Mixing and pumping with oscillating bubbles

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ABSTRACT

An oscillating bubble will generate a jet towards a solid surface in its collapse phase. This phenomenon has been observed for example in underwater explosions for large bubbles (tens of meters in diameter) and it has also been confirmed for smaller bubbles. Such a collapsing bubble has been shown to be able to pump liquid from one side of a plate with a hole to the other side (provided that the bubble and the hole are aligned), (Lew et al. (2007). The working principle is still the same, i.e. a high speed jet is formed in the collapse phase of the bubble towards the hole in the plate. In the current study we will investigate if it is possible to mix fluids with an oscillating bubble based on the jetting phenomenon. Bubbles are created experimentally with a spark or a laser, and high speed camera images are taken to study the bubble and fluid dynamics. First, experiments involving two immiscible fluids, Hydrofluoroether (HFE) and water, are performed. When a bubble collapses near the interface of these immiscible fluids, the density difference between the two fluids causes the formation of a jet, which will mix the two fluids. The formation of a crown near the HFE water interface is observed, when the bubble collapses very close to this interface. This phenomenon appears to be similar to the crown often observed in splashing drops on a layer of liquid. Secondly, experiments involving two miscible fluids are also performed to investigate if the surface tension of the fluid-fluid interface plays any role. In order to do so, a layer of honey was used with a layer of water. The bubble dynamics and the mixing of the fluids appear to be very similar to the case with immiscible fluids. Finally, some additional experiments were performed in a microchannel using a laser generated bubble. The resulting flow phenomena are interesting but not yet fully understood.

INTRODUCTION

It is well known from underwater explosion research that a collapsing bubble produces a jet towards a nearby structure (Cole 1948, Blake et al. 1997). This property was later utilised by Lew et al. (2007) to create a pumping system by introducing a small hole at the location of jet impact on the structure after having being predicted theoretically by Khoo et al. (2005). Dijkink and Ohl (2008) further minituarized this principle in a microchannel. Similarly, an oscillating bubble near a fluid-fluid interface will create a jet towards the denser of the two fluids (Klaseboer and Khoo 2004). For example, a bubble collapsing near a free surface will generate a jet away from this surface (Blake and Gibson 1981).

In this paper, we will investigate if it is possible to utilise the jet of a collapsing bubble for the mixing of two distinct fluids. The current article describes observations on electrically generarated spark bubbles (radii ~ 5 mm), while the final application area (microchannels) and also study involving small laser induced bubbles in a microchannel (radii~100 μm). Eventually, we deem the bubble mixer useful for applications involving microchannels because traditional mixers using valves or turbines are not applicable for these small scales (potentially by using ultrasonically generated bubbles).

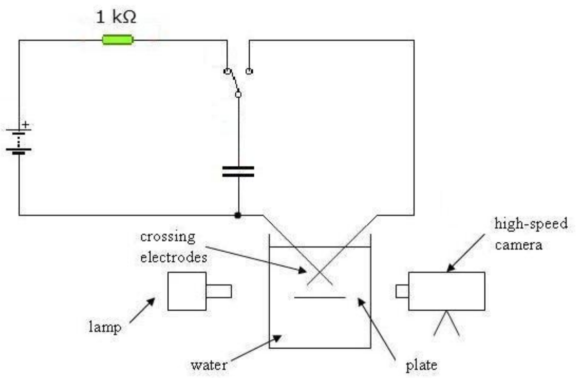

Figure 1. Experimental setup for the spark generated bubbles. Two capacitors placed in parallel were used (total 3000 μF, voltage supplied 60 to 90 V). The switch is used to short-circuit the capacitors and creates a bubble of about 5 mm radius through the (touching) electrodes in the water tank.

In Figure 1 the experimental setup for most of the experiments is shown. In a water tank (22 x 22 x 22 cm) two charged electrodes are short-circuited. The energy is stored in a capacitor which can be discharged through a two-way switch. The charging circuit consists of a voltage supply, a resistor, the capacitor and a two-way switch. The bubble generated using an electrical spark discharge at the crossing of the electrodes is placed near a fluid-fluid interface or a solid surface with a hole. The electrodes are deliberately placed in contact so a relatively low voltage (60 to 90V) is enough to generate a bubble. They are 0.2 mm thick copper alloy wires. The whole sequence is filmed with a high speed camera (Photron FastCam SA1.1 operating typically at 20,000 fps and placed at a distance of 10 to 20 cm from the electrodes). Besides (ordinary tap-) water, HFE-7100 from 3M is used as a second liquid. HFE (hydrofluoroether) is denser than water (1500 kg/m^3 vs. 1000 kg/m^3). Both liquids are supposed to behave as invisid liquids (at least for the experiments shown here, HFE has a viscosity of 0.6 mPas). HFE has rather high vapor pressure when compared to water (26.9 kPa vs 3.2 kPa at 25̊C respectively). In some experiments, honey has been used as well.

PUMPING WITH A COLLAPSING BUBBLE

In this section we will show the ‘pumping mechanism’ with a collapsing bubble. In order to do so, the electrodes are placed below a plate (dimensions 15 x 15 cm, thickness 5 mm). In Figure 2, the sequence of events is illustrated. Frame 1 shows the initial crossed electrodes below the plate (the plate is the dark region halfway up the image). The electrodes and the hole are exactly aligned. Once the electrical circuit is discharged (Frame 2), the bubble starts to grow. In Frame 3, the top of the bubble can be seen to exhibit a ‘cusp’ which protrudes almost into the hole. During the collapse phase of the bubble (Frames 4, 5 and 6) this protrusion disappears again. This cusp does not appear for bubbles collapsing near plates without a hole.

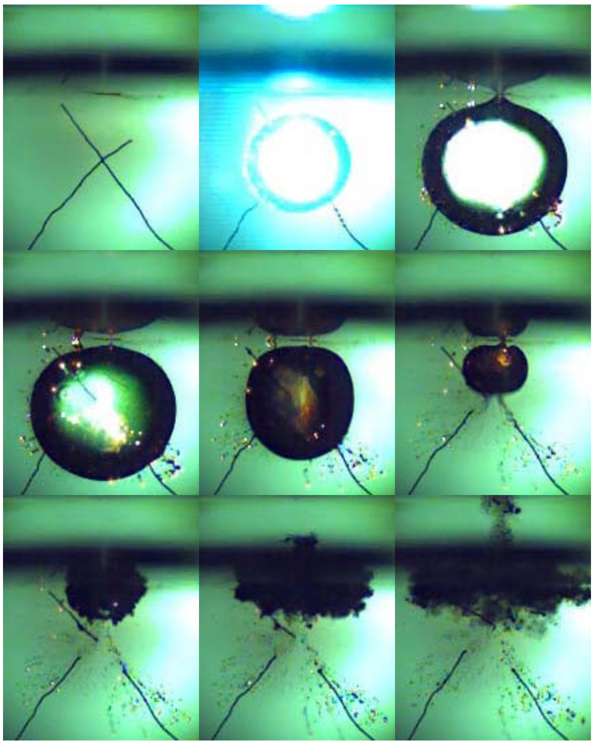

Figure 2. Jetting effect with a collapsing bubble near a plate with a 1.5 mm hole submerged in water. The maximum bubble radius is 5.5 mm. The frames shown correspond respectively to the times 0.0, 0.35, 0.80, 0.98, 1.30, 1.48, 1.60, 1.80 and 2.57 ms. The electrodes are placed about 5.5 mm below the plate which can be seen as the dark shaded region in frame 1. The discharge of the capacitor creates a ‘mini-explosion’. The brigh light from this explosion fades away in Frames 3 and 4. In frames 8 and 9 some liquid is ‘pumped’ from the bottom of the plate through the hole to the top of the plate.

The bubble is clearly attracted towards the plate in its collapse phase (gravity does not play a role for such fast oscillating bubbles of this size). A jet penetrates the bubble (which cannot be seen from the images). However, this jet is responsible for the observed amount of liquid that exits from the hole (Frames 8 and 9). The main bubble has broken up in many parts by this time and can be observed as a ‘cloud’. The green color shown in the background of Figure 2 originates from the slightly colored glass of the water tank used in the experiments. Other examples with much bigger hole sizes can be found in Lew et al. (2007). It was shown there that an amount equal to the maximum volume of the bubble could be displaced by the collapsing bubble. In this particular experiment, the fluid above and below the plate were the same (water). In the next section, we will see if a similar mechanism can still work if the plate is removed and replaced by a fluid-fluid interface. As was observed by Klaseboer and Khoo (2004), a jet towards the denser fluid will occur for an oscillating bubble near a fluid-fluid interface. Yet, the mixing ability of such a system has never been examined to the authors’ best knowledge.

A slight disadvantage of the current experimental setup is that due to the violent bubble creation process, the electrodes break off. Therefore, in order to do another experiment, the electrodes have to be reset into place and properly aligned. The current set-up has been used for a variety of experiments in the past; for example the removal of particles from a tube (Pavard et al. 2009) and the study of the dynamics of multiple interacting oscillating bubbles by Fong et al. (2009).

MIXING OF IMMISCIBLE FLUIDS

Water/HFE, (spark-) bubble generated in water

In the previous section we have seen that a bubble can indeed ‘pump’ liquid from one side of a plate to another. In this section we will investigate the behaviour of an oscillating bubble near a fluid-fluid interface and in particular its capability to mix the two fluids during or after its collapse phase. We will first investigate the case of immiscible fluids; water and HFE.

Many experiments have been performed and only a few typical cases will be shown here. Such an example is shown in Figure 3. A layer of HFE is created at the bottom, with a layer of water on top. The fluid-fluid interface can be found-just below the center of Frame 1. The maximum bubble radius is 4.9 mm and the bubble has been generated at a distance of 6.4 mm. The bubble expands (Frames 1 to 4) and an apparent distortion of the fluid-fluid interface appears. However, this distortion appears to be just the relection of the bubble in the fluid-fluid interface. Therefore the fluid-fluid interface remains essentially flat during this stage. The collapse of the bubble appears in Frame 5. A jet emerges out of the bottom of the bubble in Frame 6. It enters the fluid-fluid interface and a certain amount of water together with some remnants of the collapsed bubble enter the HFE liquid (Frame 6 onwards).

The two fluids appear at first to attain an equilibrium after the jet entrance (after 8 ms). However, a surprising event happens relatively long after the bubble has collapsed. A counterjet emerges from the fluid-fluid interface (Frames 10 to 12). This jet is not strong enough in this particular case to produce any HFE droplets in the water above it (also due to the relatively large density of HFE). A possible explanation for this phenomenon could be that the fluid-fluid interface has been pushed down as the bubble collapses. It reacts with a counterjet, much alike a stone being thrown on a water surface. The exact origins of this phenomenon are still not yet fully understood, yet it appears to occur for most of the experiments shown in this article. It could be due to the restoring effect of either gravity or surface tension.

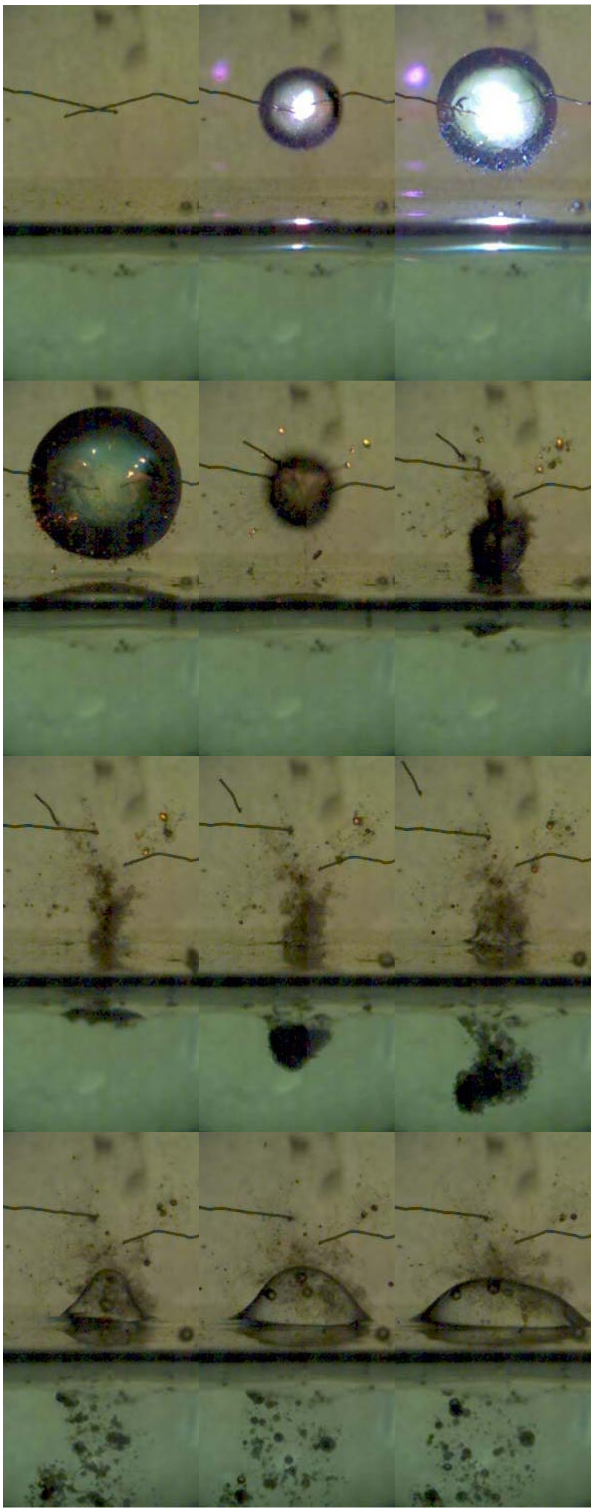

Figure 3. Mixing of water (on top) and HFE (bottom) with a spark-generated bubble (maximum radius 4.9 mm) in water. As the bubble collapses, the jet enters the HFE, followed by a counterjet creating a dome-shaped amount of HFE long after the bubble has vanished. The frames shown correspond respectively to the times 0.0, 0.4, 1.0, 1.6, 2.1, 2.6, 3.8, 5.5, 7.9, 17, 34, 46 ms. The apparent elevation of the fluid-fluid interface in frame 4 is an optical illusion, created by the reflection of the bubble in this interface.

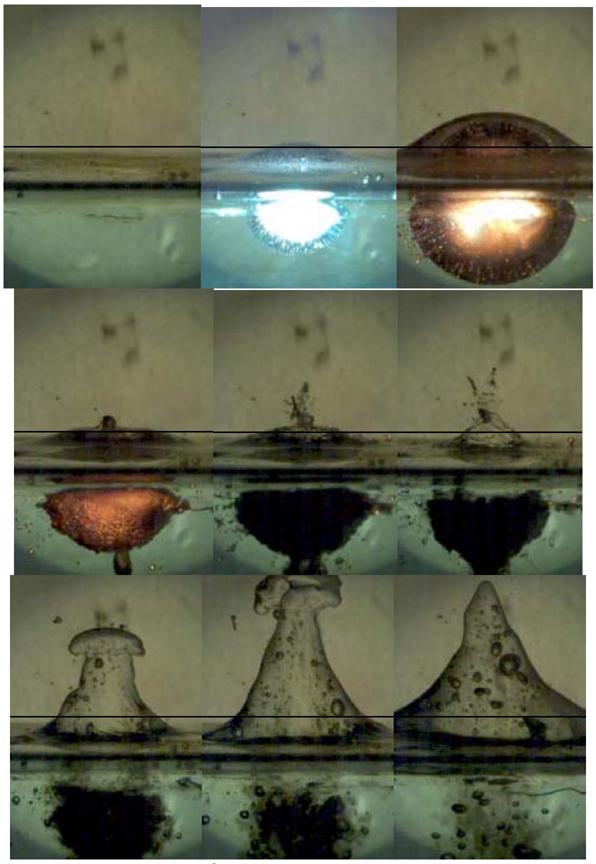

Figure 4. Mixing of water (top) and HFE (bottom) with a spark-generated bubble in HFE. The maximum radius of the bubble is 6.5 mm. As the bubble expands, the interface is distorted. During the collapse phase, two simultaneous jets occur in opposite direction, followed by a rising mushroom-shaped amount of HFE, which splits off a droplet (not shown). The frames shown correspond respectively to the times 0.0, 0.5, 1.7, 2.9, 4.4, 6.3, 22, 42 and 112 ms.

Water/HFE, (spark-) bubble generated in HFE

After having shown a typical example of a bubble initiated in water, we will now proceed to show a typical example of a bubble generated in HFE instead.

In Figure 4 a bubble has been generated in HFE. The original flat fluid-fluid interface can be observed just below the center in Frame 1. The electrodes are obscured by the interface in this case and are placed at a distance of 4.3 mm below the fluid-fluid interface. In Frame 2 the bright light of the spark generated bubble can be observed. Simultaneously, due to the close proximity of the bubble to the fluid-fluid interface, this interface moves upwards. At its maximum size (maximum radius 6.5 mm), the bubble pushes the fluid-fluid interface upwards in Frame 3. The collapse phase of the bubble is not as violent as in Figure 3. This difference was attributed to the relatively high vapour pressure of HFE. It can be observed that the bubble does not contract as violently (Frames 3 to 6) as in the case of a bubble generated in water. Nevertheless, it appears as if a jet is generated in the bubble (Frame 5). In this case, it moves away from the fluid-fluid interface (Klaseboer and Khoo 2004). A second jet is observed at the fluid-fluid interface (Frame 5).

As in the previous case, the fluid-fluid interface starts to move upwards long after the bubble has collapsed (the bubble lifetime is less than 6 ms). Part of the HFE liquid forms a mushroom shape (Frames 7 and 8) and eventually breaks off from the main jet (not shown here). The jet retreats back finally due to the effect of gravity (Frame 9). Long after, the drop that split off from the main jet also falls back onto the fluid-fluid interface around 300 ms (not shown here). The droplet has an estimated radius of 2 mm.

Other similar experiments have been performed. In these experiments, the distance of the bubble to the fluid-fluid interface has been changed. For a distance larger than 1.5 times the maximum bubble radius, the surface jet does not appear anymore. However, for lower distances, this jet can reach a height of 25 mm (for a distance of 0.5 times the maximum bubble radius). The mixing capability of the oscillating bubble appears to be most effective, when the bubble is placed rather close to the fluid-fluid interface.

CROWN FORMATION

During the course of the experiments, an interesting phenomenon was observed at the fluid-fluid interface when the bubble was created very close to this interface. Again a HFE – water interface was used. It turns out that under those circumstances a crown shaped layer of HFE was generated in the water as shown in Figure 5. The appearance of this 'crown' is very similar to the one observed when drops splash into a layer of liquid (see for example Toole, 2009). A thin 'rim' of fluid is pushed outwards and upwards by the expanding bubble. Due to flow instabilities the rim breaks up into multipole smaller droplets forming a 'crown'.

Figure 5. Spark-generated bubble at the interface water (top) - HFE (bottom) during the expansion phase. The fluid-fluid interface is situated just below the center of the image. A crown surrounding the bubble can be observed in water (located roughly at 1/3 of the bubble radius above the fluid-fluid interface). Parts of the burning electrodes can still be seen in the lower HFE submerged part of the bubble as brightly colored spots. The bright light in the center originates from the original short circuiting of the electrodes. The water has been colored with an orange dye.

MIXING OF MISCIBLE FLUIDS (SPARK BUBBLES)

A set of experiments was carried out using two miscible fluids, instead of the immiscible fluids described in the previous sections. The two fluids employed are water and honey (viscosity about 10 Pas). The density of the honey is larger than that of water, and it is thus placed below. A layer of water is then added on top. The two fluids are miscible, yet the characteristic mixing time is very long (hours). Thus the fluids can still be considered as two fluids for the duration of our experiments.

A typical example of such an experiment is shown in Figure 6. The bubble is generated right at the fluid-fluid interface. The bubble expands to its maximum size (Frame 2) and during the collapse phase a jet towards the honey is observed (around 3 ms). The remnants of this jet can be seen from Frame 3 onwards (the dark area at the bottom of the frames). Due to the large viscosity of honey, the fluid entrained by the jet remains stagnant after Frame 3. Nevertheless a counterjet appears on the fluid-fluid interface in Frame 4 (at about 16 ms after the spark generation). A vortex like honey structure emerges from the fluid-fluid interface at a relatively very low speed.

Other similar experiments were performed with bubble generated at different distances from the fluid-fluid interface. They yield comparatively similar results. Yet as could be expected, the most effective mixing occurs when the bubble is generated very close to the fluid-fluid interface.

The experiments show that similar phenomena occur whether the liquids are miscible or immiscible. That is, a jet is always created due to the bubble collapse towards the heavier of the two fluids. After the bubble has collapsed, a (much slower) counterjet can be observed moving in the opposite direction.

The absence of surface tension in this case would exclude the possibility of surface tension being responsible for the counterjet that was observed a long time after the bubble has disappeared.

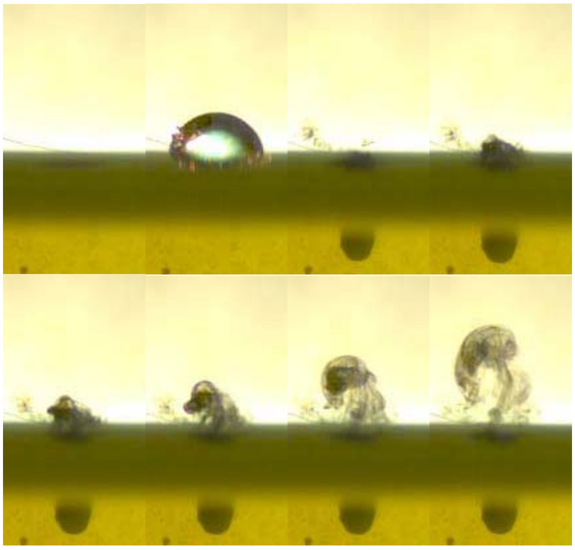

Figure 6. Mixing of water (top) and honey (bottom) with a spark-generated bubble (maximum radius 5 mm). The jet of water into honey happens 2 ms after the spark (Frame 3), whereas the honey jet into water reaches its maximum height 160 ms after the spark (not shown). The frames shown correspond respectively to the times 0.0, 1.25, 6.25, 16.0, 21.3, 29.5, 47.5 and 75.8 ms. Note the waterjet inside the honey and the counterjet of honey at the fluid-fluid interface for larger times.

THREE-LAYER FLUIDS EXPERIMENTS (SPARK BUBBLES)

It is well known that a jet occurs when a bubble collapses near a solid surface (see for example Benjamin and Ellis, 1966 or Blake et al. 1986). It is also known that a jet away from a free surface occurs for such bubbles (Chahine, 1977 or Klaseboer et al. 2005). As mentioned in the introduction, an oscillating bubble near a fluid-fluid interface will create a jet towards the denser of the two fluids (Klaseboer and Khoo

2004). In this section we will see if a mixing effect can be induced by letting the bubble oscillate in between two fluid-fluid interfaces.

A bubble is introduced by the above mentioned spark method in a layer of water, which is placed on top of a layer of HFE. The water layer is thin (1.8 cm) and is bounded by an air-water interface. Figure 7 shows the results of such an experiment. The water layer is colored orange with a dye in order to enhance the visibility of the results. The bubble is introduced towards the top of the water layer and attains a maximum radius of 6.1 mm. During its expansion phase, it pushes the air-water interface upwards (Frame 2). The water-HFE layer does not appear to move at all (at least not discernable). In Frame 3, the bubble collapses away from the air-water interface (note the flattened top of the bubble). The air-water interface develops a jet. Also one can observe some microdroplets being injected into the air (Frame 4) at this interface. The bubble has now moved towards the water-HFE layer and pierces through it (Frame 5). In the mean time, the air-water interface jet develops to a considerable height (much higher than the bubble radius, Frames 5 to 8). After the bubble jet has traversed the water-HFE interface, a counterjet appears on this surface (Frames 5 to 8), finally developing into a mushroom shaped jet (Frame 8).

It thus appears that a three layered approach can still produce a mixing effect, very similar to that of the previous sections.

Figure 7. Three layers experiment (HFE-water-air). The layer of water is 1.8 cm high and has been colored with an orange dye. The maximum radius of the bubble is 6.1 mm. The two interfaces both exhibit an upwards jet. The frames shown correspond respectively to the times 0.0, 0.9, 1.15, 1.95, 3.15, 6, 8.9 and 17 ms.

MIXING IN MICROCHANNELS (WITH LASER GENERATED BUBBLES)

Since the previous experiments are only showing results on the mm scale, we will now investigate if the principle of mixing with oscillating bubbles can still work on a much smaller scale (microchannel).

In order to do so a microchannel was made in-house; it was printed on silicon plates, PDMS was then poured onto these plates, which was, after heating, bonding to a glass plate; see Tandiono (2010) for more details. The channel is 100 µm wide and has an estimated height of about 200 to 250 µm. Through two separate inlets, the liquids (HFE and water) are being introduced in the microchannel (see Figure 8). The bubble was introduced with a laser in this case.

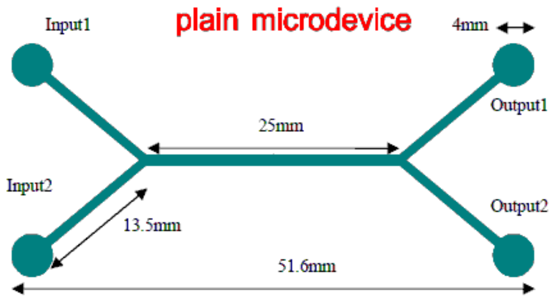

Figure 8. The design of the microchannel device

The results of one of the experiments are shown in Figure 9. In Frame 1, the bottom consists of water, while the top layer consists of HFE. A bubble with maximum radius 43 µm is being created (Frame 3) in the water layer at a distance of 24 µm from the fluid-fluid interface.

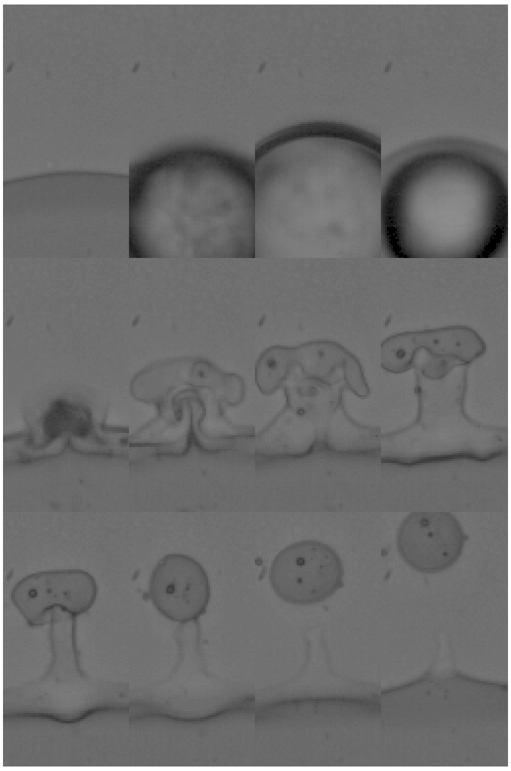

Figure 9. Mixing of water (bottom) and HFE (top) in a microchannel with a laser-generated bubble created inside water. The maximum radius of the bubble is 43µm (frame 3). Water jets inside HFE: the height of the jet is 55µm. The frames shown correspond respectively to the times 0.000, 0.010, 0.013, 0.017, 0.020, 0.023, 0.027, 0.033, 0.040, 0.050, 0.073 and 0.130 ms. The results were filmed with a black and white high speed camera.

The fluid-fluid interface moves upwards with the expanding bubble. The dynamics of the process are extremely rapid and even a 300,000 fps high speed camera is no longer able to observe the jetting phenomenon. Nevertheless, in Frame 4, clearly fluid can be seen moving towards the denser HFE. This could be considered as indirect evidence of a jet. This jet penetrates further into the HFE fluid (Frames 6 to 8). Finally part of the water breaks off and forms a droplet inside the HFE fluid (Frames 9 to 12). This experiment clearly shows that mixing on the microscale with an oscillating bubble is possible.

An interesting observation is that there is no HFE counterjet into the water as was observed in Figure 3. Since gravity is assumed not to play a role in such microsystems, it might be possible that the jet observed in Figures 3 and 4 originate from the restoring effect of gravity. More research in this direction should be done however, in order to certify this assumption.

When investigating other experiments in this microchannel configuration, it was observed that a droplet of water forms in the HFE liquid, when the distance from the bubble to the fluid-fluid interface is smaller than about half the maximum bubble radius. For larger distances, the jet does not cause the droplet to be created. For very large distance, say two times the maximum bubble radius, the fluid-fluid interface hardly moves alltogether.

We have not explored the possibity of using sound waves to generate oscillating bubbles. Recently it has been shown by Tandiono et al. (2010) that cavitation in microchannels can indeed be created by generating small microbubbles from an air-water interface in the channel (acoustically driven capillary waves). Thus it is possible to use ultrasound induced bubbles for mixing and pumping instead of spark or laser generated bubbles in the current study.

CONCLUSIONS

In this article, the possibility of pumping and mixing fluids with an oscillating bubble is shown. This bubble could be generated by ultrasonic means, but for simplicity it has been produced with a spark and laser setup in the current work. An interesting phenomenon observed was the appearance of a counter jet long after the bubble has disappeared. The exact physical explanation for this phenomenon has not yet been clarified. Another interesting observation was the appearance of a ‘crown’ when the bubble was generated very close to a fluid-fluid interface.

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