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Drop motion during mass transfer accompanied by interphase convection

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Abstract

The article deals with the experimental study of the mass transfer of acetic acid from the dispersed phase (butyl acetate) to the continuous phase (water). The experiments were carried out on a laboratory column with single floating drops. The presence of the Marangoni effect during the movement of drops and its influence on the trajectories of movement of drops and the kinetics of mass transfer during extraction are shown. The influence of the Marangoni effect is most clearly observed when the driving force of the process is 0.1...0.2 mol/l.

Keywords

interphase convection
mass transfer
marangoni convection
liquid droplet
continuous phase

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Key findings

- The work shows the presence of the Marangoni effect when a drop of acetic acid solution moves in the extractor.
- Small drops with a diameter of 2.5 mm should move straight like hard drops, but the Marangoni effect causes the drops to deviate from a straight trajectory.
- The Marangoni effect is clearly observed at acetic acid concentrations of 0.5 mol/l and below in a water/butyl acetate extraction system.

1. Introduction

Extraction is used for the selective separation of a wide range of substances (aromatic hydrocarbons, pesticides, antibiotics, etc.) from reaction solutions, culture media, and liquid waste [1]. The calculation of extractors is carried out on the assumption that the mass transfer coefficient is independent of the driving force of the process – the difference between the equilibrium and current concentration of the transferred substance in the media [2, 3]. However, in a number of industrial processes, there is a deviation of the real parameters from the calculated ones [4, 5]. Laterly, these facts have beenere studied by a number of researchers [6, 7]. It has turned out that the mass transfer coefficient can change several times at certain values of the driving force [8].

2. Experimental

Experiments to determine the velocities of the droplets and study the kinetics of mass transfer were carried out in a thermostated column (Figure 1) made of borosilicate glass. The column was 1000 mm high and 75 mm in inner diameter.

The dispersed phase was fed into the column through a steel capillary (pos. 5) using a syringe pump (pos. 3a). In order for the drops of a certain diameter to be detached from the capillary, the needle was connected to an electromagnetic device (pos. 4). This device generated fast pulses at specified time intervals, due to which the needle dropped sharply downward and droplets of the desired size were separated.

Before the experiments, the dispersed and continuous phases were mutually saturated in order to exclude additional mass transfer between them. In order to limit the influence of contamination, all parts of the setup in contact with the continuous or dispersed phases underwent a thorough multi-stage cleaning procedure. For the same reason, stainless steel, glass and fluoropolymer-4 were used as materials for the setup.

To obtain data on the instantaneous velocities of the ascent of the droplets, video recording of their movement was carried out using a Canon 600D camera (pos. 9) with the possibility of high-speed video filming. In the work, the following settings were used for video filming: spatial resolution of 1280x720 pixels and a frame rate of 50 Hz. The position of the camera relative to the column was determined so that the entire path of the droplet through the column could be captured during the shooting. To align the position of the camera vertically and horizontally, a two-axis spirit level was used. The required intensity and uniformity of illumination was achieved using a gas-discharge lamp (pos. 8) with a power of 21 W and a long tube of 850 mm. The recorded video fragments were transferred to a computer for analysis.

The obtained fragments were processed using the Media Cybernetics Image-Pro Plus software version 6.0. The first processing step was to determine the scale of the image. After that, the background image was subtracted from each image of the sequence of video frames. The Track Objects tool was applied to the sequence of frames processed in this way, with the help of which the coordinates of the drop center on each image from the sequence were automatically determined. As a result of the processing procedure, the instantaneous velocities of the droplets were calculated.

To collect the dispersed phase, droplet separators with an inner diameter of 70 mm (item 7) were installed in the experimental setup. A small constant volume of the dispersed phase was accumulated in the droplet separator for the coalescence of droplets. The dispersed phase collected in the droplet separator was sampled using a second syringe pump (pos. 3b).

The acid concentration was determined by titration with an aqueous solution of sodium hydroxide in the presence of phenolphthalein.

3. Results and discussion

The results of experiments on the mass transfer of acetic acid from butyl acetate droplets into water are presented. A series of experiments were carried out with different initial concentrations of acetic acid (0.1, 0.2, 0.3, 0.5, 0.7 mol/l). Figures 2–6 show the trajectories of droplets with a diameter of 2.5 mm. The mass transfer at high values of the concentration of the transferred substance took place under practically stable conditions, the trajectories of the droplets coinciding with the symmetry axis of the column. At the final stage of the mass transfer process, the influence of interfacial convection was already noticeable. Drops with a concentration of 0.1 mol/l almost immediately deviated from the axis; at concentrations up to 0.5 mol/l, this effect influenced the motion of particles in the upper parts of the trajectories. However, the acid concentration of 0.7 mol/l was too high, so the droplet deflection did not occur.

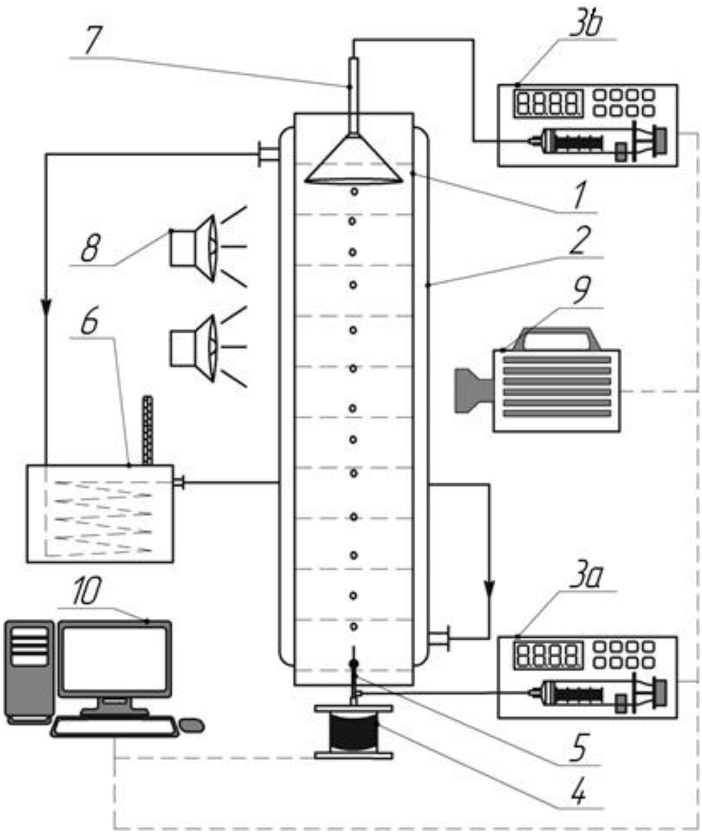

Figure 1 Schematics of the experimental setup: 1 – borosilicate glass column; 2 – shirt; 3a, 3b – syringe pumps; 4 – electromagnetic device; 5 – capillary; 6 – thermostat; 7 – drop catchers; 8 – lamps; 9 – video camera; 10 – personal computer.

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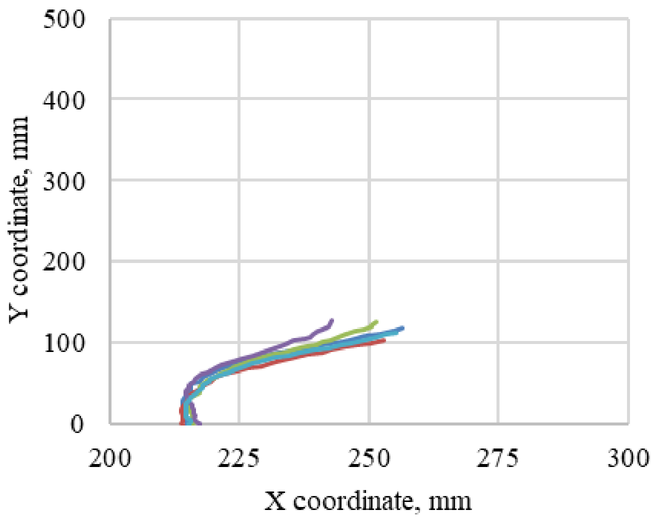

Figure 2 Trajectories of droplets (0.1 mol/l).

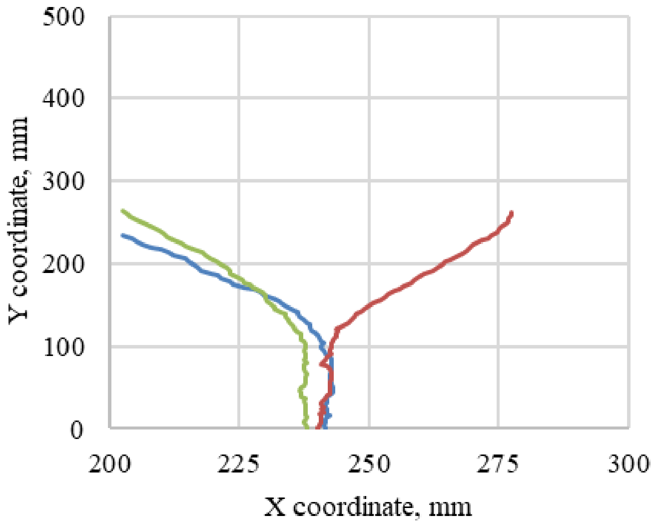

Figure 3 Trajectories of droplets (0.2 mol/l).

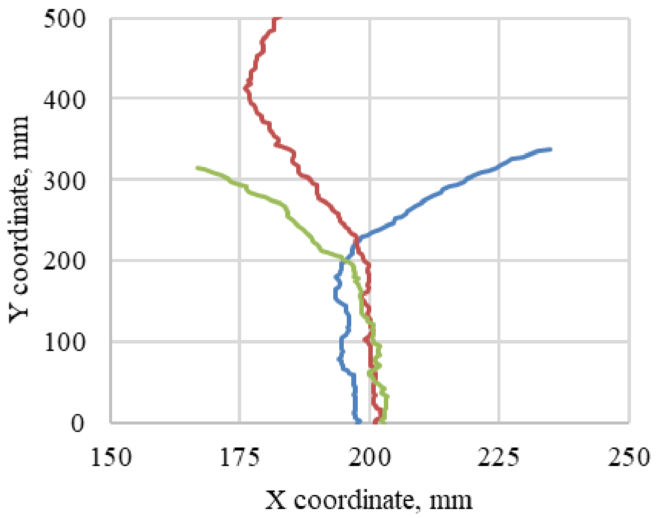

Figure 4 Trajectories of droplets (0.3 mol/l).

The data on the ascent rate of drops are shown in Figure 7. The upper horizontal line on the plot corresponds to the calculated ascent rate for a liquid droplet without mass transfer, the lower horizontal line corresponds to the calculated ascent rate for a rigid sphere. The experimental data for a liquid droplet with zero acid concentration practically coincide with the calculated data. The movement of droplets containing acid is different. As the acid concentration increases from 0.1 to 0.7 mol/l, the ascent rate decreases to the ascent rate of a rigid sphere. This dependence is explained by a change in the structure of flows inside the droplet. In an ordinary case, a drop squeezes through the thickness of the continuous medium due to the internal circulating toroidal currents. In the case of mass transfer with convection, the structure of streamlines in the droplet changes, convection disturbances impede the coordinated toroidal flow, reducing the speed of the droplet ascent.

The kinetics of mass transfer (Figures 8 and 9) is also highly dependent on the presence of interfacial convection. At small values of the driving force of the process (0.1...0.2 mol/l), the dependence is pronounced; it is observed in the form of an ascending line. At large values of the driving force (more than 0.2 mol/l), the dependence changes its character and approaches horizontal lines. The dependence of the acid concentration on the total contact time of the phases is inversely proportional, asymptotically approaching the horizontal line at the concentration level of 0.05...0.1 mol/l.

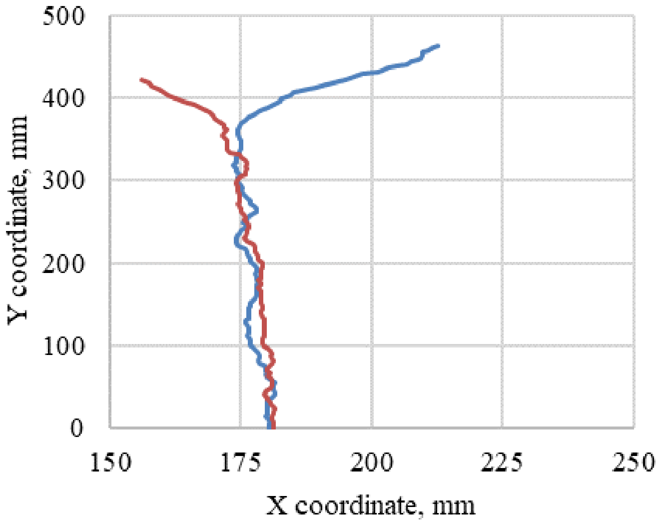

Figure 5 Trajectories of droplets (0.5 mol/l).

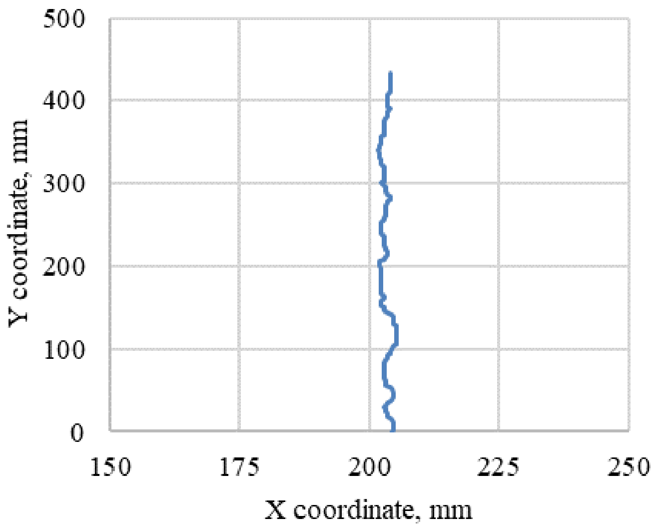

Figure 6 Trajectories of droplets (0.7 mol/l).

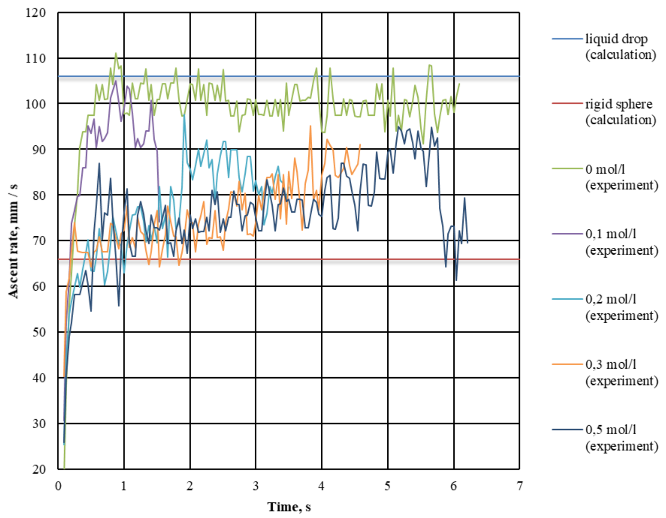

Figure 7 Dependence of the ascent rate on the process time.

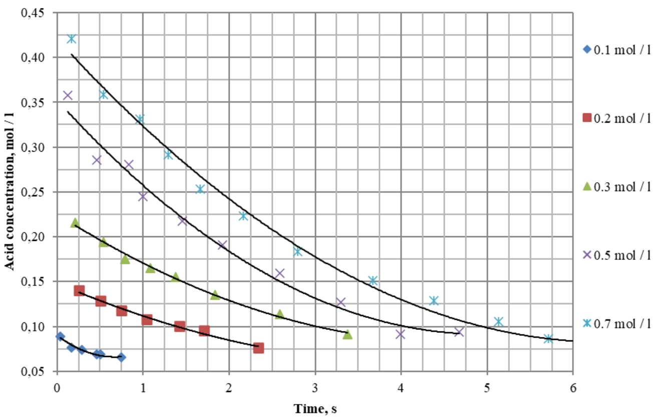

Figure 8 Dependence of the acid concentration on the total contact time of the phases.

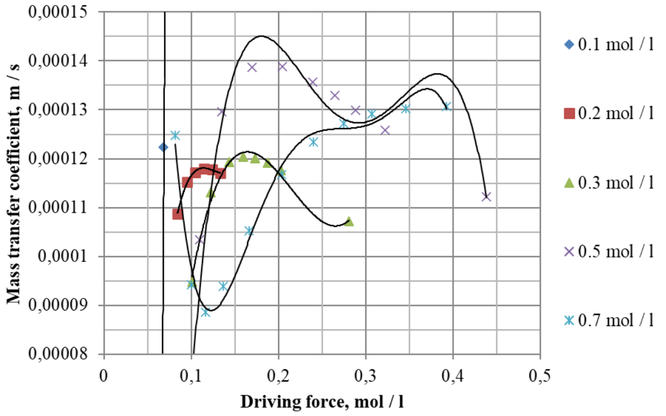

Figure 9 Dependence of the mass transfer coefficient on the driving force.

4. Conclusions

The Marangoni effect has a significant influence on the mass transfer of acetic acid from the dispersed phase (butyl acetate) to the continuous phase (water). The most pronounced effect is observed at a driving force of 0.1...0.2 mol/l. The drops with a concentration of 0.1 mol/l almost immediately deviated from the axis; at concentrations up to 0.5 mol/l, this effect influenced the motion of the particles in the upper sections of the trajectories.

The Marangoni effect also affects the ascent rate of a liquid droplet. The experimental data for a liquid droplet with zero acid concentration practically coincide with the calculated data. The movement of droplets containing acid is different. As the acid concentration increases from 0.1 to 0.7 mol/l, the ascent rate decreases to the ascent rate of a rigid sphere.

Supplementary materials

No supplementary materials are available.

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Author contributions

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Investigation: Z.R.R., E.A.K.
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Project administration: A.G.T.
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Conflict of interest

The authors declare no conflict of interest.

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