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Droplet breakup in subsea oil releases – Part 2: Predictions of droplet size distributions with and without injection of chemical dispersants

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ABSTRACT

A new method for prediction of droplet size distributions from subsea oil and gas releases is presented in this paper. The method is based on experimental data obtained from oil droplet breakup experiments conducted in a new test facility at SINTEF. The facility is described in a companion paper, while this paper deals with the theoretical basis for the model and the empirical correlations used to derive the model parameters from the available data from the test facility. A major issue dealt with in this paper is the basis for extrapolation of the data to full scale (blowout) conditions. Possible contribution from factors such as buoyancy flux and gas void fraction are discussed and evaluated based on results from the DeepSpill field experiment.

1. Introduction

The size distribution of oil droplets formed in deep water oil and gas blowouts is known to have strong impact on the subsequent fate of the oil in the environment (Johansen, 2003). Deep water blowouts are more sensitive to crossflow and ambient density stratifications than blowouts in moderate to shallow water. This is due to reduced buoyancy caused by the strong compression of the gas in deep water, together with other factors such as non-ideal gas behavior and the potential for a substantial fraction of gas dissolved in the oil phase. In blowouts from moderate to shallow depths, the large buoyancy generated by the expanding gas will in general bring the plume of entrained water to the sea surface together with dispersed oil droplets and gas bubbles. A relatively homogeneous thin surface oil slick will then form as the dispersed oil droplets settles out of the outward flow of the surfacing entrained water. A deep water plume (with small buoyancy) is more likely be trapped by the ambient density stratification or bent over by crossflow. In both cases, gas bubbles and oil droplets will separate from the plume and rise to the surface with their own terminal velocities. Large droplets will rise relatively rapidly and come to the surface relatively close to the discharge location, while small droplets will rise more slowly and can be transported long distances from the discharge location with ambient currents before reaching the sea surface. The smallest droplets may even be kept suspended in the water masses for prolonged time periods by vertical oceanic turbulent mixing, subject to enhanced dissolution and natural biodegradation. Releases which are predominantly producing large oil droplets (in the millimeter size range) may thus result in relatively thick surface oil slicks, while thin surface films may be expected from releases producing small droplets (micrometer range). Thin oil films may not form water-in oil emulsions and will thus be more susceptible to natural dispersion. This implies that films will have distinctly shorter persistence on the sea surface than thicker oil slicks, and the possibility of oiling of adjacent shorelines may thus be strongly reduced.

Reliable predictions of the droplet size distribution in deep water blowouts will thus improve our ability to forecast the fate of oil in the environment, provide guidance for oil spill response operations and relevant information to the public. Presently, the only available experimental droplet size data at near full scale was obtained in the DeepSpill experiment conducted at 844 m in the Norwegian Sea (Johansen et al., 2003). These limited observations have formed the basis for a Weber number scaling based prediction method for droplet size that are used in many deep water blowout models today (Chen and Yapa, 2007). Other studies of oil droplet breakup have been conducted at a much smaller scale (Masutani and Adams, 2000; Tang and Masutani, 2003), but extrapolation of such small scale results to larger scales are doubtful. However, more recently, SINTEF has initiated laboratory studies of oil droplet breakup in a meso-scale test facility, comprising a cylindrical tank with a height of 6 m and a diameter of 3 m. This test facility is presented in a companion paper, with a description of the experimental setup and examples of findings from oil only experiments and experiments with injection of chemical dispersants (Brandvik et al., in press). In this paper, we present a new model for prediction of initial droplet size distributions in subsea oil and gas releases that has been derived from the experimental

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data presented in the companion paper, supported by findings from a review of theoretical aspects of droplet breakup.

2. Theory

2.1. Droplet breakup regimes

Droplet breakup may be caused by different mechanisms depending on the properties of the fluid and the outlet conditions, ranging from pendant droplets that separate from the nozzle when the buoyant forces outrange the interfacial tension forces, through various axial or transverse instabilities of the jet, to full atomization where droplets of a wide size range are generated almost instantaneously at the jet exit.

The full range of breakup regimes of oil jets in water were investigated in laboratory experiments reported by Masutani and Adams (2000) and Tang and Masutani (2003). As previously observed from breakup experiments with liquid jets in air, Masutani et al. found that the breakup regimes of oil jets in water could be delimited in a Reynolds number (Re) vs Ohnesorge number (Oh) diagram. The two non-dimensional numbers are defined as $\mathrm{Re} = \rho U D/\mu$ and $\mathrm{Oh} = \mu/(\rho\sigma D)^{1/2}$, where U is the exit velocity, D the orifice diameter, σ is the interfacial tension (oil–water), and ρ and μ are the density and dynamic viscosity of the jet fluid. The Ohnesorge number is a combination of the Reynolds number and the Weber number, i.e. $\mathrm{Oh} = \mathrm{We}^{1/2}/\mathrm{Re}$, where $\mathrm{We} = \rho U^2 D/\sigma$. The boundaries between laminar and transitional breakup and the boundary between the transitional and turbulent (atomization) breakup regimes were found to represent linear relationships of the form $\mathrm{Oh} = c\,\mathrm{Re}^{-1}$, where c is a constant of proportionality. From the definition of Ohnesorge number mentioned above, this relationship implies that both boundaries are lines for constant Weber number, with $\mathrm{We} = c^2$. For the boundary between the transitional and turbulent breakup regime, the constant was found to be 18, implying that $\mathrm{We} = 18^2 = 324$.

In the present study, where the main focus is on turbulent breakup, these findings were useful as a basis for limiting the experimental conditions for the breakup experiments.

Fig. 1 shows how the Ohnesorge vs. Reynolds number diagram can be used to delimit the range of discharge conditions. The parallelogram formed grid in the diagram depicts a range of possible orifice diameters and oil flow rates that might be used in the tower tank experiments. The orifice diameters are here limited to the range from 0.5 to 20 mm, with oil flow rates in the range from 0.1 to 20 L/min. The thick solid line drawn in the diagram shows the boundary between the transition regime and the turbulent breakup (or atomization) regime. The preferred range of experimental conditions is shown with crossed markers. Some of the cases in the turbulent breakup regime that will produce high outlet velocities (>40 m/s) are also left out. These cases could be difficult to realize due to high pressure loss in the oil supply line.

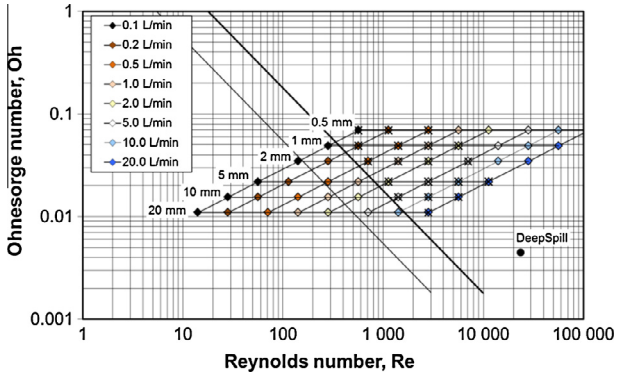

Fig. 1. Possible experimental conditions plotted in an Ohnesorge vs. Reynolds number diagram. Injection rate varied from 0.1 to 20 L/min, with nozzle diameters varied from 0.5 to 20 mm. Oil viscosity is presumed to be 5 cP. The thick line in the diagram shows the boundary between transitional and atomization breakup. Approximate location of the DeepSpill experiment is shown for comparison.

2.2. Weber number scaling

The classical theory of droplet splitting in stationary turbulence predicts a maximum stable droplet size d_{max} given by the equation

$$d_{max} = a(\sigma/\rho)^{3/5}\varepsilon^{-2/5} \tag{1}$$

where a is a constant of proportionality, ρ is the density of the continuous phase (water), and ε is the turbulent dissipation rate (Hinze, 1955).

However, in a turbulent round jet, the turbulent dissipation rate ε decreases with the distance from the nozzle exit. Thus, during the time needed for the droplets to finish its break up process, they will be transported to regions with decreasing values of ε. Still, Hinze's model may serve as a starting point for experimental design and development of more practical empirical equations. According to Martines-Bazán et al. (2002), Eq. (1) can be used to define a critical droplet size based on the local (downstream) value of ε in the turbulent jet. They argue that the break up process will be completed at the downstream distance X' where the breakup has reduced the local maximum droplet size to this value. By taking into account that the dissipation rate in a turbulent round jet scales with the relative downstream distance X/D and the exit dissipation rate $\varepsilon_0 \sim U^3/D$, the corresponding equation for d_{max} can be expressed as $d_{max}/D = A\,\mathrm{We}^{-3/5}$. Here A is an empirical factor depending on the relative break up length X'/D, and $\mathrm{We} = \rho U^2 D/\sigma$ is the exit Weber number. It should be noted that a Weber number scaling is also predicted by simple dimensional analysis based on the governing variables U, D, ρ and σ, but this will leave the exponent in the power law unknown (to be determined experimentally). It should also be noted that the maximum diameter can be substituted by any chosen characteristic diameter (e.g. the volume median diameter d_{50}) by an appropriate choice of the empirical factor A. So far, we have no guarantee that this factor is a constant, but empirical data will show if this is a reasonable assumption.

This scaling law is supposed to be valid when the breakup is limited by the interfacial tension of the jet liquid. However, as Hinze (1955) also pointed out, internal viscous stresses in the fluid droplets may also influence the breakup. Hinze introduced a dimensionless viscosity group N_{Vi} to account for this effect. Hinze's viscosity group is actually identical to the Ohnesorge number defined above. More recently, Wang and Calabrese (1986) proposed to replace Hinze's viscosity group by the viscosity number $\mathrm{Vi} = \mu U/\sigma$ to account for the effect of viscous stresses. This dimensionless number is also defined in terms of the Weber number and the Reynolds number, i.e. $\mathrm{Vi} = \mathrm{We}/\mathrm{Re}$.

The same authors found that droplet breakup was governed by the Weber number scaling for small viscosity numbers ($\mathrm{Vi} \to 0$), but that a Reynolds number scaling would apply for large viscosity number ($\mathrm{Vi} \gg 1$):

$$d_{max}/D = C\,\mathrm{Re}^{-3/4} \tag{2}$$

They derived a semi-empirical equation for the intermediate case, where both interfacial tension and viscous forces are influencing droplet breakup:

$$d_{50}/D = A\,\mathrm{We}^{-3/5}[1 + B\,\mathrm{Vi}(d_{50}/D)^{1/3}]^{3/5} \tag{3}$$