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Behavior and dynamics of bubble breakup in gas pipeline leaks and accidental subsea oil well blowouts

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ABSTRACT

Subsea oil well blowouts and pipeline leaks release oil and gas to the environment through vigorous jets. Predicting the breakup of the released fluids in oil droplets and gas bubbles is critical to predict the fate of petroleum compounds in the marine water column. To predict the gas bubble size in oil well blowouts and pipeline leaks, we observed and quantified the flow behavior and breakup process of gas for a wide range of orifice diameters and flow rates. Flow behavior at the orifice transitions from pulsing flow to continuous discharge as the jet crosses the sonic point. Breakup dynamics transition from laminar to turbulent at a critical value of the Weber number. Very strong pure gas jets and most gas/liquid co-flowing jets exhibit atomization breakup. Bubble sizes in the atomization regime scale with the jet-to-plume transition length scale and follow −3/5 power-law scaling for a mixture Weber number.

1. Introduction

During an oil spill in the ocean, the size distributions of gas bubbles and oil droplets are key variables that control both the transport of bubbles and droplets, through their independent rise velocity and their advection with the ambient mean flow and turbulence, and their rates of transformation by dissolution, volatilization, and photodegradation and biodegradation (Yapa et al., 2010; North et al., 2015; Wang and Adams, 2016). In the case of an oil well blowout, such as the Deepwater Horizon (DWH) accident, bubbles and droplets form near the orifice of the release under conditions of high discharge velocity, temperature, and local ambient pressure (Spaulding et al., 2015; Socolofsky et al., 2016). Smaller bubbles and droplets have longer residence times and experience greater interfacial mass transfer (e.g., dissolution and surface-film biodegradation) in the ocean water column owing to their smaller rise velocities and greater surface area to volume ratio compared to larger particles. Adding to this complexity is the role of intervention, which can affect the bubble and droplet size distributions by injection of chemical dispersants at the source, as was done during the DWH to reduce the initial oil droplet size distribution and thereby enhance subsea dissolution, dispersion, and subsequent biodegradation (Socolofsky, 2015; Spaulding et al., 2015). The oil droplet size distribution is thus of crucial importance for the fate and transport of oil, and various works have emerged recently to predict it (Johansen et al., 2013; Zhao et al., 2014; Li et al., 2017a,b). The prediction of the initial oil droplet size distribution is one of the key components in oil spill models, e.g., CDOG (Yapa and Zheng, 2001; Chen and Yapa, 2003; Zheng et al., 2003), DeepBlow (Johansen, 2000), OILMAP DEEP (Spaulding et al., 2015, 2017), and others.

Gas bubbles are expected to be present in an oil well blowout, for instance, in the dramatic ROV videos captured at the gushing wellhead during the DWH accident. The presence of these gas bubbles may also affect the oil droplet sizes (Johansen et al., 2013; Belore, 2014). Compared to oil droplets, the size distribution of gas bubbles from underwater blowouts has attracted less attention. Early models used oversimplified assumptions for gas bubble sizes such as uniform diameters. These uniform diameters are largely set equal to the maximum stable bubble sizes or to observations from limited field experiments, e.g., DeepSpill (Zheng et al., 2003; Johansen, 2000; Johansen et al., 2003). Some recent model developments considered the bubble sizes in subsurface blowouts using more sophisticated approaches (Zhao et al., 2016). Li et al. (2017a) proposed a new scaling relationship for the sizes of oil droplets and suggested that this relationship is also valid for gas bubbles; however, there remains a lack of validation data to test these

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models for bubble sizes.

This paper presents laboratory observations of the flow behavior near the orifice of a submerged air jet and measurements of the asymptotic bubble size distribution. We also include literature data for jets containing co-flowing of gas and liquid phases. The aim of this paper is to develop a scaling law for characteristic gas bubble sizes in turbulent flows as the result of gas pipe leaks or oil well blowouts. This work is important to develop models of bubble breakup in these types of subsea accidents, which are needed to both predict the fate and transport of petroleum compounds in the water column and to assess the effectiveness of subsea intervention through dispersant injection during an accidental blowout.

Numerous studies have investigated the breakup dynamics of drops and bubbles in both turbulent flows and quiescent conditions (e.g., Hinze, 1955; Grace et al., 1978; Martinez-Bazan et al., 1999; Eastwood et al., 2004; Solsvik et al., 2016). Among those studies, the breakup dynamics in subsea oil well blowouts is unique. In a subsea blowout jet, the jet itself releases large fluxes of momentum and mass that enter a relatively calm ambient water, and the breakup of drops and bubbles evolves with time as these fluids propagate away from the leak. There are two main approaches to predict gas and oil breakup in a blowout jet. The first approach relies on physics-based numerical models that have been developed to solve the population balance for the mass of fluid particles (whether gas bubbles or oil droplets) in different size classes as a function of distance from the orifice (Zhao et al., 2014; Nissanka and Yapa, 2016; Zhao et al., 2016). Advantages of this approach are that it considers the forces responsible for breakup at the particle level, where processes may be expected to be scale independent, and that it solves directly for the particle size distribution without any assumption about the statistical form of the distribution. The second approach for predicting the size of oil droplets in a blowout jet relies on empirical equations that predict characteristic scales of the particles size distribution based on the dominant non-dimensional parameters controlling the breakup (Johansen et al., 2013; Li et al., 2017a,b). These equations may also include a physics-based theory through scaling laws. These equations with the estimated parameter values based on fitting to data are most reliable for prediction when used over a similar scale to the orifice size used for the calibration. In the case of jet breakup, most of the available observations are for the oil droplet phase in pure oil jets, except for the DeepSpill experiment, and the governing non-dimensional parameters in the laboratory are usually smaller than those expected at the field scale (Socolofsky, 2015).

Following the Deepwater Horizon accident, new experimental data and empirical models compared to these data have improved the understanding of the breakup process for oil droplets. For instance, Brandvik et al. (2012, 2013) reported on a series of experiments for an oil jet into water without and with dispersant injection in the SINTEF Tower Basin facility. Johansen et al. (2013) proposed an empirical equation based on Weber number scaling to predict the measured data in Brandvik et al. (2013). This scaling is developed from the original theory of particle breakup in turbulent flows proposed by Hinze (1955). By dimensional analysis in the cases without dispersant injection, the scaling equation gives $d_{50}/D = A' We_p^{-3/5}$, where d_{50} is the volume median droplet diameter, D is the jet orifice diameter, A' is an empirical coefficient, and $We_p = \rho_p U_E^2 D/\sigma$ is the Weber number; ρ_p is the density of the dispersed phase, U_E is the exit velocity of the oil jet, and σ is the interfacial tension between the oil and water. Here, we use the notation following Clift et al. (1978) that a subscript p denotes the property of a dispersed-phase particle (bubble or droplet), and variables without a subscript denote properties of the continuous phase (the ambient water).

The Weber number correlation reflects the fact that breakup is a balance between destructive forces due to the turbulent kinetic energy of the flow and resisting forces due to surface tension. When dispersants are added, σ is reduced, generating smaller droplets for the same discharge. However, as the interfacial tension drops, viscosity begins to dominate the resistance to breakup, and Johansen et al. (2013) use the viscosity number $Vi_p = \mu_p U_E/\sigma = We_p/Re_p$ to capture this effect, where μ_p is the dynamic viscosity of the oil and $Re_p = \rho_p U_E D/\mu_p$ is the Reynolds number at the jet orifice. This resulted in the so-called modified Weber number (Hinze, 1955; Calabrese et al., 1986) which allowed researchers to capture the contribution of both surface tension and droplet viscosity in resisting droplet breakup. In Johansen et al. (2013), the focus was on relatively light and medium oils, and thus their equation allowed collapsing of the data for pure oil jets without and with dispersant injection:

$$\frac{d_{50}}{D} = A\left[\frac{We_p}{1 + BVi_p(d_{50}/D)^{1/3}}\right]^{-3/5} = AWe_p^{*-3/5} \tag{1}$$

where A and B are empirical coefficients that are determined from the experimental data. Johansen et al. (2013) determined $A = 15.8$ and $B = 0.8$; whereas, Brandvik et al. (2012) found $A = 24.8$ and $B = 0.08$ by calibrating to a larger dataset. Thus, the Weber number scaling law captures the competing effects of turbulent breakup with interfacial tension and viscosity resisting breakup, where the model coefficients must be evaluated by comparison to measured data.

A recent scaling relationship proposed by Li et al. (2017a,b) suggests that the droplet sizes should be scaled with the Rayleigh-Taylor instability maximum diameter d_o when it is smaller than the orifice diameter D:

$$\frac{d_{50}}{d_s} = r(1 + 10Oh_{p,s})^p We_s^q \tag{2}$$

where d_s is the smaller value between D and d_o; the Weber number We_s and the Ohnesorge number $Oh_{p,s}$ are defined using d_s: $We_s = \rho U_E^2 d_s/\sigma$; $Oh_{p,s} = \mu_p/\sqrt{\rho_p \sigma d_s}$; r, p, and q are numerical parameters determined from data.

These scaling laws have been validated to oil droplet breakup, but the applicability of these equations for predicting gas bubble sizes is questionable. Gas has a lower density than oil, therefore, it carries less momentum and more buoyancy per unit volume if discharged with the same exit velocity as oil from a subsurface jet. The lower momentum flux may induce less turbulence in the entrained ambient water than for an equivalent oil jet. Likewise, the large buoyancy flux of a gas discharge will behave more like a plume, which has a different scaling relationship for turbulent dissipation rate as a function of distance from the nozzle than for a pure jet (Zhao et al., 2015, 2016). In addition, gas is more compressible than liquid oil and will expand after release when a large pressure drop is experienced across the orifice. The expanding gas may lead to different bubble sizes than predicted by Eqs. (1) or (2) and may also change the instability mechanism controlling the jet breakup into gas bubbles. When dispersant is injected with the gas/oil mixture, the effectiveness of dispersant to the oil may be reduced by the presence of gas bubbles (Belore, 2014; Ross, 2014). Finally, when gas plus oil are co-released in a subsea blowout (such as DWH), the presence of the gas provides an additional phase that involves a full suite of parameters parallel to oil (e.g., density, surface tension, and viscosity of the gas) (Zhao et al., 2017). As a result the controlling non-dimensional numbers (e.g., the Weber number) in the breakup equations may need adjustment due to the involvement of the gas phase. For instance, Johansen et al. (2013) corrected the exit velocity of the oil using the void fraction (accounting for the volume of gas constricting the orifice) and Froude number (correcting for the plume effect of the gas buoyancy) in the Weber number scaling. Yet, this correction has only been validated to predict oil droplet sizes for measurements in the DeepSpill field experiment (Johansen et al., 2001) and in laboratory experiments by SINTEF in their TowerBasin and at the Southwest Research Institute (SwRI) hyperbaric chamber (Brandvik et al., 2017). Hence, a comprehensive study of the gas bubble breakup process is presently lacking, and models to predict gas bubble sizes may not be equivalent to the existing non-dimensional number correlations (Eqs. (1) and (2)).