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Prediction of drop size distribution in a horizontal pulsed plate extraction column

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ABSTRACT

Mean drop size and drop size distribution in a horizontal pulsed plate extraction column were investigated using different four binary systems. The effects of pulse intensity (af) and flow rates of both liquid phases have been investigated. The drop size decreased more rapidly with the increase of pulse intensities. It was observed that an increase in intensity of the pulses will lead to narrower ranges of distribution for the drop size. Increasing the flow rate of dispersed phase tends to increase the drop size. The effect of continuous phase flow rate is weaker than the effect of the dispersed phase flow rate. By using results, a semi empirical correlation obtained for the estimation of mean drop size which proves to be in good agreement to the experimental data. The average absolute relative error (AARE) of this correlation is about 15.6%. In order to find a predictive correlation for drop size distribution, four models of distribution functions are tested. The normal probability density function is the only suitable way for representing the experimental drop size distributions with an AARE of 13.7%.

1. Introduction

Liquid–liquid extraction is one of the classical methods in separation technology and finds applications in the chemical and petroleum industry, hydrometallurgy, biotechnology, nuclear technology, food industry, waste management, and other areas [1–6]. The efficiency of liquid–liquid contactors is primarily dependent on the degree of turbulence imparted to the system and the interfacial area available for mass transfer. The rate of mass transfer can be enhanced by pulsating motion imparted to the liquids by an external mechanical or electronic device. Internal mechanical parts are eliminated, leakage is minimized, and the pulsator can be isolated [7]. The pulsed columns have a clear advantage over other mechanical contractors when processing corrosive or radioactive solutions, since the pulsing unit can be remote from the column. The absence of moving mechanical parts in such columns slightly obviates repair and servicing. These advantages have led to the application of these columns in chemical, biochemical and petroleum industries [8–10]. The pulsed liquid–liquid extraction columns can be divided as follows:

1. The vertical pulsed columns
   (a) The pulsed sieve plate columns.
   (b) The pulsed packed columns.
   (c) The pulsed disc and doughnut columns.
   (d) The pulsed spray columns.
2. The horizontal pulsed columns
   (a) The horizontal sieve plate columns.
   (b) The horizontal packed columns.

The main advantages and disadvantages of the two types of columns in identical conditions are as follows:

- Throughput of the horizontal pulsed columns is less than the vertical pulsed columns [11].
- The requirement time to start up horizontal pulsed columns is more than the vertical pulsed columns.
- The vertical pulsed columns are proper for industries that there is surface area limitation [12–14].
- The horizontal pulsed columns are proper for industries that there is height limitation [15].
- The mass transfer efficiency for both types of columns is comparable [16].

Therefore, the advantages of vertical pulsed column are more than the horizontal pulsed columns but when we cannot use

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Nomenclature

af pulse intensity (m/s)
d_{32} Sauter mean diameter (m)
d_i drop diameter (mm)
n_i number of droplets of mean diameter d_i
P probability of number density
Q volumetric flow rate (m^3/s)

Greek letters
α constant parameter of probability of density function
β constant parameter of probability of density function
μ viscosity (Ns/m^2)
ρ density (kg/m^3)
σ interfacial tension between two phases (N/m)

Subscript
c continuous phase
d dispersed phase
n normal probability density function

vertical pulsed column because of height limitation for installation as indoor, the horizontal pulsed column can be a proper contactor.

It is well known that the mean drop size and drop size distribution are important parameters in the study and design of the extraction column [17]. In the modeling of liquid–liquid extraction columns, where a dispersed phase exists as discrete drops, an average volume surface diameter is commonly used to predict the interfacial area for mass transfer, contact times and mass transfer coefficients [18–21]. In order to develop appropriate design procedures for a given type of extraction column, a knowledge of average drop size in terms of operating parameters, liquid physical properties is thus of paramount importance. Some investigations have been carried out on the drop size and drop size distribution in vertical pulsed column. Yadav and Patwardhan [22] presented a review on the drop size. Gholam Samani et al. [23] presented an experimental study of the Sauter mean drop size in a pulsed packed extraction column. Usman et al. [24] investigated the effect of the pulse intensity, and the dispersed phase and continuous phase velocities on the Sauter mean diameter. However, it is rare to find such reports about the drop size and drop size distribution of the HPC. A limited investigation has been carried out on the holdup and throughput capacity of the HPC.

It is the first time that, the effect of operating parameters in horizontal pulse column has been studied on mean drop size and drop size distribution. By the use of resulting data two empirical correlations have been proposed for the Sauter mean drop diameter and drop size distribution as a function of operating parameters, physical properties of the liquid systems and active column height.

The average absolute relative error (AARE) was used as an objective function to calculate the fitted parameters:

$$AARE = \frac{1}{n}\sum_{i=1}^{n}\frac{|X_i(exp) - X_i(thoe)|}{X_i(exp)} \quad (1)$$

where n is the number of data points, and X_i(exp) and X_i(theo) represent the experimental and theoretical data, respectively.

Table 1
Geometrical characteristics of the column used.

Material used for settler and column	Glass
Column length (m)	1.46
Column diameter (cm)	6.2
Upper and lower settler diameter (cm)	9
Upper settler length (cm)	60
Lower settler length (cm)	30
Material used for plate	**Stainless steel**
Plate thickness (mm)	1
Hole diameter (mm)	2
Hole pitch (mm)	4
Spacing the plate pairs (cm)	5
Spacing between each plate (cm)	1
Fractional free area (–)	0.22

2. Material and methods

2.1. Description of equipment

Experiments were carried out in a semi-industrial horizontal pulsed sieve plate column. The material used for construction was glass. The active part of column was a pipe housing an internal plate cartridge consisting of 25 pairs of sieve plates constructed from 304 stainless steel. Each plate has perforations 2 mm in diameter, located only over half of the available plate area with a net free area of 22%. They contained 106 circular holes laid on triangular pitch of 4 mm.

The sieve plates were arranged as pairs with 1.0 cm spacing between each plate. The perforations on the plate nearest the light-phase inlet were located on the bottom and the perforations on the plate nearest the heavy-phase inlet were located on the top. Individual cells inside the column were created by spacing the plate pairs 5.0 cm apart. The column characteristics are listed in Table 1. A settler of 9 cm diameter at both ends of the column was employed to separate the two liquid phases. The inlet and outlet streams of the column were connected to four tanks, each of 25 l capacity. The flow rates of the two phases were measured by two rotameters.

The pulsator is an air pulsing system. The interface location of two phases at the top of the heavy-phase inlet and under light-phase outlet in upper settler was automatically controlled by an optical sensor. A solenoid valve (a normally closed type) was provided at the outlet stream of heavy phase. This valve received electronic signals from the optical sensor. When the interface location was going to change, the optical sensor sent a signal to solenoid valve and the heavy phase was allowed to leave the column by opening the diaphragm of solenoid valve. The light phase was allowed to leave the column via an overflow. A schematic diagram of experimental apparatus is shown in Fig. 1.

2.2. Liquid–liquid systems used

Four liquid–liquid systems were chosen to cover a wide range of values of interfacial tension (9.1–46.5 mN/m). The systems were kerosene–water, toluene–water, *n*-butyl acetate–water and butanol–water. First three systems were recommended by the European Federation of Chemical Engineering [25]. The physical properties of these systems are listed in Table 2.

Technical grade solvents were used at least 99.5 wt% purity as the dispersed phase, and the distillated water was used as the continuous phase. All experiments were carried out at the temperature up to 20 °C. The operating conditions of some of the experiments are shown in Table 3.

2.3. Procedure

Initially, the whole column was filled with the water which is considered as the continuous phase. The dispersed phase was then