**Plenary Lecture of MARINE 2025**

# Numerical Simulations of Wave Breaking Flows with Air Entrainment

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## Abstract

Wave breaking is a critical interfacial phenomenon with significant implications for ocean-atmosphere interactions and marine engineering systems. It is often accompanied by the entrainment of large volumes of air into water, forming white, aerated bubbly flows. This plenary lecture will present the persistent computational challenges associated with resolving air entrainment dynamics and multiphase interactions in violent wave breaking events. A novel numerical method developed based on a coupled Level Set and Volume of Fluid (CLSVOF) method will be presented to overcome the limitations of conventional interface-capturing approaches. The hybrid CLSVOF formulation ensures high-fidelity interface reconstruction while maintaining mass conservation, further enhanced by a mass-momentum consistent transport scheme to achieve physically accurate air–water momentum exchange. To handle the multi-scale characteristics of bubble dynamics and air entrainment, an adaptive mesh refinement (AMR) strategy is employed. This enables localized grid refinement near interfaces and in regions of high curvature, vorticity, and turbulent kinetic energy, thereby improving resolution where it is most needed. A series of benchmark cases are presented to validate the accuracy of the proposed numerical method, including plunging breakers in quiescent water, hydrofoil-induced free surface breaking in near-surface conditions, flows around a circular cylinder, and wedge-induced wave breaking, etc. These cases collectively demonstrate the method's accuracy, robustness, and versatility in capturing the complex behaviors of wave breaking and air entrainment. Furthermore, the simulations of plunging flat plates, transom stern flows, and bow wave breaking of the KCS container ship are presented to show the applicability of the proposed numerical method in realistic marine engineering problems. In these cases, the numerical results illustrate very well the key flow features such as surface wave deformation, air entrainment, bubble generation, and turbulent mixing, highlighting the great potential of the present numerical method for the understanding and prediction of wave breaking phenomena in marine hydrodynamics.

**Keywords:** Wave breaking flows, air entrainment, coupled level set and volume of fluid, adaptive mesh refinement, mass-momentum consistent transport