Pontifícia Universidade Católica do Rio de Janeiro

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Analysis of Drop Breakup Phenomenon of Diluted Oil in Water Emulsions in Turbulent Flow

DISSERTAÇÃO DE MESTRADO

Dissertation presented to the Programa de Pós Graduação em Engenharia Mecânica of the Departamento de Engenharia Mecânica, PUC Rio as a partial fulfillment of the requirements for the degree of Mestre em Engenharia Mecânica.

Advisor. Prof. Márcio da Silveira Carvalho

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To Kelly,

Your love gives meaning to my life.

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Abstract

Penuela Munoz, Johann Humberto; Carvalho, Márcio da Silveira (Advisor). **Analysis of drop breakup phenomenon of diluted oil in water emulsions in turbulent flow**. Rio de Janeiro, 2014. 115p. MSc. Dissertation Department of Mechanical Engineering, Pontifícia Universidade Católica do Rio de Janeiro.

A high-speed camera has been used to visualize the drop breakup process at turbulent conditions in a rotor – stator mixer and through an orifice in a pipe. Two special cases were considered: the breakup of diluted emulsions and the breakup of single oil droplets. 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). For the case of breakup in the rotor – stator mixer, two mechanisms were identified. An initial fragmentation is caused by the combination of the vortex (generated by the circular motion of the rotor) and the jet zone emerging from the stator holes. The second mechanism is a mechanical breakup caused by the high shear stresses that droplets suffer in the rotor – stator gap. In the case of breakup through an orifice in a pipe, it was shown that breakage 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. These results were in agreement with 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 was possible to conclude that the orifice length does not influence the breakup mechanisms. In addition, visualization has allowed to analyze the relative influence of interfacial tension and dispersed phase viscosity for both cases. Experimental values for the maximum stable drop diameter were obtained for the breakup of diluted oil-in-water emulsions in both studied cases. 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 to provide a basis for correlation. The model was adjusted to experimental data using a nonlinear 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 obtained for the breakup in the mixer; however, this was not the case for the breakup 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. In addition, a linear curve fitting based in a power law model, showed that interfacial effects drive the breakup process in the restriction.

Keywords

Drop breakup; emulsions; visualization; turbulent flow.

Resumo

Penuela Munoz, Johann Humberto; Carvalho, Márcio da Silveira. **Análise do fenômeno de quebra de gota de emulsões de óleo em agua diluídas em escoamento turbulento**. Rio de Janeiro, 2014. 115p. Dissertação de Mestrado – Departamento de Engenharia Mecânica, Pontifícia Universidade Católica do Rio de Janeiro.

Uma câmera de alta velocidade foi utilizada para visualizar o processo de quebra de gota em um misturador rotor – estator e através de um orifício em um duto em condições de escoamento turbulento. Dois casos especiais foram considerados: quebra de emulsões diluídas e quebra de gotículas de óleo individuais. Dois óleos minerais de viscosidade moderada foram dispersos em duas fases continuas diferentes, água da torneira e uma fase contínua formada por uma mistura de água do mar padrão e o surfactante aniônico STEOL® CS-330 (Stepan Company). No caso de quebra no misturador rotor – estator, dois mecanismos foram identificados. Uma fragmentação inicial é causada pela combinação do vórtice (gerado pelo movimento circular do rotor) e a região de jato emergente dos furos do estator. O segundo mecanismo é uma quebra mecânica causada pelas altas taxas de cisalhamento que as gotas sofrem na abertura entre o rotor e o estator. No caso de quebra através do orifício, foi mostrado que a ruptura das gotículas ocorre somente a jusante da restrição, após percorrida certa distancia a partir da borda do orifício. Nesse comprimento de quebra, o gradiente radial de velocidade axial no escoamento é suficientemente grande para superar as tensões resistivas (exercidas pelas gotículas) e produzir a ruptura da gota. Esses resultados estão em concordância com as observações previas feitas por Galinat et al. (2005) para o caso de quebra de gota através de uma placa de orificio. No entanto, a partir das observações feitas neste trabalho, foi possível concluir que o comprimento do orifício não influencia os mecanismos de quebra. Também, a visualização permitiu analisar a influencia relativa da tensão interfacial e da viscosidade da fase dispersa para os dois casos considerados. Dados experimentais do tamanho de gota máximo estável foram obtidos para o caso de quebra de gota de emulsões de óleo em água diluídas nos dois casos estudados. A análise dos dados revelou que os tamanhos de gota

máximos estáveis encontravam-se dentro da sub-faixa inercial, caracterizada exclusivamente pela taxa de dissipação de energia por unidade de massa, ε. Um modelo mecanístico linear para a sub-faixa inercial, baseado na teoria de turbulência isotrópica de Kolmogorov, foi desenvolvido para ajudar na interpretação dos dados e suprir uma base para correlação. O modelo foi ajustado aos dados experimentais utilizando uma ferramenta de otimização não linear baseada no código GRG2 (Generalized Reduced Gradient), e sua precisão calculada a partir da raiz quadrada media das diferenças entre os dados experimentais e os previstos. Boas previsões foram obtidas para o rompimento no misturador, no entanto, este não foi o caso da quebra através do orifício. A baixa precisão relativa do modelo utilizado para correlacionar a quebra através do orifício reside na falta de consideração da escala de tempo requerida para a ruptura. Além disso, uma regressão linear baseada em um modelo "Power Law" mostrou que os efeitos interfaciais dominam o processo de quebra de gota na restrição.

Palavras-chave

Quebra de gota; emulsões; visualização; escoamento turbulento.

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Nomenclature

a	- Droplet radius (m).
a_T	- Stator tooth spacing (m).
A_0	- Cross sectional area of the orifice (m^2).
b	- Radius of curvature at the apex of the drop (m).
Bo	- Bond Number (dimensionless).
C_K	- Kolmogorov's constant (dimensionless).
C_n	- Proportionality constant (n is an integer, dimensionless).
CFD	- Computational Fluid Dynamics.
CMC	- Critical Micelle Concentration.
d	- Drop diameter (m).
d_0	- Diameter Median (m).
d_m	- Maximum stable diameter (m).
D_0	- Orifice diameter (m).
D_e	- Droplet equatorial diameter (m).
D_R	- Rotor Diameter (m).
D_s	- Droplet diameter at a distance from the apex equal to D_e (m).
DNS	- Direct Numerical Simulation.
DSD	- Drop Size Distribution.
E	- Spectral energy density function (m^3/s^2).
$\dot{E}$	- Energy dissipation rate (W).
g	- Acceleration of gravity (m/s^2).
h	- Gap between the dispersing element and the vessel's bottom (m)
H	- Modified Bond number.
H_F	- Fluid's height (m).
HLB	- Hydrophilic Lipophilic Balance.
IFT	- Interfacial tension.
k	- Turbulent eddy wavenumber (m^{-1}).
k^*	- Constant (dimensionless).
K	- Turbulent kinetic energy per unit mass (m^2/s^2).
L	- Characteristic Length (m).
L_b	- Breakup length (m).
L_{dis}	- Dissipation length (m).
MSDD	- Maximum Stable Drop Diameter.
N	- Rotor speed (revolutions per second).
N^*	- Number of data points (dimensionless).
O/W	- Oil in water.
p	- Pressure (Pa).
P	- Power dissipated by fluid (W).
P_0	- Power number (dimensionless).
PDF	- Probability Density Function.
PIV	- Particle Image Velocimetry.
Q	- Volumetric flow rate (m^3/s).
r_1	- Radius of curvature on the x-z plane (m).
r_2	- Radius of curvature on the plane normal to z axis (m).
RANS	- Reynolds Averaged Navier Stokes.
Re	- Reynolds Number (dimensionless).

RSM - Rotor – Stator Mixer.
S - Droplet shape factor.
t - Time (s).
T - Time Period (s).
u - Fluctuating velocity (m/s).
u'^2 - Turbulent mean squared velocity difference (m^2/s^2).
U - Fluid velocity component (m/s).
$\bar{U}$ - Mean Velocity (m/s).
U_0 - Velocity in the orifice (m/s).
v_T - Tip velocity (m/s).
V - Volume of the fluid (m^3).
x - x direction (dimensionless).
$\vec{x}$ - Position vector (m).
z - z direction (dimensionless).

Greek Symbols.
α - Numeric constant (dimensionless).
ε - Turbulent kinetic energy dissipation rate per unit mass (m^2/s^3).
λ_K - Kolmogorov's length micro-scale (m).
μ - Dynamic viscosity (Pa.s).
μ_c - Dynamic viscosity of the continuous phase (Pa.s).
μ_d - Dynamic viscosity of the dispersed phase (Pa.s).
ν - Kinematic viscosity (m^2/s).
ρ - Density (Kg/m^3).
ρ_c - Continuous phase density (Kg/m^3).
ρ_d - Dispersed phase density (Kg/m^3).
σ - Interfacial tension (mN/m).
σ_g - Geometric standard deviation of the drop size distribution.
τ_c - Continuous phase stress ($Kg/m.s^2$).
τ_d - Dispersed phase viscous stress ($Kg/m.s^2$).
τ_s - Surface or interfacial stress ($Kg/m.s^2$).
τ_n - Kolmogorov's time micro-scale (s).

Mathematical Symbols.
Δ - Difference.
∇ - Gradient operator: $\nabla \equiv \partial/\partial x_i$.
∇^2 - Laplacian operator: $\nabla^2 \equiv \partial^2/\partial x_i^2$.