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Emulsification using a "Sonolator" liquid whistle: A new correlation for droplet size from pilot-scale experiments

David J. Ryan [a], Michael R. Baker [b], Adam J. Kowalski [b], Mark J.H. Simmons [a,*]

[a] School of Chemical Engineering, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK
[b] Unilever Research & Development, Port Sunlight Laboratory, Quarry Road East, Bebington, Wirral CH63 3JW, UK

HIGHLIGHTS

- Emulsion drop sizes measured on a pilot – scale liquid whistle device.
- Three orders of magnitude of dispersed phase viscosity considered.
- Drop size scales with pressure drop, drop viscosity and surfactant concentration.
- Expected regime change from turbulent inertial to turbulent viscous not observed.

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ABSTRACT

Emulsification experiments have been carried out on a pilot-scale Model ACIP2 Sonolator liquid whistle device by examining the change in droplet size distributions of silicone oil in water emulsions, using SLES as a surfactant, before and after processing. The process variables considered were mass flow rate, pressure drop across Sonolator, oil viscosity (from 10 to 10,000 cSt), oil concentration (0.5–10 wt%), surfactant concentration (0.00003–0.5 wt%) and orifice size. All experiments were carried out in the turbulent flow regime. The oil phase was added as either a pure phase or as a pre-emulsion stabilised using SLES. The oil was injected just before the blade or mixed at a T-junction prior to the Sonolator; the pre-emulsion was exclusively introduced via the latter method. The resultant droplet size distributions were obtained from offline sampling using laser diffraction. The most significant parameters found to influence the drop size were found to be pressure drop, dispersed phase viscosity and surfactant (SLES) concentration, which formed the basis for an empirical power law correlation. Indices in this correlation were compared to findings in the literature for other emulsification devices, and to those predicted from the theories of droplet breakage in turbulent inertial flow. Despite an expected regime change from turbulent inertial to turbulent viscous break-up being common in the literature as the dispersed phase viscosity is increased, this phenomenon was not observed in the experimental data obtained, suggesting breakage in an intermediate regime.

1. Introduction

The Sonolator (ex. Sonic Corp, USA) is an inline fluids processing device of the liquid whistle type which causes mixing and emulsification of multiphase fluids resulting in finely dispersed droplets. To enable the integration of such a device into a process line, it is necessary to understand how the process parameters are correlated with the reduction in droplet size, with critical parameters including the mass flow rate of fluid and the size of the orifice. Such information is necessary for industrial research and development enabling minimization of costly and lengthy pilot scale experimentation. New products or necessary modifications could then be applied to existing plant with confidence *a priori*, with the ultimate gain of reduction of time to market for new products and their associated processes.

The theoretical treatment of droplet breakage under the action of fluid flow stems from the principle that a droplet in a flow remains stable provided that the internal cohesive forces (due to viscosity and interfacial tension) are greater than the external deformation stresses; if the opposite is true then breakage occurs. In turbulent flows, which are relevant to the Sonolator used in this study, the external forces are driven by the turbulent eddies within the flow; the smallest of these can be estimated using the Kolmogorov length scale, l_e and time scale, t_e

* Corresponding author.
E-mail address: m.j.simmons@bham.ac.uk (M.J.H. Simmons).

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Nomenclature

Symbol

A_o	area of Sonolator orifice (m^2)
a_s	specific surface area (m^{-1}, or $m^2 \cdot m^{-3}$)
C	numerical constant in a correlation
d	general droplet size (m)
$d(k)$	diameter of the *k*th percentile droplet in the volume-weighted DSD (m)
d_{32}	volume-surface (Sauter) mean diameter (m)
d_{43}	volume-weighted mean diameter (m)
d_{max}	maximum stable droplet size in turbulent flow (m)
d_{nm}	generalized moment-moment mean diameter (m)
$f(x)$	the number weighted droplet size distribution
l	length scale intermediate between Kolmogorov microscale and flow geometry (m)
l_e	Kolmogorov eddy length microscale (m)
L	characteristic length scale (m)
M	mass flow rate ($kg \cdot s^{-1}$)
N	angular velocity in stirred tank experiments in literature (rpm)
P	power dissipated in Sonolator (W)
ΔP	pressure drop across Sonolator (Pa)
Q	volumetric flow rate ($m^3 \cdot s^{-1}$)
s	logarithmic skewness of a droplet size distribution
t_e	Kolmogorov eddy time microscale (s)
U	characteristic velocity (for Re)
V'	"V prime" – size of average velocity fluctuation ($m\ s^{-1}$)
w_{SLES}	concentration of SLES (w/w)
w	logarithmic span of a droplet size distribution
x	variable on horizontal axis of graph
y	variable on vertical axis of graph

Units

cSt	centistokes, unit of kinematic viscosity; equivalent to $10^{-6}\ m^2\ s^{-1}$

Subscripts

c	continuous phase (water)
d	discrete phase (oil)
def	deformation
e	eddy
max	maximum (droplet size)

Greek symbols

β	beta, constant relating effect of viscosity to interfacial tension
ε	epsilon, local specific turbulent energy dissipation rate ($m^2 \cdot s^{-3}$ or $W \cdot kg^{-1}$)
ν_c	kinematic viscosity of continuous phase ($m^2 \cdot s^{-1}$)
ν_d	nu, kinematic viscosity of dispersed phase ($m^2\ s^{-1}$)
μ_d	mu, dynamic viscosity of dispersed phase (Pa s)
ρ	rho, density of fluid ($kg\ m^{-3}$)
σ	sigma, interfacial tension ($N\ m^{-1}$)

Dimensionless groups

φ	dispersed phase volume fraction
C_D	discharge coefficient of Sonolator orifice
R^2	coefficient of determination, close to unity when scatter is close to zero.
Re	Reynolds number
We	Weber number

Abbreviations

CMC	critical micelle concentration (of a surfactant)
DSD	droplet size distribution
INJ	oil inlet condition of being injected at the orifice
PE	oil inlet condition of aqueous pre-emulsion with 0.5 wt % SLES
SLES	sodium laureth sulphate, or sodium lauryl ether sulphate
TI	turbulent inertial droplet breakage regime
TMIX	oil inlet condition of mixing at a T-junction
TV	turbulent viscous droplet breakage regime

$$l_e = \left(\frac{\nu_C^3}{\varepsilon}\right)^{1/4}, \quad (1)$$

$$t_e = \left(\frac{\nu_C}{\varepsilon}\right)^{1/2}, \quad (2)$$

where ε is the power input per unit mass of fluid and ν_C is the continuous phase kinematic viscosity. The largest turbulent eddies are at length scales (L) comparable with the flow geometry and $l_e \ll L$. Regarding external forces, if $l_e \ll d \ll L$ for a breaking droplet of diameter, d, then the droplet tends to be broken apart by pressure fluctuations from multiple turbulent eddies surrounding the droplet. This case is the turbulent inertial (TI) regime. Alternatively, if the droplet is smaller than l_e (e.g. $d \ll l_e$) then only viscous shear, if sufficient, can disrupt the droplet: this turbulent viscous (TV) regime has been observed in very high shear devices such as small-gap homogenisers. For low-viscosity dispersed phases, the cohesive force comes from interfacial tension whilst for high-viscosity dispersed phases, the cohesive force comes from the viscous force opposing deformation. These two regimes (low/high viscosity) can also be separated out by considering the deformation time compared to the characteristic time of the surrounding turbulent eddy or eddies. For further discussion see Walstra and Smulders (1998), Padron (2005) and Hall (2012).

In the Sonolator after the orifice (where droplet breakage is believed to occur) the Reynolds number is in the turbulent range, with typical values between 7000 and 150,000 at the orifice. Moreover, the droplet sizes are initially much larger than the associated Kolmogorov microscale, and remain so throughout emulsification. Hence breakage occurs fully within the turbulent inertial (TI) regimes. Many droplet size correlations have been developed to predict droplet size on the basis of existing emulsification experimental data, with TI experiments being easier to carry out than TV experiments, since the final droplet size is larger and requires less energy to access. Hinze (1955) gave the well-known result for prediction of maximum stable droplet size, d_{max} in inviscid TI droplet breakage assuming local isotropy and a dilute dispersed phase,

$$d_{max} = C \cdot \varepsilon^{-2/5} \rho_c^{-3/5} \sigma^{3/5} \quad (3)$$

where σ is the interfacial tension, ρ_c is the continuous phase density, and the constant, $C = 0.725$ (i.e. of order of unity). For apparatus where ε is proportional to flow rate cubed (e.g. the Sonolator) the dependence of d_{max} upon flow rate (mass or volumetric) would therefore be a power law of index −1.2.

Davies (1985, 1987) modified Hinze's expression to incorporate the effects of dispersed phase viscosity. During turbulent droplet breakage, as the dispersed phase viscosity increases, the dominant