SNAP-OFF OF AN OIL DROP IMMERSE IN WATER FLOWING THROUGH A CONSTRICTED CAPILLARY

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Abstract. *Uncertain conditions for emulsion generation in oil production, including the resulting drop size distribution and stability, limits operators ability to adequately evaluate and plan well productivity, artificial lift processes, separation equipment as well as equipment location. Emulsions may be formed in turbulent flow through valves, pumps, and other equipments or inside the reservoirs. The present work focuses on the study of one possible mechanism of oil-water emulsion generation in porous media. Different constricted capillaries, i.e. owning a converging-diverging section, were used as a model geometry of the flow channels inside a porous media. Flow of large oil drops through the capillary constriction was visualized using an optical microscope. The experiments were performed with three capillaries (different constriction-to-capillary diameter ratios), several viscosity ratios for a range of capillary numbers. The conditions at which the snap-off occurs were mapped as a function of the operating parameters.*

Keywords: *Capillary pressure, emulsion generation, oil production, porous media, snap-off, constricted capillaries, visualization.*

1. Introduction

Dispersions are systems made up of at least two immiscible phases, where one of the phases is dispersed in a second, continuous phase. There are three different types of dispersions that can be formed with a liquid as the continuous phase: foams (gas-liquid), emulsions (liquid-liquid), and suspensions (solid-liquid). Becher (2001) mentions five other less common possibilities of dispersions: Liquid-solid, solid-solid, gas-solid, liquid-gas and solid-gas. Dispersions may be classified according to the features size of the dispersed phase (droplets, bubbles or grains) in molecular solutions, colloids and dispersions. In this work, we concentrate on emulsions, i.e. liquid-liquid systems. Emulsions are generally stabilized by the addition of a surfactant, which acts by reducing the interfacial tension between the two liquid phases involved, and by creating repulsive (steric) forces between droplets, to inhibit coalescence of different drops. Emulsions are frequently encountered in industrial processes such as manufacture of adhesives, inks, foods, cosmetics, controlled dosage medicines and in practically all the stages of oil production. Emulsions can be produced spontaneously or in controlled ways. Controlled emulsion production involves shear or physical-chemical processes, separately or combined. Spontaneous emulsion production may occur, for instance, during events of oil production, because oil and water phases of certain composition enter in contact. According to Davies G. A. et al. (1996) and Sarbar, M.A. et al. (1997), such emulsions may be stabilized, additionally, by the presence of other oil components, typically heavy oil fractions such as asphaltenes and possibly suspended solids.

Emulsion formation during oil production may take place in the flow inside the reservoir or in the two-phase flow down hole in production wells, and through tubes and valves in surface facilities. Emulsions cause a number of operational problems such as tripping of equipment in gas-oil separations plants (GOSPs) and high pressure drops in flowlines (Kokal et al.,1999). Uncontrolled and undesired emulsion production causes problems and production cost increment, related to frequent equipment shutdown for maintenance, and need for demulsifying processes. Emulsions have to be treated to remove the dispersed water and associated inorganics salts to meet crude specification for transportation, storage, and export and to reduce corrosion and catalyst poisoning in downstream-processing facilities (Kokal, 2005). In high water-cuts production wells, the continuous phase may be water. Emulsions are classified on the basis of their degree of kinetic stability as [Kokal, 2005]:loose emulsions (those that separate in few minutes), medium emulsions (will be separated in then minutes or more) and tight emulsions (will separate, some only partially, in a matter of hours or days).

Separation of emulsions is found to be extremely sensitive to the size of the droplets, and it is controlled by settling of drops in the order of 30-60μm. Separation time is usually greater than residence time of fluids in separation equipments (Davies et al., 1996). The separation step may be critical in some cases for emulsions having drop diameters smaller than 30 microns in the case of plate separator, and for diameter smaller than 5 microns in the case of separation by centrifugation (Van der Zande et al., 1999).

Flow conditions through porous media in the near-wellbore area, in turbulence downhole and through pumps leading to emulsions are generally not sufficiently known. The effects of the different flow accidents on the drop size are not very

well understood. Knowledge of the morphology of the resultant emulsions is important input data in the design of process conditions and separation equipments. Better knowledge of emulsification in porous media and in surface facilities is required to achieve good predictability of the produced emulsions morphology and behavior, and to improve production planning. Emulsification by liquid breakup mechanisms in flow accidents in oil operations is the focus of the present work.

Porous media emulsion generation can occur because of the flow of the two liquids (oil and water) through a complex interconnected pore-neck network. One of the mechanism by which emulsions are formed in porous media is the so-called snap-off mechanism, which is a type of drop breakup. This mechanism may be described as an invasion of the wetting phase flowing adjacent to the pore-neck wall, into a constriction occupied by a non-wetting phase. The wetting film grows like a collar, until it creates a discontinuity in the non-wetting phase (drop breakup). Such phenomenon is illustrate in Fig.1.

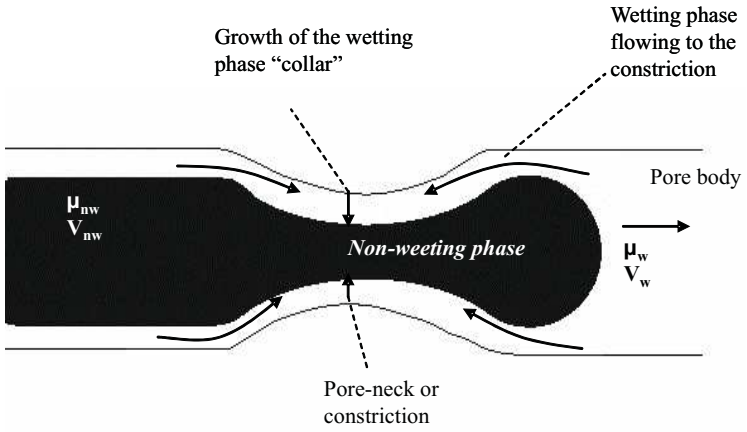

Figure 1. Snap-off mechanism in a porous media for a system having water as continuous phase.

The snap-off mechanism has been extensively studied to explain foam and emulsion generation in oil reservoirs. Roof (1970) studied the effects of channel geometry on snap-off using an oil/water system. Results of his experiments agree with his proposed theory, which suggests that given a constriction geometry, a minimum protrusion of the non wetting phase through the pore-neck is required for snap-off to occur. According to Roof, snap-off happens only in the case of a tube/constriction diameter ratio of at least 2:1. Rossen (2002) completed a review on the snap-off mechanism of foam generation. He concluded that the pressure drop for snap-off to occur depended on the pore-neck geometry, and that snap-off, in agreement with Roof's criterion, stops when the downstream pore body is filled with one or more bubbles or drops. One important parameter in Rossen's (2003) analysis is the capillary pressure at the bubble tip at the throat of a circular constricted capillary Pc_e, defined as:

$$Pc_e = \frac{2\sigma}{R_c}, \tag{1}$$

where σ is the interfacial tension and R_c is the circumferential radius at the constriction.

After the tip of the bubble passes through the constriction, the capillary pressure at the throat falls to Pc_{sn}. For straight cylindrical throats $Pc_{sn} = Pc_e/2$. For gently constricted capillaries, the value of Pc_{sn} can also be approximated by $Pc_{sn} = Pc_e/2$.

According to Janssen et al. (2000), wettability also influences the drops diameter in emulsion produced from a reservoir: relatively big drops diameter in oil-wet porous media and small drops, of the order of the pore body scale diameter, in water-wet porous media.

Snap-off phenomena in a pore-neck inside a porous media may be physically simulated by flowing a two-phase liquid system through a constricted capillary. Several variables may influence the breakup of drops inside a constricted channel: the capillary number (Ca), capillary geometry, viscosity ratio, density ratio, drop-to-neck diameter ratio, wettability of the capillary wall, surfactant concentration gradient and chemical nature of the phases. Variables studied in the present work are discussed in what follows.

The capillary number Ca expresses the ratio of viscous to interfacial forces in the system, and it is defined as:

$$Ca = \frac{\mu_w V}{\sigma}, \tag{2}$$

where μ_w is the viscosity of the continuous phase (water); V is the average velocity of the flow; and σ is the interfacial tension between the two liquids. The capillary number influences significantly the deformation and snap-off of drops

flowing through capillaries. It represents the ratio between the viscous flow resistance of the wetting phase adjacent to the capillary walls and the capillary pressure that drives the flow of the wetting phase to the neck of the constricted capillary. Below a critical value of the capillary number, referred here as the critical capillary number, drop breakup occurs.

According with Gaulitz et al.(2002), snap-off for foam generation in porous media depends on the dynamics of the local capillary pressure at the pore throat. The authors estimated the value of the pressure gradient, for the case of an air bubble suspended in a liquid and passing trough a constriction. As depicted in Fig.2 (Gauglitz, Laurent and Radke,1988), if the pressure on the gas bubble is considered constant, the capillary pressure gradient between the region identified as (1) and (2) is defined by:

$$P_{L1} - P_{L2} = \sigma(\frac{1}{R_2} - \frac{1}{R_1} - \frac{1}{R_3}), \tag{3}$$

where:

P_{Li} Liquid pressure at the point i,

σ Interfacial tension,

R_1 Liquid radius in the straight section,

R_2 Circumferential liquid radius at the constriction,

R_3 Transverse radius at the constriction.

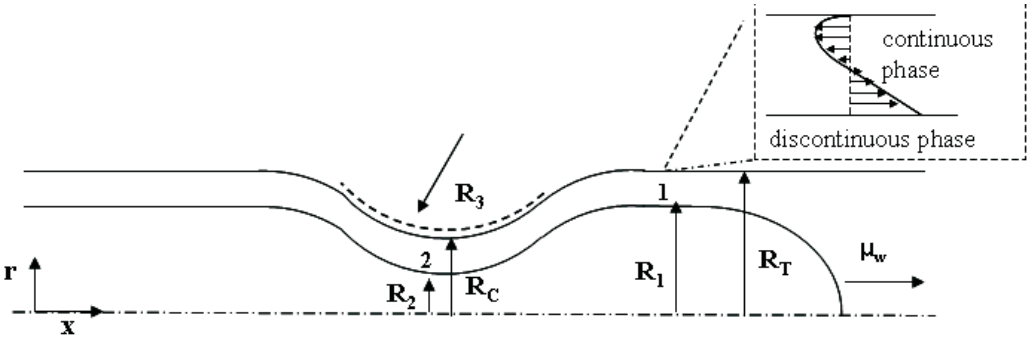

Figure 2. Bubble or drop movement, film deposition, and snap-off in a constricted capillary.

The capillary constriction causes a capillary pressure gradient that drives the wetting phases towards the capillary throat, which may lead to a drop break up.

Cuthiell et al. (1995) studied emulsion generation in the two phase flow inside a porous media sample. They used both mineral and reservoir oils in their experiments. They observed that emulsions were formed in the same range of capillary number tested, for both of the oils used. In this study, and because of reasons exposed in this paragraph, the dispersed phase was selected as pure and transparent substances as possible to limit chemical interferences and to facilitate the visualization of the flow trough the capillary.

The goal of this work is to use previous analysis of foam generation in porous media and extend it for its application to emulsion formation due to liquid drop breakup as it flows through pore throats. The pore geometry was simulated by a glass constricted capillary. Three different constriction-to-capillary diameter ratios and seven different viscosity ratios between the liquid phases were tested. The regions of the parameters space at which drop break up occurs was mapped and the sequence of events that lead to drop break up was visualized.

2. Materials and Experimental Procedure

2.1 Materials

Properties of the oil-water systems used are listed in Tab.1.

Mineral oils (OP3, OP10, OP35 and Talpa30) and pure n-heptane were selected as dispersed phase to avoid chemical interferences of foreign components, and to permit a wide range of water-oil viscosity ratio. The wetting phase consisted of deionized water (treated by reverse osmosis), pure or mixed with surfactant or glycerin. The surfactant, when used, was Sodium Dodecyl Sulfate (SDS), at a concentration of 0.03M (three times the critical micelle concentration). Such

Table 1. Properties (@ 25^{o}C) of liquids used in the experiments

System	Components (non-wetting/wetting phases)	Viscosity ratio (κ)	Interfacial tension (mN/m)
I	n-heptane/water+glycerin 55%	0.056	21.7
II	n-heptane/water+glycerin 40%	0.124	25.5
III	n-heptane/SDS	0.4	17.2
IV	OP3/SDS	3.5	9.8
V	OP10/SDS	13.36	6.7
VI	OP35/SDS	57	6.7
VII	Talpa 30/SDS	460	5.3
VIII	Talpa 30/water	460	17.9

Table 2. Studied velocities and capillary numbers

Geometry	Studied Geometries ($2R_c$ /$2R_T$)(in μm)	$\frac{1}{R_3}$ (in μm^{-1})	Velocity (in the straight section, (m/s))	Ca (in the straight section)
a	20/200	0.09972	8.84×10^{-5} - 5.31×10^{-4}	9.02×10^{-6} - 5.41×10^{-5}
b	50/200	0.039182	8.84×10^{-5} - 1.77×10^{-3}	4.05×10^{-6} - 5.75×10^{-4}
c	50/100	0.03924	3.54×10^{-4} - 2.12×10^{-3}	3.61×10^{-5} - 4×10^{-4}

solutions are denoted in this paper as SDS. Because the low values of the Bond number [$O(10^{-6})$], differences in density do not affect the experiments (Gauglitz, Laurent and Radke, 1988) and are not considered in this work.

Viscosity was measured (except for the n-heptane) by using of a Cannon Fenske viscosimeter, and interfacial tension by the ring method. Viscosity and density of the n-heptane was taken from the product's specification data sheet.

Borosilicate glass constricted capillaries were used to simulate a pore passage in a porous medium. Three different geometries consisting of different neck-to-straight section diameter ratios were used. Transversal curvature at the constriction, 1/ R_3, was also different for each capillary. The geometries used are shown in Fig.3, and listed, together with the flow conditions analyzed, in Tab.2.

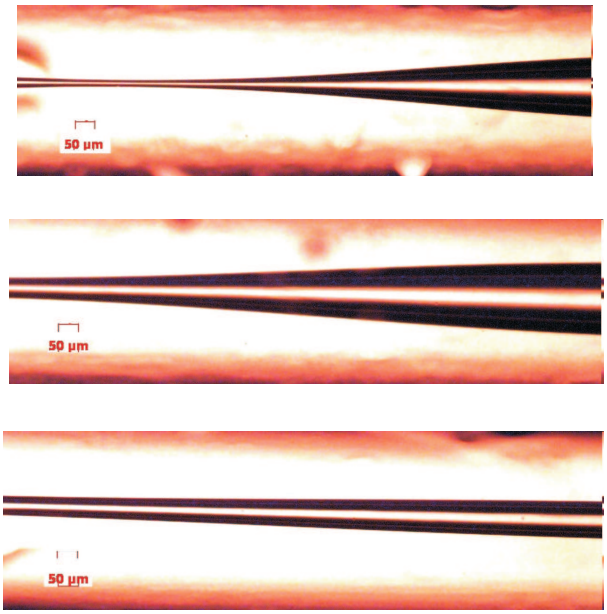

Figure 3. Constricted capillaries used in the study. (a) 20/200 (constriction/straight section diameter ratio) geometry; (b) 50/200 and (c) 50/100

2.2 Experimental Procedure

Phases were filtered using a membrane, to avoid blocking the capillaries at the constriction, caused by impurities present in the liquids. A low-Reynolds number regime, corresponding to volumetric flow rates in the range of 0.01 ml/h

to 0.2 ml/h, was studied. The flow rate was controlled by using a syringe pump (Colle Parmer). The flow parameters explored are listed in Tab.2, they represent typical values for flows in reservoirs. The visualization setup is shown in Fig.4.

Undesirable refractive index contrasts were mitigated by submerging the capillaries in glycerin, for the visualization of the flow of oil drops through the capillaries. Flow images were captured using a CCD camera coupled to an Axiovert 40 MAT Inverted Microscope (Carl Zeiss). The frame-grabbing rate of the CCD camera was 15 frames per second. Lenses of 2.5X, 5X and 10X magnifications were used to observe the constriction region. An objective of 10X was used to provided details of the snap-off, while objectives of 2.5X and 5X were used to gather wider field of view for the constriction where drop breakup occurs.

The video camera was connected in parallel with a video recorder (for long-time video recording purposes) and to a computer (for still pictures or frame grabbing and short-time period video recording). Videos were converted to a digital format using a LabView interfaces, and the images were analyzed using the Axiovision software (Carl Zeiss), in order to measure details of the experiments, i.e. droplets size, capillary geometries and distances into the constriction.

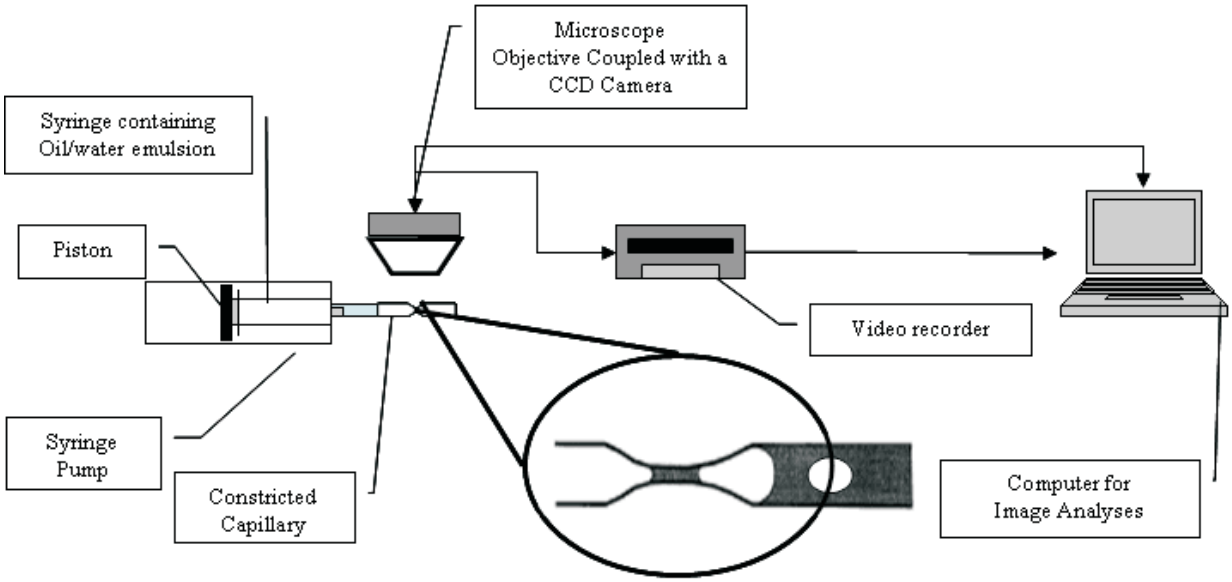

Figure 4. Visualization experimental Set-up.

3. Results

As the oil drop flows through the straight portion of the capillary, a thin film of water wets the capillary wall. As the drop flows through the constriction, a capillary pressure gradient is generated, as indicated in Eq.(3). This pressure gradient drives water towards the capillary throat, creating a collar structure that grows until it closes breaking the oil drops break up.

An example of this sequence of events is shown in Fig.5. These results were obtained with capillary b and liquid system IV. The oil drop is moving from left to right in each frame. The initial stages of the formation of the collar structure are shown in Fig.5(a). The growth of the collar and the choking process of the oil drop is clear in Figs.5(b) and (c). In the last frame, the oil drop breaks up into two drops.

The water flow rate towards the throat is a function of the capillary pressure gradient, responsible for driving the flow, the wetting phase viscosity, that resist the flow, and the shear stress at the interface, proportional to the non-wetting phase viscosity, that drives the flow away from the constriction. If the net flow rate is towards the capillary throat, an infinite drop will break. Therefore the occurrence of drop break up can be mapped as a function of the capillary number, the viscosity ratio and the capillary geometry.

For each of the three capillaries tested and for each of the eight liquid systems tested, the flow rate was slowly raised. The flow of large drops through the constriction was observed at each flow rate, i.e. capillary number. The occurrence or not of drop break up was recorded. The results for the capillary geometry b ($2R_c/2R_T = 50/200$) is shown in Fig.6. The open, "x" or "+" symbols in the plot indicate experimental conditions at which drop break up was not observed. The filled symbols indicate conditions at which it occurs. At the lowest viscosity ratio tested, i.e. κ = 0.056, drop break

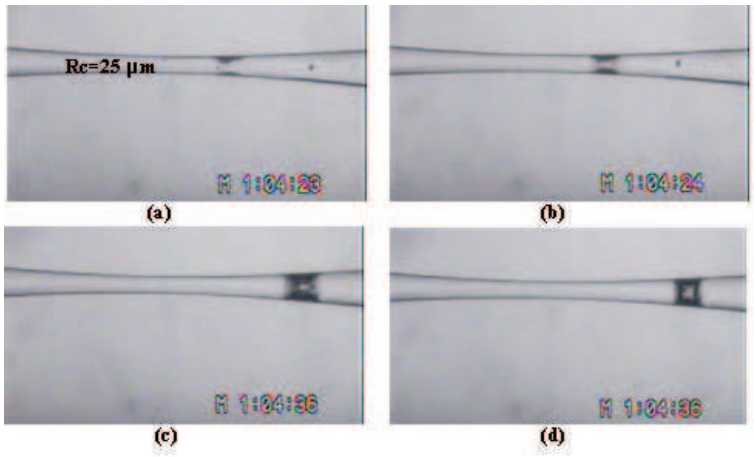

Figure 5. Typical event sequence leading to snap-off of an oil drop. System IVb. The oil is the clear fluid.

up was always observed, even at the largest capillary number tested. The drop viscosity is lower than the continuous phase viscosity and the shear stress at the interface that drives the water away from the capillary throat is small. This observation agrees with the conclusion reported by Rossen (2003) that a gas bubble, i.e. $\kappa \rightarrow 0$ will always break in any constricted capillary. As the viscosity ratio increases, there is a capillary number above which the drop flows through the constriction without breaking. This critical value of the capillary number falls as the viscosity ratio rises. The shear stress at that interface grows as the non-wetting phase viscosity increases, pushing the wetting phase away from the constriction. Consequently, the relative magnitude of the force that drives water to the collar structure with respect to the flow resistance has to rise, i.e. the capillary number necessary for drops break up falls. At high viscosity ratio, i.e. $\kappa > 57$, drop break-up was never observed in the range of capillary number explored. This observation agrees with those reported by Olbricht (1996) and Tsai et.al. (1994) and more recently by Janssen (2000), who all state that snap-off only occurs for low viscosity drops, i.e. for low viscosity ratio.

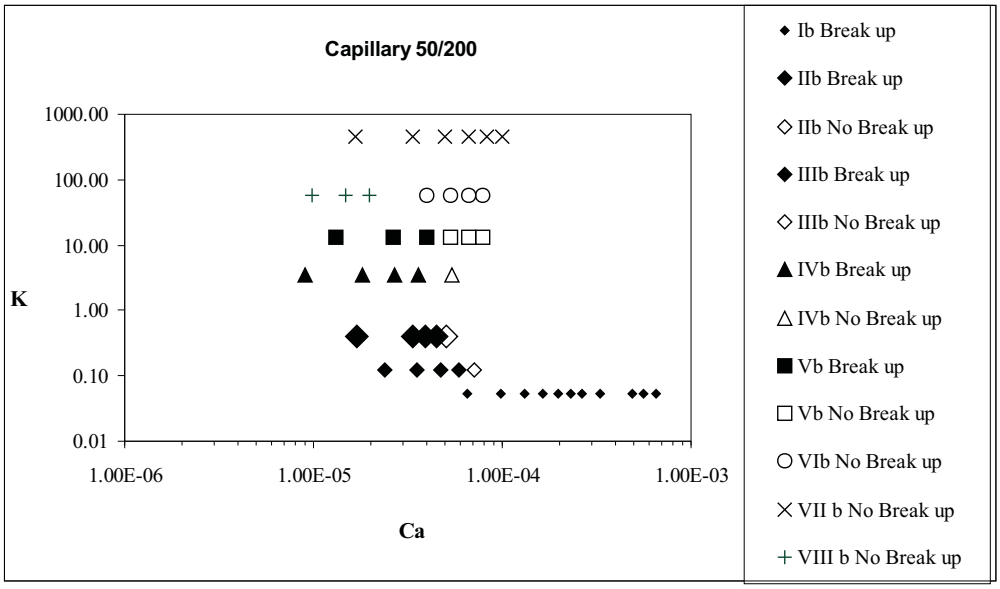

Figure 6. Mapped regions for snap-off. Viscosity ratio κ vs Ca. Capillary b.

The critical capillary number for drop break up is also a function of the capillary geometry, as expected. The stronger the contraction, the larger the capillary pressure gradient, and consequently the stronger the driving force for the snap-off mechanism. Figure 7 presents the results for the other two geometries tested (a, 20/200, and c, 50/100) in the range of viscosity ratio from 3.5 to 57. When the strongest contraction ratio was used, e.g. geometry a, drop break up could be observed at a viscosity ratio of $\kappa = 57$. At this value of viscosity ratio, the snap-off mechanism was not observed with geometry b. The capillary pressure gradient was not strong enough to overcome the high shear stress at the interface. At

viscosity ratios of κ = 13.36 and 3.5, the critical capillary number below which the snap-off occurs rises as the contraction ratio becomes larger. When geometry c was used, contraction ratio of 5/10, drop breakup was not observed, in the range of capillary number explored, for viscosity ratio κ > 13.36. The capillary pressure gradient and consequently the driving force for drop break up is weak. With this geometry, snap-off was only observed with liquid system IV (viscosity ratio κ = 3.5); and at lowest value os capillary number tested.

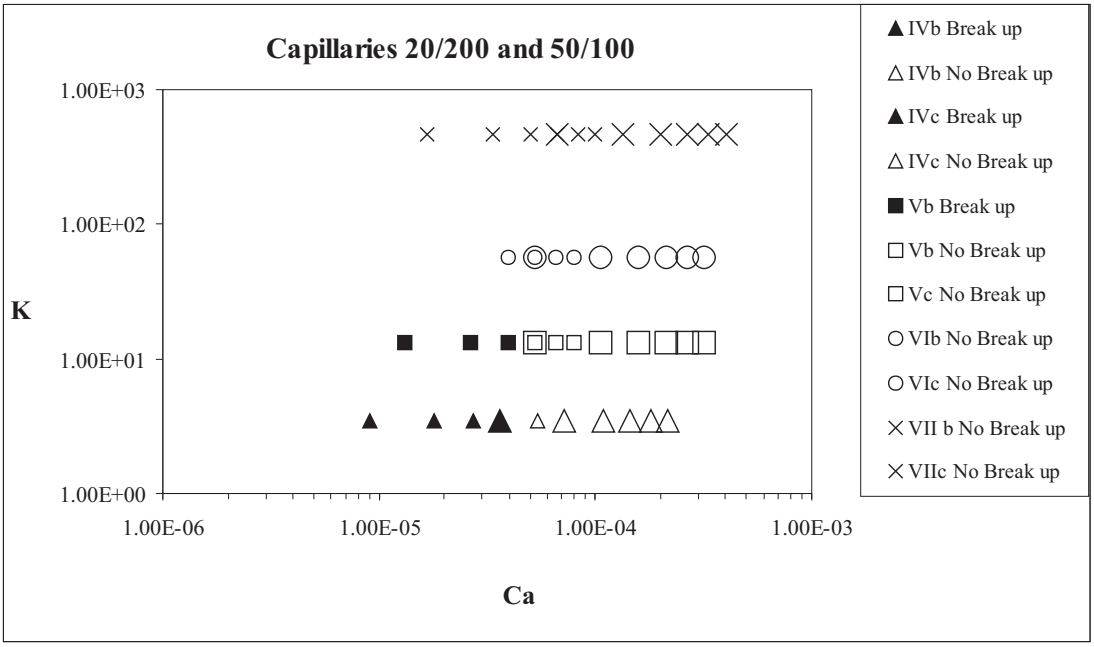

Figure 7. Mapped regions for snap-off. Viscosity ratio κ vs Ca. Capillaries a and c; Systems IV, V, VI and VII.

From the two previous plots, it is clear that the region of the parameters space at which drop occurs is a function of the capillary geometry. For each geometry, a new critical capillary number would have to be determined. It would be useful is a single master curve that limits the region of snap-off could be obtained for different capillaries. This is done by analyzing the relative magnitude of the important forces. All the experimental data points presented in Figs. 6 and 7 can be written in terms of two dimensionless variables: (i) the capillary number $Ca = \mu_w V/\sigma$ that represents the ratio of the resisting viscous to the capillary forces, and (ii) the capillary pressure gradient, defined by:

$$\nabla P^* = [\frac{1}{R_2} - \frac{1}{R_1} - \frac{1}{R_3}]/[\frac{1}{R_1}\frac{\mu_{nw}}{\mu_w}], \tag{4}$$

where:

∇P^* is the dimensionles pressure gradient,

R_1 Liquid radius in the straight section,

R_2 Circumferential liquid radius at the constriction,

R_3 Transverse radius at the constriction.

μ_{nw} Non-wetting phase viscosity,

μ_w Wetting phase viscosity.

This number gives a ratio of the capillary pressure gradient to the shear stress at the interface, that is proportional to the viscosity of the drop. The first drives liquid towards the throat and the later away from it. All the experimental condition tested are plotted in terms of Ca and∇P^* in Fig.8. Again, the open, "x" or "+" symbols in the plot indicate experimental conditions at which drop break up was not observed, and the filled symbols indicate conditions at which it occurs. The region of the plot at which snap-off occurs for the three different capillary geometries tested collapse into a single region. For $Ca < \ 4 \times 10^{-5}$, drop break up only occurs at $\nabla P^* > \ 10^{-1}$. For $Ca > \ 10^{-4}$, drop break up only occurs at ∇P^* > 60. The continuous phase viscosity resistance, represented by the capillary number, requires a high driving force, i.e. large ∇P^*. Between these two limits, i.e. 4×10^{-5}<$Ca < \ 10^{-4}$ the critical value of ∇P^* above which snap-off occurs rapidly rises from 10^{-1} to 60.

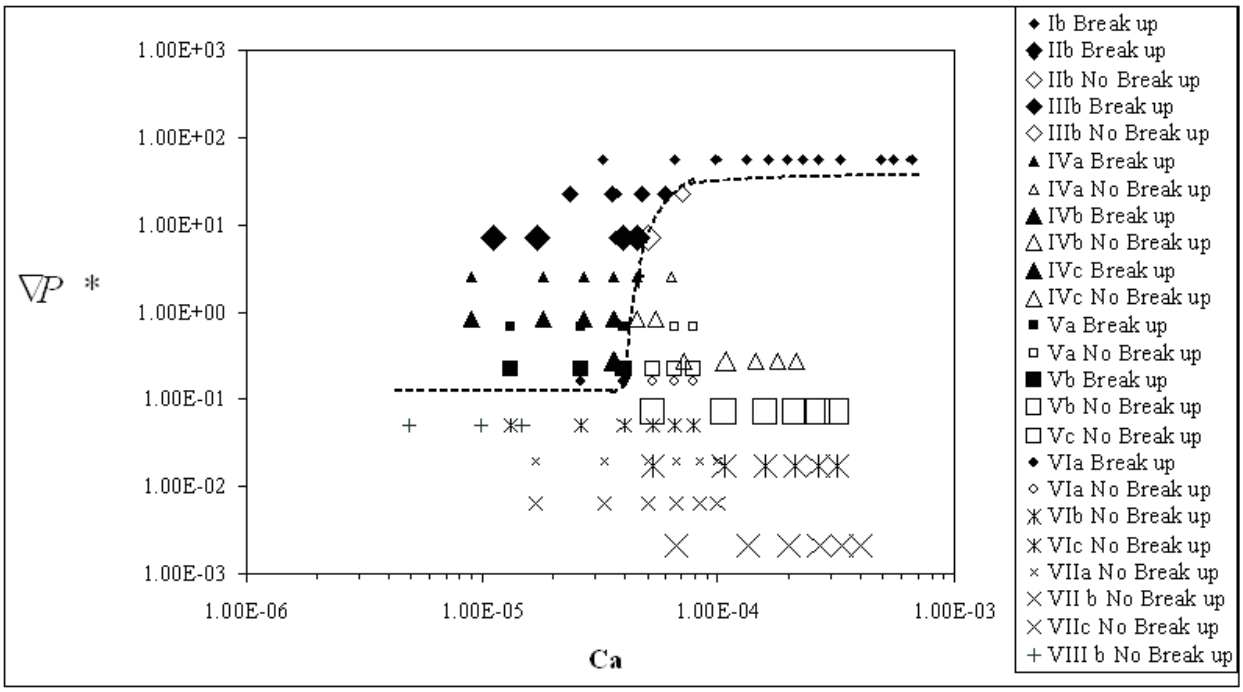

Figure 8. Mapped regions for snap-off. Dimensionless capillary pressure gradient vs Ca.

4. Final Remarks

Visualization of drop breakup through the snap-off mechanism at the micron scale was achieved by flowing oil droplets through circular constricted capillaries. The dependence of snap-off on experimental parameters such as capillary pressure gradient, contraction-to-capillary diameter ratio, viscosity ratio between the two liquid phases, and capillary number was explored. The set of flow parameters at which drop breakup occurs was determined for different capillary geometries and oil-water systems.

The use of appropriated dimensionless number, namely ∇P^*, made possible to map the snap-off region for different capillary geometries in a single plot.

∇P^* was shown to be one of the parameters that allows to describe the snap-off, in an ideal (circular) pore throat, for the capillary number values typically founded in oil reservoirs. This dimensionless parameter, ∇P^*, included some of the main quantities accounting in the studied phenomenon: capillary pressure gradient, associated the capillary geometry, interfacial tension, and viscosity ratio between involved phases.

The other important parameter that determines the drop break up is the ratio between the driving force of the water flow through the thin film (the capillary pressure gradient) and the viscous resistance to the flow, i.e. the capillary number.

5. Acknowledgements

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