Measurements and Modeling of Size Distributions, Settling and Dispersion Rates of Oil Droplets in Turbulent Flows

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Objective

This project aims to measure and parameterize the effects of turbulence and oil properties on the mean settling velocity, dispersion (turbulent diffusion) rate, and characteristic size distributions of oil droplets in sea water. The oil slicks forming as a result of spills are broken up by waves and turbulence into droplets. Quantitative data on the transport of these droplets by oceanic turbulence is needed for predicting and modeling the environmental damage and effectiveness of the approaches to treat oil spills . The measurements will be performed in a specialized laboratory facility that enables generation of carefully controlled, isotropic, homogeneous turbulence at a wide range of fully characterized intensities and length scales (Kolmogorov scale varying from 80 µm - 1mm), covering most turbulence levels that one may expect to find in coastal waters. Crude (e.g. Prudhoe Bay and South Louisiana) and processed oil droplets (e.g. Diesel oil) will be injected into the sample volume of size about 5cmx5cmx5cm, and their three-dimensional trajectory will be measured at high resolution using high-speed digital holographic cinematography. The selected oils have varying viscosity, density and surface tension, especially due to introduction of dispersants, and the droplets vary in size from 30 µm to 2 mm. We will also introduce large oil droplets and/or small patches of oil and measure the size distribution of droplets resulting from exposure to turbulence-induced shear. Since effectiveness of dispersants varies with water salinity, the measurements will be performed in water with varying salt concentration. Subsequent analysis, consisting of calculating the Lagrangian autocorrelation functions of droplet velocity, will provide the turbulent dispersion rates, along with their mean settling/rise velocity as a function of droplet and turbulence properties. The results will be expressed in terms of dimensionless variables that can be conveniently incorporated into computational models that forecast the entrainment and dispersion of oil droplets generated as oil sleeks break.

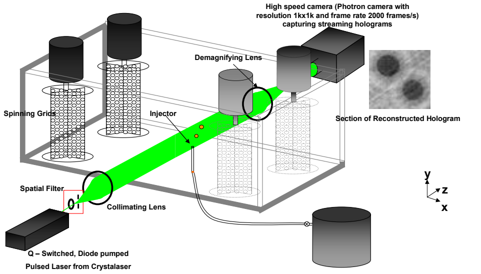


Figure 1: Isotropic turbulence generating facility with optical setup of one view digital in-line holography

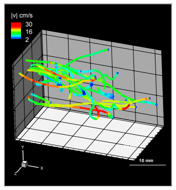


Figure 2: 3-D diesel droplet tracks obtained from two view digital holography with velocity magnitude shown through color coding

Mixer rpm	**225**	**337.5**	**506.3**
Vertical Mean Velocity (cm/s)	0.56	0.78	1.02
RMS Velocity u' (cm/s)	4.63	7.1	9.4
Anisotropy ratio (u_y'/u_x')	1.24	1.26	1.2
Dissipation ε (m^2/s^3)	0.0019	0.0099	0.0256
Integral Length Scale, L (mm)	52	35	32
Kolmogorov Lengthscale, η (mm)	0.151	0.1	0.079
Kolmogorov Timescale τ_η (s)	0.0229	0.01	0.0063
Taylor Microscale, λ (mm)	4.11	2.75	2.28
Taylor-scale Reynolds Number $Re_\lambda = u' \lambda / \nu$	190	195	214

Table 1: Turbulence facility parameters

Nomenclature

D_{ii}	Diffusion Coefficient (subscript i: x - Horizontal, y - Vertical)
St	Stokes number (τ_d/τ_η) is the ratio of droplet response time to Kolmogorov timescale
u'	Turbulence rms velocity
U_i	Droplet velocity fluctuation
U_q	Droplet rise velocity in quiescent flow
$\overline{U}_{slip}$	Droplet mean rise velocity in turbulence
$[Y_i^2]$	Mean square displacement
μ_j	Dynamic viscosity (subscript j: c - continuous , d - disperse)
ν	Kinematic viscosity (μ/ρ)
ρ_j	Density
τ_d	Droplet response time = $\rho_d d^2/18\mu_c$ is the time taken for the droplet to adjust to the change in a Stokes flow
τ_L	Droplet integral timescale is the droplet diffusion coefficient normalized by droplet rms velocity

Experiment

The test facility, illustrated in Figure 1, generates nearly isotropic turbulence with weak mean flow. This January experiments have been conducted with research grade diesel fuel LSRD-4 (Specific gravity 0.85), provided by Specified Fuels and Chemicals inc. of Channel-view – Texas, for sizes varying from (0.6-1.2mm) at zero salinity and water temperature of 20°C. 2D Particle image velocimetry (PIV) measurements are used to calculate the turbulence parameters. Table 1.0 shows the turbulence parameters for the three grid rotational velocities for which data have been obtained. Data are recorded with a high speed camera at 250 frames/s – 1000 frames/s using the technique of digital holographic cinematography. In holography a reference beam is added to the object beam and the resulting interference pattern (having both amplitude and phase information) is recorded. This interference pattern can be numerically reconstructed at different distances along the longitudinal direction, providing a three dimensional information of the sample volume. The data obtained in January in addition to the previous data that we have obtained has provides us with diesel droplet statistics of over 22000 separate droplets.

Droplets in all Figures implies Diesel Droplets

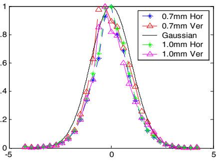


Figure 3: PDF of droplet fluctuation velocity scaled by droplet velocity rms for $Re_\lambda = 190$

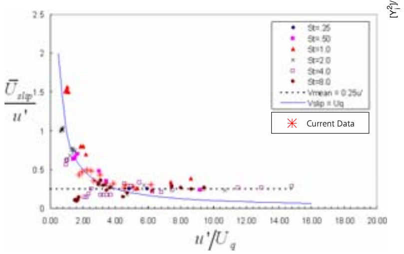


Figure 4: Droplet mean rise velocity in turbulence compared with the results of Friedman & Katz (2002)

$$\left[U_x^2\right]^{0.5}/u_x'$$

Bracket denotes ensemble average over all droplet tracks and denominator is fluid velocity rms

$$\left[U_y^2\right]^{0.5}/u_y'$$

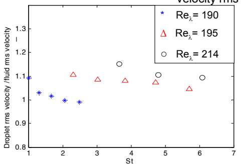


Figure 5: Variation of droplet rms velocity scaled by corresponding directional fluid rms velocity with stokes number in horizontal direction

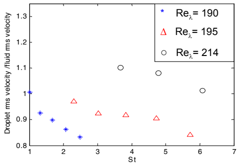


Figure 6: Variation of droplet rms velocity scaled by corresponding directional fluid rms velocity with stokes number in vertical direction

$$\tau_L = Max\left(\int_{t=0}^{\tau}[U_i(t)U_i(t+\tau)]dt \Big/ \int_{t=0}^{\tau}[U_i^2(t)]dt\right)$$

Bracket denotes ensemble average over all droplet tracks

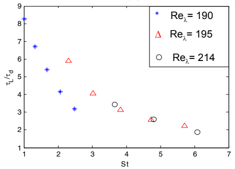


Figure 7: Variation of droplet integral timescale, scaled by droplet response time, with stokes number in horizontal direction

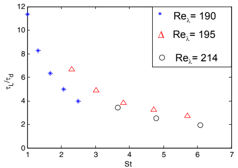


Figure 8: Variation of droplet integral timescale, scaled by droplet response time, with stokes number in vertical direction

$$D_{ii} = Max\left(\int_{t=0}^{\tau}[U_i(t)U_i(t+\tau)]dt\right)$$

Bracket denotes ensemble average over all droplet tracks

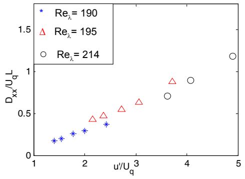


Figure 9: Variation of droplet horizontal diffusion coefficient scaled by fluid integral lengthscale and quiescent velocity with turbulence intensity scaled by quiescent velocity.

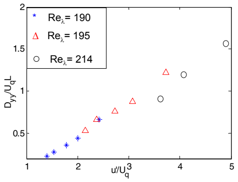
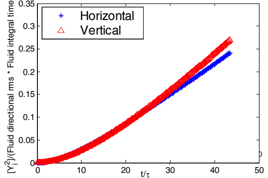


Figure 10: Variation of droplet vertical diffusion coefficient scaled by fluid integral lengthscale and quiescent velocity with turbulence intensity scaled by quiescent velocity.



$$[Y_i^2(\tau)] = 2\int_{t=0}^{\tau} D_{ii}(t)dt$$

Figure 11: Comparison of dispersion (mean square displacement) in horizontal and vertical direction scaled by directional fluid rms (to account for anisotropy) and fluid integral timescale ($T_f = L/u'$) squared. The dispersion initially varies quadratically with time and later becomes linear at $t/\tau_\eta \sim 40$ as predicted by Taylor's model.

Conclusions

- Figure 3 shows that the PDF of the droplet velocity fluctuation. It is close to Gaussian.
- The close agreement between the recently obtained mean rise velocity with that obtained by Friedman & Katz (2002) is shown in Figure 4.
- For certain Stokes number the droplet rms velocity exceeds the fluid rms velocity as shown in Figure 5,6.
- From Figure 7,8 we can see that as the Stokes number increases the droplet integral timescale decreases.
- The vertical droplet diffusion coefficient exceeds the horizontal droplet diffusion coefficient as seen by comparing Figure 9 and Figure 10. Also the linear variation in Figure 9 and Figure 10 suggests a following empirical relationship

$$D_{ii}/(U_q{*}L) \sim c_1{*}(u'/U_q) + c_2$$

where c_1 and c_2 primarily depends on the Reynolds number. There is also a slight Stokes number behavior in addition to above scaling.

Reference

Friedman, P. D. and Katz, J., Mean rise rate of droplets in isotropic turbulence, *Physics of Fluids* 14 (2002), pp. 3059-3073.

Taylor, G. I., Diffusion by continuous movements, *Proc. Roy. Soc. London* 2 (1921) , pp. 196-211.

Website:: http://me.jhu.edu/~lefd/stratified/Diffusion/holomain.htm

Acknowledgement

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