EVALUATION OF TURBULENCE PARAMETERS IN LABORATORY FLASKS USED FOR DISPERSANT EFFECTIVENESS TESTING

Vikram J. Kaku[1], *Michel C. Boufadel*[2], *Albert D. Venosa*[3]

ABSTRACT

The effectiveness of dispersants used as countermeasures for oil spills is commonly evaluated by conducting tests in laboratory flasks. The success of the test relies on the replication of sea conditions in the flasks. We used a Hot-wire Anemometer (HWA) to characterize the hydraulics in the Swirling Flask (SF) and the Baffled Flask (BF) at orbital shaker speeds of 150 and 200 rpm's. We used these measurements to compute velocity gradient, G, turbulence microscale, η, and energy dissipation rate per unit mass, ε. The flask average energy dissipation rates in the SF were about two orders of magnitude smaller than those in the BF. The sizes of the microscales in the BF were found to be much smaller than that in the SF. Also, in the BF, the sizes of the microscales approached the size of oil droplets observed at sea (50 to 400 micron), which means that the hydraulics in the BF closely resembles the hydraulics occurring in the top few cm of a breaking wave. Hence, the BF is preferable for dispersant effectiveness testing in the laboratory.

INTRODUCTION

The adverse economic and environmental effects of offshore oil spills are greatest when the oil slick reaches the shoreline. For this reason, much effort is put on preventing offshore oil spills from reaching the shoreline. In rough seas, the use of chemical dispersants appears to be the promising approach for cleanup (Delvigne et al., 1987; Fingas, 2000).

A dispersant is a mixture of surfactants and solvents that causes the oil slick to break into small droplets in a process known as dispersion. The generated small oil droplets get transported or transferred into the water column due to wave action and sea turbulence. They could eventually adhere to suspended particulate matter and/or biodegrade. The dispersion of oil is a chemico-physical process that depends both on the type of dispersant/oil pair and on the sea state.

Various field studies and laboratory experiments have been conducted to evaluate the effectiveness of dispersants under various sea conditions. Field studies are accompanied by large experimental uncertainties in the sea; replicates are usually difficult to achieve due to constantly changing climatic conditions and for economic reasons. Smaller scale testing is, therefore, relied upon to study dispersant effectiveness. Fingas (1991) reports that there are about fifty different laboratory test methods available for determining the effectiveness of dispersants on oil. The laboratory tests can be categorized into four general groups: tank tests, rotating flask tests, interfacial surface tension tests, and flume tests (Clayton et al. 1993).

The Swirling flask (SF) test consists of placing a mixture of oil, seawater, and a dispersant in the SF positioned on an orbital shaker (Fingas et al., 1987, 2000), then mixing the contents for a specified amount of time, allowing a short settling time, and then extracting the contents from the SF and measuring the concentration of oil dispersed in the water. The claimed advantages of this test are its ease of use and simplicity. Experiments with the SF test have come under scrutiny by the U.S. Environmental Protection Agency (EPA), because of the lack of reproducibility in the hands of different analysts (Venosa et al., 2002) and because it was suspected that the mixing does not resemble the mixing occurring at sea, especially due to breaking waves. EPA will soon be adopting a new flask, the baffled flask (BF), which has four baffles in it. The irregular geometry of the BF results in an apparent over-and-under motion of water flow somewhat more characteristic of the type of mixing that occurs from breaking waves at sea.

As dispersion of oil into fine oil droplets takes place at the smaller scale (i.e., below the 1-cm scale), simulation of these interactions in laboratory experiments is possible because the smallest eddies in the flask are similar to those at sea. This means that, following the work of Delvigne et al. (1987), the energy dissipation rate per unit mass, ε, can be used as an appropriate scaling parameter. The units of ε 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 is directly proportional to velocity gradients, which play an important role in the mixing of chemicals, such as oil and dispersant. A well known relation exist between _ and the absolute velocity gradient G (s^{-1}) at every location in the fluid (Tennekes and Lumley, 1972):

$$\varepsilon = \nu G^2 \qquad (1)$$

where ν is the kinematic viscosity of water ($10^{-6} m^2/s$ at 20°C).

Hence, knowledge of ε is equivalent to knowledge of velocity gradient, and subsequently the intensity of mixing of chemicals. Alternatively, one may use velocity measurements in a selected water body to compute the velocity gradient, and subsequently the energy dissipation rate. This is the approach that we adopt in this work to evaluate energy dissipation rates in the SF and the BF. We used a Hot-Wire Anemometer (HWA) to measure the instantaneous water velocity distributions in the flasks.

[1] Temple University, Dept. of Mech. Engg., 1947 N. 12th St, Philadelphia, PA 19122, USA
[2] Temple University, Dept. of Civil & Environmental Engg., 1947 N. 12th St, Philadelphia, PA 19122, USA
[3] U.S. Environmental Protection Agency, National Risk Management Research Lab., 26 W. Martin Luther King Dr, Cincinnati, OH 45268, USA

EXPERIMENTAL SET-UP

The experimental setup consisted of a 150-mL Swirling flask (SF) and a 200-mL baffled trypsinizing flask (BF), an orbital shaker (3518, Lab-Line Instruments Inc.). Each flask contained 120mL of tap water as the working fluid. The flasks were held in place on the orbital shaker using flask holders. Two rotation speeds of the orbital shaker were considered, 150, and 200 rpm's. The orbital distance of the shaker was 1.9 cm. During rotation, the location of the flasks with respect to the 360 degree circumference was measured using a Position Transducer (PN150-0121, SpaceAge Control Inc.). A Hot Wire Anemometer, HWA, (TSI 1210-20W, with single cylindrical sensor) was mounted on the orbital shaker to measure the water speed in the flasks. All measurements were interfaced to a computer using a data-acquisition board, DAS 1401, by Keithley Instruments, Inc., (Cleveland, Ohio) with a built-in analog-to-digital circuit. The data logging software LABTECH (Notebook Pro, Laboratory Technologies, Inc.) was used.

The radial and tangential (i.e., azimuthal) velocities were measured using the HWA. 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 velocities were measured in the center vertical plane of both the flasks at a spatial interval of 2mm in the horizontal (i.e. radial) direction and 5mm in the vertical direction. This totaled in 70 locations in the SF and 80 locations in the BF. The data collection frequency was 1,000 Hz. The sampling duration was 10 seconds for each velocity component. This resulted in a time series of 10,000 measurements for each component.

RESULTS AND DISCUSSIONS

Figure 1 and 2 shows azimuthal velocity snapshots in the SF and the BF, respectively, at various times for 200 rpm. These snapshots were obtained numerically by plotting instantaneous velocities at different locations at the same time step of the cycle. The beginning of the cycle at same orbital location was obtained by using position transducer. Fig. 1 shows that there is a quasi-stagnant core in the SF, where the velocity is very low relative to the outer areas.

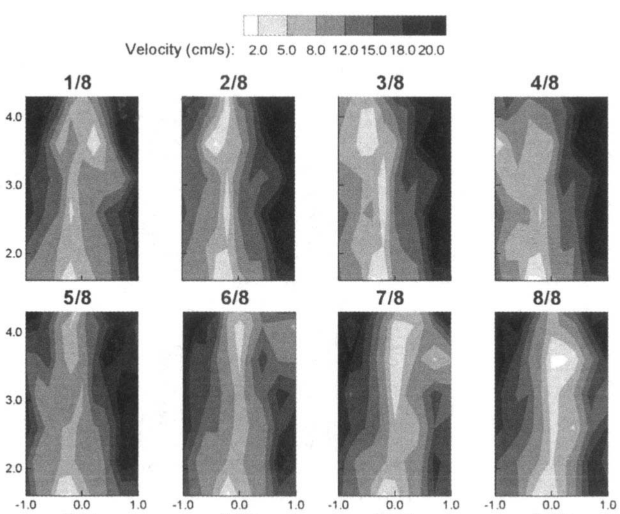

FIGURE 1: AZIMUTHAL VELOCITY SNAPSHOTS IN THE SF AT VARIOUS TIMES FOR 200RPM. THESE SNAPSHOTS ARE EVERY 1/8TH OF THE CYCLE. X, IS DISTANCE FROM THE CENTER OF THE FLASK.

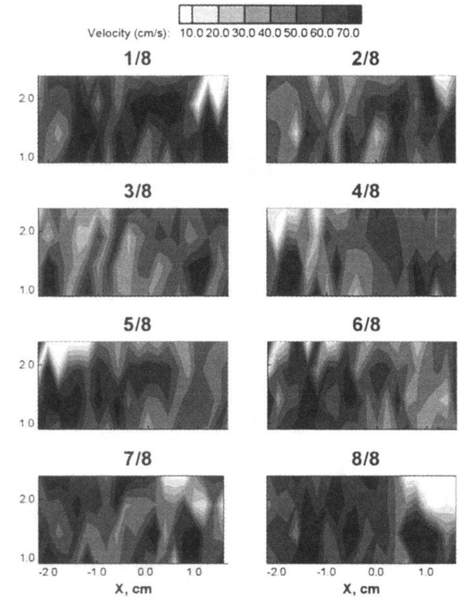

FIGURE 2: AZIMUTHAL VELOCITY SNAPSHOTS IN THE BF AT VARIOUS TIMES FOR 200RPM. THESE SNAPSHOTS ARE EVERY 1/8TH OF THE CYCLE. X, IS DISTANCE FROM THE CENTER OF THE FLASK.

This is also known as "solid body motion", where shear flow (i.e., velocity gradient) is essentially absent (i.e., mixing is small). The velocities in the BF tended to be more variable in space displaying high and low values throughout the flask. In addition, while the velocity in the SF decreased with depth, the velocity profile in the BF displayed no discernible pattern, especially at 200 rpm. Note that the maximum velocities in the BF were about three times larger than the corresponding ones in the SF.

At 150 rpm, the average of all velocities (azimuthal and radial) was 0.046 m/s in the SF and 0.27 m/s in the BF. At 200 rpm, they were 0.101 m/s and 0.533 m/s for the SF and BF, respectively. Hence, the average speeds in both flasks almost doubled as the shaker rotation speed increased from 150 to 200 rpm.

To further investigate the effects of turbulence, we plotted in Fig. 3 the natural logarithm of the Fourier spectrum as function of the natural logarithm of frequencies of eddies for the azimuthal velocity at 200 rpm. The spectra were computed by averaging the spectral amplitudes at all locations corresponding to the same frequencies. Fig 3 also shows the theoretical -5/3 slope based on Kolmogorov theory (Eq. 2).

$$E \propto f^{-5/3} \tag{2}$$

where, E is the magnitude of the spectrum and f represents the frequency of velocity fluctuations. Eq. 2 is valid in situations where Taylor's "frozen turbulence" hypothesis is applicable (Monin and Yaglom, 1975). The observed spectra displayed periodicity, which is to be expected due to the periodic nature of the motion. The highest peak occurred at the frequency of rotation (150 rpm or 200 rpm). The peaks that followed occurred at multiple frequencies of the main one. The spectra of radial velocities were similar and are not reported for brevity.

The energy dissipation rate per unit mass, ε, was obtained by using (Wu and Patterson 1989):

$$\varepsilon = A \frac{(u_{rms}')^2}{\tau_E} \tag{3}$$

where, u_{rms}' is the root mean square (RMS) value of the turbulent component of velocity, A is a constant of order unity, and τ_E is the integral time scale. One value of ε, in azimuthal and radial direction, was computed at each location. The average of these two values was then obtained, and it is considered as representative of the energy dissipation at that location. The values of ε in the SF were higher at the surface and decreased rapidly with the increase in depth. The values of (in the BF were much higher at the edges due to the presence of baffles. The flask-averaged value of ε, $\bar{\varepsilon}$, is reported in Tables 1 and 2.

The velocity gradient G was computed from Eq. 1 at each location using the local ε value for each velocity component. The local G value was obtained as the average of the two radial and azimuthal values. The flask-averaged velocity gradient, $\bar{G}$, is reported in Tables 1 and 2.

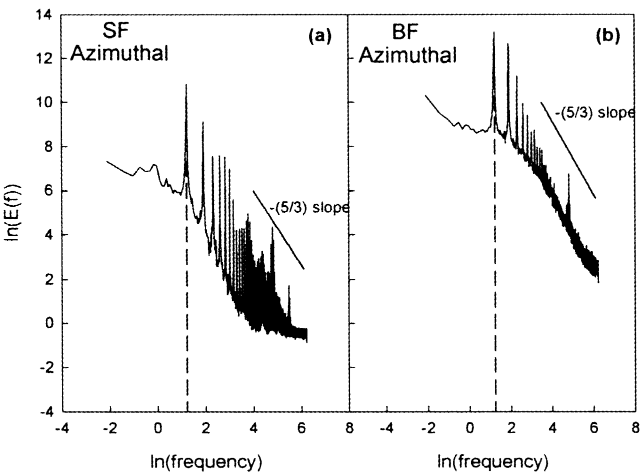

FIGURE 3: AVERAGE ONE-DIMENSIONAL ENERGY SPECTRA IN THE SF AND THE BF FOR 200RPM BASED ON AZIMUTHAL VELOCITY. THE PEAK ON THE DASHED LINE SHOWS ORBITAL SHAKER FREQUENCY OF 3.33 HZ.

The Kolmogorov scale, η, provides an estimate of the smallest eddy that can exist prior to the dissipation by (molecular) viscous friction. It is estimated based on dimensional arguments (Tennekes and Lumley, 1972) as:

$$\varepsilon = A\frac{(u_{rms}')^2}{\tau_E} \qquad (4)$$

The local η value was obtained as the average of the two values. The flask-averaged Kolmogorov scale, $\bar{\eta}$, was obtained by taking the arithmetic average of the local η values. The values are reported in Tables 1 and 2. If the smallest eddies are larger than the oil droplets, they tend to entrain oil droplets within them without breaking them. However, if the smallest eddies are smaller than an oil droplet, they would "share" it between them causing it to break. The size distribution of dispersed oil at sea was observed to range from 50 _m to about 500 μm (Delvigne, 1983; Mackay et al., 1986; Delvigne et al., 1987). The value of $\bar{\eta}$ in the SF at 150 rpm is about 410 μm. This implies that the mixing in the SF at 150 rpm does not theoretically create a high number of oil droplets whose sizes are smaller than 410 μm. This discrepancy indicates that there might be theoretical objections to using the mixing in the SF at 150 rpm to represent the mixing at sea. The average Kolmogorov scale in the BF at 200 rpm is about 50 μm, which should cause breakup of oil droplets approaching that scale.

TABLE 1: Average Parameters for the Flasks at 150 rpm

Type of Flask	Mean Velocity U_{avg} (m/s)	RMS Velocity u_{rms}' (m/s)	Avg. Diss. Rate $\bar{\varepsilon}$ (m^2/s^3)	Avg. Velocity Gradient $\bar{G}$ (s^{-1})	Kolmogrov Microscale $\bar{\eta}$ (μm)
SF	0.0466	2.25×10^{-3}	4.43×10^{-4}	11.56	409.11
BF	0.272	1.62×10^{-2}	1.55×10^{-2}	96.97	115.66

TABLE 2: Average Parameters for the Flasks at 200rpm

Type of Flask	Mean Velocity U_{avg} (m/s)	RMS Velocity u_{rms}' (m/s)	Avg. Diss. Rate $\bar{\varepsilon}$ (m^2/s^3)	Avg. Velocity Gradient $\bar{G}$ (s^{-1})	Kolmogrov Microscale $\bar{\eta}$ (μm)
SF	0.1013	5.41×10^{-3}	2.07×10^{-3}	28.84	245.28
BF	0.533	4.95×10^{-2}	1.63×10^{-1}	349.86	57.90

CONCLUSIONS

Two components of instantaneous velocity were used to characterize turbulent flow in the Swirling Flask (SF) and the Baffled Flask (BF) using an HWA. General flow patterns, turbulent flow parameters, and local dissipation rates were determined. The study shows that the mixing in the BF is more uniformly distributed than in the SF. The approximation of local isotropy was supported by (–5/3) slope of the turbulence frequency spectra in case of the BF.

Flask average energy dissipation rates in the SF were about two orders of magnitude smaller than those in the BF. The sizes of the microscales in the BF were found to be much smaller than that in the SF. Also, in the BF, the sizes of the microscales approached the size of oil droplets observed at sea (50 to 400 micron) (Delvigne, 1983; Mackay et al., 1986; and Delvigne et al., 1987). This could be used to infer that the turbulence in the BF closely resembles the turbulence occurring in the top few cm of a breaking wave. Hence, the BF is preferable as a laboratory surrogate for dispersant testing.

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BIOGRAPHY

Dr. Michel C. Boufadel received his M. S. (1992) and Ph. D. (1998) in Environmental Engineering from the University of Cincinnati, Ohio. He has been an Assistant Professor since 1999 and currently also serves as Graduate Director for Temple University's Department of Civil and Environmental Engineering. The author of numerous articles in publications such as *Journal of Hydrology* and *Water Resources Research*, Dr. Boufadel has been the principal investigator in several U.S. Environmental Protection Agency research projects.

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