Discharge and dispersion for CO_2 releases from a long pipe: Experimental data and data review

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The CO2PIPETRANS Joint Industry project (JIP) aims to fill knowledge gaps associated with safe pipeline transport of CO_2. This included experimental work at the UK Spadeadam site involving the release of 100 barg liquid phase CO_2 from one end of a 200m long, 50mm diameter horizontal pipe. These pipe depressurisation experiments were performed by filling the pipe to the required test pressure and temperature whereupon a bursting disc at one end was deliberately ruptured. Pressure, temperature and mass instrumentation along the pipe recorded the immediate and subsequent depressurisation with additional data being recorded within the release plume. Video footage was also recorded of the release plume as well as through the pipe at the mid-length location. The experimental programme included 8 releases of 100 barg CO_2 through orifice diameters ranging from full-bore releases (50mm) down to 10mm. The pipe was insulated for some of the releases.

This paper describes the CO2PIPETRANS JIP CO_2 pipe depressurisation programme and the depressurisation data recorded. It details the test rig design, instrumentation and operation as well as each release undertaken. The paper also provides an overview of the subsequent high-level data review and the conclusions of this review.

The depressurisation data review was carried by DNV GL Software with the purpose of providing an initial assessment of the robustness of the data recorded. The review used the long pipeline model PIPEBREAK in the Phast consequence modelling package as a reference source.

The pressure and temperature data collected during each test clearly demonstrate an initial pressure wave that travels with the speed of sound from the open to the closed end, and the very rapid depressurisation from the initial pressure to the saturated vapour pressure. During the subsequent two-phase flow the data review confirmed that the measured pressure was very close to saturated vapour pressure at the measured temperature (i.e. equilibrium between phases), adding further confidence to the quality of the data.

Keywords: CO_2, experiments, pipe depressurisation, shock tube, data release

Introduction

The implementation of Carbon Capture, Utilisation and Storage (CCUS) will require very large quantities of high concentration CO_2 to be transported from point of capture to point of injection into a geological repository. Pipelines are seen as the primary transportation means for CCUS CO_2 streams. There is limited experience in pipeline transportation of CO_2 in its liquid and/or supercritical phase (i.e. collectively termed “dense phase”) in the scale that will be required for CCUS.

There are international standards today that may be, and have been, used to design and operate pipeline systems for CO_2 transport. There is, however, a heightened awareness both among the emerging CCUS industry and the authorities regarding the potential issues and challenges of CO_2 transportation in large and potentially interconnected pipeline systems. Limited relevant CO_2 pipeline operating experience results in a lack of understanding of failure probabilities and combined with the absence of validated dense phase CO_2 release models leads to increased uncertainty in the assessment of CO_2 pipeline risks. Linked with this, is the continuously increasing scientific and industrial learning with regard to CO_2 and the increased understanding of the technical difference between transportation of CO_2 in large volumes in pipelines compared to transportation of hydrocarbons.

In 2008, DNV GL launched a well-supported Joint Industry Project (JIP) called CO2PIPETRANS with the objective to develop a Recommended Practice (RP) for transportation of dense phase CO_2 in onshore and submarine pipelines. In April 2010, DNV-RP-J202 was released to the public (DNV GL, 2010).

In the process of developing this RP several knowledge gaps were identified. As a consequence, to be able to better investigate and understand these areas DNV GL initiated in 2011 Phase 2 of the CO2PIPETRANS JIP. The participants of Phase 2 are: Arcelor Mittal, BP, DNV GL, Endesa, ENI, E.on Ruhrgas, Gassco, Gassnova, Health and Safety Executive (HSE) UK, Maersk Oil, Petrobras, Petroleum Safety Authority (PSA) Norway, Shell, Vallourec, and Vattenfall. Phase 2 involved the development and execution of a number of large-scale experimental programmes to collect knowledge and data. The information gained from these additional JIP experiments is being used to update DNV-RP-J202 and, by sharing the data, to help model developers validate their CO_2 release models. The goal of Phase 2 of the CO2PIPETRANS JIP is to raise confidence in CCUS developers, operators and regulators that risks can be managed to acceptable levels.

This paper details the experimental setup, procedure and results of a programme of work to perform experiments to investigate the decompression behaviour of dense phase CO_2. The experiments were performed using a purpose built 50mm nominal bore (2" NB), 200m long shock tube at the DNV GL Spadeadam Test Site in Cumbria, UK. Experiments were performed by introducing dense phase CO_2 into the shock tube until the required test pressure and temperature were achieved. The experiment was then initialised by the deliberate failure of a bursting disc arrangement on the front end of the shock tube by an explosive charge giving rise to an instantaneous opening of the pipe, releasing the CO_2 contents to atmosphere.

The conditions within the shock tube were measured using an array of pressure, temperature and load transducers recorded on a data acquisition system throughout each experiment. The characteristics of the dispersing vapour plume were measured using an array of gas and temperature measuring devices as well as video recording equipment.

See the report by Armstrong and Allason (2014) for full details of the experimental setup and instrumentation.

Experimental Arrangement

The test arrangement comprised of 200m of 50mm (2"NB) pipe rated for working pressures of up to 100 barg. The pipe used was ASTM A333 Grade 6 material with a specified minimum toughness requirement to accommodate the low temperatures that were experienced during testing. Prior to construction each pipe had its diameter, wall thickness and internal roughness recorded for each pipe end. The completed shock tube had an internal volume of nominally 432 litres which would hold approximately 410kg of pure CO_2 (at 5˚C and 100 barg) prior to testing.

The pipeline was fabricated by butt welding the pipes together using an approved weld procedure and ensuring that weld bead protrusion into the pipe bore was minimised. To control root bead size during construction a gauging plug was used and any welds through which the gauging plug with a diameter of 49mm would not pass were removed and replaced.

The pipeline was mounted on supports spaced every 4.5m along its length and was nominally 0.7m above ground level. The pipe was as straight as practicable and had a fall of nominally 0.5° toward the front end. One end of the pipeline was positioned close to a CO_2 storage vessel and the other routed onto a flat area where free field gas dispersion measurements could be made. A schematic diagram of the experimental facility is shown in Figure 1 with a photo shown in Figure 2.

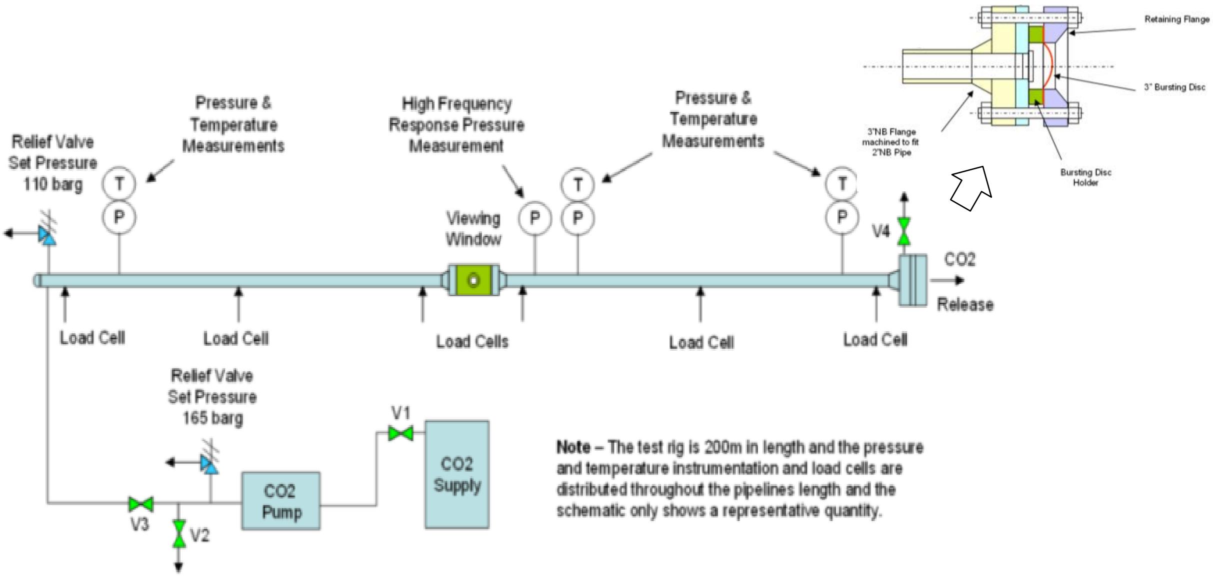


Figure 1. Schematic Layout of Test Facility

Figure 2. Photos of Test Facility (Open End and Closed End)

To the front end of the pipeline a bursting disc assembly was mounted between the outlet flange and the instrument flange, as detailed in Figure 1. The bursting disc was 75mm diameter and was rated to fail at 120 barg ±5%. The reason for the bursting disc being a larger diameter than the pipe bore was to ensure that the ‘petals’ formed when the bursting disc failed did not interfere with the escaping fluid flow and that the flow ‘choked’ at the clean sharp edge of the orifice in the instrument flange. In order to achieve releases from the pipeline through different diameter holes a range of instrument flanges with different orifice sizes machined through them were used, the instrument flange being swapped for the required orifice before a test commenced. To initiate the test release a circle of explosive detonation cord was bonded to the face of the bursting disc prior to pressurisation. When test conditions were achieved, the detonation cord was ‘fired’ to fail the bursting disc and initiate the release. Photos of a bursting disc with explosive detonation cord prior to a test and the outlet after a test are shown in Figure 3.

Figure 3. Bursting Disc Before and After a Test

During commissioning trials it was observed that the firing method introduced a significant pressure pulse in the shock tube on initiation and to prevent this blanking plugs needed to be inserted into the release orifices. Blanking plugs were made to fit each release orifice and had 2mm holes drilled through the centre of them to permit CO_2 to pass through them during the filling process but limit any pressure generated in the shock tube on test initiation. The blanking plugs were a ‘push fit’ in the bore of the release orifices and were ejected by the escaping CO_2 on test initiation. Also during the commissioning trials the optimum size and explosive strength of the detonation cord was determined to ensure that a clean bursting disc failure was achieved without any damage to the release flange arrangement.

To understand the behaviour of the CO_2 release the pipeline was supported on compression load cells at each support location (45 off). The pipe was also constrained laterally to ensure it remained on the load cell while permitting expansion and contraction of the pipeline in the axial and hoop dimensions. Care was taken to ensure the supports did not foul on the pipe and generate incorrect load cell readings. To ensure the pipeline remained in positive load at each support location it was loaded with a set of plastic buckets containing stone aggregate. The buckets had their contents adjusted at each load cell location to give a nominally equal load at each support location.

The front and rear end restraint used on the pipeline was also evaluated during the commissioning trials which were carried out on a short pipe length of approximately 21.5m. The original restraint at the front of the pipeline comprised of a collar clamped to the pipeline and incorporated roller bearings mounted either side of the pipe on spigots welded to the collar on the horizontal centreline of the pipeline. These bearings were captive in vertical channels secured to a concrete foundation to permit limited vertical movement of the pipe and restrain any axial movement. This mounting arrangement enabled the load cells to measure the pipe weight at the front end with very little influence from the mounting. This arrangement during the commissioning trials successfully restrained the axial movement but due to the bearings on the front mount it allowed some axial rotation of the release flange which subsequently resulted in pipe deflection and caused the pipe to then oscillate along its length. This pipe oscillation was reflected in the load cell data making it difficult to sum the mass values and produce a representative mass flow rate. It was subsequently decided that the front mount would be a rigid frame attached to the outlet flange to resist both the thrust and axial rotation generated on a test release. When tested this method proved to be successful but load cell data from the unit closest to the flange (LC1) had to be omitted from the total mass calculation as it measured in incorrect load change due to the fixed flange position, this however had minimal influence on the accuracy of the mass flow which gave good correlation to the mass added to the pipe prior to test initiation. The fixed outlet mounting arrangement, as shown in Figure 3 was used for the full-scale shock tube tests with equal success.

The intermediate pipe supports were fitted with roller guides either side of the pipe to ensure it remained aligned on the load cells along its length, the pipe itself sat directly on the load cells. The rear of the pipeline was secured to a spring arrangement pre-loaded with approximately 1000N of tension. At intervals along the pipeline bosses were welded to the pipe to enable pressure transducers to be attached to monitor the pressure within the pipe during a release and the temperature of the fluid at each location. At some of the boss locations, thermocouples were welded to the outer pipe wall to measure the surface temperature of the steel. These thermocouples measured the temperature of the pipe during a release and were insulated with a small section of foam insulation to reduce any ambient effects. The pressure and temperature instruments located at the front and rear of the pipeline were positioned as close as practical to the front and rear flanges. At the front, pressure and temperature were measured at the release orifice.

To be able to see the internal conditions within the pipe, a viewing window arrangement was installed for some of the experiments between flanges at approximately mid-way along the length of the pipeline. The window comprised an acrylic tube with a bore of 49.25mm mounted inside a steel holder which had two 50mm holes opposite each other so a camera could be positioned to view through the acrylic tube during the test release. A light was placed behind the window to help view the contents of the pipe. The viewing window arrangement is shown in Figure 4.

Figure 4. Viewing Window Mid-Length Along Pipe

For tests where the shock tube was required to be thermally insulated the full length was wrapped in a closed cell foam insulation 19mm thick which had a thermal conductivity of 0.035W/m.˚K (at 0˚C).

Instrumentation

Schematic diagrams of the layout of the pipeline instruments are given in Figure 5 and Figure 6.

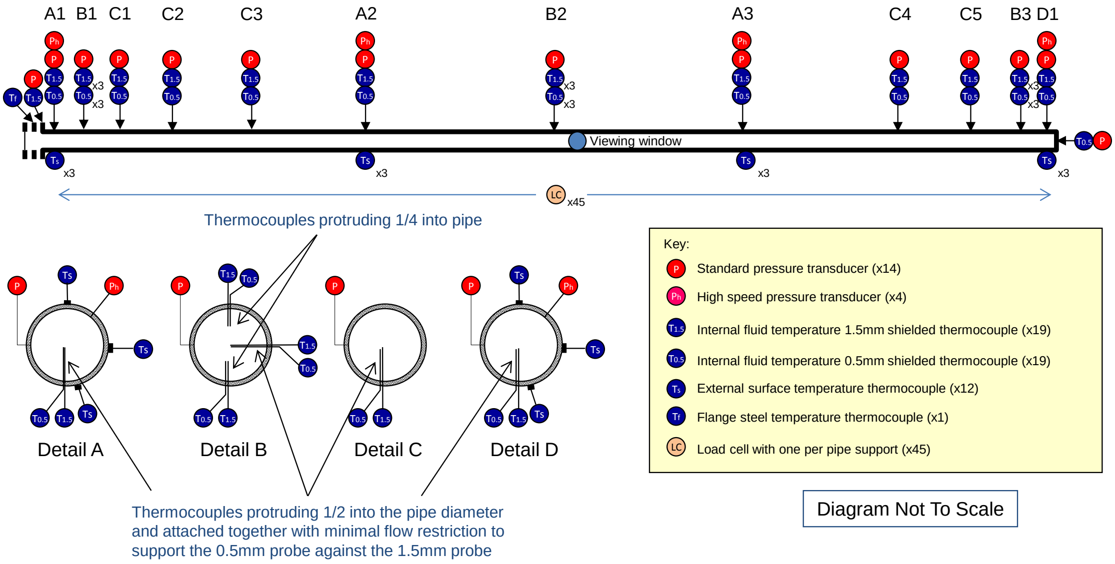


Figure 5. Shock Tube Instrumentation Schematic

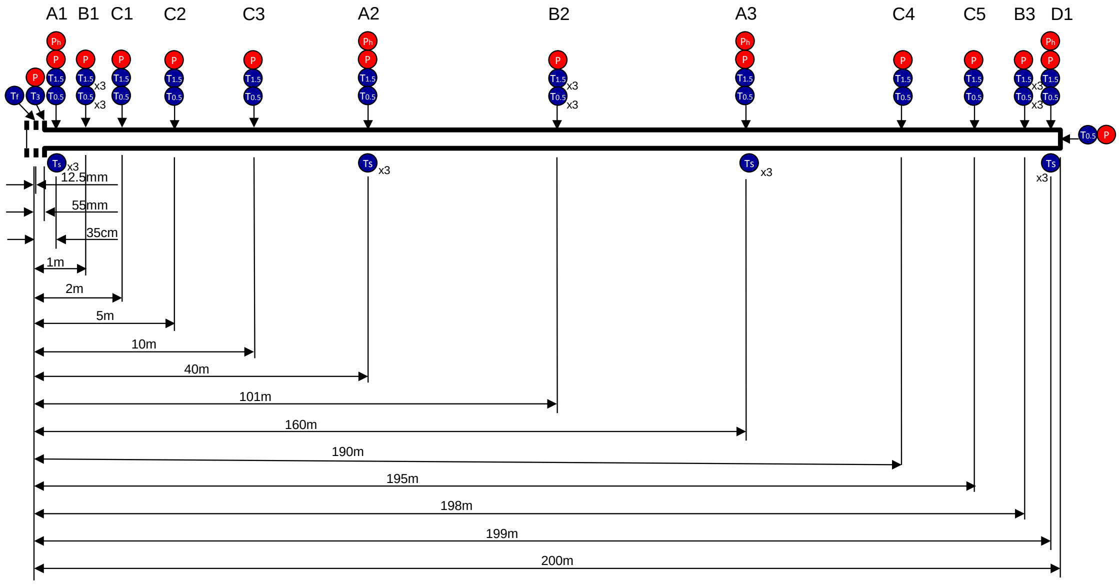


Figure 6. Instrument Location

An indicative presentation of the field instrument array used to characterise the dispersing plume is shown in Figure 7.

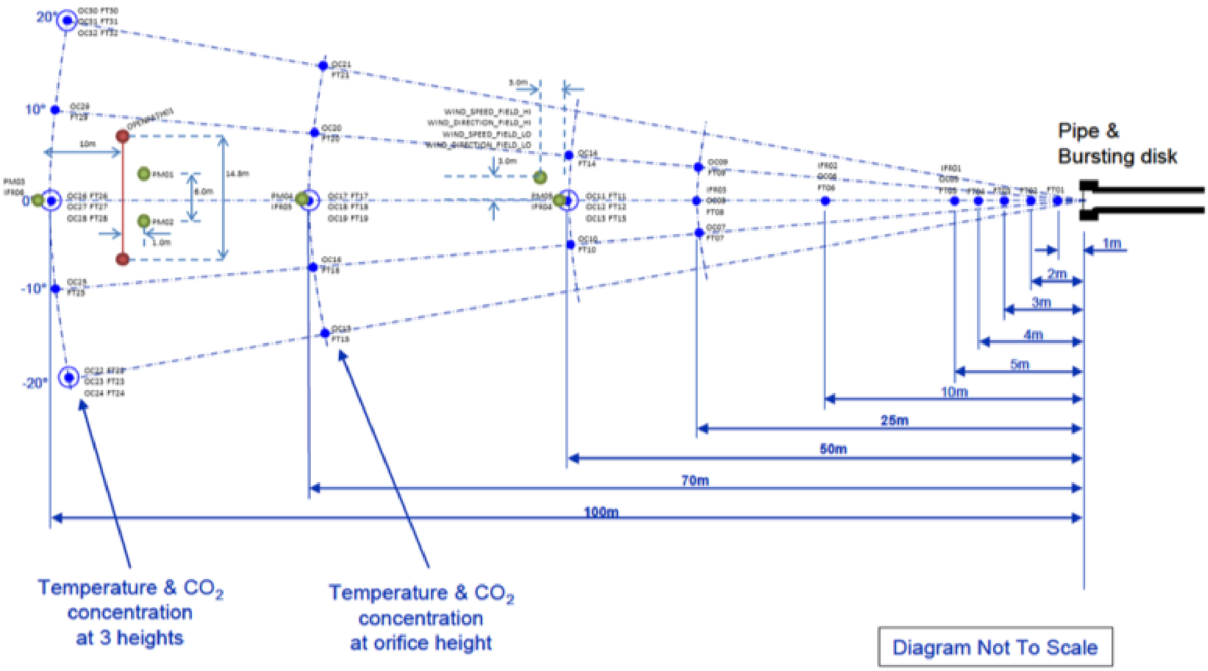


Figure 7. Indicative Field Instrument Array

The pressure of the medium in the pipeline was measured using a high frequency response Kulite CT375M transducers at one of 4 locations and standard frequency response Druck UNIK5000 transducers at a further 14 locations. During the test programme there was only one functioning high frequency response transducer which was moved to different positions for different tests. A comparison of the time response of the CT375M and UNIK5000 sensors showed that they had a time discrepancy of less than 0.3ms when measuring the same pressure pulse.

The signals from the pressure transducers were recorded on a Hi Techniques Synergy data acquisition system at a rate of 100kHz for the duration of each test.

The wall temperature of the pipeline was measured using PTFE insulated, welded tip Type 'T' thermocouples spot welded to the outer wall of the pipe at 12 locations. The fluid temperature was measured at 38 locations along the pipeline by 1.5mm and 0.5mm diameter, stainless steel sheathed Type 'T' thermocouples passing through the pipe wall via a threaded boss and pressure tight gland. The 0.5mm thermocouples were wrapped around the 1.5mm thermocouples to prevent them from being 'bent' during a release and ensure the sensing tips remained close to each other throughout the test.

The temperature of the instrument flange was measured using a 1.5mm diameter, stainless steel sheathed Type 'T' thermocouple inserted into a close fitting machined hole in the side of the flange. This thermocouple was held in place using a retaining gland and the sensing element was positioned within 3mm of the bore of the release orifice.

The load exerted at each of the 45 support points along the length of the pipeline was measured using a FUTEK LTH350 load cell with a range of 0 to ±230kg and were accurate to ±0.15% full scale. The load cells were fixed between the bracket supporting the pipe and the concrete support blocks.

The wind speed and direction were recorded using Gill Windsonic Sonic Anemometers at two or three heights at one location in the field. The measurements were made at 1m, 2m and 4m above ground level.

At least three video cameras were deployed on the dispersion tests.

The dispersion of the CO_2 released from the experiment was measured using an array of 32 oxygen sensors at locations shown indicatively in Figure 7. Some oxygen sensors were arranged one per location at a height of 1m from the ground, and at some measurement locations the instruments were arranged three per location at heights of 0.2m, 1.0m and 1.5m from the ground. The oxygen sensors had a signal output range corresponding to 0-25% oxygen in air by volume and CO_2 concentration was then inferred by calculation from the recorded signal variation during the test. For each oxygen sensor there was a Type 'T' thermocouple located close to the sensing face of the oxygen sensor.

In addition, CO_2 concentration data was recorded from 6 Draeger PIR7200 point infrared CO_2 detectors and a single Senscient open path CO_2 detector. The output from these additional sensors was recorded on the same data acquisition device (and time-base) as all of the other field instruments deployed for each test. An array of Draeger personal CO_2 monitors were also used during each test to provide additional CO_2 concentration data.

The data collection array was reviewed prior to each test and adjusted as appropriate to reflect the predicted size of the release plume.

Apart from the signals from the high frequency response pressure transducers all other signals were recorded on a Spartan data acquisition system at a rate of 500Hz throughout each test.

Experimental Programme

The experimental test programme is detailed below in Table 1.

Table 1. Experimental Programme of Tests

Test	Orifice Diameter (mm)	Initial Pressure (barg)	Initial Temperature* (˚C)	Pipe Insulated	Viewing Window Installed
1	35	98.4	6	No	No
2	35	100.4	3.9	Yes	No
3**	35	100.5	2.9	Yes	No
4	50	100.5	4.9	Yes	No
5	20	100.9	6.4	Yes	Yes
6	10	101.2	5.8	Yes	Yes
7	26.5	100.8	13.7	Yes	Yes
8	50	105	10.7	No	Yes

*Average temperature along the pipe at the beginning of the test.

** Test 3 was a repeat of Test 2 due to issues with load cell data

Experimental Procedure

To perform an experiment the pipe was initially purged clear of air using gaseous CO_2. The CO_2 was supplied to the closed end of the pipeline and expelled through a vent valve at the bursting disc end of the pipeline. The escaping gas was monitored until the oxygen content reached zero then the vent valve was closed.

The gaseous CO_2 continued to be admitted into the pipeline until a nominal pressure of 30 barg was attained. The supply was then isolated and filling with liquid CO_2 from the storage vessel commenced. The liquid CO_2 was pumped into the pipeline using a positive displacement pump until a nominal pressure of 60 barg was achieved. Filling was paused and the pipeline permitted to reach nominal ambient temperature before continuing.

After test instrumentation was confirmed operational and pre-test checks carried out, the test exclusion zone was enforced and video recorders started. The pipeline was then pressurised remotely to 100 barg using the positive displacement pump before being isolated. The pipeline pressure was stabilised before the bursting disc was failed by 'firing' the detonation cord on the face of the bursting disc to initiate the CO_2 release. On completion of the experiment the pipeline was isolated and the test area checked for the presence of CO_2 before lifting the test exclusion zone. The pipeline was allowed to return to ambient conditions before preparations for another test commenced.

Data Review

A high-level review of the experimental discharge results for the pipe depressurisation experiments was carried by DNV GL Software (Witlox, 2014). The data review used the long pipeline model PIPEBEAK in the Phast consequence modelling package (Version 6.7) as a reference source.

The data review included looking at the following:

- Measured expelled mass - effect of hole diameter and insulation
- Measured pressure and temperature
    - Variation along the pipe (between open and closed ends)
    - Pressure/temperature at open and closed ends – effect of hole diameter and insulation

The review of measured and predicted expelled mass versus time included data for overall expelled mass, both including all load cells and excluding some load cells near the open and closed ends and also some obviously faulty load cells.

As an example, Figure 8 shows the effect of hole diameter on expelled mass for the tests with insulation (tests 3-7). The figure includes experimental data (solid curves; based on all load cells, and excluding possibly faulty load cells) as well as model predictions by the Phast model PIPEBREAK (dashed curves). As would be expected, it is seen that the expelled mass increases with hole diameter and duration decreases with hole diameter. PIPEBREAK predicts quite accurately the release duration, but under-predicts the expelled pipe mass. This is because it does not account for mass resulting from the depressurisation from the initial pressure to the saturated vapour pressure. In PIPEBREAK the initial pressure is always presumed the saturated vapour pressure.

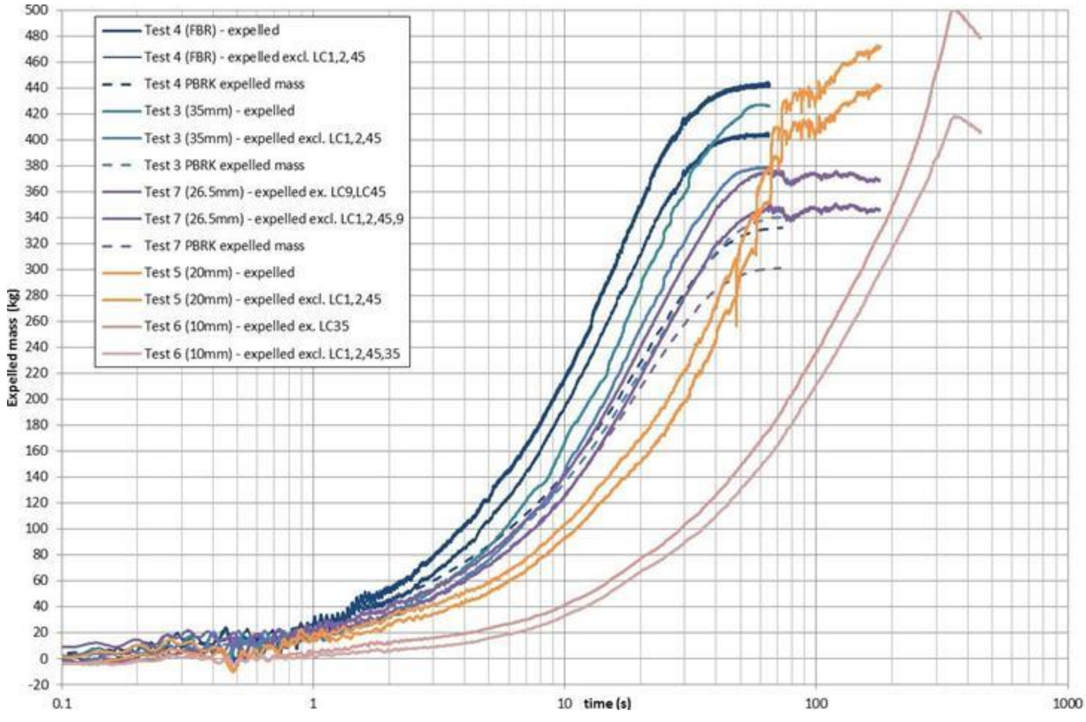


Figure 8. Expelled mass – effect of hole diameter (with insulation; tests 4,3,7,5,6)

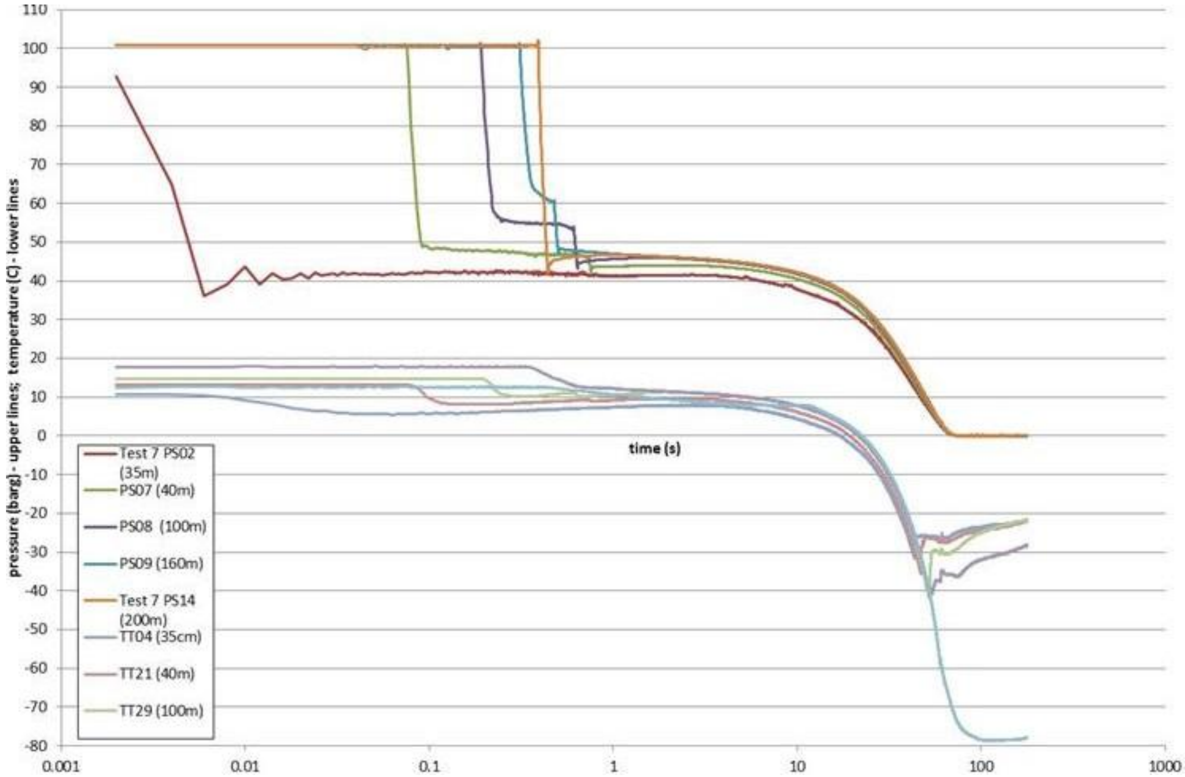
An example of a set of pressure and temperature measurement graphs used in the review for each test is presented in Figure 9 for the case of test 7 (with insulation, hole diameter 26.5mm):

- Figure 9a plots the measured pressure and measured temperature versus time for the following axial distances from the open end: 35 cm – open end, 40m, 100m, 160m and 200m – closed end. It clearly shows the pressure wave propagating from the open end to the closed end. Furthermore as would be expected, at a given time, the pressures increases towards the closed end.
- Figure 9b plots the measured pressure versus the measured temperature (corresponding to the above pressure sensors and thermocouples), where the measured results are compared against the saturated temperature curve as obtained from the DIPPR property database in Phast. It shows that the initial pressure very rapidly drops to the

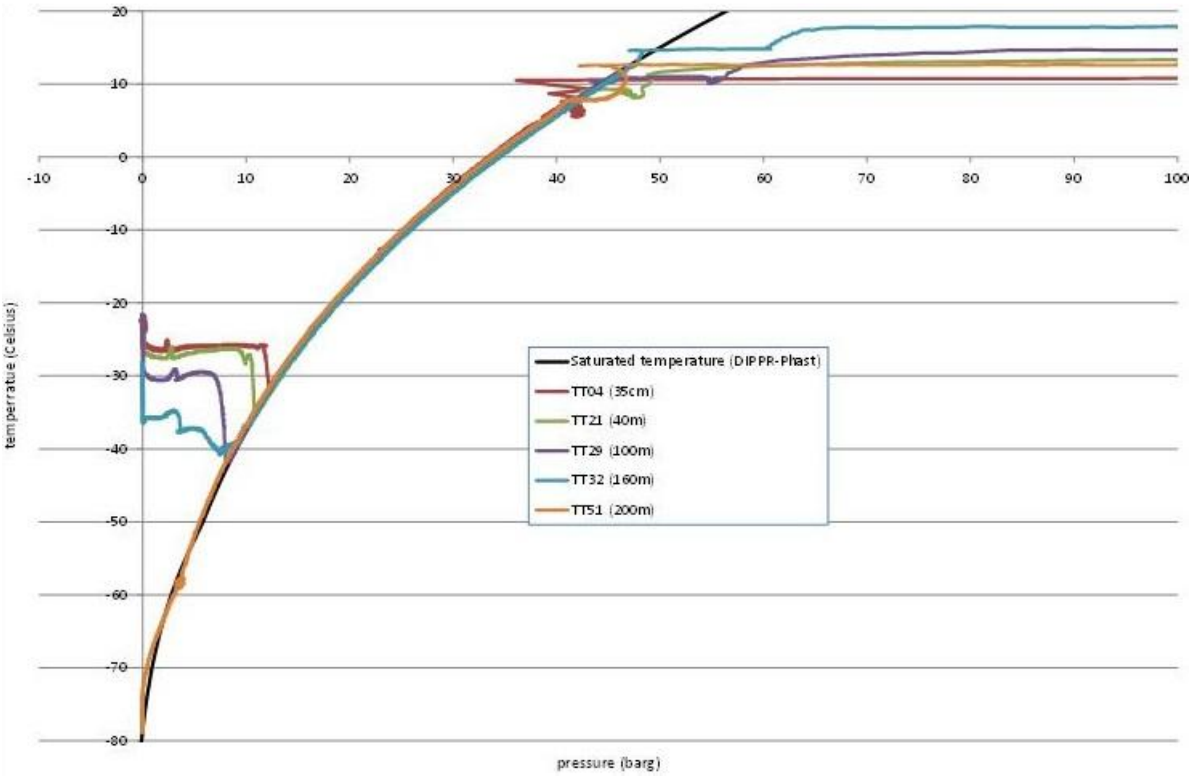
saturated vapour pressure (well within one second along the entire pipe), where for smaller times there may be some non-equilibrium effects (but also largely caused by response time of the temperature sensors; the 0.5mm thermocouples much more quickly align to the saturated curve than the 1.5mm thermocouples). As also expected, the non-equilibrium effects are largest for the open end, and smaller for the closed end. As expected these non-equilibrium effects are largest for the full-bore tests 8 and 4. After the initial time, the measured data fit very close to the saturated vapour curve.

The measured data are slightly higher than the actual data because of the delayed response time of the temperature sensors. It is seen that at later final times (after pure liquid and 2-phase stages), the pressure drops below the vapour pressure, i.e. pure vapour CO_2 present at the thermocouple in question.

The above observations confirm that the pressure sensors and temperature thermocouples show qualitatively the correct behaviour and this adds considerable confidence to the experiments.



(a) measured pressure and temperature versus time

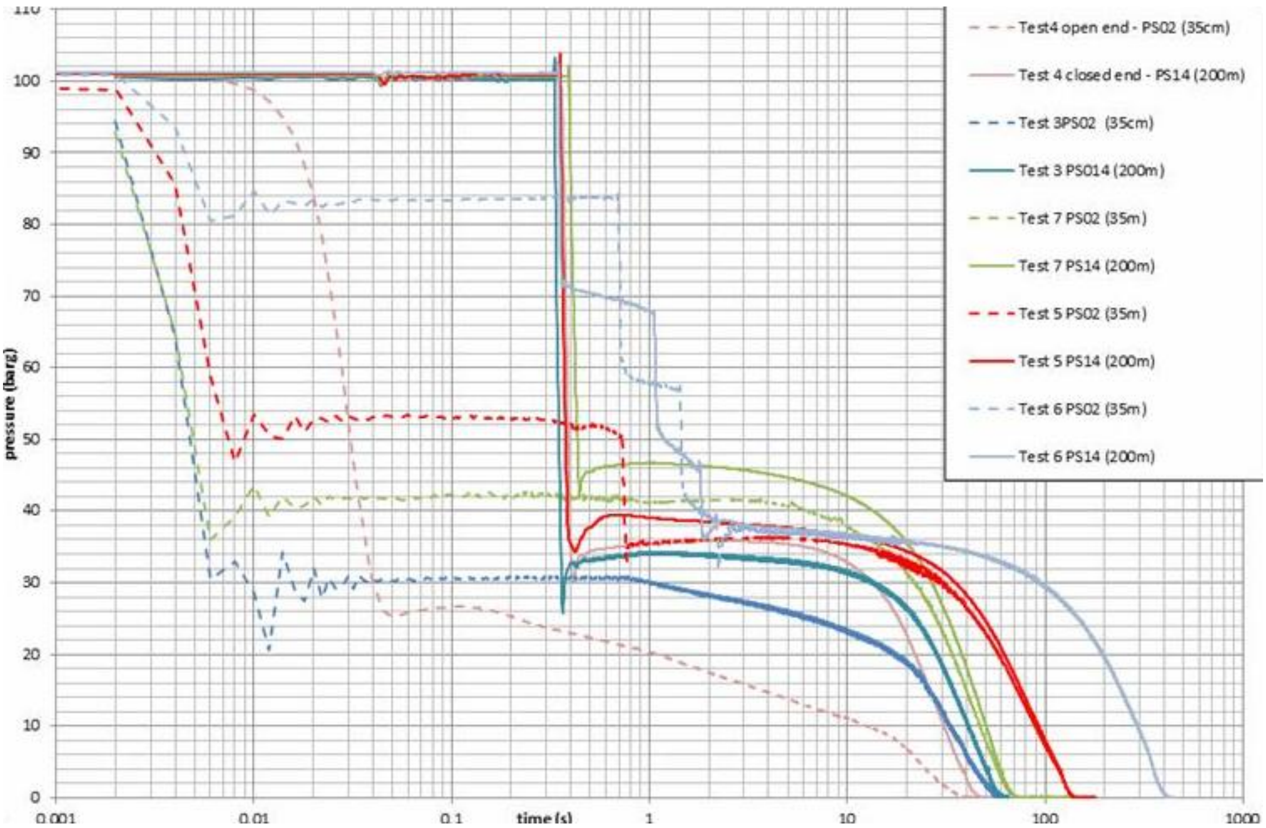


(b) measured temperature versus pressure

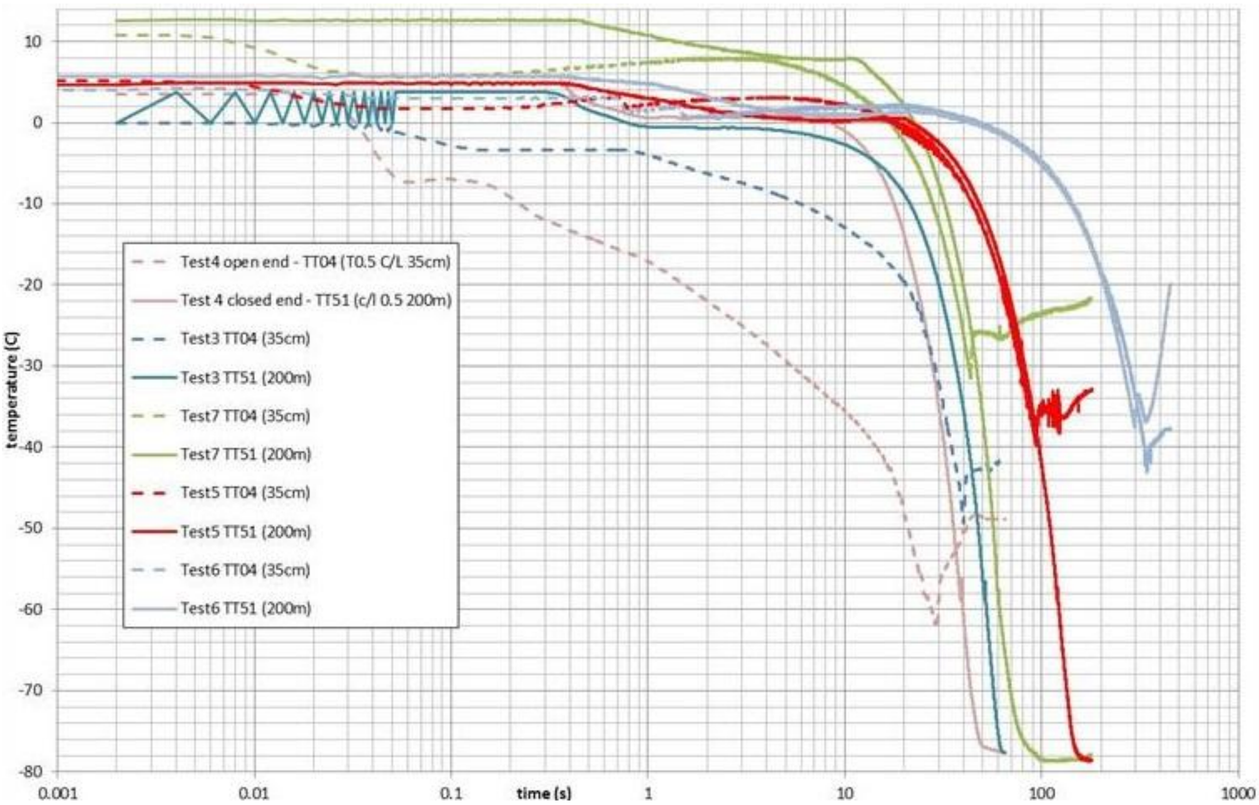
Figure 9. Measured pressure and temperature - Test 7 (26.5mm)

Another example of data plots used in the data review is shown in Figure 10 which includes results for all tests measured pressure versus time and measured temperature versus time for both open ends and closed ends:

- Results at closed end
  - It is seen that the pressure wave hits the pipe closed end at the same time (+/- 0.1s) relative to the initiation of the release for all tests, as would be expected. This shows that the release mechanism was repeatable for each test.
  - After the pressure wave hits the closed end (and virtually immediately drops to the saturated vapour pressure), there is a very brief period of non-equilibrium (presuming the pressure sensor readings are correct), with the pressure dropping very briefly below the saturated vapour pressure.
  - Subsequently saturated flow occurs with the CO_2 cooling down while the saturated vapour pressure drops.
  - With the CO_2 inventory being released through the orifice, the liquid/vapour interface level will go down. As the pressure in the pipe drops below the triple point, some solid CO_2 will be deposited on the pipe base which will then sublime to vapour, further cooling the pipe even after the pipe is at ambient pressure. This cooling effect can be seen with the exception of test 6 (smallest aperture ratio 0.04). For this test it was concluded from the pressure/temperature curve that all the liquid CO_2 evaporates to vapour before the triple point pressure is released and therefore no solid CO_2 is deposited, and as a consequence there is no post-release pipe cooling.
- Results at open end
  - At the open ends the pressure drops very rapidly immediately after the release is initiated with a rapid drop to the saturated vapour pressure (typically within 0.01s).
  - Subsequently two-phase flow occurs with pressure equal to saturated vapour temperature.
  - Finally after all liquid (or solid) has been evaporated (or sublimed), the temperature rises above the saturated vapour temperature and pure vapour outflow occurs.



(a) Pressure versus time



(b) Temperature versus time

Figure 10. Pressure/temperature at open/closed ends – effect of hole diameter (tests 4,3,7,5 & 6)

The data review concluded that based on the high level review of the pipe depressurisation data, using Phast Version 6.7 as a reference, the data sets for all eight tests look robust and of significant value for model developers.

A review of the dispersion data collected from the field instrument array has not been undertaken.

Video Footage

A large amount of video footage was recorded for each test. This footage provides additional valuable information about the releases.

Figure 11 shows two pictures taken from videos recorded during tests.

Figure 11. Views From Video Footage (Release Cloud and Window View)

Public Sharing Of Experimental Data

A significant knowledge gap identified within Phase 1 of the CO2PIPETRANS JIP was the lack of model validation data for computer models used for dense phase CO_2 release modelling. An objective of Phase 2 of the JIP was to help fill this gap by making publicly available suitable data from large scale CO_2 release experiments.

The datasets from the following three CO_2 experimental programmes have now been made available by the CO2PIPETRANS JIP for download from www.dnvgl.com/ccus:

1. BP 2006/7: CO_2 of up to 150 barg and 150°C through 6, 12 and 25mm diameter orifices
2. Shell 2010/11: Extension of BP experiments including similar sized releases into an enclosed space
3. CO2PIPETRANS Phase 2: Pipe depressurisation as detailed in this paper

Datasets from the recently completed CO_2 release experiments up to 150mm diameter will be released by CO2PIPETRANS within the near future.

Conclusions

Understanding how CO_2 is released and disperses in the atmosphere under both planned and accidental scenarios is an essential element in the risk management of CCUS CO_2 systems. Computer models are used to simulate and assess what might happen in the case of a release. Up until now these models have not been validated using large scale experimental results, as experimental data for CO_2 has not been publicly available. The on-going second phase of the DNV GL led CO2PIPETRANS JIP aims to fill knowledge gaps with three main focus areas, namely, collection of experimental data and experience on pressurised dense phase CO_2 release model validation data, pipeline fracture arrest, and corrosion.

The CO_2 release model validation data now made publicly available through CO2PIPETRANS includes two programmes of experiments previously undertaken for BP (2006/7) and Shell (2010/11), and the pipe depressurisation "shock tube" experiments detailed within this paper. Prior to release the datasets were reviewed by DNV GL Software with the purpose of providing an initial assessment of the robustness of the data.

The pressure and temperature data collected during the eight shock tube experiments clearly demonstrate an initial pressure wave that travels with the speed of sound from the open to the closed end, and the very rapid depressurisation from the initial pressure to the saturated vapour pressure. During the subsequent two-phase flow the data review confirmed that the measured pressure was very close to saturated vapour pressure at the measured temperature (i.e. equilibrium between phases), adding further confidence to the quality of the data

Full details of the experimental programmes, the data reviews, and datasets from each test can be downloaded for free from www.dnvgl.com/ccus.

Information and data from another CO2PIPETRANS JIP experimental programme which was recently completed at the Spadeadam test site will also be made publically available soon. This experimental program (Brown et al., 2015) involved the release of CO_2 with initial pressures ranging between 36 - 96 barg and temperatures between 10 - 15°C through release orifices ranging in diameter from 25mm up to 150mm.

The CO2PIPETRANS JIP Phase 2 will be completed in 2015 with the update of DNV GL's Recommended Practice for transportation of dense phase CO_2 in onshore and submarine pipelines, DNV-RP-J202. This update will reflect the knowledge gained during the delivery of the various experimental programmes undertaken by the JIP.

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