

Risk of Subsea Blowouts in Marine CCS

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In the foreseeable future, Carbon dioxide Capture and Sequestration (CCS) technique represents a promising method to contribute to the fulfilling of the ambitious objectives of carbon dioxide (CO₂) emission reduction posed by the European Commission (EU). The permanent storage of CO₂ is a step in the CCS chain that is of great concern due to the possibility of major accidents that could harm both humans and the environment. In the Adriatic Sea, the perspective of reusing depleted natural gas fields to stock CO₂ has become more and more appealing since it provides a competitive option to reduce emissions in the short term. With that comes the need to estimate the risk of potential CO₂ leakage events, particularly of blowout scenarios, which are one of the main hazards in CO₂ injection due to the potential extended duration and high flow rate of the release. Thus, in the present study an assessment of the effects of CO₂ blowouts in shallow water has been performed, identifying a set of models and tools available for the analysis of the consequences of subsea gaseous leakages and applying them to specific case studies. The aim of the current investigation is to highlight the specific aspects of the risk profile of CO₂ blowouts with respect to those of natural gas, considering that the risk of gas blowouts is not new and has previously been effectively controlled and managed in areas where natural gas reservoirs were exploited.

1. Introduction

In recent years, the Carbon dioxide Capture and Sequestration (CCS) technology has been recognised as a possible contributor to the emissions mitigation, at least in the mid-short term (IEA, 2021). The exploitation of CCS aims at achieving the objectives of curbing carbon dioxide (CO₂) emissions by the capture and storage of hard to abate emissions (IEA, 2020). A step of the CCS chain that is highly concerning is the storage stage, which can take place either onshore or offshore (Chadwick and Eiken, 2013). Abandoned oil and gas reservoirs, deep saline formations and unmineable coal seams are proposed as onshore geological sequestration sites (IPCC, 2005). Proposed offshore storage, instead, includes saline aquifers and depleted oil and gas reservoirs. In Europe, more specifically in the North Sea region, CO₂ sequestration involves saline aquifers, while in the Adriatic Sea, the possible storage of CO₂ in exhausted natural gas fields is proposed, since reusing existing infrastructures will allow costs to be highly competitive (ENI, 2020). However, the exploitation of offshore CCS requires to estimate the extent of the risk of potential blowout scenarios, which are characterized by high flow rates and very long durations (Dissanayake et al., 2018). Since there is previous evidence of CH₄ blowouts occurred from injection wells, the occurrence of CO₂ blowouts, in the case of marine CCS involving depleted gas reservoirs, is deemed possible as well (Gasda et al., 2004). Keeping in mind that risk depends on the likelihood and the severity of the consequences of the unwanted events, evaluating the risk of CO₂ blowouts implies estimating their occurrence frequencies and damage effects. On the one hand, considering that there is no information about CO₂ incidental release occurrences in the literature, it is reasonable to assume - as advised in technical reports - that the frequency of CO₂ blowouts should be similar to that of CH₄ blowouts, that may be estimated e.g., by an analysis of previous accidents (Beyer et al., 2016). On the other hand, it is impossible to compare the effects of the two substances directly, due to the differences in their chemical and physical properties, and of the inherent dangerous characteristics. In fact, as CO₂ dissolves well in water, the solubility of CH₄, in the same media, is negligible (Olsen and Skjetne, 2020). Hence, it is possible that CO₂ is released at the sea surface depending on the mass transfer process and the depth of the release (Huser et al., 2017).

In such situations, CO₂ disperses in air as a heavy cloud while CH₄ behaves as a light gas (Matheson, 2014). Additionally, CO₂ is a mildly toxic substance while CH₄ is flammable (Airgas, 2001). Because of these differences, the assessment of the effects of CO₂ once mixed with air needs to be carried out through a specific modelling approach. Moreover, in the case of a CO₂ blowout, the subsea plume of CO₂-enriched seawater causes the acidification of the marine environment, potentially causing a harm to the marine organisms in the water column and on the seafloor (Blackford and Gilbert, 2007). Therefore, in addition to the effects of atmospheric dispersion, estimating the dispersion of the undersea CO₂ plume is important for the assessment of the consequence of subsea releases. Several models are proposed in the literature to evaluate the effects arising from marine blowouts: source term models, water column dispersion models and atmospheric dispersion models of the degassing flowrate (Pan and Oldenburg, 2014). In the present study, the estimation of the effects of CO₂ blowouts occurring in shallow waters by means of integral models and tools for the analysis of the consequences of subsea gaseous leakages is presented. The investigation has the aim of analysing which is the potential impact of releases on specific targets, i.e., humans and animals living on the sea surface. In the following, the modelling approach developed is provided in Section 2 along with the integral models and simulation tools for subsea accidental leaking incidents. Section 3 presents some case studies used to benchmark the models. The results are presented and discussed in Section 4. Finally, the study is concluded in Section 5.

2. Modelling approach

A generic gaseous blowout scenario entails the release of a jet at high speed. The jet experiences a vertical ascent, which is aided by momentum and buoyancy contributions, while interfacial drag forces slow it down. During the rise to the sea surface, seawater entrains in the jet and horizontal currents contribute to the spreading of the plume, causing turbulent mixing. Additionally, the released bubbles and the surrounding water create an interphase mass transfer that, occasionally, results in enriched seawater in the compound of interest (Cloete et al., 2009). In the context of the present study, all the processes mentioned affect CO₂ seawater transportation. In fact, the water column provides positive buoyancy, viscous resistance, turbulent seawater entrainment, and surface tension leading to bubble formation. Moreover, seawater has a large capacity to absorb CO₂ (Olsen and Skjetne, 2020). This process implies seawater acidification and, consequently, density modification which can affect ships or vessels buoyancy (IPCC, 2005). Depending on the depth of the release and all the phenomena cited, a gaseous release of CO₂ can be totally dissolved in the water column or not. In the second case, CO₂ degassed at the free sea surface and disperses into the atmosphere as a heavy gas, so it tends to suffer gravity slumping towards the free sea surface and then gravity spreading.

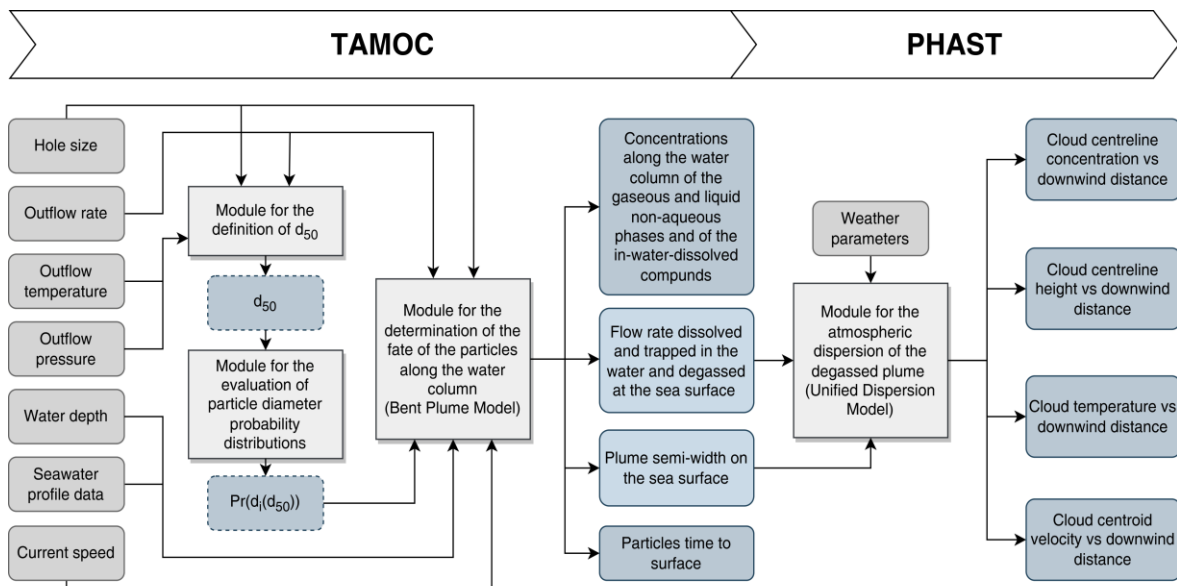


Figure 1: Methodology schematization.

In order to understand CO₂ transport processes both in the water column and in the atmosphere following major well blowouts, specific software tools were applied to model the sequence of phenomena occurring.

Figure 1 shows the schematization of the modelling approach applied. As shown in the figure, the first tool applied is the Texas A&M Oilspill Calculator (TAMOC). TAMOC is a modelling suite capable of predicting the nearfield dynamics of oil and gas released from subsea incidental events (Socolofsky et al., 2015). The software contains general modules for handling ambient seawater data, equations of state, and bubbles and droplets dynamics in the water column, providing steady-state simulations (Gros et al., 2018). For the purpose of modelling well blowouts, TAMOC Bent Plume Model (BPM) module was applied since it can handle large-scale releases, which are typical of blowout scenarios. The software considers the effect of water tides, which imply the deflection of the plume trajectory in the downwind direction and the eventual upwards transfer of gaseous bubbles escaping from the upstream edge of the plume (Dissanayake et al., 2018). The size of the orifice from which the substance of interest is released, the leakage flowrate, the outflow temperature and pressure, the depth of the water column, information on the seawater profile data, and the background cross current speed in the water column are all inputs to the TAMOC software. As an integral model, TAMOC does not simulate the behaviour of individual bubbles but the one of several bubble size classes. For this reason, it provides additional modules for calculating the initial bubble sizes and subsequent distributions (Wang et al., 2018). The estimates carried out with the Bent Plume Model provided the specific outputs used as an input to the simulation of the degassed CO₂.

The software used to run atmospheric dispersion simulations and to assess the consequences of blowout scenarios on humans and animal targets is PHAST by DNV-GL. This software tool is widely adopted for estimating the consequences of major accidents. The integral model implemented in the code to model air dispersion is the Unified Dispersion Model (UDM), which applies the steady-state plume mode (Witlox et al., 2012). Inputs to PHAST include meteorological parameters in addition to the free surface plume extent and degassed flow rate.

3. Case studies

In the present section a collection of case studies has been defined and analysed with the aim of highlighting the potential application of the identified modelling tools to plausible CO₂ gaseous well blowout scenarios occurring from depleted natural gas fields displaced in the Adriatic Sea. In detail, four case studies have been considered. In each case-study, a seawater column depth value ranging from 10 m to 60 m has been assigned while a single value of the outflow rate, equal to 200 kg/s, has been assumed for all the cases. The latter parameter has been selected based on literature data, and it represents a typical value of a severe blowout (Blackford et al., 2009). The choice of the temperature and pressure outflow values, selected equal to 10 °C and 40 bara, respectively, has been made using the same logic. To complete the definition of the source term, the size of the hole from which the substance escapes from the seafloor has been chosen equal to 15 cm, checking not to relapse into choked flow conditions. Moreover, TAMOC Bent Plume Model requires the initial mean diameter (d_{50}) and the sizes probability distribution of the bubbles released as inputs. To this regard, d_{50} has been set equal to 0.5 mm and the Rosin-Rammler distribution has been assumed to determine the diameter distributions of the bubbles in the water column (Oldenburg and Pan, 2020). Furthermore, ambient data are demanded to satisfy the input requirements for the simulations. As such, spring seawater temperature and salinity profiles of the north Adriatic Sea have been extracted from (Artegiani et al., 1997). Regarding the atmospheric dispersion, each case study shares the same meteorological data, which includes an air temperature of 10 °C and an ambient relative humidity of 70 %. Table 1 summarizes the input parameters adopted in the simulations.

Table 1: Details of the case studies.

Parameter	Value
Mass outflow rate	200 kg/s
Outflow temperature	10 °C
Outflow pressure	40 bara
Hole size	150 mm
Mean bubble diameter (d_{50})	0.5 mm
Water column depth	10, 20, 40, 60 m
Air temperature	10 °C
Humidity	70 %

4. Results and discussion

Figure 2 reports the TAMOC outcomes concerning the marine dispersion of CO₂ bubbles, reporting the CO₂ flow rate dissolved in the water column for the different release depths assumed for the case studies.

As shown in the figure, the CO₂ leakage flow rate is strongly attenuated for water column heights greater than 30 m. Almost all the leaked CO₂ dissolves in the water column for the 60 m-deep case. Differently, when the release occurs at a depth of 10 m, nearly all the leaked CO₂ is emitted to the atmosphere. The factors that influence the behaviour of CO₂ along the water column are the solubility and the dimension of the gaseous bubbles. In detail, the high solubility of CO₂ in water together with the small dimension of the bubbles formed enhance the dissolution process. In particular, small bubble size crates a high surface area to volume ratio improving fast dissolution (Olsen and Skjetne, 2016). Moreover, smaller bubble sizes imply higher time for dissolution due to slower rise velocities, so impacting on the dissolution rate. Since CO₂ dissolves either partially or totally in the water column, it might be interesting to discuss the trend of the dissolved CO₂ concentration along the water column. Figure 3 shows the tendency analysed for the 10, 20, 40, and 60 m-deep spill events. As depicted, for the 10 and 20 m-deep scenarios, the concentration of CO₂ dissolved in the seawater increases with the water column depth. On the contrary, for the other case studies, the concentration of the dissolved CO₂ increases up to a water column depth of approximately 35 m, then decreases.

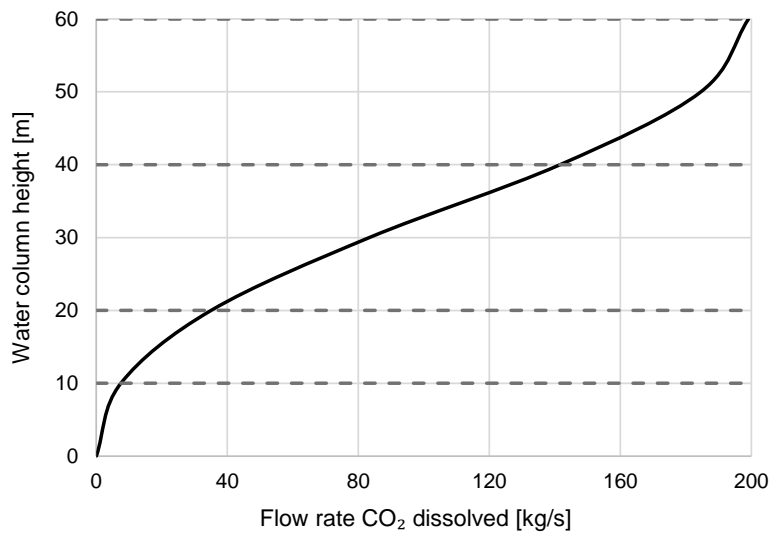


Figure 2: Flow rate of CO₂ dissolved in the water column as a function of water column height; dashed lines correspond to the different water column depths considered in the case studies (see Table 1).

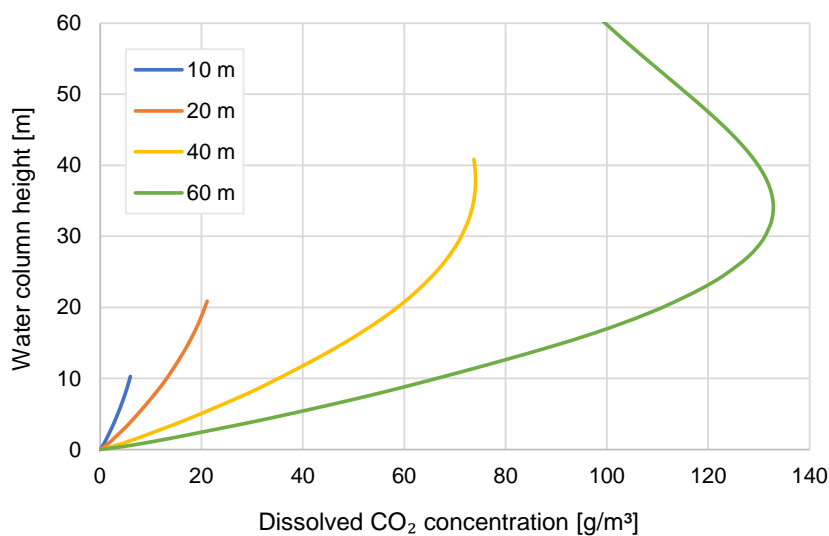


Figure 3: Concentration of dissolved CO₂ in the water column as a function of water column height.

When atmospheric dispersion is considered, Figure 4 reports the results obtained from the PHAST software. The figure reports the damage distances corresponding to specific CO₂ damage thresholds with respect to human and animal targets. The graph displays the values of the damage distances corresponding to the IDLH (Immediately Dangerous to Life and Health), equal to 40,000 ppm for CO₂, as a function of the height of the water column. In general, at increasing outflow rate, the damage distances increase. However, as shown in Figure 4, this behaviour is not present in the 10 m-deep case since the atmospheric discharge velocity strongly affects PHAST outcomes. In fact, the 10 m-deep case is the only one deemed as vertical jet release; the high speed of the jet allows to keep the plume away from the source facilitating the incorporation of air and leading to reduced impacts. This behaviour can be numerically illustrated showing that moving from 10 to 20 m water column height, the absolute damage distance percentage variation is equal to 462 %.

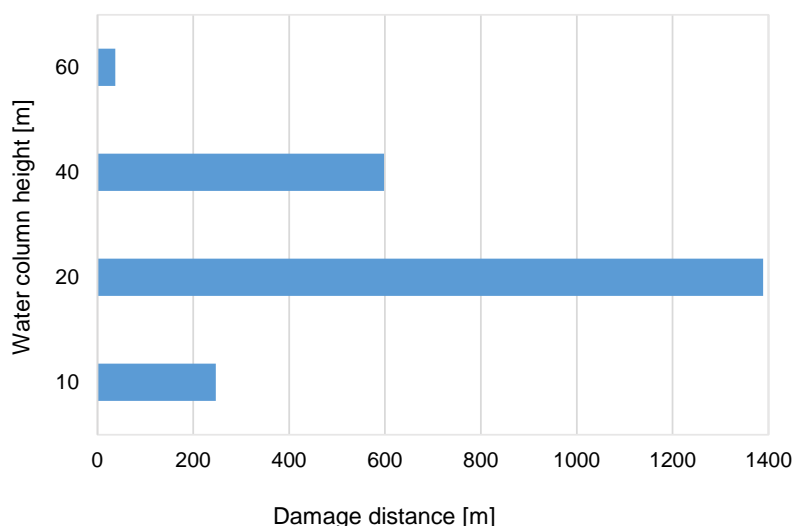


Figure 4: CO₂ damage distances corresponding to IDLH as a function of water column height.

5. Conclusions

In the present study, a modelling approach to assess the consequences of major blowout scenarios occurring from depleted natural gas reservoirs in shallow waters is developed. The analysis of a set of case studies has shown that the chemical and physical characteristics of the substance escaping from the well, the release depth, and the release flow rate have significant effects on the distribution of the dissolved compound in the water column. Actually, CO₂ emissions are significantly attenuated by the dissolution of CO₂ in water along the water column. Only when the release takes place at a depth of 10 m, the compound degasses at the sea surface without a significant dissolution in water. Thus, CO₂ major blowouts in shallow waters may pose a non-negligible risk for animals and for humans on the free sea surface. When the IDLH concentration is considered as a damage threshold to assess the impact area of such scenarios, the 20 m-depth release resulted in the highest damage distance. This outcome confirms that the release flow rate is not always the primary factor influencing the atmospheric dispersion of blowouts. Actually, a key role is also played by the release velocity that promote mixing with air in favour of safety, as is the 10 m-deep case.

Dissolved CO₂ may also pose a potential threat to the marine environment, since it may reduce seawater pH leading to higher acidity. Therefore, a comprehensive risk assessment should integrate the modelling tools with tools able of handling the dissolution in water and chemical equilibria both in the near field and in the far field compartments.

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