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Review paper
Pregledni rad

HYDRODYNAMICS AND MASS TRANSFER IN A VIBRATING PLATE EXTRACTION COLUMNS

HIDRODINAMIKA I PRENOS MASE U EKSTRAKCIONIM KOLONAMA TIPA VIBRACIONE PLOČE

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ABSTRACT

In this work experimental data available in the literature presenting the results of different studies on hydrodynamics and mass transfer in two-phase liquid-liquid (L-L) extraction columns with vibrating perforated plates (VPE) were considered. The data for different two-phase L-L systems were analyzed. The following hydrodynamic characteristics were observed: the mean drop diameter, dispersed-phase hold-up, relative velocity, and flooding velocity. The influence of operating parameters such as the agitation speed, superficial velocity of the continuous and dispersed phases, and the direction of mass transfer on the hydrodynamic characteristics of the VPE column was established. Empirical correlations for the prediction of hydrodynamic characteristics based on the data for operating parameters: column geometry, and physical properties of the fluids were presented and analyzed from the point of view of applicability. In addition, the mass transfer coefficients in VPE columns were presented and commented.

Keywords: *agitation speed, dispersed-phase hold-up, Sauter mean drop diameter, mass transfer coefficient.*

REZIME

U ovom radu analizirani su eksperimentalni rezultati, preuzeti iz literature, a odnose na ispitivanje uticaja radnih parametara na hidrodinamiku i prenos mase u ekstrakcionoj koloni sa perforiranim vibracionim pločama (VPE). Razmatrani su podaci za različite dvofazne sisteme tečno-tečno (T-T). Analizirane su sledeće hidrodinamičke karakteristike: srednji prečnik kapi, sadržaj dispergovane faze, relativna brzina faza i brzina plavljenja.Utvrđeno je da postoji uticaj radnih parametara, kao što su brzina agitacije, površinske brzinekontinualne i dispergovane faze, kao i smer prenosa mase na hidrodinamičke karakteristike

VPE kolone. Empirijske korelacije za predviđanje hidrdinamičkih karakteristika na osnovu podataka o radnim parametrima: geometriji kolone i fizičkim svojstvima tečnih fluida su prikazane i analizirane sa stanovišta primenljivosti. Pored toga, predstavljeni su i komentarisani keficijenti prenosa mase u VPE kolonama.

Ključne reči: *brzina agitacije, sadržaj dispergovane faze, Sauterov srednji prečnik kapi, koeficijent prenosa mase.*

INTRODUCTION

Liquid-liquid extraction (so called solvent extraction) is the separation of one or more components from a liquid solution through contact with another immiscible or partially immiscible liquid. It belongs to the type of counter-current diffusion separation operations and is considered to be the second most common operation in industrial practice, right after distillation (*Mohanty and Vogelpohl, 1997)*. Solvent extraction is used in various industrial processes, such as the chemical and petrochemical industries, biotechnology, hydrometallurgy, nuclear industry, waste water treatment, etc. (*Robbins and Cusak, 1999; Sovilj, 2004*). Liquid-liquid (L-L) extraction is very common in the food industry, especially for purification, separation of components and production of high-quality ingredients. It is used for the purification of oils and fats, the removal of caffeine, the isolation of aromas, odors and colors, as well as for the separation of functional ingredients from complex mixtures, ensuring the efficiency and high quality of the product. There are different types of mechanically agitated extraction columns in practice, such as the Kühni column, the Karr column with vibrating mixers, the rotary disc contactor (RDC), the Hanson mixer-settler column, the Scheibel column, the asymmetric rotary disc contactor (ARDC), etc. (*Pratt and Stevens, 1992*; *Simons, 1983*). The hydrodynamic characteristics of some of these extraction columns are presented in our previous works (*Sovilj et al., 2019; Sovilj and Spasojević, 2020*; Sovilj and Spasojević, 2021). In the paper (*Veljković et al., 2024*) was reviewed the fundamental research and application of reciprocating plate extractors in Serbia in the period from 1970 to 2020. Hydrodynamics and mass transfer were analyzed, such as the pressure drop, power consumption, dispersed phase hold-up, axial dispersion, liquid mass transfer coefficient, specific interfacial area, and volumetric mass transfer coefficient. The vibrating perforated plate extractor (VPE) belongs to the group of columns with mechanical agitation and has significant advantages over conventional extraction devices. In addition to suitable column dimensions (diameter and height) and appropriate perforated plate design, the VPE extractor has a number of parameters that can be adjusted as a function of used frequencies and amplitudes, free plate surface, phase flow and device capacity. The VPE column was developed *by Prohazka et al. (1971*). There are two variants of this column used in industrial practice. The first variant has perforated plates on a vertical shaft with a large number of small holes through which the dispersed phase moves, ensuring the direct movement of the plates (*Figure 1.)*. In the second variant of the same extractor, the perforated plates are placed on two vertical shafts moving with the same amplitude and frequency, but with a phase shift of π rad. This way of shaft movement achieves counter-current movement of perforated plates, which increases the extraction efficiency in the device. This type of extraction device has found application in industrial practice, with the largest internal diameter of commercial columns being about 120 cm. The main difference between the VPE and the Karr column is that the former has small holes on perforated plates (smaller free surface of holes) and chambers for phase separation, while the latter has larger diameter holes (larger free surface of holes) on the plates and no phase separation chambers. The VPE column operates at relatively small amplitudes and frequencies compared to the Karr column, which means that it has less mechanical stress and energy consumption (Lo *et al*., 1983). At the same time, it has been found that the Karr column consumes more energy to achieve the same values of the mass transfer. At the same time, it has been found that the Karr column consumes more energy to achieve the same values of the mass transfer coefficient than the VPE column (*Ioannou et al., 1976*).

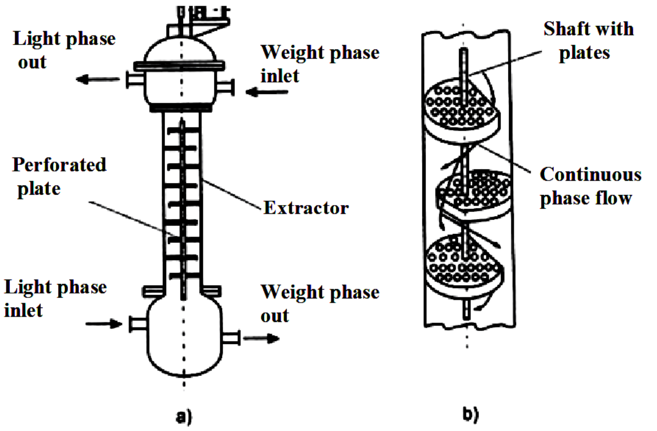

Fig. 1. Schematic representation of an extraction column with vibrating perforated plates: a) vibrating column; b) flow of continuous phase through the column (Reprinted from Sovilj, 2004).

The vibrating perforated plate column consists of the vertical tube with height of 205 cm and diameter of 5 cm (Figure 1). The perforated plates (9 pieces), each of which had a 40 mm with a 2 mm opening, are mounted on a vertical shaft driven by a motor located at the top of the column.

The aim of this paper is to present and analyze the experimental results for the hydrodynamic characteristics of vibrating plate extraction (VPE) columns taken from the literature regarding the treatment of various two-phase liquid-liquid systems. The following quantities were observed as hydrodynamic characteristics: the mean drop diameter, the dispersed-phase hold-up, slip velocity, and flooding velocity. The influence of operational parameters (agitation speed, continuous and dispersed-phase superficial velocities, and mass transfer direction) on the hydrodynamic characteristics of the VPE column is considered. The application of empirical relations developed as a function of hydrodynamic characteristics of operational parameters, column geometry, and physical properties of two-phase systems are analyzed. The influence of hydrodynamic characteristics on the mass transfer performance in the VPE column is also checked. The mass transfer parameters in this extraction column are considered.

NOMENCLATURE

Symbols

A (m) - amplitude of vibration
A f (m/s)- vibrating speed
A f₀ (m/s) - critical value of vibration speed (*A f₀ = 1.9 cm/s*)
a (m^2/m^3) - interfacial area
d_{32} (m) - Sauter mean drop diameter
d_0 (m) - mean drop diameter in the absence of plate vibration
d_{0p} (m) - hole diameter on perforated plate
E_{ka} - enhancement factor with respect to mass transfer coefficient
f (1/s) - vibrating frequency
K_0 a (1/s) - volumetric mass transfer coefficient
K_{0c} a (m/s) - overall mass transfer coefficient in the continuous phase
L (m) - column height (cm)
m - slope of equilibrium line
n_i - number of drops of diameter d_i
NN - overall number of drops in the dispersion
U_c, U_d (m/s) - continuous- and dispersed-phase superficial velocity, respectively
U_0 (m/s) - dispersed phase velocity on hole of perforated plate
X - variable defined by Equation (4)
X_{out} - (m x_{out}/y_{in}) dimensionless solute concentration in continuous phase at outlet
x_{out} (mol/m^3) - solute concentration in continuous phase at outlet
y_{in} (mol/m^3) - solute concentration in dispersed phase at inlet (mol/cm^3)

Geek symbols

ε_d - dispersed-phase hold-up in the presence of disc vibration
ε_{d0} - dispersed-phase hold-up in the absence of disc vibration
$\Delta\rho$ (kg/m^3) - density difference
γ - $\gamma = U_c / (m\ U_d)$, extraction factor
σ (N/m) - interface tension.

Abbreviations

HETS (cm) - height equivalent to theoretical stage ratio
HTU (cm) - height of transfer unit
NTU - number of transfer unit.

HYDRODYNAMICS

Tojo et al. (1975) investigated a multistage extraction column with vibrating discs (MCVD). The column was made of eight Pyrex-glass cylinders, with an inner diameter of 50 mm and a height of 38 mm, each of which had a 40 mm diameter vibrating plate with a 2 mm opening. The vibration of the plates was achieved by means of a centrally placed shaft connected to two electric motors at the top of the cylindrical tubes, so that the plates could vibrate or rotate. The vibration amplitudes were adjusted by changing the length of the cam arm. In this study methyl isobutyl ketone (MIBK)-acetic acid-water system was used. Water was introduced as the continuous phase at the top of the column, while the MIBK, as the dispersed phase, was introduced at the bottom of the column. Mass transfer (acetic acid) was achieved from the dispersed to the continuous phase. The values of the dispersed-phase hold-up were determined by the method of simultaneously stopping the flow of the dispersed and continuous phases and measuring the interface between the phases. All experiments were performed at a constant room temperature of 22 ^{0}C. In the same paper, the measured values of the dispersed-phase hold-up for the MCDV extractor in the counter-current flow of the phases were correlated using the following equation:

$$\varepsilon_d = \varepsilon_{d0} + 0.30 U_d (Af - Af_0) \qquad for Af \geq Af_0$$

$$\varepsilon_d = \varepsilon_{d0} for Af \langle Af_0$$

On the other hand, based on photographic measurements, in the same paper an influence of agitation speed on the Sauter mean drop diameter was determined, as shown in the following expression:

$$\frac{d_{32}}{d_0} = 0.41 (Af)^{-0.53} for Af \geq 0.2\ cm/s$$

$$\frac{d_{32}}{d_0} = 1.0 for Af \langle 0.2\ cm/s$$

Heyberger et al. (1983) presented the results of determining the dispersed-phase hold-up and the limit values of the phase flow in an experimental VPE column. The extraction column had five different diameters, and the obtained experimental data for the relative velocity of the phases were compared with the results from the literature. A two-phase toluene-water system was used in the experimental work, with toluene as the dispersed and water as the continuous phase. Empirical relations were determined to demonstrate the dependence of the dispersed- phase hold-up on the flow of the phases. These relations also enabled satisfactory determination of boundary phase velocities. Within the range of values under experimental operating conditions, the data on the characteristic velocity and the limit values of phase velocities were obtained approximately, using the linear dependence of the frequency applied in this work. The same work determined that the extraction column height did not affect the limit value of phase velocity. On the other hand, the deviation of individual columns from geometric similarity had a significant impact on the dispersed-phase hold-up and flooding velocity. Such effect was explained by the notion of the dispersed-phase hold-up longitudinal profile, the shape of which depended on the boundary conditions in a particular column. This explanation was supported by research using the polydisperse mathematical model in the presence of a dispersed-phase hold-up profile, showing that the influence of phase velocities on the dispersed-phase hold-up could be correlated with constant parameter relationships that depend on the dispersed-phase hold-up profile.

Sovova (1986) developed a computer simulation (polydisperse) model for the calculation of the dispersed-phase hold-up in the VPE extractor. In this model, the equations describing the motion, breaking, and coalescence of drops were solved simultaneously, with the degree (sub)divided into two parts: the inner part and the part related to dense packing of the dispersion layer on the plate. A simulator for the results verification was used to predict and analyze the stationary dispersed-phase hold-up and its dynamics. The simulator could help in the design of a VPE column or pulsation extractor with perforated plates. The dispersed-phase hold-up was experimentally determined for a system in which toluene was dissolved in water in the absence of mass transfer. The simulation using the developed model brought satisfactory results in the form of standard deviation (6%) for the whole range of extractor modes, from the mixer-separator to the emulsion. In accordance with the considerations presented in the paper (*Boyadzhiev and Spassov, 1982*), the Sauter mean drop diameter was defined, and expressed by the following equation:

$$d_{32} = \sum_{i=1}^{NN} n_i d_i^3 / \sum_{i=1}^{NN} n_i d_i^2 \; (3)$$

In the research (*Baird et al., 1991*), was found that the frequency of vibration affected the size of the drop diameter significantly more than the amplitude of vibration. It was also suggested that the data for the phase flow ratio and the given system could be very well correlated as a function of the agitation speed squared ($(A{\cdot}f)^2$). The axial mixing and countercurrent mass transfer characteristics of a 5 cm diameter extraction column agitated by vibrating perforated Teflon plates have been investigated. The dispersed phase was an organic liquid (usually kerosene) and the continuous phase was water. Axial mixing was measured in both phases using pulse tracer techniques; in the continuous phase the axial mixing was estimated to have a significant effect on mass transfer, but axial mixing in the dispersed phase had a negligible effect. Mass transfer was measured for several different solutes; *n*-butyric acid, benzoic acid and phenol. The overall heights of a transfer unit (cont. phase) were in the order of 10-20 cm for the organic-acids but higher for transfer of phenol from very dilute solutions. The characteristics of the vibrating plate column have been compared with those of other types of extractor and suggestions are made for further development.

In the paper (*Bensalem, 1985)* a comprehensive study related to the research of hydrodynamics and mass transfer in a pilot VPE column with a diameter of 7.6 cm was presented, using plates with larger hole diameters and free surface. It was shown that the Sauter mean drop diameter and droplet size distribution, the dispersed- phase hold-up, and the axial dispersion coefficient in both phases can be determined in the presence and absence of mass transfer, using the two-phase toluene (dispersed phase)-acetone-water (continuous phase) system. At the same time, it was possible to compare the experimental data from this paper with the previously published results. The value of the axial dispersion coefficient in the dispersed phase was higher than the coefficient measured in the continuous phase, since the combined effect of forward and backward mixing was more present in the dispersed phase. It was found that the direction of mass transfer between the phases has the same effect on the hydrodynamics of the column, as is the case when measuring the mean drop diameter and the dispersed-phase hold-up.

In accordance with the considerations of *Boyadziev and Spassov* (1982), the Sauter mean drop diameter was defined and expressed by the following equation:

$$d_{32} = \rightleftarrows\rightleftarrows\rightleftarrows\; 0.0001\, exp(-X)$$

where:

$$X = 9.98x10^{-5}(Af)^2 d_{0p}^{0.5} U_0^{-1.2} U_d^{-1.5} \Delta\rho^{-1} \sigma^{-0.4}$$

Rama Rao et al. (1991) presented the results of determining the hydrodynamic behavior of several two-phase liquid-liquid systems in a VPE column of a 5 cm diameter, in which perforated plates were agitated at frequencies (*f*) of 10-100 Hz and amplitudes (*A*) from 0.024-1.5 mm. The Sauter mean drop diameter (d_{32}) ranged from 0.1 to 1 mm. In this paper, an empirical correlation was developed as a drop diameter function of the agitation speed ($(A{\cdot}f)^2$), operational parameters, and physical properties of two-phase systems. The dispersed-phase hold-up (ε_d), when given as a function of the agitation speed, had a minimum value during the transition from the mixer-separator to the transition regime. On the other hand, the dispersed-phase hold-up was a function of the mass transfer direction between the phases. The formation of small drops in the continuous phase occurred at high agitation speed values, but was reduced by adding a coalescent plate at the bottom of the extraction column. Entrainment of fine droplets in the continuous phase occurs at high agitation levels, but can be reduced by the addition of coalescence plates at the base of the column. Energy dissipation rates greatly exceed predictions from the quasi-steady-state model.

In the literature (*Jong-Dae et al.,* 1990), axial dispersion and phase hold-up characteristics have been determined in a 0.102-m i.d. × 3.5 m high QVF glass column. The axial dispersion coefficient decreases with increasing reciprocating frequency and amplitude in the homogeneous dispersed phase flow regime, whereas it increases in the emulsion flow regime. The axial dispersion coefficient with a perforated plate increases with continuous and dispersed phase velocities. However, the effect of phase velocities on axial dispersion is less pronounced with the fan plate. The axial dispersion coefficient can be correlated with Af, fluid velocities, and the free fractional opening area of the plates. The dispersed phase hold-up increases with an increase in agitation intensity and decreases with the free opening are of the plate. *Rathilal et al. (2011)* investigated the hydrodynamics of a VPE column with an inner diameter of 4.77 cm and a hole diameter on the perforated plate of 2.98 mm in the presence of mass transfer, using the standard two-phase toluene-acetone-water system. It was found that the hydrodynamic characteristics (dispersed-phase hold-up, mean drop diameter, and drop size distribution) could not be investigated without the presence of mass transfer for the purpose of predicting the behavior of a two-phase system during mass transfer. The dispersed-phase hold-up was lower in the case of column operation without mass transfer between the phases, which was a consequence of the transition of part of the solute from the dispersed to the continuous phase. The opposite occurred during the transition of the solute from the continuous to the dispersed phase, where the dispersed-phase hold-up was higher than in the absence of mass transfer. The drop size distribution had a wider range during the mass transfer. The Sauter mean drop diameter was larger (especially in the mixer-separator regime) due to the increased influence of coalescence on mass transfer in the column. For these reasons, it was necessary to work in the presence of mass transfer when determining the hydrodynamic characteristics of VPE column (*Rathilal et al., 2011).* As the main operational parameter, the agitation speed (product of frequency and amplitude) had a significant influence on the hydrodynamic characteristics of the VPE column. An increase in the agitation speed resulted in the formation of small dispersed-phase drops, i.e. a decrease in the Sauter mean drop diameter, and a significant increase in mass transfer in the VPE column, (*Figure 2*). In the mixer-separator regime, a large difference was observed between the Sauter mean drop diameter related to hydrodynamics with or without mass transfer, while this difference was minimal during the dispersion regime of operation. The extraction column functioned in a very stable manner close to the conditions corresponding to the flooding point.

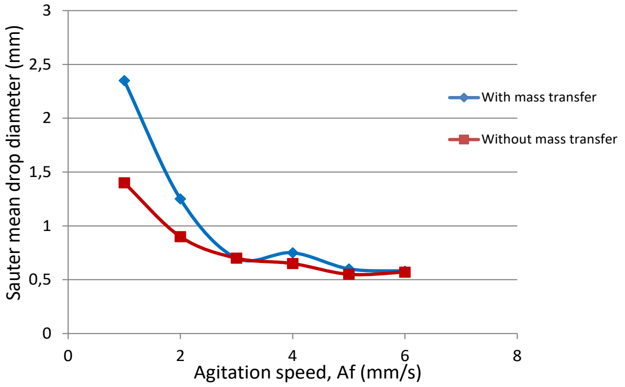

Fig. 2. Effect of the agitation speed (A·f) on the Sauter mean drop diameter (d_{32}) in the toluene-acetone-water system (Reprinted from Rathilal et al.˒ 2011).

*Sincuba et al. (*2015) examined the influence of operating parameters on the hydrodynamic characteristics of a VPE column with a 4.77 cm inner diameter in a two-phase toluene-acetone-water system. Three types of perforated plates were used, with different plate hole sizes (1.5, 3, and 4.5 mm). The total number of plates was 31. What was, in fact, investigated was the influence of the agitation speed and hole diameter on the perforated plate on the dispersed-phase hold-up, the Sauter mean drop diameter, and drop size distribution. It was found that the mean drop diameter decreased with an increasing agitation speed and decreasing diameter of the holes on the perforated plate. At the same time, it was observed that the dispersed-phase hold-up in the mixer-separator regime decreased with an increasing agitation speed, reaching its minimum value at the agitation speed of 3.75 mm/s in the case of all three tested hole diameters on the perforated plate, (*Figure 3*). In the dispersion regime, increasing the agitation speed led to the dispersed-phase hold-up increase. In this paper, an empirical correlation was developed describing the dependence of the Sauter mean drop diameter on the agitation speed. The dispersed-phase hold-up was correlated as a function of hole diameters on the perforated plate (mixer-separator and dispersion regimes). Perforated plates with a hole diameter of 3 mm proved to be the most efficient.

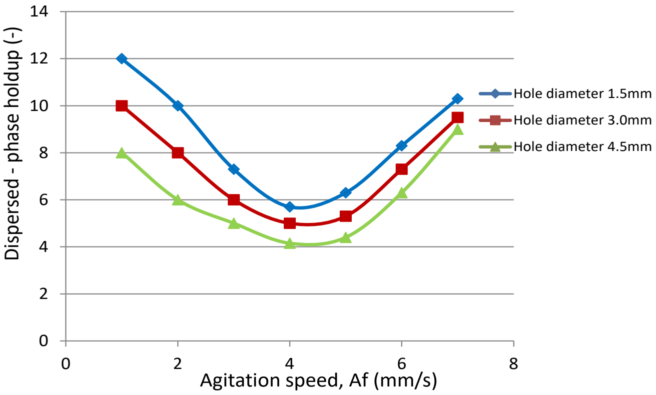

Fig. 3. Effect of hole diameter on perforated plates and agitation speed (A·f) on the dispersed-phase hold-up (ε_d) (Reprinted from Sincuba et al. , 2017).

Sincuba et al. (2017) investigated the influence of different shapes of overflow pipes on the hydrodynamics in a VPE column of the cylindrical glass pipe type, with an internal diameter of 4.77 cm, operating height of 470 cm and hole diameter on the perforated plate of 2.98 mm. A two-phase toluene-acetone-water system was used, with the agitation speed ranging from 1 to 7.5 mm/s. The influence of the perforated plate shape on the dispersed-phase hold-up, the Sauter mean drop diameter, and drop size distribution was investigated. Two types of overflow pipes were used (Type I - cylindrical overflow pipes and Type II - flat overflow pipes). It was determined that Type I gave better results, i.e. a higher dispersed-phase hold-up and a smaller Sauter mean drop diameter, with a higher percentage of extracted solution (95.05%). As shown in *Figure 4.* the value of the Sauter mean drop diameter was greatest when a 4.5 mm hole diameter on the perforated plate was used. This indicates that the Sauter mean drop diameter depends on the hole diameter on the perforated plate and that drops are formed as a function of the hole diameter. On the basis of the above, it can be concluded that the Sauter mean drop diameter depends primarily on the agitation speed and the hole diameter on the perforated plate.

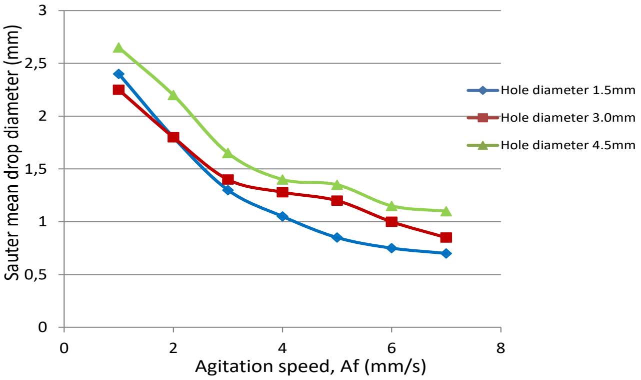

Fig. 4. Effect of the agitation speed (A·f) and hole diameter on the perforated plate on the Sauter mean drop diameter (d_{32}) with a perforated plate of Type I (Reprinted from Sincuba, et al., 2017).

Despite the fact that the efficiency of VPE columns has been well studied, there is relatively limited data on the influence of free surface on perforated plates, solvent-starting mixture ratio, and agitation speed on the dimensions of these extraction columns (*Nandoo, 2012).* These parameters affect the hydrodynamics of VPE columns and mass transfer, which means that the determination of optimal process parameters is very important in the process of achieving the highest VPE column efficiency. The standard two-phase toluene-acetone-water system was selected for the experimental work carried out in a VPE column. The aim of this study was to test the influence of free surface on the perforated plates and the agitation speed, as well as the relationship between the continuous and dispersed phase rates on the number of required steps (plates) in order to optimize the efficiency of the VPE column. The experimental data for the Sauter mean drop diameter and the dispersed-phase hold-up were determined at different operational parameters (agitation speed, superficial phase velocities and direction of mass transfer between the phases). It was concluded that there was a decrease in the value of dispersed-phase hold-up with increasing solvent-starting mixture ratio, while an increasing agitation speed resulted in a decrease of the Sauter mean drop diameter. On the other hand, low values of free surface on the perforated plates caused higher values of extracted acetone. The presence of a higher value of back mixing in the dispersed phase affected a larger number of necessary contacts in the column.

In the literature (*Nemecek and Prochazka, 2009*) longitudinal mixing in the continuous phase of an extractor with vibrating plates was investigated. Special attention was focused on the effect of the dispersed phase flow, which turned out to be of great importance. Three regimes can be observed that show distinctly different character of longitudinal mixing. The flow within the stage was studied in detail and it was shown that the stage can be divided into two regions with different flow characteristics. A model was proposed that accounts for the total longitudinal mixing effect from the return flow through the plate plus the axial dispersion within the stage. Correlations were proposed that link the axial dispersion coefficient with hold-up and droplet diameter.

MASS TRANSFER

Axial mixing in extraction columns is known to reduce the overall mass transfer. It was found that in the case of the MCDV extractor (*Tojo et al., 1975*) an increased value of agitation speed caused an increase in axial mixing. In the general case, the axial mixing coefficient in the continuous phase was determined by means of a one-dimensional dispersion model using the method of pulse injection of an aqueous solution of 0.1 KCl. The results obtained in this work showed that the values of the axial mixing coefficients were very low, amounting to about 2 cm^2/s in the absence of emulsification conditions. The data for the mass transfer coefficient determined in this paper were analyzed on the basis of the assumption of plug flow of the fluid. Based on this assumption, the overall mass transfer coefficient was shown by the following relation *(*Tojo *et al.,* 1975):

$$K_0 a = \frac{U_c}{L} \rightleftarrows\rightleftarrows\rightleftarrows\rightleftarrows \frac{1}{(1-\gamma)} \ln \frac{X_{out}\gamma-1}{X_{out}-1}$$

In the paper (*Tojo et al., 1975*) it was concluded that the effect of the dispersed-phase velocity on the overall continuous-phase mass transfer coefficient based on the continuous phase was significant. The relation between the mass transfer coefficient and dispersed-phase superficial velocity was similar to that of the dispersed-phase hold-up *vs* U_d.. On the other hand, the effect of the continuous phase on the $K_0 a$ was negligible in the range studied. The value of the $K_0 a$ in the absence of disc vibration was empirically correlated:

$$K_o a = \rightleftarrows\rightleftarrows 0.015 U_d$$

In this paper was found that the mass transfer rate increased with increasing agitation speed. A much slower rate was observed at higher values of agitation speed. The enhancement factor can be correlated with agitation speed using the following equation:

$$E_{ka} = 1 \rightleftarrows\rightleftarrows +0.34 \rightleftarrows\rightleftarrows (Af)^{1.6}$$

Figure 5 shows the dependence of the extracted acetone percentage in the two-phase toluene-acetone-water system on the agitation speed (*A·f*), at three different values of the solvent-initial mixture flow ratio (*S/F*) and two distances between two adjacent holes on the perforated plate[20]. It can be seen that the percentage of extracted acetone increases with increasing the agitation speed, with the highest values being obtained when using the highest ratio of solvent flow to the flow rate of the starting mixture (*S/F* = 2: 1). As mentioned earlier, the efficiency of mass transfer increases with increasing the specific interfacial area available for mass transfer. This is also true in the case presented in *Figure 5.,* which shows an increase in the amount of extracted acetone. The explanation for this trend lies in the fact that the extraction efficiency is higher for a higher *S/F* ratio because there is more available solvent used to remove acetone, thus increasing the acetone concentration gradient. When the distance between the centers of adjacent holes on the perforated plate increases (up to 20 mm), the extraction efficiency is drastically reduced, since there are far fewer mass transfer units to achieve adequate mass transfer. However, the extraction column examined was not close to its flooding conditions at an agitation speed of 7.5 mm/s, as was the case during operation with a 10 mm distance between the centers of adjacent holes on the perforated plate. As a consequence of such behavior, the agitation speed may increase beyond these limits before flooding is formed in the column, resulting in higher extraction efficiency. Figure 5. also shows that there is an increase in extracted acetone with increasing agitation speed. This percentage is significant when using perforated plates of 1.5 and 3 mm in diameter (*Sincuba et al., 2015).* This effect is a consequence of the reduction of the hole diameter from 4.5 to 3 mm, which results in the presence of a larger number of holes and the formation of smaller drops on the holes in a longer time interval. However, the effect of hole diameter on the perforated plate is not particularly significant when using plates with a hole diameter of less than 1.5 mm. The specific interfacial area available for mass transfer is fully developed with a hole diameter of 3 mm. There is no evidence that more acetone is extracted when using holes smaller than 3 mm, even if the dispersed-phase hold-up is higher and the Sauter mean drop diameter smaller. On the other hand, producing plates with 1.5 mm holes is much more complicated because of more holes needed, which makes the process of making a perforated plate more expensive. The percentage of extracted acetone when using a perforated plate with a hole diameter of 3 mm is slightly lower. A plate with this hole diameter may be cheaper to make than those with smaller hole diameters, which means that the cost of making a plate with smaller hole diameters cannot be justified. For all the reasons mentioned above, it is recommended that perforated plates with a hole diameter of 3 mm be used. *Rathilal et al. (2013*) developed a mathematical model to predict mass transfer characteristics such as the *NTU/HETS* , where *NTU* is number of transfer unit, *HETS* (cm) is height equivalent to theoretical stage ratio and overall mass transfer coefficient for the continuous phase (K_0 c). K_0c is overall continuous-phase mass transfer coefficient in the VPE column, It was based on the plate agitation speed, free plate surface, and phase flow, which contributes to the simplification of the design process of these columns.

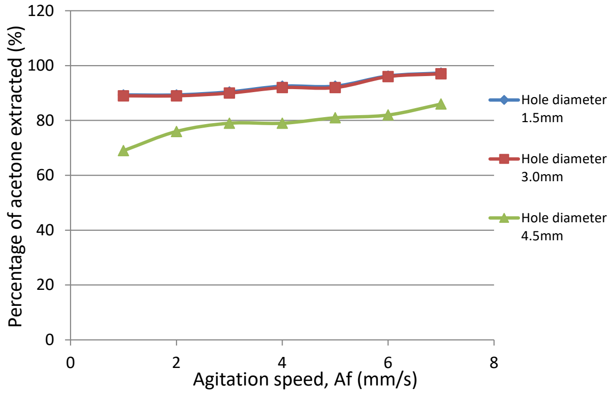

Fig. 5. Effect of the agitation speed (A f) and hole diameter on mass transfer in the dispersion with a perforated plate of Type I (Reprinted from Sincuba et al., 2017).

There are significant numbers of studies related to the development of columns with mechanical agitation, but they are limited to RDC columns and columns with vibrating mixers, with the largest number of studies related to RDC columns. This work used a two-phase toluene-acetone-water system, where toluene (dispersed phase) flew upwards from the bottom of the column, while water (continuous phase) flow in the opposite direction, i.e. from the top of the column. The experiments were set up so as to obtain the hydrodynamics of the dispersed-phase drops moving towards the top of the column (drop size, drop size distribution, and the dispersed-phase hold-up) and the values responsible for mass transfer: *NTU*, K_{oc} and *HTU*, where *HTU* is height of ransfer unit. On the other hand, the influence of mass transfer on the hydrodynamics of the column was investigated, with varied agitation speed and free surface on the column plate. A successful model based on experimental data was developed in the paper. The correlations obtained were verified with additional data. Liquid-liquid mass transfer has been experimentally studied for the kerosene (dispersed)-water (continuous) system in a reciprocating-plate column, using benzoic acid and n -butyric acid as solutes (*Harikrishnan et al., 1994).* The effect of the flow rates of the phases, the agitation rate of the plate stack, the perforation diameter and free area of the plate and the mass transfer direction have been investigated. Correlations for volumetric and mass transfer coefficients have been proposed in terms of power dissipation rate and the physical properties of the system. The mass transfer coefficient is compared with the predictions of the drop models to establish the extent of internal mobility of the dispersed phase droplets.

CONCLUSION

This paper analyzed the experimental results related to the hydrodynamics and mass transfer performance in extraction columns of the vibrating plate (VPE) type, using the data for different two-phase liquid-liquid (L-L) systems. Special emphasis was placed on hydrodynamic characteristics such as the mean drop diameter, dispersed-phase hold-up, longitudinal mixing and flooding velocity. The influence of operating parameters (agitation speed, superficial velocities of the continuous and dispersed phases, and direction of mass transfer between the phases) on the hydrodynamic characteristics of the VPE type column was presented. The authors analyzed empirical correlations for the prediction of hydrodynamic characteristics based on the data for operating parameters, column geometry, and physical properties of *L-L* systems. Finally, the values for mass transfer performance in these extraction columns were presented and discussed.

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