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Source: Journal of Coastal Research, 115(sp1) : 417-420

Published By: Coastal Education and Research Foundation

URL: https://doi.org/10.2112/JCR-SI115-118.1

Journal of Coastal Research	SI	115	417–420	Coconut Creek, Florida	2020

Study on Breakage Mechanism in the Swirl Generating Stage of an Oil-Water Separator for Marine Oil Extraction and Its Verification

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ABSTRACT

Shi, S.Y.; Su, Z.L.; Lin, L.M.; Xu, J.Y.; He, Y.T.; Wang, S., and Shi, S.J., 2020. Study on breakage mechanism in the swirl generating stage of an oil-water separator for marine oil extraction and its verification. *In:* Bai, X. and Zhou, H. (eds.), *Advances in Water Resources, Environmental Protection, and Sustainable Development*. *Journal of Coastal Research*, Special Issue No. 115, pp. 417-420. Coconut Creek (Florida), ISSN 0749-0208.

High-efficient oil-water separator is badly-needed in marine oil extraction. Droplet breakage is common during the conversion from pipe to swirl flow in separators. Avoiding oil droplets break into small ones in the swirl generating stage is beneficial to improve the separator's separation efficiency. Information regarding the breakage mechanism and dispersed droplet distribution is critical for optimum design of the conversion structure, such as guiding vanes and prediction of the oil-water separation performance. However, little work has been related to the study of droplet sizes in a swirl flow produced by guiding vanes. The present work focuses on the oil droplet sizes generated by the passage of oil-water mixture goes through guiding vanes in a vane-type separator and the different breakage mechanism. Experiments were performed under different flow rates and maximum droplet sizes were measured in situ downstream from the guiding vanes. The maximum droplet size was found to fit a modified-T model. Besides, Modified-T model was found to fit different studies data the best in the noncoalescence system. The studies shows that reducing the energy loss also reduces the probability of droplet breakage which put forward a new method to improve the separator's design.

ADDITIONAL INDEX WORDS: *Swirl flow field, droplet breakage mechanism, maximum droplet size, analytical solution.*

INTRODUCTION

Vane-type pipe separator (VTPS) is a new compact type of oil-water separator and very suitable for marine oil extraction (Shi, 2012). Studies regarding the droplet breakage mechanism in a vane-type separator are important for achieving the optimal design of the separator's structure such that droplets are inevitably broken into small ones in the high shear flow field. This phenomenon can be used to produce cosmetics, foods, paints, *etc.* (Gong, 2018); however, for oil-water separation, breakage of dispersed droplets is hoped to be avoided because larger diameters of dispersed droplets result in higher oil-water separation efficiency in hydrocyclones (Abiev, 2018). Centrifugal force in the swirl flow field is proportional to the third power of oil droplet size, therefore, droplet size distribution is of paramount importance to the design and evaluation of oil-water separators (Huang, 2018). However, extensive job has been devoted to the research of the maximum droplet in liquid-liquid multiphase flow, with the aim of characterizing the dispersion and/or emulsion behavior in pipes (Lavenson *et al.*, 2016). In contrast, less information about maximum droplet produced in the generation stage of a swirl flow field can be found in the literature (Lin, 2019; Gomez, 2001). The maximum droplet size is collected with the breaking mechanism. Understanding the breaking mechanism during the rotational flow generation stage can provide guidance for the design of its optimal inlet structure.

EXPERIMENT AND METHODS

Guiding Vanes

In this paper, a 0.025 m ID tube was used to test the characteristics of the droplet size distribution (DSD) in swirl flow. Figure 1 shows this tube contained the guiding vanes made of transparent plexi glass which were fixed to the pipe wall. Three central symmetry,

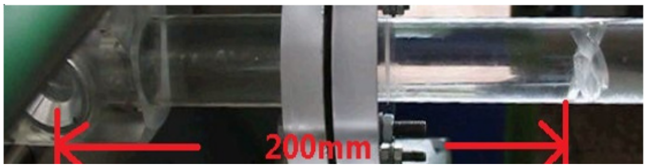

Figure 1. Photograph and schematic for guiding vanes.

DOI: 10.2112/JCR-SI115-118.1 received 25 Jan 2020; accepted in revision 28 May 2020.
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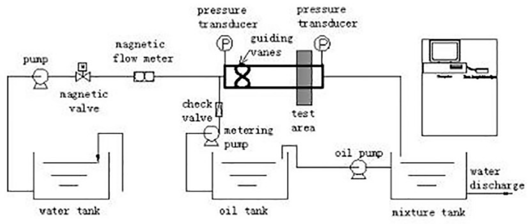
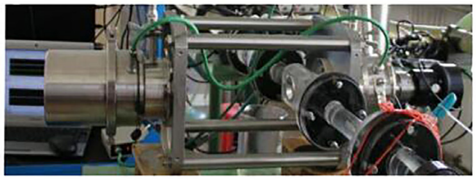


(a) Schematic diagram



(b) The Malvern Insitec SX

Figure 2. Experimental system.

Table 1. *Physical properties of the experimental liquids.*

	Density (kg/m^3)	Viscosity (Pa·s)	Interfacial tension (N/m)
Water	998.2	0.001	0.045
Oil	836.0	0.215	

semi-elliptical plates were adopted with an angle of 30° to the cross section of the tube (Figure 1). The distance L from the guiding vanes to the detection location is 0.20 m.

Experimental Setup

Experiments were shown in Figure 2(a). During the experiments, oil and water's mixture flowed through the tube with the guiding vanes, after which the oil phase was broken into small droplets and flowed into the detection location.

Figure 2(b) shows the Malvern Insitec SX and a schematic of the online sample pool. The Malvern Insitec SX was used to measure the DSD and the maximum droplet in the VTPS. The device illuminates the droplets with a collimated low-power He-Ne laser beam, with the scattered light passed through a Fourier transform lens. The DSD was then acquired from the scattered light intensity by the controlling computer. The size measurement range of the instrument is dependent upon the focal length of the Fourier lens used, which varies with application. In the present study, a 500 mm lens was chosen, which outputs a size measurement range from 0.5 to 2500 µm. For the experiments, LP-14 white oil and tap water were chosen. Their physical properties under the test conditions are shown in Table 1; the temperature of the mixture was 16-18°C.

THEORETICAL ANALYSIS

The H-Model

The maximum oil droplet size in a swirl flow by the passage of an oil-water mixture (oil content is within 1%) through guiding vanes is determined by droplet breakup in turbulence. Coalescence is considered negligible, and droplet breakage can be isolated for study (Karabelas, 1978). When the internal viscous forces in the droplet are sufficiently small to be neglected, H-model can be expressed by using the Young-Laplace equation as

$$\frac{1}{2}\rho_c\overline{u'^2} \propto \frac{4\sigma}{d_{\max}} \tag{1}$$

where ρ_c is the continous phase's density, σ is the interfacial tension, $d_{\max}$ is the maximum stable discrete phase droplet diameter, and $\overline{u'^2}$ is the mean value of the product of velocity fluctuation with length scale similar to $d_{\max}$

In this case, the H-model for predicting maximum droplet size in a dilute turbulent flow field can be expressed as follows (Batchelor, 1951):

$$d_{\max} = 0.55D(\frac{\rho_c u_c^2 D}{\sigma})^{-0.6} f^{-0.4} \tag{2}$$

where u_c is the velocity of the continuous phase and D is the hydraulic diameter.

The Modified H-Model

Oropeza-Vazquez *et al.* (2004) used modified Hinze models as follows:

$$d_{\max} = 0.34(\frac{\sigma}{\rho_c})^{0.6}(\frac{2fu_c^3}{D})^{-0.4} \tag{3}$$

The Modified T-model

Listewnik *et al.* (Gomez, 2001) proposed that droplet breakup does not arise if the free surface energy of the droplet exceeds the kinetic energy of the turbulent motion:

$$\frac{\pi}{6}\rho_c d^3 \frac{\overline{u'^2}}{2} \le \sigma\pi d^2 \tag{4}$$

$$We^* = \frac{\rho_c \overline{u'^2} d}{\sigma} \le 12 \tag{5}$$

where We^* is the modified Weber number and d is the droplet diameter.

By considering isotropic turbulence, we can estimate the mean square of velocity fluctuations as (Anand, 2016):

$$\overline{u'^2} = 2(\bar{e}d)^{2/3} \tag{6}$$

During oil-water mixture flows through guiding vanes in a swirl flow, the mean rate of energy dissipation, $\bar{e}$, is defined as the mean energy dissipation rate per unit mass:

$$\bar{e} = \frac{u_c \Delta p}{L\rho_c} \tag{7}$$

where Δp is the energy loss from the guide vanes to the detection location, L, V is the distance and fluid volume from the guiding vanes to the detection location.

Thus, a new correlation to calculate the maximum droplet size is deduced in this paper as follows (modified T-model):

$$d_{\max} = (\frac{We_{crtit}}{2})^{0.6}(\frac{\sigma}{\rho_c})^{0.6}\bar{e}^{-0.4} \tag{8}$$

Table 2. *Collected literature data for maximum droplet size.*

Author	System	Dispersed Phase Conc.(% vol)	Fluid Properties
Kubie and Gardner (1977)	Pipe flow D=0.0172 m Dispersion of acetate-water Alcohol-water	<1	$\rho_c = 828$ and 884 kg/m^3;μ_c=4.8 and 0.7mPa·s; σ=4.86 and 14.5 mN/m; 20 points
Karabelas (1978)	Pipe flow D=0.0504 m Water-oil dispersion	<1	$\rho_c = 798$ and 890 kg/m^3; μ_c=1.8 and 16mPa·s; σ=33 and 34 mN/m; 10 points
El-Hamouz and Stewart (1996)	Pipe flow D=0.025 m Oil-water dispersion	1	$\rho_c = 1000$ kg/m^3; μ_c=1.00 mPa·s; σ=38 mN/m;7 points
Simmons and Azzopardi (2001)	Pipe flow D=0.063 m Water-oil dispersion	1.2-3.3	$\rho_c = 1166$ kg/m^3; μ_c=1.6 mPa·s; σ=10 mN/m;4 points
Lemenand, Dupont, and Valle (2013)	Static mixer D=0.02 m Water-oil dispersion	2.5-15	$\rho_c = 850$ kg/m^3; μ_c=30 mPa·s; σ=20 mN/m; 24 points
Shi, Xu, and Sun (2012)	Swirling flow D=0.05 m Oil-water dispersion	<1	$\rho_c = 1000$ kg/m^3; μ_c=1.002 mPa·s; σ=45 mN/m; 11 points

Table 3. *Statistical results for the error of different data sources in turbulent dilute liquid-liquid dispersions.*

Sources of Data	H-model			Modified H-model			Modified T-model			Data Points
	E_1	E_2	E_3	E_1	E_2	E_3	E_1	E_2	E_3	
Kubie and Gardner (1977)	17.8	42.1	21.5	-53.6	53.6	0.5	-0.9	12.2	2.4	20
Karabelas (1978)	-56.0	56.0	0.3	-58.1	58.1	0.2	-10.5	13.2	0.9	10
El-Hamouz and Stewart (1996)	-3.6	10.5	1.5	-54.9	54.9	0.3	-3.6	10.5	1.5	7
Simmons and Azzopardi (2001)	8.4	19.9	0.7	-49.2	49.2	24.3	8.4	19.9	0.7	4
Lemenand, Dupont, and Valle (2013)	49.0	49.0	5.2	-30.1	30.1	1.1	13.0	16.7	3.0	24
Current Study	-52.3	52.3	0.2	-61.1	61.1	0.1	-4.4	7.4	0.4	11

THE RESULTS AND ANALYSIS

The collected literature data for droplet breakup in the turbulent inertial regime for dilute liquid-liquid flow are shown in Table 2. However, the data corresponding to an oil content within 15% are also included because droplets will not coalesce in a multifunctional exchanger-reactor of the vortex generator type. In this case, the droplet of maximum size is formed by a droplet breakup process. The table includes 76 data points for pipe, static mixers, and a swirl generating pipe. For pipe flow, the critical Weber number is 1.172 (Doulah, 2002); for the swirling flow, the critical Weber number is 12.

The accuracy of the developed model is demonstrated in light of statistical parameters, such as the average percent error (E_1), the average absolute percent error (E_2), and the percent standard deviation (E_3), which are calculated as follows:

The average percent error, E_1:

$$E_1 = (\frac{1}{N}\sum_{i=1}^{N} f_i) \times 100 \tag{9}$$

where N is the number of data points.

$$f_i = \frac{(d_{\max})_{Pred.} - (d_{\max})_{Meas.}}{(d_{\max})_{Meas.}} \tag{10}$$

The average absolute percent error, E_2:

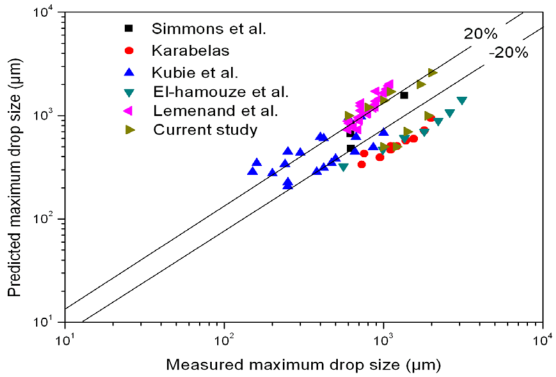
$$E_2 = (\frac{1}{N}\sum_{i=1}^{N} |f_i|) \times 100 \tag{11}$$

The percent standard deviation, E_3:

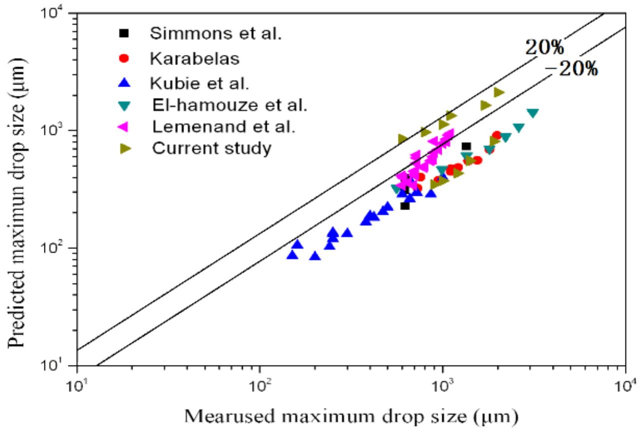
$$E_3 = \sqrt{\sum_{i=1}^{N} (f_i - E_1)^2 / (N-1)} \tag{12}$$

As shown in Table 3, the current model exhibits the lowest E_1, E_2 and $E_{3.}$ So the modifies T-model is the best.

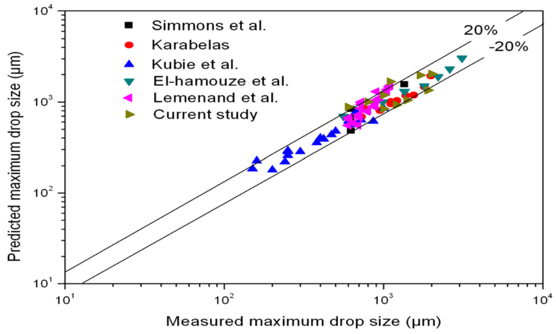
A comparison between the three models for predicting maximum particle size in a dilute liquid-liquid turbulent flow is presented in Figure 3. The modified T model predictions and experimental maximum stable droplet size shows significant reduction in scattering for all of the experimental data. The modified T model provides an analytical solution to calculate the maximum stable droplet compared with the numerical solution given by Pereyra *et al.* (Simmons, 2001). Notably, however, the new model is limited to a dilute liquid-liquid dispersion and to droplet breakup in the turbulent inertial regime. For pipe flow and multiphase mixing, the critical We* is 1.172. For swirling flow, the critical We* is 12 and $\bar{e}$ is calculated by Eq. [6] with the maximum stable droplet calculated by Eq. [7].



(a) Comparison between the H-model by Eq. (1) predictions and experimental maximum stable droplet size



(b) Comparison between the modified H-model by Eq. (2) predictions and experimental maximum stable droplet size



(c) Comparison between the modified T-model by Eq. (6) predictions and experimental maximum stable droplet size

Figure 3. Comparison between the different model.

CONCLUSIONS

A new model for the prediction of the maximum stable droplet sizes in a dilute turbulent liquid-liquid flow is proposed in this study. The proposed model has been tested against a database collected from studies related to turbulent dilute dispersions. Good agreement is observed between the predictions and experimental data. In this model, when the We is greater than We_{crit}, the droplet will break up into smaller droplets. For VTPS, as the fluid flows through the guiding vanes, reducing the energy loss will substantially reduce the probability of droplet breakage. The proposed model can be used to model droplet migration in the separators and improve its separation efficiency in marine oil extraction.

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