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Consequence modelling of CO_2 pipeline failure

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Abstract

This paper describes the experimental investigation and Computational Fluid Dynamics (CFD) simulations of the dispersion of CO_2 following high-pressure dense phase CO_2 pipeline failure. A full-scale burst test was carried out to simulate a CO_2 pipeline failure in the real world. The atmospheric dispersion of the CO_2 following the explosive release was measured. The CFD models were validated against the experimental data. The models were then used to estimate the consequence distances related to CO_2 dispersion following failure of pipelines with various diameters under different wind speeds. This approach provides a predictive formula for the consequence distances of CO_2 transmission pipelines.

Keywords: Carbon Capture and Storage; CO_2 pipeline; pipeline fracture; CO_2 dispersion; CFD modelling

1. Introduction

As a method of reducing excessive CO_2 concentration levels in the atmosphere, the Carbon Capture and Storage (CCS) technique has attracted increasing attention. In the International Energy Agency (IEA) blue map scenario, the CCS technique is expected to contribute up to 19% reduction of CO_2 emissions by 2050 [1]. With the growing application of CCS, extensive networks of CO_2 pipelines may be required in the near future, as the preferred method of transportation of CO_2 from source to storage location is using high-pressure pipelines, especially for large quantities of CO_2 over long distances [2, 3]. Although CO_2 is not a combustible gas, consequences of CO_2 pipeline failure may be catastrophic. This is because gaseous CO_2 is an asphyxiant that can lead to coma and even death at relatively low concentrations [4, 5]. In order to develop controls that may be needed to protect humans from possible harmful effects of pipeline failures, it is necessary to gain a better understanding of the consequence of CO_2 released

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from high-pressure pipelines.

In this paper, an investigation of the dispersion of CO_2 in the atmosphere following its release from high-pressure pipelines is presented. A full-scale burst test of a buried steel pipeline carrying high-pressure dense phase CO_2 was performed, with dispersion profiles measured using a concentration sensor array placed downwind. Computational Fluid Dynamics (CFD) models were designed to simulate the CO_2 dispersion from the rupture into the atmosphere. The simulation results were validated against measurements carried out in the experiment. A parametric study was carried out by varying the pipeline size and wind speed in the CFD models. Consequence distances of CO_2 pipeline failure were then evaluated through analysis of the coverage of CO_2 clouds with hazardous concentrations.

2. Experimental study and validation of numerical model

In order to reduce the cost and improve the safety of CO_2 pipelines by developing and validating predictive models for CO_2 pipeline design, the CO2SafeArrest Joint Industry Project (JIP) was initiated in June 2016. This goal was to be achieved by carrying out two instrumented full-scale burst tests on steel pipelines filled with high-pressure dense phase CO_2. The two tests would 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 CO_2 in the atmosphere following release from the high-pressure pipeline. This paper deals only with the dispersion aspects of the first test.

2.1. Experimental conditions

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 featured a 600 mm OD, X65 steel pipe, filled with a mixture of about 91% CO_2 and 9% N_2, and pressurised to 15 MPa. The initial temperature of the mixture was about 12 °C. The 'test section' consisted of an assembly of eight pipe segments connected to reservoirs at either end. The overall pipe length was 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 pipe at half-length was detonated to initiate a propagating fracture in the pipe which extended along the pipeline in both directions before arresting about 20m from the initiation site on both sides of the initiation point.

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. 1 shows the fan-shaped sensor layout for spot measurements of CO_2 concentration compatible with this expected wind direction.

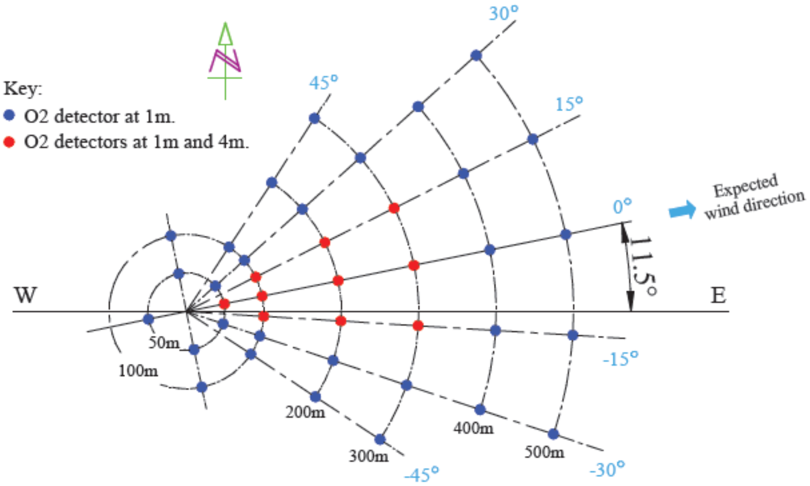

Fig. 1. Field instrumentation in the experiment

A total of 50 sensors were installed at the locations indicated by the red and blue dots in Fig. 1. 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 ± 45° 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 pipe.

2.2. Full-scale burst test

The burst test was initiated in the afternoon on 30 September 2017 when the measured wind speed and direction looked promising. Fig. 2 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 CO_2 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 CO_2 cloud.

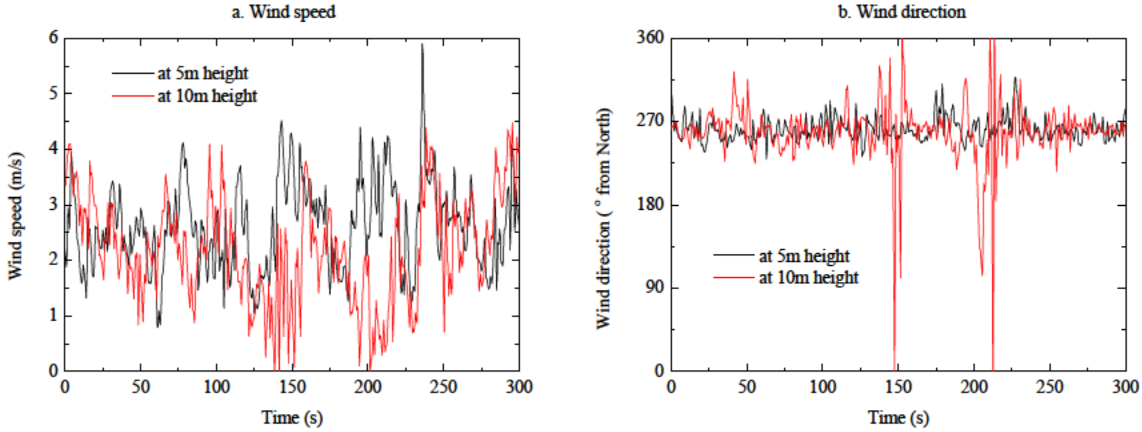

Fig. 2. Measured wind speed and wind direction histories

Fig. 3 shows a snapshot of the explosion as captured by a camera located East-Northeast (ENE) of the explosion, as well as the fractured pipe and crater formed by the CO_2 explosion. The CO_2 cloud that rose momentarily to about 250 m is clearly seen, as is 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 fracture in the pipe wall propagated along the top surface towards both ends, and was arrested when the total fracture length reached 42.5 m.

Fig. 3. A view of the explosion from the ENE direction, and the fractured pipe and crater formed by the pipeline rupture

2.3. Numerical methods and validation

The dispersion simulations were carried out using ANSYS Fluent, which solves the Reynolds-Averaged mass, momentum, energy and scalar transport equations. The *SST* k-ω model was used for representing the effects of turbulence. The vertical wind profile was modelled by a power law correlation [6]:

$$u = u_r \left(z/z_r \right)^{\alpha} \quad (1)$$

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.

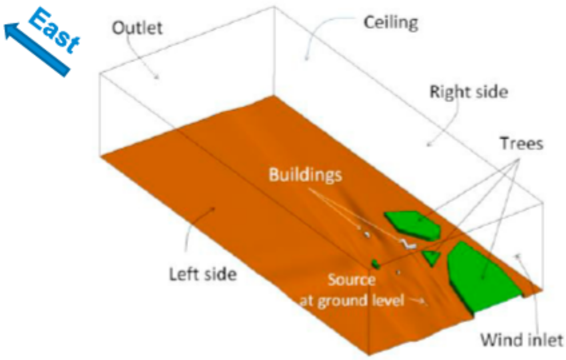

Fig. 4. Computational domain

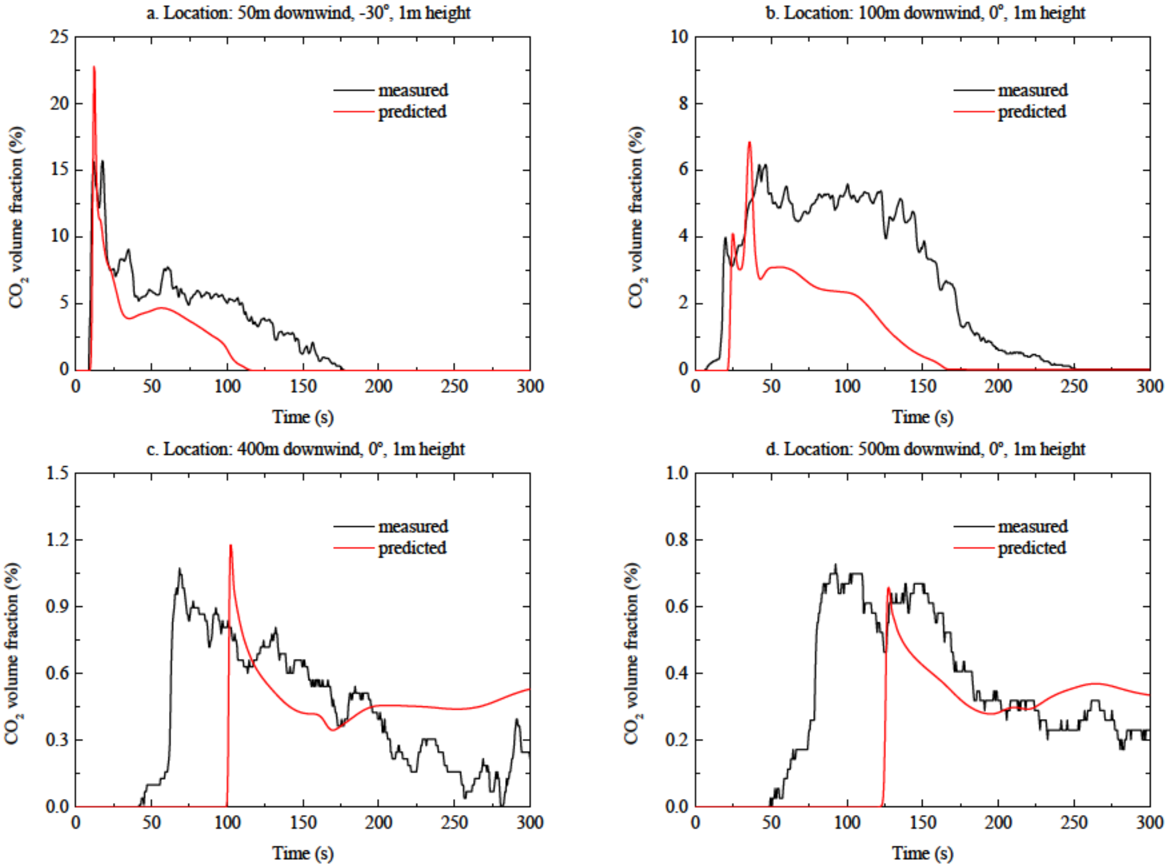

Fig. 5. CO_2 concentration at downwind locations: measured vs predicted

The trench opening at the ground level was used as the 'CO_2 inlet' boundary for the computational domain. The total mass ejected out of the trench opening into the atmosphere must equal the total mass originally contained in the pipeline and reservoirs. For the pipeline in this experiment, the mass release rate (kg/s) was approximated by:

$$\dot{m} = c_1 * [\exp(c_2 t) - \exp(c_3 t)] \tag{2}$$

where t is the time, and the constants are: c_1 = 75300 kg/s; c_2 = -1 s^{-1} and c_3 = -10 s^{-1}. This suggests that the 67.6 tonnes mass contained in the pipeline was almost completely released into the atmosphere in about 7 seconds, with the majority of the release occurring within 2 seconds.

Fig. 4 shows the computational domain, along with the other five flat faces of the box – Wind Inlet, Left Side, Right Side, Outlet, and Ceiling. The wrinkles in the floor show that floor conforms to the actual terrain topography at the test site. The wind inlet was placed 200 m upstream of the source at ground level. The computational domain was aligned with the wind direction and measures 1500 m, 600 m and 300 m in the downwind, crosswind and vertical directions respectively. 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 measured wind speed was applied to the Wind Inlet boundary, and a steady-state simulation was carried out to establish the wind field over the terrain. Subsequently, a transient simulation was performed in which the CO_2 was introduced with the mass flow rate described by Eq. (2).

Fig. 5 compares the measured and predicted histories of CO_2 concentration at specific locations 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 over-predicted. However, for risk assessment, a conservative prediction is usually preferable. 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.

3. 'Generalised' Consequence distance prediction

To obtain a comprehensive understanding of the consequence due to high-pressure CO_2 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 CO_2 with internal diameter (ID) varying from 200 mm to 800 mm. For a well-designed pipeline, the fracture propagation should be arrested within four pipes. As the length of one pipe is 15 m, in this study, the length of the fracture is assumed to be 60 m to maximise the mass flow rate. This provides the basis for the estimation of mass flow rate and the dimensions of the inlet plane of the dispersion model. In all the subsequent dispersion simulations, a 'neutral' atmospheric stability class was assumed.

In the following analysis of the consequence distance, two concentration levels were considered: 50,000 ppm and 80,000 ppm. According to the Australian Standard [7], a CO_2 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'. The downwind consequence distance was determined as the maximum distance away from the pipe rupture contained by two concentration envelopes corresponding to these two concentration levels.

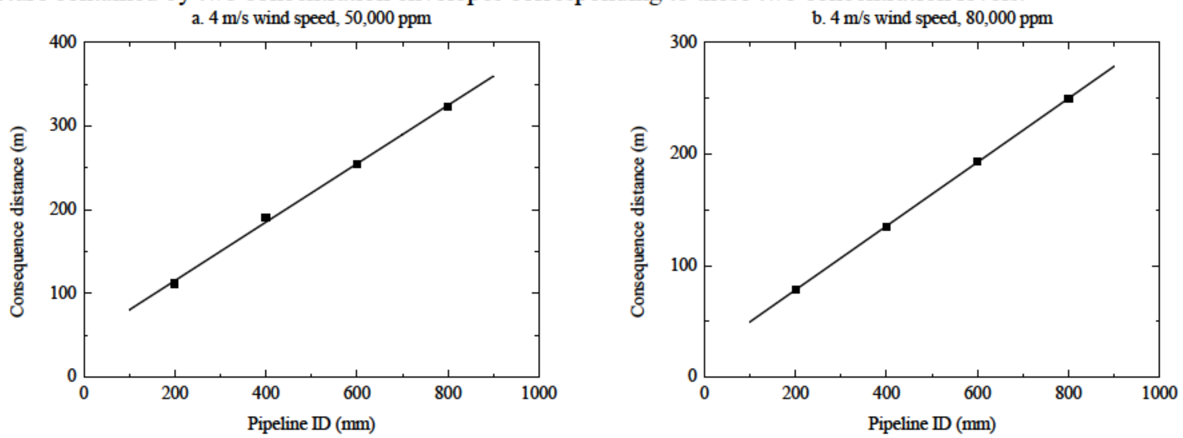

Fig. 6. Consequence distances under 4 m/s wind speed (P_0: 15 MPa, T_0: 15 °C).

Fig. 6 shows the predicted consequence distances for different pipe sizes for a wind speed of 4 m/s, considering internal pipeline pressure and temperature of 15 MPa and 15°C respectively. For a certain stagnation pressure, it is seen that larger pipe results in longer impact distance and that the consequence distance varies almost linearly with pipe diameter.

Fig. 7 shows the predicted consequence distances for pipeline with ID of 600 mm for different wind speeds. It is found that wind speed has a significant effect on the consequence distance. Higher wind speed produces longer consequence distance. When wind speed is below 10 m/s, the consequence distance increases linearly with the increase of wind speed. Previous studies with natural gas dispersion suggest that the consequence distance will plateau out to a maximum value with further increase in the wind speed. In further studies, simulations with wind speeds higher than 10 m/s will be carried out to obtain a more comprehensive view.

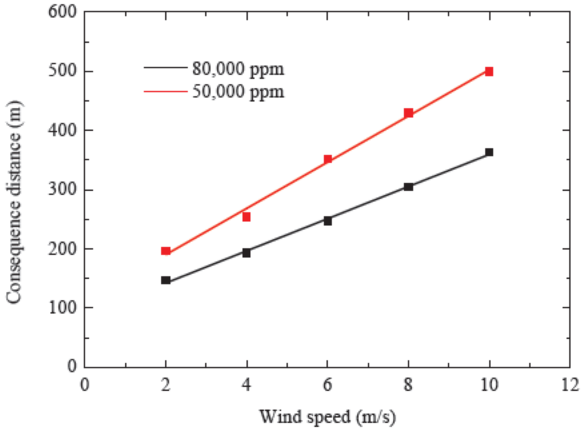

Fig. 7. Consequence distances under different wind speeds (Pipe ID: 600 mm).

4. Conclusion

In this study, the experimental investigation and CFD simulations of the dispersion of CO_2 following the pipeline fracture are presented. The CFD model is validated against experimental data. The model is employed to simulate releases from CO_2 pipelines with various sizes and under different wind speeds.

Simulation results indicate that there is a linear relationship between the consequence distance and the pipe size (ID). Also, with wind speed below 10 m/s, the consequence distance increases linearly when increasing the wind speed. This will help obtain a predictive formula for the determination of required separation between CO_2 pipeline and residential area.

It should be noted that the consequence distances obtained in this study were based on the total mass of CO2 contained in what was effectively a 317 m long pipeline. In reality, the released mass may be much larger, corresponding to a longer and/or larger diameter pipeline. The total released mass and the fracture characteristics dictate the definition of the source strength. For larger mass releases, the source strength can be assumed to be similar to two full-bore rupture releases facing one another, each releasing half the total mass. It is possible that such a release will be less explosive and last for a longer time than the cases considered in this paper. This may affect the consequence distance. Estimation of the consequence distance in such cases will be the objective of further studies.

Acknowledgements

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