Evaluation of mixing energy in the swirling and baffled flasks

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Abstract

A USEPA laboratory screening protocol for dispersants effectiveness consists of placing water, oil, and dispersants in a flask placed on an orbital shaker. Two flasks are being investigated, the Swirling Flask and the Baffled Flask. The BF contains baffles that induce an over-and-under type of mixing that somewhat better simulates breaking waves. We use hot-wire anemometer to measure the velocity distributions in both flasks rotating at a speed of 150 rpm. The measurements were conducted in small portions near the centers of the flasks. We found that the average velocity in the BF was about 5 times larger 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 per unit integral length scale were about 0.03 and 0.92 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, \( e \), as a scaling parameter, appears to be a promising venue (Delvigne et al. [1]). The units of \( e \) are watts/kg or simply \( \text{m}^3/\text{s}^3 \).

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 \( e \) and shear rates are well established for both laminar and turbulent flows (Camp [2]). Hence, knowledge of \( e \) 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 \( e \) 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 dispersants in a Erlenmeyer flask positioned on an orbital shaker. The SF test has come under scrutiny by the US 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 agitated seas, a situation where dispersants are most effective. The EPA is considering the use of a baffled flask whose baffles results in an over-and-under motion of water flow. The goal of this study is to evaluate the kinematics and the energy dissipation rates in both flasks.

2 Apparatus and data handling

The apparatus used in this work consisted of a Baffled and Erlenmeyer flask, Orbital shaker with a flask-holder, and a HWA with computer data acquisition. A picture of orbital shaker with flask holder is shown in Fig. 1. The flasks, filled with 120mL water as the working fluid, were open at the top and held with a flask-holder.
The velocity was measured using a Hot Wire Anemometer (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. We calibrated the HWA in the velocity range \([0, 50 \text{ cm/s}]\). 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. In each measurement, 10,000 instantaneous voltage values were collected at 1000 Hz sampling frequency. This output was converted to velocity by 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 150 rpm. The computed average velocities were 0.27 m/s and 0.06 m/s in the BF and the SF, 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 2 through 5. 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. It can be seen that velocities in case of baffled flask are comparatively higher than that of erlenmeyer flask. The velocities of baffled flask appear to be independent of depth, while those in the SF decreased with depth. It can also be noticed that velocities were more turbulent in the BF than in the SF. Hence, it was expected that mixing energy would be higher in the case of BF.
Figure 2: Azimuthal velocity in Baffled flask at various times at 150 rpm

Figure 3: Radial velocity in Baffled flask at various times at 150 rpm
Figure 4: Azimuthal velocity in Erlenmeyer flask at various times at 150 rpm

Figure 5: Radial velocity in Erlenmeyer flask at various times at 150 rpm
The one-dimensional energy spectrum $E(f)$ as a function of the frequency is defined as:

$$u_{\text{rand}}^2 = \int E(f) \, df$$

where $u_{\text{rand}}$ is the velocity fluctuation due to turbulence, the bar represents time average, and $f$ is the radian frequency ($2\pi$/time).

Figure 7 shows the logarithm of the spectra plotted as a function of the logarithm of the frequency. These spectra were obtained using the radial velocity measurements. The spectra show typical characteristics of the turbulence energy spectrum; at high frequency a $-5/3$ slope emerges. The peaks in both spectra correspond to the $f=2.5$ Hz, which is the orbital shaker frequency. The spectra are expected to fall off at a slope higher than $-5/3$ at very high frequency due to dissipation of energy by viscosity. This is not observed in Figure 7, probably due to noise. An investigation of the cause of noise is being conducted. The effect of noise was found to be greater for the SF, probably due to the low velocities in that flask.

![Figure 6: One-dimensional (radial) energy spectra at 150 rpm](a) Baffled flask (b) Erlenmeyer flask]

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

$$\varepsilon = \frac{A u^3}{L}$$

with $A$ is a constant of order unity. The value of $L$ is obtained according to the equation:

$$L = U \tau_{\varepsilon}$$
where $U$ is the convection velocity and $\tau_E$ is the Eulerian integral time scale (also known as the Eulerian correlation time scale). The equation above is used when the large scale flow is steady, while the large-scale flow in our experiments is periodic. For this reason, we computed $U$ as the average of the absolute velocities at each location. The Eulerian integral time scale is obtained by:

$$\tau_E = \int_{0}^{\infty} R_E(\tau) d\tau$$

(4)

where $R_E$ is the correlation function of the velocity fluctuations. A plot of the correlation of the total velocity (large-scale and turbulent) is shown in Fig. 6 (solid line). Also shown is the correlation function of velocity fluctuations. The latter was obtained using a procedure developed by Wu & Patterson, [4]. However, the computed turbulence correlation function still displays strong periodicity. We are currently exploring methods to remove this periodicity. Meanwhile, we computed $\tau_E$ using the correlation function of the total velocity. The integral was evaluated numerically using Simpson’s rule. But we have reported energy dissipation rate $\varepsilon$, by keeping $\lambda$ and $L$ constant in eqn. (2). It was found to be $0.03 \text{ m}^2/\text{s}^3$ and $0.92 \text{ m}^2/\text{s}^3$ for the Swirling Flask and the Baffled Flask, respectively.

![Figure 7: Autocorrelation function for total velocity (solid line) and turbulence velocity (dashed line) obtained using radial velocities at R=0.8 cm, Z=1.9 cm. Unfortunately, our procedure did not completely remove the periodicity to obtain the correct turbulence velocity correlation function.](image-url)
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References


