Evaluation of mixing energy in flasks used for dispersant effectiveness testing

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Abstract

A U.S. Environmental Protection Agency (EPA) laboratory screening protocol for dispersant effectiveness consists of placing water, oil, and a dispersant in a flask and mixing the contents on an orbital shaker. Two flasks are being investigated, a simple Erlenmeyer (used in EPA's official Swirling Flask Test) and a baffled Erlenmeyer (used in a newly developed Baffled Flask Test). The baffled flask (BF) contains baffles that induce an over-and-under type of mixing that somewhat better simulates breaking waves. A hot-wire anemometer was used to measure the velocity distributions in both flasks rotating at a speed of 150 rpm. The measurements were conducted in small areas near the centers of the flasks. The average velocity distribution in the BF was about 5 times higher than that in the SF. The velocity in the BF was essentially uniform with depth, while that in the SW decreased sharply with depth. The computed energy dissipation rates were about 0.75 and 23 m^2/s^3 in the SF and the BF, respectively.

1 Introduction

There have been many studies dealing with oil dispersion since the late 70's. The evaluation of the effectiveness of a particular dispersant at sea has been hampered by large experimental uncertainties in the sea. For this reason, various governmental agencies have adopted laboratory experiments. The effectiveness of a particular dispersant is typically evaluated by introducing oil and dispersant in a vessel containing seawater and agitating the mixture to simulate the mixing occurring at sea due to waves. The use of energy dissipation rate per unit mass, $\in$, as a scaling parameter, appears to be a promising venue (Delvigne et al. [1]). The units of $\in$ are watts/kg or simply m^2/s^3.

The dissipation of kinetic energy occurs due to laminar and turbulent shears within the water. The shear, being directly proportional to velocity gradients, plays an important role in the mixing of chemicals (oil, dispersants) at sea. The mathematical relations between $\in$ and shear rates are well established for both laminar and turbulent flows (Camp [2]). Hence, knowledge of $\in$ is equivalent to knowledge of the shears and subsequently the intensity of mixing of chemicals. Alternately, one may use velocity measurements in a selected water body to compute the shear, and subsequently the energy dissipation rate. This is the approach that we adopted in computing $\in$ in the EPA flask tests.

A widely used test is the Swirling Flask Test (Fingas et al. [3]). The test consists of placing a mixture of seawater, oil, and a dispersant in an Erlenmeyer flask positioned on an orbital shaker. The SFT has come under scrutiny by the U.S. Environmental Protection Agency (EPA) because of the vortexing that occurs when using this flask; the fluid moves as a solid body unlike the kinematics at sea, especially those due to wave breaking. Therefore, it is believed that the test cannot represent highly or even moderately agitated seas, a situation where dispersants are most effective. EPA is considering adopting a new procedure incorporating the use of a baffled flask that results in an over-and-under motion of water flow. The goal of this study is to evaluate and compare the kinematics and the energy dissipation rates in both types of flasks.

2 Apparatus and Data Handling

The glassware used in this work consisted of a 150-mL simple Erlenmeyer flask (SF) and a 200-mL baffled Erlenmeyer flask (BF), and the equipment included an orbital shaker with a flask-holder and a Hot Wire Anemometer (HWA) integrated with a computer data acquisition module. The flasks contained 120mL water as the working fluid and were held in place by a flask-holder.

The velocity was measured using a HWA, (TSI 1210-20W, with single cylindrical sensor). The HWA is essentially an electric resistor that cools upon passage of water flow. The change in temperature alters the voltage that passes through the resistor. Hence, voltage reading across the HWA provides a surrogate measure of the water velocity. The HWA was calibrated in the velocity range [0, 50 cm/s]. The HWA was interfaced to a computer using a data-acquisition board, DAS 1401, by Keithley with a built-in analog-to-digital circuit. The constancy of the data speed, which is important to the computation of time-dependent turbulence quantities, was always maintained using data acquisition software. The software, LABTECH Notebook pro, by Laboratory technologies has a high data acquisition speed. A Dell personal computer with 32-Mb memory was used for data acquisition and computation. The data collection frequency was 1,000 Hz resulting in a measuring duration of 10 seconds. Hence, a time series of 10,000 instantaneous voltage values were collected at each location. These values were converted to velocity using the calibration curve.

3 Results

The azimuthal (i.e., tangential) and radial velocities were measured in the flasks at a spatial interval of about 2mm. In the SF, the measurements were conducted in a vertical rectangle centered on the axis of the flask. The BF does not possess symmetry with respect to the center. For this reason, the velocity was measured in a prismatic-like volume extending from the center axis of the flask to the tip of two consecutive baffles. The orbital shaker speed used was about 150 rpm. The averages of the absolute values of the velocities (azimuthal and radial) were 6 cm/s and 27 cm/s in the SF and the BF, respectively.

The radial and azimuthal velocities measured at different locations in the flask were plotted at the same time intervals. Velocity snapshots of two components of velocity in the BF and the SF are shown in Figs 1 through 4. R denotes the distance from the center of the flask and Z is elevation from the bottom of the flask. Units are cm and sec. Velocities in the BF were significantly higher than those in the SF (note the differences in magnitude of the velocity scales between the BF and SF figures). The velocities of the BF appeared to be independent of depth, while those in the SF decreased with depth. The mixing regime was much more turbulent in the BF than in the SF. Hence, it would be expected that mixing energy would be higher in the BF.

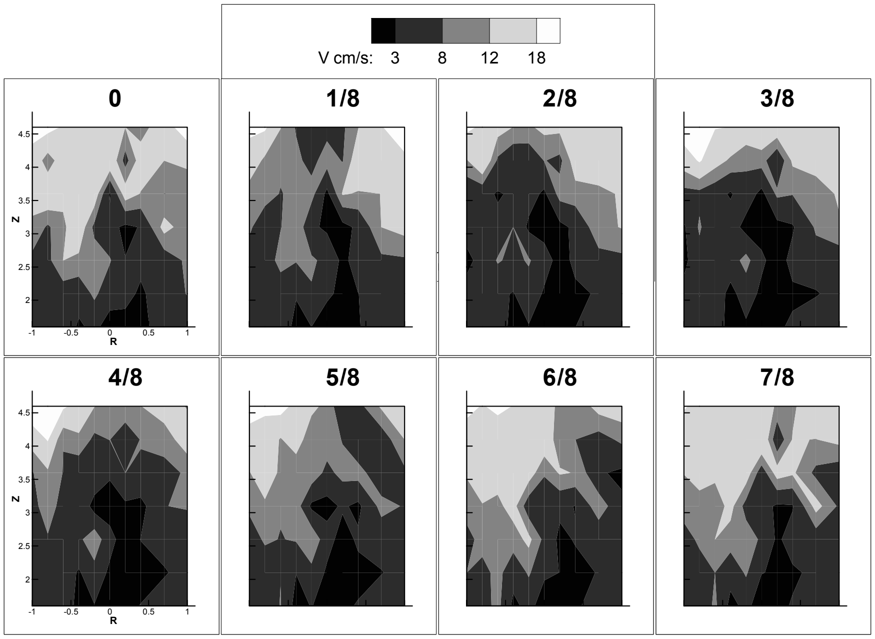

Figure 1: Azimuthal velocity in the Swirling flask at various times at 150 rpm

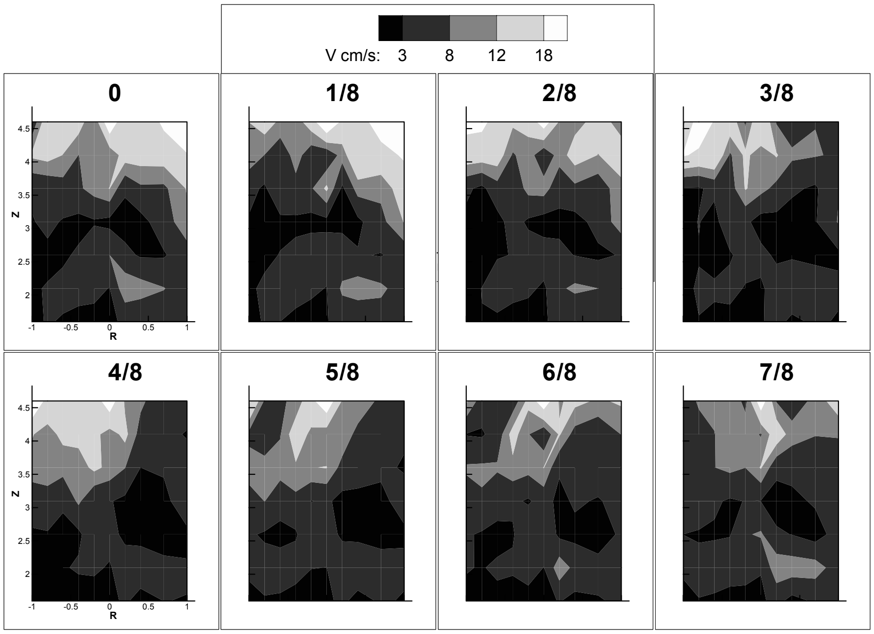

Figure 2: Radial velocity in the Swirling flask at various times at 150 rpm

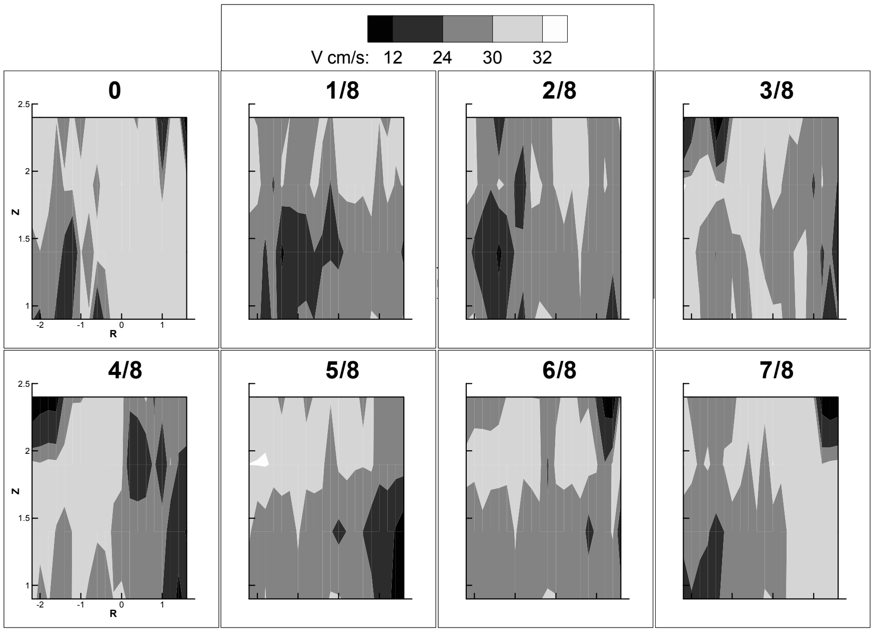

Figure 3: Azimuthal velocity in the Baffled flask at various times at 150 rpm

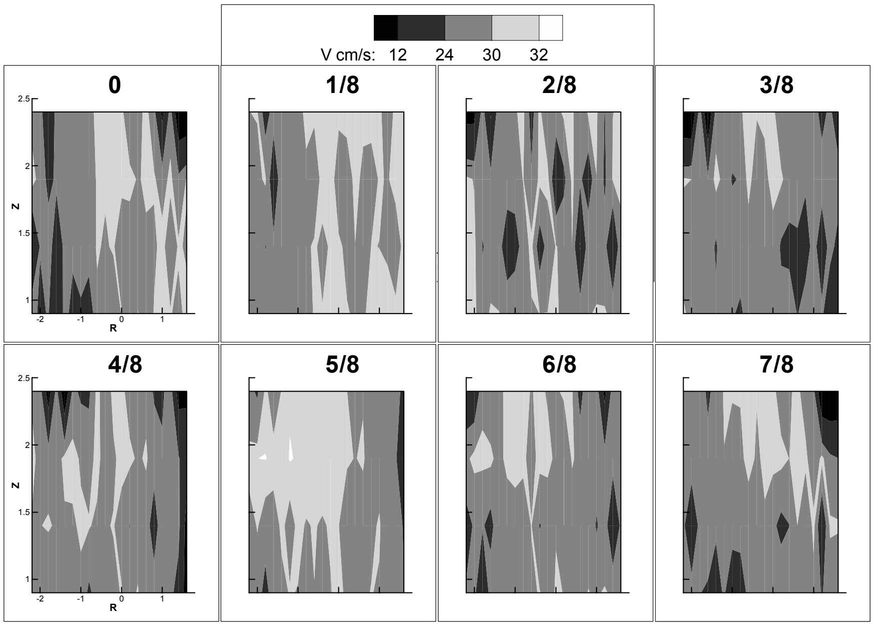

Figure 4: Radial velocity in the Baffled flask at various times at 150 rpm

3.1 Spectral Analyses

A standard approach for analyzing turbulent flows is the Fourier spectrum (Frost [4]), whose terms are the magnitudes of the Fourier transforms of the velocity field (Monin and Yaglom [5]). The spectrum represents the amount of kinetic energy per frequency. As in most experimental work, the velocity is usually measured at a fixed location in space. Hence, one attempts to infer the spatial structure of turbulence from the time series obtained at the measuring location. In addition, because turbulence may be considered isotropic at the small scale, the one-dimensional spectrum provides essentially the same information as the three-dimensional spectrum. Figure 5 shows plots of the logarithm of one-dimensional spectra as a function of the logarithm of the frequency. These spectra were obtained using the radial velocity measurements at the locations (R=-0.4cm, Z=4.1cm) and (R=-1.4cm, Z=1.9cm) for the swirling flask and the baffled flask, respectively. The linear trend indicates that the flow in both flasks is turbulent. The slopes of the observed spectra appear to be steeper than -5/3 predicted based on the Kolmogorov theory, known as K41. This is not surprising because K41 relates to the spectrum of velocity as a function of the wave number (i.e., 1/distance). In other words, it relates to the spatial distribution of the turbulent velocity. When the large-scale flow is steady, such as in a steady flow in a pipe, the -5/3 slope is carried to the temporal spectrum. The large-scale flow in the flasks was periodic; hence, one should not expect to find an exact -5/3 slope. Nevertheless, the signature of turbulence in both flasks is evident.

The peaks in both spectra correspond to about f=2.5 Hz, which was the frequency of the orbital shaker. The spectra are expected to fall off rapidly (at slopes much steeper than -5/3) at very high frequency due to dissipation of energy by viscosity. This is not observed in Figure 5, probably due to noise. An investigation of the cause of noise is being conducted. The effect of noise appears to be greater in the SF, probably due to the low velocities in that flask.

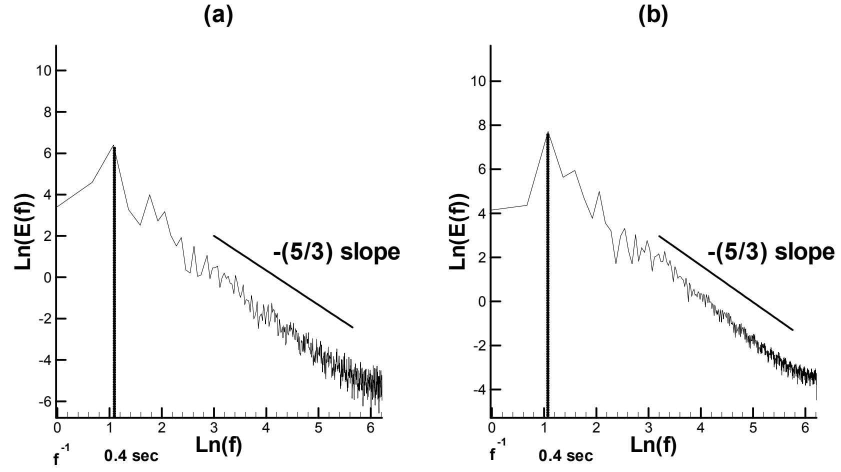

Figure 5: One-dimensional (radial) energy spectra at 150 rpm
(a) Swirling flask (b) Baffled flask

3.2 Energy Dissipation Rate

The dissipation rate can be calculated from the turbulence kinetic energy of eddies with size L:

$$\varepsilon = \frac{Au^{'3}}{L} \qquad (1)$$

where A is a constant of order unity, L is a length scale discussed below, and u` is the root mean square (rms) of velocity fluctuations. These fluctuations were obtained at each hot wire location by subtracting the average velocity from the total velocity. In other words, the velocity u was assumed to consist of a local temporal average U and a fluctuation u`, viz:

$$u\,(t) = U(t) + u`(t) \qquad (2)$$

where the time dependence is explicitly shown. The U value at each time was calculated using a weighted moving average. The value of L in eqn. (1) is obtained according to the equation:

$$L = U_L \tau_E \qquad (3)$$

where U_L is the large-scale convection velocity and τ_E is the Eulerian integral time scale (also known as the Eulerian correlation time scale). The eqn. (3) above is used when the large-scale flow is steady. In such a case $U(t) = U_L =$ constant. However, the large-scale flow in our experiments is periodic; hence, eqn. (3) cannot be directly applied. For this reason, we assume that A and L do not vary between flasks and/or locations within the flasks. We further assume for simplicity that A = 1 and L = 4 cm, which is the diameter of the baffled flask. We found ε to be 0.75 m^2/s^3 and 23 m^2/s^3 for the Swirling Flask and the Baffled Flask, respectively. Hence, the energy dissipation rate in the baffled flask is about 30 times higher than that in the swirling flask. The value of ε in breaking waves and mildly turbulent seas is in the range of 1 to 10 m^2/s^3 (Delvigne and Sweeney [6]). Hence, the SF at 150 rpm substantially underestimates the dissipation energy at sea, whereas the BF more closely mimics moderately energetic sea states.

4 Discussion

The use of a laboratory protocol has become a standard procedure for testing dispersant effectiveness. Although replicating the hydrodynamics in the ocean in a laboratory flask is still an unresolved issue from a theoretical point of view, there is a need to adopt an empirical methodology. This work is a first step in characterizing the hydrodynamic properties in the flask. We found that the regime in both flasks is turbulent as evidenced by the existence of the linear behavior in Fig. 5. The computation of the energy dissipation rate per unit mass revealed that there is about 30 times more dissipation in the BF in comparison with the SF for the same rpm of the shaker. Increasing the rotation speed of the SF to achieve the same ε would cause water to spill out of the SF. Hence, using the BF appears to be more flexible than the SF. Note that one could always reduce the rotation speed of the BF to simulate a calmer sea. The velocity distribution in the SF decreases sharply with depth (Figs. 1 and 2), while that in the BF is more heterogeneous and does not display a decreasing trend with depth (Figs. 3 and 4). Hence, the BF is preferable because its hydraulics closely resembles that occurring in the top few centimeters of a breaking wave.

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