Gallery of Fluid Motion

High-fidelity simulations of submerged turbulence interacting with a free surface

Andre Calado and Elias Balaras*

Department of Mechanical and Aerospace Engineering, The George Washington University, Washington, DC, 20052, USA

(Received 10 June 2024; published 22 November 2024)

This paper is associated with a poster winner of a 2023 American Physical Society's Division of Fluid Dynamics (DFD) Gallery of Fluid Motion Award for work presented at the DFD Gallery of Fluid Motion. The original poster is available online at the Gallery of Fluid Motion, https://doi.org/10.1103/APS.DFD.2023.GFM.P0005

DOI: 10.1103/PhysRevFluids.9.110508

Turbulent structures interacting with the free-surface play a major role in the process of air entrainment in many practical applications. Understanding this phenomenon is crucial for various fields such as oceanography, naval engineering, and environmental science. In oceanic flows, for example, understanding aeration is essential for evaluating gas transfer between the ocean and the atmosphere [1,2]. In the context of a ship's wake, bubble formations beneath the surface are responsible for the wake's persistence and its characteristic acoustical signatures [3,4]. Experimental measurements in such turbulent, bubble-laden flows are challenging due to high bubble concentrations and the complexity of measuring stresses, pressure, and other local variables important to the mechanics of entrainment. For most engineering problems, Reynolds averaged Navier-Stokes (RANS) approaches are still the paradigm due to their affordable computational cost. However, for two-phase turbulence, classical models (e.g., $k-\varepsilon$, $k-\omega$) fail near large-scale interfaces and must be corrected, even for simple problems such as stratified cocurrent flow [5]. Bubble transport modeling within the RANS framework has reached a level of maturity today, but most of the uncertainty in predicting bubbly wakes originates from the fairly crude air-entrainment models available. Direct numerical simulations (DNS) can help address these challenges by developing mechanistic air-entrainment models and providing high-fidelity data that complement experiments to improve and calibrate new turbulence models.

In this work we report DNS of forced homogeneous isotropic turbulence (HIT) interacting with a free-surface. The reference length scale is the turbulence integral scale $\ell_0 = u_0^3/\varepsilon$ and the reference velocity scale, $u_0 = (2k_0/3)^{0.5}$, (ε is the turbulent dissipation rate and k_0 is the turbulent kinetic energy), resulting in a Taylor microscale, $\lambda = (15\nu\ell_0/u_0)^{0.5}$. The corresponding Reynolds, $\mathrm{Re}_\lambda = u_0\lambda/\nu$, Froude, $\mathrm{Fr}^2 = u_0^2/g\lambda$, and Weber, $\mathrm{We} = \rho u_0^2\lambda/\sigma$, numbers are $\mathrm{Re}_\lambda \approx 125$, $\mathrm{Fr}_\lambda^2 \approx 4.7$, and $\mathrm{We}_\lambda \approx 113$, respectively, with density and viscosity ratios of air water. HIT is sustained through linear forcing in physical space designed to maintain the Re_λ above. The forcing is attenuated from the bulk region to zero at $1.25\ell_0$ below the free-surface. After an initial transient, the flow becomes

*Contact author: balaras@gwu.edu

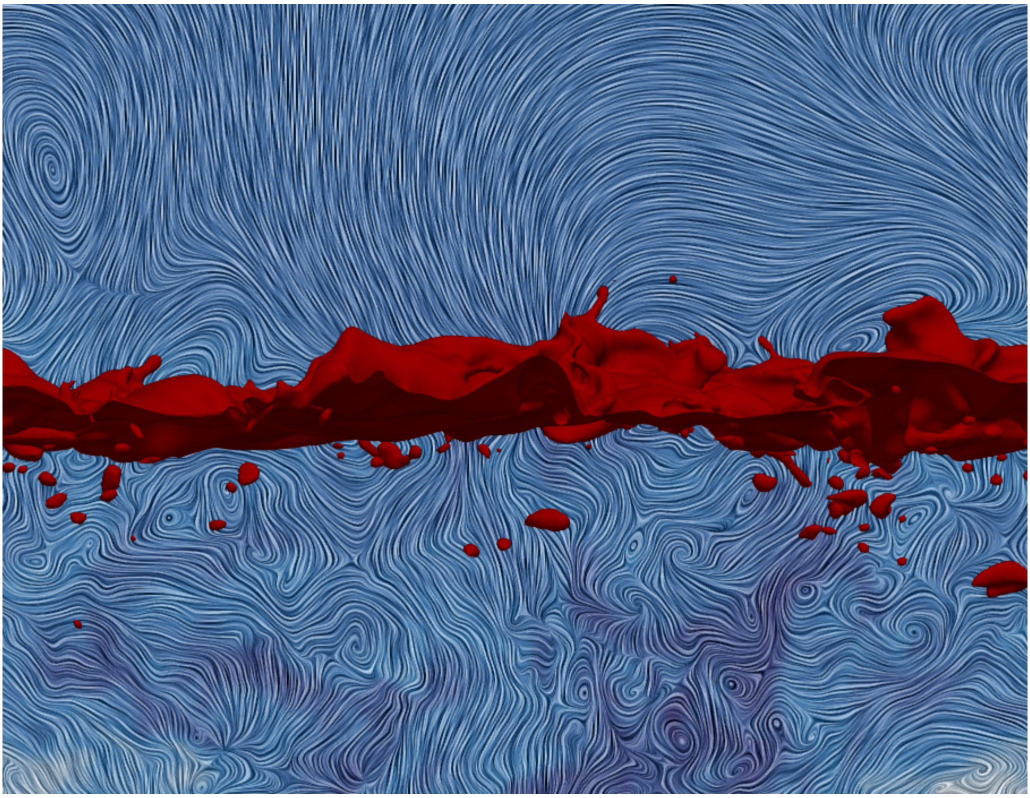

FIG. 1. Slice view of the turbulent velocity field with 3D interface shown in red. See [7].

statistically stationary which allows sampling over uncorrelated snapshots in time. The domain size is $5\ell_0 \times 5\ell_0$ in the horizontal plane, and $15\ell_0$ in the vertical direction, with $2.5\ell_0$ above the free-surface. The grid is uniform with a resolution of the order of the Kolmogorov scale $\eta = (\nu^3/\varepsilon)^{0.25}$.

An instantaneous view of the flow is shown in Fig. 1, with interface colored in red. Air entrainment is seen to occur below the free-surface, with a large number of bubbles present at any given time. Entrained bubbles below the free-surface are analyzed using multiple snapshots such as this one, which are uncorrelated in time. Distributions of bubble volume and surface area can be calculated from these datasets by first mapping the interface from a level-set contour into a triangulated surface, identifying disconnected regions (bubbles) and their centroid, and computing the volume of each bubble as a sum of the signed tetrahedral volumes defined from the surface triangles and the centroid [6]. These distributions are crucial for understanding the dynamics of air entrainment and for validating theoretical models, which are needed for the macroscopic characterization of gas-liquid mass and momentum transfer. In our simulations we observe that the entrained bubble sizes follow a $-10/3$ power law which is derived from dimensional analysis and has been verified in both experiments and computations in the literature.

In cases of strong free-surface turbulence, where both Froude and Weber numbers are large, the free-surface becomes notably wavy, with “scars” and entraining the air above [8]. This phenomenon is evident from a top view of the free-surface in Fig. 2, where the interface is highly deformed and complex due to the wide range of turbulent eddies under the free-surface. Understanding such surface deformations and their correlation to turbulent structures is key to improving models of air-sea interaction, wave dynamics, and other related phenomena.

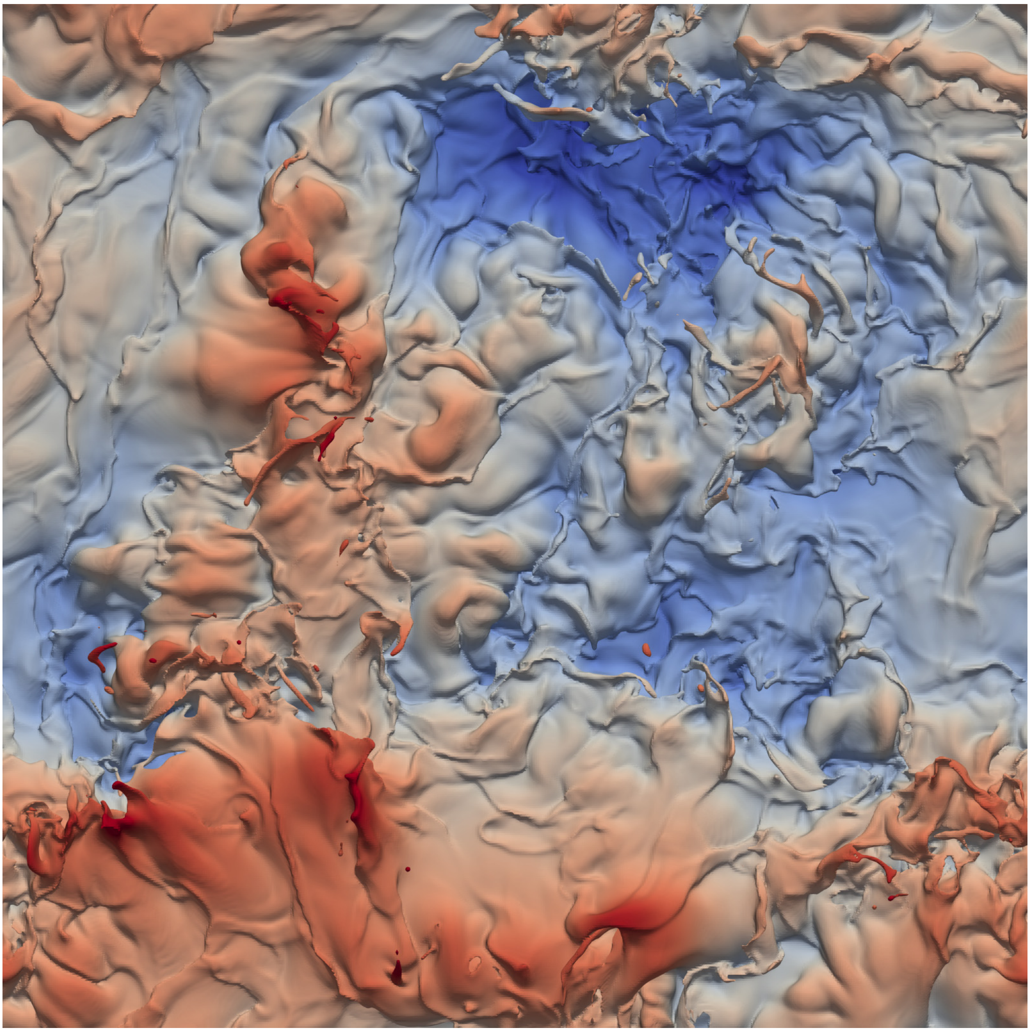

FIG. 2. Top view of deformed free-surface, colored by elevation.

Currently, most free-surface computations consider very large or infinite Weber numbers, and limited Re_λ, while experiments are limited to Earth's gravity and low Froude numbers. Investigating bubble entrainment and fragmentation at finite Weber number is important given the role of the Hinze scale, which splits the regime between larger bubbles which fragment from turbulence, and smaller bubbles which are stabilized by surface tension. In future work we intend to complement experimental campaigns by reducing the gap and achieving closer matching of the relevant dimensionless numbers. In conclusion, our DNS approach provides a powerful tool for understanding and modeling air entrainment in turbulent flows. The detailed insights gained from these simulations can help refine existing theoretical models and contribute to practical applications in marine and environmental engineering.

Financial support for this work is provided by the Office of Naval Research (ONR) Grant No. N00014-22-1-2639. The computational resources were provided by the Department of Defense High Performance Computing Modernization Program and by the Advanced Cyberinfrastructure

Coordination Ecosystem: Services & Support (ACCESS) program via allocation PHY230058 utilized on the Anvil cluster at Purdue University.

---

[1] H. Chanson, Air bubble entrainment in free-surface turbulent flows, Tech. Report No. CH46/95 (Department of Civil Engineering, The University of Queensland, 1995).

[2] L. Deike, Mass transfer at the ocean–atmosphere interface: The role of wave breaking, droplets, and bubbles, Annu. Rev. Fluid Mech. **54**, 191 (2022).

[3] Q. Gao, L. Shen, and G. B. Deane, A numerical simulation framework for bubbly flow and sound generation in laboratory-scale breaking waves, JASA Express Lett. **1**, 100801 (2021).

[4] N. Masnadi, M. A. Erinin, N. Washuta, F. Nasiri, E. Balaras, and J. H. Duncan, Air entrainment and surface fluctuations in a turbulent ship hull boundary layer, J. Ship Res. **64**, 185 (2020).

[5] E. M. Frederix, A. Mathur, D. Dovizio, B. J. Geurts, and E. M. Komen, Reynolds-averaged modeling of turbulence damping near a large-scale interface in two-phase flow, Nucl. Eng. Des. **333**, 122 (2018).

[6] S.-L. Lien and J. T. Kajiya, A symbolic method for calculating the integral properties of arbitrary nonconvex polyhedra; a symbolic method for calculating the integral properties of arbitrary nonconvex polyhedra, IEEE Computer Graphics Applications **4**, 35 (1984).

[7] A. Calado and E. Balaras, Submerged turbulence interaction with a free-surface, in *76th Annual meetting of the APS Division of Fluid Dynamics (November 19, 2023–November 21, 2023)* (APS, 2023).

[8] M. Brocchini and D. H. Peregrine, The dynamics of strong turbulence at free surfaces. part 1. description, J. Fluid Mech. **449**, 225 (2001).