

CO_2PIPEHAZ: QUANTITATIVE HAZARD ASSESSMENT FOR NEXT GENERATION CO_2 PIPELINES

Haroun Mahgerefteh[7], Michael Fairweather[1], Sam Falle[1], Jens Melheim[2], Mathieu Ichard[2], Idar Storvik[2], Ole Jacob Taraldset[2], Trygve Skjold[2], Ioannis Economu[3], Dimitrois Tsangaris[3], Laurence Cusco[4], Mike Wardman[4], Simon Gant[4], Jill Wilday[4], Yong Chun Zhang[5], Shaoyun Chen[5], and Christophe Proust[6]
[1]University of Leeds, UK
[2]GEXCON AS, Norway
[3]National Research Centre for Physical Sciences, Greece
[4]Health and Safety Laboratory, UK
[5]Dalian University of Technology, People's Republic of China
[6]Institut National de l'Environnement et des Risques, France
[7]UCL, UK

This paper presents an overview of the recently commenced CO_2PipeHaz project focused on the hazard assessment of CO_2 pipelines to be employed as an integral part of the Carbon Capture and Storage (CCS) chain. Funded by the European Commission FP7 Energy programme, the project's objective is to address the fundamentally important and urgent issue regarding the accurate predictions of fluid phase, discharge rate and subsequent atmospheric dispersion during accidental releases from pressurised CO_2 pipelines. This information is pivotal to quantifying all the hazard consequences associated with failure of CO_2 transportation pipelines forming the basis for emergency response planning and determining minimum safe distances to populated areas. The developments of the state of the art multi-phase heterogeneous discharge and dispersion models for predicting the correct fluid phase during the discharge process will be given special consideration given the very different hazard profiles of CO_2 in the gas and solid states. Model validations are based on both small scale controlled laboratory conditions as well as large scale field trials using a unique CCS facility in China, the world's largest CO_2 emitter. A cost/benefit analysis will be performed to determine the optimum level of impurities in the captured CO_2 stream based on safety and economic considerations. The project will embody the understanding gained within safety and risk assessment tools that can be used for evaluating the adequacy of controls in CO_2 pipelines, with best practice guidelines also being developed.

KEYWORDS: CO_2, pipeline transportation, accidental discharge, CCS

INTRODUCTION

It is commonly accepted that pressurised pipelines represent the most reliable and cost effective way of transporting captured CO_2 from fossil fuel-fired generation plant for subsequent sequestration. This has enormous implications for the EC since a significant proportion of its electricity is fossil fuel power generated [1]. Given that most electricity generation plants are built close to energy consumers, the number of people potentially exposed to risks from CO_2 transportation facilities will be greater than the corresponding number exposed to potential risks from CO_2 capture and storage facilities [2].

Ironically (in line with its abbreviation), CCS and related legislation generally focus on the capture and storage of CO_2, and not the link, its transportation. This is despite the Intergovernmental Panel on Climate Change [2] concluding that "public concerns about CO_2 transportation may form a significant barrier to large-scale use of CCS".

A transportation infrastructure that carries CO_2 in large enough quantities to make a significant contribution to climate change mitigation will require a large network of pipelines spanning over hundreds of kilometres. Given that the most economical means of transporting CO_2 is in the supercritical state due to its low viscosity and high density, a typical 100 km, 0.8 m diameter CO_2 pipeline under such conditions would contain approximately 9000 tonnes of inventory. In the event of pipeline failure, for example a full bore rupture, a significant proportion of the inventory would be discharged in the first few minutes. At a concentration of 10%, an exposed individual would lapse into unconsciousness in 1 min. Furthermore, if the concentration is 20% or more, the gas is instantaneously fatal [3]. The ability of CO_2 to collect in depressions in the land, in basements and in other low-lying areas such as valleys near the pipeline route, presents a significant hazard if leaks continue undetected.

There are very few risk-based reference points in handling high pressure CO_2 in large (1000 tonne) quantities against which estimated risks to persons can be compared to establish if a robust case for safety has been made [4]. In addition, there is very little understanding of the impact impurities on the phase equilibrium properties of CO_2 and hence its discharge behaviour.

It is clear that the hazards associated with CO_2 pipelines are quite different compared to those posed by hydrocarbon pipelines, presenting a new set of challenges. Present experience in using CO_2 transportation pipe lines is limited to those used for enhanced oil recovery [5]. However, these are either confined to low populated areas, and/or designed for transportation of CO_2 gas at low pressures. Additionally, due to the small number of CO_2 pipelines, it is not possible to draw a meaningful statistical representation of the risk [2].

A recent EC commissioned study [6] classifies pipelines as a "major-accident hazard". In order to address this issue CO_2PipeHaz project has been launched by the EC in December 2009 [7]. The project combines experimental and numerical modelling approaches to develop and validate the hazard assessment tools for the future CO_2 transportation pipelines, including emergency response planning and determining minimum safe distances to populated areas. This project brings together leading scientists, industrialist and legislative organisations from UK, China, France, Greece and Norway. An important aspect involves the validation of the mathematical models based on comparison with the results obtained following the controlled rupture of a real CO_2 pipeline in China.

This paper presents an overview of the recently commenced CO_2PipeHaz project focused on the hazard assessment of CO_2 pipelines to be employed as an integral part of the Carbon Capture and Storage (CCS) chain. The project funded by the European Commission FP7 Energy programme involves close collaboration between scientists and industrialists including University College London (UCL), University of Leeds (UoL), GEXCON AS, Institut National de l'Environnement et des Risques (INERIS), NCSR and Dalian University of Technology (DUT).

The project's objective is to address the fundamentally important and urgent issue regarding the accurate predictions of fluid phase, discharge rate and subsequent atmospheric dispersion during accidental releases from pressurised CO_2 pipelines.

METHODOLOGY

The CO_2PipeHaz project is carried out in five Work Packages (WP). Figure 1 is a schematic representation of their relationship to the release process following the accidental failure of a CO_2 pipeline.

The main technical developments will be carried out in WP1 and WP2. The composition and level of impurities transported in the CO_2 pipeline based on a cost/benefit analysis will be determined in WP 1.1. WP1.2 will concentrate on the development of the equations of state for CO_2 and its mixtures. This will provide the thermodynamic and physical properties data needed for the multiphase discharge model to be developed under WP1.3. This information will in turn serve as the source condition for subsequent work near-field (WP1.4) and far-field (WP1.5) dispersion models that will consider the atmospheric concentrations of the dispersing material. WP2 involves experiments that will provide a basic understanding of these complex flows, as well as data to assist in the formulation and validation of the outflow and near-field dispersion models. WP3 deals with Decision Support Tools, and covers geographical information systems input, a review and refinement of best practice guidelines, and the provision of safety and risk assessment tools followed by their application in test cases. WP4 and WP5 deal with Dissemination and Project Management strategies respectively.

The following is a more detailed description of the various work packages.

CO_2 COMPOSITION AND PHASE EQUILIBRIUM STUDIES

Likely ranges for the composition of captured CO_2, and factors affecting those ranges, will be identified for the basic CO_2 capture technology options including post-combustion, pre-combustion and oxyfuel.

Assessments of the requirements for CO_2 purification, through minor component and impurity removal

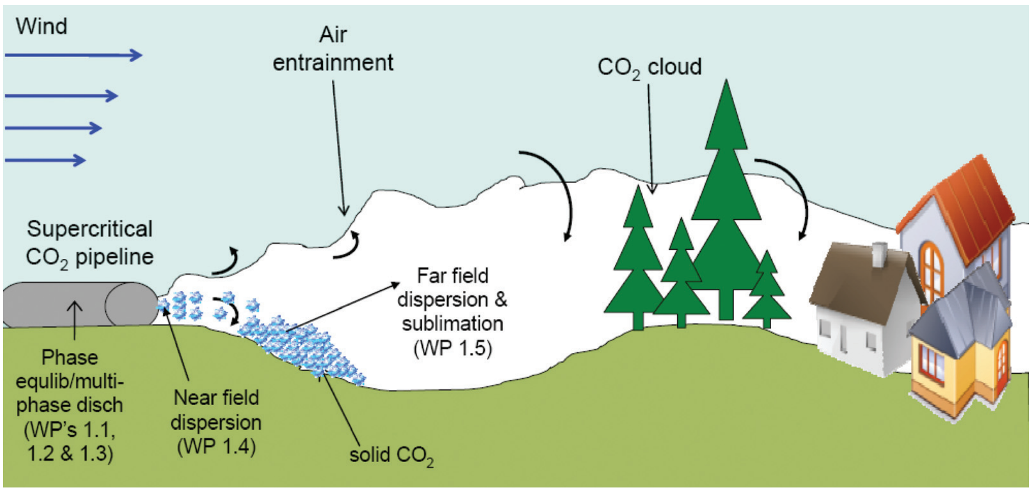

Figure 1. Schematic representation of the release process, highlighting the different work packages (WP) in the CO_2Pipe Haz project

from CO_2 mixtures, in order to protect pipelines during transportation and the environment following accidental release will be carried out. In particular, heavy metals such as Mercury and Arsenic are highly hazardous, and must be removed completely. Acidic gases such as SO_2, HCl, NO_x and H_2S in the presence of water would lead to corrosion of the pipe wall. On the other hand, small gaseous molecules such as H_2, N_2 and O_2 would penetrate and damage the pipeline material.

Recommendations will be made regarding acceptable CO_2 compositions and required purification methods. The costs for achieving higher CO_2 purity will be assessed on the basis of estimates for the reduced performance (i.e. operating costs and possibly capture level) and also increased capital costs. Here the unique experience of DUT in developing large scale processes for producing food-grade CO_2 (>99.99%) will be of key importance. We will use an existing pilot absorption unit for removing contaminants from CO_2 at DUT's research laboratories. The CO_2 generated from a small scale boiler is mixed with the various impurities which are then removed in various stages in the process. The setup is used to investigate the absorption duty and hence the estimated relative costs associated with producing acceptable levels of CO_2 purity using systematic optimisation based methods and scale up.

A dedicated Equation of State (EoS) for predicting thermodynamic and phase equilibrium properties of CO_2 in the presence of impurities covering a wide range of temperatures and pressures including the supercritical and triple point regions is being developed by NCSR using perturbed chain-polar statistical associating fluid theory (PC-PSAFT) [8, 9].

An existing small-scale high pressure facility at INERIS is used for validating the CO_2 EoS for the mixtures of CO_2 with the compounds identified from the cost benefit analysis. Briefly, the high pressure unit comprises a 1 litre, 500 bar pressure vessel fitted with thermocouples, pressure gauges and a sapphire observation window. The unit can be weighed continuously to obtain the Mollier diagram (pressure/enthalpy) of the contents. The setup also allows measurement of the phase content and viscosity of the fluid.

NUMERICAL MODELLING OF OUTFLOW AND DISPERSION FOLLOWING PIPELINE RUPTURE

This work package aims to develop mathematical models for the accurate computation of transient multi-phase heterogeneous outflow and atmospheric dispersion of CO_2 including the typical impurities from the ruptured pipe.

Multi-Phase Heterogeneous Outflow Model

The development of a rigorous outflow model requires the precise tracking of the expansion waves and their propagation as a function of time and distance along the pipeline. This involves detailed consideration of several factors including heat and mass transfer, unsteady and heterogeneous nature of the flow and thermodynamics of the multiphase fluid. The fact that the speed of sound is markedly affected by the state of the fluid means that the model must also incorporate an accurate equation of state. Due consideration must also be given to the effects of friction which is both flow and phase dependent. More specifically, in the case of CO_2 pipelines, the widely different densities of gas, liquid and solid during the highly transient flows will very likely lead to phase slip and hence non-equilibrium or heterogeneous flow.

In this WP the heterogeneous flow in a ruptured pipe is simulated by UCL using a multi-fluid flow model. The solution of the mathematical model is obtained using a numerical technique based on the Finite-Volume Method (FVM), incorporating a conservative Godunov type finite-difference scheme [10]. The model validation will be based on comparison against the small and large scale pipeline outflow test data obtained as described in the experimental studies and model validation section.

Near-field Dispersion Model

In line with the methods used to model flow in a pipe, the near-field gas phase dispersion model is based on solutions of the time-averaged Navier–Stokes equations. This model involves the system of partial differential equations that describes the conservation of mass, momentum and total energy, as well as equations of the turbulence model [11]. The mixing field of the gas phase jets is predicted by solution of an equation for a mixture fraction probability distribution function (PDF). A similar approach is used to model liquid droplet and dry ice formation within the dispersing jet. Relevant thermodynamic and thermophysical properties will be determined as described above for the outflow model, with the individual nucleation, condensation, evaporation and coagulation terms modelled using classical approaches [12, 13].

The near-field dispersion model is being implemented in a general purpose computational fluid dynamic code [14, 15] developed at UoL. The code permits solution of the descriptive equations in two- or three-dimensions, with the system of equations integrated numerically using a second-order accurate finite-volume scheme.

Initial conditions for the near-field dispersion model are taken from the outflow model. Output from both models will be used as the initial condition for the far-field dispersion models described in the following section.

Far-field Dispersion Model

In order to predict hazard ranges for CO_2 pipeline failures, the far-field dispersion of CO_2 in the atmosphere has to be simulated using an accurate and reliable model. For this purpose, Computational Fluid Dynamics (CFD) models will be used by GexCon. These account for the effects of terrain, buildings and wind, typically considering a distance of around one kilometre from the CO_2 source. Two-phase CO_2 jets will be described using the Eulerian–Lagrangian approach where the droplets/particles are tracked in a continuous gas phase.

The far-field dispersion simulations use a source model to account for the complex near-field flow behaviour as described in the previous section. This can be a source of gaseous CO_2 from the gas jet, a fraction of sublimating solid dry-ice particles in the jet, and a low-momentum source of CO_2 due to sublimation from a dry-ice bank of material. GexCon and HSL have considerable experience in the application of source models in CFD simulations for hazardous area classification [16–18], as well as far-field dispersion studies [19, 20].

The far-field dispersion model developed will be validated using the measurements obtained from the industrial scale pipeline release experiments described in section the next.

EXPERIMENTAL STUDIES AND MODEL VALIDATION

Small-Scale Experimental Studies

The small-scale experiments are aimed to investigate the heterogeneous flow patterns in the ruptured pipe and the near-field dispersion region, as well as assist the design of the experimental techniques for large-scale experimental studies.

The small-scale test setup comprises a 20 mm i.d. 40 m long pipe attached to a 2 m^3 feed pressure vessel. The thermally insulated vessel has a maximum operating pressure and temperature of 200 bar and 200 ^oC respectively. It is equipped with 10 thermocouples and 2 high precision pressure gauges as well as sapphire observation windows. The relevant impurities can be added to the CO_2 feed.

The discharge rate from the ruptured pipe is determined based on the continuous weighing of the entire vessel, thus allowing the validation of the discharge model. Also, transparent sections of the discharge pipe allow the recording of the various fluid flow regimes using high speed digital recording. In-house miniaturised fast response Pitot tubes are used to determine the gaseous mass fraction and velocity.

At the exit of the pipe, the temperature, velocity, momentum of the flow and solids particle size distribution will be measured. Further downstream, the temperature, CO_2 concentration and velocities in the dispersed cloud will be measured using oxygen depletion meters and anemometry.

Industrial-Scale Experimental Studies

Extensive large scale experiments are necessary to obtain a complete understanding of the discharge phenomena and gas plume behaviour from a large CO_2 release and to validate the flow models developed. Large scale tests remove uncertainties regarding scale effects and test the validity of assumptions in the derivation of the models. In particular, the mutli-phase discharge and the far-field dispersion models need to be verified against industrial-scale outdoor experiments with a high release rate for credibility.

Until now, no large-scale dense gas CO_2 dispersion experiments with massive releases have been undertaken to investigate the effects of building wakes and depression in the terrain.

The large scale CO_2 release experiments will be conducted at the CCS enhanced oil recovery plant in the Liaohe Oil field close to the Gulf of Bohai in the Liaoning province, China. The remote location of the plant allows the unique opportunity of a test site of over 4 square kilometres.

In these investigations, the fully instrumented 500 m long, 20 cm i.d. pipeline will be charged with the CO_2 captured from the coal-fired flue 23 tonne steam per hour boiler. The release tests will cover both supercritical as well as gas phase CO_2 using a variety of puncture diameters including full bore rupture.

Several temperature and pressure transducers will be located along the discharge pipe length to collect the data for the discharge model validation. In addition, pressure and temperature will be measured at the outlet. The discharge rate will be confirmed from pressure and temperature measurements as well as calibrations performed using a small-scale laboratory setup at INERIS. 30 m tall masts will be erected in the vicinity of the discharge point. The units will be equipped with meteorological equipment such as sonic anemometers to obtain the wind/temperature profiles, friction velocities, and meteorological length scales. Video systems will be used to record the discharge flow and the lateral evolution of the cloud. In the far-field of the release, oxygen depletion detectors will be located on several arches at different distances from the release point.

Whenever possible, tests will be carried out under different wind conditions and different terrain configurations including flat terrain, flat terrain with obstacles and excavated crater. The measurement locations will be moved such that the effects of walls and the valley are captured.

SUPPORT AND RISK ASSESSMENT TOOLS

New knowledge from the experimental and theoretical investigations on the project will be incorporated into the hazard assessment tools by HSL. A risk assessment methodology will be developed using an integral consequence modelling methodology. This will be achieved by using integral models of CO_2 dispersion validated against the results of the above described experimental and numerical studies. Other methodologies for risk assessment of CO_2 pipelines will include the ARAMIS methodology and short-cut risk assessment methodology incorporating topography.

All the developed risk assessment tools will be applied to test cases designed for possible CO_2 transportation pipelines configurations.

CONCLUSION

The safety assessment of CO_2 pipelines will be play a key role in the public acceptably of CCS as a safe and reliable method for mitigating the impact of global warming. Yet, despite its urgency, only a handful of such studies are taking place across the globe.

The CO_2PipeHaz consortium is made up of seven partners from five different countries involved in diverse but complementary aspects of what is a complex project. It includes experts in the fields of thermodynamic and transport properties, CO_2 purification, multi-phase heterogeneous flows, and dispersion at both small and large scales (near- and far-field).

This expertise spans the experimental measurement of relevant processes and parameters, as well as the mathematical modelling of such processes, and the embodiment of theoretical understanding within computational design and decision support tools. The grouping contains experts in the development of good practice guidelines, in performing cost/benefit analysis, consequence, safety and risk assessments and developing the tools required to undertake them, and in the means that can be used to mitigate the impact of any accident. Expertise is also available in the areas of knowledge transfer and commercial exploitation. Additionally, the collaboration contains experts with direct practical experience of capturing, processing and transporting carbon dioxide, and in one case, experts who have direct experience of CCS systems at an industrial scale.

The above gives the CO_2PipeHaz partners the confidence to generate the basic engineering science required to ensure understanding of the safety of CO_2 transportation systems, and to translate that knowledge in to the tools needed for practical application in order to ensure the safe and commercial deployment of power generation technology based on CCS.

ACKNOWLEDGEMENTS

The authors are grateful to the European Commission for funding this work under the 7th Framework Energy Program (Project Reference: 241346).

REFERENCES

1. Energy Review, Cabinet Office PIU, Feb 2002.
2. Intergovernmental Panel on Climate Change, Carbon Capture & Storage, ISBN 92-9169-119
3. Pohanish, PR, Greene SA, Hazardous Materials Handbook, Carbon Dioxide, 330–331, Van Nostrand Reinhold, 1996.
4. Connolly S, Cusco L, Loss Prevent & Safety Perform in Process Ind Symp, IChemE, 2007
5. CRS Report for Congress, Carbon Dioxide Pipelines for Carbon Sequestration: Emerging Policy Issues, 2007.
6. Pipeline Safety Instrument for COMAH Involving Pipelines, Joint Research Centre, European Commission, Major Accident Hazards Bureau, Ispra (Va), Italy, 1999.
7. WWW.CO_2PipeHaz.eu
8. Karakatsani E.K., Spyriouni T., Economou I.G., "Extended SAFT Equations of State for Dipolar Fluids", AIChE J., 51 (2005) 2328.
9. Karakatsani E.K., Economou I.G., "Perturbed Chain-Statistical Associating Fluid Theory Extended to Dipolar and Quadrupolar Molecular Fluids", J. Phys. Chem. B, 110 (2006) 9252.
10. Cumber PS, Fairweather M, Falle SAEG, Giddings JR, J Fluids Eng 116 (1994) 707.
11. Jones WP, Musonge P, Closure of the Reynolds Stress and Scalar Flux Equations, Phys Fluids 31 (1988) 3589–3604.
12. Jacobson MZ, Fundamentals of Atmospheric Modelling, Cambridge University Press, 1999.
13. Vehkamäki H, Classical Nucleation Theory in Multicomponent Systems, Springer, 2006.
14. Olivieri DA, Fairweather M, Falle SAEG, An AMR Solution Method for the Transported PDF Equation, Proc 3rd European Combustion Meeting, Chania, Greece, 11th–13th April 2006, ECM 2007 Paper 8–4, 2007.
15. Olivieri DA, Fairweather M, Falle SAEG, Chemically Reactive Flow Modelling Involving Physical and Compositional Space AMR, Proc 7th International Symposium on Engineering Turbulence Modelling and Measurements, Limassol, Cyprus, 4th–6th June 2008, Vol. 3, pp. 786–791, 2008.
16. Ivings, M.J., Azhar, M., Carey, C. Lea, C.J., Ledin, H.S., Sinai, Y., Skinner, C. and Stephenson, P., 2004, Outstanding safety questions concerning the use of gas turbines for power generation: final report on the CFD modelling programme of work. Health and Safety Laboratory Report CM/03/08.
17. Gant, S.E., Ivings, M.J., Jones, A. and Santon, R., 2006, Hazardous area classification of low pressure natural gas systems using CFD predictions. Proc. IChemE Hazards XIX Symposium, Manchester, UK, 27–30 March 2006.
18. Ivings, M.J., Clarke, S., Gant, S.E., Fletcher, B., Heather, A., Pocock, D.J., Pritchard, D.K., Santon, R. and Saunders, C. J., 2008, Area classification for secondary releases from low pressure natural gas systems. Health and Safety Executive Research Report RR630
19. Ichard, M., Hansen, O. R., Melheim, J. A., 2009, Modelling of lashing releases around buildings. In 89th Annual Meeting of American Meteorological Society, Phoenix, AZ, Paper J14.2.
20. Hanna, S. R., Brown, M. J., Camelli, F. E., Chan, S. T., Coirier, W. J., Hansen, O. R., Huber, A. H., Kim, S., Reynolds, R. M., 2006, Detailed simulations of atmospheric flow and dispersion in downtown Manhattan, Bulletin American Meteorological Society 87: 1713–1726.