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Back Analysis of Pipeline Leakage Caliber Model Based on Supercritical Phase CO2 Hazard Distance

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ABSTRACT:

Carbon neutralization is gaining increasing attention in various countries, and the risk of leakage is inevitable in the transport of captured CO_2 to storage. High pressure Carbon Dioxide (CO_2) pipeline transport is an important component of the Carbon Capture Utilization and Storage (CCUS) chain. Hence, accurate estimation of the leak caliber is an important component in determining the risk level when leakage happens. Carbon dioxide leaks are hazardous accidents, and accidental releases from pipeline transportation can lead to catastrophic damage. To ensure safety in the process of pipeline transportation, it is necessary to understand the impact of different leak sizes on the risk range after the occurrence of a pipeline failure. In this paper, a proposed model for estimation of pipe leak caliber based on back analysis through experimental and numerical studies. First establishes that the danger of CO_2 leakage from supercritical phase transport using a large pipe experiment (258 m long, internal diameter is 233 mm). Then a two-stage Computational Fluid Dynamics (CFD) model to predict different caliber supercritical phase CO_2 leakage ranges was proposed, and the CFD model was validated by experimental data. The error between numerical simulation values and experimental results is within 5%. The numerical model calculated the leakage ranges at different calibers, back analysis of the CO_2 concentration data, a model capable of predicting leakage caliber by leakage range is proposed. When a leakage accident of a pipe occurs, the leakage caliber is confirmed by this model, which provides a new method for determining the time of appearance of leakage.

Keywords: CCUS; Greenhouse gases; CFD; Back Analysis; Safety engineering.

1 INTRODCTION

It is widely accepted that the primary contributor to global warming is the emission of carbon dioxide from human activities and industrial production. The combustion of fossil fuels leads to a significant increase in carbon dioxide concentration [1,2].

In order to make clear the leakage characteristics of CO2, scholars have done a lot of researches. In a study by Yang et al. [3], a numerical model was developed to simulate CO2 leakage from geological sequestration sites and predict CO2 diffusion and dissolution in soil pores. The model was corrected using measured CO2 values from experiments, but did not consider the change in temperature after CO2 leakage. Liu et al. [4] developed a predictive model for heavy gas diffusion and expansion based on the P-R equation and the SST K-ω turbulence equation, but did not consider the transient phase or match experimental measurements well. Another study by Kang Li et al. [5] developed a model that can predict the near-field multiphase flow dynamics and phase behavior after CO2 is released from a supercritical state, but did not consider suitable boundary conditions or match measured velocities well.

In this paper, we investigate the hazardous distance of CO2 that is released from high-pressure pipelines into the atmosphere. This study is a response to the inadequacies observed in the existing research fields. The high-pressure supercritical CO2 leakage law is investigated using a large experimental pipeline bench, which has a length of 258 meters and a diameter of 233 millimeters. The experimental data validate the precision of the computational model and also provide practical and efficient initial values and boundary conditions for the numerical model. The findings of this study have led to the development of a prediction model

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that can estimate the diameter of the leakage by considering the range of the hazardous zone.

2. EXPERIMENTAL STUDY

This study conducts high-pressure CO2 pipe discharge experiments with varying leakage pore sizes, using an industrial-scale experimental setup [6].

Fig.1. Diagram of large-scale experimental apparatus.

3. NUMERICAL METHODS AND MODEL VALIDATION

The diffusion behavior of CO2 following a pipe rupture can be divided into three stages: the reduced pressure segment within the pipe, the expanded segment of the leakage jet, and the static advected diffusion segment. During this process, the supercritical CO2 jet expands and changes into a gas-liquid two-phase flow, while also experiencing a drop in temperature that results in the formation of dry ice particles near the leakage port. As the CO2 flows into the atmosphere, the dry ice and liquid-phase CO2 interact with the environment, gradually transforming into the gas phase, and the jet's movement changes accordingly. The near-field of the jet involves a complex phase transition process, including the accumulation and sublimation of dry ice particles. However, a uniformly established process mechanism for this behavior is lacking, making detailed computational fluid dynamics (CFD) simulation of the entire process challenging. To address this challenge, the process is simplified by treating the solid-phase dry ice particles and the liquid phase as in-phase, using the two-phase flow model.

3.1. Numerical methods

The CFD companion software ICEM was used for geometry modeling in this model. Numerical models for high-pressure CO2 pipeline leakage were built using Fluent. The model primarily solved equations for mass conservation, momentum conservation, energy conservation, turbulence, component transport, and phase change.

Fig 2 presents the time-varying alteration of the CO2 concentration at 11 m, 20 m, and 60 m away from the axis of the leakage orifice. The simulation outcomes provide a clear and relatively accurate forecast of the diffusion tendency at different positions. The anticipated time to achieve the peak concentration is almost identical, and the difference in mean concentration is less than 10%.

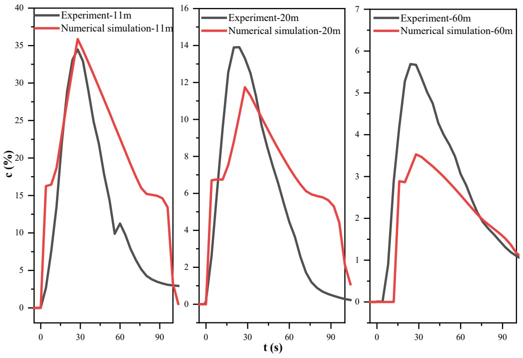

Fig. 2. Changes of CO2 concentration at different points.

4. RESULTS AND DISCUSSION

Fig. 3 shows a contour plot of the peak concentration for various leakage calibers of 20 mm, 50 mm, 100 mm, 150 mm, and 233 mm.

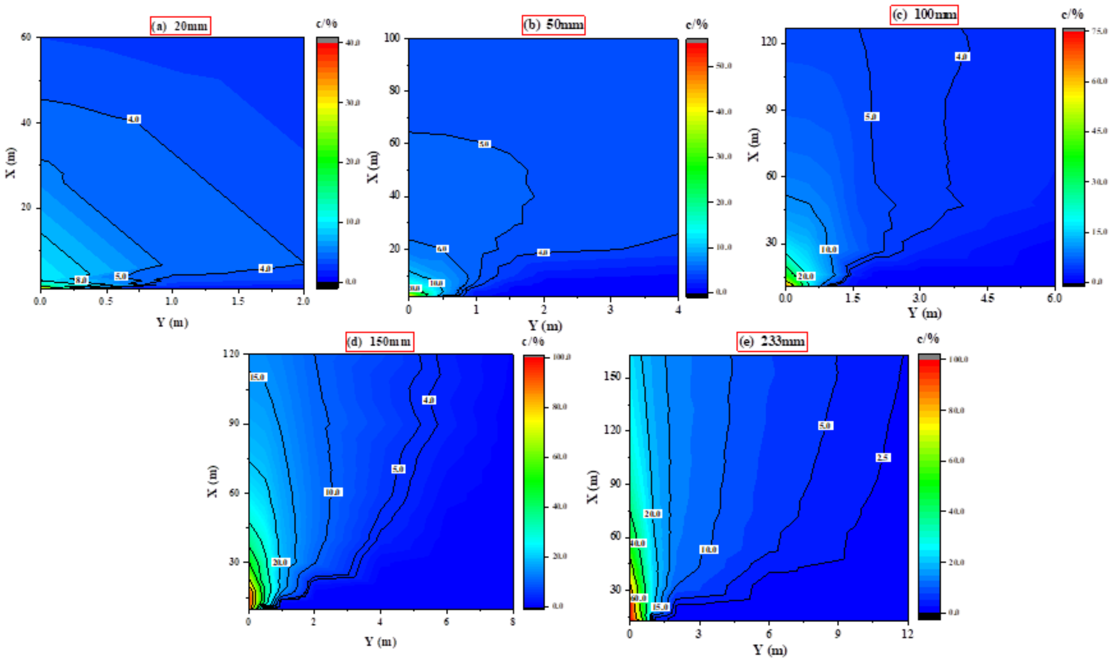

Fig.3. Numerical simulation results.

$$C = 9.88212 \times L \times 10^{-4} - 1.96012 \times L \times 10^{-6} + 2.52605 \times L \times 10^{-9} \quad (1)$$

where L is the hazard distances; C is the leakage caliber.

The numerical simulation results were used to gather the risk range under different leakage calibers, which helped to determine the diffusion range data under different leakage aperture, as shown in Figure 4. This data was used to develop a formula for the relationship between the risk area in different directions and the leakage caliber.

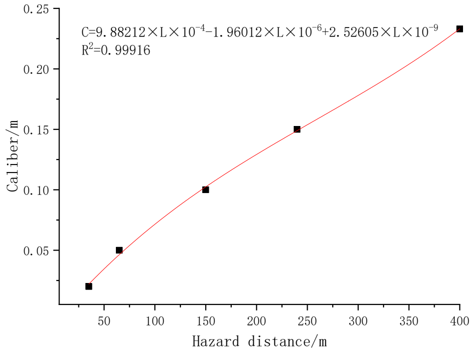

Fig.4. Diagram of the relationship between the maximum danger distance and the leak caliber.

4 CONCLUSION

This paper presents an analysis of CO2 leakage diffusion experiments conducted on an industrial scale high-pressure CO2 discharge setup. Based on the simulation results, we propose a formula for determining the maximum radius of hazard for different CO2 leakage calibers. This formula enables a quantitative analysis of the relationship between the leakage caliber and the distance of the hazardous range for supercritical CO2.

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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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