Observations of flow repeatability and secondary circulation in an oscillating grid-stirred tank

Sean P. McKenna[a)]
Department of Applied Ocean Physics and Engineering, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543

Wade R. McGillis[b)]
Geochemistry, Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York 10964

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An oscillating grid-stirred tank was studied for flow repeatability and the existence of secondary circulations. For the particular tank studied, results indicate that mean flow values may vary by up to 25% and turbulent fluctuations may vary by up to 15% from one run to another. This result was observed to exhibit a potential grid geometry dependence. More importantly, there is evidence of significant flow field sensitivity to initial conditions. Particle image velocimetry results were used to reveal secondary mean flows in the grid-stirred tank. Because these characteristics are believed to be intrinsic to grid-stirred tanks, studies using such tanks must recognize and consider these effects. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1779671]

Oscillating grid-stirred tanks have long been used in experimental studies of turbulent mixing and transport processes in a variety of fluid systems (e.g., Refs. 1–5). The flow produced by an oscillating grid is the result of interactions between the individual jets and wakes created by the motion of the grid bars. At sufficient distance from the grid, these jets and wakes interact and break down into turbulence that is carried away from the grid by the jet motions. In concept, no mean flow exists and the turbulence is considered near isotropic and homogeneous in planes parallel to the driving grid.

The oscillating grid-stirred tank examined here was used as part of a larger study of free-surface air–water gas transfer in the presence of subsurface turbulence.[6] As part of that investigation, several diagnostic experiments were conducted with the grid tank to quantify its particular characteristics. Among these were flow repeatability experiments and studies of secondary circulations. The findings from these investigations revealed some subtle characteristics of grid-stirred tanks that may have important consequences.

The tank studied had dimensions $45\times 45\times 57\ \text{cm}^3$ and was fitted with a vertically oscillating grid, making it similar to tanks used by those cited above. Two stirring grids were used. Grid A was a 7×7 square grid of solid bars. The cross section of each bar was $d=1.3$ cm square, and the bars were spaced equally in both directions by $M=6.4$ cm. Grid A closely resembled the grid used by Brumley and Jirka.[2] Grid B was a 5×5 square array of the same bars, spaced 8.9 cm apart in both directions. The grid was rigidly attached at its center point to a stainless steel shaft that passed through the tank floor with a watertight seal. A gearmotor-driven reciprocating mechanism beneath the tank vertically oscillated the shaft and grid. All experiments were performed with a water depth of 51 cm. The mean vertical position of the grid was located midway between the tank bottom and the free surface. For both grids, the distance from the extreme edge of the grid bar ends to the tank side wall was 4 mm. Several different grid stroke S and frequency f combinations were explored and are summarized in Table I. Other parameters appearing in Table I were determined using the empirical expressions of Hopfinger and Toly,[4] who found that for a planar grid of square cross-section bars with $M/d=5$, the rms (root-mean-square) horizontal turbulent velocity could be related to the grid parameters as

$$u_{HT}=0.25\ M^{0.5}S^{1.5}fz^{-1}, \tag{1}$$

where z is the vertical distance from the mean grid position. Furthermore, the longitudinal integral lengthscale was found to increase linearly with distance from the grid as

$$L_{HT}=\alpha z. \tag{2}$$

The constant α has been shown to fall in the range 0.1–0.4. As in Brumley and Jirka,[2] our measurements indicated a choice of 0.1. The turbulent Reynolds number based on the Hopfinger and Toly values at the free surface ($z=z_s$) was defined as $\text{Re}_{HT}=2u_{HT}L_{HT}/\nu$ and was used to characterize the bulk turbulence.

In order to study flow repeatability, a 10 MHz acoustic Doppler velocimeter (ADV), capable of making single-point, three-dimensional velocity measurements at 25 Hz was utilized. The sensor was mounted in one corner of the tank such that the probe measurement volume was 10 cm from each side wall and 17.4 cm above the mean grid position. A specific experiment was conducted to assess the repeatability of the grid tank flow. Grid B was used and the grid was run at $\text{Re}=555$. Ten experimental runs were performed. The procedure was to start the grid oscillating, wait 15 min for a steady state to be reached, take 15 min of velocity data, and then wait 45 min for the fluid motion to dissipate. This procedure

a)Electronic mail: smckenna@alum.mit.edu
b)Also at Department of Earth and Environmental Engineering, Columbia University, New York, NY. Electronic mail: wrm2102@columbia.edu

TABLE I. Grid forcing characteristics.

S (cm)	f (Hz)	$u_{HT}(z_s)$ (cm/s)	Re_{HT}
8.9	0.70	0.46	234
6.4	1.73	0.69	349
10.2	1.15	0.92	469 (grid A)
10.2	1.15	1.09	555 (grid B)
7.6	2.25	1.17	596
11.4	1.50	1.44	730
10.2	2.20	1.77	898

was followed consecutively for runs 1–6, and also for runs 7–10. However, between runs 6 and 7, the wait time was ≈2 h and 45 min. Figure 1 shows the results of the 10 runs. It is evident that the repeatability of both the mean flow and the turbulence is quite good within each grouping of runs 1–6 and separately 7–10. The maximum deviation from the average of each group is roughly 10% for the mean velocities, and only 3% for the fluctuations. However, there is a distinct change in behavior between runs 6 and 7, indicating that the additional wait time of 2 h induced a somewhat different flow. The most dramatic variability in the mean flow occurred for U, which underwent a change of nearly 1.3 cm/s. The greatest variability in the turbulent components occurred for v, which changed by ≈0.5 cm/s (≈20%). It is believed that this variability is likely due to a sensitivity of the flow to initial conditions. This type of behavior was also reported by McDougall,[7] and is mentioned briefly in the work of E and Hopfinger.[8] In a much smaller grid-stirred tank (25.4 cm square and 46 cm deep), McDougall encountered mean motions that were found to depend on the initial state of the tank. In particular, McDougall describes how the addition of a laser Doppler velocimetry (LDV) seed particle mixture gave rise to a large scale mean circulation that "became a permanent feature of the flow." Furthermore, the location of seed mixture introduction was found to have a considerable effect on this mean circulation. McDougall also noted that such mean motions were found to persist for very long periods of time. As an explanation, McDougall points to the nonlinear character of the formation of a mean flow by an oscillating grid. Therefore, slight differences in the initial ambient flow could give rise to very different mean circulations as well as influence the resulting characteristics of the turbulence. This explanation is consistent with the present observations. It is very likely that the initial conditions for run 1 were different from those for run 7. (The tank was idle overnight prior to run 1.) Additional measurements would be necessary to further explore these differences. It is plausible, however, that one may never be able to reproduce a set of initial conditions to the degree required to produce a tank flow with identical turbulence and mean circulation characteristics. One could conceive of special procedures that could be taken to reduce the degree of variability from run to run. For the purposes of our larger air–water gas transfer study, the level of repeatability exhibited by the grid tank was sufficient since measurements of the flow that characterized the specific conditions were made during each experiment.

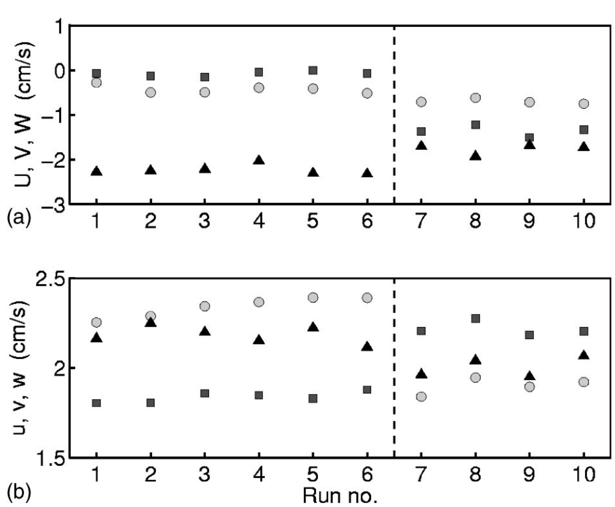

FIG. 1. Repeatability measurements for Re=555 with grid B. (a) Mean flow estimates, and (b) rms turbulent fluctuations. ■, u, U; ●, v, V; ▲, w, W.

Another group of results obtained during the course of the grid tank diagnostics provide further assessment of the flow repeatability. The data represent a collection of ADV measurements over a range of grid forcing conditions (Re =234, 349, 469, 596, 730, 898) using grid A where multiple measurements of mean velocities and turbulent fluctuations were available at the same location in the tank. At least three separate measurement records were available for each forcing condition. These results indicate that the mean flow velocities may vary by up to 25% and the turbulent fluctuations may vary by up to 15% from any given run to another. This result is slightly worse than that found for Re=555 using grid B (above), implying that flow repeatability may exhibit, at the very least, a grid geometry dependence.

Additional experiments using the ADV in a horizontal (xy plane) array of measurement locations showed evidence of persistent flow motions in the grid tank. In particular, zones of consistent upwelling and downwelling were detected as well as horizontal mean flows. For forcing conditions with $S<8$ cm, the horizontal mean flows were very nonsymmetric and unorganized when compared to the flows with larger strokes. The larger stroke results showed consistent, outwardly directed mean flows in the horizontal plane at the 8 cm measurement depth. The mean vertical velocities at the measurement locations were almost always directed toward the free surface. By conservation of mass, this implies that a significant downward return flow must exist somewhere else in the tank. For the cases where $S>8$ cm, the directions of the horizontal mean flows would indicate that the return flow exists at the tank side walls. Significant mean upwelling motions were often found in the regions of the tank corners. The upwelling regions became less localized for the larger Reynolds numbers. At the free surface, the center area of the tank generally showed the least mean motion. In a number of the low Reynolds number cases, the center was a region of mean downwelling. Based on these measurements, a picture of the overall mean flow can be developed. Above the grid, a mean flow exists that consists of four upward jets in the tank corner regions. The fluid carried by these jets is returned downward predominantly along the tank side walls, and in some cases, is also returned within a downward jet located at the middle of the tank. While not measured, a similar image flow is expected to exist below the grid.

To further explore the nature of the bulk flow structure and the spatial distribution of the turbulence for the grid-stirred tank, a series of particle image velocimetry (PIV) measurements were made for two grid forcing conditions. Measurements were made in three separate vertical planes above the grid to provide an overall assessment of the flow. Data acquisition was arranged such that a velocity field was acquired every 3 s for ≈8 min. The xz vertical planes studied were located at $y=10$, 23, and 35 cm. Collected velocity field data nearly spanned the complete x direction of the grid tank, approached the free surface to within 0.7–3.1 cm, and measured down to near the top of the grid stroke. The two forcing conditions chosen were considered representative in terms of mean flow behavior: Re=596 and Re=730, both with grid A. The earlier ADV measurements indicated that strong, localized jets existed for the Re=596 forcing. The Re=730 condition represented a potentially different regime where such jets were not as predominant and the vertical mean flow appeared more spatially homogeneous.

Complete two-dimensional pictures of the mean flow and turbulent kinetic energy were produced for each of the three xz planes. The turbulent kinetic energy (per unit mass) was defined as

$$q(x,z;y) = \tfrac{1}{2}(2u^2 + w^2), \tag{3}$$

where the assumption of horizontal isotropy, $u=v$, has been used. For a single xz plane, the velocity field measurements were ensemble averaged to produce a mean velocity field: $U(x,z;y), W(x,z;y)$. This mean velocity field was subtracted from each individual velocity field realization to yield the turbulent fluctuation velocity fields: $u(x,z;y), w(x,z;y)$. The turbulent fluctuation velocity fields were ensemble averaged to produce a mean turbulent kinetic energy field. Figure 2 shows the results for Re=596. The regions where $x>20$ cm and no measurements exist are due to the absence of light sheet illumination. Inspecting first the mean flow behavior, the PIV results provide exceptional whole-field quantitative visualizations of the persistent bulk flow structure. The results from the three planes confirm the hypothesized mean circulations based on the earlier ADV measurements. Evidence of consistent upwelling is found in the majority of the tank (above the grid) with a highly localized region of downwelling located in the center region of the tank. Significant additional downwelling occurs along all side walls. In response to this flow pattern, a number of rotational cells emerge in the mean. One such cell is obvious in the $y=10$ cm plane, and another is present in the opposite corner of the tank in the $y=35$ cm plane. Some flow symmetry can be found from these mappings. It appears that the mean flow may show symmetry about the tank diagonals. It also might be speculated that the two tank vertical midplanes exhibit some degree of symmetry.

Turning to the turbulent kinetic energy, the spatial variability is somewhat less dramatic. In the $y=10$ cm plane and

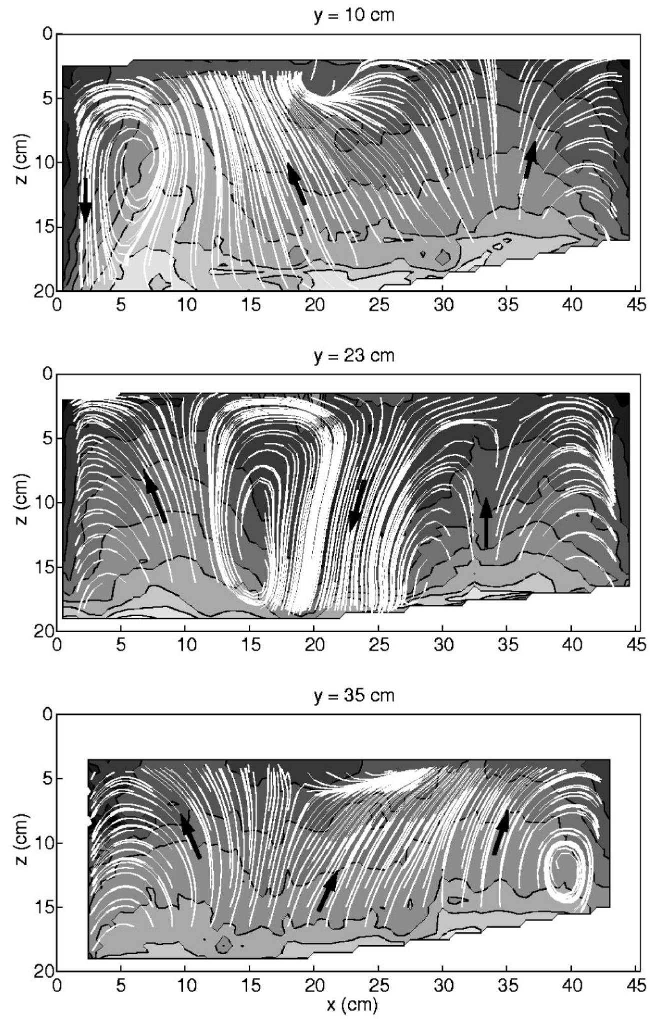

FIG. 2. Mean flow and turbulent kinetic energy (TKE) visualization in three vertical planes for Re=596. The ensemble-averaged mean flow (streamlines) and TKE (contours) are shown for the xz planes at $y=10,23$, and 35 cm. The TKE is shown as the base-10 logarithm of the actual energy for improved visualization. The free surface is at $z=0$, the top of the grid stroke is at $z=21.6$ cm, and the mean grid position is $z=25.4$ cm. The contour levels in each panel, and those of Fig. 3, are identical.

the $y=35$ cm plane, the turbulent energy is roughly constant across the x direction for a given depth. However, higher intensities are found in the corner regions. In the midplane ($y=23$ cm), the turbulent energy undergoes a significant reduction in the center region where the mean downwelling occurs. This would indicate that for this grid forcing, the central region of the flow is a relatively low energy region with a persistent downward flow. To either side of this region, the net flow is upward and the turbulence levels are similar to those in other regions about the tank.

The same collection of measurements and results for the Re=730 grid forcing condition are shown in Fig. 3. Consistent with the ADV results, the mean flow for this grid forcing does not show strong localized jet structures as in the case for Re=596. Instead, the mean flow is upward throughout the tank, with the downward return flow existing exclusively at the tank side walls. Unlike the Re=596 condition, mean rotational cells do not appear to form in the bulk for this flow, with the exception of a weak circulation near the free

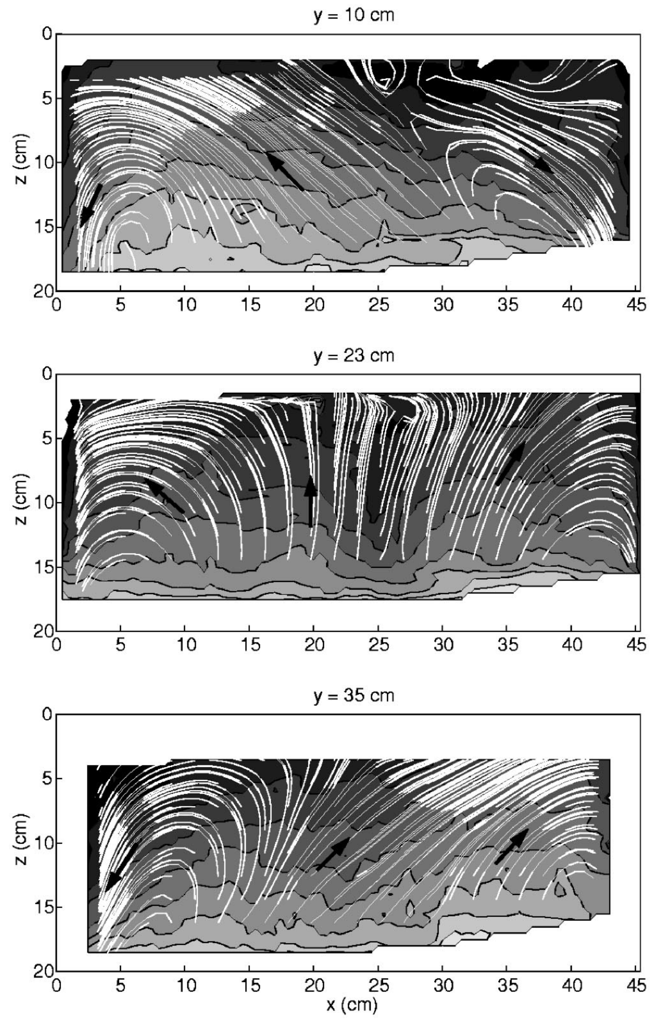

FIG. 3. Mean flow and TKE visualization in three vertical planes for Re =730. Details are as in the Fig. 2 caption except that the top of the grid stroke is at $z=19.7$ cm.

surface in the $y=10$ cm plane. In addition, it appears the same diagonal symmetry that was observed for the Re=596 case is also found for this grid forcing. Considering the turbulent kinetic energy, the distribution of the energy is much more spatially homogeneous compared to the Re=596 case. The midplane shows slightly less turbulent energy than the other two planes, and the center region of the tank is again the area of weakest turbulent intensity. To gauge the strength of the turbulence relative to the mean flows, the ratio of the two was examined. For all seven forcing conditions studied, the ratio of turbulent velocity to mean flow velocity was typically between 2 and 8. The smaller values were often associated with the vertical velocities, where the ratio approached unity in some cases. Very similar results were found by Thompson and Turner[5] and McDougall.[7]

Although only two Reynolds numbers were studied intensively using PIV, the results have provided a clear description of the overall nature of the flow within the grid turbulence tank. Since the two Reynolds numbers selected were felt to span a possible range of flow patterns, the results presented here may serve as qualitative bounds for the complete group of forcing conditions. It is worth noting that the two grids used in these studies do not have bars parallel to the side walls at the edges of the grid. These grids therefore have "correct" grid end conditions, where the tank side wall acts as a place of symmetry, as discussed by De Silva and Fernando.[3] While the results of De Silva and Fernando led them to conclude that correct end conditions can significantly reduce secondary circulations, the mean flows observed here were still substantial. One reason for this possible discrepancy may be the different forcing conditions used in the two studies. De Silva and Fernando used much shorter strokes and much higher oscillation frequencies.

Historically, oscillating grid-stirred tanks have been described as "zero-mean-shear" or having no mean flow. When secondary motions have been reported, these features typically are not given significant or adequate attention. However, the present results have shown that these mean flows are a characteristic of grid-stirred tanks. It is felt that this particular tank is not in any way distinct in its behavior. Mean secondary circulations should therefore be recognized as an intrinsic feature of oscillating grid-stirred turbulence. Some degree of spatial nonuniformity is also inherent in these flows. However, both of these deficiencies can be relatively benign, provided they are acknowledged and that sufficient spatial sampling exists to properly quantify the effects. The role of flow repeatability should also be considered. As shown here, the exact nature of the flow that develops in a grid-stirred tank may be very sensitive to the initial conditions of the tank. Depending on how critical repeatability is for a given experimental study, certain precautions may be required. Alternatively, new tank designs may prove to be more ideal sources of isotropic turbulence with zero-mean-shear.[9]

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