Gallery of Fluid Motion

Direct numerical simulations of dilute gas transfer by breaking waves

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The gas exchange at the ocean-air interface is significantly enhanced by bubbles entrained by breaking waves [1,2]. When waves break at the ocean surface, air bubbles are entrained in the turbulent ocean water [3,4]. However, the precise contribution of mass transfer from bubbles in the ocean is not well understood [5]. Moreover, field measurements of the contribution by bubbles remain challenging. Separately, the developments of numerical methods and increased computational speed enabled researchers to perform direct numerical simulations (DNS) of breaking waves [3,6,7]. Furthermore, the numerical methods for gas transfer in multiphase flows are being developed [8–11] and scientists can investigate mass transfer problems across turbulent interfacial flows through DNS.

We approach the problem starting with the gas transfer from a single bubble [12]. The velocity gradient at the interface develops a boundary layer around the rising bubbles in the quiescent liquid that increases the diffusion of the gas. Figure 1(a) shows the concentration field of a rising bubble in quiescent liquid from DNS. A helical concentration wake following the trajectory of the bubble is seen. In our recent studies where a single bubble is subjected to homogeneous and isotropic turbulent flow [12], the mass transfer is enhanced by the presence of turbulent motion around the bubbles, with a thin boundary layer following the vorticity structure of the flow [Fig. 1(b)].

We perform DNS of a breaking wave similar to the configuration from [7] with the diffusion of a dilute gas (bubble volume remains constant). Figure 2 shows the concentration field of gas waves reaching a critical amplitude and breaking [Fig. 2(a)], a large envelope of air in entrapped and breaks [Figs. 2(b) to 2(d)] and bubbles are rising to the surface [Figs. 2(e) and 2(f)]. The total amount of gas exchanged in breaking waves is controlled by the individual bubble transfer rate and the residence time (or rise velocity) of the bubbles in the water, both modulated by turbulence.

This work paves the way for DNS of mass transfer in multiscale air-water turbulent flows. Furthermore, the complementary DNS investigation of these problems and experiments and direct measurements can significantly improve models predicting mass transfer in turbulent flows.

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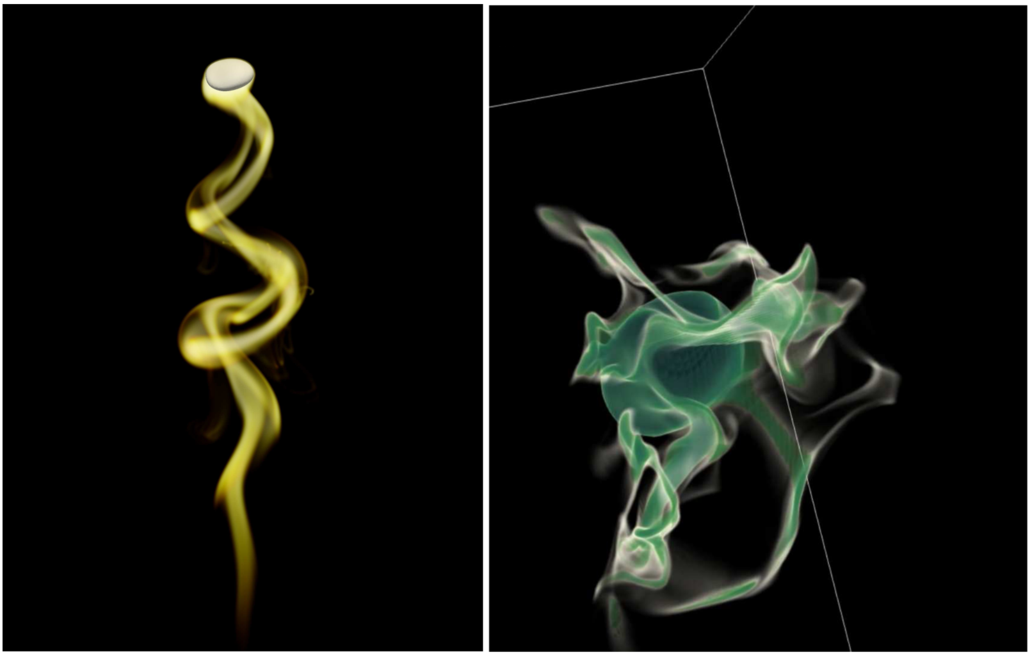

FIG. 1. Concentration field of a gas diffusing from (left) bubble rising in the quiescent liquid and (right) bubble subjected to homogeneous isotropic turbulent flow.

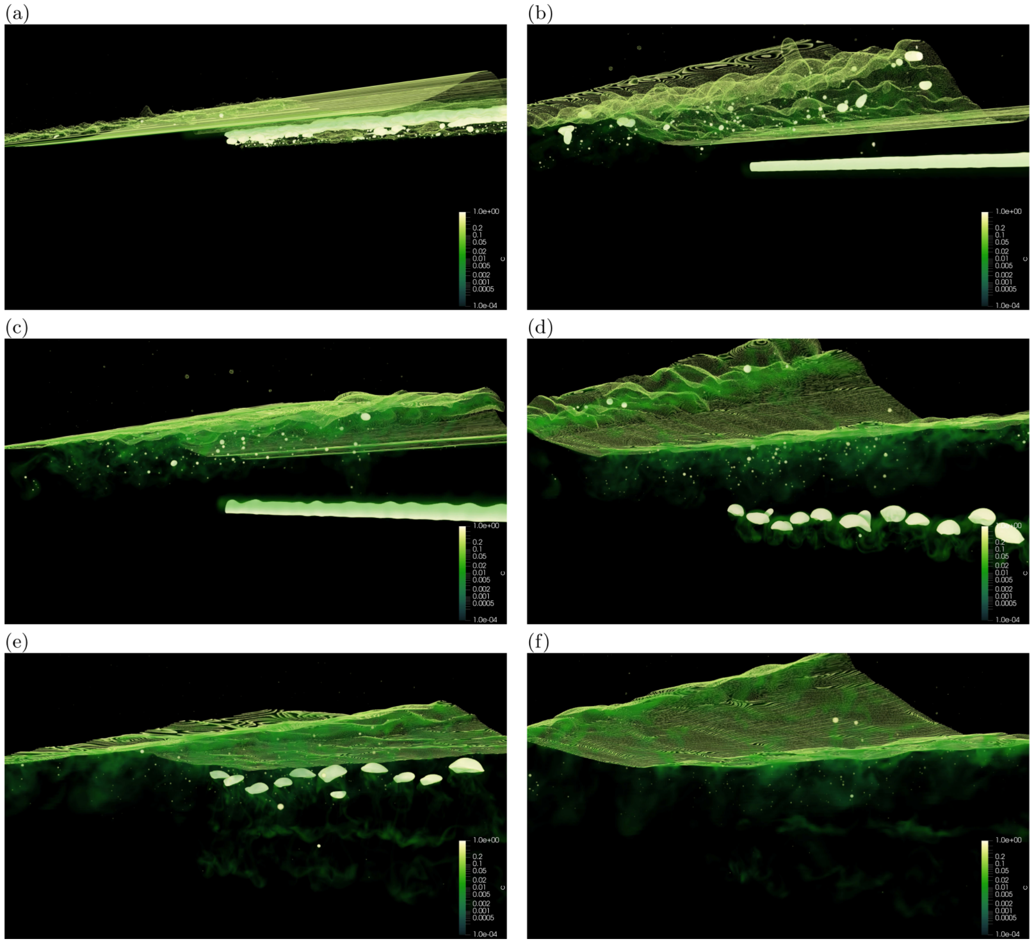

FIG. 2. Concentration field stills at different times of gas from direct numerical simulations of breaking wave using the BASILISK PDE solver [12,13]. See [14]. (a) $\tilde{t} = 1$, (b) $\tilde{t} = 1.43$, (c) $\tilde{t} = 1.68$, (d) $\tilde{t} = 2.05$, (e) $\tilde{t} = 2.5$, (f) $\tilde{t} = 3$.

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