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Numerical simulations of turbulent thermal, bubble and hybrid plumes

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ABSTRACT

To understand the near-field dynamics of blowout plumes such as the one produced by the 2010 Deepwater Horizon oil spill in the Gulf of Mexico, the effects of gas bubbles on turbulent mixing and entrainment are studied via turbulence resolving simulations. We compare the evolution of three plumes where extremely large buoyancy anomalies are produced either thermally (single phase), solely by an imposed gas phase volume fraction, or by a combination of both buoyancy forcings. The plumes, with identical volume, momentum and buoyancy fluxes at the inlet, are released into an environment stratified with a constant temperature gradient. To clarify the first-order effects of dynamically active, dispersed bubbles, we employ a simple model which neglects the momentum of the gas phase while retaining bubble induced buoyancy in the seawater momentum equation. The gas phase is then distinguished by a single, measurable parameter, the slip velocity relative to that of the liquid phase. We find that bubbles, parameterized simply by a constant slip velocity, without any explicit assumptions of direct bubble induced turbulent production, significantly increase turbulent mixing in the plume in agreement with previous experimental results. Examination of mean momenta and turbulent kinetic energy budgets shows that the increased turbulence is due to direct modification of the mean profiles of both the momentum and the active scalar fields by the slipping gas phase. The narrowing of the active scalar field in the two-phase flow results in larger direct buoyancy production of turbulent energy at all vertical levels. The turbulence production is, however, primarily mechanical. At modest values of z/D, where the slip velocity is only a small fraction of the liquid phase velocity, slip stretches the mean vertical velocity field producing larger radial gradients and increased conversion of mean to turbulent energy. This first order effect, acting on the mean vertical velocity component and not directly on the turbulence, implies that even relatively small gas volume fractions significantly enhance turbulent mixing with respect to a single phase plume.

1. Introduction

This work, motivated by the 2010 Deepwater Horizon (DwH) incident in the northern Gulf of Mexico, focuses on modeling and simulating the near-field region of flows driven by the extreme buoyancy fluxes typical of deep water oil well blowouts (Camilli et al., 2010). Deepwater blowout plumes are formed by the sustained point release of a hot, multiphase wellhead mixture through the riser pipe. The resulting buoyancy flux, released into a stratified fluid, was thermally equivalent to $B_0 = \mathcal{O}(1\ \mathrm{GW})$ in the Deepwater Horizon case (McNutt et al., 2011). The magnitude of the buoyancy anomaly, sustained over a period of months, and the extremely large range of spatial scales involved (0.5 m source at 1500 m depth) implies that these multiphase plumes are far from realizable laboratory conditions (Lima Neto, 2012). The extremely large, sustained buoyancy fluxes also imply that the wellhead convection problem has the potential to dynamically alter the larger scale, rotating and stratified environment.

The DwH release underscored the need for rapid and informed response to such events. An integral part of that response is the prediction of both the distribution of hydrocarbon effluent throughout the water column and the eventual form of its expression at the ocean

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surface. Since the near-field turbulent entrainment plays a critical role in the evolution of the plume buoyancy, mass and momentum fluxes, understanding and modelling *multiphase* plume dynamics in the vicinity of the release is potentially critical to accurate prediction of the near-surface pollution transport problem over of the *last mile*, where the spill encounters the public. The inlet buoyancy flux generates a strongly turbulent buoyant plume in which sea water entrained from the environment is mixed with the plume core fluids as they move along the water column. The evolution of the plume is strongly affected by the level of turbulent mixing and entrainment in the near-field with the 'entrainment coefficient' being the main parameter in classic integral solution approaches (Morton et al., 1956). It is well-known that the presence of a gas phase changes the turbulent transport properties, with bubble plumes typically exhibiting larger turbulence levels (McDougall, 1978; Milgram, 1983). There are distinct differences in the along-column effluent distribution in single and multiphase cases (Asaeda and Imberger, 1993; Lemckert and Imberger, 1993). The effects of bubbles on turbulent dynamics are studied here by comparing plumes distinguished only by the phase distribution of the (fixed) inlet buoyancy flux, either thermal (single phase) or due to the presence of gas (multiphase).

Modeling in complete, accurate detail, the physicochemical dynamics of the high pressure release of hot, multicomponent, multiphase effluent into a stratified, turbulent ocean environment is beyond our present theoretical and computational abilities. As in the case of the DwH incident, both short and intermediate term prediction and analysis of any future event will rely on simplified models for which there is existing literature. How the validity of underlying assumptions and the values of explicit parametrizations in simplified models change when such models are scaled up from the laboratory to the environment requires careful examination of the many physical and chemical processes involved.

Given their environmental and industrial importance, buoyant plumes have been the focus of considerable study. Schmidt (1941) presented an earlier dimensional analysis of thermal plumes, and the problem has attracted the attention of Batchelor (1954), Morton et al. (1956), Turner (1973; 1969) and others. Many of these efforts represent the depth dependence bulk plume measure, like momentum and buoyancy flux, in terms of the basic system parameters. Turner discusses several laboratory experiments in support of the scaling laws. List and Imberger (1973) is an early reference on plumes in stratified environments, pointing out the creation of intrusion layers. McDougall (1978) performed perhaps the first experiments of two phase convective systems, discussing the presence of dual plumes. Classification of bubble plume experiments and observations appear in Lemckert and Imberger (1993), Socolofsky et al. (2002) and Socolofsky and Adams (2005). Classical modeling efforts directed at oil spill prediction have been posed as a Lagrangian problem, in which integral plume measures, like momentum flux and centerline trajectory were computed (Zheng and Yapa, 2003). These have been tested against laboratory and limited field experiments and have demonstrated skill. In all cases, the equations are closed by relating the turbulent radial flux to the characteristic mean vertical velocity via an entrainment coefficient (Morton et al., 1956). Enhanced turbulent mixing of vertical momentum due to multiphase physics is typically modelled by a larger momentum amplification factor, reducing the vertical momentum growth rate in comparison to single phase plumes.

The goal of the present work is to understand and quantify, in the context of turbulence resolving simulations, basic physical properties of plumes driven by the extreme values of the expected buoyancy flux in a deepwater blowout. This fills a significant gap in our present knowledge of deep spills, specifically the role played by the gas in increasing the turbulent mixing. The DwH blowout involved both oil and gas escaping from the well head (McNutt et al., 2011). As a first step, we isolate the effect of bubbles on the turbulence by considering idealized situations where admittedly important physicochemical phenomena (hydrate formation, dissolution or biodegradation) are neglected and the input buoyancy is due solely to thermal and gas contributions. Given that it is not possible in such incidents to determine the exact proportions of oil and gas involved at specific instances or periods, we explore distinctions in the turbulent behavior of plumes produced by varying the relative importance of the inlet gas buoyancy contribution. Such idealized cases are closer to the flow configuration used in most experimental studies of bubble plumes but differ significantly in the magnitude of the inlet buoyancy flux. Moreover, to our knowledge there are no experimental observations of the combined effects of thermal and gas sources. Laboratory experiments of bubble and oil plumes face a number of challenges. Usually the tank size is limited in the vertical direction and the reflection of the plume from the upper boundary can change the flow field significantly. Due to box-filling problems, limited tank size necessarily limits both the inlet oil flux and the overall time scales of experiments. To attain flows that are highly turbulent, nozzle sizes used in the laboratory are typically on the order of a few millimeters. Even then, the observation period for measurements is typically minutes (Brandvik et al., 2013; Johansen et al., 2013). It is unclear how representative plumes from such small nozzles are for the real oceanic case. Finally, we are not aware of laboratory experiments of hybrid (bubble and oil) plumes and highly-parameterized models do not allow direct exploration of the details of the turbulent behavior in such cases.

Computationally, significant efforts have been devoted to the study of multiphase plumes at oceanographic scales in the context of CO_2 sequestration (Alendal and Drange, 2001; Sato and Sato, 2002). These studies emphasize the effects of physico-chemical phenomena on overall plume behavior using standard eddy-viscosity and eddy-duffusivity models to account for turbulent transport. Characterization of the differences in the turbulent mixing between single and multiphase plumes requires explicit resolution of finer scale motions. This is particularly important for plumes where differences in near-field turbulent entrainment processes significantly influence far field behavior and, consequently, the overall distribution of effluents in the water column including the fraction of effluent reaching the ocean surface.

While complete spatial and temporal descriptions via direct numerical simulations are typically unfeasible even for laboratory scale plumes, large-eddy simulations (LES) of bubble plumes have been conducted (Buscaglia et al., 2002; Deen et al., 2001; Niceno et al., 2008) using finite-difference or finite-volume discretizations to explicitly resolve the largest, most energetic scales while parametrizing sub-grid scales by Smagorinsky models. In this work the approach is slightly different: instead of low-order spatial discretizations, we use high-order spectral element methods characterized by exponential convergence. In lieu of explicit Smagorinsky models, the specifics of which are still uncertain for bubbly flows (Dhotre et al., 2013), we adopt an alternate approach based on spectral filtering (Karamanos and Karniadakis, 2000; Koal et al., 2012). Progressive filtering of the highest modes of the Legendre polynomial approximations is equivalent to a hyperviscosity subgrid-scale model whose influence is explicitly confined to near-grid scale processes (Boyd, 1998; Fischer and Mullen, 2001). This approach has been shown to maintain spectral accuracy with increasing resolution and provide resolution independent solutions. The computational efficiency afforded permits the explicit resolution of a larger range of spatial scales.

For large-scale plumes, adequate turbulence resolution, in reasonable time, on available computational resources requires both limiting the vertical extent of the domain and simplifying the full multiphase equation set. Starting from the conservation equations for multiphase systems, following (Sokolichin et al., 2004), we derive a simplified, Boussinesq model by neglecting the momentum carried by the gas which is much smaller than that of the liquid phase. Even with