 concentration in the input gas is

Open Access
Vol. 14, No. 4, December 2024, pp. 75-93

P- ISSN: 2220-5381
E- ISSN: 2710-1096

constant) thus the CO_2 concentration in water increased with *vvm* as shown in Figure (12). However, at bubble and baffled columns the effect of *vvm* is small due to the poor performance of these column in dissolution of CO_2 while at OBC the effect of *vvm* on CO_2 concentration in water are clear this indicating the ability of OBC in processing even higher *vvm*. In addition, this increasing results instantly in enhancement of mass flux into water.

The summary of the *vvm* effect on the CO_2 mass flux (g/m^2.min) in the three column configurations is shown in Figure (13). It's clear to observe that the mass flux increased in arrangement OBC> baffled column> BC for all *vvm*. Where the maximum increase in the CO_2 mass flux obtained by OBC was 10-fold at Re_o' = 1449 and *vvm* =0.8 compared with the results obtained by the bubble column (BC).

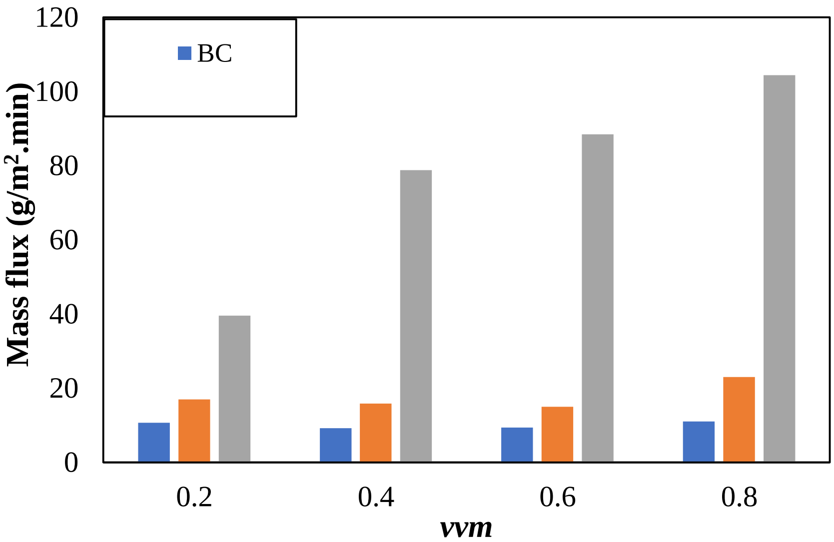

Fig. (13): Effect of *vvm* on the CO_2 mass flux (g/m^2.min) in the three column configurations (Bubble column, Baffled column and OBC), at Re_o' = 1449, for OBC

4. Conclusions

CO_2-water mass transfer was investigated in a semi-batch mode using three column designs: bubble column (BC), baffled column and an oscillatory baffled column (OBC) over a wide range of operating conditions (Re_o' =0- 1450, *vvm*= 0-1). The baffled column (without oscillation) had a smallest effect on mass transfer of CO_2. The mass transfer enhancement (as concentration ratio to be smaller or increase in mass flux and CO_2 concentration in water) increased with oscillation conditions and aeration rate (*vvm*). The OBC demonstrated the highest performance where up to 10- fold of mass transfer enhancement was achieved over the bubble column. The CO_2 mass flux increased from 11.02 to 109.82 (g/m^2.min) at *vvm*= 0.8 and Re_o' = 1449.

Open Access
Vol. 14, No. 4, December 2024, pp. 75-93

P- ISSN: 2220-5381
E- ISSN: 2710-1096

Nomenclature:

GHGs	Greenhouse gases
MOBC	Multi-orifice oscillatory baffled column
BC	Bubble column
OBC	Oscillatory baffled column
GC	Gas chromatography
St	Strouhal number, dimensionless
Re_n	Net flow Reynolds number, dimensionless
Re_o	Oscillatory flow Reynolds number, dimensionless
Re'_o	The modified Oscillatory Reynold number, dimensionless
St'	The modified Strouhal number, dimensionless
vvm	aeration rate, the flowrate of gas per volume of liquid per minute
Q_{gas}	Volumetric flow rate of gas, ml/min
C/C_o	The concentration ratio of CO_2 in gas phase
μ	viscosity, Pa. s
ρ	density, kg/m^3
α	Open cross-sectional area, dimensionless
d_o	Orifice diameter, m
D	OBC diameter, m
f	Oscillation frequency, Hz
x_o	oscillation amplitude, m
l_b	Baffle spacing, m
$[CO_2]_L$	CO_2 concentration in water, g/l
U_G	Superficial gas velocity, m s^{-1}
t	time, min
n	the number of orifices in baffle

Open Access
Vol. 14, No. 4, December 2024, pp. 75-93

P- ISSN: 2220-5381
E- ISSN: 2710-1096

References:

[1] F. Khosroabadi, A. Aslani, K. Bekhrad, and Z. Zolfaghari, "Analysis of Carbon Dioxide Capturing Technologies and their technology developments", *Clean Eng Technol*, vol. 5, Dec. 2021, https://doi.org/10.1016/j.clet.2021.100279

[2] E. Mostafavi, O. Ashrafi, and P. Navarri, "Assessment of process modifications for amine-based post-combustion carbon capture processes", *Clean Eng Technol*, vol. 4, Oct. 2021. https://doi.org/10.1016/j.clet.2021.100249

[3] L. O. Nord and O. Bolland, "Carbon dioxide emission management in power generation", *John Wiley & Sons*, 2020.

[4] U. Berge, M. Gjerset, B. Kristoffersen, and M. Lindberg, "CARBON CAPTURE AND STORAGE", 2016. [Online]. Available: www.zeroco2.no.

[5] F. M. Pereira, D. Z. Sousa, M. M. Alves, M. R. Mackley, and N. M. Reis, "CO2 dissolution and design aspects of a multiorifice oscillatory baffled column", *Ind Eng Chem Res*, vol. 53, no. 44, pp. 17303–17316, Nov. 2014. https://doi.org/10.1021/ie403348g

[6] H. A. Ahmed, H. N. Mohammed, O. S. Lateef, and G. H. Abdullah, "Simulation of CO2removal from pressurized natural gas stream contains high CO_2 concentration by absorption process using membrane contactors", *Chemical Product and Process Modeling*, vol. 16, no. 1, pp. 1–19, Mar. 2021. https://doi.org/10.1515/cppm-2019-0137

[7] S. M. R. Ahmed, A. N. Phan, and A. P. Harvey, "Mass transfer enhancement as a function of oscillatory baffled reactor design", *Chemical Engineering and Processing - Process Intensification*, vol. 130, pp. 229–239, Aug. 2018. https://doi.org/10.1016/j.cep.2018.06.016

[8] M. S. Lucas, N. M. Reis, and G. Li Puma, "Intensification of ozonation processes in a novel, compact, multi-orifice oscillatory baffled column", *Chemical Engineering Journal*, vol. 296, pp. 335–339, Jul. 2016. https://doi.org/10.1016/j.cej.2016.03.050

[9] S. M. R. Ahmed, A. N. Phan, and A. P. Harvey, "Scale-Up of Gas-Liquid Mass Transfer in Oscillatory Multiorifice Baffled Reactors (OMBRs)", *Ind Eng Chem Res*, vol. 58, no. 15, pp. 5929–5935, Apr. 2019. https://doi.org/10.1021/acs.iecr.8b04883

[10] M. Avila, D. F. Fletcher, M. Poux, C. Xuereb, and J. Aubin, "Mixing performance in continuous oscillatory baffled reactors", *Chem Eng Sci*, vol. 219, Jun. 2020, https://doi.org/10.1016/j.ces.2020.115600

Open Access
Vol. 14, No. 4, December 2024, pp. 75-93

P- ISSN: 2220-5381
E- ISSN: 2710-1096

[11] K. B. Smith and M. R. Mackley, "An experimental investigation into the scale-up of oscillatory flow mixing in baffled tubes", *Chemical Engineering Research and Design*, vol. 84, no. 11 A, pp. 1001–1011, 2006. https://doi.org/10.1205/cherd.05054

[12] P. Bianchi, J. D. Williams, and C. O. Kappe, "Oscillatory flow reactors for synthetic chemistry applications", *J. Flow Chem*, pp. 475–490, 2020. https://doi.org/10.1007/s41981-020-00105-6

[13] A. Laybourn, A. M. López-Fernández, I. Thomas-Hillman, J. Katrib, W. Lewis, C. Dodds, A. P. Harvey, and S. W. Kingman, "Combining continuous flow oscillatory baffled reactors and microwave heating: process intensification in the production of metal-organic frameworks", *chemical engineering journal*, 2018. https://doi.org/10.1016/j.cej.2018.09.011

[14] N. Reis, R. N. Pereira, A. A. Vicente, and J. A. Teixeira, "Enhanced gas-liquid mass transfer of an oscillatory constricted-tubular reactor", *Ind Eng Chem Res*, vol. 47, no. 19, pp. 7190–7201, Oct. 2008. https://doi.org/10.1021/ie8001588

[15] M. R. Hewgill, M. R. Mackley, A. B. Panditf, and S. S. Pannu, "Enhancement of Gas-Liquid Mass Transfer Using Oscillatory Flow in A Baffled Tube", *Chem Eng Sci*, vol. 48, no. 4, pp. 799–809, 1993. https://doi.org/10.1016/0009-2509(93)80145-G

[16] T. Taslim and M. S. Takriff, "Gas-Liquid Mass Transfer in Continuous Oscillatory Flow Baffled Columnia", *ASEAN Journal of Chemical Engineering*, vol. 4, no. 2, pp. 1-6, Dec. 2004. https://doi.org/10.22146/ajche.50832

[17] M. Avila, B. Kawas, D. F. Fletcher, M. Poux, C. Xuereb, and J. Aubin, "Design, performance characterization and applications of continuous oscillatory baffled reactors", *Chemical Engineering and Processing - Process Intensification*, vol. 180, Oct. 2022. https://doi.org/10.1016/j.cep.2021.108718

[18] T. Mcglone, N. E. B. Briggs, C. A. Clark, C. J. Brown, J. Sefcik, and A. J. Florence, "Oscillatory flow reactors (OFRs) for continuous manufacturing and crystallization", *Org. Process Res. Dev.*, vol. 19, no. 9, pp. 1186–1202, 2015. https://doi.org/10.1021/acs.oprd.5b00225

[19] S. M. R. Ahmed, A. N. Phan, and A. P. Harvey, "Scale-Up of Oscillatory Helical Baffled Reactors Based on Residence Time Distribution", *Chem. Eng. Technol.*, vol. 40, no. 5, pp. 907–914, May 2017. https://doi.org/10.1002/ceat.201600480

Open Access
Vol. 14, No. 4, December 2024, pp. 75-93

P- ISSN: 2220-5381
E- ISSN: 2710-1096

[20] X. Ni and P. Gough, "On the discussion of the dimensionless groups governing oscillatory flow in a baffled tube", *Chemical Engineering Science*, vol. 52, no. 18, pp. 3209-3212, 1997. https://doi.org/10.1016/S0009-2509(97)00104-8

[21] A. Al-Abduly, P. Christensen, A. Harvey, and K. Zahng, "Characterization and optimization of an oscillatory baffled reactor (OBR) for ozone-water mass transfer", *Chemical Engineering and Processing - Process Intensification*, vol. 84, pp. 82–89, Oct. 2014. https://doi.org/10.1016/j.cep.2014.03.015

[22] M. S. N. Oliveira and X. W. Ni, "Effect of hydrodynamics on mass transfer in a gas-liquid oscillatory baffled column", *Chemical Engineering Journal*, vol. 99, no. 1, pp. 59–68, May 2004. https://doi.org/10.1016/j.cej.2004.01.002

[23] A. Shaikh and M. H. Al-Dahhan, "A Review on Flow Regime Transition in Bubble Columns a Review on Flow Regime Transition in Bubble Columns", *International Journal of Chemical Reactor Engineering*, vol. 5, no. 1, 2007. https://doi.org/10.2202/1542-6580.1368

[24] M. S. N. Oliveira and X. Ni, "Gas hold-up and bubble diameters in a gassed oscillatory baaed column", *Chemical Engineering Science*, vol. 56, no. 21-22, pp. 6143-6148, 2001. https://doi.org/10.1016/S0009-2509(01)00257-3