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Investigation of the consequence of high-pressure CO₂ pipeline failure through experimental and numerical studies

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Investigation of the consequence of high-pressure CO₂ pipeline failure through experimental and numerical studies¹

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Abstract

Transportation of Carbon Dioxide (CO₂) via high-pressure pipelines from source to storage site forms an important link in the Carbon Capture and Storage (CCS) chain. To ensure the safety of the operation, it is necessary to develop a comprehensive understanding of the consequences of possible pipeline failure. CO₂ is a hazardous substance and an accidental release may lead to catastrophic damage. This paper describes an experimental investigation of the dispersion of CO₂ in the atmosphere in a full-scale burst test of a pipeline containing high-pressure dense phase CO₂. The experiment was carried out to simulate a CO₂ pipeline failure in the real world. The test rig consisted of a buried 85 m long, 610 mm diameter pipeline test section connected at either end to 116 m long reservoirs. An explosive charge detonated at test section half-length initiated a rupture in the pipe wall top surface, releasing the high-pressure contents. The atmospheric dispersion of the CO₂ following the explosive release was measured. The paper also describes Computational Fluid Dynamics (CFD) simulations of the dispersion of CO₂ following the release. The CFD models were validated against the experimental data. The models were then extended to estimate the consequence distances related to CO₂ dispersion following failure of longer pipelines of various diameters under different wind speeds and directions. Comparison of the results with prior studies was carried out.

Keywords: Carbon Capture and Storage; CO₂ pipeline; pipeline fracture; CO₂ dispersion; CFD modelling

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1. Introduction

In the foreseeable future, fossil fuels will continue to be critical to economic and social development across the world and are predicted to provide the bulk of the world's primary energy [1, 2]. As a product of burning fossil fuels, Carbon Dioxide (CO₂) is a major contributor to global warming [3]. Inevitably, continued use of fossil fuels has led to concerns about increased CO₂ concentration levels in the atmosphere. The Carbon Capture and Storage (CCS) technique has attracted increasing attention in recent years as it is widely accepted as a viable method of reducing excessive concentrations of CO₂ in the atmosphere.

In CCS, CO₂ is captured from anthropogenic sources, transported to a storage location and then isolated in geologic formations [2, 4]. The storage involves either permanent underground storage or Enhanced Oil Recovery (EOR). EOR is a proven technology used to recover more oil from depleting oil fields as well as to store the captured CO₂ [2, 5]. The growing application of CCS will be inevitably accompanied by extensive deployment of CO₂ pipelines, as transportation of CO₂ via high-pressure pipelines is considered to be the most economical method, especially for large quantities of CO₂ conveyed over long distances [6, 7].

In the deployment of CO₂ pipelines, safety is of paramount importance. Although CO₂ is not a combustible gas, the loss of containment of a CO₂ pipeline may be catastrophic. This is because gaseous CO₂ is an asphyxiant that can lead to coma and even death at relatively low concentrations [8]. It is also heavier than air, and thus tends to sink as it disperses in the atmosphere. This adds to the risk for human and animal populations and the environment. In order to protect humans from possible harmful effects of pipeline accidents, it is necessary to provide sufficient separation between residential areas and high-pressure CO₂ pipelines. This calls for accurate predictive modelling of CO₂ dispersion in the atmosphere resulting from pipeline failure.

2. Literature review

In the recent decades, a number of studies have addressed the dispersion of CO₂ to evaluate possible hazards presented by CCS infrastructures. The studies have included modelling techniques as well as experiments to generate model validation data. Some early experiments [9] were carried out using small-scale, low-momentum releases of CO₂, which probably could not reflect a real release from high-pressure pipelines. With

the aim of generating validation data for dispersion models for liquid and supercritical CO₂ releases relevant to CO₂ transportation facilities, a series of CO₂ discharge and dispersion experiments have been carried out under the CO2PIPETRANS project. The first two experiments [10, 11] in this project were delivered by BP and Shell respectively, featuring small-scale liquid and supercritical CO₂ releases from large storage tanks, with the source orifice size ranging from 6.4 mm (1/4 inch) to 25.4 mm (1 inch). The third experiment [12] was carried out by DNV GL, performed using a 50 mm Internal Diameter (ID), 200 m long pipeline containing pure CO₂ in the liquid state, released from orifices ranging from 10 mm to 50 mm in diameter. As part of the COOLTRANS research programme, Woolley et al. [13] tested CO₂ releases using a 2 m³ pressure vessel connected to a 9 m long, 50 mm ID discharge pipe. The near-field temperature and concentration data was measured to study the jet flow structure. In this programme, investigators at the Dalian University of Technology (DTU) also performed experiments on CO₂ releases from a 256 m long, 233 mm ID pipeline, using a 50 mm diameter orifice at one end as the source [14]. In these experiments, CO₂ was mostly released horizontally. Some vertical CO₂ release tests were carried out in the CO2QUEST project, where Guo et al. [15] used a 258 m long, 233 mm ID CO₂ pipeline. The CO₂ was released vertically from a 15 mm diameter orifice to investigate the flow and dispersion characteristics.

In addition to the above small-to-medium scale CO₂ release experiments, some large scale release experiments have also been conducted in recent years. In the CO2QUEST project, release from a full-bore rupture was studied using a 258 m long, 233 mm ID horizontal pipeline [16]. The pipeline was pressurised to a supercritical state with a mass inventory of 3.6 tonnes. Pressure decay inside the pipeline as well as the CO₂ dispersion were measured in the test. A test of CO₂ release and dispersion following pipeline fracture was conducted in the COSHER joint industry project [17]. The test rig featured a 227 m long, 219 mm ID pipeline loop, which was fed from both ends by a 148 m³ reservoir of CO₂ initially pressurised to 15 MPa. A fracture about 4 m long was created by a shaped explosive charge and about 136 tonnes of CO₂ were released within 204 s. As part of the SARCO2 project [18], two full-scale burst tests of CO₂ pipelines were carried out at the Nettuno military shooting range near Rome. In both tests, the test section was a 48 m long, 610 mm (24 inch) diameter pipe, connected to reservoirs at both ends, amounting to a total length of 220 m. In the first test, the fracture propagation was arrested within a short distance, while in the second test, the fracture stretched to over

40 m. The main purpose of the two tests was a study of fracture control strategies, but the dispersion was also monitored for consequence modelling. Overall, the above experimental studies provided valuable data for model validation and experience for future experimental investigations.

Theoretical modelling of gas dispersion can be carried out using analytical or Computational Fluid Dynamics (CFD) models. The simplest analytical model is the Gaussian model [19, 20]. Although the Gaussian model was not originally developed for heavy gas dispersion, with fine-tuned ‘dispersion parameters’, it can be used to satisfactorily predict the consequences of small CO₂ releases [2]. Other analytical models better suited for heavy gas dispersion but with more complicated forms than the Gaussian model include SLAB [21], DEGADIS [22], HEGADAS [23], Phast UDM [24] etc. The advantage of analytical models is quick estimation with reasonable accuracy. Performance validation of analytical models for small gas releases can be found in prior work [2, 9, 25, 26]. However, their predictive ability in case of large-scale gas release is unclear.

Although CFD models are much more complicated and time-consuming than analytical models, they are being employed to an ever-increasing degree in atmospheric dispersion simulation. Apart from the availability of high performance computing resources, the ability of CFD models to represent complex physical phenomena such as turbulence in complicated geometries is also a driving force for this trend. Mazzoldi et al. [8] compared the performance of CFD and Gaussian models of CO₂ dispersion through simulations of the Kit Fox experiment [9]. It was found that CFD models performed much better than Gaussian models. Schleder and Martins [27] used a CFD tool, FLACS, to simulate a CO₂ dispersion field test. They found that FLACS could simulate peak concentrations well, while keeping all the statistical performance measures well within the acceptable range. Toja-Silva et al. [28] simulated CO₂ dispersion from thermal power plant powered by natural gas using OpenFOAM. The simulation results showed good agreement with measurements and it was found that a turbulent Schmidt number of 0.6 is the most adequate for CFD simulations of CO₂ emissions from power plants in urban areas. CFD techniques have also been used in simulations of CO₂ dispersion of in complex environments [29-31], such as in complex terrains. Tan et al. [31] simulated CO₂ dispersion in street canyons using ANSYS Fluent. The model was validated against a wind tunnel experiment and it was found that the SST $k-\omega$ turbulence model showed the best performance. As part of the COOLTRANS research programme, Wareing et al. [32, 33] studied the near-field CO₂ dispersion using CFD models employing the Reynolds-

Averaged Navier-Stokes (RANS) hydrodynamic method with adaptive mesh refinement. Far-field CO₂ dispersion modelling in the COOLTRANS programme was undertaken by Wen et al. [34, 35]. In Ref. [34], CO₂ dispersion patterns following release from a vertical vent as well as from a horizontal ‘shock tube’ test rig were simulated. Ref. [35] describes a dedicated CFD solver developed specifically for the dispersion of CO₂ from pipeline releases. The solver was validated against experimental measurements in Case Study 3 in the COOLTRANS programme, in which CO₂ was released through a puncture in a buried pipe. Liu et al. [26] simulated the BP DF1 CO₂ dispersion experiments conducted by DNV [10], which featured CO₂ releases from a half-inch nozzle on a pipe connected to a high-pressure vessel. A comparison between CFD models and the Phast UDM was carried out. It was found that CFD models performed well in predicting the time-varying CO₂ concentration pattern, but Phast UDM tended to under-predict the concentration levels. Joshi et al. [36] also simulated the BP DF1 experiments using ANSYS Fluent V16.2. The far-field CO₂ dispersion was predicted and found to be in good agreement with measurements up to 100 m downwind.

In the above CFD modelling exercises, the release strength ranged from small to medium scale, compatible with the experiments. Also, these studies focused on validation of the respective models rather than on application of the models to more realistic release scenarios. Comprehensive studies of large-scale releases from CO₂ pipelines are still rare. Wareing et al. [37] simulated the rupture of a 96 km long, 610 mm diameter CO₂ pipeline, assuming a mid-point rupture which left two clean ‘guillotine breaks’ in the pipeline. In this study, only six steady-state simulations were performed to provide snapshots of the near-field dispersion at six pre-selected instants of time. Hill et al. [38] modelled the releases due to a full-bore rupture of a 500 mm ID pipeline using DNV Phast. The source strength was specified in terms of the maximum initial release rate and steady-state calculations were performed. In their study, the CFD method was also used for one case and found to produce a more conservative prediction. Mazzoldi et al. [39] modelled full-bore ruptures of pipelines of various sizes carrying a CO₂ mixture with 97% CO₂, 2% CH₄ and 1% N₂. The CFD dispersion code ‘fluidyn-PANACHE’ was used for the simulations and ‘consequence distances’ corresponding to 10% and 25% CO₂ concentration levels were estimated. Liu et al. [7] also investigated the consequence distances of full-bore ruptures of CO₂ pipelines carrying CO₂ mixtures, with the pipe ID ranging from 400 to 800 mm, and stagnation pressure ranging from 10 to 20 MPa. To achieve a conservative prediction of the consequence distance, the

dispersion source fluid was assumed to be a gaseous CO₂ mixture.

The above studies of large-scale CO₂ release all assumed full-bore ruptures of a pipeline to estimate the source strength, and considered a horizontal release as the worst case. However, this may not reflect a realistic accident adequately. In reality, a crack on the pipeline may induce a fracture propagating to a certain distance before it is arrested. This may lead to much a higher initial release rate of CO₂ than that represented by a full-bore rupture. In addition, models used in the above studies of large-scale CO₂ release were not validated against large-scale CO₂ release experiments due to the scarcity of publicly available dispersion data. Therefore, a large-scale CO₂ release experiment and a validated model to predict a comprehensive view of the possible consequences of a full-scale pipeline fracture would be valuable to the CCS community.

In this paper, an investigation of the dispersion of CO₂ in the atmosphere following its release from high-pressure pipelines is presented. The investigation began with a full-scale burst test of a buried steel pipeline carrying high-pressure dense phase CO₂. The dispersion profiles were measured using an array of CO₂ concentration sensors placed downwind of the release. CFD models were designed to simulate the atmospheric dispersion of CO₂ resulting from the fracture. The simulations were carried out using the commercially available CFD software ANSYS Fluent v14.5. The simulation results were validated against measurements carried out in the experiment. The study is then extended to a parametric study by varying the pipeline size and wind speeds in the validated CFD models. Consequence distances of CO₂ pipeline failure are estimated through an analysis of the spread of CO₂ clouds with hazardous concentration levels. Results are compared with those obtained in prior studies assuming full-bore rupture and horizontal release. Effects of pipeline length and orientation with respect to the wind direction on the consequence distances are also estimated.

3. Experimental study

In order to address the gaps in the knowledge associated with fracture control of high pressure, dense phase CO₂ pipelines and CO₂ dispersion modelling, the CO₂SafeArrest Joint Industry Project (JIP) was initiated in June 2016 [40]. Two instrumented full-scale burst tests on steel pipelines filled with high-pressure dense phase CO₂ were carried out to provide experimental data that could be used to validate predictive models of (1) the pipe fracture propagation and arrest characteristics, and (2) the dispersion of CO₂ in the atmosphere following release

from the high-pressure pipeline. This paper deals only with the dispersion aspects of the first of the two tests.

3.1. Test site

The first full-scale burst test was carried out on 30 September 2017 at the DNV GL Testing and Research Centre at Spadeadam, Cumbria, UK. The test site is a raised, relatively flat mound stretching West-East about 1,600 m. It is sparsely dotted with buildings and patches of trees about 10-15 m tall. The surrounding terrain is also relatively flat with a gentle rise on the North side of the site, and a large patch of cultivated forest with trees about 25 m tall on the south side. Fig. 1 shows an aerial view of the test site, along with the test section location and orientation.

Fig. 1. Aerial view of test site, with the test pipe laid West-East, highlighted using a red rectangle.

As the dispersion is expected to be affected by the terrain topography, for the purpose of model validation, details of the ground topography in the immediate vicinity of the dispersion ‘source’ were measured in the form of ground altitude along the pipe axis (WE000), and along five perpendicular lines 100 m apart (NS000 – NS500), as shown in Fig. 2.

Fig. 2. Terrain topography measurement lines, downwind from the source, 100 m apart.

3.2. Experimental conditions

The test featured a 610 mm Outer Diameter (OD), X65 steel pipe, filled with a mixture of about 91% CO₂ and

9% N₂ pressurised to 15 MPa. The initial temperature of the mixture was about 12 °C. The test section was about 85 m long, and consisted of an assembly of eight pipe segments connected to reservoirs at either end. The reservoirs are also pipes of 610 mm OD, each about 116 m long. The overall pipe length was thus about 317 m.

The pipe was laid West-East, and buried under about one metre of soil. An explosive charge installed on the top surface of the test section at half-length would be detonated to initiate a propagating fracture in the pipe which extended along the pipeline in both directions. It was expected that the fracture would be arrested within about 20 m on either side of the initiation point. The released gas would disperse over the terrain in response to the prevailing wind conditions on the day.

Weather forecasts suggested that around the date of the test, the wind at the site would blow predominantly from the West-Southwest (WSW) direction about 11.5° with respect to the pipe axis laid West-East. Fig. 3 shows the fan-shaped sensor layout for spot measurements of CO₂ concentration compatible with this expected wind direction. The sensors were oxygen cells set up to measure the spot concentration of O₂, from which the CO₂ concentration could be deduced.

Fig. 3. Field instrumentation in the experiment, showing locations of O₂ detectors downwind.

A total of 50 sensors were installed at the locations indicated by the red and blue dots in Fig. 3. Two probes were located directly upstream of the source, and another four in the cross-wind direction. The remaining 44 probes were arranged in a 'fan' pattern spanning an angle of $\pm 45^\circ$ symmetrically on either side of the expected wind

direction, and located on 50 m, 100 m, 200 m, 300 m, 400 m and 500 m arcs centred at the mid-point of the test section.

3.3. Full-scale burst test

The burst test was carried out in the afternoon on 30 September 2017 when the wind speed and direction looked promising as measured using two wind probes placed about 460 m upstream of the test site, at 5 m and 10 m height from the ground. Fig. 4 shows the measured wind speed and direction over a period of 300 sec, starting at the instant when the explosive charge was detonated and the CO₂ was released into the atmosphere. Over this period, the wind speed was reasonably consistent. The wind direction was close to the expected direction. This meant that the test scenario was such that all of the sensors would lie in the path of the spreading CO₂ cloud. This conclusion was reached based on the results of a number of pre-test CFD simulations carried out to validate the sensor arrangement.

Fig. 4. Wind speed and wind direction histories at 5 m and 10 m heights, measured from the instant of the test initiation at about 460 m upstream of the source.

Fig. 5 shows a snapshot of the spreading CO₂ cloud captured by an aerial drone, as well as the crater formed by the CO₂ explosion and the fractured test section. In the test, the CO₂ cloud rose momentarily to about 250 m, as was the debris that was thrown out of the crater formed. Thereafter, the cloud sank to the ground, even as it was dispersed by the prevailing wind. The measurements reflect that the CO₂ cloud took about 300 seconds to blow over the site.

The fracture in the pipe wall propagated along the top surface towards both ends, and was arrested when the total

fracture length reached about 42.5 m. Fig. 5 also shows that the force of the explosion caused the pipe to bend sideways at about half-length, even as the bent half was thrown out of the crater.

a. Spreading CO₂ cloud

b. Crater and the fractured test section

Fig. 5. Aerial views of the spreading CO₂ cloud, crater formed by CO₂ explosion, and the fractured test section.

After the event, a series of measurements using drones were carried out to estimate the area of the crater opening at ground level. Fig. 6 shows the result in the form of an outline of the crater. The total length of the crater is 44.85 m, slightly longer than the fracture length. The average width of the crater is about 7.4 m, which is 12 times of the pipe OD.

Fig. 6. Crater outline as measured in the West-East and South-North directions.

Fig. 7 shows the measured pressure decay in the reservoir. It indicates that the contents of the pipe were released in less than 12 seconds. The kink in the reservoir pressure transients corresponds to the saturation pressure of about 7.8 MPag.

Fig. 7. Measured pressure decay in the reservoirs.

4. Numerical methods and model validation

4.1. Assumptions and model simplification

For a pipeline containing high-pressure CO₂ in liquid or supercritical state, the initiation of a fracture will be followed by rapid depressurisation of the gas. This will result in a two-phase flow in the pipe, and a decompression wave travelling along the pipe away from the opening, at nearly the speed of sound. Also, the released gas will be exposed to the ambient pressure, leading to a highly under-expanded region near the fracture [7]. During the atmospheric expansion, the fluid will cool down significantly due to the Joule-Thompson effect [7, 41]. This may cause the formation of dry ice particles in the fluid. The solid particles may sublimate in mid-flight or deposit on the ground, but eventually will undergo sublimation due to the much warmer environment.

The depressurisation and expansion of the CO₂ along with details of the fracture propagation directly affect the release source strength. However, as this process is highly complicated, a numerical simulation to obtain the release rate will be very time-consuming. In this study, the release rate due to the fracture propagation is approximated by:

$$\dot{m} = C_1(e^{C_2 t} - e^{C_3 t}) \quad (1)$$

where t is the time, and C_1 to C_3 are constants controlling the peak release rate, the release rate decay and the overall released mass. This functional form can describe a large variety of highly transient physical phenomena, including the response of a spring-mass system to an impulsive ‘hammer blow’ [42].

For a specific explosive release due to pipeline fracture, the constants in Eq. (1) are determined to give the right values of mass inventory (equal to the area under the $\dot{m}(t)$ curve), the peak release rate and the release duration. In conjunction with the source plane used in the dispersion modelling, the peak release rate tuned by the constants will ensure that the corresponding maximum fluid velocity after expansion agrees with the fluid velocity calculated by the atmospheric expansion model [7].

For the above full-scale burst, considering that the mass inventory was emptied within 12 seconds (see Fig. 7), the constants are defined as: $C_1 = 75,300 \text{ kg s}^{-1}$, $C_2 = -1 \text{ s}^{-1}$ and $C_3 = -10 \text{ s}^{-1}$. Fig. 8 shows the simulated time history of the release rate. The specified constants ensured that the total mass released within 12 seconds is about 67 tonnes, which agrees with the mass inventory in the pipeline.

Fig. 8. Assumed release rate for the full-scale burst test.

The possible formation of solid CO_2 particles in the source may affect the dispersion. However, in the experiment, it was not observed that there were dry ice particles deposited on the ground. This may be because the particle size was quite small and they did not have a chance to deposit on the ground to form a visible dry ice bank before sublimating in mid-flight. To reduce the complexity of the model, the source fluid for dispersion modelling was assumed to be in a gaseous state. This is also preferable for risk assessment as conservative gas concentrations will be predicted [7, 38]. In the model, the effect of low temperature at the CO_2 source on thermodynamic properties such as density was considered. However, constant values were used for transport properties like viscosity and thermal conductivity. The viscosity and thermal conductivity of CO_2

were set as $1.37 \times 10^{-5} \text{ kg m}^{-1} \text{ s}^{-1}$ and $0.013 \text{ W m}^{-1} \text{ K}^{-1}$ respectively in the dispersion model.

In the experiment, the CO_2 was released from an opening created in a buried pipe. The released fluid had to burst through the soil cover, creating a trench above the pipe, before emerging out into the atmosphere. Fig. 9 shows schematically the possible sequence of steps resulting in the creation of the trench in the experiment. The pipe axis is perpendicular to the plane of the diagrams. In this study, the trench opening at ground level was assumed to be the inlet to the dispersion domain. It is assumed that at the ground level, the fluid is already at post-expansion stage and the pressure reaches the ambient pressure. Therefore, incompressible flow can be assumed in the dispersion model to reduce the computing time. According to the crater opening dimensions obtained in the test (see Fig. 6), a rectangle on the ground surface with a length of the fracture length and a width of 12 times of the pipe diameter will be used as the CO_2 inlet plane for dispersion modelling.

Fig. 9. Schematic trench opening process (not to scale).

4.2. Numerical methods

In this study, ANSYS Fluent V14.5 [43] was employed for the dispersion simulation, which solves the Reynolds-averaged mass, momentum, energy and scalar transport equations.

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \quad (2)$$

Momentum equation:

$$\frac{\partial (\rho \vec{v})}{\partial t} + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot (\bar{\tau}) + \rho \vec{g} \quad (3)$$

Energy equation:

$$\frac{\partial (\rho E)}{\partial t} + \nabla \cdot [\vec{v}(\rho E + p)] = \nabla \cdot [k_{\text{eff}} \nabla T - \sum_i h_i \vec{j}_i + (\bar{\tau}_{\text{eff}} \cdot \vec{v})] \quad (4)$$

where ρ is the density, $\vec{v}$ the velocity vector, p the pressure, $\rho \vec{g}$ the gravitational body force per unit volume, E the total energy, k_{eff} the effective thermal conductivity, T the temperature, h_i the specific enthalpy of species i , $\vec{j}_i$

the diffusion flux of species i , and

$$\bar{\tau} = \mu \left[(\nabla \vec{v} + \nabla \vec{v}^T) - \frac{2}{3} \nabla \cdot \vec{v} I \right]$$

where μ is the dynamic viscosity and I the unit tensor.

The ‘species transport’ model was employed to predict the fraction of each species, by solving the convection-diffusion equation given by [43]:

$$\frac{\partial(\rho Y_i)}{\partial t} + \nabla \cdot (\rho \vec{v} Y_i) = \nabla \cdot \vec{J}_i + R_i \quad (5)$$

where Y_i and R_i are the mass fraction and the net rate of production of species i respectively.

The SST k - ω model [43, 44] was used for representing the effects of turbulence, as it was proposed to be more appropriate for dispersion modelling of high-momentum CO₂ releases [26]. Compared with the standard k - ω model, the SST k - ω model has a modified turbulent viscosity formulation to account for the transport effects of the principal turbulent shear stress, and it also applies gradual change from the standard k - ω model in the inner region of the boundary layer to a high-Reynolds number version of the k - ε model in the outer part of the boundary layer [43, 44]. The transport equations for the turbulence kinetic energy k and the specific dissipation rate ω are given by [43, 44]:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial}{\partial x_i} (\rho k v_i) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k - Y_k \quad (6)$$

and

$$\frac{\partial(\rho \omega)}{\partial t} + \frac{\partial}{\partial x_j} (\rho \omega v_j) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\omega} \right) \frac{\partial \omega}{\partial x_j} \right] + G_\omega - Y_\omega + D_\omega \quad (7)$$

where v_i and v_j are the velocity components; μ and μ_t the dynamic viscosity and the turbulent viscosity respectively; σ_k and σ_ω the turbulent Prandtl numbers for k and ω respectively; G_k and G_ω the generation of k and ω respectively; Y_k and Y_ω the dissipation of k and ω due to turbulence respectively; and D_ω the cross-diffusion term. Standard coefficients were used for turbulence modelling and the Boussinesq approximation was used to model the effect of buoyancy.

In the dispersion modelling, appropriately simulating the wind velocity is very important, as it will directly affect the dispersion process. In the atmospheric boundary layer, the wind velocity usually reduces with a decrease in

altitude due to frictional effects. To account for the variation in wind velocity with elevation, a power-law [45] is used to describe the vertical wind profile:

$$u = u_r \left(\frac{z}{z_r} \right)^\alpha \quad (8)$$

where u is the wind velocity at height z , u_r a reference wind velocity measured at the reference height z_r , and α the wind shear exponent.

4.3. Model validation

The proposed numerical methods were used to simulate the CO₂ dispersion in the full-scale burst. Fig. 10a shows the computational domain of the dispersion model, measuring 1,500 m (length) $\times$ 800 m (width) $\times$ 400 m (height). The wrinkles in the ground surface show that floor conforms to the terrain topography. The computational domain was aligned with the time-averaged wind direction during the test (refer to Fig. 4b). The wind inlet was placed 200 m upstream of the source at ground level. The lateral and vertical dimensions were chosen such that the dispersion plume could be accommodated within the computational domain throughout the duration of the dispersion.

The outlet of the computational domain is located sufficiently far downstream of the source and the region most likely to be affected by the dispersion. Since the aim is to model the dispersion in the atmosphere, obstacles such as patches of trees and buildings are ‘removed’ from the computational domain, so that they are not part of the atmosphere.

Boundary conditions for the dispersion model were defined as follows (see Fig. 10a):

- (a) Wind inlet: velocity inlet, ambient pressure and temperature, velocity profile described by Eq. (8).
- (b) CO₂ source: mass flow inlet, gaseous CO₂ at ambient pressure and temperature of -78°C, mass flow rate described by Eq. (1).
- (c) Outlet: pressure outlet with ambient pressure and temperature.
- (d) Ground, surfaces of buildings and tree blocks: no-slip, isothermal wall with temperature equal to the ambient temperature.
- (e) Ceiling, left side and right side: impermeable ‘symmetry’ boundaries.

a. Computational domain for the dispersion simulation

b. Surface mesh of terrain and left side

Fig. 10. Computational domain showing the wind direction and boundaries, and the corresponding computational mesh showing the local refinement and the detail of ‘inflation’ layers.

Fig. 10b shows part of the surface mesh at ground level and the left side of the computational domain. As the geometry is relatively complex, the computational domain was mainly discretised into tetrahedral cells. The overall mesh consists of a total of about 1 million cells, which are densely packed in regions where large gradients in the flow parameters are expected, such as near the source and in the ridges on the ground. The detail in Fig. 10b also shows 5 inflation layers were used adjacent to the ground surface for adequate simulation of the boundary layer.

The time-averaged wind speeds at 5 m and 10 m heights measured during the test (Fig. 4a) were used to deduce the wind shear exponent of the power-law correlation for the Wind Inlet boundary. With a reference height of 5 m, the reference wind velocity and the wind shear exponent were obtained as 2.7 m s^{-1} and 0.055 respectively.

Both the vertical wind profile described by Eq. (8) and the mass flow rate time history shown in Fig. 8 were modelled using User-Defined Functions (UDFs) [46], and they were applied to the Wind Inlet and CO_2 Source boundaries respectively.

The overall simulation was carried out in two steps: 1) a steady-state simulation to establish the wind field over the terrain, which provided the initial conditions; 2) a transient simulation in which the CO_2 was introduced from the ‘source’ (CO_2 inlet to the dispersion domain).

Fig. 11 compares the measured and predicted histories of CO_2 concentration at specific locations (refer to Fig. 3 for the locations where the concentrations were monitored) at progressively increasing distances from the

release location at time intervals after the rupture event. Overall, there is good agreement between the simulated and measured CO_2 concentration over time at different distances from the rupture site. At a downwind location, the CO_2 concentration tends to rise to a maximum value initially and then gradually reduce. This trend was well captured by the model at different distances. At almost all downwind distances, the maximum CO_2 concentration was captured reasonably well. Although the CFD model tended to over-predict the peak concentration, it is usually preferable for risk assessment. In the experiment, it seems that the CO_2 was dispersed slower than in the simulation. This may be due to the variation of the wind direction in reality. In the CFD model, average (and constant) values of wind speed and direction were applied, with the variation ignored.

Fig. 11. CO₂ concentration at downwind locations: measured vs predicted.

To evaluate the performance of a dispersion model, Hanna and Chang [25] proposed a set of statistical performance measures. These include the Geometric Mean (MG), the Geometric Variance (VG), the Fractional Bias (FB), the Normalised Mean Square Error (NMSE), and the fraction of C_p (predicted concentration) within a FACTor of 2 (FAC2) of C_o (observed concentration) [25, 47]. A perfect model would have $MG = VG = FAC2 = 1$ and $FB = NMSE = 0$. While these values are virtually impossible to achieve in reality, a model with acceptable performance has been defined as one with the following features [25, 47]: (1) $FAC2 > 0.5$; (2) $-0.3 < FB < 0.3$ or $0.7 < MG < 1.3$; (3) $NMSE < 4$ or $VG < 1.6$.

Table 1 Summary of model performance measures.

MG	VG	FB	NMSE	FAC2
0.86	1.14	-0.18	0.25	0.96

Considering the predicted and observed peak concentrations at all the monitored downwind locations, the performance measures of the CFD model were calculated as shown in Table 1. It indicates that all performance measures are within the acceptable range. This suggests that the proposed numerical methods are capable of handling the dispersion simulation of a large CO₂ release in a full-scale burst test and providing satisfactory predictions of the dispersion patterns.

5. Consequence distance prediction of CO₂ pipeline failure

To obtain a comprehensive understanding of the consequences of high-pressure CO₂ pipeline failures, the proposed CFD model was applied in a number of simulations to predict the consequence distance following fracture of a pipeline carrying pure CO₂ with ID varying from 200 mm to 800 mm. The length of the pipeline

considered here is 10 km, with the fracture initiated at the mid-point and propagating towards either end. The initial pressure and temperature inside the pipeline were assumed 15 MPa and 10°C respectively.

For a well-designed pipeline, the fracture propagation is expected to be arrested within four pipe segments. As the length of one pipe segment is about 15 m, in this study, the length of the overall fracture is assumed to be 60 m. This provides the basis for the estimation of two-stage mass flow rate specification (explained below) and the dimensions of the CO₂ inlet to the dispersion domain in the CFD model.

The release rate due to the fracture was estimated at first. Table 2 lists the basic source parameters, including the mass inventory, release duration and the maximum release rate. It indicates that for pipelines with the same length, larger pipe diameter leads to shorter emptying time. Fig. 12 shows the release rate time history of the 400 mm ID pipeline. The release consists of two stages (refer to Fig. 13). The first stage is an explosive discharge due to the propagating fracture. This lasts for a very short time and presents a spike in the release rate. Following the method introduced in Section 4, the release rate in this stage was modelled using Eq. (1). The second stage represents the CO₂ release after the arrest of the fracture propagation. In this stage, the total release rate is made up of discharge from two full-bore ruptured pipelines. The release rate due to a full-bore rupture can be solved using one-dimensional transient mass, momentum and energy balance equations expressed in terms of fluid velocity, density, and pressure in conjunction with a real gas equation of state [39, 48, 49]. The detail in Fig. 12 clearly shows the transition from explosive discharge to full-bore discharge.

Table 2 Summary of release parameters.

Pipeline ID (mm)	Mass inventory (tonnes)	Release duration (s)	Peak release rate (kg s ⁻¹)	C_1 (kg s ⁻¹)	C_2 (s ⁻¹)	C_3 (s ⁻¹)
200	292	890	19,950	40,000	-3.45	-15.55
400	1,170	730	40,290	58,500	-1.46	-14.20
600	2,632	665	62,710	90,010	-1.00	-10.00
800	4,679	630	80,920	195,500	-0.95	-3.11

Fig. 12. Release rate of the 10 km long pipeline with 400 mm ID, with the initial variation shown in detail.

Fig. 13. A schematic diagram of the release stages: 1) stage 1, during fracture propagation; 2) stage 2, after arrest of propagating fracture, release rate modelled as discharge from two full-bore ruptured pipelines.

The dispersion was modelled over a flat featureless terrain. In all subsequent dispersion simulations, a ‘neutral’ atmospheric stability class was assumed. Wind speeds from 2 m s^{-1} to 10 m s^{-1} at a reference height of 10 m were used to evaluate the wind inlet velocity profiles, and setting up the steady-state wind field. Table 3 shows the wind shear exponents used in the simulations. It should also be noted that the pipeline is assumed parallel to the wind direction, as this configuration was supposed to result in the longest consequence distance.

Table 3 Wind shear exponent α used for different wind speeds.

Reference wind speed (m s^{-1})	α
2	0.20
4	0.13

6	0.12
8	0.11
10	0.10

Simulations were carried out on a high performance computing cluster. Resources allocated to this study included six computing nodes. Each node was equipped with an Intel Xeon CPU E5-2637 v4 @ 3.50GHz and 16 GB memory. The Intel Xeon CPU E5-2637 v4 possesses 8 processors (threads). Six processors and 8 GB memory were allocated to each simulation. The computing time is dependent on the size of the computational grid and the wind speed. Averagely, the computing times for the pipelines with 200 mm, 400 mm, 600 mm and 800 mm IDs are 30, 38, 57 and 98 hours respectively.

In the following analysis of the consequence distance, two representative CO₂ concentration levels were considered: 50,000 ppm and 80,000 ppm. According to the Australian Standard [50], a CO₂ concentration level of 50,000 ppm will result in ‘very rapid breathing, confusion and vision impairment’, while that of 80,000 ppm will cause ‘loss of consciousness after 5–10 min’ [30, 50]. The consequence distance was determined as the maximum distance away from the pipe fracture centre contained by two concentration envelopes corresponding to these two concentration levels. Fig. 14 shows how the consequence distance is measured. It is seen that the farthest reach of the CO₂ cloud is not necessarily in the strictly downwind direction.

Fig. 14. Schematic of the measurement of consequence distance. The distance is determined as the maximum distance away from the pipe fracture centre contained by the concentration envelope, indicating the farthest reach of the cloud.

Fig. 15 shows the predicted evolution of the CO₂ cloud (represented by 80,000 ppm isosurfaces) in a typical case, dispersion following the fracture of a 400 mm ID pipeline, simulated assuming a 4 m s⁻¹ wind speed. It is found that initially the dispersion reflects the high release rate, causing the heavy gas plume to reach a high altitude. In this case, the 80,000 ppm envelope can reach a height of over 200 m. After travelling for a certain distance with the wind, the cloud loses its initial vertical momentum and gradually begins to sink towards ground level. Simultaneously, the CO₂ cloud is weakened due to diffusion, turbulent mixing and entrainment of the ambient air into the cloud. Eventually, the envelope corresponding to a certain concentration value reaches its maximum distance on the ground when the source strength is too weakened to cause further spread. In this test case, at 480 s, the 80,000 ppm CO₂ envelope reaches its maximum distance from the release centre. Subsequently, it is gradually weakened by the wind.

Fig. 15. Evolution of CO₂ envelope (80,000 ppm isosurface) due to release of the 400 mm ID pipeline under 4 m s⁻¹ wind.

Fig. 16 shows the predicted consequence distances for the 10 km long pipeline with different IDs as a function of wind speed. For the same stagnation pressure, it is clear that larger diameter pipelines correspond to longer consequence distance, reflecting the larger initial mass inventory released into the atmosphere.

Fig. 16. Consequence distances obtained for different wind speeds.

Fig. 16 shows that the wind speed significantly affects the consequence distance. For wind speed ranging from 2 m s⁻¹ to 10 m s⁻¹, compared to the minimum values, the consequence distance defined by the 80,000 ppm concentration envelope can be increased by 90%, while that of 50,000 ppm concentration can be increased by 60%.

Fig. 16 also shows that most of the time higher wind speed produces longer consequence distance and this works well for the 200 mm ID pipeline. However, for pipelines with larger ID, it is seen that the consequence distances produced by 2 m s⁻¹ wind are longer than those produced by 4 m s⁻¹ wind. This may be due to the less mixing due to lower turbulence levels at the lower wind speed. If the release source is strong enough, it will take a long time before the CO₂ cloud is sufficiently diluted. During this longer time, even a low wind speed can transport the cloud over longer downwind distances.

Fig. 17. CO₂ envelope (50,000 ppm isosurface) at its longest distance from release centre under different wind speeds (400 mm ID pipeline).

Fig. 17 shows the CO₂ envelopes due to the release of 400 mm ID pipeline at their longest impact distances from release centre under different wind speeds. Clearly, the dispersion under 2 m s⁻¹ wind speed is much slower, taking 750 s for the cloud to travel downwind (Fig. 17a) before it starts shrinking. On the contrary, with a wind speed of 6 m s⁻¹, the 50,000 ppm envelope stops advancing much sooner (in ~210 s, Fig. 17c). It is also seen in Fig. 16 that: for the 80,000 ppm envelope, a 2 m s⁻¹ wind can result in a longer consequence distance than a 6 m s⁻¹ wind, for a 800 mm ID pipeline; for the 50,000 ppm envelope, a 2 m s⁻¹ wind can result in a longer consequence distance than a 6 m s⁻¹ wind, for both 600 mm and 800 mm ID pipelines, while a 4 m s⁻¹ wind can produce a longer consequence distance than a 6 m s⁻¹ wind, for a 800 mm ID pipeline. It is noted that a V-shaped envelope develops for a 6 m s⁻¹ wind speed (Fig. 17c). A V-shaped envelope is usually seen in a vertical release, which is due to vortices set up by the difference in buoyancy between air and the released gas. The V-shaped concentration profiles can also be observed in natural gas dispersion [51, 52].

6. Discussion

The above exercises attempt to provide a more realistic view of the possible consequences of a CO₂ pipeline failure by simulating a vertical release due to a full-scale pipeline fracture. However, in previous studies [6, 7, 38], usually release rate due to a full-bore rupture was used as the source strength for the dispersion modelling, and a horizontal release was assumed as the worst scenario.

Hill et al. [38] studied the consequence of release from a 500 mm ID pipeline. They considered a full-bore rupture for the estimation of source strength. DNV Phast was employed for the dispersion modelling. Two release directions, horizontal and 19° from horizontal, were simulated and the horizontal release was found to produce longer impact distance. Fig. 18 compares the results obtained by Hill et al. with those obtained in this study.

Fig. 18. Comparison with results obtained by Hill et al. [38].

As Hill et al. considered a wind speed of 5 m s^{-1} and a 500 mm ID pipe, the consequence distances obtained for wind speeds of 4 m s^{-1} and 6 m s^{-1} and pipe diameters of 400 mm and 600 mm in the present study were used for comparison, as shown in Fig. 18. If the proposed model in this study is used, it would be expected that the consequence distance prediction for a 500 mm ID pipeline with a 5 m s^{-1} wind should be within the shaded areas in Figures 18a and 18b, and that a linear interpolation could be used. Clearly, the consequence distances were significantly under-predicted by Hill et al.

Fig. 19 compares the results of the present analysis with the authors' previous work [7]. In Ref. [7], horizontal releases due to a full-bore rupture of 400 mm to 800 mm ID pipelines were simulated under 2 m s^{-1} wind speed. Results of this study shown in Fig. 19 for comparison are also those obtained under 2 m s^{-1} wind speed. It is found that the consequence distances were significantly under-predicted in Ref. [7].

Fig. 19. Comparison with results obtained by Liu et al. [7] (2 m s^{-1} wind speed).

The above comparisons indicates that, although prior work assumed a horizontal release, the consequence distances predicted are far from conservative. This may be due to the much lower release rate from a full-bore rupture compared to the explosive release rate due to a full-scale fracture. Therefore, in the risk assessment, to provide sufficient confidence, results from simulation of a full-scale fracture should be used.

6.1. Effect of pipeline orientation with respect to wind direction

The dispersion simulations described in Section 5 were carried out assuming the pipeline to be parallel to the wind direction, as depicted in Fig. 20, Case A. Although it is generally expected that this scenario will result in the maximum impact distance, it is necessary to verify this through simulations.

Fig. 20. Schematic of cases simulated to evaluate the effect of pipe orientation w.r.t. wind direction (top view).

Fig. 20 shows schematically the other two cases investigated in this study: pipeline at 45° to the wind direction (Case B) and pipeline perpendicular to wind the direction (Case C). A 400 mm ID pipeline was used for these two cases. Simulations were performed for wind speeds ranging from 2 m s^{-1} to 10 m s^{-1} .

Fig. 21 compares the results obtained for these three cases. It is observed that the difference in results between Case A and Case C is limited. For 80,000 ppm CO_2 concentration, Case C results in a longer consequence distance for wind speed lower than 8 m s^{-1} but shorter consequence distance for wind speed higher than 8 m s^{-1} . For 50000 ppm CO_2 concentration, Case A corresponds to mostly longer consequence distance than Case C.

Fig. 21. Consequence distances obtained for pipeline in different angles from the wind direction (400 mm ID pipeline).

The results for Case B are quite interesting. For a wind speed less than 6 m s^{-1} , Case B results in consequence distance (80,000 ppm envelope) between those obtained for Case A and Case C, and produces consequence distance (50,000 ppm envelope) shorter than those obtained for Case A and Case C. However, for wind speeds above 6 m s^{-1} , there is a significant increase in the consequence distance predicted by Case B. This suggests that the dispersion in Case B has the greatest impact on the environment. For wind speeds above 6 m s^{-1} , compared to the other two cases, the consequence distance for Case B can be increased by up to 60%.

Fig. 22. CO₂ envelope (80,000 ppm isosurface) at its longest distance from release centre for 8 m s^{-1} wind speed (400 mm ID pipeline).

Fig. 22 shows the predicted CO₂ envelopes for these three cases for a wind speed of 8 m s^{-1} . Both Case A and Case C present symmetrical dispersion patterns, unlike Case B. This implies that in an asymmetrical configuration, a high wind speed is able to bring the pollutant mainly to one side. This may result in much longer consequence distance measured on that side.

6.2. Effect of pipeline length

In the exercises described above, the consequence distances corresponding to a substantially long (10 km) pipeline have been estimated for a number of scenarios. However, it is still valuable to investigate the effect of pipeline length on the consequence distance. Additional dispersion simulations were carried out to investigate the effect of pipe length. The pipe length was varied from 2 km to 30 km. The pipe diameter was maintained at 400 mm. The initial pressure and temperature inside the pipeline were also assumed 15 MPa and 10°C respectively. Table 4 shows the mass released from these pipelines and the corresponding release duration.

Table 4 Summary of release parameters for 400 mm ID pipeline.

Pipeline length (km)	Mass inventory (tonne)	Release duration (s)
2	234	130
5	585	340
10	1,170	730
20	2,340	1,710
30	3,510	2,900

Dispersion simulations were carried out considering a 4 m s^{-1} wind speed. Fig. 23 shows the predicted consequence distances. It is seen that the consequence distance increases with pipeline length. It is also noted that, the consequence distance tends to plateau off for pipelines longer than 10 km. However, from 10 km to 30 km, the consequence distance of 80,000 ppm CO_2 concentration is still increased by 17%, while that of 50,000 ppm CO_2 concentration increased by 11%.

Fig. 23. Consequence distance vs pipeline length (400 mm ID pipeline, 4 m s^{-1} wind speed).

6.3. Low temperature effect

Generally, for a release due to fracture of pipeline carrying dense-phase CO₂, formation of dry ice particles is expected near the exit plane due to the significant cooling of the under-expanded jet. Therefore, in the dispersion model, although the CO₂ source was assumed at a gaseous state, the temperature of the gas was assumed as that of a gas-solid CO₂ mixture in equilibrium state at ambient pressure, which is about -78°C.

The low temperature of the released CO₂ will inevitably cause a cold zone in the atmosphere. Fig. 24 shows the temperature contours on a 1 m high horizontal plane at different times, considering the fracture of a 400 mm ID pipeline. It is clear that, initially, the low temperature zone expands both longitudinally and laterally, but it will eventually shrink gradually due to the entrainment of the warmer air and the reduction of the release rate.

For a 400 mm ID pipeline, the temperature of a region within a distance up to 600 m from the release centre can be reduced by 10 °C, while temperature reduced by 20 °C will be kept to within 140 m from the release centre.

Fig. 24. Temperature contours on horizontal plane at 1 m height at different times (400 mm ID pipeline, 4 m s⁻¹ wind speed).

7. Conclusions

In this study, an experimental investigation and CFD simulations of the dispersion of CO₂ following a full-scale burst test are presented. The full-scale burst test featured a 610 mm OD, 317 m long steel pipe, filled with a CO₂-N₂ mixture of 91% CO₂ and 9% N₂, pressurised to 15 MPa. The fracture was initiated at half-length of the pipe, propagating towards both ends, and was arrested when the total fracture length reached about 42.5 m. The full-scale burst was instrumented to measure (1) the pipe fracture propagation characteristics, and (2) the dispersion of CO₂ in the atmosphere following release from the fractured pipe. This study deals only with the dispersion aspect.

A site-specific CFD model is employed to simulate the experimental scenario and the predicted downwind concentrations showed good agreement with measurements. The evolution of CO₂ concentration at different downwind locations was well captured and the peak concentrations were also predicted reasonably well. The performance of the CFD model in predicting a full-scale pipeline fracture is further validated through a set of statistical performance measures proposed by Hanna and Chang [25].

The CFD model is extended to simulations of releases due to the fracture of a 10 km long CO₂ pipeline. Dispersion patterns are generated for various combinations of pipe diameter (200 mm to 800 mm ID) and wind speed (2 m s⁻¹ to 10 m s⁻¹), and assuming a flat featureless terrain. The consequence distances obtained provide a basis for the estimation of the ‘measurement length’ before the deployment of CO₂ pipelines. This information will contribute to the identification of safe distances and the selection of appropriate safety class and design factors. This will help encourage industry investment in further deployment of CCS technology through removal or reduction of technical, safety and economic factors currently hindering these projects.

Wind speed significantly affects the consequence distance. Usually higher wind speeds will produce longer consequence distances. However, for a relatively large release, even lower wind speed can result in longer consequence distance due to lower turbulent mixing rate and entrainment, requiring more downwind travel time before the gas cloud is sufficiently diluted. For example, for pipeline ID ranging from 400 mm to 800 mm, a 2 m s⁻¹ wind speed results longer consequence distance than a 4 m s⁻¹ wind speed.

In prior studies, estimates of the consequence distance were based on the analysis of a horizontal release due to

a full-bore rupture, which were expected to provide conservative prediction. Results in the present study indicate that, compared to a vertical release due to a full-scale pipeline fracture, the consequence distances were significantly under-predicted in prior work. This is due to the much larger release rate from a full-scale fracture compared to the release rate due to a full-bore rupture. To provide sufficient confidence, results from simulations of full-scale fractures should be used in the risk assessment.

The orientation of the pipeline with respect to the wind direction may significantly affect the consequence distance for relatively high wind speeds. If the pipeline is neither parallel nor perpendicular to the wind direction, a high wind speed can spread the pollutant mainly on one side, resulting in much longer consequence distance measured on that side. Simulation results show that a wind speed greater than 6 m s^{-1} can result in a much longer consequence distance when the pipeline is aligned 45° to the wind direction. For a 400 mm ID pipeline with its axis at 45° to the wind direction, the consequence distance can increase by up to 60% for wind speed higher than 6 m s^{-1} , compared to a symmetrical configuration and dispersion pattern.

Release from a longer pipeline will usually produce longer consequence distance. However, the rate of increase of the consequence distance diminishes progressively longer pipelines. Simulations of a 400 mm ID pipeline under 4 m s^{-1} wind speed indicate that the consequence distance curves tend to plateau off when the pipeline length is increased up to 30 km.

Due to the Joule-Thompson effect, CO_2 exits from the high-pressure pipeline with very low temperature following an accidental release. Although the CO_2 cloud will be gradually warmed up by the warmer air, it will create a relatively low-temperature zone in the atmosphere as it disperses. Simulation results show that, for the fracture of a 400 mm ID pipeline, the temperature of a region within a distance up to 600 m from the release centre can be reduced by 10°C .

It should be noted that, the consequence distances obtained in this study were calculated for wind speeds below 10 m s^{-1} . If the effects of pipeline length and the pipeline orientation with respect to wind direction are considered in determining the separation between a CO_2 pipeline and residential areas, an appropriate safety factor should be carefully chosen.

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