

## The Mass Transfer and Coalescence Time Scales in Binary Droplet Systems for Copper Extraction

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### Abstract

In this work, we studied whether coalescence has a direct effect on mass transfer in copper extraction. The coalescence of pendant and sessile droplets containing diluted Acorga M5640 in an aqueous copper sulfate solution was recorded on video. The videos were analyzed to determine droplet rest times, sizes, and concentrations. Concentration measurements revealed that coalescence does not enhance mass transfer because coalescence is a rapid phenomenon. A comparison of the experiments performed with and without mass transfer showed that the coalescence dynamics are not affected by mass transfer. A bimodal rest time distribution was observed when the copper sulfate solution was in the continuous phase. The surface flows and cell-like structures observed on the droplet interface are presumed to be because of a Marangoni convection, which is caused by concentration changes because of extraction. The presence and absence of surface flow is anticipated to lead to a bimodal rest time distribution. The presence of surface flow improves coalescence probability because of very short binary droplet rest times.

**Keywords:** Binary droplet coalescence; Mass transfer; Copper extraction; Liquid–liquid extraction; Image analysis

### Notations

a, b: Interpolation function parameters to fit apparent absorptivities

c: Concentration

d: Diameter

l: Length

n: Amount of copper

t: Time

x: Volume percentage

V: Volume

$\dot{V}$ : Volumetric flow rate

$\Delta$ : Difference

$\epsilon$ : Absorptivity

$\chi$ : Chi-test

$d_{outer}$ : Outer (diameter)

$d_{inner}$ : Inner (diameter)

c: Continuous phase

$d_{ch}$ : Chord length

$d_{coal}$ : Coalesced

d: Droplet or droplet phase

$t_f$ : Formation (time)

$t_{fc}$ : First contact between droplets

$t_{ps}$ : Start of the feed pumps

$p$ : Value for a pendant droplet

$r$ : Rest (time)

$s$ : Value for a sessile droplet

$t_{sc}$ : Start of the film rupture between droplets

aq: Aqueous phase

CFD: Computational Fluid Dynamics

$CuA_2$ : Copper complex

HA: Hydroxyoxime i.e., active component of Acorga M5640

Org: Organic phase

### Introduction

The basic operating principle in liquid–liquid extraction processes is to mix two phases and the driving force, that is, the deviation from the equilibrium, enables the solute to transfer between the phases. In addition to the driving force, the area available for mass transfer is an important parameter that can affect the mass transfer rate. The mass transfer area is increased by generating droplets using impellers, spargers, or perforated plates. In contacting units, droplets collide with each other and unit walls. Depending on the hydrodynamic conditions, two or more droplets can coalesce into one large droplet, or a single droplet can be broken into smaller droplets. Coalescence is expected to decrease the mass transfer rate by reducing the available mass transfer area.

The binary droplet, that is, droplet-droplet coalescence, has been studied using different operating principles. For example, researchers

[1-4] have studied the coalescence of pendant and sessile droplets, while other group of researchers [5-10] studied the coalescence of adjacent droplet or bubble pairs. The droplet pair was either a pendant or sessile. Eiswirth [11] studied the coalescence of free rising droplets. Mitra and Ghosh [12] have used a different approach, where the set-up consisted of a series of cup-type cells immersed in the continuous phase.

Several studies using binary droplets [1,8,13] have revealed that the coalescence rate depends on the direction of mass transfer. When the direction was from the continuous to dispersed phase, coalescence times increased compared with the opposite direction. Solute concentrations because of the Marangoni convection are also expected to affect coalescence [14]. The effect of droplet size on coalescence was studied by Villwock, Gebauer, et al. [2], and their results indicated that coalescence proceeds only if a rising droplet is larger than a stationary pendant droplet. In experiments with sessile and pendant droplets, on the other hand, Kamp and Kraume [1] were not able to find a clear relationship between the droplet size ratio and coalescence. Some studies have also explored the effect of different additives on coalescence. For example, Mitra and Ghosh [12] found that surfactant addition leads to a notable increase in droplet rest times. The addition of a small amount of salt increased the coalescence times, whereas when increasing the amount of salt, shorter rest times were observed. These studies, however, have not analyzed whether binary droplet coalescence itself influences mass transfer because of interface deformations.

In the present work, the goal was to study whether the coalescence phenomenon itself has any effect on mass transfer because of deformations and movement during the binary droplet coalescence; here, sessile and pendant organic droplets were formed in ambient aqueous solution and using a direct measurement method. Droplet concentrations were determined before and after the coalescence, and the effect of coalescence on mass transfer was determined [15]. The organic feed contained commercial copper extractants in a commercial hydrocarbon diluent; the continuous phase was a copper sulfate solution. The feeds used in the present work are complex compared with the pure liquids used in most literature studies. Typical coalescence studies with mass transfer consist of chemical systems where one substance is transferred between two immiscible phases, and there is no chemical reaction present; in addition, the direction of the mass transfer can be easily controlled. This contrasts with the chemical system used in the present work.

Copper extraction is an interfacial equilibrium reaction, one where copper is complexed at the interface, and the complex is then transferred to the organic phase. Copper ( $\text{Cu}^{2+}$ ) extraction with hydroxyoxime (HA) has the following stoichiometry [16-18].



The reaction mechanism for copper extraction with LIX 65N was presented [16] and has been applied on copper extraction with extractants such as LIX 984 [17] and Acorga M5640 [18]. Copper extraction is also an ion exchange reaction; hydrogen ions are released as aqueous phase copper is complexed with hydroxyoxime. This further complicates the situation because the mass transfer direction is not well defined because there is mass transfer to and from both phases. Also, the transferring species are changing because of the complex formation.

In the current study, the copper concentration in the organic droplets was determined using the image frames of recorded videos, which were analyzed with the image analysis method proposed by Tamminen et al. [15]. The measured copper concentrations in the droplets before and after coalescence (film rupture) were compared with each other. The comparison revealed that the coalescence had a minor effect on the mass transfer mainly because of the short time scale.

## Materials and Methods

### Experimental set-up

The set-up for the coalescence experiments was custom-made (Figure 1). The pendant and sessile droplets were formed on the tips of two identical steel needles. The droplet formation was made by dispensing the droplet phase with two identical high-precision syringe pumps (World Precision Instruments). The cell was made of PVC plastic, and the top was left open. Two opposite side walls were made from transparent glass to allow for video recording. The set-up used here was like those used previously [1,2]. The volume used in earlier works [1,2] was 500  $\text{cm}^3$ , but in this work, the set-up volume was smaller, 100  $\text{cm}^3$ . It is noted here that although both droplets were attached to needle tips, experiments with one stationary and one moving droplet can be made with the present set-up. The organic feed solution consisted of technical grade chemicals, but organic feeds were not used in extraction prior to the coalescence experiments. The preparation of the feed solutions is described in the supplementary information.

### Coalescence experiments

The droplets were formed on the tips of the needles. The pumps were started manually, but they were programmed to dispense a predetermined volume (8  $\mu\text{L}$ ) at a constant flow rate of 0.4  $\text{cm}^3/\text{min}$ . The pumps were set to stop automatically. The same volumetric flow rate setting was used in both pumps. The distance between the needle tips was set to 5 mm, putting the formed droplets in contact with each other. Because the contact between the droplets was gentle, the mass transfer during the coalescence could be studied in the absence of possible mixing effects from droplet collision. All experiments conducted at room temperature.

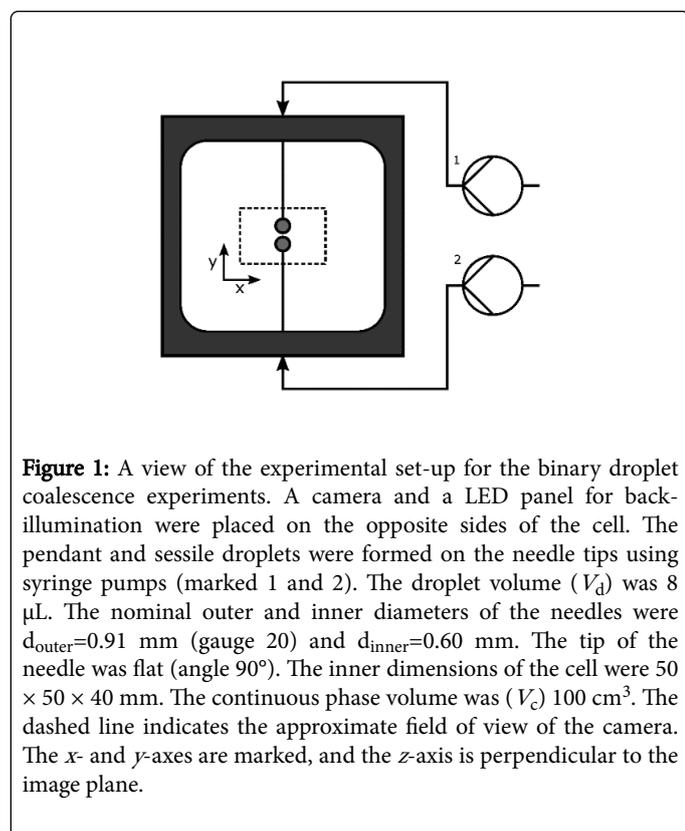
The experiments were repeated 150 times for the 20 vol% Acorga solution droplets when the continuous phase copper sulfate solution concentration was 0.16 mol/L. The mass transfer during the coalescence was studied by varying the droplet phase extractant concentration and the continuous aqueous phase copper sulfate concentration. Ten repetitions were made to show whether coalescence has any effect on mass transfer when the feed concentrations are changed.

The videos of the coalescence of the pendant and sessile droplets were recorded in color using a Casio Ex-F1 digital camera at a frame rate of 300 fps. The image resolution in the physical dimensions was determined by recording a 5 mm grid with a transparent background. The details of the calibration procedure and concentration analysis are reported [15]. The frame size was 512  $\times$  384 pixels, which corresponds approximately to 13  $\times$  10 mm. Three close-up lenses (+1, +2, and +4 diopter) [19] were attached to the camera lens to have a more detailed view of the droplet. The camera settings were kept constant in all experiments. The recorded videos were later manually analyzed for

droplet formation, rest, and coalescence times. The droplet sizes and concentrations were determined from the recorded video frames using an image analysis. The image analysis of all experiments was made for individual video frames, which were extracted from the video using FFmpeg [20]. All image and data analyses were done using MATLAB version 2016a [21].

The concentration analysis of the droplets was conducted using a method [15], with the exception that the droplet region selection was done manually. Recorded droplet image data were correlated with concentrations using the measured droplet geometry and Lambert-Beer law. The experimental results are presented in more detail by Peltola [22]. The measured concentration data are characterized by using the mode, which shows the most typical value of the data set.

The droplet sizes were measured based on fitting ellipsoids to the droplet image data. The lengths of the droplets' minor and major axes were calculated from the measured ellipse dimensions. The droplets were assumed to have a rotational symmetry along the y-axis; that is, it was assumed that the x- and z-axis lengths were equal (Figure 1).



Light scattering and refraction generally cause the droplet image edge to be darker than the image center, and this was considered by calculating the apparent absorptivities ( $\epsilon$ ) of standard solution droplets [15]. An interpolation function was fitted to the apparent absorptivities and was used in the calculation of the concentrations in the droplet. The interpolation function is  $\epsilon = a/\ln(l_{\text{ch}} + 1) + b$ , where a and b are parameters, and  $l_{\text{ch}}$  is the chord length [15]. The parameters of the interpolation function used in the current work are shown in Table S1. The analysis in the present work was carried out using the method described in an earlier work [15], except the green color channel and a different camera were used. A different camera was used in the present work because the camera used in earlier work had an insufficient

frame rate (7.5 fps) for the current coalescence experiments. The calibration was made for copper containing 10 and 20 vol% Acorga-solution droplets. The continuous phase was 0.16 mol/L  $(\text{NH}_4)_2\text{SO}_4$  solution.

The droplet copper concentrations were measured just before and after coalescence. For each coalescence experiment, the concentration difference ( $\Delta c$ ) is calculated from the following:

$$\Delta c = c_{\text{coal}} - \frac{(n_s + n_p)}{(V_s + V_p)} \quad (2)$$

where the amount of copper complex in the sessile and pendant droplets is  $n_s$  and  $n_p$ , respectively. The volumes of the droplets are  $V_s$  (sessile) and  $V_p$  (pendant). The concentration in a coalesced droplet is  $c_{\text{coal}}=n_{\text{coal}}/V_{\text{coal}}$ .

The times of the coalescence process were determined from the video by counting the relevant frames. The droplet formation time ( $t_f$ ) is as follows:

$$t_f = t_{fc} - t_{ps} \quad (3)$$

where  $t_f$  is the difference between the start time of pumping ( $t_{ps}$ ) and the time of the first contact ( $t_{fc}$ ) between the pendant and sessile droplets. The droplet rest time ( $t_r$ ) is as follows:

$$t_r = t_{sc} - t_{fc} \quad (4)$$

where  $t_{sc}$  is the start time of film rupture. The time between the interfacial film rupture and the formation of the coalesced droplet is the coalescence time ( $t_{\text{coal}}$ ). Droplet contact time describes the time available for mass transfer, that is, in practice, the sum of the formation and rest times.

### The coalescence hydrodynamics modeling

The hydrodynamics in the coalescence of sessile and pendant droplets were simulated using Comsol Multiphysics v5.2 [23] software. The two-phase laminar Level-Set method was used to track the droplet-ambient interface in coalescence modeling. The model was implemented without mass transfer and extraction reaction. The main objective of the computational fluid dynamics (CFD) simulation was to determine whether the coalescence of the droplets was affected mainly by the hydrodynamic conditions or whether the mass transfer had any effect on the coalescence process.

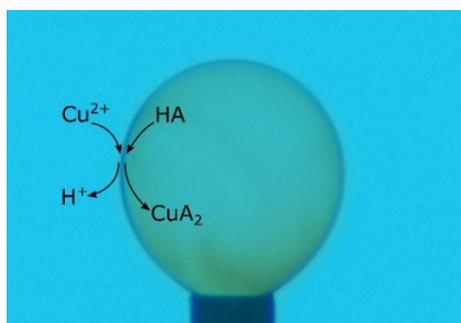
The details of the CFD model are described in the supplementary information.

## Results and Discussion

### Copper reactive extraction

Figure 2 shows a schematic presentation of the reaction. The copper is complexed with the hydroxyoxime at the droplet interface, and a brown-colored copper complex ( $\text{CuA}_2$ ) is formed as the result of the reaction. The time for the reaction (22 s) for the droplet in Figure 2 was not long enough for the diffusion of the complex to fill the droplet, leaving the complex near the droplet surface. At the beginning of the experiment, the droplet was filled with a lighter-colored hydroxyoxime solution. In the image, the droplet's center is observed through two interfaces and layers with a higher complex concentration, which causes the center of the image to have a brown color. Figure 2 is

consistent with the copper extraction being an interfacial reaction and having a low complex concentration in the droplet center.



**Figure 2:** The copper extraction in a sessile organic droplet containing 20 vol% Acorga M5640. The copper extraction reaction (Eq. 1) can be seen to proceed at the droplet interface. Copper cation ( $\text{Cu}^{2+}$ ) reacts with hydroxyoxime (HA) and releases hydrogen ions ( $\text{H}^+$ ) into the aqueous phase. The formed brown-colored complex ( $\text{CuA}_2$ ) can be observed at the droplet surface, especially near the droplet's edge. The continuous phase was the aqueous  $\text{CuSO}_4$  solution at a concentration ( $c_c$ ) of 0.16 mol/L. The droplet has been in contact with the continuous phase 22 s.

### Determined rest and formation times

The droplet rest times were determined from the coalescence videos of 20 vol% Acorga M5640 droplets (Figure 3) with 0.16 mol/L ammonium sulfate solution as the continuous phase. Without any copper transfer, the droplet rest time has a wide distribution, with a median of 10 s, and the rest times were normally distributed according to the results of the  $\chi$ -test for normality.

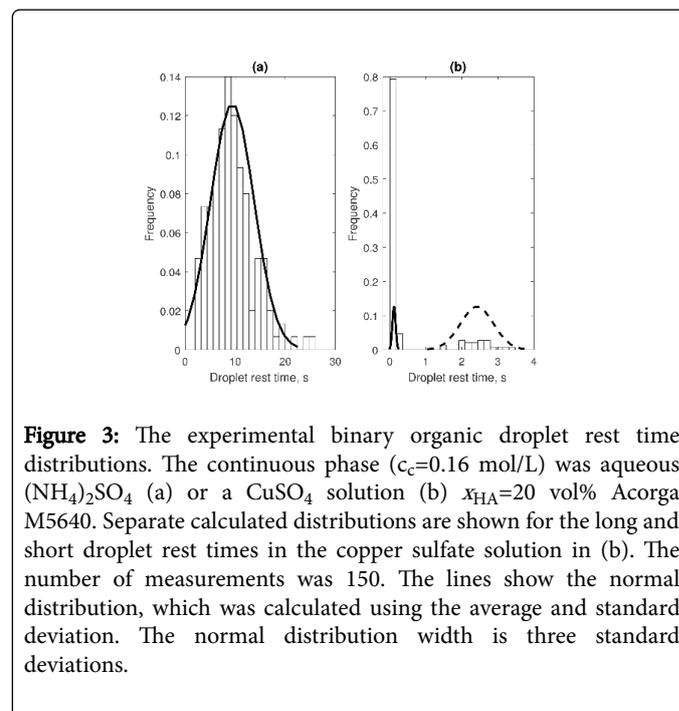
On the other hand, the rest times obtained from the copper sulfate binary coalescence experiments have a bimodal distribution (Figure 3b). Most of the observations (about 120 of 150) have rest times shorter than 0.5 s. The other observations have much longer rest times, about 2-3 s. If both the long and short rest times are treated as individual data sets, they are both normally distributed according to the  $\chi$ -test for normality. Thus, the bimodal distribution implies that there are two different phenomena or mechanisms affecting droplet coalescence during copper extraction.

The droplet phase extractant and continuous phase copper concentrations have no clear effect on the observed droplet rest times (Figure S1). These results imply that the measured rest time distributions at the different feed concentrations are like those presented in Figure 3b. Ten measurements were made when the extractant and copper feed concentrations were varied.

The formation times of the pendant and sessile droplets are typically almost equal, but because the feed pumps and droplet formation were started manually, there can be differences. The formation times of the single experiment pendant and sessile droplets are parallel determinations, and the average of them is used as a formation time in the further data analysis.

A short needle distance and low droplet approach velocities were chosen to maximize the probability of droplet contact. Droplet pairs came into contact in all the coalescence experiments, but coalescence

did not always occur. This effect was the most prominent when 0.50 mol/L copper sulfate was used as the feed solution. It is acknowledged here that the frame rate of the camera (300 Hz) was perhaps too low for a detailed coalescence study. However, it is considered enough for determining droplet formation and rest times, which are long compared with the frame interval (3.3 ms).



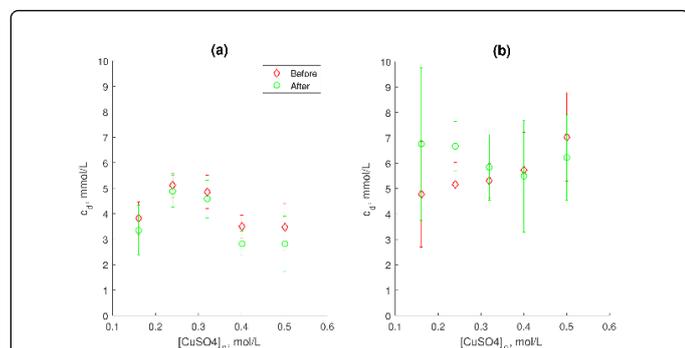
**Figure 3:** The experimental binary organic droplet rest time distributions. The continuous phase ( $c_c=0.16$  mol/L) was aqueous  $(\text{NH}_4)_2\text{SO}_4$  (a) or a  $\text{CuSO}_4$  solution (b)  $x_{\text{HA}}=20$  vol% Acorga M5640. Separate calculated distributions are shown for the long and short droplet rest times in the copper sulfate solution in (b). The number of measurements was 150. The lines show the normal distribution, which was calculated using the average and standard deviation. The normal distribution width is three standard deviations.

### Mass transfer during coalescence

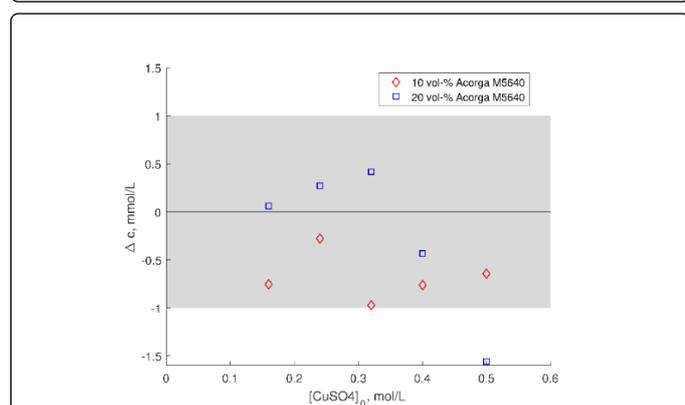
The mass transfer during the binary organic droplet coalescence was studied by determining the concentrations in the droplets before and after coalescence, that is, before and after the film rupture and combination of the droplets. The measured concentrations in the pendant and sessile droplets are almost equal because they almost have the same contact times. Like the formation times, the pendant and sessile droplet concentrations of one experiment are considered parallel determinations. The average of the pendant and sessile droplet concentration is the measure of droplet concentration before coalescence (Figure 4).

The concentration (in the coalesced droplet) after coalescence was found to be like the concentration before coalescence. The coalescence time was about 30 ms, as can be seen in the section Coalescence dynamics. This is a short time for the mass transfer to take place. Therefore, all the measured concentrations are essentially the same (Figure 4). In Figure 4, the variation of the concentration data is due to the variation in droplet contact times, that is, in the formation and rest times.

The concentration differences in coalescence are calculated from Eq. 2 and are shown in Figure 5. The calculated differences are small, and some are even negative. The experimental conditions used in the present work are such that copper extraction proceeds according to forward reaction (Eq. 1), and the copper complex concentration is expected to remain the same or increase. However, in Figure 5 [15], certain trends can be observed, but it is believed that they are caused by the experimental variation.



**Figure 4:** The modes of droplet concentration distributions before and after coalescence. The droplet phase was either 10 (a) or 20 vol % Acorga M5640 (b). The continuous phase was the aqueous copper sulfate solution having an initial concentration  $[CuSO_4]_0$ . The concentrations before coalescence are an average of the pendant and sessile droplet concentrations. The error bars indicate one standard deviation.



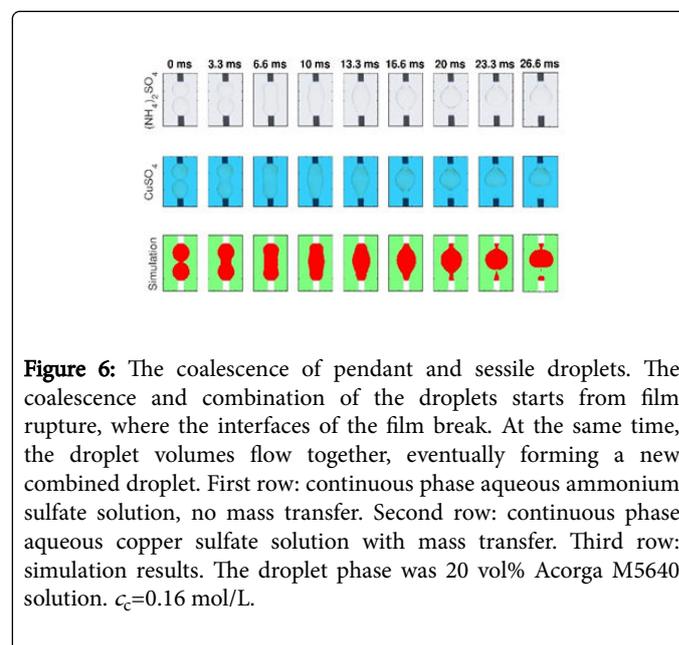
**Figure 5:** The mode of concentration differences during binary droplet coalescence. The concentration difference was defined as the difference between the droplet concentrations before and after coalescence (see Eq. 2). The difference was calculated separately for each experiment, and as a result, the mode of each data set is presented. The droplet phase was the organic Acorga M5640 solution, and the continuous phase was the copper sulfate solution. The shaded area shows the reproducibility of the method.

The concentration values before and after coalescence are approximately equal (Figure 4), and the subtraction of concentrations can then lead to negative values because of concentration measurement accuracy. The calculated negative concentration differences imply that coalescence does not enhance mass transfer. The variation in the concentration differences and in the measured concentration data (Figure 4) are similar. The variation is approximately 4 mmol/L. The data show that binary droplet coalescence has no major effect on the mass transfer in copper extraction within the studied concentration range, which is mainly because of a short coalescence time (about 30 ms). However, coalescence has an indirect effect on mass transfer because it changes the interfacial area available for extraction.

## Coalescence dynamics

The droplet coalescence dynamics from the film rupture to the combination of the pendant and sessile droplet volumes is shown in Figure 6. Coalescence in 0.16 mol/L ammonium (no mass transfer) and copper sulfate (with mass transfer) show that the coalescence dynamics are very similar in both cases. Here, the droplet phase is essentially the same in both cases because the measured organic phase copper concentration was below 10 mmol/L. In Figure 6, the third row shows the coalescence simulation results. The measurements and simulation match remarkably well, implying that the duration of coalescence is defined by the bulk properties of the droplet phase as the droplet contents are flowing together. The simulation and experimental results in Figure 6 indicate that chemical reaction (Eq. 1) and presence of a Marangoni convection (Figures 7 and 8) do not affect droplet combination dynamics.

The coalescence time is approximately the same (about 27 ms) in the experiments and simulations. It is noted here that determining the coalescence time would indeed be more accurate if a higher frame rate would have been used in the experiments. However, how the current study determined coalescence time is considered to have enough accuracy for the purposes of this work. According to Eiswirth [11], the duration of the coalescence of equal-sized toluene droplets in water was 30 ms; this is the same order of magnitude found in the current work (Figure 6). The difference is presumed to be because of the differences in the physical properties of the feeds, such as density, viscosity, and interfacial tension.



**Figure 6:** The coalescence of pendant and sessile droplets. The coalescence and combination of the droplets starts from film rupture, where the interfaces of the film break. At the same time, the droplet volumes flow together, eventually forming a new combined droplet. First row: continuous phase aqueous ammonium sulfate solution, no mass transfer. Second row: continuous phase aqueous copper sulfate solution with mass transfer. Third row: simulation results. The droplet phase was 20 vol% Acorga M5640 solution.  $c_c=0.16$  mol/L.

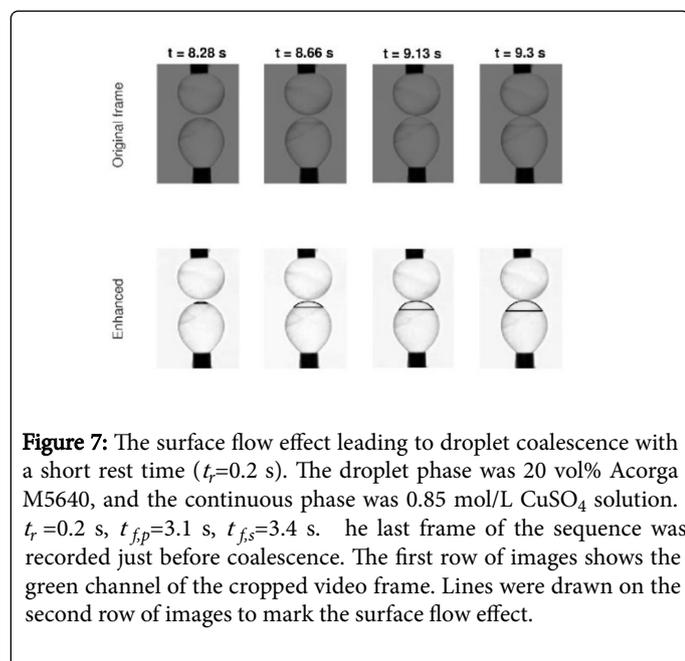
The droplet contents are not mixed together in coalescence. The features present in the pendant and sessile droplets prior to coalescence also tend to be visible in the coalesced droplet. In the case of the copper sulfate experiment shown in Figure 6, there is a noncolored layer in the middle of the combined droplet that is being formed. This feature can be seen quite early on, and it remains visible throughout the rest of the coalescence event. The noncolored layer is the result of surface flows away from the droplet apices during later stages of the droplet approach. An example of these surface flows is shown in Figure 7. It is reported that the droplet contents are not

mixed in coalescence when the droplets are similar in size, as is case in the current work [11]. The droplet deformations are then similar because of the symmetry in droplet interactions. This leads to a balance in the forces on both sides of the coalesced droplet. When the droplet sizes are different, the lack of symmetry leads to internal mixing in the coalesced droplet.

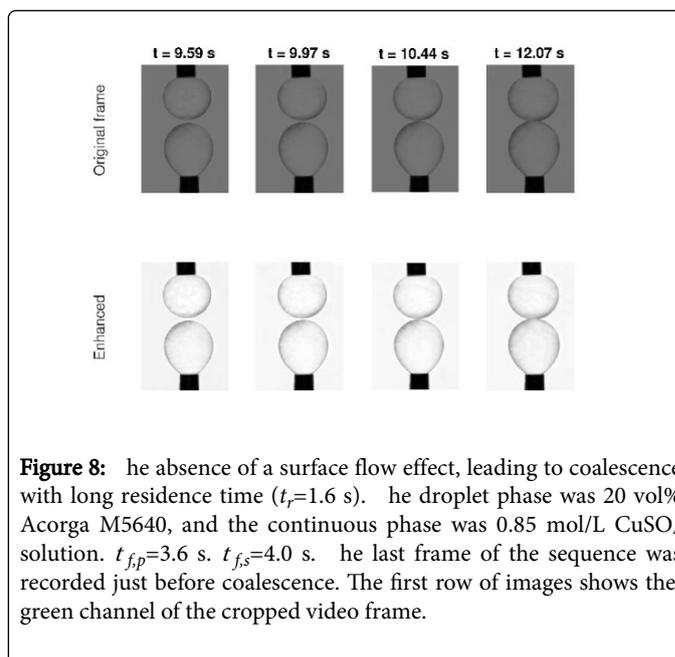
### Surface flows and marangoni convection

The observed bimodal rest time distribution for copper extraction implies the presence of two phenomena that each have a different effect on coalescence. The presence (and absence) of surface flow (Figures 7 and 8) could be one such phenomenon, where interfacial tension driven flow may lead to the breakage of the film and, thus, coalescence [24].

A surface flow starts from the apex of the droplet and moves toward the needle, and it is made visible because of the strong color of the copper complex (Figure 7). In the case of a pendant droplet, the surface flow was observed to move upwards, away from the droplet apex. The lighter-colored areas on the droplet surfaces contain mostly the extractant, and the darker colored areas contain more of the copper complex (Figures 7 and 8). The surface flow is presumed to be caused by a thin-film type of Marangoni convection [24]. The flow starts from the droplet apex where the film between droplets is the thinnest. The surface-active extractant moves into the thinnest part of the film faster than the other parts, leading to a decrease of the interfacial tension in the droplet apex. Because the interfacial tension is the lowest at the droplet apex, the Marangoni convection direction is away from it [14,24].

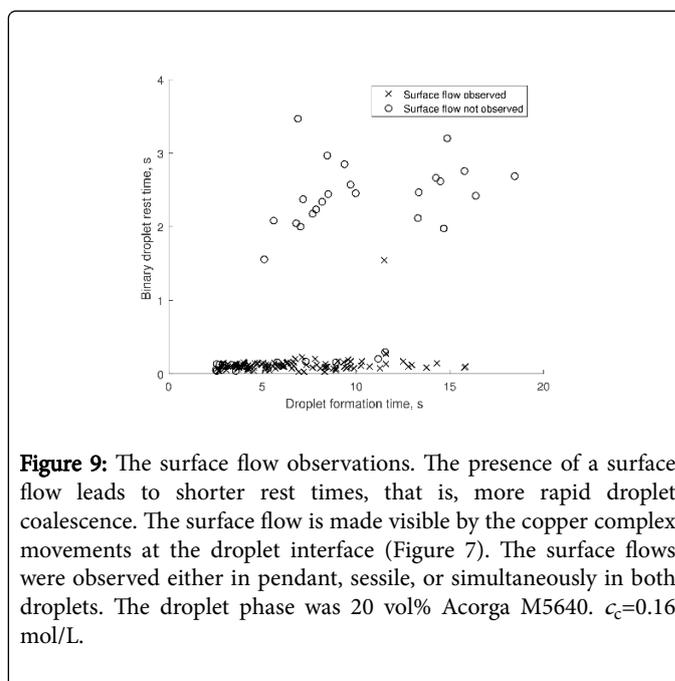


**Figure 7:** The surface flow effect leading to droplet coalescence with a short rest time ( $t_r=0.2$  s). The droplet phase was 20 vol% Acorga M5640, and the continuous phase was 0.85 mol/L  $\text{CuSO}_4$  solution.  $t_r=0.2$  s,  $t_{f,p}=3.1$  s,  $t_{f,s}=3.4$  s. The last frame of the sequence was recorded just before coalescence. The first row of images shows the green channel of the cropped video frame. Lines were drawn on the second row of images to mark the surface flow effect.



**Figure 8:** The absence of a surface flow effect, leading to coalescence with long residence time ( $t_r=1.6$  s). The droplet phase was 20 vol% Acorga M5640, and the continuous phase was 0.85 mol/L  $\text{CuSO}_4$  solution.  $t_{f,p}=3.6$  s,  $t_{f,s}=4.0$  s. The last frame of the sequence was recorded just before coalescence. The first row of images shows the green channel of the cropped video frame.

The presence of the surface flow, that is, a thin-film Marangoni phenomenon, leads to a more rapid coalescence by shortening the droplet rest time (Figure 9). Surface flows were not observed in every droplet coalescence experiment. When it occurred, it was observed in either the pendant, sessile, or even in both droplets simultaneously. Figure 9 shows that in practically all cases where the surface flows because of a thin-film Marangoni convection, there were short rest times.



**Figure 9:** The surface flow observations. The presence of a surface flow leads to shorter rest times, that is, more rapid droplet coalescence. The surface flow is made visible by the copper complex movements at the droplet interface (Figure 7). The surface flows were observed either in pendant, sessile, or simultaneously in both droplets. The droplet phase was 20 vol% Acorga M5640.  $c_c=0.16$  mol/L.

The long rest times shown in Figure 9 were observed when the droplet formation time is over 5 s. The data shown in Figure 9 also imply that the thin-film Marangoni convection induced fast coalescence depending on the droplet contact time.

## Conclusions

Copper mass transfer into extractant solution droplets during binary droplet coalescence was studied in the present work. The coalescence experiments of pendant and sessile droplets were performed in a custom-made cell and recorded using a digital camera. The organic phase contained Acorga M5640 extractant dissolved in Exxsol D80. The continuous phases were copper sulfate solutions. The coalescence experiments in an ammonium sulfate solution were made for comparison purposes.

In the ammonium sulfate solutions, the observed rest times were normally distributed, with an average of about 10 s. In the copper sulfate solutions, a bimodal distribution was found. Long rest times of about 2 s were observed when there was no surface flow present. On the other hand, the observation of a surface flow was typically found to lead to much shorter droplet rest times (below 0.5 s), thus increasing the coalescence probability. It is assumed that the surface flow was caused by a thin-film Marangoni phenomenon.

An image analysis was used to determine the droplet concentrations; they were measured before and after coalescence to determine whether coalescence had effect on the mass transfer. The concentration analysis showed no increase in the coalesced droplet concentrations; thus, the mass transfer in copper extraction was not enhanced during binary droplet coalescence. Copper extraction is an interfacial reaction, and as such, it is limited by the interfacial area and diffusion of the reactants to the interface. During a short coalescence time (30 ms), mass transfer has no time to significantly effect on the concentrations, even if the driving force has been increased because of mixing. The situation may be different when extraction without a chemical reaction is made. The results can be used to enhance and simplify the flow models because coalescence will cause an interfacial area change, and no extra effects then must be considered when using the model.

## Acknowledgements

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