

RESEARCH

DeepBlow – a Lagrangian Plume Model for Deep Water Blowouts

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This paper presents a sub-sea blowout model designed with special emphasis on deep-water conditions. The model is an integral plume model based on a Lagrangian concept. This concept is applied to multiphase discharges in the formation of water, oil and gas in a stratified water column with variable currents. The gas may be converted to hydrate in combination with seawater, dissolved into the plume water, or leaking out of the plume due to the slip between rising gas bubbles and the plume trajectory. Non-ideal behaviour of the gas is accounted for by the introduction of pressure- and temperature-dependent compressibility z -factor in the equation of state. A number of case studies are presented in the paper. One of the cases (blowout from 100 m depth) is compared with observations from a field experiment conducted in Norwegian waters in June 1996. The model results are found to compare favourably with the field observations when dissolution of gas into seawater is accounted in the model. For discharges at intermediate to shallow depths (100–250 m), the two major processes limiting plume rise will be: (a) dissolution of gas into ambient water, or (b) bubbles rising out of the inclined plume. These processes tend to be self-enforcing, i.e., when a gas is lost by either of these processes, plume rise tends to slow down and more time will be available for dissolution. For discharges in deep waters (700–1500 m depth), hydrate formation is found to be a dominating process in limiting plume rise. © 2000 Elsevier Science Ltd. All rights reserved.

Introduction

The *DeepBlow* model presented in this report has been developed with a support from the Norwegian deep-sea program (NDP), which was organised by the Norwegian oil companies engaged in deep-sea exploration drillings in Norwegian waters (water depths from 700 to more than 1350 m). For the more recently developed oil fields in the Norwegian Sea, depths are in the range from 250 to 350 m, while most of the oil fields in the central parts of the North Sea are located in depths of about 100 m. SINTEF's earlier BLOW model (Rye, 1994) was developed for applications in this depth range. Motivated by the planned deep water explorations in Norwegian waters, SINTEF, with support from NDP, conducted a literature study on deep water processes to investigate the need for improvements in this model (Johansen, 1997). The major findings from this study are summarised below.

For blowouts at shallow to moderate depths the gas may be considered as an ideal gas with a specific volume decreasing linearly with pressure. The volume flux of gas at any depth may be then derived from the

gas-to-oil volume ratio at standard conditions (GOR). However, when the blowout takes place at greater depths, the gas can no longer be assumed to behave as an ideal gas, and the pressure and temperature dependent compressibility factor (z -factor) must be introduced in the pressure–volume relationship (McCain, 1990). Normally, this will imply that the specific volume of the discharged gas will be less than predicted by the ideal gas law. Secondly, the fraction of gas dissolved in the oil will increase with pressure. This implies that the gas mass fraction of the well flow at the outlet will be reduced compared to the gas mass fraction predicted by the GOR. Together, these factors will cause a significant reduction in buoyancy flux, and as a consequence, the plume may become more sensitive to cross-currents and the presence of density stratification in the water masses.

Dissolution of gas from rising bubbles into ambient water may be negligible for blowouts at shallow to moderate depths, since the residence time of the gas bubbles are expected to be short. In deep waters, the rise time of the gas bubbles will be significantly longer. Since the solubility of the gas will also be high due to

high ambient pressures (Fogg & Gerrard, 1991), dissolution of gas in seawater may be expected to cause a significant reduction in the buoyancy flux. In addition, the natural gas tends to form gas hydrates at elevated pressures and low temperatures (Maini & Bishop, 1981; Sloan, 1990). Thus, when a blowout takes place at larger depths, the gas may be converted to hydrate in contact with cold bottom water. If that happens, then the contribution of the gas to the buoyancy flux will vanish, and the considerably smaller buoyancy caused by gas hydrates and oil will instead drive the rise of the plume.

In such cases, even small stable density gradients in the ambient water may be expected to cause trapping of the plume. However, the oil may finally arrive at the sea surface due to the buoyancy of individual oil droplets. The resulting surface spreading of the oil will then depend on the size distribution of the oil droplets and the strength and variability of the ambient current. This situation differs significantly when blowouts occur at moderate depths. In such cases, the surface spreading of the oil will be governed by the radial outflow of water entrained by the rising gas bubble plume (Fanneløp & Sjøen, 1980).

As a whole, we found that without major modifications, the existing BLOW model would produce unrealistic predictions of plume behaviour and surface spreading when applied to blowouts from deep water. Thus, in order to cope up with deep water blowouts, we decided to introduce the following major modifications in the model.

- Include effects of cross-currents.
- Take non-ideal gas behaviour into account.
- Include dissolution of gas from bubbles in sea water.
- Include formation and subsequent disintegration of hydrate in the model.

The first modification (effects of cross-currents) implies the introduction of the mechanism of forced entrainment in the first place. However, when this is included, the plume may be found to bend over due to the entrainment of momentum from the ambient water. This implies a potential for vertical leakage of gas bubbles from the plume. The second modification (non-ideal gas behaviour) implies the introduction of pressure and temperature dependent compressibility factor (z -factor) in the pressure–volume–temperature (PVT) relationship of the gas. This z -factor depends in addition on the composition of the gas phase, and is a well-known subject in petroleum physics.

The third modification implies that the process of dissolution of gases from bubbles into ambient water must be included. This process is governed by the mass

transfer coefficient between the rising gas bubbles and ambient water, the specific surface area between gas bubbles and water, and the solubility of the gas in seawater. The last modification implies that the potential conversion of gas into hydrate in contact with seawater must be introduced. At the same time, the buoyancy of hydrates formed from the gas must substitute the buoyancy of the gas bubbles.

In order to facilitate the introduction of these modifications in total, it was found that a change in the basic model concept should also be considered. Thus, as a result of a review of recent advances in plume modelling, it was found convenient to substitute the *Eulerian* concept in the original BLOW model with the *Lagrangian* concept used in more recent developments. The general aspects of the Lagrangian plume model concept are present in the next section, including the modifications primarily related to deep water. A description of various tests and demonstrations of the modified *DeepBlow* model follows this section.

Model Concepts

In most plume models, the equations for continuity of mass, momentum and scalar properties (e.g., temperature and salinity) are defined for control volumes bounded by cross-sections normal to the trajectory of the plume (see Yapa & Zheng (1997) for a detailed review of integral plume model concepts). The models may be either *Eulerian*, where the control volumes are fixed in space, or *Lagrangian*, where the control volumes are moving with the plume. Winiarski and Frick (1976) first introduced the Lagrangian concept in a model for cooling tower plumes. With slight modifications, this concept has become the dominating one from the beginning of the 90's, with the JETLAG model developed by Lee and Cheung (1990) as the pioneering work. The JETLAG model also includes a novel forced entrainment concept, based on the so-called *projected area entrainment* (PAD) hypothesis, originally formulated by Frick (1984).

In the *Lagrangian models*, the plume is represented by a series of non-interfering elements. Each element, which can be thought of as a cylinder or section of a bent cone, is characterised by its mass, location, width (radius), length (thickness), average velocity, pollutant concentration, temperature and salinity. These parameters will change as the element moves along the trajectory, i.e., the element may increase in mass due to shear-induced and forced entrainment, while rising by buoyancy and sheared over the cross-flow.

Zheng and Yapa (1997a & 1997b) extended this concept to multiphase plumes in order to represent sub-sea blowouts with oil, gas and entrained sea-

water. In their model, the plume was considered as a mixture of non-miscible fluids (oil droplets and gas bubbles dispersed in seawater). The gas mass was preserved in the plume elements, and the density of the gas was assumed to change according to the ideal gas law. The authors assumed that the gas bubbles occupied an inner core of the plume element, with a radius $b_g = \beta b$, where $\beta < 1$. The authors also pointed out that the gas bubbles might have a larger vertical velocity than the plume. This slip velocity may be in the order of 0.25–0.35 m/s, and is related to the buoyancy driven rise velocity of singular gas bubbles in water. Possible effects of this slip velocity were neglected in Zheng and Yapa's model. However, when a finite bubble slip velocity is considered in a bent plume, gas bubbles may escape vertically out of the sloping plume. Also, the gas mass may no longer be assumed to be preserved when special processes occurring in deep water (e.g., hydrate formation, dissolution of gas into seawater) are taken into account. The modifications required to account for such effects are summarised in the following sections. More details are presented in a SINTEF report on the *DeepBlow* model development (Johansen, 1998).

Conservation of mass and volume

In a multiphase plume model, e.g., with water, oil and gas, the conservation equation for mass must reflect the actual composition of the plume element, as well as subsequent changes in this composition due to loss of certain constituents (e.g. gas). In order to account for the differences in the density of the constituents, the volume of the plume element is computed as

$$V = \sum \frac{G_i}{\rho_i}, \quad (1)$$

where ρ_i is the density (kg/m^3) of each constituent with mass G_i (kg). The density of water is computed from temperature and salinity by the equation of state for seawater. Gas that is dissolved in seawater is not presumed to contribute to the volume of the plume element, but will contribute to the mass. The density of oil is a presumed constant, independent of pressure, while the density of the gas is computed from pressure and temperature by the compressibility equation of state (McCain 1990).

$$pv = ZRT, \text{ or } \rho = \frac{p}{ZRT}. \quad (2)$$

The Z -factor is the compressibility of the gas, and represents the deviation of the gas density from the one computed by the ideal gas law ($Z = 1$). Z depends on the gas composition, as well as pressure and temperature. At "normal" atmospheric pressure and

temperature conditions, Z tends to be close to $Z = 1$ for most gases, but at more elevated pressures, Z tends to be reduced ($Z < 1$). The pressure p is computed as hydrostatic pressure, i.e.,

$$p = \rho_w g H + P_0, \quad (3)$$

where ρ_w is the density of sea water, H the water depth at the element location (distance to sea level), and P_0 is the atmospheric pressure at sea level.

According to Sloan (1990), hydrate consists of 85% water and 15% gas on a molar basis. On a mass basis, the corresponding water to gas ratio will be 6.4:1 for hydrate made up of Methane (molar weight 16 kg/kmol), or about 5:1 for hydrate made up of a typical natural gas mixture (molar weight of about 20 kg/kmol). The density of the hydrate lattice (gas excluded) is according to Sloan (1990) about 80% of the density of normal ice (917 kg/m^3 for ice at 0°C), while Stern *et al.* (1996) gives a density of 780 kg/m^3 for the empty hydrate lattice (structure I). Based on this density value for the hydrate lattice, and the water to gas mass ratios given by Sloan (1990), hydrate from methane will have a density of about 900 kg/m^3 , while the density of hydrate from a typical natural gas mixture will be about 930 kg/m^3 .

This implies that volume of the plume element will change if a fraction of the gas is converted into hydrate. With a fraction X_H of the gas mass converted into hydrate, a gas mass $\Delta G_g = X_H G_g$ will be combined with a water mass $\Delta G_w = X_W \Delta G_g$ to form hydrate with density ρ_H . The factor X_W represents the previously mentioned mass ratio between water and gas in the hydrate. The volume of the element will then be reduced by ΔV_H , compared to the volume without hydrate formation

$$\Delta V_H = \frac{\Delta G_w}{\rho_w} + \frac{\Delta G_g}{\rho_g} - \frac{\Delta G_w + \Delta G_g}{\rho_H}, \quad (4)$$

where ΔG_w and ΔG_g are the mass of seawater and gas combined into hydrate, while ρ_w , ρ_g and ρ_H are densities of water, gas and hydrate, respectively.

Conservation of heat

In a multiphase plume, the specific heat capacity will be different for the different constituents. The temperature of the element must then be computed from a conservation equation for heat, $Q = \sum G_i c_i T$, where c_i is the heat capacity (J/kg K) of the different constituents with masses G_i . In cases with no phase transition (only sensible heat), the change in temperature from one time step to the next may be written as

$$T_{k+1} = \frac{Q_k + \Delta Q_a}{\sum G_i c_{i/k+1}}, \quad (5)$$

where $\Delta Q_a = \Delta E c_w T_a$ is the heat content of the mass of ambient water ΔE with temperature T_a , entrained in the last time step.

In case of phase transitions, e.g., formation or dissociation of gas hydrates, release or consumption of latent heat must be taken into account in the heat balance equation. The latent heat per unit mass of hydrate is about 440 kJ/kg, which corresponds to about 30% more than the latent heat of freezing of water (Sloan 1990). The equilibrium temperature for formation of hydrate from natural gas mixtures at a certain ambient pressure depends on the composition of the gas, and will increase as the amount of heavier hydrate forming gases (ethane, propane) increases. Sloan (1990) offers a computer program that may be used to compute the equilibrium temperature of mixtures of hydrate forming gases and the corresponding composition of the hydrate. Calculations with this program demonstrates that when hydrates forms from natural gas mixtures, the first hydrate to be formed will be rich in the heavier hydrate forming gases (ethane, propane). The remaining gas will then be enriched in methane. This implies that the equilibrium temperature will be reduced, and finally approach the equilibrium temperature for methane, as more gas is converted into hydrate. This implies that the latent heat will be released over a temperature interval T_1 to T_2 , where T_1 is the equilibrium gas-seawater-hydrate temperature for methane and T_2 is the equilibrium temperature for the actual (natural) gas mixture. In the *DeepBlow* model, this has been taken into account as described in the following.

First, the heat content Q_{k+1} in the element at time step $k + 1$ is updated by the equation

$$Q_{k+1} = \sum G_i c_i T_k - X_H G_g L_H + \Delta Q_a, \quad (6)$$

where X_H is the mass fraction of the gas mass G_g present as hydrate in the previous (k th) time step, and L_H is the latent heat of hydrate formation given per unit mass of gas (J/kg). Note that this value will be considerably larger than the value given per unit mass of hydrate — each kg of gas will combine with about 5 kg of water and forms hydrate of about 6 kg. Next, the change in hydrate mass fraction resulting from the change in the heat content is estimated, based on the assumption that hydrate formation takes place in the temperature range $T_1 < T < T_2$. The total heat content of the plume element is computed for each of these equilibrium temperatures

$$\begin{aligned} Q_1 &= \sum G_i c_i T_1 - G_g L_H, \\ Q_2 &= \sum G_i c_i T_2. \end{aligned} \quad (7)$$

If the value of Q_{k+1} is found between Q_1 and Q_2 , the mass fraction of gas X_H present as hydrate at time step $k + 1$ is estimated as

$$X_H = \frac{Q_2 - Q_{k+1}}{Q_2 - Q_1}. \quad (8)$$

For the same condition, i.e., if $Q_1 < Q_{k+1} < Q_2$, the new temperature in the element is estimated as

$$T_{k+1} = T_2 - X_H \Delta T. \quad (9)$$

If Q_{k+1} is found to be larger than Q_2 , no gas will be present as hydrate, i.e., $X_H = 0$, and Eq. (5) may be applied to compute the new temperature. This equation also applies when Q_{k+1} is less than Q_1 and the gas is completely converted to hydrate. Finally, it should be mentioned that when plume rise causes a *reduction* in the hydrate fraction X_H from one time step to the next, the corresponding released gas mass is presumed to be converted directly into dissolved gas. This presumption is made to reflect that the size of the gas bubbles formed by “melting” of hydrate will have to be small, mainly due to the small and irregular size of the hydrate “flakes” formed from rising gas bubbles (Maini & Bishop, 1981).

Dissolution of gas into seawater

The rate of change in the gas mass contained in bubbles due to dissolution may be expressed by the equation

$$\frac{dQ_g}{dt} = -kA(s - C_a), \quad (10)$$

where k (m/s) is the mass transfer coefficient, A (m²) the total surface area of the gas bubbles in the plume element, s (kg/m³) the solubility of gas in seawater, and C_a (kg/m³) is the ambient concentration of dissolved gas. By presuming that the ambient concentration is negligible ($C_a \ll s$) — and by introduction of the specific surface area $S = A/V$, which for spherical bubbles with diameter D_b is $S = 6/D_b$ — this equation may be written as

$$\frac{dQ_g}{dt} = -\frac{6kQ_g}{D_b} \frac{s}{\rho_g}. \quad (11)$$

The mass transfer coefficient k in Eqs. (10) and (11) depends on the diffusivity κ of gas in seawater (e.g., $\kappa \cong 10^{-9}$ m²/s for Methane), the bubble slip velocity and size. In the present model, k is computed from empirical correlations derived by Hughmark (1967) for rigid spheres and gas bubbles. Note that Hughmark’s correlation for rigid spheres is used up to the point where the correlation for oscillating bubbles starts to provide the largest value for k .

The bubble slip velocity is computed according to the general expression for the terminal velocity of rigid spheres (see e.g., Hu & Kintner (1955)), modified

with a prescribed maximum slip velocity (e.g., $w_b \leq 0.30$ m/s)

$$w_b = \sqrt{\frac{4D_b g'}{3C_D}}, \quad \text{where } g' = g \frac{\rho_a - \rho_g}{\rho_a}. \quad (12)$$

The drag coefficient C_D is a function of the Reynolds number. For small value of Re ($Re < 1$), $C_D = 24/D$, while for large values of Re ($Re > 1000$), C_D approaches a constant value $C_D \approx 0.4$. For solid spheres, Delnoij *et al.* (1997) have proposed the following relationship between C_D and Re :

$$\begin{aligned} Re < 1000, \quad C_D &= \frac{24}{Re} (1 + 0.15 Re^{0.687}), \\ Re > 1000, \quad C_D &= 0.44. \end{aligned} \quad (13)$$

In the present model, we have instead chosen to estimate the rise velocity as the harmonic mean of two extremes, i.e.,

$$w_b = 1/(w_1^{-1} + w_2^{-1}), \quad (14)$$

where w_1 is computed from Eq. (13) with $C_D = 24/Re$, while w_2 is computed from the same equation with $C_D = 0.44$ (constant). Note that a prescribed maximum bubble rise velocity $w_{b\max} = 0.2\text{--}0.3$ m/s limits the possible range of this value. This method is found to produce practically the same results as the more cumbersome implicit solution required when Eq. (13) is used.

In order to apply Eq. (11), the gas bubble size D_b must be updated for each plume element. This implies that a representative initial bubble size D_0 is prescribed together with a corresponding initial (exit) gas density ρ_0 . This bubble size is adjusted for changes in gas density ρ and any relevant reductions in gas mass, i.e., dissolution and hydrate formation will reduce the gas mass per bubble, while leakage of bubbles from the plume will have no effect on the bubble size of the remaining gas. If the adjusted bubble size is found to be larger than a prescribed maximum (stable) bubble size, the bubble diameter is set equal to that maximum.

Gas leak from a bent plume

As the plume is bent over by the cross-current, gas bubbles may escape from the plume due to their individual rise velocity. The rise velocity of gas bubbles depends on the size of the bubble and the density difference between the gas and the ambient water. As mentioned before, since the gas bubbles may contract as well as expand, the rise velocity is subject to changes in the present model.

Due to entrainment of ambient water into the plume element, escaping bubbles will be met by a radial inflow of water with a velocity w_R corresponding to the expansion rate of the plume radius, i.e., $w_R = db/dt$. The net escape velocity w_E of the gas bubble in the direction normal to the plume element may then be expressed as

$$\begin{aligned} w_E &= 0 \quad \text{for } w_N < w_R, \\ w_E &= w_N - w_R \quad \text{for } w_N > w_R, \end{aligned} \quad (15)$$

where $w_N = w_b \cos \varphi$ is the component of the bubble rise velocity normal to the plume element axis, and φ is the angle of the plume axis from the horizontal. By presuming that the gas is well mixed in the plume in a concentration C_g (kg gas/m³), the gas leak rate from the element may be represented as

$$\Delta G_g = -\frac{2w_E C_g \Delta t}{\pi b}, \quad (16)$$

where Δt is the model time-step, and b is the plume radius. Gas that is escaping from the plume by this mechanism is not tracked further in the model. In reality, the gas is expected to continue to rise as individual bubbles. These bubbles are likely to be dissolved in the ambient water before arriving at the sea surface.

Applications

Comparisons with field experiment

IKU Petroleum Research, with Norwegian Clean Seas (NOFO), ESSO Norway and Norsk Hydro conducted a total of five different experimental sub-sea releases with gas (compressed air) together with oil or seawater (Rye & Brandvik 1997). The experiments were made at about 100 m depth near the Frigg field in the North Sea. Measurements of hydrographical data, wind, waves and ocean currents were made in parallel with the experiments.

One of the experiments was made with stabilised crude oil, while seawater dyed with Rhodamin was used in the four other experiments. The volume flow of oil or water was adjusted to 1 m³ per min in all the experiments, while the gas-to-water or -oil volume ratio was varied between 7:1 and 67:1 (see Table 1). Note that the numbers are referred to standard conditions (atmospheric pressure).

The bubble plumes were observed with video camera and scanning sonar mounted on a ROV. Pictures were also taken from airborne video cameras during the experiments to map the surface spreading of the plumes. Simulations have been made with *DeepBlow* for these five cases based on the observed

Table 1 Discharge conditions in the 1996 field experiments. The discharge rate of water or oil was 1 m³/min in all experiments. Volume ratio between air and water or oil refer to standard conditions (atmospheric pressure)

Case	Period (1996)	Volume ratio	Discharge
1	11 June, 18:30–19:30 GMT	7.25:1	Water
2	12 June, 07:45–08:35 GMT	18:1	Water
3	12 June, 11:15–11:53 GMT	65:1	Water
4	12 June, 12:20–14:10 GMT	46:1	Water
5	12 June, 08:40–10:00 GMT	67:1	Crude oil (Troll)

hydrographical profiles and ocean current data. The computed plume-geometry is shown for two cases in Fig. 1, while the partitioning of the gas phase at different distances from the outlet – measured along the plume centreline – is shown for the same cases in Fig. 2.

These simulations demonstrate that the leakage of gas bubbles from the plume and dissolution of gas in ambient water plays an important role in the behaviour of the plume. By including these mechanisms, the simulations were found to be in agreement with the following observations.

- In experiment 1, the observations from the ROV indicated that the plume was bent over and carried away with the current at a depth of about 60 m. No air bubbles or dyed water was observed to come to the surface in this case.
- In experiment 2, the sonar images from the ROV indicated that the plume was weakened as it approached the surface, and that it vanished completely at a depth of about 20 m. Also in this case, no air bubbles or dyed water was observed to come to the surface.
- Air bubbles and dyed water was observed at the surface in all the remaining three cases.

However, in simulations where these mechanisms were neglected, the plumes with the smallest gas-to-water ratios (experiments 1 and 2) were also found to surface, contrary to the observations during the experiments.

Deep water blowouts

In this section, the *DeepBlow* model is used to simulate a potential blowout in the region of the Norwegian Sea that have been opened for deep-water exploration drillings. For this purpose, local current measurements were obtained from Oceanographic Company of Norway ASA (OCEANOR) for a period from the middle of September to the beginning of November 1990. The measurements in the top 300 m were made with an acoustic doppler current profiler (ADCP), while the recordings at greater depths were

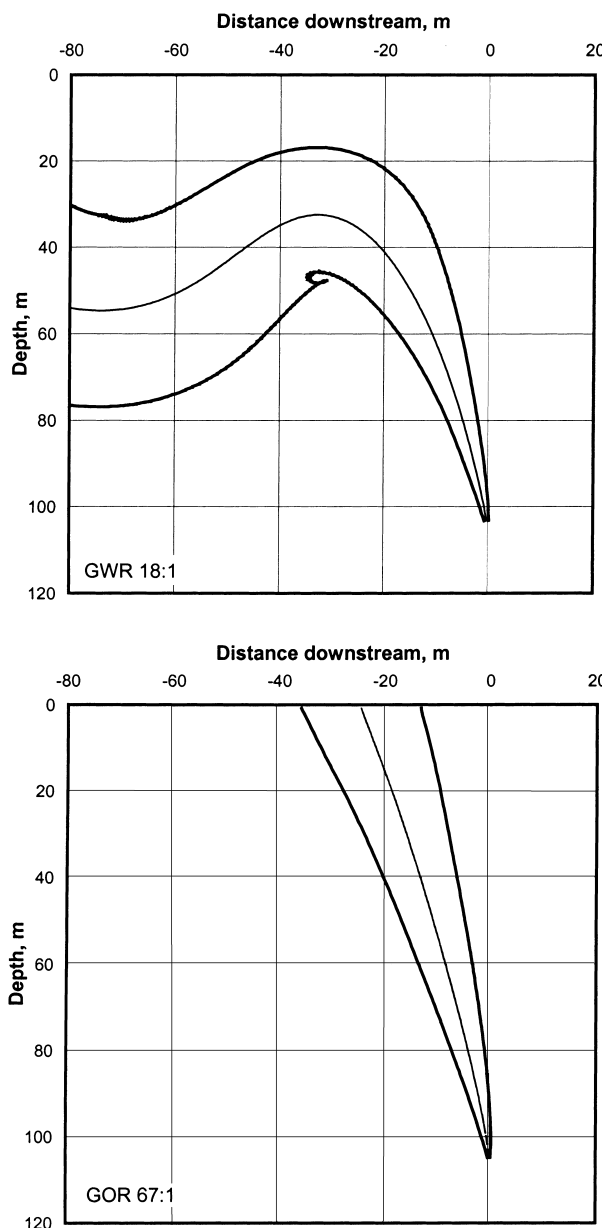


Fig. 1 Simulated plume geometry for two of the five experiments. The calculations are based on observed ocean currents and hydrographical data during each experiment.

made with Aanderaa rotor current meters mounted in a rig.

From these measurements, simultaneous time series with 0.5 h intervals were compiled for 8 different

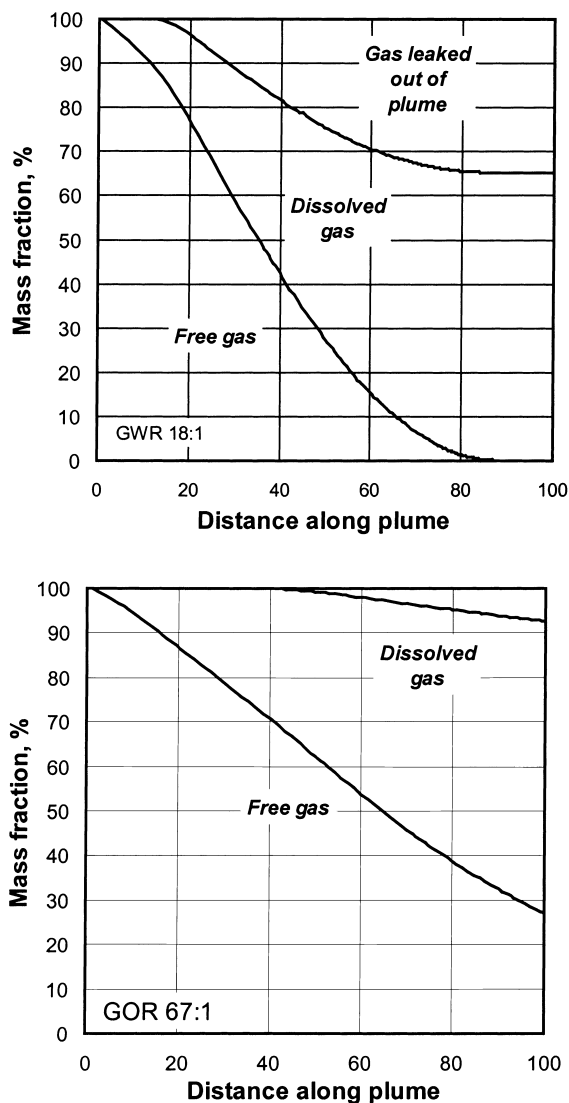


Fig. 2 Partitioning of the gas phase in two of the five experiments. The results are shown as a function of the distance measured along the centreline of the plume.

depths for the use in the model simulations. Representative hydrographical profiles (sea temperature and salinity) were obtained from the Norwegian Marine Research Institute (Fig. 3).

The water depth at the site was presumed to be 1360 m, and the simulations were made for two different blowout cases from a: (a) gas well (GOR 2000:1) and (b) oil well (GOR 150:1) with discharge conditions as summarised in Table 2.

Table 2 Discharge conditions for deepwater blowouts

	Gas well (condensate)	Oil well
Discharge rate of oil or condensate	2500 m ³ /day	4000 m ³ /day
Gas-to-oil ratio, standard conditions	2000:1	150:1
Oil density	800 kg/m ³	850 kg/m ³
Gas density, standard conditions	0.8 kg/Sm ³	1.0 kg/m ³

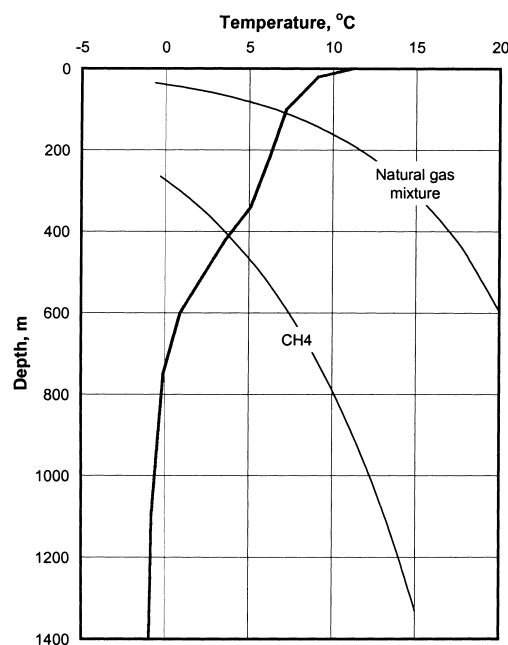


Fig. 3 Sea temperature profile measured July 29, 1984 at the Vøring Plateau in the Norwegian Sea (position 66°N, 3°E). Data obtained from the research vessel “Håkon Mosby”, Norwegian Marine Research Institute. Thin lines show gas–water–hydrate equilibrium lines for pure Methane (CH₄) and a natural gas mixture (75% Methane).

In order to reflect the potential effect of the ambient current on plume behaviour, the *DeepBlow* simulations were made for a selection of measured current profiles. Results from these simulations are summarised in Fig. 4. The figure shows the variations in the depth of trapping with the current speed measured at that depth. Note that in the present context, the *depth of trapping* has been defined as the maximum point of the plume trajectory.

The plumes were found to rise to the highest level for the gas well blowout, as it is expected to be due to the larger buoyancy flux caused by the larger gas flow rate. The difference in the depth of trapping between the two cases was not more than 200 m, and in the same order of magnitude as the differences caused by the variations in the current conditions. This may be partly explained by the fact that in both cases, the gas was completely converted into hydrate almost immediately after discharge. It should also be noted that the plume rise (in both cases) was found to terminate well below the equilibrium depth for hydrate (about 400 m depth, according to Fig. 3). Hydrate (in the form of

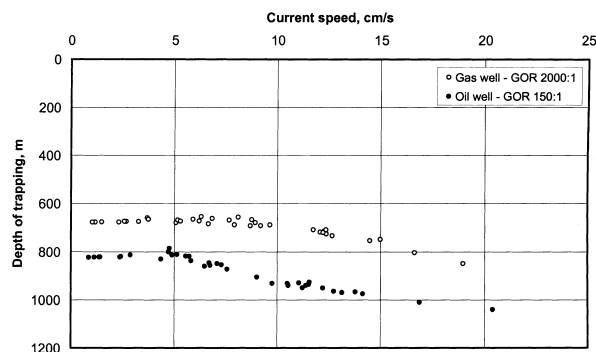


Fig. 4 Simulations of blowouts from 1360 m depth. Depth of trapping computed for two different discharge conditions (see Table 2) and a set of current situations.

small flakes) will be kept in suspension by turbulence in the water masses, and no gas may thus be presumed to come to the surface from these deep-sea blowouts. However, dispersed oil droplets may escape from the trapped plume and rise to the surface. The surface spreading of this oil will depend on the size distribution of the oil droplets and the local variability of the ocean currents.

Surface spreading

In order to provide a basis for calculations of the surface spreading, SINTEF, supported by the previously mentioned Norwegian Deep-sea Program, conducted a literature review on droplet formation in oil and gas jets (Rye *et al.*, 1998). The review showed that droplet formation was caused by different mechanisms depending on the flow conditions at the outlet (Lefebvre, 1989), and that droplet size distributions could be predicted only for special cases, such as low velocity liquid jets (Kumar & Harland, 1996) or dispersed flow in tubes (Karabelas, 1978). However, no reliable predictions were found available when droplets are formed by atomisation, which is the most likely case with the large volume flows of oil and gas and oil normally connected with sub-sea blowouts. An experimental study of droplet formation in turbulent jets with oil and gas is obviously required to fill this gap in the present knowledge.

Meanwhile, presuming that the droplet size distribution is known, the corresponding distribution in times of rise from a certain depth of trapping may be computed from well-established formulas. The resulting spreading of the oil on the surface may then be computed from measured time series of ocean currents. An example of a surface slick computed on this basis is shown in Fig. 5. The depth of trapping was presumed to be at 900 m depth, the discharge rate corresponded to the oil well blowout case (Table 2), and the oil droplets were presumed to be in the size

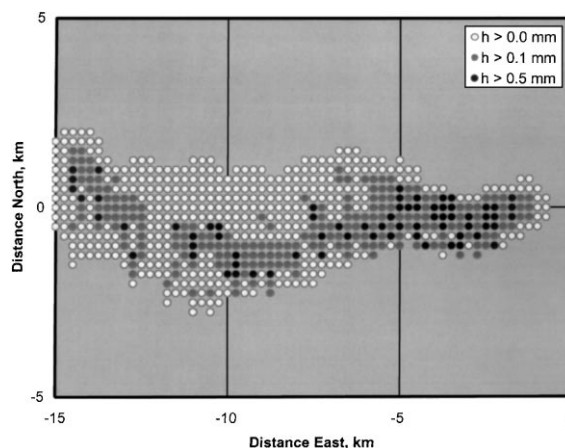


Fig. 5 Example of surface slick formed by oil droplets rising from 800 m depth in a time variable (measured) ocean current. The discharge rate corresponds to the oil well blowout case (Table 2), and the oil droplets are presumed to be in the size range from 0.5 to 5 mm.

range from 0.5 to 5 mm. The ocean current data were taken before the mentioned current measurements.

Summary and Recommendations

This paper presents a new integral plume model developed with special emphasis on deep water applications. The model is based on a Lagrangian model concept, similar to earlier models developed for aqueous discharges (e.g., the JETLAG model), which were later extended to multi-component discharges (sub-sea blowouts with oil and gas) by Zhen and Yapa. In the present model, the Lagrangian concept is extended further to include relevant phase transitions in each plume element, e.g., gas dissolved in seawater, and gas converted into hydrate.

Examples are presented in the paper to demonstrate that these processes are of major importance for the development of plumes generated from sub-sea blowouts. When the dissolution of gas in seawater was included, the model was found to reproduce the observed behaviour of plumes from a set of experimental discharges of pressurised air, dyed water or oil. However, when this mechanism was omitted in the simulations, plumes that were actually trapped at the thermocline were found to rise to the surface. An example of a possible deep water blowout from 1360 m depth in the Norwegian Sea showed that the gas was converted almost into hydrate instantaneously after the release, and that the gas was preserved as hydrate also after the plume was trapped at the perennial pycnocline.

Both examples are demonstrations of cases where no gas will come to the sea surface from a sub-sea blowout, either due to complete dissolution of the gas

in seawater, or due to complete conversion of gas into hydrate. It must be emphasised, however, that an oil slick may form at the surface even in cases where the plume is trapped below the surface. The spreading of such slicks will depend on the size distribution of the oil droplets formed in the outlet jet, and the strength and variability of the ocean currents in the region of concern. In this conjunction, it should be noted that there is an unfortunate lack of reliable methods for prediction of droplet size distributions formed in large volume liquid–liquid jets. Experimental studies designed to reveal the relevant relationships would give valuable contributions to the predictions of the spreading of oil slicks formed from sub-sea blowouts. Finally, it should also be noted that for the same reason, efforts should be continued to improve modelling of the interaction of plumes with the sea surface and with density stratifications in the water column. The wide range of possible plume-surface interactions has been reviewed by Jirka and Doneker (1991), but this knowledge has not been implemented in the Lagrangian model concept.

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