CHEMICAL ENGINEERING TRANSACTIONS

VOL. 26, 2012

Guest Editors: Valerio Cozzani, Eddy De Rademaeker

ISBN 978-88-95608-17-4; ISSN 1974-9791

A publication of

AIDIC

The Italian Association
of Chemical Engineering
Online at: www.aidic.it/cet

DOI: 10.3303/CET1226096

Conceptual Models for CO_2 Release and Risk Assessment: a Review

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The current state of the art in the analysis of risk for CO_2 transport by pipeline is briefly reviewed, in particular in respect of current models for CO_2 release, the assessment of impact from such release, and overall risk analysis. For a simple case study, a comparative analysis is presented of alternative models for the calculation of consequences. This comparison indicates that different assumptions, models and software lead to important differences in the calculation of consequences. Key unresolved problems and some directions for research needed are identified. One of the problems for assessment of the results is the lack of experimental data.

1. Introduction

Carbon capture and storage (CCS) is a technology for mitigating the contribution of fossil fuel emissions to global warming. The technology is based on capturing carbon dioxide (CO_2) from point sources and storing it in geological formations in such a way that is does not enter the atmosphere. CCS requires the transport of CO_2 from source to sink. This can involve one or a combination of transport media: truck, train, ship or pipeline. Transport by pipeline is the preferred option for transporting large quantities of CO_2 over long distances.
The majority of CO_2 pipelines are in the USA and Canada, along with substantial in-field pipework for Enhanced Oil Recovery (EOR) projects (Kelliher et al, 2009; Kadnar, 2008). The USA experience cannot be easily applied to other regions or situations, because the CO2 pipelines are located in areas with low population density. In general, as stated in the report of the IPCC on CCS (IPCC, 2005), there is a lack of knowledge regarding the safety of pipeline transmission of CO_2 in densely populated areas.

2. Quantitative Risk Assessment

Risk is the likelihood of an undesired occurrence happening when performing a practice: risk analysis is a methodology for quantifying the risk involved in a practice. Quantitative risk assessment (QRA) requires calculations of two components of risk: the magnitude of the potential loss and the probability that the loss will occur. In order to determine a risk, several aspects need to be defined and quantified:
i) Identification of hazards; ii) Frequency of occurrence of hazards; iii) Consequences of hazard occurring.
As shown by Koornneef et al. (2009, 2010), this analysis presents the problem of evaluating uncertainties in input parameters and sensitivity to underlying assumptions. In particular knowledge gaps exist with regards to i) failure frequency and ii) dispersion modeling and consequences calculation. In the following these issues are briefly considered and a case study is reported.

Please cite this article as: Vianello C., Macchietto S. and Maschio G., 2012, Conceptual models for co2 release and risk assessment: a review, Chemical Engineering Transactions, 26, 573-578 DOI: 10.3303/CET1226096

2.1 Failure frequency

The first requirement is to identify a suitable failure frequency of pipeline components (pipeline segments, booster stations, connections with capture and injection plants). For CO_2 pipelines many studies, e.g. Hooper et al. (2005) and Turner et al. (2006), simply assume the same failure frequency as for natural gas. Table 1 shows that even the values of natural gas pipeline failure frequency vary by a factor of 6. Natural gas is different from CO_2 and these failure rates may not be valid (Koornneef et al., 2010). There are some failure rate data for CO_2 pipelines (Vendrig et al., 2003) but these cannot be easily compared with natural gas because the CO_2 pipeline cumulative experience is limited.

Table 1 Cumulative frequency - natural gas

Pipeline failure	Reported values		
Cumulative failure frequency [incidents km^{-1} $year^{-1}$]	$6.1 \cdot 10^{-4}$	$1.55 \cdot 10^{-4}$	$1.1 \cdot 10^{-4}$
References	CPR, 2005b	NEB, 1998	EGIG, 2007

2.2 Dispersion and consequences modeling

The second aspect relates to the CO_2 *dispersion* model and calculation of the *consequences*.

Release depends on the conditions of CO_2 transport which can be in three states: liquid, gas or supercritical. In cases where CO_2 is transported in the liquid phase, the release following a full bore rupture is usually calculated using a model for non-stationary two-phase outflow from a large pipeline (CPR, 2005). In cases where the CO_2 is transported in the gas phase, a model for a non-stationary outflow from a gas pipeline is generally used, or coupled with a spray-release model and a dense gas dispersion model based on SLAB (Ermak, 1990).

There are several methods for calculating the dispersion of CO_2, based on heavy gas dispersion:

- TNO method (CPR, 2005) – software EFFECT
- DEGASIS+ (Kruse and Tekiela, 1996)
- Universal Dispersion Model (UDM) in the DNV PHAST Software

Figure 1 highlights various phenomena that may occur and would need to be assessed to calculate the consequences of CO_2 dispersion (Koornneef, 2009).

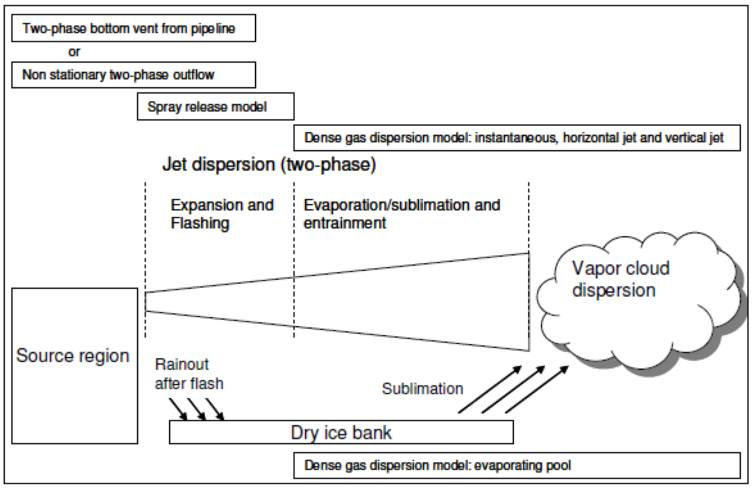


Figure 1: Key phenomena occurring following a puncture or full rupture of a carbon dioxide pipeline.

The dispersion calculation should consider the formation of dry ice and then its sublimation. This will have an effect on heavy gas cloud dispersion. This aspect is under study (Mazzoldi et al, 2011), but at the moment there are no generally accepted models and software for the calculation of this phenomena and indeed, very few primary experimental data. Other issues relevant to the calculation of

consequences are the lack of critical comparison of different studies on a similar basis and the critical assessment of different models returning different results. This is often due to the undocumented use of different assumptions and models.
To highlight this point the following section shows a comparative analysis for a simple case study.

3. Case Study

A study is performed of an example proposed by Kruse and Tekiela (1996), which has all data required to also perform a simulation using the PHAST software. Kruse and Tekiela (1996) focused on the cost and consequences of large-scale CO_2 transport in a steel pipe, transporting CO_2 in liquid or gaseous form (gas data are shown in table 2). The calculation of consequences (e.g. max distance to threshold value) was carried out according to the concentration limits of CO_2 effects on human health (NIOSH 2007). We refer to these results as a CASE 1. The later simulation of the same event conducted with PHAST is denoted as CASE 2.

3.1 Transmission system

The pipeline modeled is 30 km long and transports a CO_2 flow of 250 t/h. Stable meteorological conditions are assumed with an average ambient temperature of 20 °C and surface temperature of 15 °C. Horizontal wind component with speed of 5 m/s and flat terrain were assumed.

Table 2: Characteristics of CO_2 transport in pipeline (Kruse and Tekiela, 1996)

Data		Gaseous
Pipeline length	km	30
Internal diameter	m	0.65
Hold up volume	m^3	9955
Transport pressure	bar	35
Soil temperature	˚C	7

3.2 Release modeling and consequence – CASE 1

The emission from the pipeline was determined on the basis of physical and thermodynamic properties calculation of the gas/liquid according to equation 1.
A worst-case emission was assumed, defined by a complete pipe rupture a both ends near two check valves causing outflow from both pipe ends. For such a rupture, the period of time taken for release of the large amount of CO_2 involved is assumed to be short (initial puff model).

3.2.1. Release – CASE 1

After the rupture it is assumed the gas/liquid will continue to flow into the damaged segment, but this flow was disregarded in the calculation as it was assumed to have no influence on the amount included in the initial puff. The outflow release was modeled on the basis of a relatively simple equation (CPR, 2005a).

$$Q_m = A \cdot c_1 \sqrt{P_t \cdot \rho_t \cdot c_2} \qquad (1)$$

where Q_m is outflow [kg/s], A is a cross sectional area [m^2], P_t time dependent pressure in pipe [bar],ρ_t time dependent density in pipe (kg/m^3), c_1 is a coefficient of discharge (here 0.98) and c_2 is a material constant (here 1.29). Figure 2 gives the resulting gas CO_2 release time profile (essentially exponential).

3.2.2. Consequences – CASE 1

A dense gas model, the US-EPA DEGASIS+ (Ermak, 1990), was used to estimate the transport and dispersion of the CO_2 gas in the atmosphere. The amount of gas contained in the puff was determinate by using the decay period ($t_{1/2}$):

$$t_{1/2} = \frac{\tau}{2} \qquad (2)$$

where τ is a time required for the release gas flow rate to reduce to 63 % of the initial release rate. Here, $t_{1/2}$ is 54 seconds and (results not shown) the pipe becomes 90 % empty in 163 s.

Adiabatic expansion of the released CO_2 will cause the temperature to decrease to -56 ˚C (triple point), but as the outflow is modeled as a puff and some mixing with ambient air was assumed, an average temperature of -20 ˚C was assumed after the expansion.

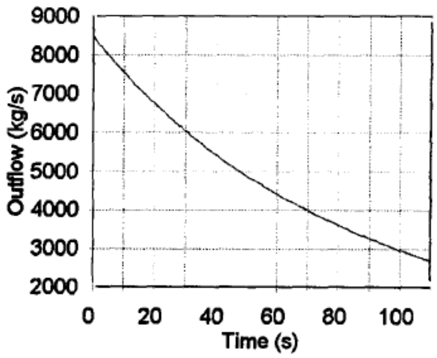


Figure 2: CASE 1 - Outflow release from pipe segment as a function of time *(Kruse and Tekiela,1996)*

The results from the dispersion modeling are listed in Table 3.

Table 3: CASE 1 - consequences calculation at time equal to the decay period

Data		Gas
Period of decay	s	54
Amount of CO_2 in puff	t	346
Max. distance to threshold value	m	750

3.3 Release and consequences – CASE 2

Here the calculation of the release of CO_2 from the same pipeline is calculated using PHAST. The PHAST 6.6 version used includes a new model that can handle gas or liquid CO_2 in the pipeline, a release following depressurisation as a mixture of gas and liquid, and neglects the formation of an ice dry bank and snow-out (for discharge of supercritical CO_2 from a long pipeline, the new version includes non ideal effects, important as they may significantly increase the expelled mass). It is possible to consider CO_2 as a toxic material by specifying the appropriate probit function value (HSE, 2009). The simulation has been carried out considering the same input as in the simulated CASE 1, but with small changes. In PHAST it is not possible to define a pipe rupture at both ends of a pipeline segment. An equivalent diameter was therefore calculated that gives the same gas hold up volume as in CASE 1. This gives a pipeline length of 15 km and an equivalent diameter of 0.919 m (Table 4). In all simulations the release is defined by the full bore rupture (hole diameter = diameter pipeline).

Table 4: Input pipeline data in PHAST models

Data		Gas
Pipeline lengh	km	15
Equivalent diameter	m	0.9192
Hold up volume	m^3	9955
Transport pressure	bar	35
Soil temperature	°C	7

In PHAST it is possible to calculate a discharge from a vessel or a pipeline according to two distinct models. The first model, called initial rate, calculates the discharge rate based on the initial conditions only. The discharge is assumed to continue at this rate until the inventory is exhausted. The second, time-varying model, calculates the change in the pipeline conditions and release rate profile as a function of time as the release continues. A fixed discharge coefficient may be specified (here a value

of 0.98 was set to match CASE 1). Alternatively the discharge coefficient may be calculated by PHAST using its Universal Dispersion Model. The release in CASE 1 was calculated neglecting any pump flow into the pipeline. This situation can be approximated in PHAST using a *vessel* model. For the more realistic *pipeline* model PHAST also includes pump flow after the rupture time. We therefore considered the following models:
i) Vessel with initial rate model (CASE 2.A); ii) Vessel with time varying model and variable discharge coefficient (CASE 2.B); iii) Vessel with time varying model and fixed discharge coefficient (CASE 2.C); iv) Long pipeline whit time varying model with variable discharge coefficient (CASE 2.D).
All simulations considered CO_2 transport in the gas phase.

3.3.1. Vessel with initial discharge modeling – CASE 2.A

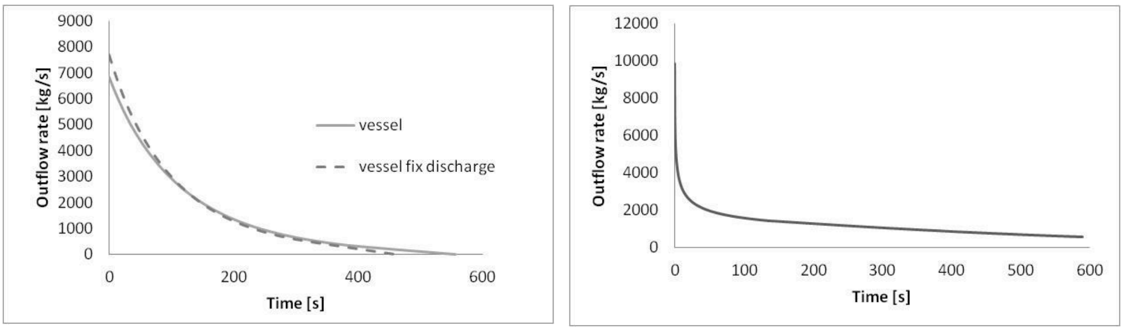
The key results are shown in Table 5.

Table 5: CASE 2A - Release rate and consequence at time equal to the decay period

Period of decay	s	61,7
Amount of CO_2 in puff	t	828
Max. Distance to threshold value	m	643

3.3.2. Vessel with time varying model – CASE 2.B, C and long pipeline – CASE 2.D

These models evaluate the release rate as a function of time, shown in figure 3. Figure 3(a) results are comparable to those of CASE 1 (Figure 2) as they share similar assumption. The outflow from long pipeline model (Figure 3(b)) shows a rather different profile as the pump flow assumptions are different. The key consequence results (Table 6) are very different from CASE 1.



(a) (b)

Figure 3: Outflow gas release as a function of time: (a) Vessel with time varying modeling CASE 2.B and CASE 2.C; (b) long pipeline model CASE 2.D

Table 6: Results at decay period case 2.B-D at time equal to the decay period

		Case 2.B	Case 2.C	Case 2.D
Period of decay	s	65	57	193
Amount of CO_2 in puff	t	337	337	364
Max. Distance to threshold value	m	358	382	183

4. Conclusion

There are various models for calculating release rates, dispersion and consequences. As noted by Koornneef (2009, 2010) it is difficult to compare their results, as assumptions, methodology and parameters are typically different. The comparison presented here for a simple application indicates that calculated release rate can be very different if a “vessel model” is used instead of a “long pipe” model due to ignoring pump flow. Release rates must be calculated very accurately because the consequences analysis is very sensitive to its results. An important factor is the accurate calculation of thermodynamic properties. Even when release rates are similar consequences calculated with different software may be very different. Here, the maximum distance calculated with PHAST is half of that calculated with DEGASIS+, due to different heavy gas dispersion models. Other experiences indicate that the modeling of liquid phase and droplet formation is especially important. Most available software ignore the formation of ice dry bank and sublimation effects, which could considerably affect the time profile of vapor cloud size, CO_2 concentration, maximum distance and risk from an accidental release. The critical assessment of various model is hampered by the absence of reliable experimental data.

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