Axial Dispersion and Mass Transfer of a Pulsed Solvent Extraction Column with Novel Ceramic Internals

Heng Yi^{a,b}, Yong Wang^b, Kathryn H. Smith^b, Weiyang Fei^{a,*} and Geoffrey W. Stevens^{b,*}

^a Department of Chemical Engineering, Tsinghua University, Beijing, 100084, China

^b Department of Chemical and Biomolecular Engineering, The University of Melbourne, Parkville, Victoria 3010, Australia

ABSTRACT: Two types of novel anti-corrosive ceramic internals, the hybrid ceramic internal and ceramic plate, are designed and tested under pilot conditions for future industrial application in lithium extraction from salt lake brine. A standard liquid-liquid system with medium interfacial tension, 30% TBP in Shellsol 2046–water with acetic acid as solute, is used to test axial dispersion and mass transfer parameters, which are important to determine height of extraction columns, over a range of operating conditions. Results show that the hybrid ceramic internal has 50% lower axial dispersion coefficient and 50% higher mass transfer coefficient, both contributing to better mass transfer performance. Under proper operating condition, height of transfer unit of hybrid ceramic internal can reach as low as around 0.2m, which shows very good efficiency and makes it promising to be applied in the near future.

Key words:

Solvent extraction column, Ceramic internal, Axial dispersion, Mass transfer

1. Introduction

Liquid-liquid extraction is an important separation process. An extraction column has advantages such as high volume efficiency, small footprint and environmentally friendly features over other solvent extraction contacting devices, so they have been used for a range of applications in chemical, petroleum, nuclear, hydrometallurgical and other industries for many years¹⁻³. Among the different types of extraction columns, the pulsed sieve plate column is characterized by the absence of moving mechanical parts which avoids frequent maintenance and the mode of providing energy which makes remote operation possible^{4, 5}. Because of these advantages, pulsed sieve plate columns are widely applied especially in the nuclear fuel reprocessing field^{6, 7}.

Researchers have made efforts to investigate the performance of pulsed sieve plate columns for decades. Yadav et al.⁸ gave a thorough summary of previous work and a comparison of different correlations about design aspects of pulsed sieve plate column including drop size, holdup, flooding point and mass transfer, among which the first three can be classified into hydrodynamic parameters. Hydrodynamic parameters are important to determine the column throughput, while mass transfer is the key parameter to determine separation efficiency^{9, 10}. Recent studies have investigated hydrodynamic¹¹⁻¹⁴ and mass transfer performance^{13, 15, 16} of pulsed sieve plate columns. According to Yadav et al.⁸, many researchers interpret the mass transfer data without taking into account the effect of axial dispersion, which according to Nabli et al.¹⁷ would cause over-prediction of the separation efficiency by up to 30%. Therefore the ability to predict axial dispersion coefficients is necessary to better understand the mass transfer process in an extraction column.

43 Researchers are still making efforts to develop better ways to investigate axial dispersion in
44 pulsed sieve plate columns^{5, 18, 19}.

45 Extraction of lithium from chloride brine in salt lakes is a separation process of great
46 importance²⁰. It is also a promising industrial field where solvent extraction columns are
47 likely to be used, since efforts have been made to apply pulsed sieve plate columns in
48 another hydrometallurgy application of copper extraction^{21, 22}. However the extraction
49 solution is corrosive to traditional stainless steel column internals because of their high
50 chloride content, thus the development of novel anti-corrosive internals is necessary.
51 Therefore two types of novel ceramic internals, the ceramic plate and the hybrid ceramic
52 internal have been designed and manufactured. Ceramic plate is designed based on
53 standard sieve plate, while hybrid ceramic internal is designed by adding ceramic packing on
54 ceramic plate. This design is likely to intensify mass transfer by reinforcing
55 breakage-coalescence cycle for dispersed droplets along the column.

56 Because the difference in wettability resulted from material types will effect
57 performance of pulsed sieve plate columns^{23, 24}, it's necessary to evaluate the novel ceramic
58 plate and hybrid ceramic internal under pilot plant conditions before industrial applications.
59 The hydrodynamic results including holdup, characteristic velocity and drop size for these
60 two types of ceramic internals have been reported by Yi et al²⁵. The focus of the current
61 study is to investigate the mass transfer performance of these novel ceramic internals. A
62 prior investigation is conducted to provide information about axial dispersion coefficients, in
63 order for a better interpretation of mass transfer data and a better explanation of the
64 performance comparison between these two types of internals.

2. Previous studies

2.1. Axial dispersion

In the axial dispersion model for solvent extraction columns, deviation caused by non-ideality from plug flow is taken into account via an axial dispersion coefficient for each phase²⁶, which makes it an important design parameter for determining the height of an extraction column for a given separation. The effect of axial dispersion in the dispersed phase is usually regarded as negligible for pulsed columns²⁷, thus most attention is paid to axial dispersion in the continuous phase. Axial dispersion in the continuous phase has been studied by researchers in various types of liquid-liquid extraction columns, such as pulsed sieve plate extraction columns^{19, 28, 29}, reciprocating plate extraction columns^{30, 31} and spray towers³².

In order to predict the extent of axial dispersion, various correlations for the axial dispersion coefficient, E_c , have been proposed. In some of these studies, the correlations were based on limited experimental data and therefore are only applicable to the specific situations and operating variables for which the correlation was developed. An example is given in Equation 1 by Kagan et al.³³ for two-phase operation of a pulsed sieve plate column:

$$E_c(1 - x_d) = 1.26 \times 10^{-4} A^{1.2} f^{1.35} / (V_c + V_d)^{1.4}$$

Equation 1

Later Tung and Luecke³⁴ made an effort to develop a more generalized correlation for E_c with published data for pulsed sieve plate columns, which takes into account the effect of column geometries. A similar correlation (shown in Equation 2) proposed by Srinikethan

et al.³⁵ further takes into account the effect of pulsation rate (Af) and continuous phase velocity (V_c) on E_c separately via different number groups:

$$\frac{E_c}{h_c V_c} = k_1 \left(\frac{Af}{V_c} \right)^{k_2} \left(\frac{\mu_c}{V_c d_0 \rho_c} \right)^{k_3} \left(\frac{d_0}{h_c} \right)^{k_4} \alpha^{k_5}$$

Equation 2

where $k_1 = 3.65, k_2 = 0.3, k_3 = 0.2, k_4 = 0.45, k_5 = -0.22$ for the mixer-settler region, and $k_1 = 3.25, k_2 = 0.3, k_3 = 0.2, k_4 = 0.8, k_5 = -0.8$ for the emulsion region.

Later Kumar and Hartland²⁸ collected 992 data points with and without mass transfer for 28 liquid-liquid systems from 13 different sources, and presented a unified correlation (shown in Equation 3) for E_c in pulsed sieve plate columns:

$$\frac{E_c \Delta \rho}{\mu_c} = k_1' \exp(k_2' \psi') \left(\frac{V_d \mu_c}{\gamma} \right)^{0.11} \left(\frac{\mu_c}{\mu_d} \right)^{-0.37} \left(\frac{\mu_c}{(\gamma \Delta \rho h_c)^{0.5}} \right)^{-0.61} \left(\frac{d_0}{h_c} \right)^{0.36} \left(\frac{\Delta \rho h_c}{\rho^* h_c^*} \right)^{1.05}$$

Equation 3

where the standard density of water $\rho^* = 998 \text{ kg/m}^3$, standard plate spacing $h_c^* = 0.05 \text{ m}$, $k_1' = 46.15$ and $k_2' = 0.80$ or 0.34 depending on pulsation intensity range. This correlation could be used with a wide range of systems and over a range of operating conditions.

2.2. Mass transfer

The mass transfer performance of an extraction column is usually determined as a height of mass transfer unit, including the apparent mass transfer unit H_{oxp} and the true mass transfer unit H_{ox} ³⁶. The number of mass transfer units, N_{oxp} , and H_{oxp} can be determined (as shown in Equation 4) with inlet and outlet solute concentrations of both

phases and solute equilibrium data, together with the assumption of plug flow along the column.

$$N_{\text{oxp}} = \int_{x_{\text{out}}}^{x_{\text{in}}} \frac{dx}{x - x^*_{\text{plug flow}}}, \quad H_{\text{oxp}} = \frac{H}{N_{\text{oxp}}}$$

Equation 4

$$H_{\text{ox}} = \frac{V_c}{K_{\text{ox}}a}, \quad N_{\text{ox}} = \frac{H}{H_{\text{ox}}}$$

Equation 5

N_{ox} and H_{ox} are defined in terms of the volumetric mass transfer coefficient $K_{\text{ox}}a$ (as shown in Equation 5) when the effect of axial dispersion is taken into account. When axial dispersion coefficients are given, by solving the coupled ordinary differential equations (ODEs) shown in Equation 6³⁶ with inlet and outlet solute concentrations as boundary conditions, $K_{\text{ox}}a$ and H_{ox} can be calculated.

$$E_d \frac{d^2y}{dz^2} + V_d \frac{dy}{dz} + K_{\text{ox}}a(x - x^*) = 0$$

$$E_c \frac{d^2x}{dz^2} - V_c \frac{dx}{dz} - K_{\text{ox}}a(x - x^*) = 0$$

Equation 6

As a special case, Miyauchi et al.³⁷ proposed an simpler iterative estimation method for determining H_{ox} and $K_{\text{ox}}a$ without solving the ODEs when the solute concentration equilibrium relationship is linear. In order to model $K_{\text{ox}}a$, researchers have proposed correlations and a typical one for reciprocating plate column is presented by Harikrishnan et al.³⁸ in Equation 7,

$$K_{ox}a = k_1'' U_d^{k_2''} (1 + k_3'' \psi^{k_4''})$$

Equation 7

where $k_1'' = 30 \times 10^{-4}$, $k_2'' = 0.76$, $k_3'' = 8.8 \times 10^{-3}$, $k_4'' = 0.85$ for benzoic acid with the mass transfer direction of $d \rightarrow c$, and ψ is the average power dissipation per unit mass.

3. Experimental

The two types of novel ceramic internals designed and manufactured for use in this study are shown in **Error! Reference source not found.**. The ceramic sieve plate (Figure 1B) has a standard design with 23% open area and 3 mm diameter holes with a plate thickness of 2 mm. The specific surface area of the hybrid ceramic packing internal is $650 \text{ m}^2/\text{m}^3$. The plates are held in place with three steel rods and 48 mm long spacer sleeves (see Figure 1C) to evenly divide the length between each plate to be 50 mm, which is the height of a single compartment. The packing can be placed on the plates with the sleeves crossing three holes to keep its position (see Figure 1A). The two types of internals are called hybrid ceramic internal (Figure 1A and 1D) and ceramic plate (Figure 1B). A photo of the installed hybrid ceramic internals is shown in Figure 1D.

Figure 1 Schematic diagrams and photograph of ceramic internals (A) hybrid ceramic internal (B) ceramic plate (C) tie rods (D) photograph of hybrid ceramic internal

All experiments were performed in a pilot plant column, refer to process flow diagram shown in Figure 2³⁹. This is made up of a 1.0 m long QVF® precision bore glass column with an internal diameter of 72.5 mm. The organic phase outlet is a glass T-piece on top of the column body. The internal diameter of the glass section at the bottom of the column increases to 100 mm with a stainless steel distributor inside. A stainless steel conical adapter then reduces the diameter to 50 mm and is connected to a piston-type pulsing unit. This pulsing unit consists of a motor, a variable speed unit (controls the frequency), a variable eccentric drive head (controls the amplitude), a crank arm and a plunger equipped with a Teflon cylinder and two rubber seals in a stainless steel cylinder. Sinusoidal motion is provided by the plunger to the fluids in the column.

Figure 2 Experimental pilot plant column process flow diagram

The organic phase used in this study is 30 vol% TBP (Tributyl phosphate), supplied by Myer (Shanghai) in Shellsol 2046®, supplied by Shell Australia. Glacial acetic acid supplied by Thermo Fisher is diluted in water and used as solute. The aqueous phase is tap water. The tracer used in axial dispersion experiments is 1 w% tartrazine yellow (Acid yellow 23) solution, supplied by Sigma Aldrich. The physical properties, including densities, viscosities and interfacial tension were measured and are presented in Table 1. This system is a widely used standard system with medium interfacial tension to evaluate performance of new types of extraction column internals.

Table 1 Physical properties and solute equilibrium of the two phases

	Aqueous	Organic
Density (kg/m ³)	1008	844

Viscosity (Pa·s)	1.06×10^{-3}	2.05×10^{-3}
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Interfacial tension (mN/m)	10.1
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Equilibrium relationship	$x^* = 1.6306 \times y, \quad 0 < y < 0.11 \text{ mol/L}$
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In order to measure the axial dispersion coefficient, one tracer injection point and two sampling points were set along the column height (as shown in Figure 2). The injection point is located at the upper part of the column, while the two sample points are located in the middle part of the column and are 30 cm apart from each other. All three points are sealed with Teflon caps through which stainless steel sample tubes can be inserted. The column is operated with a continuous aqueous phase and dispersed organic phase with the interface maintained at the top of the column. In a typical experiment, aqueous phase samples are taken continuously via a Watson Marlow 505S peristaltic pump. The tracer concentration is measured and recorded with two pre-calibrated UV/Vis spectrophotometers (723, Shanghai Jinghua Scientific& Technology Instrument Co., Ltd.) which are equipped with a 10 mm path length flow cell. To prevent the dispersed phase entering the sample tube, hydrophilic stainless steel caps are added at the tip of the sample tubes.

In order to measure mass transfer performance, the solute (acetic acid) equilibrium relationship was measured within the concentration range used in the column experiments. The equilibrium data can be well represented by a linear relationship (shown in Table 1), which can be explained by the low concentration of solute. This feature also means that the estimation method by Miyauchi et al.³⁷ for H_{Ox} can be used with good accuracy. In a typical mass transfer experiment, the extraction column is operated under desired conditions for

about 50 minutes until steady state condition is reached. At this point approximately 15 mL of each phase will be taken from the inlet and outlet as samples, and then analyzed by titration with pre-calibrated sodium hydroxide solution. H_{oxp} and N_{oxp} can then be calculated from the data via a pre-coded MATLAB program according to Equation 4. The results are considered reliable if the mass balance error is less than 10%.

4. Results and Discussion

4.1. Axial dispersion

The continuous phase axial dispersion coefficient is determined with tracer concentration-time curves from the two sample points. A typical set of experimental data is shown in Figure 3(A), in which the curve from sample point 2 is lower and wider than that from sample point 1 as a result of axial dispersion. Once the experimental data is collected, the one-dimensional (axial direction) differential equation for tracer transport is solved with the first experimental curve as the boundary condition. Different value of E_c will result in different prediction for the second curve, thus a searching method for E_c is used to fit the predicted curve of sample point 2 with experimental data. Prediction of the two curves is also shown in Figure 3 (A) with the solid lines which are in good agreement with the experimental data. With the correctly fitted axial dispersion coefficient, tracer concentration distribution on the two-dimensional position-time domain is shown in Figure 3 (B) by solving the transport differential equation for the tracer.

(A)

(B)

Figure 3 MATLAB program output for calculation of axial dispersion coefficient: (A) Typical experimental tracer concentration data with time and predicted curves at two sample points (B) Reconstructed tracer distribution on two dimensional position-time domain

Experimental E_c for both types of ceramic internals are shown in Figure 4, Figure 5 and Figure 6, in which the effects of pulsation intensity and two phase velocity are considered. Pulsation intensity varies from 0.3 cm/s to 1.8 cm/s, while superficial velocities for continuous and dispersed phase vary from 9×10^{-4} to 2.3×10^{-3} m/s and 6×10^{-4} to 2.1×10^{-3} m/s respectively. In these figures, experimental data is shown with points, while the solid lines are the predicted values of correlation regressed from experimental data which will be discussed later. E_c for both types of internals slightly increases with an increase of pulsation intensity and continuous phase velocity, while the effect of dispersed phase velocity is negligible. The small effect of pulsation intensity on axial dispersion may be explained by the fact that no experiments were conducted with an amplitude that exceeds the free spacing between the stages, which significantly increases the axial dispersion. To determine the accuracy of these experiments the average relative error is calculated from repeated experiments of E_c for the two types of internals and the ceramic plate was found to vary by 10.9% while that of hybrid ceramic internal is 7.5%.

With the ceramic packing added, the hybrid ceramic internal has lower E_c than ceramic plate by about 1/2 under all the conditions investigated. This means the flow is more plug flow like for the hybrid ceramic internal, which results in better mass transfer efficiency. A possible explanation for the difference between E_c for the two types of ceramic internals is that adding the packing on the ceramic plates reduces the free spacing between the stages, where axial dispersion is most likely to occur. The explanation is reasonable when considering that the ratio of free spacing between the two types of ceramic internals is about 1/2, which is the same as the ratio of experimental E_c variation.

Figure 4 Effect of pulsation intensity on axial dispersion coefficients for two types of ceramic internals

Figure 5 Effect of continuous phase velocity on axial dispersion coefficients for two types of ceramic internals

Figure 6 Effect of dispersed phase velocity on axial dispersion coefficients for two types of ceramic internals

In order to predict E_c with these two new types of internals, correlations are proposed based on Equation 2. The parameters k_1 to k_3 in Equation 2 are refitted, while values of k_4 and k_5 for emulsion region are taken from Srinikethan et al.³⁵ The parameters for the new correlations are shown in Table 2. Accuracy of the prediction is measured with the average relative deviation (ARD) which is defined as:

$$ARD = \frac{1}{n} \sum_{i=1}^n \frac{|\text{predicted value} - \text{experimental value}|}{\text{experimental value}} \times 100\%$$

Equation 8

Table 2 Parameters for predicting the axial dispersion coefficient using refitted Equation 2 for the two types of ceramic internals used in this study

Internals	k_1	k_2	k_3	k_4	k_5	ARD
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Hybrid ceramic internal	6.4506	0.1916	0.6729	0.8	-0.8	6.0%
Ceramic plate	14.8636	0.1815	0.6885	0.8	-0.8	6.9%

With the refitted parameters, the ARD for the hybrid ceramic internal and ceramic plate are 6.0% and 6.9% respectively. The predicted E_c is also compared with experimental data in Figure 4, Figure 5 and Figure 6, and the predicted E_c (shown by solid lines) agrees well with the experimental data shown as discretized points. A systematic comparison is shown in Figure 7, in which the deviation between prediction and experiments are within 10%.

Figure 7 Experimental and predicted axial dispersion coefficients from refitted Equation 2 using constants from Table 2

4.2. Mass transfer

Systematic mass transfer experiments were performed to compare the mass transfer performance of the two types of internals. The results are shown in Figure 8 and Figure 9, in which the effects of pulsation intensity and two phase superficial velocity are considered.

Pulsation intensity varies from 0.3 cm/s to 1.8 cm/s and the continuous-dispersed phase ratio varies from 0.5 to 2 while total throughput of the two phases is kept constant. When the effect of dispersed phase velocity is investigated, V_d varies from 6×10^{-4} to 3.5×10^{-3} m/s. With an increase of pulsation intensity, H_{oxp} (calculated according to Equation 4) decreases accordingly for both types of internals under every V_c/V_d condition, indicating an improvement in mass transfer efficiency. For each type of internal, H_{oxp} decreases when V_c/V_d decreases from 2 to 0.5. The effect of V_d on H_{oxp} is shown in Figure 9, in which H_{oxp} decreases with an increase of V_d . With the ceramic packing added, the hybrid ceramic internal has lower H_{oxp} than ceramic plate by around 40% under all the conditions investigated, which means 40% in reduction of column height for a given separation task. This can be partly explained by the less non-ideality caused by axial dispersion for hybrid ceramic internal discussed in the previous part. Higher volumetric mass transfer coefficient resulted from the add of packing may be another cause, and this possibility will be discussed in the following parts. It should be noted that under the best condition, H_{oxp} of the hybrid ceramic internal is as low as 0.2 m, which indicates very good mass transfer efficiency.

Figure 8 Effect of pulsation intensity and continuous-dispersed phase ratio on height of apparent mass transfer unit for two types of ceramic internals

Figure 9 Effect of dispersed phase velocity on height of apparent mass transfer unit for two types of ceramic internals

The accuracy of the mass transfer experimental data is checked via mass balance, and the results are shown in Figure 10. All the data points are located in the region with an error of less than 10% indicating the collected data has high accuracy.

Figure 10 Solute mass balance for all mass transfer experiments

Using the overall mass transfer data and continuous phase axial dispersion coefficient predicted with refitted Equation 2, the volumetric mass transfer coefficient, $K_{ox}a$, can be calculated using the axial dispersion model³⁷. The calculated values of $K_{ox}a$ are shown in Figure 11 and Figure 12 as a function of pulsation intensity and dispersed phase velocity respectively. $K_{ox}a$ increases with an increase of pulsation intensity and dispersed phase velocity, and a decrease of V_c/V_d . Increased dispersed phase velocity increases holdup, and higher pulsation intensity results in smaller Sauter mean diameter for droplets for these two internals²⁵. These two factors contribute to higher specific interfacial area, thus can be an explanation for the trend of $K_{ox}a$. With the ceramic packing added, hybrid ceramic internal has higher $K_{ox}a$ than ceramic plate by around 50% under the range of conditions investigated in this study. Hydrodynamic experimental results by Yi et al.²⁵ shows that holdup of hybrid ceramic internal is higher than that of ceramic plate by around 50%, and Sauter mean diameter d_{32} of hybrid ceramic internal is smaller than that of ceramic plate

by around 40%, both of which contribute to larger mass transfer area and larger volumetric mass transfer coefficient for the hybrid ceramic internal.

Figure 11 Effect of pulsation intensity and continuous-dispersed phase ratio on volumetric mass transfer coefficient for two types of ceramic internals

Figure 12 Effect of dispersed phase velocity on volumetric mass transfer coefficient for two types of ceramic internals

In order to predict $K_{ox}a$ for these two new types of ceramic internals, correlations are proposed based on Equation 7 and the parameters k_1'' to k_4'' which have been refitted with values shown in Table 3.

Table 3 Parameters for predicting the mass transfer coefficient using refitted Equation 7 for the two types of ceramic internals in this study

Internals	k_1''	k_2''	k_3''	k_4''	ARD
Hybrid ceramic internal	6.4195	1.3230	0.2744	0.8121	12.0%
Ceramic plate	3.0246	1.2047	0.0637	0.9515	7.0%

With the refitted parameters, the ARD for the hybrid ceramic internal and ceramic plate are 12.0% and 7.0% respectively. A systematic comparison of predicted and experimental $K_{ox}a$ is shown in Figure 13, in which the deviations are within 20%.

Figure 13 Experimental and predicted volumetric coefficient from refitted Equation 7

315 5. Conclusions

316 Two types of novel anti-corrosive ceramic internals for a pulsed solvent extraction
317 column were designed and pilot plant experiments were performed with standard
318 liquid-liquid system to evaluate and compare their axial dispersion and mass transfer
319 performance. The conclusions from this study can be summarized as follows:

- 320 1. Axial dispersion coefficients, E_c , of the hybrid ceramic internal is less than that of the
321 ceramic plate by around 50%. E_c for both types of internals slightly increases with the
322 increase of pulsation intensity and continuous phase velocity, while the effect of
323 dispersed phase velocity is negligible.
- 324 2. A correlation for E_c is chosen and refitted to predict the experimental data, and the
325 ARD for the hybrid ceramic internal and ceramic plate are 6.0% and 6.9% respectively.
- 326 3. The height of mass transfer unit, H_{oxp} , of the hybrid ceramic internal is less than that
327 of the ceramic plate by around 40%, indicating better mass transfer efficiency for hybrid
328 ceramic internal. H_{oxp} of both types of internals decreases with an increase of
329 pulsation intensity and dispersed phase velocity, and a decrease of V_c/V_d .
- 330 4. Volumetric mass transfer coefficient, $K_{ox}a$, for both types of ceramic internals are
331 calculated, and results show that $K_{ox}a$ of hybrid ceramic internal is higher than that of
332 ceramic plate by around 50%.
- 333 5. A correlation for $K_{ox}a$ is chosen and refitted to predict the experimental data, and the
334 ARD for hybrid ceramic internal and ceramic plate are 12.0% and 7.0% respectively.

335 ■ **Author information**

336 **Corresponding authors**

337 W.Y. Fei: Tel: +86 10 62789637. E-mail: fwy-dce@tsinghua.edu.cn

338 Geoffrey W. Stevens: Tel: +61 3 83446621. E-mail: gstevens@unimelb.edu.au

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343 ■ **Nomenclature**

344 A: amplitude, m

345 a: specific interfacial area, m^2/m^3

346 ARD: average relative deviation, dimensionless

347 c: tracer concentration, mol/L

348 d_{32} : Sauter-mean drop diameter, m

349 d_0 : plate perforation diameter, m

350 E: axial dispersion coefficient, m^2/s

351 f: frequency, Hz

352 H: height of effective part of the column, m

353 H_{ox} : height of true mass transfer unit, m

354 H_{oxp} : height of apparent mass transfer unit, m

355	h_c : compartment height, m
356	h_c^* : standard compartment height, m
357	K_{ox} : mass transfer coefficient, m/s
358	k_1 to k_5 : constants in Equation 2, dimensionless
359	k_1' to k_2' : constants in Equation 3, dimensionless
360	k_1'' to k_4'' : constants in Equation 7, dimensionless
361	N_{oxp} : number of apparent mass transfer unit, dimensionless
362	N_{ox} : number of true mass transfer unit, dimensionless
363	V : superficial velocity, m/s
364	x : solute concentration in aqueous phase, mol/m ³
365	x^* : equilibrium solute concentration of the contacting dispersed phase, mol/m ³
366	y : solute concentration in dispersed phase, mol/m ³
367	x_d : volume fraction holdup of the dispersed phase, dimensionless
368	Greek Symbols
369	α : fractional free area of perforated plate, dimensionless
370	γ : interfacial tension, N/m
371	μ : viscosity, Pa.s
372	ρ : density, kg/m ³
373	ρ^* : standard density of water at 20 °C, kg/ m ³
374	$\Delta\rho$: density difference between phases, kg/m ³
375	ψ : average power dissipation per unit mass, W/kg
376	ψ' : translated agitation group in Equation 3, dimensionless

377 Subscripts

378 c : continuous phase

379 d: dispersed phase

380 in: inlet of phases

381 out: outlet of phases

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Hybrid ceramic
internal

Ceramic plate
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Author/s:

Yi, H;Wang, Y;Smith, KH;Fei, W;Stevens, GW

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