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DROPLET BREAKUP IN TURBULENT FLOW THROUGHT AN ORIFICE

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Abstract. *As the two-phase oil-water mixture flows through the producing wells, risers and valves, the disperse phase may break leading to stable emulsions. The size of the dispersed oil drops has a strong effect on the flow resistance and on the phase separation process. Most of the drop breakup occurs as the oil-water mixture flows in turbulent regime through valves and narrow passages. Despite the large volume of experimental work reported in the literature, the relationship between the drop size distribution downstream of an orifice and the flow conditions is not clearly understood.*

In this work, we study experimentally the drop breakup of an oil-water emulsion as it flows through an orifice. Two mineral oils of moderate viscosity were dispersed in two different continuous phases, tap water and a continuous phase formed by a mixture of substitute ocean water and the anionic surfactant STEOL® CS-330 (Stepan Company). The drop size distribution downstream of the flow restriction is measured as a function of the flow conditions, liquid properties and drop size distribution upstream of the orifice. Results show that, for each flow condition, there is a maximum stable drop diameter below which the drops do not break. Analysis of the data revealed that maximum stable drop sizes were in the inertial sub range, characterized exclusively by the energy dissipation rate per unit mass.

Details of the breakup process was studied by visualizing the breakup of a single drop using a high-speed camera. The images show that drop breakup only occurs downstream of the restriction and takes place at a certain distance from the edge of the orifice. At this breakup length, the radial velocity gradient in the flow is large enough to overcome the resistance stresses (exerted by the droplet) and produce the rupture of the droplet. The visualization has also allowed the analysis of the relative influence of interfacial tension and dispersed phase viscosity.

Keywords: *Drop Breakup, emulsions, visualization, turbulent flow*

1. INTRODUCTION

As the two-phase oil-water mixture flows through the producing wells, risers and valves, the disperse phase may break leading to stable emulsions. The drop size distribution (DSD) of this emulsions are a very important parameter, because significantly affects the separation processes efficiency. Therefore, accurate models for prediction of the drop size are greatly desired.

To optimize the phase separation and due to the environmental impact generated by disposal of large amounts of oil (dispersed in millions of cubic meters of water), the best alternative to reduce harmful effects is to study where, when and how oil droplets break in the road they travel during production, and try to control the equipment and/or mechanisms responsible for high fragmentation rates.

Research efforts aimed to solve this problem started when Davies *et al.*(1996) by identifying the flow zones where small droplets are formed in the production system.

Then, Janssen and Harris (1998) investigated the size of the droplets flowing out of the reservoir into the bottom of the well, concluding that droplets are typically of the size of the pore neck or larger (tens of micrometers up to millimeters). Previously, Sarbar and Wingrove (1997) showed that for some field cases, droplets smaller than 5 µm are encountered downstream of the choke valve.

Muntinga (1998) studied the effect of the geometry of the choke in the breakup process. He showed that breakage in the choke is not a stationary process, and droplets need a specific time to reduce their size to the maximum stable drop diameter.

Van der Zande et al. (1999) considered that flow through a circular orifice in a pipe exhibits the same characteristics as flow through a choke valve. They studied the turbulent breakup of a diluted O/W emulsion in the orifice and concluded that the breakup mechanism described previously by Percy and Sleicher (1983) was not the dominant mechanism (acceleration at the entrance of the restriction). They showed that drop breakup in a restriction is caused by the turbulent velocity fluctuations in the high velocity zone downstream of the restriction, and that the maximum stable drop diameter was (aside from the fluid properties) a function of the average energy dissipation rate per unit mass.

Galinat et al. (2007) reported experimental and numerical results of the breakup probability of a drop travelling through inhomogeneous turbulent flow generated in a pipe downstream of a restriction, where various Reynolds numbers, damping coefficients and drop volume fractions were tested. Their simulations predicted well the main features observed in the experiments. In addition, the model was used to compute the breakup probability in concentrated dispersed two-phase flows when the oscillation frequency and the damping rate were provided.

Various researchers have developed models for drop breakup in turbulent flows (Kolmogorov, 1949; Hinze, 1955; Shinnar and Church, 1960; among others), usually based on the theory of isotropic turbulence first proposed by A.N. Kolmogorov (1941). Many of these models are restricted to dilute, inviscid systems at equilibrium in stirred tanks. However, several investigations have been extended or modified to include the effect of higher dispersed phase concentration (Coulaloglou and Tavlarides 1976; Chatzi *et al.*1989), the dispersed phase viscosity (Calabrese *et al.* 1986; Wang and Calabrese, 1986; Davies, 1987), and to predict transient drop sizes (Baldyga and Podgórska, 1998). Despite the large volume of experimental work reported in the literature, the relationship between the drop size distribution downstream of an orifice and the flow conditions is not clearly understood.

The drop breakup mechanisms in turbulent flow of single droplets and diluted O/W emulsions were investigated for a flow through an orifice in a pipe. The aim of the work was to analyze the breakup mechanisms for different flow cases by visualization of the process using a high-speed camera. In addition, the relative influence of geometry, interfacial tension and dispersed phase viscosity were analyzed. Finally, a mechanistic model was obtained to predict the droplet size downstream of the orifice as a function of the properties of the fluids and the flow conditions.

The mechanistic model used to describe the breakup process in the inertial sub-range is the linear model (balance of cohesive and disruptive forces acting on the droplet). The equations of turbulence stress acting on the drop (Kolmogorov,1941 and Paul *et al.* 2004), the interfacial stress (Finn,1999) and the viscous stress (Hinze, 1955), are showed, respectively, bellow:

$$\tau_c \sim \rho_c \varepsilon^{2/3} d^{2/3} \tag{1}$$

$$\tau_s \sim \frac{\sigma}{d} \tag{2}$$

$$\tau_d \sim \frac{\mu_d}{d}\left(\frac{\tau_c}{\rho_d}\right)^{1/2} \tag{3}$$

Where τ_c, τ_s, τ_d are the turbulence, interfacial and viscous stresses, respectively, ε is the energy dissipation rate, σ interfacial tension, μ_d is the viscosity of the disperse phase, ρ_c and ρ_d are the continuous phase and disperse phase's density, respectively.

From the balance of equations (1), (2) and (3), it's possible to obtain the Maximum Stable Droplet Diameter (MSDD), d_m, equation:

$$d_m = C_3\left(\frac{\sigma}{\rho_c}\right)^{\frac{3}{5}} \bar{\varepsilon}^{-\frac{2}{5}}\left[1 + C_4\frac{\mu_d}{\sigma}\sqrt{\frac{\rho_c}{\rho_d}}\,\bar{\varepsilon}^{\frac{1}{3}} d_m^{\frac{1}{3}}\right]^{\frac{3}{5}} \tag{4}$$

Where C_3 and C_4 are constants of proportionality and $\bar{\varepsilon}$ is the average energy dissipation rate.

2. EXPERIMENTAL PROCEDURE

The experimental work described in this paper can be separated in two different segments: visualization of the droplet breakup mechanism through an orifice and statistical analysis of droplet breakup through an orifice.

2.1 Visualization

For the visualization experiment, the continuous phase used was a tap water for the case of high interfacial tension systems. Its density and viscosity were obtained from CRC Handbook of Chemistry and Physics (http://www.hbcpnetbase.com/). Finally, the electrical conductivity and pH values of both continuous phases were measured in the Oakton PC700 pH/mV/Conductivity/°F/°C bench meter. The detailed table of properties of STEOL CS-330 and continuous phases can be obtained at (Peñuela and Carvalho, 2014)

As dispersed phase, two mineral oils of paraphinic base, the 500PS and the Drakeol 7, both provided by local company AGECOM were employed. In the special case of Drakeol 7 (Transparent oil), a green aniline from Lacxe was used to dye it (50 mg/L). The physicochemical properties of the oils were measured in the Laboratory for Fluids Characterization of PUC Rio and are summarized at (Peñuela and Carvalho, 2014).

For the experimental setup it was used a flow arrangement made of a standard ¼ in. 316L Swagelok tubing (ID = 4.57mm). The continuous phase was pumped from 60 L plastic tanks by a helical pump (Amboretto, Max. Flow Rate = 2 L/min, Max. Pressure = 2 bar, Motor Nominal Power = 2 CV) equipped with a WEG CFW08 frequency converter, and its flow rate was measured using a Micromotion R025S flow meter.In order to visualize the breakup process,two high-speed cameras were used: one monochromatic (Photron Fastcam UX100) and one colored (Photron Fastcam SAE3). Both cameras were equipped with an adapter tube (Navitar 2X F-mount) and a body tube zoom system (Navitar 6.5X Zoom, 12 mm FF). A LojaLab 150 W halogen backlight was used as source of light.

The dispersed phase (pure oil) was pumped by a Teledyne Isco 500D syringe pump connected to a metallic cylinder where oil was stored. The dispersed phase was injected through a tee just before the restriction to avoid any external source of breakup (flow through tubing accessories). A set of transparent orifices (designed with different orifice diameter and length) was fabricated by local company Incomplast using high medium impact acrylic in order to allow the visualization of the flow. Images of the design of the acrylic circular orifice can be obtain at (Peñuela and Carvalho, 2014).

2.2 Statistical Analysis (MSDD)

The continuous phases used in the statistical analysis segment was a surfactant based continuous phase which was a solution of the anionic commercial surfactant STEOL CS-330 (Sodium Lauryl Ether Sulfate derived from fatty alcohols, ethoxylated to an average of 3 moles and manufactured by Stepan® Company) in substitute ocean water. The surfactant concentration in the solution was 1122.5 mg/L (2.5 times the Critical Micelle Concentration). The substitute ocean water was prepared following the indications given by the ASME D1141-98 Standard (with exception of stock solution number 3) and its density and viscosity were estimated using the theory given by Sverdrup, Johnson and Fleming (1942) for a salinity of 35 g/Kg (estimated from chemical composition).

For this section, it was used the same dispersed phases that were used in the visualization experiments.

The liquid-liquid setup used was also the same used in the first experiment, with the difference that in the statistical analysis setup an O/W emulsion with a concentration of 5% of dispersed phase (formed inline) flowed through a transparent device, which contain the orifice. The DSD upstream and downstream of the restriction was measured in a particle size analyzer (Malvern Mastersizer 2000) for various flow conditions.

The dispersed phase was pumped in the form of a concentrated emulsion by the Teledyne Isco 500D syringe pump. To assure the dispersed phase stability under storage conditions (prevent creaming process), a concentrated emulsion (87% in volumetric basis) was prepared from an original 50% emulsion, whose d90 was corresponding to the required d90 upstream of the orifice (adjusted in the RSM as a function of mixing speed and time conditions). Then, this 50% emulsion was aged for one day in a separation funnel of PYREX glass (where it is concentrated up to 87%). The concentrated emulsion was removed from the funnel and poured into the metallic cylinder for storage. After that, its DSD was measured just to discard structural changes. Finally, the concentrated emulsion and continuous phase flow rates were adjusted to get an emulsion stream with an oil concentration of 5%, before entering the orifice.

The pressure drop through the restriction was measured by a Dwyer 490 Wet-Wet differential manometer (pressure range of 0 – 100 psi) and sample takers were located upstream and downstream of the orifice were used to determine the difference of DSD for different flow rate values. The discarded emulsion volume was redirected to a 1000 L sludge tank.

The Maximum Stable Droplet Diameter (MSDD) for each set of flow conditions was found evaluating the difference between the DSD obtained upstream and downstream the restriction. In a mathematical form, MSDD was the d90 value of the DSD when it matches the following criterion:

$$\Delta(d_{10}, d_{50}\ and\ d_{90}) < 1\mu m \quad (5)$$

Where d_{10}, d_{50} and d_{90} are the diameter greater than 10%, 50% and 90%, respectively, of the volume of the measured sample.

Equation 5 means that MSDD for a given sample is the d_{90} value of the downstream distribution when the difference between the upstream and downstream DSD (calculated as the change of the d_{10}, d_{50} and d_{90} values), is lower than one micrometer (1 μm).

3. RESULTS

3.1 Visualization Experiment

The general features of the turbulent drop breakup process through an orifice were determined for different combinations of dispersed phase viscosity, interfacial tension and geometry of the orifice (β = Orifice Diameter/Pipe Diameter).In Fig.1 and 2 showed below, the Reynolds number in the orifice was maintained at a fixed value (Reo = 6800). There was no evidence of any kind of breakup upstream along the orifice. Although the droplet is deformed by the restriction in the entrance zone, the fragmentation only occurs in the turbulent zone developed downstream of the orifice.

The figure 1 is a typical image obtained in this experiments and it shows accurately that the breakup occurs downstream of the orifice.

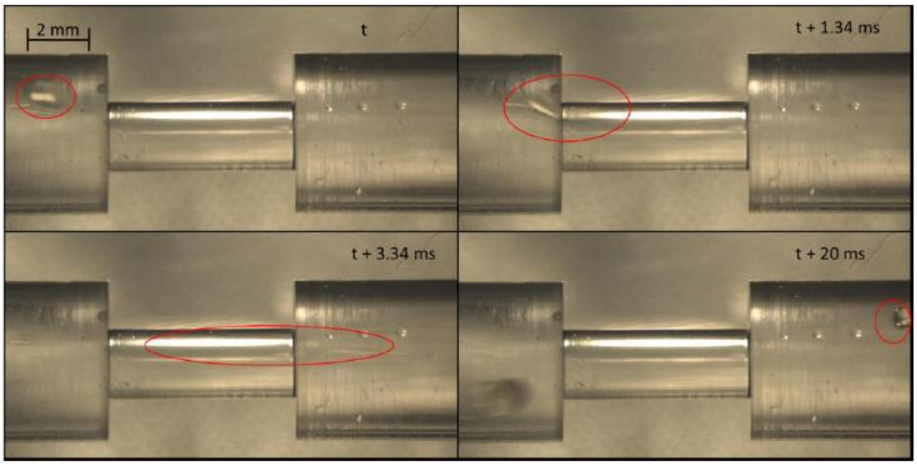

Figure 1. General Scheme for turbulent Drop Breakup through an orifice. $\mu_d = 0.192$ Pa.s, $\sigma = 24.51$ mN/m, $\beta = 0.44$, Orifice Length = 5mm, T=25ºC

Figure 2 shows the evolution of a single droplet breakup occurring downstream of an orifice ($\beta = 0.22$). The oil phase, which is deformed by the restriction, leaves the jet zone as a single drop (Figure 2.a). There was no evidence of breakup in the core of the jet zone (Figure 2.b). The difference between the velocity in the jet (~7 m/s) and the bulk velocity downstream of the orifice (~0.3 m/s) causes the droplet deceleration and deformation in the radial direction. The droplet is then exposed to a high velocity gradient as it stretches from the jet zone and the lower velocity flow away from the jet. At some distance from the edge of the restriction (Breakup Length, Lb, Figure 2.c), the turbulent stress (Eq.1) overcomes the resistance stresses exerted by the droplet and (Eq.2 and Eq. 3, respectively), and finally the drop breaks (Figure 2.d). As defined from Eq.1, the turbulent stress is a function of the velocity gradient in the flow, which can be axial (in the direction of the flow) or radial. As already stated, there is no breakup in the core of the jet; therefore, the axial gradient of velocity is not responsible for the droplet breakup. Instead of that, it seems to be that the radial gradient of axial velocity is the responsible for starting the fragmentation process, because at Lb, it is large enough to overcome the resistance stresses and produce the droplet breakage. After the drop disintegrates, several "daughter droplets" are generated in specific turbulent regions of the flow (Figure 2.e). Some of them will enter in a recirculation zone, where apparently, the deformation stresses are not strong enough to produce additional fragmentation (Figure 2.f). In some cases, the flow pattern can carry the daughter droplets to breakup regions (zones where the radial velocity gradient is large enough to produce breakage), where more daughter droplets are generated (Figure 3). Therefore, from the observations made in this work, it is possible to conclude that the orifice length does not influence the breakup mechanisms.

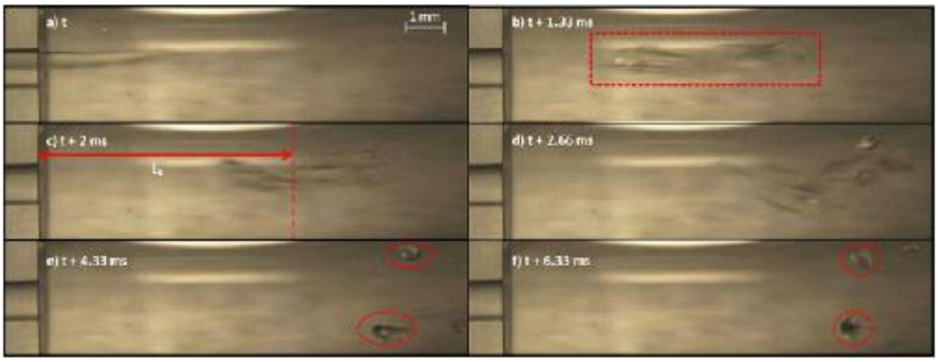

Figure 2. Sequence of turbulent drop breakup downstream of an orifice.$\mu_d = 0.192$ Pa.s, $\sigma = 24.51$ mN/m, $\beta = 0.22$, Orifice length = 5mm, T = 25ºC

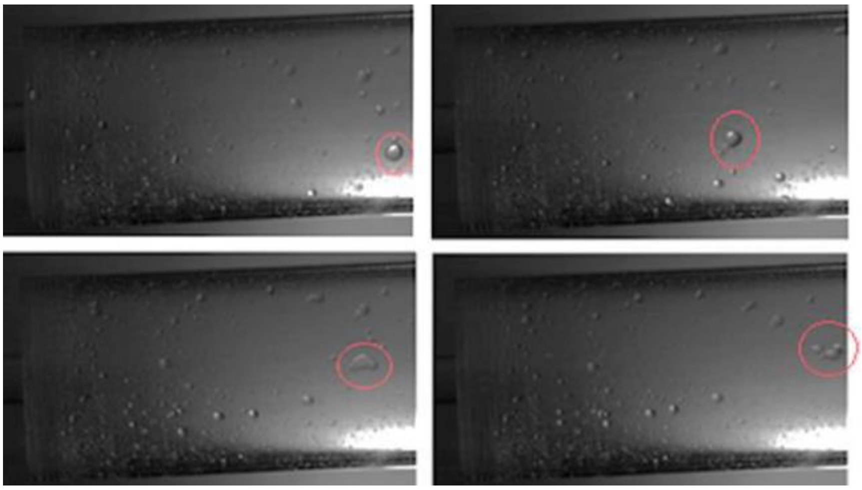

Figure 3. Sequence of daughter droplets reentering the jet zone and breaking into smaller drops.

3.2 Statistical Analysis (MSDD)

In this experiment, the MSDD was determined from the difference between the drop size distributions obtained upstream and downstream of the restriction for the flow of 5% O/W emulsions through an orifice (β = 0.22, orifice length = 5 mm) using the criterion given by Eq. 5.

The dissipation length (Ldis) (required parameter to calculate the average energy dissipation rate per unit mass) was estimated from visualization of a region where no noticeable shear stresses were acting on the droplets. To do that, images obtained from the visualization experiments for the case of turbulent breakup through an orifice were used. A comparison from the calculated values to numerical predictions obtained by van der Zande (2000) for drop breakup through a restriction in a pipe of 4.5 mm of internal diameter was made. The similarity between the estimated values from the visualization technique and the calculated values by van der Zande allowed to use them as a base for calculation of the average energy dissipation rate and the Kolmogorov's length micro scale (Peñuela and Carvalho, 2014).

Figure 4 and 5 shows the typical charts for MSDD determination for different flow conditions as explained in Table 1. The black line represents a zero breakup probability line; meanwhile, blue and orange series represent the data for both evaluated oils. In the chart, the d90 upstream of the orifice is plotted against the d90 downstream of the orifice. The MSDD is obtained when the criterion given by Eq. (5) is satisfied.

Table 1. Experimental data obtained in MSDD determination for turbulent drop breakup through an orifice

Flow Case	Total Flow Rate (L/min)	Velocity in the Orifice (m/s)	Reynolds Number in the Orifice ($*10^3$)	Permanent Pressure Drop ($*10^4$, Pa)	Average Energy Dissipation Rate ($*10^4$, W/Kg)	Kolmogorov's Length Micro scale (μm)
1	0.488	10.36	9.93	4.94	3.29	2.423
2	0.658	13.96	13.38	8.83	7.94	1.945
3	0.817	17.34	16.61	13.53	15.11	1.656
4	0.976	20.71	19.85	18.91	25.23	1.457

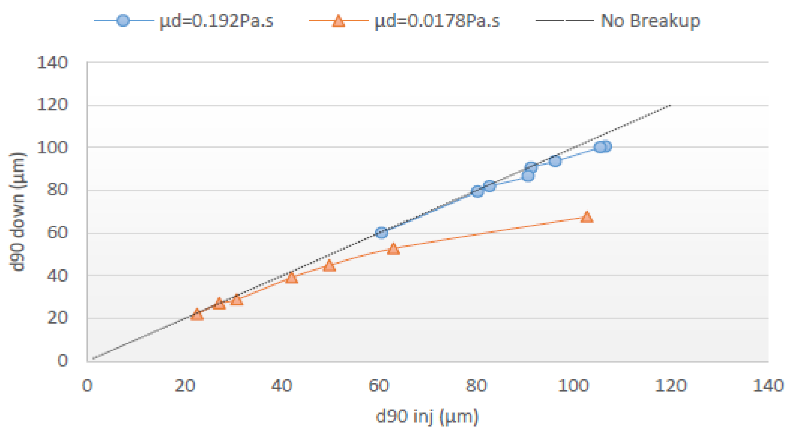

Figure 4. Typical chart of determination of MSDD for turbulent breakup through an orifice. Flow case 1

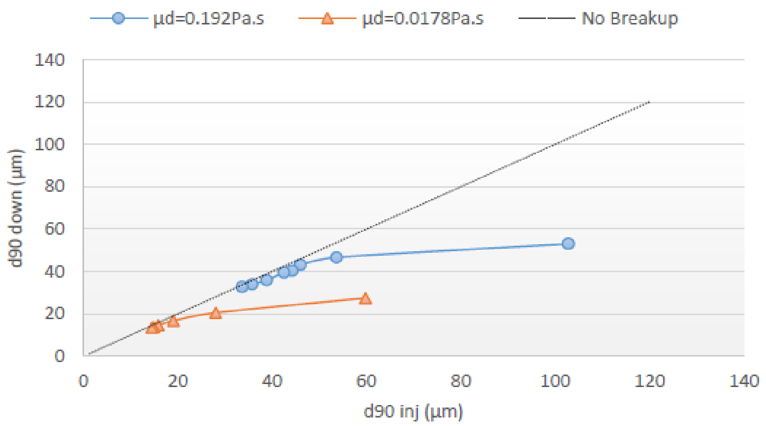

Figure 5. Typical chart of determination of MSDD for turbulent breakup through an orifice. Flow case 4

It is important to note that for high Reynolds number, high dissipation rate, the fragmentation rate is higher, leading to an intense breakup. Figure 6 reports the MSDD values as a function of the energy dissipation rate per unit mass for both evaluated oils and the Kolmogorov's length micro scale values. The experimental maximum stable drop sizes (d90) were always larger than the Kolmogorov's length micro scale but smaller than the characteristic length of the flow (L, the orifice diameter). For that reason, the drop breakup process through the orifice can be described according to the theoretical considerations of the inertial sub range.

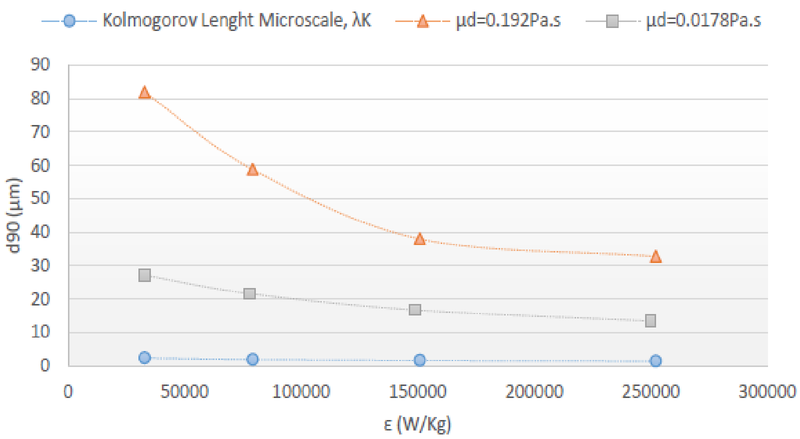

Figure 6. MSDD and Kolmogorov's length micro scale for different values of energy dissipation rate per unit mass.

It was also observed that the less viscous oil produces smaller droplet sizes and that the data showed a decreasing behavior becoming less sensitive for high energy dissipation rates.

After gathering all the MSDD data, the correlated linear mechanistic model can be presented for the 500PS and Drakeol 7, respectively:

$$d_{90} = 0.27\left(\frac{\sigma}{\rho_c}\right)^{3/5} \bar{\varepsilon}^{-2/5}\left[1 + 4.00\frac{\mu_d}{\sigma}\left(\frac{\rho_c}{\rho_d}\right)^{1/2} \bar{\varepsilon}^{1/3}\, d_{90}^{1/3}\right]^{3/5}$$
$$RMSD = 21.82\,\% \tag{6}$$

$$d_{90} = 0.49\left(\frac{\sigma}{\rho_c}\right)^{3/5} \bar{\varepsilon}^{-2/5}\left[1 + 4.05\frac{\mu_d}{\sigma}\left(\frac{\rho_c}{\rho_d}\right)^{1/2} \bar{\varepsilon}^{1/3}\, d_{90}^{1/3}\right]^{3/5}$$
$$RMSD = 12.36\,\% \tag{7}$$

4. CONCLUSIONS

The mechanisms responsible for the turbulent drop breakup of a single droplet and diluted O/W emulsions through an orifice in a pipe were analyzed by visualization of the flow with a high-speed camera and by determining the drop size distribution change as an emulsion is subjected to a turbulent flow.

It was shown that breakage only occurs downstream of the restriction. The breakup takes place at a certain distance from the edge of the orifice (Lb, breakup length). At this breakup length, the radial gradient of axial velocity in the flow (turbulent stress) is large enough to overcome the resistance stresses (exerted by the droplet) and produce the rupture of the droplet. The generated daughter droplets enter in a recirculation zone, where apparently, the deformation stresses are not strong enough to produce additional fragmentation. In some cases, the flow pattern can carry the daughter droplets to breakup regions, where more daughter droplets are produced. These observations are in agreement with the previous observations made Galinat et al. (2005) for the case of drop breakup through an orifice plate. However, from the observations made in this work, it is possible to conclude that the orifice length does not influence the breakup mechanisms.

The interfacial tension and dispersed phase viscosity effects were similar for both geometrical cases. Low magnitude of deformation, low fragmentation rate and larger equilibrium drop sizes were particular characteristics for high interfacial tension and moderate dispersed phase viscosity systems. It was demonstrated that for breakup through the orifice, and at experimental conditions evaluated in this work, Lb depends strongly on the interfacial tension.

Experimental maximum stable drop diameter data were obtained for the turbulent breakup of diluted O/W emulsions. Analysis of the data revealed that maximum stable drop sizes were in the inertial sub-range, characterized exclusively by the energy dissipation rate per unit mass ε. A linear mechanistic model for the inertial sub-range, based in Kolmogorov's theory of isotropic turbulence, was developed to aid in data interpretation and provides a basis for correlation. The model was adjusted to experimental data using a non-linear optimization tool based in the Generalized Reduced Gradient code (GRG2), and its precision was calculated from the root mean squared difference between experimental and predicted data. Good predictions were not obtained the breakup of a moderate viscosity oil through the orifice. The relative low precision of the model used to correlate the breakup through the restriction lied in the lack of consideration of the time scale required for the breakup.

Future work will focus in a deeper analysis of the turbulent drop breakup phenomenon for the case of a single droplet (considering both geometrical cases). A statistical analysis will allow having an idea of the fragmentation process, determining the main properties in the flow field (velocity field, shear stress field, breakup probability zones, etc.). Then, numerical simulations could be made to validate experimental data and finally determine if the kinematics of both processes have a natural correspondence between them. In addition, efforts will be directed to the determination of novel mechanistic models for breakup in diluted emulsion systems that include residence time in the high deformation rate zone, and resulting drop size as a function of the initial (upstream) drop.

5. ACKNOWLEDGEMENTS

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