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# Study on jet morphology parameters of large-scale carbon dioxide pipeline with different leakage apertures

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## ABSTRACT

Carbon capture, utilization and storage (CCUS) has become a key technology in the process of promoting low-carbon development, where the safe transportation of high-pressure pipelines is crucial. In order to study the discharge characteristics of $CO_2$ pipelines, a large-scale experimental pipe with a length of 258 m and an inner diameter of 233 mm was developed to simulate the real leakage scenario as much as possible. The jet morphology generated during the rupture of the pipeline under different leakage sizes (15mm, 50mm, 100mm, 233mm) was photographed from the side of the discharge port with a high-frequency camera, and it was found that there were different degrees of under-expanded jet areas near the leakage outlet in the initial stage of leakage, which gradually developed and formed visible clouds, but there were obvious differences in their development scale and duration. In this paper, we analyzed the theoretical structure of the jet. And we extracted key features such as leak duration and jet length by analyzing the morphology of jets under different calibers. So as to propose the correlation between the morphology of the jet and cracks. When a leakage accident occurs, the scale of the crack can be quickly and accurately estimated from the leakage morphological characteristics of the periphery of the accident, and the degree of the accident can be judged, which provides a basis for the formulation of the early warning plan.

**Keywords:** CCUS; $CO_2$ pipelines; Jet morphology; Leakage sizes

## 1. INTRODUCTION

CCUS technology is the main way to achieve carbon peaking and carbon neutrality goals [1,2]. With the development of industrial technology, carbon dioxide gas generated from fossil fuel utilization accounts for about 65% of the total emissions [3]. Carbon dioxide pipeline transportation is a key component in CCUS technology. Generally, carbon dioxide pipelines have low transportation cost under high pressure, so the consideration of their safety has attracted more and more social attention [4]. Carbon dioxide gas is colorless and odorless, and it is not easy to find when it leaks out. Besides, the diffusion process of carbon dioxide gas is similar to heavy gas diffusion, which will cause long-term accumulation under the condition of no wind，the limit of more than 10% will affect the health of the surrounding population [5,6,7].

Due to the special thermodynamic properties of CO2, when the high pressure gas accidentally leaks from the pipeline, the Joule Thomson effect will be significant. And the instantaneous expansion will accelerate along with a sharp drop in the ambient temperature, which can drop below the triple point [8]. Therefore, many scholars have made relevant studies on the complex gas dynamics and thermodynamic characteristics of CO2 jet flow, and analyzed the prediction degree of near-field jet flow by different calculation models, as well as the influence of the release of mixtures containing impurities on thermodynamic properties [9]. Kan Li et al. [10] studied the typical flow characteristics of jet flow from small-scale CO2 leakage. They pointed out indirect

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measurement of jet blocking strength and captured the changes of near-field jet structure by numerical simulation. Teng Lin et al. [11] simulated near-field jet behavior based on a Homogeneous Relaxation Mode, and proposed the parameter relationship between Mach disk position and leakage position, which was of great significance for the study of jet microstructure.

## 2. EXPERIMENTS

The experiment was carried out on a well-established experimental platform. The main channel length of the test device was 258m and the diameter was 273×20mm. The manufacturing material of the pipe was 16MnR. At the end of the pipe, a dual-disc blasting structure was set up. The pressure difference between the inside and outside of the pipe was balanced by the pressure of nitrogen between the two bursting discs. This structure could realize instantaneous gas initiation and release, which could better simulate the real leakage scene. In each experiment, the leakage orifice plate at the end of the pipeline was replaced to realize the experimental study of drainage under different diameters. A high-frequency camera was used to shoot the morphology of the jet stream at the side of the jet stream direction. The structure of the leakage end is shown in Fig. 1.

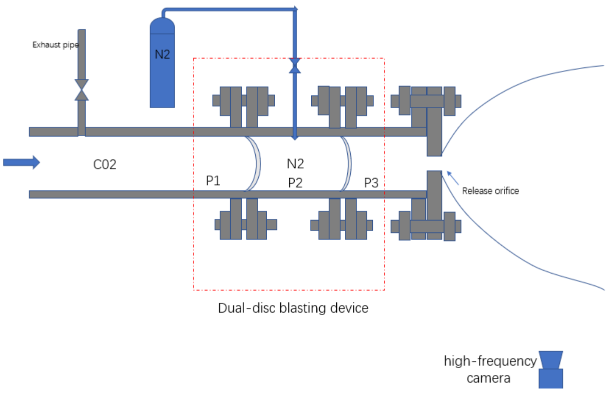


Fig.1. The structure of the leakage end

In order to study the morphology of jet flow under different discharge diameters, this paper conducted discharge experiments under the conditions of 15mm, 50mm, 100mm and full diameter. The high-frequency camera was used to shoot the jet morphology, and then the jet morphology of each group of experiments were intercepted according to the time node. Then we analyzed the development process of jet flow and the morphologies of jet flow under different leakage apertures.

## 3. RESULTS AND DISCUSSION

### *3.1 Jet structure analysis*

Generally, $CO_2$ is transported under high pressure, and there is a huge pressure difference between the gas in the pipe and the environment. Therefore, in the process of leakage, high-pressure gas will leak and high-speed jet will be formed at the outlet. Due to the large exit velocity, which leads to the approximate adiabatic condition with the outside, the one-dimensional steady isentropic flow model in gas dynamics can be used to qualitatively analyze the jet flow. The gas expands faster near the exit, creating a series of expansion waves. The ratio between the gas pressure in the high-pressure pipeline and the ambient pressure is much greater than 2, which belongs to the highly under-expanded jet. After the acceleration of expansion, a low pressure region with pressure lower than the external environment will be formed in the subsequent central region. This leads to compression waves, which are constantly superimposed to form shock waves. Due to sufficient $CO_2$ capacity during the experiment, the outlet flow state could be maintained stably for a period of time. Mach disk structure would be generated within a distance from the outlet, and the theoretical structure of the jet is shown in the Fig. 2.

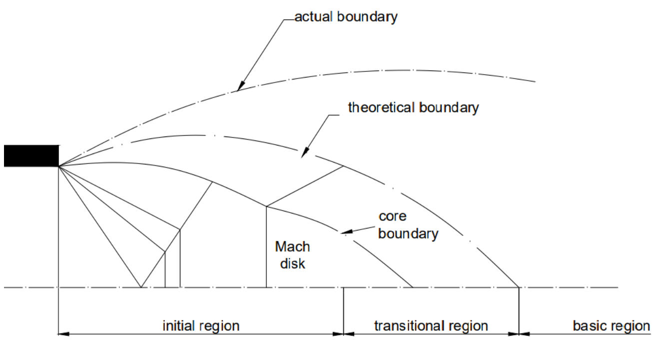


Fig.2. The theoretical structure of the jet

According to the knowledge of jet mechanics, the jet structure can be divided into three parts: initial region, transition region and basic region. With the continuous expansion of the fluid, the high-speed air flow formed will constantly produce shear effect on the static gas in the surrounding environment. So that more gas will be added to the flow area and generate resistance to the jet stream, which reduces the jet edge velocity and gradually develops to the jet center. Thereafter, the whole section develops into turbulent flow.

### *3.2 Jet morphology*

Through experiments, it was found that the experimental morphology development of each group of jets could be roughly divided into rapid expansion stage, stable stage and attenuation stage. Generally, the attenuation stage occupied most of the whole leakage process.

Fig.3. The jet morphology of 233mm aperture

As shown in Fig. 3, it is the morphologic diagram of jet flow under the leakage aperture of 233mm. By comparing the jet flow scale at different times, it could be found that the rapid expansion stage was completed within 0.4s after the bursting disc was opened. And the jet strength remained stable for a short time and then entered the decay stage. The whole experiment lasted about 18s.

Fig.4. The jet morphology of 100mm aperture

As shown in Fig. 4, the near-field morphology with a diameter of 100mm was photographed from below the side near the leakage port. The experiment lasted for about 30s, and the barrel-shaped jet structure and jet boundary were clearly visible, which was consistent with the theoretical jet structure. With the attenuation of the airflow force, the jet Angle also shrinks continuously, which is verified by the dynamic theory.


Fig.5. The jet morphology of 50mm aperture

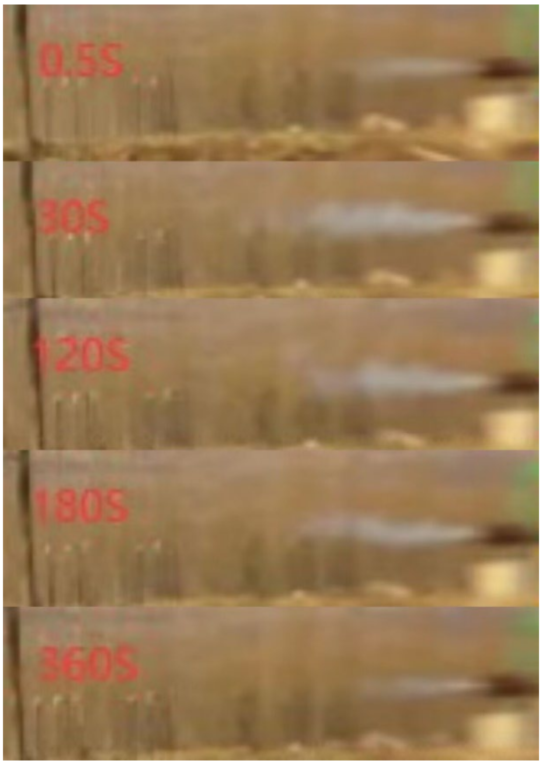


Fig.6. The jet morphology of 15mm aperture

Fig. 5 is a long view shot with a leakage aperture of 50mm. The diffusion behavior of visible clouds in the far-field region can be seen macroscopically. It could be seen that the cloud wake showed an alternating oscillating state at the beginning and a wide dispersion state later, and the whole leakage process lasted about 150s.

Fig. 6 shows the efflux situation under the discharge diameter of 15mm. Due to the small leakage diameter, the efflux scale was small, and the influence scope was mainly concentrated in the axis area near the leakage port. However, the continuous influence time was long, and the attenuation of jet strength was not obvious in the middle of the experiment, and the whole discharge time was more than 360s.

By comparing the above four visible cloud analyses with different apertures, it could be seen that with the increase of the aperture, the scale of the release would increase, the length and height of the visible cloud would increase, and the damage to the surrounding environment would increase. With the increase of aperture, the fluidic process was unstable and tended to be instantaneous. The leakage time increased with the decrease of aperture.

## 4. CONCLUSIONS

Based on large $CO_2$ pipelines, the morphologies of jets under different discharge diameters were observed in this paper, and the following conclusions were obtained through analysis combined with microscopic jet structure theory:

(1) High pressure $CO_2$ leakage was a highly under-expanded jet process. Due to the existence of strong Joule Thomson effect, the temperature near the leakage port dropped sharply during the leakage process. As a result, the law of the jet stream presented an unstable change, and the barrel jet structure and Mach disk were formed in the near-field area, which caused varying degrees of harm to the surrounding personnel and the environment.

(2) Under the pipeline condition with close initial conditions, the scale of the initiation instantaneous jet stream was continuously enhanced with the increase of leakage diameter. But the duration of the impact is shortened, the intensity and scope of damage to the surrounding environment increased.

(3) The leakage scale can be judged by judging the influence range of jet flow and the change of jet Angle.

## 5. ACKNOWLEDGEMENT

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## 6. 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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