

Coalescence of Surfactant-Stabilised Adjacent Droplets using Surface Acoustic Waves

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Abstract

A novel, on-demand microfluidic droplet merging mechanism is presented in this paper. We demonstrate that a narrow beam surface acoustic wave (SAW), targeted at the oil buffer, causes nearby surfactant-stabilised droplets to coalesce. The lack of direct exposure of the droplet to the excitation stimulus makes this method ideal for sensitive samples as harm will not occur. This powerful technique works on a straight channel with no special design, is not affected by surfactant concentration and droplet volume hence promises seamless integration into existing microfluidic systems. It offers high-throughput, biologically safe, on-demand droplet merging for applications ranging from fast reaction kinetics to microfluidic high throughput screening (μ HTS). We thoroughly characterise the physical mechanism triggering droplet-droplet coalescence and observe a cut-off distance from the centre of the acoustic beam to the droplet-droplet interface after which the merging mechanism does not work any more. We establish that the most likely mechanism for merging is acoustic streaming induced droplet deformation.

Introduction

As microfluidics successfully continues to shrink down common laboratory procedures, its adoption by life sciences laboratories around the globe is accelerating. By offering rapid results with reduced sample volumes and better sensitivity, microfluidics not only replaces the existing tools¹ but also provides researchers with new ways to carry out analysis.² A promising subset of microfluidics investigates two-phase flow in microchannels - droplet microfluidics. In droplet microfluidics, individual reaction chambers are formed via cyclic dispersion of one phase in an immiscible medium. Droplets ranging from nanoliters to femtoliters reduce the amount of reagents required significantly while promising high throughputs and single-cell capabilities.³

The potential of droplet microfluidics technology has been the subject of many researchers^{4,5} and the authors have recently reviewed this technology in detail.⁶ When droplets are confined within closed microchannels, basic manipulations such as sorting, splitting and mixing become challenging yet crucial for workflows. One such operation is *addition* in droplet microfluidics, often referred to as merging, fusion or coalescence. While the use of surfactants in the surrounding phase improves the stability of the droplets, it prevents spontaneous coalescence allowing droplets to be packed adjacently yet stay isolated physically and, to an extent, chemically.⁷ Droplet merging, especially active merging, finds impactful applications in chemistry and biology such as fast reaction kinetics,⁸ drug discovery,^{9,10} biomolecule¹¹ and nanoparticle¹² synthesis. Gu *et al.*⁹ and Feng *et al.*¹³ have extensively reviewed droplet merging techniques in microfluidics.

Historically, there have been three major techniques exploited for facilitating droplet coalescence; physical, chemical and electrical merging. In the first method, droplets are forced to collide or push against each other so that the repulsive forces in the droplet-droplet interface are overcome and merging takes place. Chemically induced merging is usually achieved through depleting the surfactant in the system either by replacing the continuous medium or moving the droplets to another stream. In the presence of electrical forces, when

the droplet interfaces are sufficiently close, they will get attracted towards each other leading to interface rupture and subsequent merging, this is often referred to as electrocoalescence.¹⁴

As a physical merging example, Niu *et al.*¹⁵ designed a sieve-like physical restriction that allows continuous phase to flow through but traps only one droplet; when the next droplet comes in and merges, it must exit the restriction due to hydrodynamic forces. Other examples include designing an expansion in the channel^{16–18} which slows droplets down due to continuity and allows the successor to catch up and form a droplet-droplet interface. While these techniques are highly reliable and easy to integrate, they do not offer selectivity.

To offer droplet merging on-demand, external forces can be used. For example; thin, flexible membranes integrated into a microfluidic chip deform with pressure, usually applied through an air compressor and a valve.^{19,20} This deformation imparts a sudden change of pressure in the fluid as well as deformation of the microfluidic channel. This technique has been used to facilitate the merging of multiple droplets caught in entrapments.^{21,22} In a study by Lee *et al.*,²³ they regulate the global pressure of their microfluidic chip to force paired droplets into a compartment for merging. Yet another method is the use of acoustic forces to merge droplets. In a study by the authors, surface acoustic waves (SAWs) were used to trap droplets in an expansion chamber until successive droplets arrived and collided into the trapped one leading to droplet fusion.²⁴

Depleting or weakening the surfactant can be used for coalescence. For instance, it was shown that if the main, surfactant stabilised oil stream is supplemented with a secondary stream of lower surfactant concentration^{25,26} or a destabilising chemical,²⁷ adjacent droplets coalesce. Tullis *et al.*²⁸ trapped two or more droplets in surface energy wells²⁹ and flushed the system with a surfactant free oil stream leading to spontaneous fusion of the trapped droplets. In a study by the authors, a vibrating membrane is used to transfer selected droplets from a surfactant rich oil stream to one without the surfactant.³⁰

The most common and preferred method for droplet fusion is electrocoalescence.^{31–39} It is well known that droplets sufficiently close to each other will coalesce under intense

electric fields. Recently, electric fields have been utilised to print and merge microdroplets in individual wells for studying biological assays.^{40,41} It is our understanding that the physical mechanisms behind this phenomenon are still not well understood.^{14,36,42} However, it should be noted that some of these discussions involve the vibrations in the droplet interface caused by AC electric fields leading to instabilities in favour of coalescence.^{33,42}

Surface acoustic waves (SAWs) are Rayleigh type surface waves propagating on piezoelectric substrates. Despite their nanometre scale amplitudes, they efficiently couple to fluids and give rise to acoustic streaming,^{43–45} jetting,^{46–49} acoustic radiation^{50–52} and interface deformation.^{53–55} They have been widely used in the antenna industry;⁵⁶ they are being integrated to microfluidic chips for various applications⁵⁷ such as mixing, particle separation,^{52,58} cell characterisation⁵⁹ and sorting,^{60,61} droplet manipulation^{6,24,45,53–55,62} and drug delivery.⁶³ Recently, the use pulsed SAW in microfluidics, the technique used in this work, is attracting broad interest and finding valuable applications.^{60–62,64–68}

Presented here is a novel, potentially high-throughput droplet merging method using surface acoustic waves (SAWs). We show that surfactant stabilised droplet-droplet interfaces could be selectively ruptured with a short pulse of SAWs targeted at the spacer oil between droplet pairs. This method does not require special channel geometry, therefore, could be integrated with existing chip designs. Moreover, focussed SAWs acting on the surrounding medium rather than the droplet can prevent unwanted electrical, heating or shearing damage to the contents of the droplet. It was previously shown that high-frequency acoustic forces (MHz) are gentler on biological media which is why they are preferred for long-term cell studies.^{51,69} We characterise the proposed system in depth discussing the effects of surfactant concentration, the distance of the SAW from the droplet-droplet interface and the physics responsible for droplet-droplet coalescence.

Physics Background

Surface Acoustic Waves

SAWs are generated by an AC electric field applied to electrodes deposited on piezoelectric substrates. These electrodes are usually designed as equally spaced finger pairs called interdigitated transducers (IDTs) (Fig. 1(A)). Each finger is spaced by $\lambda/2$ where λ is the wavelength of the acoustic wave. When the frequency of the applied electrical signal matches the medium and finger spacing (i.e $f = c_s/\lambda$ where f is frequency and c_s is the speed of sound in the substrate), electromechanical coupling between the electrodes and the substrate gives rise to nanometre scale amplitude SAWs. SAWs are classified as Rayleigh type waves; these type of waves do not penetrate deep into the substrate retaining their energy during transit. Rayleigh waves, therefore, propagate to the application zone with minimal losses. Moreover, SAWs are localised - the beam waist can be as low as $25\text{ }\mu\text{m}$,⁶⁰ possibly even narrower - allowing single particle, cell sorting capabilities.⁶⁷

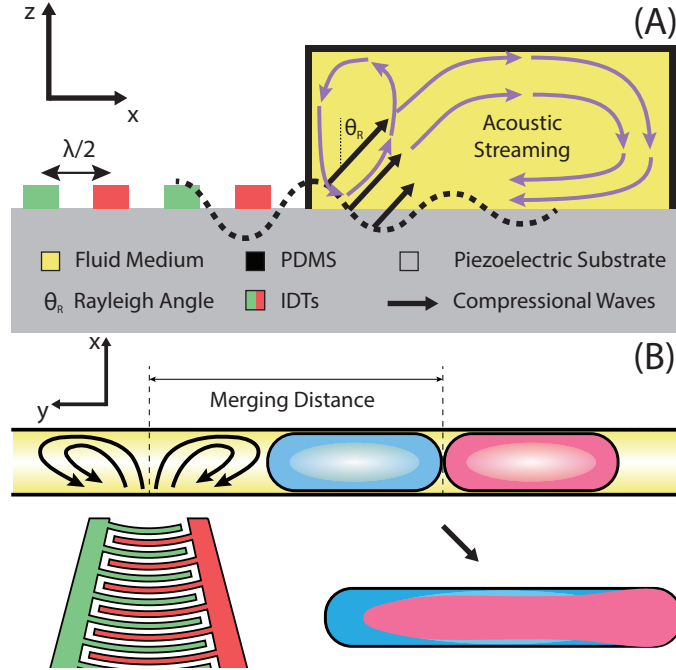


Figure 1: (A) SAW streaming in xz plane and (B) xy plane

SAWs refract with the Rayleigh angle, θ_R upon contact with fluid media giving rise to

compressional waves within the fluid (Fig. 1(A)). This coupling can be used to manipulate droplets via interface deformation,^{53–55} separate particles with acoustic radiation forces^{52,58} or drive fluids like a pump with acoustic streaming.⁷⁰ Acoustic streaming takes place due to Rayleigh angle and attenuation, the time averaged pressure at the first point of coupling is significantly larger as you go away from the IDTs. This drives a circulatory flow in the xz plane (Fig. 1(A)) as well as in the xy plane (Fig. 1(B)). The acoustic streaming velocity is affected by the SAW frequency and amplitude, attenuation length of the SAW beam, channel height and PDMS thickness as shown before with μ -PIV measurements and simulation studies.^{71,72} We will discuss how this might play a role in the merging mechanism in *Results & Discussion*.

126 MHz, 1W SAWs are targeted along a narrow beam to fluoruous oil for 50 ms in this study; this is still 6.3 million cycles of pressure waves attenuating into the fluid medium. Time averaged effects of the SAW pulse can be considered analogous to a poke or a pressure pulse applied by a membrane valve - the latter, for instance, has been used to sort droplets previously.⁷³ The local pressure suddenly and significantly increases leading to disruption of the fluid flow in the vicinity of the SAW beam. Similarly as with acoustic streaming, this effect might be responsible for the observed droplet merging which will be discussed with detail in *Results & Discussion*.

Setting aside the time averaged effects of the applied SAWs, it's important to discuss real time vibrational effects of the waves. The 126 MHz sound wave propagates on the substrate, couples into the fluid and attenuates in all directions potentially reaching to and affecting the droplet-droplet interface. This suggests that the droplet and the interface will be vibrating with the same frequency which might hit a natural frequency or lead to instabilities^{33,42} causing droplet coalescence as suggested in previous merging studies.

Droplet Coalescence

The preliminary requisite for droplet coalescence is adjacent droplet interfaces; this could be achieved by oil draining,⁷⁴ a channel expansion,¹⁸ droplet trapping,^{15,23,28,75,76} pairing^{26,32,77,78} or tweezing.^{21,24} Once the interfaces are sufficiently close, coalescence depends on various parameters including surfactants used, contact angle, capillary number (Ca), fluid viscosity, and channel geometry.¹³

Some of these parameters are well understood such as Ca . There exists a critical capillary number, $Ca_c \approx 10^{-2}$.^{13,79} It is predicted for systems with a capillary number smaller than the critical value, $Ca < Ca_c$, that merging will take place easily and vice versa.

In the absence of surfactants, aqueous droplets in oil media will spontaneously merge. This is well explained by the film drainage theory;⁸⁰ a thin film of oil prevents neighbour droplets' coalescence and it will take $t_{drainage}$ seconds for the film thickness to halve:

$$t_{drainage} = 40r \sqrt{\frac{\mu_c}{\gamma u}} \quad (1)$$

where droplet radius is given by r , continuous medium viscosity is shown by μ_c , interfacial tension is denoted by γ and u stands for the constant approach velocity. As the liquid film thins out (red arrows indicate liquid film drainage Fig. 2(A)), intermolecular forces grow stronger and cause the droplet-droplet interface to rupture and coalesce. With a similar system excluding the use of surfactants, we calculate droplet merging to spontaneously occur within tens of milliseconds, comparable to the pulse length used in this study.

Surfactants, however, are widely used in droplet microfluidic studies. They are often added to the continuous phase to improve droplet stability and prolong shelf-life. Surfactants reduce interfacial tension to promote droplet production and transport. By preventing spontaneous merging, they allow droplets to become individual micro-reactors that can be packed tightly for incubation⁸¹ and visualisation.⁸² They are also known to have effects on droplet-droplet chemical exchange⁷ and to exhibit various biocompatibilities⁸³ therefore they

should be carefully considered.

Surfactant molecules have hydrophilic heads (yellow circles in Fig. 2(B)) that reside in the aqueous side of the droplet interface and hydrophobic tails extending towards the oil medium. As more surfactant is added to the medium, the droplet/oil interface becomes saturated with surfactant molecules. At this concentration, surfactant molecules start to form micelles; this is known as the critical micelle concentration (CMC). Beyond the CMC, the interfacial tension stays constant, yet the dynamic interfacial tension and the adsorption rate of surfactants on droplet/oil interface keep changing.⁸⁴ These parameters are important for droplet microfluidics because the availability of excess micelles during droplet formation provides stability and prevents merging.^{85,86} For this reason, surfactant concentrations well beyond the CMC are often preferred in droplet microfluidics.⁸⁵⁻⁸⁸ Similarly in this study, surfactant concentrations above the CMC are chosen for studying droplet-droplet coalescence.

When two interfaces come closer in the presence of surfactants, steric repulsion of the surfactant tails act to prevent coalescence⁷ while Marangoni effect attracts an inward flow (green arrows indicate Marangoni flows Fig. 2(B)). Marangoni flow is caused by the discontinuities in the surfactant concentration at the interface of the droplet. Surfactant molecules accumulate at the rear of the droplets due to flow and molecular diffusion^{13,85} leading to an increase in surface tension near the droplet-droplet interface which pulls the surrounding liquid to drive an influx that counteracts liquid film drainage explained earlier and stabilizes droplets.

Materials & Methods

The oil phase used in the experiments was an engineered fluid (3MTMNovecTM7500) stabilised by the commercial surfactant Pico-SurfTM1 (Sphere Fluidics, UK) at 5 different concentrations (v/v); 2%, 2.75%, 3.5%, 4.25%, 4.7%. The aqueous phase was Milli-Q water. The fluids were loaded to syringes and the syringes were attached to syringe pumps (NE-1000, New Era

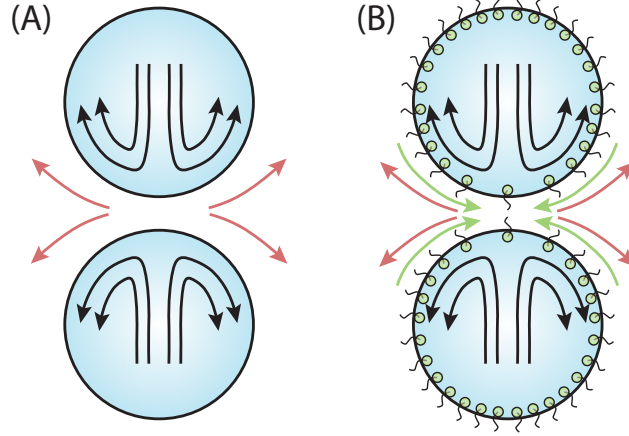


Figure 2: (A) Film drainage (red arrows) schematic with the absence of surfactant and (B) with the surfactant where Marangoni stress (green arrows) counteracts film drainage.

Pump Systems, Inc.). The microfluidic chip included three inlets for droplet production, one for the oil phase where the flow rate was set to $100 \mu\text{L}/\text{hr}$ and two for the aqueous phases set to $20 \mu\text{L}/\text{hr}$ each. The droplet producing channel design was based on previous works;^{12,77} after production, droplets flowed through a serpentine channel for pairing before merging. The flow velocity of droplets is measured around $5 \text{ mm}/\text{s}$; the 50 ms pulse used in this study corresponds to a distance of $250 \mu\text{m}$ travelled by the droplets during actuation window. The timing errors are estimated as 2 ms translating a mere $10 \mu\text{m}$ distance error on the results reported.

Focused inter-digital transducers (FIDTs) were used in this study to generate surface acoustic waves (SAWs) along a narrow beam.⁸⁹ The FIDTs had a λ spacing of $30 \mu\text{m}$ and were actuated with an AC signal of frequency 126 MHz and power 1W using a signal generator (F20, PowerSAW) (BelektroniG, Bruenig & Guhr Elektronik). The actuation was applied as a pulse signal of 50 ms duration for the merging to occur. It was ensured that the SAW actuation took place on the continuous medium and not the droplets during reported experiments.

Single side polished, 128°Y -cut, X-propagating LiNbO_3 (LN) wafers were patterned with the electrode designs. A chromium adhesion layer (10 nm) followed by an aluminium layer (200 nm) was deposited onto the substrate. Photoresist was lifted off and the wafer was

coated with 250 nm of SiO_2 for protection and isolation of the electrodes from the fluids in the microfluidic chip. The channels were fabricated with standard polydimethylsiloxane (PDMS) moulding and bonding.⁴⁵

Results & Discussion

When a 50 ms SAW pulse is applied to the oil phase immediately after two interfacing droplets (Fig. 3 A,B) stabilised by a surfactant, the interface ruptures (Fig. 3 C) and merging takes place. The interface quickly recovers (Fig. 3 D) and minimizes its surface energy by forming a pill shape.

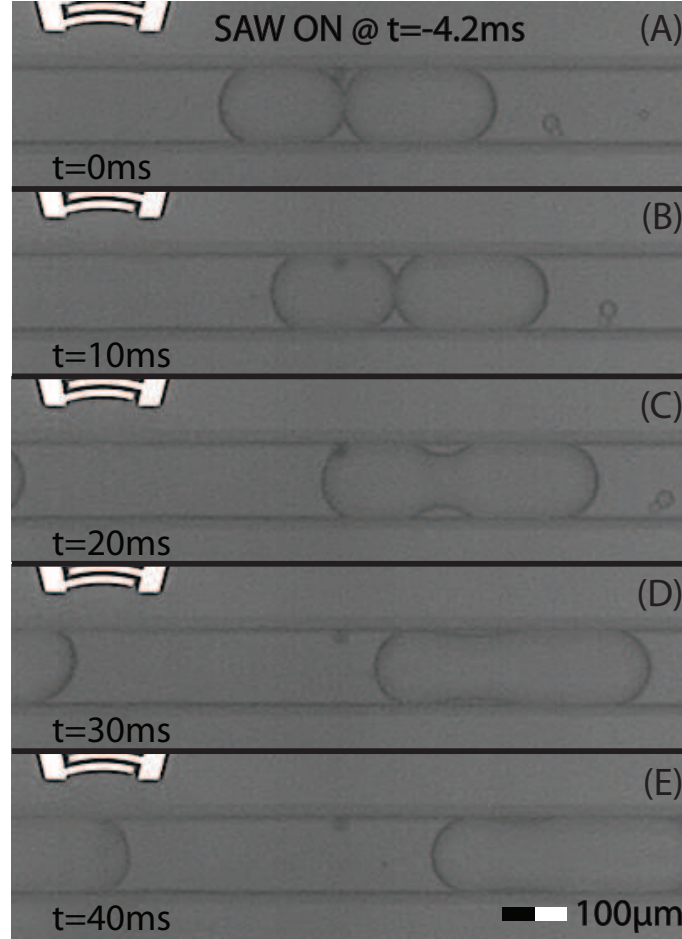


Figure 3: Timelapse micrographs of droplet coalescence.

In our experiments, we observed merging when the SAWs are targeted on the front or the

back droplet, even on the first droplet of the next pair if they are sufficiently close, however, we will only discuss the suggested operating region which is targeting the oil phase after a pair of adjacent droplets. This way droplets are free from direct SAWs, therefore rendering it safer for sensitive content within droplets. Moreover, it prevents unexpected outcomes such as droplet splitting as observed elsewhere.^{54,55}

Following up on the discussion around acoustic streaming, we will now discuss its role in the merging of adjacent droplets. We observed in our experiments, the effects of acoustic streaming flow in xy plane (Fig. 1(B)) described earlier. It draws a strong current towards the source of acoustic energy. When the back end of the trailing droplet is close to the centre of the acoustic beam (Fig. 4(B)), this flow can be seen as it deforms the droplet asymmetrically following the streamlines (Fig. 4(C) and inset). This phenomenon results in droplet-droplet coalescence as observed in Fig. 4(D).

There's a good chance that the physics of this type of merging is representative of the one shown in figure 3. The surfactant might be momentarily transported with the acoustic streaming flow or the deformation of the trailing droplet interface might lead to a change in the surface tension at the interface causing merging to take place. The mechanism could also be the disruption of the natural progression of flow, akin to a virtual speed-bump in the microchannel. In any case, there's clear evidence of acoustic streaming having a strong impact on the flow.

When either the droplet breaks free from the current or the SAW pulse ends, it is also observed that the droplet slingshots back to its original shape with minimum surface energy (Fig. 4(E)). It was also observed that this slingshot effect triggers droplet-droplet coalescence upstream of the acoustic zone. To be clear, neither of these scenarios are the suggested operation conditions for merging adjacent droplets with SAWs. These are only special cases where the visible deformation is indicative of the presence of strong acoustic streaming within the oil phase.

The system was further characterised by analysing the effects of two parameters on

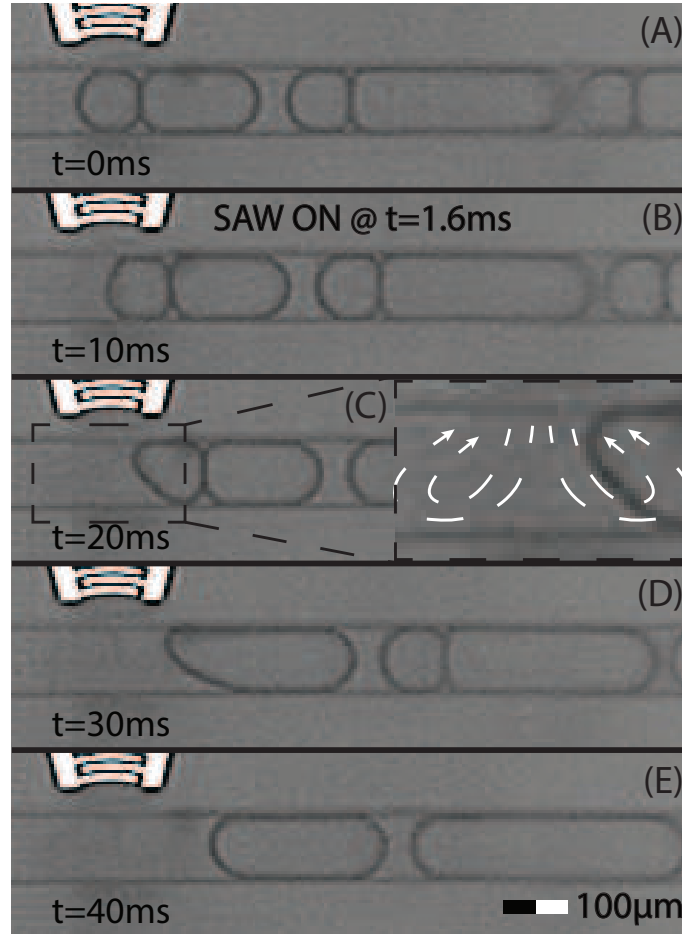


Figure 4: Timelapse micrographs of droplet coalescence when the trailing edge of the second droplet is close to acoustic beam waist.

merging success, the concentration of the surfactant added to the oil phase and the distance of the droplet-droplet interface to the centre of the IDTs (Fig. 1(B)). 5 different concentrations of the surfactant were tested, 2%, 2.75%, 3.5%, 4.25%, 4.7%. The results of this experiment are shown in figure 5. The figure is divided into two regions where the merging was successful and unsuccessful ¹.

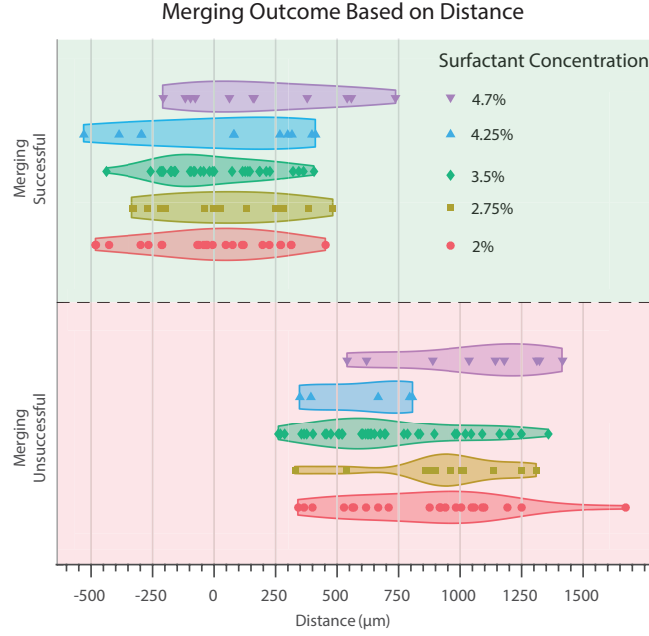


Figure 5: The distance from the center of the IDTs to the droplet-droplet interface at the onset of actuation with different concentrations of the surfactant as well as the merging outcome (successful | unsuccessful)

The results surprisingly show that the tested surfactant concentrations do not have a significant effect on the merging outcome (Fig. 5). Since the tested values are well above the CMC, the droplet/oil interfaces are already saturated with surfactant molecules prior to application of the SAW pulse. At these concentrations, the static interfacial tension remains constant, whereas the dynamic interfacial tension plays an active role in droplet systems.⁸⁴ The hypothesis was that the vibrations of the SAW pulse lead to surfactant depletion at the droplet/oil interface; by increasing the availability of surfactant molecules in the oil medium, it was expected that this depletion would be counteracted by the higher adsorption

¹Gramm toolbox was used for plotting this figure⁹⁰

rate of the surfactant molecules. This was not observed in the experimental results (Fig. 5), thus it is concluded that the coalescence mechanism does not heavily depend on surfactant concentration; and surfactant depletion is less likely to be the dominant mechanism.

The distance of the droplet-droplet interface to the centre of the acoustic beam, on the other hand, shows a clear cut-off after $\approx 500 \mu m$ distance with an overlapping region where the outcome can either be successful or unsuccessful.

With the importance of distance and the neutrality of surfactant concentration on the merging outcome established, it is reasonable to expect the coalescence mechanism fit these criteria. The time averaged effects of the SAW pulse, discussed earlier, particularly stand out in that regard. To revisit this idea; the SAW pulse creates a sudden pressure wave at the location of the SAW beam waist, therefore disrupting the fluid flow. The extent of this effect will diminish with distance as the wave attenuates into the fluid and the surrounding PDMS. It is important to note that this effect is coupled with the acoustic streaming discussed earlier.

To explore the idea of natural flow progression disruption that is caused by the sudden pressure change, the effect of acoustic actuation on the velocity of a droplet within the channel is investigated. For this study, single droplets sufficiently away from the IDTs are considered for observation. With the aid of Droplet Morphology and Velocimetry (DMV)⁹¹ software, the velocity of a droplet before, during and after SAW actuation is extracted from videos recorded at 5000 fps. A smoothing function⁹² is applied to the data to better visualise the results which are shown in figure 6. While the midline is the smoothed function, the area above and below the line shows the breadth of the actual data.

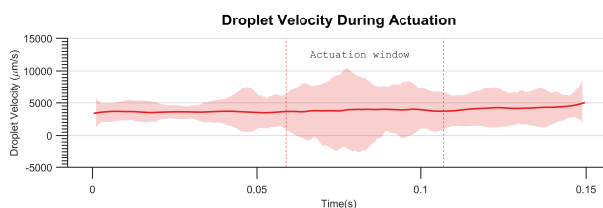


Figure 6: Droplet velocity as a function of time before, during, and after SAW actuation. A smoothing function⁹² is applied to obtain the midline while the shaded region is the actual breadth of the data.

The results show that the application of the SAW pulse leads to a discrepancy which doesn't necessarily slows down or speeds up the flow but rather disturbs, destabilizes it. This effect, almost vibrational in nature, could potentially be responsible for the coalescence of the adjacent droplets akin to cars driving over grates rather than a speed bump or a chain accident.

We discussed in *Surface Acoustic Waves* that the real-time vibrational effects caused by SAWs might be triggering a natural frequency response from the droplet interface leading to instabilities allowing merging to take place. To test this idea, we tested different frequencies with the same and different set of IDTs. Different from the 126 MHz that the experiments are carried out, we tested 64, 122 and 148 MHz and observed that the merging was not affected by the frequency change (results not shown). The power requirement for coalescence was slightly different at different frequencies which was due to impedance matching characteristics of the IDTs tested.

Overall, experiments investigating the effects of surfactant concentration, merging distance, SAW pulse on droplet velocity and frequency were carried out and discussed. It was observed that surfactant concentration, droplet volume and acoustic frequency does not play a significant role on droplet coalescence broadening the applications of the proposed technique. The strong presence of acoustic streaming in the oil phase was evident from the experiments with the actuation close to the edge of the trailing droplet. SAW pulse leads to small fluctuations in the droplet velocity and the merging was cut-off after a certain distance between the IDTs and the droplet-droplet interface was established. In the light of these results, it is safe to rule out matching the natural frequency of the interface nor the droplet; it is expected that the mechanism responsible for SAW induced merging diminish by distance and not be affected by surfactant concentration. We hypothesize that the strong acoustic streaming within the oil phase pushes and pulls on the droplet interface leading to destabilization and consequent merging. Furthermore, this mechanism is potentially complemented by the vibrational effects on the interface of the droplets as was suggested elsewhere^{33,42} and

backed up by the droplet velocity measurements.

Conclusion

A novel droplet coalescence method is presented and investigated where surface acoustic waves (SAWs) are targeted at the continuous medium in between two droplet pairs. A 50 ms pulse was shown to rupture surfactant stabilised droplet-droplet interfaces. To uncover the physics responsible for SAW pulse induced droplet merging, the effects of SAW frequency, distance, surfactant concentration as well as droplet velocity during SAW actuation is investigated. While the frequency and surfactant concentration did not impact the merging significantly, the natural progression of the flow was somewhat disturbed by the SAW pulse and the merging was unsuccessful after a critical distance between the SAW and the droplet interface has been established. We hypothesize that the merging is caused by acoustic streaming disrupting the flow and droplet-droplet interface leading to rupture and coalescence. Future work involves studying the effects of acoustic streaming magnitude, actuation frequency, droplet velocity and size, fluids and surfactants used and transducer geometry. For example, to understand how the system behaves at kHz frequencies, piezoelectric transducers could be integrated on chip⁹³ to characterise the role of frequency in detail.

The merging presented here is rapid and takes place during the applied electrical pulse duration of 50 ms. The actuation potentially has no harmful effects on the sensitive content of the droplets as the narrow SAW beam is applied on the continuous phase and does not affect the droplets directly. The channel geometry used for coalescence is just a straight channel and the coalescence mechanism is not affected by surfactant concentration and droplet volume, making this technique broadly applicable to existing designs.

This novel merging technique is on-demand as the SAW pulse only affects the droplet-droplet interface within the cut-off distance. To study biological and chemical reactions in droplets, a capable droplet sensing element with content detection should be integrated into

the system. Electrical⁹⁴ or optical^{95–97} droplet detectors have been shown to sense droplets as well as the biological content within. More complicated techniques such as differential detection photothermal interferometry⁹⁸ or small-angle X-ray scattering⁹⁹ could be used to determine the analytes in the droplets. Merging could be selectively initiated with the presented technique based on the analysis of the acquired signal or with machine learning techniques.¹⁰⁰ This way, drug screening, single cells and reaction kinetics could be studied in droplets.

It is surprising that droplet coalescence is still not well understood even though it finds many important applications in chemistry and industry such as oil recovery, fast reaction kinetics and droplet microfluidics. Further investigations into acoustic streaming velocity, the effects of SAW frequency and amplitude, the effects of droplet velocity and volume will aid in determining the mechanisms leading to merging as was discussed in this study. The authors believe that studying droplet coalescence with the recent advancements in microfluidics should help better understand the physics behind it which might even be translated back to larger scale systems with a significant impact.

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Supporting Information Available

The following files are available free of charge.

- Filename: System in action: Merging droplets with SAW. This video is recorded and played at 30 frames per second (i.e 1x playback). The channel width is 100 μm .²
- Filename: Application showcase: Fast reaction kinetics. This video is recorded at 5000 frames per second and played at 30 frames per second. The width of the channel is 100 μm .³

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²This video is recorded for demonstration purposes. Experimental results are not gathered in this manner.

³This video is recorded for demonstration purposes. Experimental results are not gathered in this manner.

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Graphical TOC Entry

