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# BUBBLE-DROP INTERACTIONS IN FLOTATION COLUMNS – THE PROBABILITY OF COMPOUND DROP FORMATION

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**Abstract.** *A probability analysis of a flotation system was conducted experimentally. The rate of bubble-drop attachment was investigated by using the high-speed shadowgraph technique based on the total counts of single-fluid drops and formed compound drops. We report the probability of attachment of gas bubbles to oil drops and investigated the conditions for compound drop formation. In order to mimic the conditions often met in an offshore production site, the effect of salinity, fluid properties, and the addition of additives were also analyzed. In general, the global probability of bubble-drop attachment prevailed at roughly 30%, regardless of the system of fluids. Thus, the formation of compound drops is governed by the agitation, rather than the properties of the fluids. However, the presence of additives plays an important role in the relative probability, i.e., the rate of compound drop formation for a specific range of bubble diameters. The additives promote the formation of smaller bubbles that, according to our experiments, substantially increases the formation of bubble-drop compounds.*

**Keywords:** *compound drop, attachment, salinity, additives*

## 1. INTRODUCTION

The attachment of gas bubbles to oil drops governs the process of flotation. The oil spreads over the inserted bubbles, forming bubble-drop compounds, i.e., compound drops, that rise with increased buoyancy (Saththasivam et al., 2016). Many factors govern the bubble-drop attachment, as firstly investigated by Dudek et al. (2019). The probability of attachment was investigated for different compositions of continuous fluid. They reported that the formation of compound drops is favored by low or neutral pH; the increase in salinity also favors the bubble-drop attachment by reducing the electrostatic repulsion. However, their experiments focused only on a microfluidic system in laminar flow; a different condition from typical flotation systems in oil extraction sites.

Other parameters may affect the formation of compound drops, e.g., the contact angle between the bubble and the drop during a collision and the approaching speed, only to name a few (Lim et al., 2016). These parameters are important from a hydrodynamic perspective. To the best of our knowledge, there have been no experimental reports on the probability of bubble-drop attachment under those conditions. The majority of studies are restricted to the attachment of gas bubbles to solid spheres or within microfluidic devices. A more detailed review of the specific literature may be found elsewhere (Saththasivam et al., 2016).

In this paper, we investigate the attachment of gas bubbles to oil drops in more realistic scenarios. We promote bubble-drop collisions in an agitated liquid bulk and report experimental measurements of the probability of attachment for different compositions of continuous fluids. Our main findings include the influence of the size of the bubble in the attachment probability.

## 2. EXPERIMENTAL SET-UP

A scheme of the experimental setup is shown in Fig. 1. Tap water was fed to a glass tank kept at 20 °C and atmospheric pressure. A population of oil drops and gas bubbles was generated. As the oil drops were formed using the pinch-off method (with diameters ranging from 0.2 to 1.4 mm), the bubbles were formed by inserting compressed air into a gas chamber fixed at the bottom of the tank. A porous membrane (pore size of roughly 10  $\mu\text{m}$ ) was placed at the top of the gas chamber. The size distribution of the bubbles was controlled by manipulating the injection pressure. The formed bubbles showed a normal diameter distribution ranging from 0.2 to 2 mm. A mild agitation (60 rpm) was provided to the system to ensure a proper mixing between the generated drops and bubbles.

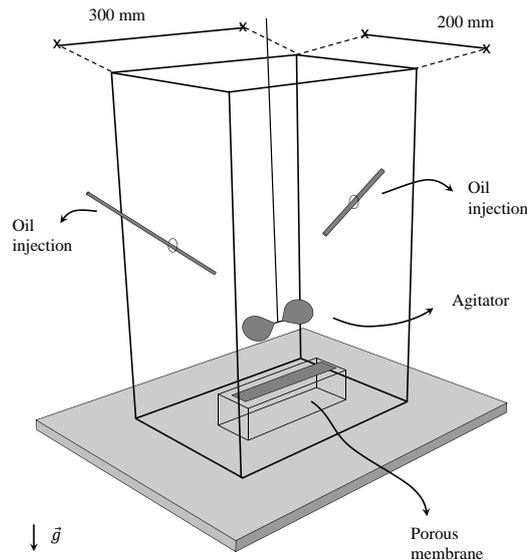


Figure 1. Scheme of the experimental set-up.

Table 1 summarizes the conditions investigated in this study. We analyzed the effect of salinity at a typical concentration found in oil separators. The effects of ethanol at different volume concentrations and the surfactant LAS (linear alkylbenzene sulphonate) were also studied. Table 1 also shows the properties of the fluids for each experiment. The viscosities were measured using a standard viscometer (Brookfield LVDV2); other fluid properties were taken from literature [1-3, 5, 12].

Table 1. Experimental conditions used in the bubble-drop attachment experiments. The physical properties of the fluids are also shown:  $\rho_M$  is the density of the mixture,  $\mu_M$  is the dynamic viscosity of the mixture,  $\sigma_{g/w}$  is the surface tension and  $\sigma_{o/w}$  is the interfacial tension at the oil-water interface. The values are obtained from literature (Anachkov et al., 2015; Bashir et al., 2014; Biscay et al., 2011; Sohounhloue et al., 1987).

	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 6
Tap water	X					
Ethanol 6% (v/v)		X	X			
Ethanol 20% (v/v)				X		
Salt (70 g/L)			X	X		X
LAS (100 ppm)					X	
$\rho_M$ ( $kg/m^3$ )	998	982	986	989	998	1020
$\mu_M$ ( $mPa \cdot s$ )	1.0	0.93	0.94	1.96	1.0	1.1
$\sigma_{g/w}$ ( $mN/m$ )	73.5	69.6	69.8	66.1	51.2	74.1
$\sigma_{o/w}$ ( $mN/m$ )	41.1	37.4	36.9	34.1	34.9	31.4

Figure 2 shows a sample image of the compound drops (circled in red) formed with the aforementioned methodology. Note that some oil drops remain unattached to the bubbles (circled in blue). The instantaneous probability of attachment was obtained by counting the total number of compound and single-fluid drops in the snapshot. The measurements were repeated 10 times for each condition. We define the probability of attachment as:

$$\alpha (\%) = \frac{n_{cd}}{n_d + n_{cd}} \quad (1)$$

where  $n_{cd}$  and  $n_d$  are the averaged counts of the compound and single-fluid drops for each condition listed in Tab. 1. Thus,  $\alpha$  accounts for the percentage of the drops that actually became attached to a bubble.

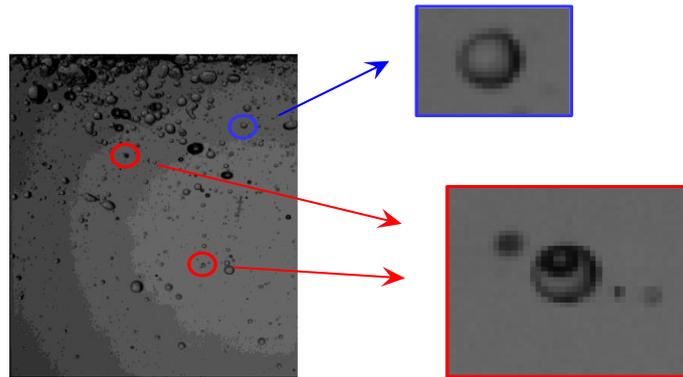


Figure 2. Snapshots of bubble-drop compound drops in flotation systems.

### 3. RESULTS

The results obtained for the probability of attachment,  $\alpha$ , are shown in Table 2 for all the measurements. Apparently,  $\alpha$  spans roughly from 28 to 36 %, regardless of the presence of additives; the variation of the probability of attachment seems to be random. This contrasts with the measurements obtained by Dudek et al. (2018), e.g., who reported an optimized condition for a bubble-droplet attachment with higher salinity. However, as previously mentioned, their experimental setup is considerably different. In this study, we also take the effect of agitation into account and promote the bubble-drop attachment for a wider diameter range. We conjecture that under those conditions it is the agitation, rather than the properties of the fluids, that determines the probability of compound drop formation. Note that these observations are valid only from an overall perspective, since  $\alpha$  does not consider the size of the bubble.

Table 2. Size range of the generated bubbles and probability of bubble-drop attachment, defined by Eq. 1, for different experimental conditions.

	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 6
$d_b$ ( $\mu\text{m}$ )	220 - 2500	200 - 1650	210 - 1720	200 - 1500	150 - 1200	230 - 2300
$\alpha$	34.5 %	29.3 %	33.9 %	35.6 %	35.1 %	27.8 %

It is interesting to know whether smaller or larger bubbles are more suitable to the formation of bubble-drop compounds. To do so, it is convenient to split the global probability  $\alpha$  into individual parameters  $\alpha_i$  where the index  $i$  refers to the following ranges of bubble diameter:

- (1) Small bubbles :  $d_b < 500 \mu\text{m}$  ;
- (2) Medium-sized bubbles :  $500 \mu\text{m} < d_b < 1000 \mu\text{m}$  ;
- (3) Large bubbles :  $d_b > 1000 \mu\text{m}$  ;
- (4)

note that  $\alpha_i$  is defined as a subparameter of the global probability  $\alpha$  and  $\sum_{i=1}^3 \alpha_i = 1$ .

Figure 3 shows the measurements of  $\alpha_i$  for all experiments. The results indicate that, regardless of the addition of additives, smaller bubbles are more suitable to form bubble-drop compounds with  $\alpha_1 > \alpha_2 > \alpha_3$ . This is in accordance with previous studies that showed that smaller bubbles promote the formation of compound drops (Lim et al., 2016). Apparently, the spreading of the oil is facilitated when the covered area of the bubble is small (Mori, 1978).

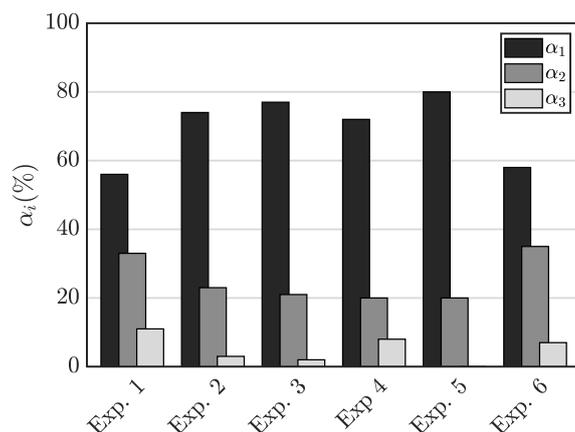


Figure 3. Effect of the diameter of the bubble on the probability of bubble-drop attachment.

In this article, the attachment of gas bubbles to oil drops in an agitated system was investigated by means of a probability analysis. The effects of the properties of the fluids by adding different additives to the system were analyzed. We focus on the probability of bubble-drop attachment in conditions that are more similar to the ones found in oil production sites.

The probability of bubble-drop attachment can be more than one order of magnitude higher when compared to millimeter-sized bubbles. We also found that the role played by the properties of the fluids is less relevant when the system is under mild agitation; this suggests that it is the bubble-drop attachment, rather than the interfacial thermodynamics, that governs the kinetics of the system.

#### 4. ACKNOWLEDGEMENTS

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