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Experimental study on leakage temperature distribution of pipeline in different CO_2 phases

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ABSTRACT

The decrease of pipe wall temperature caused by CO_2 drainage is the direct cause of the tough-brittle transformation of long distance pipeline materials. In this paper, the experimental research scheme of CO_2 pipeline small hole leakage is designed, and the corresponding experimental equipment is set up to measure the temperature of the pipe wall after CO_2 drainage. The variation rule of pipe wall temperature in leakage area under different parameters is studied.

The experimental data obtained have guiding significance for the safety evaluation and design of pipeline

Keywords: CCUS, brittle fracture, leakage punctures, safety evaluation

1. INTRODUCTION

Since 2008, several large CO_2 research project groups have been established internationally, including MATTRAN, CO_2PIPETRANS, CO_2PipeHaz, CO_2QUEST, COOLTRANS, COSHER, $CATO_2$, etc.[1]. These larger project groups are generally consortia of research institutes, universities, and commercial organizations and are mostly international collaborative studies. In recent years, these large project groups have successfully conducted experimental and numerical simulation studies on hot issues such as thermophysical properties, vent pressure-temperature properties, and vent diffusion properties of CO_2, and have published many research results. Woolley et al [2] built a small-scale CO2 leak experimental setup. The leakage was controlled by a front-end pneumatic valve and the leakage aperture was controlled by a front-end flange-mounted leakage orifice plate. It was found that the measured minimum temperature of the leakage axis could reach -108 ℃. By comparing the experimental results with the HEM model and the two-phase flow model, Mahgerefteh et al.[3] found that the two-phase flow model could better simulate the process of pressure drop and temperature drop of the two-phase flow. Wareing et al [4] relied on the COOLTRANS project carried out by the National Grid (NG) in the UK to set up a vertical upward leakage experimental setup for two groups of experiments in the gas phase and dense phase and found that the surrounding environment had a small effect on the temperature field results of the dense phase experiments, with measured temperatures of -78 ℃ at 4 m above the centerline of the dense phase group leakage port and -58℃ at 7 m. Mohammad et al[5] experimentally found that the wall temperature near the leak port before media isolation was generally near -30 ℃, indicating that the isolation process of the media after the release can have a large effect on the pipe wall temperature in the leak port region. Ahmad et al[6] of the CATO2 project team conducted small-bore leakage experiments with three different leak diameters using an experimental setup with a cylindrical pressure vessel of 610 mm diameter and a total length of 2000 mm with an external 500 mm nozzle. The connection between the leak pressure response and the media quality was investigated for different diameters, and the temperature difference between the upper and lower walls of the nozzle during leakage was investigated, and it was found that the lower wall temperature was always lower than that of the upper wall. Different leak diameters down to the same pressure when the temperature distribution in the axis of the leak, it was found that the lowest temperature point (-83 ℃) near the leak, and the smaller the diameter the more significant the temperature gradient in the axis. Vree et al[7] from Det Norske Veritas and Germanischer Lloyd (DNV GL) constructed a stainless steel coil-type pipe with a total length of 30 m and an inner diameter of 8 mm and

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studied the difference in medium temperature for different leakage diameters, and found that the larger the leakage diameter, the smaller the minimum, medium temperature and the less time it took to reach the minimum temperature. Xie et al[8] investigated the differences in CO_2 jet morphology for different nozzle sizes and found that the larger the size, the larger the size of the morphological expansion zone. It was also found that nozzle size has an effect on the medium decompression process, and the larger the nozzle size, the larger the decompression rate. Liu[9] found that the distribution pattern of medium concentration and temperature within and on the surface of the soil after CO_2 leakage was studied by varying the parameters of leakage pressure, leakage aperture, and burial depth, and the results were scaled up by the similarity criterion based on small-scale experiments. It was found that a large amount of dry ice and permafrost balls could be produced in the soil during the liquid-phase medium leakage, and the lowest measured soil temperature was -80.5 ℃.

A review of the previous studies on CO_2 pipeline fracture leakage reveals that there are only a few of previous large experimental studies on CO_2 pipeline leakage. Hence, the research on CO_2 pipeline leakage is still in its initial stage. Among the few studies on CO_2 pipeline leakage, the research focuses on the CO_2 concentration and temperature changes in the external field of the leakage process, the pressure and temperature inside the pipe, and other parameters, while the research on the distribution of pipe wall temperature along the axis in the leakage area of the pipeline leakage process is rare. At the same time, the research on buried pipeline leakage is mainly focused on large-diameter leakage conditions, while research on microporous leakage has not been carried out.

2. EXPERIMENTAL SYSTEM

Accidental leakage of CO_2 pipeline causes a decrease in pipeline wall temperature, which is the direct cause of the tough-brittle transformation of long-distance pipeline materials. Our previous research results have given a complete and detailed description of the experimental pipe. The difference in this paper is that pipes with different puncture diameters, as shown in Fig. 1, are installed at the drain end. Since no similar research results have been published so far, the diameter selection is conservative. The minimum diameter is only 1 mm, and there are 5 diameters, including 2 mm, 4 mm, 5 mm and 6 mm.

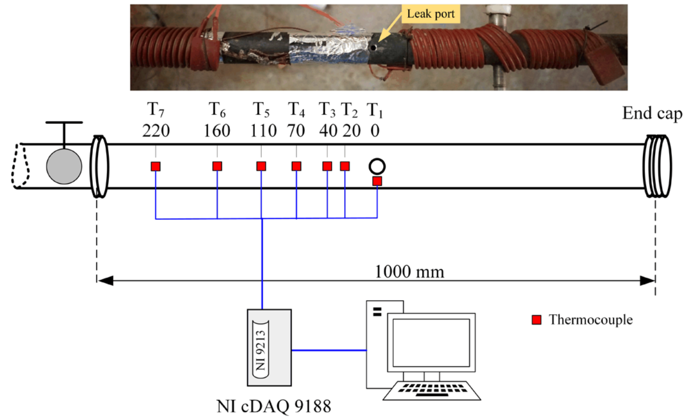


Fig. 1 Test pipe with puncture

In order to explore the emission characteristics of CO_2 in different phase states, the emission experiments of CO_2 in the gas phase, supercritical phase and dense phase were carried out. In order to compare the difference in the media discharge process with the same phase state and different pressure levels, two pressure levels were selected for each phase state. In order to verify the repeatability of the experiment and eliminate the error, each group of experiments was repeated 3 times. Based on the above considerations, the initial medium conditions for this experiment are set as shown in Tab. 1.

Tab. 1 CO_2 initial conditions parameter of pipeline

	Gas-I	Gas-II	Sup-I	Sup-II	Den-I	Den-II
P_{ini} /Mpa	6	5	9	8	9	8
T_{ini} /℃	40	40	40	40	20	20
Phase	Gaseous		Supercritical		Dense	

State: The experiment was repeated for three times in each group, denoting Gas/Sup/Den-I/II-1/2/3.

3. RESULTS AND DISCUSSION

3.1 Influence of initial CO_2 state on leakage port temperature

According to the confirmed experimental scheme, the variation rule of pipe wall temperature in the leakage area under different parameters was studied. Fig. 1 shows the change of temperature T_1 on the wall of the leakage port with time in the process of CO_2 release through the leakage port of 4 mm under different initial states.

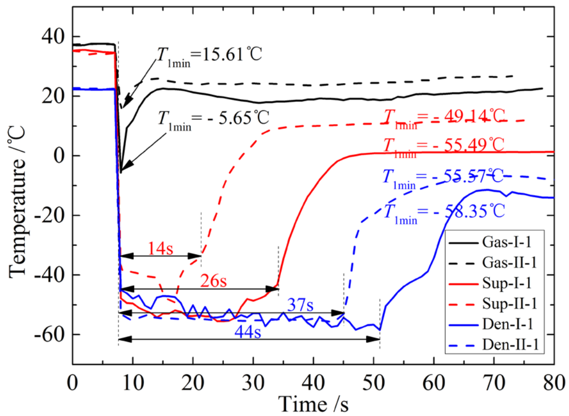


Fig. 2 The evolution of T_1 versus different initial conditions

It can be seen from Fig. 2 that when the initial phase state is the same, the higher the initial pressure Pini, the lower the minimum temperature that the leak can reach, and the longer the low temperature can be maintained; the two sets of experiments with dense phase media (Den -I-1, Den-II-1) as an example, both of them reached the lowest temperature almost at the beginning of the leak test, and the lowest temperature of Den-I-1 group was -55.57 ℃, and maintained at a lower temperature At 37 s, the lowest temperature in the Den-II-1 group was -58.35 ℃, and it remained at the low temperature for 44 s.

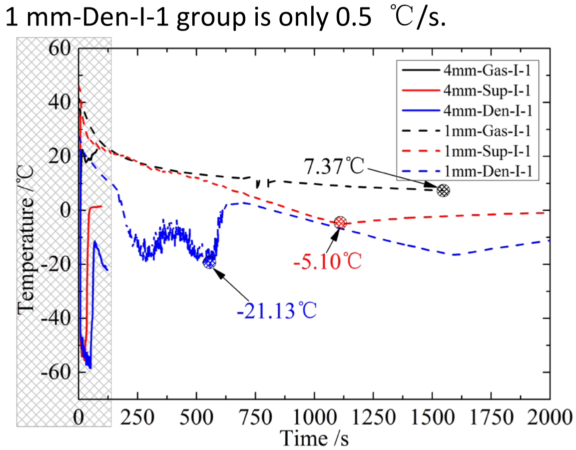
At the same time, it can be seen from Figure 4.1 that there are obvious differences between experiments under different initial phase states. For example, the lowest temperature of the Gas-I-1 group was -5.65 ℃, while the lowest temperatures of the Sup-I-1 and Den-I-1 groups were below -50 ℃. In terms of low temperature maintenance time, the Gas-I-1 group only maintained low temperature for 2 s, the Sup-I-1 group maintained low temperature for 26 s, and the Den-I-1 group maintained low temperature for 44 s. It can be seen that, compared with the differences in the experimental results caused by the differences in the initial phase states, the pressure level has little effect on the wall temperature of the leakage port.

At the same time, it is noticed that the three groups of experiments Sup-I-1, Den-I-1 and Den-II-1 are relatively close in the lowest temperature, all of which are around -55°C, and this temperature is precisely the temperature of the triple point. It shows that under the current relief conditions, the minimum temperature that the wall of the leak port can reach is limited, and this temperature is affected by the phase change of CO2. No visible dry ice particles were found in the leak test carried out under this condition. This is because the pressure of the space outside the leak is close to atmospheric pressure, and the temperature of dry ice at atmospheric pressure is -78.5°C. Previous studies[10] have shown that when a leak occurs, the temperature at a distance above the leak is the lowest. Dry ice was not produced because the center of the vent flow did not reach the temperature and pressure levels specific to dry ice formation.

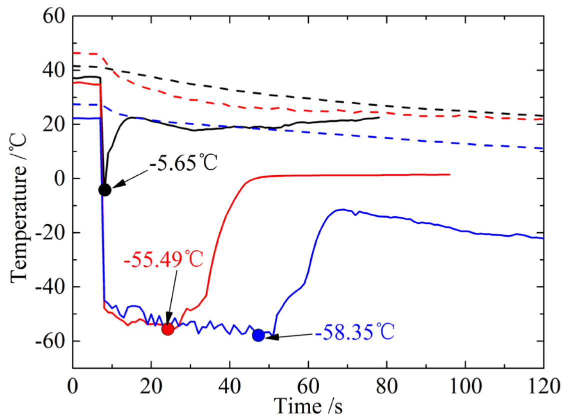
3.2 The temperature evolution versus different scale leakage port

In the previous section, the temperature change of the leak pipe wall under the leak diameter of 4 mm was studied. This section will focus on the change of the pipe wall temperature at the leak port after the leak diameter changes.

Fig. 3(a) is a comparison of the trend of leakage wall temperature T1 over time for three phase media with a leak diameter of 4 mm and 1 mm, and Fig. 3(b) is an enlargement of the shaded area in (a). It can be seen from the figure that at the lowest temperature, the leakage diameter of 4 mm is lower than the leakage diameter of 1 mm in the three phase states. The lowest temperature of -Den-I-1 group was only -21.13℃. From the point of view of the release time, still taking the release of dense-phase media as an example, the release time is only 78 s under the 4 mm diameter, while the discharge through the 1 mm leak port takes 2430 s, which is about 30 s of the 4 mm diameter. times. From the point of view of the temperature drop rate, all the discharge groups are the largest at the beginning of the discharge, but there are also large differences under different diameters. For example, the maximum temperature drop rate of the 4 mm-Den-I-1 group is about 67 ℃/s, the maximum temperature drop rate of the 1 mm-Den-I-1 group is only 0.5 ℃/s.



(a)The temperature evolution versus different puncture and phase



(b) Zoom in on shaded areas

Fig. 3 Impact on T_1 by diameter of puncture

Therefore, the influence of the leakage diameter on the temperature field of the leakage port area is similar to the influence on the temperature of the medium in the pipe, and it is mainly manifested in two aspects, namely, the discharge time and the changing trend. The reduction or increase of the leakage diameter will first directly affect the length of the discharge time. That is, the cooling time of the discharge airflow to the wall of the leakage port is different. Secondly, the change of the leakage aperture directly leads to the change of the air mass flow rate, and the temperature drop rate and temperature drop degree caused by the expansion of the air flow will change significantly, especially for supercritical and dense phase media that can undergo phase change at the leak port.

In order to further study the influence of the leakage aperture on the wall temperature of the leak opening, the discharge experiments of other leakage apertures were carried out, as shown in Fig.3, the relationship between the minimum temperature Tmin at the leakage opening and the leakage aperture d during the leakage process of the three phase media . According to the trend of scatter points, use appropriate fitting functions to fit the scatter points of the minimum temperature of each phase state with the change of leakage aperture. In the gas phase experiment, due to the short duration of the low temperature and the acquisition frequency of the temperature sensor is 1 Hz, there is a large error in the measurement of the lowest temperature, and the distribution of scattered points is slightly less regular, so a linear function is used for fitting. The regularity of supercritical and dense phase experiments is obvious, and the distribution of scatter points conforms to the characteristics of the exponential function, so the exponential function is used for fitting, as shown in Fig. 4. It can be seen from the figure that the minimum temperature of the three-phase media experiments decreases with the increase of the leakage aperture. The difference between the results of supercritical and dense-phase experiments is relatively small, and the trend of the two changes with the aperture is consistent. The minimum temperature decreases with the increase of the leakage aperture until it remains relatively stable at a certain aperture (4 mm). The minimum temperature remains Near the triple point temperature (-56.5 ℃). The measurement results of the gas phase experiment show a meandering decline. According to the trend of the curve, when the frequency of the temperature sensor is high, the gas phase experiment results will eventually reach the level of the dense phase and the supercritical experiment results under a specific diameter.

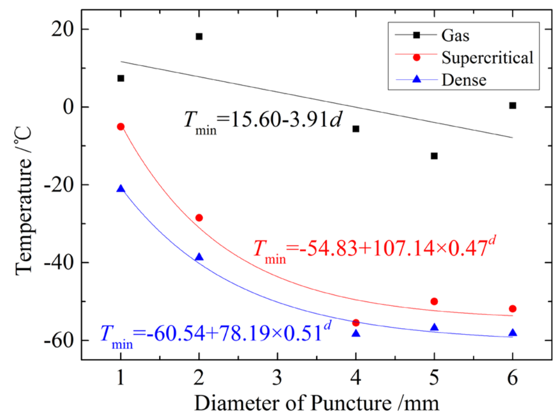


Fig. 4 Relationship between Tmin and d in different phase of carbon dioxide

Tab. 2 lists the fitting formulas for the minimum temperature Tmin /℃ of the leak area in the three phase states as it changes with the leak diameter d/mm.

Tab. 2 Formula fitting for Tmin changing with diameter of puncture

Gaseous	Supercritical	Dense
$T_{min}=15.60-3.91d$	$T_{min}=-54.83+107.14\times0.47^d$	$T_{min}=-60.54+78.19\times0.51^d$

4. CONCLUSIONS

In this paper, based on an experimental scale high-pressure CO_2 discharge experimental setup, the CO_2 leakage experiments are carried out to analyze the relevant experimental results. Through the analysis of the experimental results, the following conclusions can be obtained:

(1) The higher the initial pressure Pini, the lower the minimum temperature that the leakage port can reach, and the longer the low temperature can be maintained. There are apparent differences between the experiments under different initial phase states, and the

pressure grade has little influence on the wall temperature of the leakage port.

(2) The closer the temperature along the pipeline is to the leakage port, the more significant the temperature drop; As a whole, the temperature of the channel is the lowest in the dense phase and the highest in the gas phase, and the lowest temperature of the leakage port is almost the same when the dense phase and the supercritical phase are discharged, about -55℃. The temperature gradient near the leakage port is large, but the temperature gradient gradually disappears with the extension of the axis distance.

(3) The temperature of the large diameter 4 mm pipe wall shows a large temperature gradient in the near area of the leakage port, and the temperature in the slightly far area is almost horizontal, which can be characterized by "low and steep, large gradient". The temperature distribution of small diameter 1 mm along the pipe axis is relatively gentle, and there is no significant difference in the whole study area, and it shows good linear characteristics, which can be characterized by "high and flat, with small gradient".

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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