Highlights

1. Two types of novel anti-corrosive ceramic internals have been designed for extraction of lithium and rare earths, and their hydrodynamic performance was investigated.
2. Holdup of hybrid ceramic internal was higher than that of ceramic plate by around 50%. Correlations were proposed to predict holdup for both types of internal with AARD of 5.9% and 9.3% respectively.
3. Sauter mean diameter of hybrid ceramic internal is smaller than that of ceramic plate by around 30%. Correlations were proposed to predict d_{32} with AARD of 13.6% and 4.2% respectively.

Graphical abstract

Hydrodynamic Performance of a Pulsed Solvent Extraction Column with Novel Ceramic Internals: Holdup and Drop Size

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ABSTRACT: Chloride in the extraction of lithium from brine in salt lakes and the separation of rare earth elements are both very corrosive to stainless steel extraction column internals, which is a significant problem in large scale production. The hydrodynamics of two types of novel anti-corrosive ceramic internals, the hybrid ceramic internal and ceramic plate, are designed and tested under pilot plant conditions in order to be considered for application to these industries. The results show that holdup decreases first and then increases with an increase of pulsation intensity. Increasing dispersed phase velocity also increases holdup. Sauter mean diameter, d_{32} , decreases with an increase of pulsation intensity, while superficial velocities of both phases have little effect. A range of correlations for holdup and d_{32} from literature are compared to the data, and it is shown that new correlations are needed to accurately predict the performance of the two internal types. Characteristic velocity, which is key parameter in calculating column throughput in the emulsion regime, is also investigated as part of the holdup correlation. Results show that characteristic velocities for both internals decrease with an

increase of pulsation intensity, while that of ceramic plate are larger. The experimental results show higher holdup and smaller d_{32} when using the hybrid ceramic internal which indicates that this novel internal will provide a larger mass transfer area and hence better mass transfer efficiency.

Key words:

Solvent extraction column, Hydrodynamics, Ceramic internal, Holdup, Drop size

1. Introduction

Liquid-liquid extraction is an important separation process. Various types of solvent extraction columns have been used for a range of applications in chemical, petroleum, nuclear, hydrometallurgical industries and other fields for many years¹⁻³. Extraction columns have advantages over other devices such as its high volume efficiency, small footprint and environmentally friendly features. However, the design of extraction columns is still difficult due to the complexity of two phase interaction and mass transfer inside the column⁴. Therefore pilot plant experiments are still required for large scale design and implementation in an industrial field.

Extraction of lithium from chloride brine in salt lakes⁵ and separation of rare earth elements⁶ are separation processes of great importance. They are also promising industry fields where solvent extraction columns are likely to be used. However the extraction solutions are very corrosive to stainless steel column internals because of their high chloride content, thus the development of novel anti-corrosive internal is necessary. In order to solve this problem, two types of novel ceramic internals have been designed and manufactured. Hydrodynamic performance parameters of the internals, including holdup and drop size, are important in the design of the column as they determine the column diameter and the mass transfer area between the phases which determines the column height. In this study pilot plant experiments are performed to measure and compare the hydrodynamic performance of the two types of ceramic internals including a novel hybrid ceramic internal. Correlations for both holdup and drop size are chosen from the literature and refitted to predict the experimental data with good agreement.

2. Previous studies

2.1. Holdup

The dispersed phase holdup, x_d , is defined as the volume fraction of the active section of the column that is occupied by the dispersed phase:

$$x_d = \frac{V_d}{V_c + V_d}$$

Equation 1

where v_d represents the volume of the dispersed phase and v_c represents the volume of the continuous phase.

In a pulsed extraction column, when pulsation intensity is increased, holdup usually decreases at first and then increases. Previous researchers proposed different kinds of correlations in order to characterize this trend. Some researchers suggested splitting the range of pulsation intensity, i.e. energy input, into several regions including mixer-settler region, transition region and emulsion region and use a different correlation for each region. A typical example of this kind is the correlation proposed by Miao⁷ :

$$x_d = 2.87 \times 10^{-3} \chi^{-0.9485} V_d^{2/3} \text{ for } \chi < 0.0013 \text{m}^{11/12} \text{s}^{-1} \text{ Mixer-settler}$$

$$x_d = 4.09 \times 10^3 \chi^{1.1515} V_d^{2/3} \text{ for } 0.0013 \text{m}^{11/12} \text{s}^{-1} < \chi < 0.0044 \text{m}^{11/12} \text{s}^{-1} \text{ Transition}$$

$$x_d = 8.46 \times 10^2 \chi^{0.856} V_d^{2/3} \text{ for } \chi > 0.0044 \text{m}^{11/12} \text{s}^{-1} \text{ Emulsion}$$

Equation 2

$$\text{where } \chi = \frac{Af}{(\beta h)^{1/3}} \left(\frac{\mu_d^2}{\sigma \Delta \rho} \right)^{1/4}, \beta = \frac{\alpha^2}{(1-\alpha)(1-\alpha^2)}$$

Later Kumar and Hartland collected previously published holdup data for pulsed perforated plate columns and proposed a unified correlation which could be used in all the three operating regions⁸:

$$x_d = k_1 e^{[k_2 |Af - (Af)_m|]} V_d^{0.86} (V_c + V_d)^{0.28} \Delta \rho^{-0.30} \rho_d^{-0.93} \mu_d^{0.77} \alpha^{-0.56} h_c^{-0.56}$$

Equation 3

$$(Af)_m = 9.69 \times 10^{-3} \left(\frac{\gamma \alpha \Delta \rho^{0.25}}{\mu_d^{0.75}} \right)^{0.33}$$

Equation 4

Where the parameters k_1 and k_2 were regressed separately under different mass transfer direction. When regressing parameters in this correlation, they used data from different systems and column geometries, so physical properties and geometry parameters were taken into account. $(Af)_m$, the pulsation intensity under which holdup reaches minimum was also modelled and could be calculated with physical properties and column geometry parameters directly.

Another widely used unified correlation for holdup was proposed by Kumar and Hartland for a range of different types of solvent extraction columns. This unified correlation incorporates the effects of physical properties, flow rates, pulsation intensity and column geometry into four groups which are defined in Equation 5 below⁹. Previous data for eight types of columns were regressed separately and a set of parameters were given for each kind of column. The correlation and the parameters for the pulsed perforated-plate column are given below:

$$x_d = \Pi \cdot \Phi \cdot \psi \cdot \Gamma$$

Equation 5

$$\begin{aligned} \text{Where} \quad \Pi &= C_{\Pi} + \left[\frac{\varepsilon}{g} \cdot \left(\frac{\rho_c}{g \cdot \gamma} \right)^{0.25} \right]^{n_1} \\ \Phi &= \left[V_d \cdot \left(\frac{\rho_c}{g \cdot \gamma} \right)^{0.25} \right]^{n_2} \cdot \exp \left[n_3 \cdot V_c \cdot \left(\frac{\rho_c}{g \cdot \gamma} \right)^{0.25} \right] \\ \psi &= C_{\psi} \left(\frac{\Delta \rho}{\rho_c} \right)^{n_4} \cdot \left(\frac{\mu_d}{\mu_c} \right)^{n_5} \\ \Gamma &= C_{\Gamma} \cdot \alpha^{n_6} \left[h_c \cdot \left(\frac{\rho_c \cdot g}{\gamma} \right)^{0.5} \right]^{n_7} \end{aligned}$$

$$\varepsilon = \frac{2\pi^2(1 - \alpha^2)}{3h_c C_0^2 \alpha^2} (Af)^3$$

Equation 6

Where $C_{II}=0.13$, $C_I=153.2$, $n_1-n_7=0.80, 1.18, 7.51, -0.25, 0.88, 0, -0.54, 19.0$. This correlation extended the understanding of holdup from a more fundamental perspective, but has the disadvantage that it cannot show the decreasing trend in holdup for the mixer-settler region.

2.2. Drop size

The equilibrium droplet size distribution in a solvent extraction column is usually represented with the Sauter mean diameter (d_{32}) which is calculated as:

$$d_{32} = \frac{\sum_{i=1}^n n_i d_i^3}{\sum_{i=1}^n n_i d_i^2}$$

Equation 7

d_{32} represents the ratio between total volume to the total surface area of a droplet swarm, thus specific mass transfer area can be calculated with x_d and d_{32} as:

$$a = \frac{6x_d}{d_{32}}$$

Equation 8

When there is no pulsation or only low levels of pulsation, breakage of drops is controlled by the ratio of buoyancy to interfacial tension forces and can be predicted as¹⁰:

$$d_{32} = C_1(\gamma/\Delta\rho g)^{1/2}$$

Equation 9

where C_1 depends on the column geometry, mass transfer and the system used.

When pulsation levels are high, breakage of a drop will occur if the force by motion in the continuous phase exceeds the cohesive forces from viscosity of the dispersed phase and interfacial tension. When the interfacial tension is the dominant factor, drop size can be predicted as¹¹:

$$d_{32} = C_2 \varepsilon^{-0.4} (\gamma / \rho_c)^{0.6}$$

Equation 10

where ε is the power dissipation per unit mass of the phases. When pulsation intensity is at medium levels, empirical equations are used to give predictions for there is still no proper theory to quantify the droplet breakage.

A widely used unified correlation was proposed by Kumar and Hartland to predict drop size in several types of columns including perforated plate columns¹², and this correlation covers all pulsation intensity regions mentioned above:

$$d_{32} = \frac{C_{\Psi}' \alpha^n}{\left[\frac{1}{\left[C_{\Omega}' \left(\frac{\gamma}{\Delta \rho g} \right)^{0.5} \right]^2} + \frac{1}{\left[C_{\Pi}' \varepsilon^{-0.4} \left(\frac{\gamma}{\rho_c} \right)^{0.6} \right]^2} \right]^{1/2}}$$

Equation 11

where $\varepsilon = \frac{2\pi^2(1-\alpha^2)(Af)^3}{3C_0^2\alpha^2h_c}$ and $C_0=0.6$

After the compartment height, h_c , and gravitational constant, g , were taken into account, a dimensionless correlation with better agreement between experimental and predicted data was proposed¹² for predicting d_{32} in a range of solvent extraction columns:

$$\frac{d_{32}}{h_c} = \frac{C_{\Psi}' \alpha^n}{\frac{1}{C_{\Omega}' \left(\frac{\gamma}{\Delta \rho g h_c^2} \right)^{0.5}} + \frac{1}{C_{\Pi}' \left[\left(\frac{\varepsilon}{g} \right) \left(\frac{\rho_c}{g \gamma} \right)^{0.25} \right]^{n_1} \left[h_c \left(\frac{\rho_c g}{\gamma} \right)^{0.5} \right]^{n_2}}}$$

Equation 12

The theory of isotopic turbulence was found to be unsuitable for these systems and was modified for use in pulsed perforated columns¹³. The equation for pulsed and Karr columns became:

$$\frac{d_{32}}{h_c} = \frac{C_{\Psi}' \alpha^{0.32}}{\frac{1}{C_{\Omega}' \left(\frac{\gamma}{\Delta \rho g h_c^2} \right)^{0.5}} + \frac{1}{C_{\Pi}' \left[\left(\frac{\varepsilon}{g} \right) \left(\frac{\rho_c}{g \gamma} \right)^{0.25} \right]^{-0.35} \left[h_c \left(\frac{\rho_c g}{\gamma} \right)^{0.5} \right]^{-1.15}}}$$

Equation 13

Where values for C_{Ψ}' are 1, 0.92, 1.67 for no mass transfer and $c \rightarrow d$ and $d \rightarrow c$ directions of mass transfer, and values for C_{Ω}' and C_{Π}' are 1.55 and 0.42 respectively.

3. Experimental

The two types of novel ceramic internals designed and manufactured for use in this study are shown in Figure 1. 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 this ceramic packing in hybrid ceramic internal is 650 m²/m³. 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 50mm, 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 2¹⁴. 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

In order to measure the drop size in the column, a Perspex cubical viewing box is installed in the middle of the column. Opaque black paper is used to cover all sides of the box except for a thin slit (2.0 mm) on left facade to let in the light from an external flash, and a section on the front facade for viewing the drops. The viewing box should ideally be filled with the continuous phase fluid to prevent distortion effects caused by the curvature of the glass column wall. Due to safety considerations and the similar refractive index between kerosene (1.39) and water (1.33), tap water is used in the viewing box in this study. The drops are photographed using a Cannon PowerShot G16 digital camera. The diameters of the droplets are measured using the software Nano Measurer 1.2. For elliptical drops both the vertical and horizontal axes are measured. Approximately 150–300 droplets per photo are analyzed.

The organic phase used in this study is 30 vol% TBP (tributyl phosphate), supplied by Myer (Shanghai) in Shellsol 2046®, supplied by Shell Australia. The aqueous phase used is tap water. The physical properties, including densities, viscosities and interfacial tension were analyzed and presented in Table 1. This set of liquid-liquid system is a standard one that is widely used in the experiments for many other internals, making it easier to make comparison between these two types of ceramic

internals and other traditional internals. It's also an inevitable step to model the performance of the internals with standard experimental systems in the design of an extraction column before industrial applications, even if the tap water which is used as aqueous phase doesn't contain any Cl ions like the solutions in lithium and rare earth extraction, and the organic phase is different from real systems.

Table 1 Physical properties of the aqueous and organic phases

	Aqueous	Organic
Density (kg/m ³)	1008	844
Viscosity (Pa·s)	1.06 ×10 ⁻³	2.05×10 ⁻³
Interfacial tension (mN/m)	10.1	

4. Results and discussion

4.1. Holdup

Dispersed phase holdup is measured by the volume displacement method¹⁵. Experimental holdup for both types of ceramic internals are shown in Figure 3 and Figure 4, in which the effects of pulsation intensity and phase ratio 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. With an increase of pulsation intensity, holdup decreases at first and then increases after reaching a minimum value at $(Af)_m$. This can be explained by a change in flow regimes, at lower pulsation intensity in the mixer-settler region, dispersed phase tends to accumulate under the plates, increasing pulsation intensity makes it easier for dispersed phase to get through, leading to a reduction in holdup in this region. In the dispersion and emulsion region, most of the dispersed droplets pass through the internals easily, and higher energy input results in smaller drop size and lower rising velocity, thus higher holdup. $(Af)_m$ is predicted from Equation 4, and it agrees well with the experimental

observations. With an increase of continuous-dispersed phase ratio, holdup decreases accordingly, which can be explained by smaller dispersed phase flow rate. Figure 3 and Figure 4 also show that the holdup of the hybrid ceramic internals is higher than that of the ceramic plates alone. A clearer comparison is shown in Figure 5, in which hold up of both internals are compared under two pulsation conditions while the dispersed phase superficial velocity varies from 6×10^{-4} to 3.5×10^{-3} m/s. With an increase of dispersed phase flow rate, holdup increases accordingly. Under all pulsation conditions, the holdup of the hybrid ceramic internals is higher than that of the ceramic plates.

Figure 3 Effect of pulsation intensity (A_f) and phase ratio (V_c/V_d) on holdup (x_d) of hybrid ceramic internals (solid line is predicted data using refitted Equation 3)

Figure 4 Effect of pulsation intensity (A_f) and phase ratio (V_c/V_d) on holdup (x_d) of ceramic plates (solid line is predicted data using refitted Equation 3)

Figure 5 Effect of dispersed phase superficial velocity (V_d) on holdup (x_d) of the two different ceramic internals (solid line is predicted data using refitted Equation 3)

In order to predict holdup using these two new types of internals, correlations are proposed based on Equation 3 and Equation 4. Accuracy of the prediction is measured with the average absolute relative deviation (AARD) which is defined as:

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

Equation 14

The parameters suggested by Kumar and Hartland⁸ when mass transfer direction is from continuous to dispersed phase ($c \rightarrow d$) result in an AARD for both internals of 35.2%, which is likely to be a result of the difference of internal structure and materials between this study and the previous study. To get a better prediction (as shown by AARD values in Table 2 and Figure 6), the two parameters k_1 and k_2 in Equation 3 are refitted and shown in Table 2:

Table 2 Original and refitted parameters in Equation 3⁸ for holdup prediction in this study

Internals	k_1	k_2	AARD
Hybrid ceramic internal	1.81×10^6	88.88	5.9%
Ceramic plate	1.28×10^6	33.63	9.3%
Literature value	2.10×10^6	44.53	35.2%

Figure 6 Comparison between experimental and predicted holdup using Equation 3⁸ with refitted parameters for ceramic internals

With the refitted parameters, the AARD for the hybrid ceramic internals and ceramic plates are reduced to 5.9% and 9.3% respectively. The predicted holdup is also compared with experimental data in Figure 3, Figure 4 and Figure 5, and the predicted holdup (shown by solid lines) agrees well with the experimental data shown as discretized points. A more systematic comparison is shown in Figure 6, in which the deviation between prediction and experiments are within 20%.

Figure 7 Characteristic velocity plots for the two types of ceramic internals (A) Hybrid ceramic internal;
(B) Ceramic plate

Figure 8 Comparison of characteristic velocities (V_0) of two types of ceramic internals in the emulsion region as a function of pulsation intensity (Af)

Characteristic velocity is a key parameter that connects hold up and flooding superficial velocity, thus it is a key parameter for calculating the throughput of a solvent extraction column^{16, 17}. It is

identified as the mean relative velocity of the droplets extrapolated to zero flow rates and can be expressed with V_0 in Equation 15:

$$V_s = \frac{V_d}{x_d} + \frac{V_c}{(1 - x_d)} = V_0(1 - x_d)$$

Equation 15

Here slip velocity V_s was used to relate the dispersed phase holdup to the phase flow rates. It can be taken as the relative velocity between the two phases¹⁸. Equation 15 can be rewritten as Equation 16, thus the characteristic velocity can be calculated from the slope of the plot of $V_d + V_c x_d / (1 - x_d)$ against $x_d(1 - x_d)$:

$$V_d + \frac{V_c x_d}{1 - x_d} = V_0 x_d(1 - x_d)$$

Equation 16

Figure 7 shows the data used to calculate the characteristic velocity for hybrid ceramic internals and ceramic plates. The regressed straight lines cross the origin point, and the experimental data under a given pulsation intensity are close to the line. This agreement shows that this theory explains the mechanism of two-phase interaction well. One point that should be noted is that characteristic velocity is defined in the dispersion and emulsion region, so the calculation is only performed when pulsation is greater than $(Af)_m$, which for this study is calculated to be $9.23 \times 10^{-3} \text{m/s}$.

The two sets of characteristic velocities calculated for both types of internals are shown in Figure 8, and are both found to decrease with an increase of pulsation intensity. The characteristic velocities of the hybrid ceramic internal are smaller by around 40% than that of the ceramic plates, which is a result of lower holdup in the ceramic plate.

4.2. Drop size

Figure 9 shows experimental d_{32} for two types of internals under different pulsation intensities and continuous-dispersed phase ratios. Pulsation intensity varies from 0.3 to 2.4 cm/s, while phase ratio varies from 0.5 to 2. Results show that d_{32} for both internals decreases with an increase of pulsation intensity, and it decreases more dramatically when pulsation intensity is low. Results also show that both phase flow rates, indicated by continuous-dispersed phase ratio in this case, have little effect on drop size. This shows that the energy input is the dominant factor in determining drop size. In all cases considered in this investigation, drop size obtained with the hybrid ceramic internals is smaller than that of ceramic plates. This fact, together with the higher holdup of hybrid ceramic internals, gives larger mass transfer area for this internal and thus is likely to result in better mass transfer efficiency. Figure 10 shows the d_{32} under different dispersed phase flow rate, and also the comparison between the two types of internals. Experimental results show that dispersed phase flow rate has little effect on d_{32} .

Figure 9 Effect of pulsation intensity (Af) and phase ratio (V_c/V_d) on drop size (d_{32}) of ceramic plate and hybrid ceramic internal (solid lines are predicted data using refitted Equation 13)

Figure 10 Effect of dispersed phase superficial velocity (V_d) on drop size (d_{32}) of ceramic plate and hybrid ceramic internals (solid lines are predicted data using refitted Equation 13)

In order to predict d_{32} for these two types of ceramic internals, a correlation is proposed based on Equation 13. Accuracy of the prediction is measured with AARD. The parameters suggested by Kumar and Hartland¹² when mass transfer direction is $c \rightarrow d$ are checked but the overall AARD is found to be 27.8%, which may be a result of different internal structure and materials from the original study. To improve the prediction, parameters C_{ψ}' , C_{Ω}' , and C_{Π}' in Equation 13 are refitted and shown in Table 3:

Table 3 Original and refitted parameters in Equation 13 for d_{32} prediction¹²

Internals	C_{ψ}'	C_{Ω}'	C_{Π}'	AARD
Hybrid ceramic internal	0.909	12.15	0.231	13.6%
Ceramic plate	1.043	4.06	0.384	4.2%
Literature value	0.920	1.55	0.420	27.8%

With the refitted parameters, the AARD for hybrid ceramic internals and ceramic plates are reduced to 13.6% and 4.2% respectively. The predicted d_{32} is also compared with experimental data in Figure 9 and Figure 10, and the predicted results, shown by solid lines, agree well with experimental data which are shown as discretized points. A more systematic comparison is shown in Figure 11, in which the deviation between prediction and experiments are mostly within 20%.

Figure 11 Comparison between experimental and predicted d_{32} with refitted parameters using Equation

13¹²

■ Conclusions

Two types of novel anti-corrosive ceramic internals for a pulsed solvent extraction column were designed and experiments were performed to compare their hydrodynamic performance. The conclusions from this study can be summarized as follows:

1. Holdup of hybrid ceramic internal is higher than that of ceramic plate by around 50%. Holdup of both types of internals decreases first and then increases with an increase of pulsation intensity. Increasing dispersed phase velocity also increases holdup.

2. A correlation for holdup is chosen from literature and the parameters are refitted to better predict the holdup. For the two types of internals, holdup is correlated with AARD of 5.9% and 9.3% respectively.
3. Characteristic velocities of both types of internals are calculated using holdup data from the emulsion region and the results from the hybrid internal are lower than that of ceramic plate. All characteristic velocities decrease with an increase of pulsation intensity.
4. Sauter mean diameter d_{32} of hybrid ceramic internal is smaller than that of ceramic plate by around 40%. All d_{32} decrease with an increase in pulsation intensity, while flow rates of both phases have little effect.
5. A correlation for d_{32} is chosen from literature and the parameters are refitted to better predict the experimental data. For the two types of internals, d_{32} is correlated with an AARD of 13.6% and 4.2% respectively.

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■ Nomenclature

A: Amplitude, m

$(Af)_m$: Pulsation intensity corresponding to minimum in holdup curve, m/s

AARD: average absolute value of the relative deviation, dimensionless

C_0 : discharge coefficient for flow through holes in the perforated plate=0.6, dimensionless

C_1, C_2 : parameters in Equation 9 and Equation 10, dimensionless

C_ψ, C_Π, C_Γ : parameters in Equation 6, dimensionless

$C'_\psi, C'_\Pi, C'_\Omega$: parameters in Equation 11 to Equation 13, dimensionless

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

f: frequency, Hz

g: acceleration due to gravity, m/s^2

h_c : compartment height, m

k_1 to k_2 : constants in correlations, dimensionless

v_c : volume of the continuous phase for the effective length of the column, m^3

v_d : volume of the dispersed phase for the effective length of the column, m^3

V : superficial velocity, m/s

V_0 : characteristic velocity, m/s

V_s : slip velocity, m/s

x_d : volume fraction holdup of the dispersed phase, dimensionless

Greek Symbols

α : fractional free area of perforated plate, dimensionless

$\beta = \frac{\alpha^2}{(1-\alpha)(1-\alpha^2)}$, dimensionless

ε : mechanical power dissipation per unit mass, W/kg

γ : interfacial tension, N/m

μ : viscosity, Pa.s

ρ : density, kg/m³

$\Delta\rho$: density difference between phases, kg/m³

$$\chi = \frac{Af}{(\beta h)^{\frac{1}{3}}} \left(\frac{\mu_d^2}{\sigma \Delta\rho} \right)^{1/4}, \text{ m}^{11/12} \text{s}^{-1}$$

Subscripts

c : continuous phase

d: dispersed phase

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