Under-expanded jets and dispersion in high pressure CO₂ releases from a large-scale pipeline

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Abstract

As deeply development of Carbon Capture and Storage (CCS) project and massive application of long-distance CO\textsubscript{2} pipeline, the inevitable pipeline rupture and leakage will cause the catastrophic accidents. Study of near-field source terms and dispersion behavior after pipeline rupture is essential foundation of CO\textsubscript{2} pipeline risk assessment and provide the effective technical support for the implementation of large-scale CCS projects in the future. A 258 m long instrumental pipeline (233 mm i.d., 20 mm thickness) was used in CO\textsubscript{2}QUEST project to investigate the under-expanded jets and dispersion characteristics of a pipeline, modelling puncture/rupture of a high pressure CO\textsubscript{2} pipeline. Video cameras, thermocouples and CO\textsubscript{2} concentration sensors were deployed to monitor the formation of the visible cloud, the distribution of the temperatures and concentrations in the dispersion area during the gaseous and dense CO\textsubscript{2} release through the three orifice diameters (15 mm, 50 mm and Full Bore Rupture). The under-expanded jet flow and the formation of the dry ice particles in the near-field were studied for gaseous and dense CO\textsubscript{2} release. The safety distances along the release direction of 5\% concentration for each of the three orifice diameters were determined by the lower limit for adverse human effects.

**Keyword:** CO\textsubscript{2} release, Under-expanded jet, Dispersion, Large-scale pipeline.
1 Introduction

A Large amount of CO\(_2\) emissions lead to a series of problems such as environmental deterioration, frequent extreme weather and so on, which promote the development of various CO\(_2\) mitigation technology [1]. As the most potential mitigation technology in the future, Carbon Capture Storage (CCS) can fundamentally solve the problem of carbon emissions from electric power industry, etc [2]. The urgency of deploying carbon capture and storage (CCS) only increases if we are to achieve the stabilisation goal of low-carbon to limit the rise in global temperatures to 2 °C above pre-industrial levels [3]. Therefore, CCS is the important strategic choice to reduce carbon emissions and to control the climate warming.

The development and commercialization of CCS require an infrastructure for transportation of the captured CO\(_2\) from the sources of emission to the storage sites. It is commonly accepted that pipeline transportation of CO\(_2\) is considered as the safest and most efficient transportation option [4]. The hazards associated with CO\(_2\) pipelines are quite different compared to those posed by hydrocarbon pipelines. The ability of CO\(_2\) to collect in low-lying areas near the pipeline route, presents a significant hazard if leaks continue undetected [5,6]. At a concentration of 10%, an exposed individual would lapse into unconsciousness in 1 min. Furthermore, if the concentration is 20% or more, the gas is instantaneously fatal [7]. Safety distances in published risk assessments for underground high pressure CO\(_2\) pipelines vary from less than 1 m till 7.2 km [8]. This large variation in the safety distance is difficult to provide effective support for the actual security needs.

In the event of pipeline rupture, a significant proportion of the inventory would be discharged
in the first few minutes. Due to the relatively high Joule Thomson expansion coefficient \( \text{CO}_2 \) upon expansion may reach temperatures as low as -70 °C, which can induce brittle fracture [9]. The large cooling effect associated with \( \text{CO}_2 \) expansion will cause the formation of dry ice in the near-field [10]. A highly under-expanded flow will occur within the jet that contains a Mach disk orthogonal to the flow direction [11]. The solid \( \text{CO}_2 \) particles formed in the jet, which will subsequently sublime and a vapor cloud will be formed and dispersed in the far-field. In the process of mixing the momentum of the jet diminishes and the dispersion will continue as a vapor cloud dispersion [12].

Many experimental studies have been conducted to establish a clear understanding of the hazards associated with the failure of \( \text{CO}_2 \) pipelines. As part of the \( \text{CO}_2 \)PipeHaz project, INERIS [13-15] built a 2 m³ vessel fitted with a 9 m long pipe with an inner diameter of 50 mm to measure temperatures and concentrations in the modelled region of the flow field for the experimental studies of large-scale \( \text{CO}_2 \) releases. An important conclusion was obtained that significant solids are generated within the near-field of dense phase releases, despite the release itself containing no dry ice. Xie et al. [16,17] developed a 23 m long circulating pipeline with a 30 mm inner diameter to study the pipeline leakage process of supercritical \( \text{CO}_2 \) in a vertical direction. A typical highly under-expanded jet flow structure was observed in the supercritical \( \text{CO}_2 \) leakage, which weakened with the depressurization in the leakage process. The typical structure disappeared with the increasing of leakage nozzle size. DNV-GL [18] conducted an experimental investigation to study the discharge of liquid \( \text{CO}_2 \) from a 0.5 m³ pressurized vessel equipped with an actuator valve. The results showed
that the CO$_2$ concentrations near the orifice depend mainly on the jet shape rather than the mass flow rate. The concentrations at 9 and 15 m from the release point tend to increase continuously during the saturation phase regime and then to drop with the transition to vapor outflow. Xing et al [19] used a series of scaling rules to scale field experiments of CO$_2$ dispersion for simulating CO$_2$ blowouts. Through the comparison with the k–ε model and the statistical performance indicators, it was concluded that the scaling rules were demonstrated useful for the accidental release field experiment.

Several experimental research programs have been performed at the Spadeadam Test Site in Cumbria, UK. The COSHER JIP [20] performed a large scale pipeline rupture test using a 226.6 m long pipeline loop formed from 219.1 mm diameter steel pipe and fed from both ends by a 148 m$^3$ reservoir of CO$_2$. The results showed that a visible cloud reached a maximum height of about 60 m and a maximum distance from the rupture location about 400 m. The pseudo-steady CO$_2$ concentrations were reached at the upwind and downwind locations in the near-field in low wind speed conditions, but not reached in the far-field. Wareing et al. [21,22] studied the venting of dense phase and gas phase CO$_2$ through a single, straight vertical vent pipe of constant diameter within the framework of the COOLTRANS research programme. The near-field dispersing structures of such releases were predicted by a mathematical model against this experimental data. Witlox et al. [23,24] presented that BP and Shell experimental work from CO$_2$ PIPETRANS JIP included both high-pressure steady-state and time-varying cold CO$_2$ releases and high-pressure time-varying supercritical hot CO$_2$ releases. For all cases the solid carbon dioxide was found to sublime rapidly and no
fallout was predicted. As part of the CO₂ QUEST project [25,26], this paper carried out six large-scale experiments using a 258 m long, 233 mm inner diameter pipeline to study highly under-expanded jets and dispersion characteristics of gaseous and dense CO₂ during sudden release under three orifice sizes (15 mm, 50 mm and Full Bore Rupture). The experimental studies provided a detailed understanding of the hazards presented by CO₂ releases through experimentation, which could be used to validate the outflow and dispersion models developed.

2 Experiments

2.1 Experimental setup

Fig. 1 shows the schematic representation of the CO₂ pipeline employed for conducting the release experiments. The release experiments involved the measurement of the temperature and CO₂ concentration profiles in the discharge area using a 257 m long single pipeline with low temperature carbon steel of 16MnR and a 1 m long dual-disc blasting pipe with grade 304 stainless steel. The experimental pipeline had a 233 mm internal diameter and a 20 mm wall thickness, while had a maximum pressure rating of 16 MPa. Many concrete column foundations were built to support the pipeline at a height of 1.3 m above ground. CO₂ release experiments with different diameter punctures would be conducted using flanges with three orifice sizes (15 mm, 50 mm and Full Bore Rupture) at various ambient temperatures up to a maximum temperature of 40 °C. The external heating for the pipeline was completed by a 1200 m long heating tape with 50 kW wrapped around the pipeline and a 50 mm thick thermal insulation layer.
The dual-disc blasting device was consisted of two rupture discs and two disc holders, a solenoid valve and two pipe sections, which was designed to made the release device safe, controllable and being capable of transient release for conducting rupture and puncture experiments. In principle, disk rupture corresponding to release occurs by reducing the pressure difference between the two rupture discs using Nitrogen. Rupture experiments involve fastening a flange incorporating different diameter orifices at the pipe release end. Impulse and recoil forces of the pipeline set-up resulting from the sudden release could be huge in such a large-scale experiment, and could be dangerous to people and the pipeline. Therefore, a reinforcing device was designed to prevent the movement of the pipeline. The device consists of steel frames and anchor bolts anchored firmly to the concrete foundation. This reinforcement device can resist an acting force of 400 kN.

The feed procedure for CO$_2$ will be carried out as follows: (1) Decide the amount and state of CO$_2$ to be fed into the pipeline and transport the CO$_2$ to the field. (2) Purge the pipeline first using gaseous CO$_2$ to eliminate water and other impurities as far as possible. (3) Feed liquid CO$_2$ into the pipeline using a tank car with vapour-liquid CO$_2$ of 2.2 MPa and -10 °C. (4) Shut down all valves when the appropriate mass of CO$_2$ had been injected to the pipe. (5) Open the heating system to heat the main pipeline. (6) Isolate the experimental field when the temperature and the pressure of the pipeline reached to the experimental conditions. (7) Initiate the experiment through the dual-disc blasting device. (8) Record the measurement data through data-acquisition systems during the release. (9) Clear up the experimental field after the release.
2.2 Pipeline instrumentation

From the top of the view, the testing point locations were shown in Fig. 2. Three rows and sixteen columns were set in the dispersion region. The distances from the orifice for each row and column were labelled on the axial and the transversal direction. Thermocouples and CO$_2$ concentration sensors were both arranged on vertical tubes at the same height as the pipeline, as shown in Fig. 3. The thermocouple was T-type with the uncertainty of ±1°C and the measure range was -200 °C- 400 °C. The response times of the thermocouples was 100 ms. The CO$_2$ concentration sensor was a COZIR-W type manufactured by Gas Sensing Solution Ltd (GSS). The measure range was 0–100%, and the accuracy was ±3%. The response time was 4 s.

Two data acquisition systems ran simultaneously in a computer, one was NI cRIO-9025 system which was used to sample the thermocouples, the other one was RS485 communication system which was used to sample the CO$_2$ concentration sensors. The NI cRIO-9025 system consisted of one 9025, one 9144 chasses and two thermocouple input modules of NI 9213. The RS485 communication bus adopted a twist-pair with RVVSP 2×2×0.5 mm$^2$ and a master-slave half duplex mode. The data-acquisition code was programmed using LabVIEW software from the NI company.

A weather station was established to record the ambient temperature, ambient pressure, ambient humidity, and wind speed and direction. The ambient pressure were measured using QA-1 air pressure sensors with an accuracy of ±0.03 and a range of 55 kPa to 106 kPa. The ambient temperature and humidity were measured using PTS-S environment monitoring
sensor with an uncertainty of ±0.1 °C and ±0.2, and a range of -50 °C to 80 °C and 0 to 100%.

The wind speed and direction were measured using EC-A1 ultrasonic wind sensor with an accuracy of ±0.01 m/s and ±1°, and a range of 0 to 60 m/s and 0 to 360°. Several digital HD video cameras and the Phantom 2 Vision aerial equipment were used to record the visible cloud development during sudden release.

2.3 Experiments conducted

Six groups of CO₂ release experiments were performed to investigate dispersion behavior during the release of gaseous and dense CO₂ from a pipeline with three orifice diameters (15 mm, 50 mm and Full Bore Rupture). The purity of the CO₂ was 99.9%. The initial and environmental conditions of six tests are presented in Table 1. For tests 1 and 4, the ambient pressure and temperature, the wind speed and direction fluctuated violently as result of a long depressurization time and the unstable atmospheric conditions. Other tests had a relative stability of initial conditions.

3 Experimental results

3.1 Gas phase tests

3.1.1 Visible cloud development

For tests 1, 2 and 3 the total depressurization times for each experiment were 1946 s, 159 s and 15 s respectively. According to the observation of the visible cloud in the experiments, the development of visible cloud could be divided into the rapid expansion stage (I), the metastable stage (II) and slow attenuation stage (III). For tests 1, 2 and 3, the duration times of the initiation and stabilization stage were 2.5 s, 1 s and 0.6 s respectively, the duration
times of the metastable stage were 50 s, 4 s and 0.2 s respectively, the duration times of the slow attenuation stage were 1894s, 154 s and 14.5 s respectively.

Fig. 4, 5 and 6 show the developments of the visible cloud for tests 1, 2 and 3. Due to the Joule-Thomson cooling the temperature sharply dropped below the triple point near the orifice and hence a white visible potential core could clearly be seen in the highly under-expanded jet flow structure as a result of the formation of solid phase. For tests 1 and 2, the length of the visible cloud in the rapid expansion stage was fully developed at around 2.5 s and 1 s after the rupture respectively, remained relatively stable within 50 s and 4 s in the metastable stage respectively, and then turned into a slowly decaying while the expansion angle of the jet flow decreased in the slow attenuation stage. The white visible cloud disappeared in the forefront of the jet flow, indicating that the dry ice particles gradually had sublimated during diffusion.

For test 2. Jet boundary in near-field kept going in a straight line, which divergent angle changed little in the whole process, circa 11°. Inside the jet dispersion, an extremely low temperature led to a phase change of CO$_2$ from gas phase to solid phase. In the metastable stage the spatial scale of the visible cloud remained unchanged and the length and the maximum expansible radius of the visible cloud were circa 10 m and 1.5m respectively. At the moment of 45 s and 60 s, the intercepting shock and the Mach disc could be clearly observed in the jet flow.

For test 3. Jet velocities are indicated on the figure for the first 0.8 s. In the rapid expansion stage the visible white cloud entraining the dry ice particles and condensed water rapidly
expanded and the expanding jet velocity gradually decreased. The visible cloud presented a mushroom shape and reached a maximum distance of 40 m from the orifice. In the slow attenuation stage the white visible cloud and the mixture of gaseous CO$_2$, air and raised dust started to separate. When the limit of the former decayed to zero, the later continued to spread relying on momentum, wind and body forces. For FBR test, because the dry ice particles were spread farther away the considerable diffusion velocity and diffusion range of this test could be observed. The divergent angle of jet boundary was circa 18° in test 3.

3.1.2 Temperature distribution

Fig.7 shows the temperature evolution along the axial line of the discharge area in tests 1, 2 and 3. After rupture, the ambient temperature in the far-field dropped as result of the expansion of the escaping gas and the sublimation of the dry ice particles. The temperature evolutions along the release direction gradually rose due to the reduction of the expanding velocity and the fraction of dry ice along the axial direction. When the release ended, the temperature of CO$_2$ gradually increased to the ambient condition along with time as the continuous mixing of CO$_2$ mixture and air. For test 1, the temperature distribution range in the dispersion region was small and fluctuated because of the small orifice release and the unstable atmospheric environment. For test 2, the temperature contour lines with time quickly extended along the axial direction and reached the maximum values at 15 s and then slowly fell back. For test 3, the extending time and the down time of the temperature contour lines were similar as result of the violent mixing of the escaping gas and air and the extremely
unstable atmosphere in the full bore release. The maximum temperature drop amplitudes of
the three experiments at distance of 4 m from the orifice were 4.2 °C, 5.5 °C and 17.6 °C
respectively and appeared at the time of 35 s, 15 s and 7 s respectively. The point in time of
the lowest temperatures became shorter and the maximum temperature drop amplitudes
became bigger with the increase of the orifice diameter due to the more violent mixing of the
escaping gas and air from a bigger hole release.

Fig. 8 shows the lowest temperature distribution in the discharge area of tests 1, 2 and 3. The
y direction is along the jet axis and x direction is horizontal distance. Obviously, the
temperature of the escaping gas increased along the x direction and the y direction in the
discharge area. The lengths of the temperature contour lines along the x direction were much
longer than that along the y direction than that along the y direction, while the temperature
gradients along the x direction were much lower. For 23 °C and 24 °C in test 1, 23 °C, 24 °C
and 25 °C in test 2, 10 °C, 13 °C and 16 °C in test 3, the length ratio between the temperature
contour lines along the y direction and the x direction were 16.1, 12.9, 33.5, 29.6, 21.3, 58.3,
30.4 and 24.1 respectively. This suggested that the temperature contour lines along the y
direction were much larger than that along the x direction, which was due to the greater
expanding velocities along the release direction. The length ratio between the temperature
contour lines along the x direction and the y direction became larger with the increase of the
orifice diameter. This was mainly because the jet velocities and distribution range became
greater with with the increase of the orifice diameter. For tests 1, 2 and 3, the length and
width of the low-temperature zone were predicted to 13 m and 2.5 m, 16 m and 2.2 m, 20 m and 2.5 m in three tests respectively.

3.1.3 CO₂ concentration dispersion

Fig. 9 shows that the concentration development along the axial direction in tests 1, 2 and 3. The acute health effects of high concentrations of inhaled CO₂ are influenced by two factors, the concentration in the air and the duration of exposure. In concentrations of approximately 5% (50,000 ppm) within a few minutes the gas will cause headache, dizziness, increased blood pressure, uncomfortable breathing and so on. Consequently, the threshold value of 5% concentration is assumed to be the lower limit for adverse human effects [27].

For tests 1, 2 and 3, the contour of CO₂ concentration extended to the farthest point and stayed in the metastable state. The closer distance from the orifice, the longer the duration time would be in the area of 5% concentration. The start time of the contour of low CO₂ concentration was earlier than that of high CO₂ concentration, which was due to the response lag of CO₂ concentration sensor as a result of high-velocity gas. But the response lag had a little influence on the assessment of the dangerous concentration distances. For test 1, the contour of CO₂ concentration extended to the farthest point at the distance of 9.2 m from the release orifice, so the safety distance along the release direction in test 1 should be less than 10 m. For test 2, At the end of the release (159 s), CO₂ concentrations within the measurement area stayed above 3% concentration, which decreased below 1% concentration until 207 s after the rupture. The safety distance along the release direction in test 2 should be
at least 12 m. For test 3, the contour of 5% CO$_2$ concentration quickly extended to the farthest point at 13 s. CO$_2$ concentrations at the distance of 5 m from the release orifice reached 30.1% at the end of the release (15 s), and reached the maximum value at 27 s, which stayed above 5% concentration until 150 s after the rupture. This phenomenon was caused by the sublimation of the dry ice particles in the discharge area. The safety distance in test 3 should be at least 25 m. It was obvious that the larger discharge diameter brought a greater amount of discharged CO$_2$ into the dispersion region over the same time interval.

3.2 Dense phase tests

3.2.1 Visible cloud development

For tests 4, 5 and 6 the total depressurization time of each experiment were 7300 s, 482 s and 40 s respectively. For tests 4, 5 and 6, the duration times of the rapid expansion stage were 9 s, 6 s and 5 s respectively, the duration times of the metastable stage were 441 s, 19 s and 1 s respectively, the duration times of the slow attenuation stage were 5850 s, 457 s and 35 s respectively. Compared with the gas phase tests, the duration of each stage became longer.

Fig. 10, 11 and 12 show the developments of the visible clouds for tests 4, 5 and 6. At 0.5 s, 3 s and 6 s of test 4, the length and height of the visible cloud reached circa 11 m and 2.5 m, 25 m and 6 m, 36 m and 7 m respectively, and the expanding velocity circa 11 m/s, 5 m/s and 4 m/s respectively. This suggested that the length and height of the visible cloud became larger gradually, and the expanding velocity became smaller gradually. For tests 5 and 6, the length, width and height of the visible cloud reached circa 12 m, 3 m and 3 m, 22 m, 14 m
and 11 m at 0.5 s, and the expanding velocity circa 22 m/s and 32 m/s at 0.5 s respectively.

The indicated that the sizes of the visible cloud and the expanding velocity became larger at the same time as the orifice size increased. For test 4, the length, width and height of the visible cloud reached the maximum value at 9 s. For tests 5 and 6, the maximum length and width of the cloud were circa 80 m and 30 m at 6 s, 150 m and 70 m at 5 s respectively, but the heigh of the cloud reached the maximum value circa 12 m at 2 s and 16 m at 1 s respectively. This shown that the length and width of the cloud were still rising when the heigh of the cloud reached the maximum. The influence of the orifice size on the height was quite obvious because the angle of reflection of the high-velocity jet flow at the ground was greater as the orifice size increased. However the width of the cloud was greater than the heigh of that due to the effect of the dry ice and heavy gas.

For three dense phase tests, the divergent angle of the jet boundary reached the maximum value at the moment of the rupture and decreased gradually in the whole process. In the rapid expansion stage the jet flow expanded rapidly and the leading edge of the jet presented a arc surface, while the straight length of jet boundary in near-field increased quickly. In the metastable stage, the forefront of the cloud presented a fan-shaped form and the length of the jet boundary and the visible cloud remained unchanged nearly. The heavy gas effect started prompting the free diffusion of CO$_2$ in the low-lying areas. In the slow attenuation stage, because of the loss of the expanding velocity the visible cloud diffused mainly depending on the residual momentum. The sizes of the visible cloud began to decay and the attenuation velocity changed from fast to slow. The maximum length and divergent angle of jet boundary
were greater as the orifice size increased. Compared to the gas phase tests, the visible cloud produced in the dense phase tests had a much wider dispersion range and a greater formation amount of the dry ice particles and the condensing water. The condensation of water saturated in the ambient air was relevant to the environmental humidity and the pipeline pressure.

3.2.2 Temperature distribution

Fig. 13 shows the temperature evolution along the axial line of the discharge area in tests 5 and 6. For test 4 the temperatures in the dispersion area were missing as the result of the shedding of an aviation connector used for data acquisition. For test 5, the temperature contour lines quickly extended along the axial direction with time and reached the farthest distance at 13 s, while the temperature drop amplitude at the location of 5 m reached the maximum value of 31 °C, which was larger than that in test 2. For test 6, the temperature drop amplitude reached 24 °C at 3 s, which was larger than that at the same time for test 2. The temperature drop amplitude reached the maximum value of 102 °C at 17 s. This time was longer than 3 s in test 3 due to the continuous sublimation of a number of dry ice particles in test 6. The results indicated that there was a similar characteristic of the temperature evolution along the release direction between the dense and the gas phase tests. However, it’s extremely obvious that the low-temperature areas in the dense phase tests were much greater than that in the gas phase tests under the same orifice size.

Fig. 14 shows the lowest temperature distribution in the discharge area of tests 5 and 6. The y direction is along the jet axis and x direction is horizontal distance. The overall temperature distribution trend was that the temperature gradients along the x direction were much lower
than along the y direction, while the lengths of the temperature contour lines along the x direction were much longer than those along the y direction. For 0 °C, 3 °C, 6 °C and 9 °C in test 5, the length ratio between the temperature contour lines along the y direction and the x direction were close to 10.1. This indicated that the temperature distribution shifted to the right due to the effect of the southeast wind. For -40 °C, -30 °C, -20 °C and -10 °C in test 6, the length ratio between the temperature contour lines along the y direction and the x direction were 96.6, 45.6, 32.7 and 27.1 respectively. This shown that the diffusion velocity in the FBR release of dense phase tests was extremely fast and the temperature distribution could be considered axisymmetric. According to the contour extending trend in tests 5 and 6, it’s predicted that the maximum length and width of the low-temperature zone were 16 m and 3 m, 30 m and 5 m in both tests respectively.

3.2.3 CO₂ concentration dispersion

Fig. 15 shows the evolution of CO₂ concentration along the axial direction in tests 4, 5 and 6. For test 4, CO₂ concentrations at a distance of 5 m from the release orifice at 15 s reached 5% v/v concentration and remained this quasi steady state level until 3200 s. The concentrations at the farthest distance of 19.2 m from the orifice at 263 s reached 5%, so the safety distance along the release direction in test 4 should be circa 20 m. For test 5, the concentration contour lines fluctuated violently at some time points due to the influence of the southeast wind. CO₂ concentrations inside the measurement area at 6 s reached 5% v/v concentration and at a distance of 12 m from the release orifice had remained above 5% at the end of the release (482 s). The safety distance along the release direction in test 5 should be circa 60 m. For test
6, the CO₂ concentration contours began to stretch at 6 s and extended to their farthest point at 15 s. At the end of the release (40 s) CO₂ concentrations at a distance of 60 m from the release orifice had remained above 5% v/v concentration as a result of the continual sublimation of the dry ice particles. The time of the maximum concentration (61% v/v) 20 m from the orifice was earlier than the time of the maximum concentration (100% v/v) 5 m from the orifice. This suggested that because of the effect of the dry ice sublimation and the response time of the sensors the duration time of the maximum value were longer as the distance from the orifice decreased. The safety distance along the release direction in test 6 reached circa 160 m.

4 Discussions

This paper studied the highly under-expanded jets and dispersion characteristics of gaseous and dense CO₂ during sudden release from a large-scale pipeline. Such a large capacity pipeline was essential as it permitted the shock tube depressurization tests for long enough duration to capture sufficient data for analysis. A great many sensors were used to monitor the formation of the visible cloud, the distribution of the temperatures and concentrations in the far-field. The research results of near-field source terms and dispersion behavior in this study were necessary and of paramount importance for assessing safety distances and the impact of CO₂ pipeline releases on the surrounding environment, which were rare, reliable and close to the actual applications.

Depressurization of high pressure CO₂ following pipeline rupture or puncture, and subsequent dispersion, will almost certainly involve the high-velocity jet flow and the
transition between different physical states. Because the pre-expansion to post-expansion pressure ratio resulting from a release will initially be large, the sonic velocity will be reached at the outlet of the pipe and the resulting free jet will be sonic. This leads to a highly under expanded flow that contains a Mach disk, the precise form of which depends on the ratio of the exit to the atmospheric pressure. For CO$_2$ releases, the temperature and pressure decrease that accompanies the initial expansion will lead to the formations of dry ice particles and condensing water vapor. Likewise, sublimation of the dry ice particles results in heat removal from the gas phase and an associated temperature decrease. Formation of solid CO$_2$ will affect the shape and properties of a CO$_2$ cloud in ways different to a gas/liquid cloud [28]. In addition, Ground topography and physical objects as well as wind direction may have a significant influence on the spread and movement of a CO$_2$ cloud. These extremely complicated phenomena will be contained in the dispersion process of gaseous and dense CO$_2$ during sudden release. The high pressure CO$_2$ dispersion theoretical/modelling involves the appropriate source terms, the three-phase accurate equation of state in the near-field prediction, the suitable species transport, the precise particle tracking techniques for estimating the amount of solid CO$_2$, the effect of heat transfer between the ground and the flowing fluid, the more accurate turbulence modeling [29-31]. Because all these processes need to be included within any dispersion model, no mathematical model is currently capable of predicting such complex releases.

Currently, we concentrate mainly on the experimental research and has a lack of theoretical analysis. However this large-scale experimental results could be applied as important basic
data for CO₂ dispersion research and used to validate the outflow, near-field and far field dispersion models. Experimental characterisation of the temperatures in the immediate region of a release will also be performed to enable estimation of the risk to piping, plant or structures from embrittlement due to low temperatures. For the design, construction and operation of new high pressure CO₂ pipelines through populated areas the safety distance along the release direction of 5% v/v concentration obtained from the experiments can be considered as applied reference. This is critically important when performing consequence failure analysis and significant hazard quantification for CO₂ pipelines. The more deeply experimental and theoretical studies were conducted on the dispersion behavior during sudden release under complicated situation in the future.

5 Conclusions

This article has presented the results of a large-scale experimental study of under-expanded jets and dispersion characteristics of gaseous and dense CO₂ following pipeline rupture using three orifice sizes (15 mm, 50 mm and Full Bore Rupture). According to the experimental study, some conclusions are demonstrated as follows:

(1) A highly under-expanded flow that contained a Mach disk would be developed near the orifice during the release of high pressure CO₂. A large of dry ice particles formed in the near-field dispersion due to the Joule-Thomson cooling, and then were brought into the far-field by jet flow. The dispersing cloud was made visible by the presence of the dispersed white dry ice particles and condensing water vapor. However no dry ice bank appeared on the ground surface in the tests due to the rapid sublimation of the solid CO₂ particles before
falling to the ground.

(2) After rupture, the ambient temperature in the far-field dropped as result of the expansion of the escaping gas and the sublimation of the dry ice particles. The temperature evolutions along the release direction gradually rose due to the reduction of the expanding velocity and the fraction of dry ice along the axial direction. As the orifice diameter increased under the same initial pressure and temperature the temperature drop amplitude and the dispersion distance of CO$_2$ in the discharge area increased and the safety distance of 5% v/v concentration became greater.

(3) Compared to the gas phase tests, the visible cloud produced in the dense phase tests had a much wider dispersion range and a greater formation amount of the dry ice particles and condensing water vapor. The low-temperature areas and the safety distance in the dense phase tests were much greater than that in the gas phase tests. The heavy gas effect prompted a large number of CO$_2$ to accumulate in low-lying place when there is no wind.

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References


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<td>33.4</td>
<td>32.7</td>
<td>17.4</td>
<td>19.3</td>
<td>21.6</td>
</tr>
<tr>
<td>Orifice (mm)</td>
<td>15</td>
<td>50</td>
<td>FBR</td>
<td>15</td>
<td>50</td>
<td>FBR</td>
</tr>
<tr>
<td>Inventory (tons)</td>
<td>0.97</td>
<td>0.96</td>
<td>0.84</td>
<td>9.48</td>
<td>9.31</td>
<td>9.11</td>
</tr>
<tr>
<td>Ambient pressure (kPa)</td>
<td>99.6</td>
<td>99.7</td>
<td>99.5</td>
<td>99.9</td>
<td>99.6</td>
<td>99.8</td>
</tr>
<tr>
<td>Ambient temperature (℃)</td>
<td>26.4~26.8</td>
<td>27.5</td>
<td>23.6</td>
<td>24.9~27.4</td>
<td>25.2</td>
<td>30.1</td>
</tr>
<tr>
<td>Humidity (%)</td>
<td>87.6~86.8</td>
<td>80.2</td>
<td>82.3</td>
<td>98.1~87.8</td>
<td>80.1</td>
<td>86.7</td>
</tr>
<tr>
<td>Wind speed (m/s)</td>
<td>0.6~1.8</td>
<td>1.6</td>
<td>0</td>
<td>0.7~2.4</td>
<td>2.3</td>
<td>1.0</td>
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<tr>
<td>Wind direction</td>
<td>120~168</td>
<td>108</td>
<td>0</td>
<td>238~289</td>
<td>149</td>
<td>36</td>
</tr>
<tr>
<td>Atmospheric stability</td>
<td>B</td>
<td>B</td>
<td>A</td>
<td>B</td>
<td>B</td>
<td>B</td>
</tr>
</tbody>
</table>
Fig. 1 Process flow.
Fig. 2 Distribution of measurement points in discharge area.
Fig. 3 CO2 concentration sensor and installation.
Fig. 4 Visible cloud development of the gaseous CO$_2$ release experiments with 15 mm orifice.
Fig. 5 Visible cloud development of the gaseous CO$_2$ release experiments with 50 mm orifice.
Fig. 6 Visible cloud development of the gaseous CO$_2$ release experiments with the full bore orifice.
Fig. 7 Temperature evolutions along the centerline of the gaseous CO₂ release experiments with three different orifices (15 mm, 50 mm and FBR).
Fig. 8 Temperature distribution area of the gaseous CO$_2$ release experiments with three different orifices (15 mm, 50 mm and FBR).
Fig. 9 CO₂ concentration development along the centerline of the gaseous CO₂ release experiments with three different orifices (15 mm, 50 mm and FBR).
Fig. 10 Visible cloud development of the dense CO₂ release experiments with 15 mm orifice.
Fig. 11 Visible cloud development of the dense CO₂ release experiments with 50 mm orifice.
Fig. 12 Visible cloud development of the dense CO₂ release experiments with the full bore orifice.
Fig. 13 Temperature evolutions along the centerline of the dense CO₂ release experiments with three different orifices (15 mm, 50 mm and FBR).
Fig. 14 Temperature distribution area of the dense CO$_2$ release experiments with three different orifices (15 mm, 50 mm and FBR).
Fig. 15 CO₂ concentration development along the centerline of the dense CO₂ release experiments with three different orifices (15 mm, 50 mm and FBR).