Experimental Study on the Throttling Characteristics of High-CO_2 Content Produced Fluids

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Abstract: During the surface gathering and transportation of CO_2-enhanced oil recovery (CO_2-EOR) under ambient temperature conditions, pressure drops caused by valves or elbows result in significant throttling effects in multiphase flows with high CO_2 content, which critically impact the safe operation of the gathering system. Using a high-pressure sapphire autoclave experimental setup, this study analyzes the effects of phase state, CH_4 content, gas-liquid ratio, and water content on the throttling characteristics. The results indicate that under ambient temperature conditions, the final throttling temperature of liquid CO_2 is primarily influenced by the final throttling pressure, with no significant correlation to the pressure drop. For throttling without phase change, liquid CO_2 exhibits a weaker throttling effect, with a throttling coefficient (D_i) of approximately 0.6°C/MPa, whereas gaseous CO_2 demonstrates a stronger effect, with D_i ranging between 10-12°C/MPa. Furthermore, the influence of CH_4 content on the throttling temperature drop varies with the initial pressure. At high initial pressures (16 MPa), D_i is approximately 1.3-5.4°C/MPa, and the addition of CH_4 enhances the throttling effect of the mixed gas. At lower initial pressures (5 MPa and 4 MPa), D_i is approximately 3.4-11.9°C/MPa, and the addition of CH_4 weakens the throttling effect. An increase in the gas-liquid ratio and a decrease in water content both lead to a greater throttling temperature drop, with the gas-liquid ratio having a particularly significant impact.

1. Introduction

To actively address climate change and demonstrate its commitment to a low-carbon development path, China has introduced the "30·60" dual carbon strategy [1]. Carbon capture, utilization, and storage (CCUS) technologies, as effective means to reduce carbon emissions, have become a key research focus both in China and globally [2]. Among these technologies, CO_2-driven enhanced oil recovery (EOR) is one of the critical pathways for CCUS, and extensive research has been conducted in multiple countries [3, 4]. During the CO_2-EOR oil extraction process, pressure drops lead to the precipitation of CO_2 and other dissolved gases, and high-CO_2-content multiphase flows are often formed during the lifting and surface transportation of the produced fluids [5]. In particular, gaseous CO_2, due to its significant throttling effect, tends to experience sharp temperature drops during throttling, potentially causing issues such as crystallization or freezing blockages in pipelines and equipment, posing a potential threat to the safe operation of ambient temperature surface transportation systems [6]. Therefore, to ensure the safety of CO_2-EOR transportation systems and clarify the feasibility requirements for ambient temperature transportation, conducting research on the throttling characteristics of high-CO_2 content produced fluids is of great significance.

The study of the throttling effect of CO_2 has been underway for some time. Guo et al. [7] based their research on the QUEST project, which featured a 258 m long, 233 mm inner diameter pipeline system. Through theoretical analysis and experimentation, they investigated the throttling and expansion characteristics of supercritical CO_2 during vertical venting through elbows, valves, and orifices, finding that CO_2 experienced significant temperature drops after passing through these components. Huang et al. [8] conducted experimental research on the freezing and blockage process in downstream pipelines during the throttling of CO_2 from 5.7-6.1 MPa to atmospheric pressure. They observed that the pipeline blockage and unblocking exhibited cyclic behavior, with the cycle increasing as the gas mass flow rate increased. Kazemifar et al. [9] used a 60 cm long, 2.1 mm diameter stainless steel pipe and a 0.36 mm orifice to study the throttling effects of near-critical CO_2, finding that CO_2 transitioned from a supercritical state to a two-phase state during throttling, with the throttling temperature drop increasing as the inlet fluid enthalpy increased. Xie et al. [10] developed a 23 m long, 30 mm diameter circulating pipeline and experimentally investigated the decompression leakage behavior of high-pressure CO_2. Their research showed that due to its higher density, the pressure drop rate of supercritical CO_2 is much greater than that of the gaseous phase, and due to the effects of blocked flow, the decompression rate

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decreases with higher initial pressure under the same pressure drop conditions. Han et al. [11] studied the decompression characteristics of liquid CO_2 in 3 m and 10 m long discharge pipelines. By measuring the pressure and temperature inside the pipeline, they inferred the location of phase transition and found that liquid CO_2 had already turned into a steam-solid mixture before being released into the atmosphere. Cao et al. [12] conducted experimental research on the throttling effects of gaseous and dense-phase CO_2, finding that the temperature drop of the gaseous phase was greater and the rate of temperature drop faster than that of the dense phase. Tollak et al. [13] studied the throttling process of CO_2 with 1.8 mol% N_2 impurities under initial conditions of 12 MPa and 25℃, comparing it to the throttling of pure CO_2 and found that the impurities significantly impacted the throttling temperature dynamics. Zhang Datong et al. [14] conducted throttling experiments on gaseous CO_2 and CO_2 with N_2 impurities using a 10 m long, 15 mm diameter stainless steel annular pipe, reaching similar conclusions. Li Yuxing et al. [15, 16] used a horizontal throttling pipe with a main volume of 600 L, 4 m in length, and an inner diameter of 50 mm to study the throttling effects of CO_2 with 5 mol% N_2 impurities at different phases. They similarly found that the presence of N_2 accelerated the rate of temperature drop for CO_2, and that the temperature drop gradually decreased as the pressure drop reduced during the throttling process. They also observed that under the same pressure drop conditions, the throttling coefficient for gaseous CO_2 was larger, for liquid CO_2 was smaller, and for supercritical CO_2 was in between the two. Drescher et al. [17] and Koeijer et al. [18] built a 139 m long, 12 mm diameter pipeline to experimentally study the throttling effect of supercritical CO_2 with N_2 impurities at concentrations of 10%, 20%, and 30%. Their research found that under the same pressure drop conditions, the temperature drop rate of the CO_2-N_2 mixture increased with the N_2 concentration, but the overall temperature drop decreased.

In summary, the throttling effects of CO_2 in different phases follow the order: gaseous CO_2 > supercritical CO_2 > liquid CO_2. Additionally, the presence of N_2 accelerates the rate of temperature drop during throttling, but the overall temperature drop is reduced. However, most current studies focus on the throttling characteristics of pure CO_2 or CO_2 with N_2 impurities, while the produced fluids in CO_2-EOR operations also contain other gaseous components such as CH_4 [19]. To address this research gap, this study uses CH_4 as the primary impurity and conducts throttling experiments on high-CO_2 content produced fluids. The effects of factors such as phase state, impurities, gas-liquid ratio, and water content on throttling characteristics are systematically analyzed. Furthermore, the temperature and phase state changes before and after throttling are explored. The results provide reliable experimental data for the safety technology of high-CO_2 content produced fluid transportation systems, offering significant theoretical and practical value.

2. Experiment

2.1. Experimental apparatus

The high-pressure sapphire reactor experimental setup is shown in Figure 1. The system consists of two high-pressure reactors (one is a visual-phase equilibrium reactor and the other is a fully transparent sapphire-phase equilibrium reactor), an inlet gas system, a temperature control system, and a data acquisition system. The two reactors are connected by a 0.2m, DN20 pipeline. They are placed in an explosion-proof box, and the physical setup is shown in Figures 2 and 3.

The high-pressure transparent sapphire reactor has a volume of 100 mL and a maximum operating pressure of 50 MPa. It is equipped with built-in temperature and pressure sensors, with a temperature sensor accuracy of ±0.1℃ and a pressure sensor accuracy of ±25 kPa. The temperature range of the thermometer is -30℃ to 100℃. The reactor is surrounded by a vacuum jacket and a water bath layer. The water bath layer is connected to a constant temperature water circulation system to form the temperature control system, with a control precision of ±0.1℃. The reactor can be vertically raised and lowered by a motor, which is convenient to operate and saves labor. Additionally, a display screen is installed to show the temperature and pressure inside the reactor in real-time during the experiment. Temperature, pressure, and rotation speed are automatically collected by software in real-time during the experiment. Furthermore, the composition of the mixed gas is analyzed using a gas chromatograph.

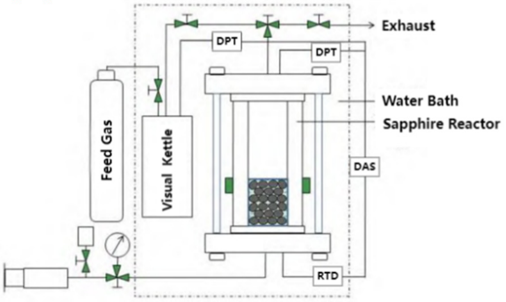

Fig. 1. Schematic Diagram of the High-Pressure Sapphire Reactor Experimental System.

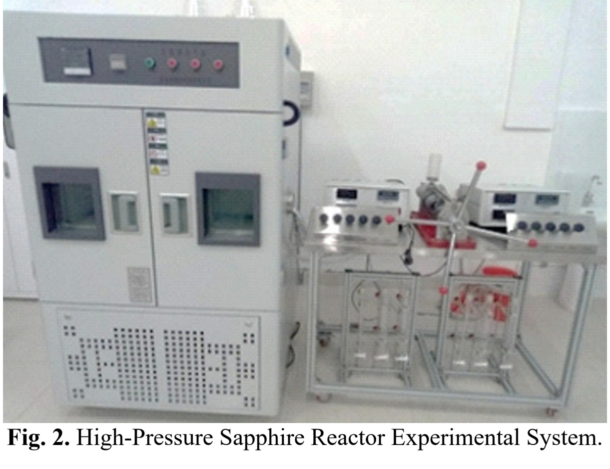

Fig. 2. High-Pressure Sapphire Reactor Experimental System.

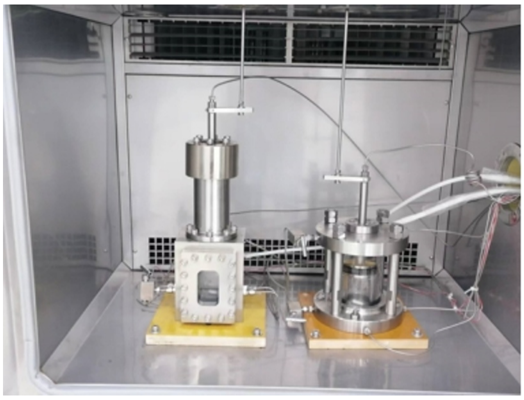

Fig. 3. Physical Photograph of the Sapphire Reactor.

2.2. Materials and methods

The CO_2 gas used in the throttling characteristic experiments has a purity of 99.99%, methane purity is 99.9%, and the crude oil and formation water are sourced from on-site sampling. In the throttling characteristic experiments, the reactor is first evacuated using a vacuum pump to create a negative pressure. Deionized water is then introduced into the reactor to clean it, followed by the introduction of a small amount of gas to expel the deionized water. This process is repeated three times until the reactor is clean. Subsequently, the same method is used to introduce the required liquid for the experiment. Next, the gas source valve is opened to inject a CO_2-containing gas with the desired composition into the reactor, and the pressure inside the reactor is adjusted to the required experimental pressure. The constant temperature water circulation system is activated, and the set temperature is adjusted to the experimental value. The pressure is adjusted to the required level using the backpressure regulator of the low-pressure reactor. Once the pressure and temperature inside the high-pressure reactor are adjusted to the required values, the high-pressure reactor valve is opened. Due to the pressure difference, high-pressure gas is released into the low-pressure reactor, and the temperature of the fluid in the low-pressure reactor is measured. By altering the initial experimental conditions (such as initial gas pressure, gas composition, or gas-liquid ratio), the above experimental process is repeated to determine the temperature drop of the high CO_2 content fluid after throttling.

3. Experimental Results

3.1. Throttling Process of CO_2 in Different Phases

At an initial temperature of 20°C, pure CO_2 was throttled from different initial pressures to 3.5 MPa, 1.5 MPa, and 1 MPa, in order to study the throttling process of CO_2 in different phases. The experimental results are shown in Table 1.

Table 1. Throttling Experimental Data of Pure CO_2 in Different Phases.

NO.	Initial P/MPa	Initial phase	Terminal P/MPa	Terminal T/°C	Terminal phase
1	15	Liquid	3.5	3.8	Gas-liquid
2	15		1.5	-21.4	Gas-liquid
3	14		3.5	4.1	Gas-liquid
4	14		1.5	-21.5	Gas-liquid
5	12		3.5	3.8	Gas-liquid
6	12		1.5	-21.9	Gas-liquid
7	10		8	19.0	Liquid
8	10		7	17.8	Liquid
9	10		6	16.9	Liquid
8	10		3.5	3.8	Gas-liquid
9	10		1.5	-24.2	Gas-liquid
10	8		1.5	-21.7	Gas-liquid
11	5	Gas	1	-33.4	Gas-liquid
12	4		1	-16.5	Gas
13	3		1	-0.9	Gas
14	2		1	11.8	Gas

The experimental results indicate that under the initial temperature of 20°C, when the initial pressure of pure CO_2 exceeds the critical pressure and is throttled down to 3.5 MPa or 1.5 MPa, the post-throttling temperature is predominantly influenced by the final throttling pressure and remains independent of the pressure drop during throttling. This behavior is due to the underlying thermodynamic process where, during throttling of liquid CO_2, as the pressure drops, the CO_2 undergoes a phase transition, precipitating gas from the liquid phase. In this process, the CO_2 fluid reaches a gas-liquid phase equilibrium at the final throttling pressure, and the temperature is directly correlated with this equilibrium pressure. Essentially, the phase change dynamics dominate the throttling temperature behavior, as the temperature and pressure relationship in the two-phase region follows the phase equilibrium curve of CO_2. This is further evidenced by the throttling experiment of pure liquid CO_2 at an initial pressure of 10 MPa, where no phase transition occurred after throttling. Under such conditions, the throttling effect coefficient (D_i) was observed to be approximately 0.6°C/MPa. The relatively low throttling coefficient in the liquid phase is due to the higher density of liquid CO_2, which reduces the degree of expansion during throttling. When the initial pressure of CO_2 is below 5 MPa, the gaseous CO_2 undergoes a much stronger throttling effect due to its lower density and higher compressibility compared to liquid CO_2. In this case, the throttling effect coefficient (D_i) increases significantly, with values ranging from 10 to 12°C/MPa for gaseous CO_2. The stronger throttling effect in the gas phase is attributed to its higher sensitivity to pressure changes and its tendency to undergo more significant temperature changes during throttling. These findings highlight that in practical engineering applications, managing CO_2 flow in multi-stage throttling systems or complex flow paths is crucial. Special care should be taken to avoid low-temperature hazards, particularly where phase transitions may occur between stages or in areas where flow path cross-sections change, as these conditions could exacerbate the throttling effect, leading to potentially hazardous temperature drops.

3.2. Effect of CH_4 Content

The design pressure of CO_2-EOR pipeline is typically 4 MPa. Therefore, an initial pressure of 5 MPa and 4 MPa is selected as the pre-throttling pressure for a normal production wellhead, with 3.5 MPa, 1.5 MPa, and 1 MPa chosen as the post-throttling pressures at the wellhead. Additionally, an initial pressure of 16 MPa is also selected to study the throttling effect of the produced fluid when gas coning occurs and the wellhead pressure increases. The experiment uses a CO_2-CH_4 mixture, with different ratios prepared for each trial. The experiment is conducted under an initial temperature of 20°C, with the initial pressures controlled at 16 MPa, 5 MPa, and 4 MPa, throttled to 3.5 MPa, 1.5 MPa, and 1 MPa, respectively. The experimental results are shown in Figure 4.

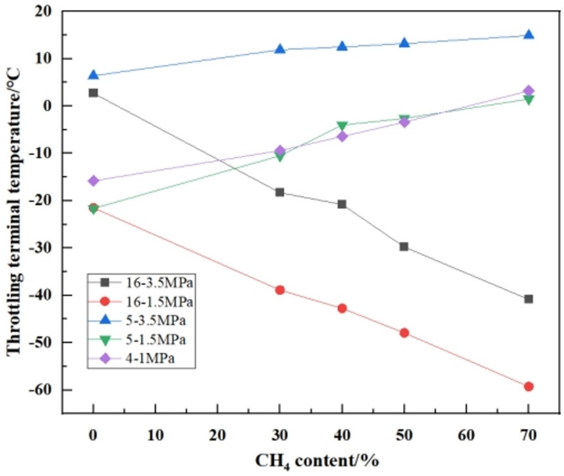

Fig. 4. Experimental data of CO_2 throttling with different of CH_4 content.

From the experimental results shown in Figure 4, it is evident that when the initial pressure is high (16 MPa), increasing the CH_4 content leads to a decrease in the final throttling temperature of the CO_2-CH_4 mixture and a corresponding increase in the temperature drop during throttling. This behavior can be explained by the phase transition occurring as the mixture enters the gas-liquid two-phase region upon throttling to 3.5 MPa or 1.5 MPa. As the CH_4 content increases, the gas-liquid ratio also increases, meaning more CO_2 gas precipitates during throttling. The throttling effect of gas is more pronounced than that of liquid due to the lower density of gas, higher compressibility, and stronger thermodynamic response to pressure changes. Therefore, the presence of more CH_4 in the mixture intensifies the throttling effect, which results in a greater temperature drop. This understanding is crucial for the operation of CO_2-EOR systems, as an increase in CH_4 content could heighten the risk of low-temperature hazards during fluid transportation. For instance, in the event of gas coning in oil wells, the produced fluid may need to be redirected to an accident tank via a bypass pipe to prevent high-pressure fluid from causing system disruptions. On the other hand, when the initial pressure is lower (5 MPa or 4 MPa), the effect of increasing CH_4 content behaves differently. In these conditions, the CO_2-CH_4 mixture remains predominantly in the gaseous phase, and the primary factors affecting the throttling temperature drop are the molecular weights and intermolecular forces of the gases. Since CH_4 has a smaller molecular weight and weaker intermolecular forces compared to CO_2, its throttling temperature drop is less pronounced. As the CH_4 content increases, the overall throttling effect of the mixture diminishes because CH_4's lower molecular weight reduces the overall density and the intensity of the throttling temperature decrease. Thus, at lower pressures, adding more CH_4 weakens the throttling effect and reduces the temperature drop.

These results underscore the significant impact of CO_2 content on the throttling behavior of CO_2 mixtures, with the effect varying depending on the initial pressure and the phase behavior of the fluid. In CO_2-EOR pipeline design and operation, it is essential to minimize the use of throttling components such as elbows and valves, and carefully consider the presence of impurities like CO_2. Such considerations are vital for controlling throttling effects, allowing real-time adjustments to operational conditions, and mitigating the risks associated with low-temperature hazards that can arise from phase transitions in high CO_2 content fluids.

3.3. Effects of gas-liquid ratio and water content

In this experiment, a CO_2-CH_4-H_2O mixed system was used to analyze the impact of water content and gas-liquid ratio on the throttling temperature of high-CO_2 produced fluids. The gas used in the experiment was a CO_2-CH_4 mixture, with CO_2 comprising 80% of the mixture. The oil-water emulsion had a total volume of 20 mL and was prepared by mixing crude oil and formation water in volume percentages of 30%, 50%, and 70%. The CO_2-CH_4 gas was mixed with the oil-water emulsion at gas-liquid ratios of 100, 200, and 300 m^3/t, creating the throttling high-CO_2 produced fluid. The experiments were conducted under initial conditions of 4 MPa pressure and 20°Ctemperature, and the throttling temperatures of the high-CO_2 produced fluids were measured after throttling to 1 MPa for different gas-liquid ratios and water contents. The experimental results are shown in Figure 5.

The experimental results show that, under the same gas-liquid ratio and pressure drop conditions, an increase in water content leads to a higher throttling temperature and a reduced temperature drop in high-CO_2 produced fluids. In contrast, under the same water content, an increase in the gas-liquid ratio results in a lower throttling temperature and a greater temperature drop. Furthermore, the influence of water content on the throttling temperature drop is smaller than that of the gas-liquid ratio, and this effect weakens as the ratio increases. The underlying reasons for these observations are as follows: compared to the gas phase, the throttling effect of the liquid phase is weaker. As the gas-liquid ratio increases in high-CO_2 produced fluids, the gas phase proportion increases, enhancing the overall throttling effect of the fluid, which demonstrates the influence of phase states on the throttling process. The increased gas-liquid ratio leads to a stronger throttling effect primarily because the gas phase has a significantly higher throttling coefficient compared to the liquid phase. When the gas-liquid ratio increases, a larger proportion of the fluid is in the gas phase, which has a more pronounced throttling effect due to its lower density and greater compressibility. As a result, the overall fluid experiences a more significant temperature drop during throttling. In contrast, the liquid phase, having a higher density and lower compressibility, exhibits a much weaker throttling effect. This phase difference enhances the overall throttling effect as the gas content increases, leading to a greater decrease in temperature. Below 20°C, within the pressure range of 4 MPa to 1 MPa, water experiences little evaporation, and the density of liquid water is higher than that of crude oil, leading to a weaker throttling effect in the liquid phase. As a result, the increase in water content weakens the average throttling effect of the entire fluid, thereby reducing the temperature drop and increasing the final throttling temperature. In contrast, the gas-liquid ratio directly affects the relative proportions of the gas and liquid phases, while water content only affects the liquid phase. Since the throttling effect of liquids is weaker than that of gases, the influence of water content on the throttling temperature drop is smaller than that of the gas-liquid ratio.

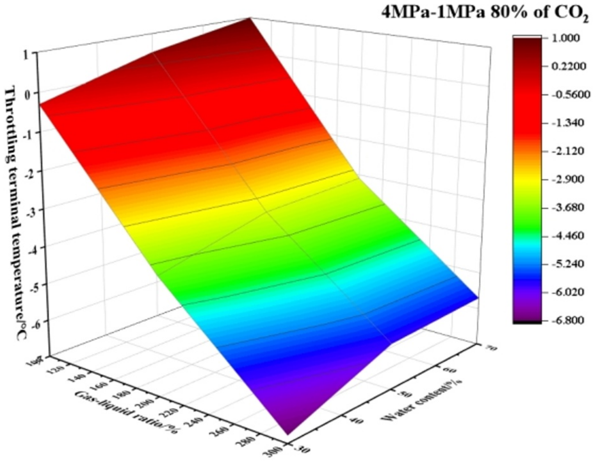

Fig. 5. Influence of gas-liquid ratio and water content on throttling characteristics of high CO_2 recovery fluids.

4. Conclusions

The high-pressure sapphire reactor experimental system was used to investigate the effects of phase state, CH_4 content, gas-liquid ratio, and water content on the throttling behavior of high-CO_2 content produced fluids. The following conclusions were drawn:

(1) Under an initial temperature of 20°C, experiments were conducted by adjusting the initial pressure and throttling it to 3.5 MPa, 1.5 MPa, and 1 MPa to study the throttling process of CO_2 in different phase states. The results show that the final temperature of liquid CO_2 is primarily influenced by the throttling end pressure, independent of the pressure drop. This is because, under these conditions, CO_2 reaches a gas-liquid phase equilibrium state at the end of throttling, where temperature and pressure are directly related. For liquid CO_2 without phase change during throttling, the throttling effect coefficient (D_i) is approximately 0.6°C/MPa. In contrast, gaseous CO_2 exhibits a stronger throttling effect, with a throttling effect coefficient (D_i) of approximately 10-12°C/MPa.

(2) The effect of CH_4 content on CO_2 throttling characteristics was also investigated. When the initial pressure is high (16 MPa), increasing the CH_4 content reduces the final temperature of the CO_2-CH_4 mixture. In the case of a gas migration incident in oil wells, the produced fluid should be diverted to an accident tank through a bypass pipe, and the corresponding wellhead pipeline valve should be closed to prevent high-pressure fluid from affecting the gathering system. Conversely, when the initial pressure is low (5 MPa or 4 MPa), increasing the CH_4 content increases the final temperature of the CO_2-CH_4 mixture. Therefore, during the design or operation of CO_2-EOR gathering systems, throttling components such as elbows and valves should be minimized, and the impact of impurities on throttling effects should be considered. This will help reduce throttling effects on the system and enable real-time adjustments to prevent low-temperature hazards caused by phase changes and enhanced throttling effects.

(3) The effects of gas-liquid ratio and water content on the throttling characteristics of high-CO_2 content production fluids were also studied. The results show that increasing the gas-liquid ratio and reducing the water content both lead to a decrease in the final throttling temperature, with the gas-liquid ratio having a more significant impact. This is because changes in the gas-liquid ratio directly reflect the influence of different phases on the overall throttling process. The throttling effect of gas is stronger than that of liquid, so an increase in the gas-liquid ratio enhances the average throttling effect of high-CO_2 content fluids. Additionally, a decrease in water content reduces the density of the oil-water emulsion, further enhancing the average throttling effect. Since the gas-liquid ratio influences both gas and liquid phases, while water content only affects the liquid phase, the impact of the gas-liquid ratio is more significant than that of water content.

Based on the above understanding, the following recommendations can be made to address the potential low-temperature hazard risks caused by the throttling effect of high-CO_2 content produced fluids.

In the event of gas coning in an oil well, the produced fluid may need to be routed through a bypass pipeline to an accident tank, and the corresponding wellhead pipeline valves should be closed to prevent high-pressure fluid from affecting the gathering system. In CO_2-EOR pipeline design and operation, the use of throttling components (such as elbows and valves) should be minimized, and the impact of impurities like CH_4 on throttling effects should be fully considered. When the gas-liquid ratio of the produced fluid is high, it is advisable to separate the fluid before throttling to prevent high-pressure mixed gas from entering the gathering system and avoid potential low-temperature hazards. This study provides important data for understanding the throttling behavior of high-CO_2 content fluids and offers crucial insights for the design and safe, efficient operation of CO_2-EOR transportation systems.

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