SIMULATIONS OF SUBSEA CO_2 LEAKAGE SCENARIOS

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Abstract

Subsea carbon dioxide leakages from geological storage complexes and transmission lines may pose a threat to the marine ecosystem in their vicinity. For high leakage flow rates (100 kg/s), buoyant dynamic plumes will form and, in shallow water depths (100-300 m) such as in continental shelves, they may reach the water surface thereby releasing gases to the atmosphere. Here, we present simulations of subsea releases of CO_2 at varying scales, such as seeps, point source plumes and line source plumes, and we discuss their behaviors. The simulated release conditions and water depths are representative of potential storage area on the Norwegian Continental Shelf. Simulations are performed with the TAMOC model, a multiphase-integral plume modeling suite developed and validated for subsea gas and oil releases.

Keywords: *subsea CO_2 leakages, integral plume model, multi-phase plumes, pipeline fracture*

1. Introduction

Potential leakages of carbon dioxide (CO_2) [1] from subsea geological storage (such as decommissioned oil and gas wells) and transmission facilities have a potential to impact marine ecosystems negatively. When CO_2 gets dissolved in water, the acidity increases depending on the amount dissolved and on the total alkalinity. Potential leakages of CO_2 cover a range of scales from seeps [2] to large-scale blowout scenarios [3][4], which create dynamic momentum and buoyancy-dominated plumes. The two release types will behave differently. Modeling tools are useful in predicting the behaviors of the different types of leakage scenarios and provide guidance in planning and enable assessment of the impact on ecosystems.

In this short paper, we present simulations of several subsea CO_2 leakage scenarios that are possible on the Norwegian Continental Shelf. The models used are described briefly, and results are presented to show varying capabilities of modeling tools and their applications.

2. Numerical Methods and Simulations

2.1 Models used for the simulations

We use modules from the Texas A&M Oilspill Calculator (TAMOC) [5][6][7] to simulate three different potential release scenarios as described in subsection 2.3. This modeling suite has been developed to simulate subsea releases of gas and oil mixtures and is extensively validated with both laboratory and field data [2] [8][9][10]. The multi-phase plume models in TAMOC are integral models that consider the conservation of mass, momentum, and buoyancy, and provide estimates of cross-sectional averages of these parameters along the plume trajectory. The models track the mass transfer of gas from bubbles to the ambient, and expansion as the pressure drops when the plume rises in the water column. The temperature and pressure dependent properties of gas mixtures are estimated based on the Peng-Robinson equation of state. The Single Bubble Model [8][6][10] is used to simulate the behaviors of seeping CO_2 bubbles in three-dimensional space in the water column. The Bent Plume Model (BPM, Figure 1b) [11] uses a Lagrangian based approach and it can simulate point source releases in stratified and cross-flow dominated ambient conditions. The Stratified Plume Model (SPM, Figure 1a) [12][13] is based on the Eulerian double-plume model theory and simulates point source plumes in the absence or near-still cross flow conditions in the stratification-dominated regime. To simulate a release from a pipeline fracture with linear geometry in the absence of cross-flow, a Stratified Plume Model extension for line source diffusers (where the width of the release opening is small when compared to its length) [11] can be utilized. The ambient water entrainment into plumes is driven by both the cross flow for BPM and shear between the ambient and rising plume in both BPM and SPM. The shear entrainment coefficient considers the stratification in the ambient in terms of the local densimetric Froude number [14]. These models predict the distribution of gas and dissolved gas in the water column, along with the approximate surfacing volume, time, and location with respect to the plume release point.

To account for the enhanced density of seawater containing dissolved CO_2, we have used the following formulation [15],

$$\rho_c = \rho + (M - \rho v)C$$

where ρ_c is the density of seawater containing CO_2 (kg m^{-3}), ρ is the seawater density based on the standard equation of state (kg m^{-3}), v is the molar volume of CO_2 (m^3 mol^{-1}), C is the total dissolved inorganic carbon (mol m^{-3}), and M is the molar mass of CO_2 (kg mol^{-1}).

pH variation in the water column can easily be estimated, based on the dissolved concentrations predicted from the different plume models described earlier in the section and assuming equilibrium within the carbonate system[2] [16] [17]. The advection of the dissolved gas in the water column can be simulated following [18], but is not presented here.

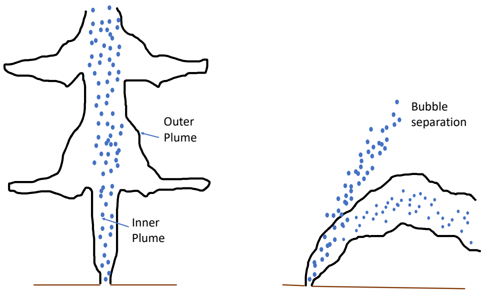

Figure 1: Schematic diagram of (a) Stratified Plume Model and (b) Bent Plume Model [5]

2.2 Validation with experimental data

We compared the model predictions for the behavior of CO_2 bubbles with recent experimental data from [19] (Figure 2). Similar validations of the dissolution of CO_2 bubbles were published in [2] and [16]. The experiments were carried out in a laboratory setup using seawater from Trondheimsfjord in Norway. Because the natural seawater contained dissolved atmospheric gases, we simulated the mass transfer of CO_2, nitrogen, and oxygen between the seawater and the bubble [2][7][9][20]. We used an initial bubble size of 2.55 mm in the simulation fitted to the data. Further model validations for subsea releases of bubbles and plumes at 1–1,500 m water depth are presented in references given in section 2.1. However, experimental data for subsea CO_2 blowout plumes that can be used for model validations are not widely available in the literature.

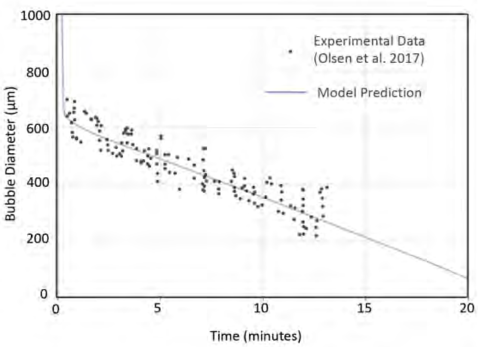

Figure 2: Bubble size variation with time according to model prediction and experimental laboratory data, for an initially pure CO_2 bubble

2.3 Simulated scenarios

We present simulations of seeps, point source releases in stratification and a line source release which is a possible scenario from a geological faultline [20] or from a pipeline fracture [22]. Water depths of the simulated releases are representative of potential CO_2 storage sites in Norway. The Norwegian Petroleum Directorate (NPD) reported that the area in the northern part of the North Sea, about 100 km west of Bergen is a good candidate for CO_2 storage. We selected a location in the area as shown in Figure 3 based on approximate drilling location tested by NPD [23]. The reported typical water depth at this location is about 307 m. Typical salinity, temperature, and dissolved oxygen profiles at the location were extracted from NOAA's World Ocean Atlas [24]. Dissolved nitrogen and CO_2 profiles in the water column that are not available in the World Ocean Atlas, were estimated by considering the equilibrium of atmospheric gases with the water column. Release water depths and flowrates used in the simulations are listed in Table 1. The diameter of the point source plume and the width of the line source plume are both 0.15 m.

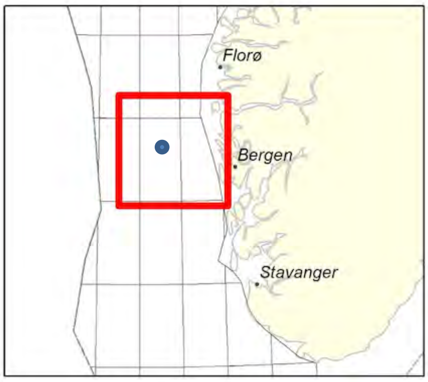

Figure 3: Location of the simulated release shown as a blue dot (map:www.npd.no)

Table 1: Simulated release conditions

Model	Release Water Depth (m)	Released amount
Seep	300	10 mm bubble
	100	10 mm bubble
Point source with ambient stratification	300	100 (kg/s)
	150	100 (kg/s)
Line source with ambient stratification	300	100 (kg/s/m)
	150	100 (kg/s/m)

3. Results and Discussion

The evolution of bubble rise depth, velocity, diameter and remaining mass fraction of CO_2 in the bubble are shown in Figure 4 and Figure 5 for the bubbles released at 100 m and 300 m depth respectively. The bubble released at 100 m depth rises about 30 m through the water column within five minutes before getting completely dissolved, while the bubble released at 300 m depth only rises to about 20 m within a similar time span. The bubble released at the deeper depth carries more mass in its volume due to higher compression than the bubble at 100 m depth with same volume. However, bubbles released at both depths experienced dissolution of 99.9 % of their CO_2 within 7- 8 m rising distance from seafloor. The simulated remaining fraction of the initial CO_2 mass in bubbles as they rise in the water column is depicted on Figs.4d and 5d. Thus, the seep at the deeper release concentrates more dissolved mass in a similar water column height compared to the shallower release, for a given leakage volume flow rate. The reason being the CO_2 in the gas mixture in the bubbles released at higher pressure at 300 m is more soluble in seawater when compared to 100 m depth release.

Figure 6 shows the plume entrained upwelling and detraining flowrates within the inner and outer plumes for a 300 m depth release simulated with the stratified plume model. The inner plume is the core of rising bubbles and upwelling entrained water that gets arrested and form intrusions when it reaches a neutral buoyancy level. The detraining water from the plume makes an intrusion and creates an outer plume shrouding the inner plume [13][25]. If the bubbles in the inner plume do not get completely dissolved by the time that the first intrusion is formed, they can escape the plume and rise further in the water column with possible subsequent intrusion formation. The release shown in Figure 6 shows a single intrusion formed between depth levels 50 – 170 m. All the CO_2 released gets dissolved in the water column, thus the plume is not reaching the sea surface. The inner plume contains a higher concentration of dissolved CO_2 than the outer plume (Figure 7).

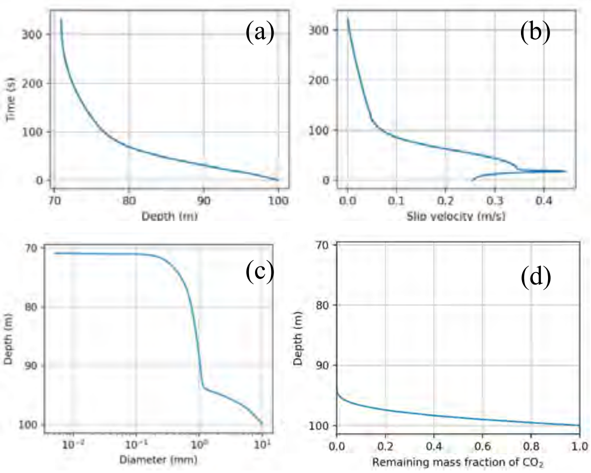

Figure 4: Evolution of bubble (a) rise depth (b) terminal slip velocity (c) size and (d) remaining CO_2 mass fraction with depth for the seep bubble release at 100 m depth.

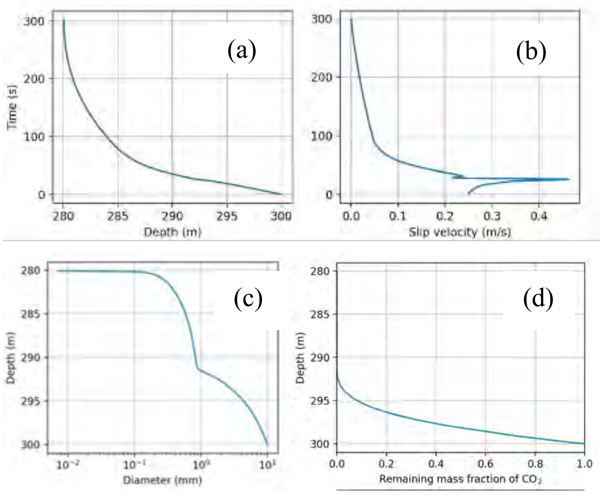

Figure 5: Evolution of bubble (a) rise depth (b) terminal slip velocity (c) size and (d) remaining CO_2 mass fraction with depth for the seep bubble release at 300 m depth.

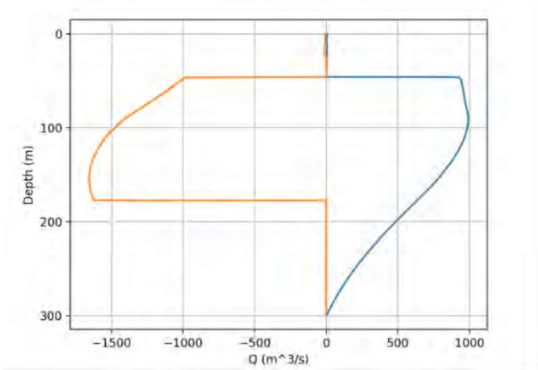

Figure 6: Entrained water flowrate (Q) in the inner plume (right) and outer plume (left) of subsea CO_2 release of 100 kg/s from a point source at 300 m depth.

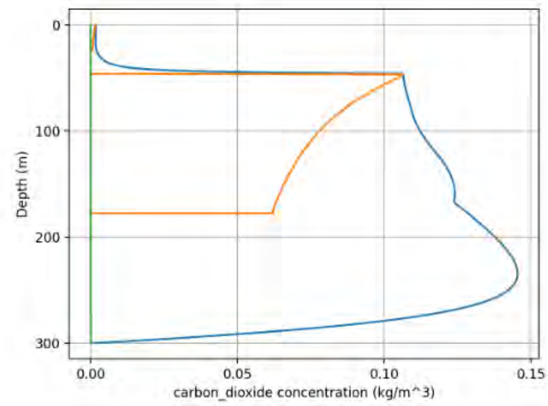

Figure 7: Concentration of dissolved CO_2 (total inorganic carbon) in the inner plume (inner) and outer plume (orange) of subsea CO_2 release of 100 kg/s from a point source at 300 m depth.

For a point-source leakage having the same 100 kg/s flowrate released at 150 m water depth, the plume reaches the water surface (Figure 8). The highest concentration of dissolved CO_2 in both the inner and outer plumes are seen in the surface water (Figure 9). This in contrast with the deeper release of the same scale (Figure 7).

A linear geometry source plume released at 300 m depth with a rate of 100 kg/s/m shows that the plume reaches the water surface, unlike the release rate from a point source release of 100 kg/s as shown in Figure 6. The main reason is that the point source has a release velocity close to 95 m/s and more water gets entrained into the plume at release, in comparison to line geometry source plume, which only has about 20 m/s release velocity at the source. When more water gets entrained, the plume slows down and tends to make intrusions within a shorter rise distance than the plume with lower ambient water entrainment. Figure 11 and Figure 12 respectively show the predicted concentration of dissolved CO_2 in the inner and outer plumes considering 7.5 mm and 10 mm bubbles, for the same linear geometry source release from 300 m depth with 100 kg/s/m release flowrate. The inner plume with 10 mm bubbles has only about 0.15 kg/m^3 concentrations below 200 m depth, while the inner plume with 7.5 mm bubbles has a higher concentration of 0.25 kg/m^3 below 200 m depth. This illustrates the importance of using the correct bubble sizes at the plume source when simulations are performed, due to the high sensitivity of the results to the initial conditions. However, to date a well validated bubble size prediction model for subsea gas blowout plumes is only available in the literature for idealized scenarios (circular orifice) [26]. Especially for a gas like CO_2 which is rapidly dissolved in the water, changing the initial bubble size may lead to significant difference in the plume behavior, and the local environmental impact.

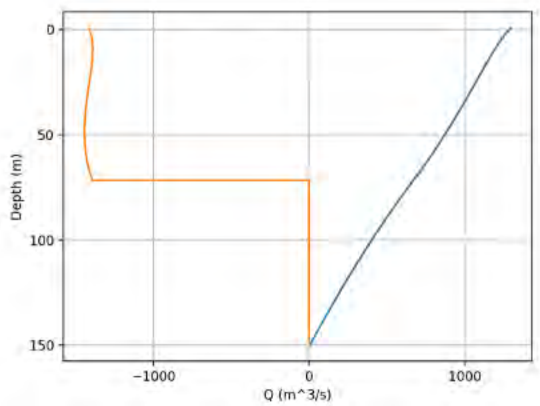

Figure 8: Entrained water flowrate (Q) in the inner plume (right) and outer plume (left) of subsea CO_2 release of 100 kg/s from a point source at 150 m depth.

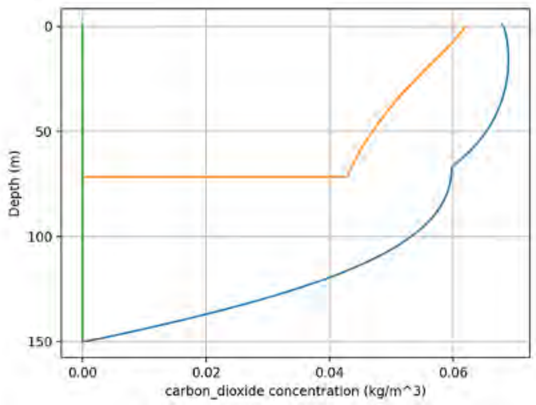

Figure 9: Concentration of dissolved CO_2 in the inner plume (blue) and outer plume (orange) of subsea CO_2 release of 100 kg/s from a point source at 150 m depth.

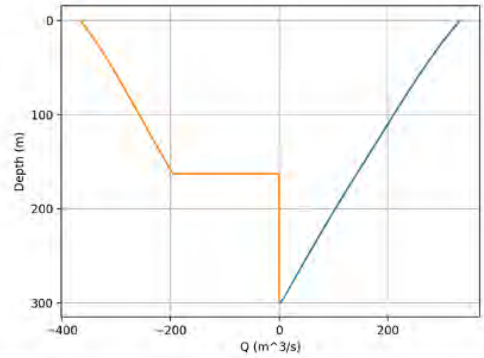

Figure 10: Entrained water flowrate (Q) in the inner plume (right) and outer plume (left) of subsea CO_2 release of 100 kg/s/m from a line source at 300 m depth.

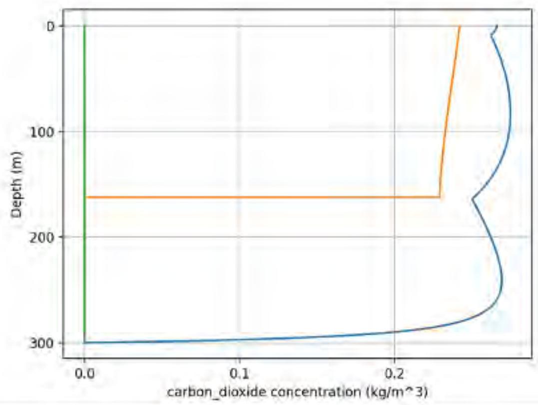

Figure 11: Concentration of dissolved CO_2 in the inner plume (blue) and outer plume (orange) of subsea CO_2 release of 100 kg/s/m from a line source at 300 m depth. The bubble size used in the simulation is 7.5 mm.

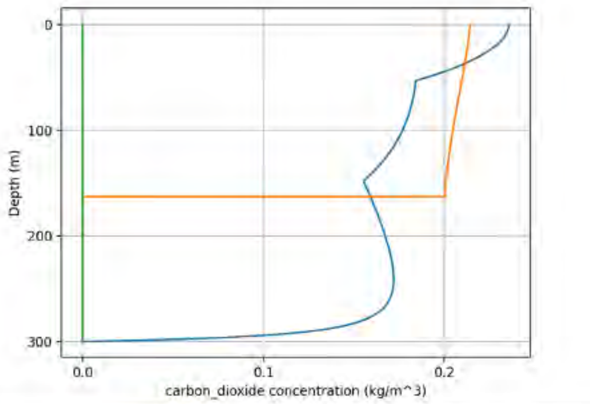

Figure 12: Concentration of dissolved CO_2 in the inner plume (inner) and outer plume (orange) of subsea CO_2 release of 100 kg/s from a line source at 300 m depth. The bubble size used in the simulation is 10 mm.

4. Summary and Conclusions

We have presented details of a modeling suite that can be used to simulate subsea releases of CO_2 at varying scales. The size distribution of the formed bubbles, the release depth, the release flowrate, and the release geometry are shown to have significant effect on the distribution of dissolved CO_2 in the water column. Dissolved CO_2 that reduces the pH in water leading to higher acidity may pose a potential threat to marine ecosystems in the vicinity of subsea CO_2 releases. Hence understanding the controlling parameters that determine the behavior of dissolved CO_2 from plumes and improving these in modeling tools will be useful for purposes of planning and risk assessment. Furthermore, integral plume models are very efficient in calculations compared to CFD models that are solving for three-dimensional detailed behavior of the plumes, as CFD models generally require far more computational time and resources. Hence, integral models are a very useful tool in predicting the behaviors of subsea CO_2 releases. Improving the capability of predicting the bubble size distributions from blowouts and seeps as well as the interaction of the plumes with the water surface are important areas for future studies of subsea bubble plume releases.

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