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A New Model for Calculation of Arrest Toughness in the Fracture Process of the Supercritical CO_2 Pipeline

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Cite This: *ACS Omega* 2021, 6, 16804−16815

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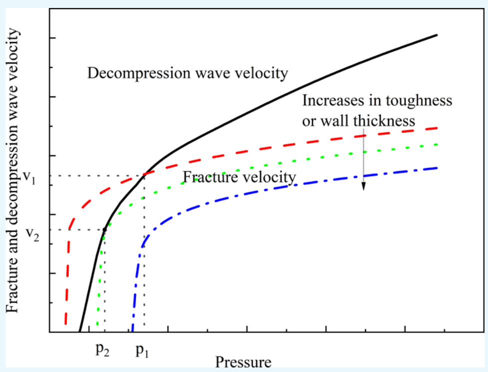
ABSTRACT: A new model based on a decompression wave prediction model and an improved BTC model has been developed to investigate the arrest toughness in the fracture process of the supercritical CO_2 pipeline. The comparison of the decompression wave velocity and the fracture propagation velocity was carried out to identify whether the pipe can prevent fracture propagation relying on its own toughness. If not, the minimum Charpy V-notch energy and the minimum wall thickness of steel pipes required for arrest fracture can be calculated using the improved BTC model. The results show that the working conditions with an initial pressure for the fracture of 11.7 MPa and a temperature of 323.15 K are the most difficult conditions to stop the fracture. The minimum wall thickness calculated only according to the strength design cannot meet the toughness requirements for ductile fracture arrest in the most difficult conditions in some cases. Then, the minimum wall thickness of the supercritical CO_2 pipeline required for ductile fracture arrest in these cases will be obtained. For instance, the minimum wall thicknesses of X65, X70, and X80 steel pipes for fracture arrest with a pipe diameter of 610 mm at a design pressure of 13.2 MPa are 17.28, 14.58, and 12.81 mm, respectively, and when the pipe diameter is 1016 mm at a design pressure of 20.4 MPa, the minimum wall thicknesses of X70 and X80 pipes can meet the requirements of arrest toughness. The model established in this study can quickly and accurately calculate the minimum wall thickness and minimum Charpy energy required to stop fracture in the supercritical CO_2 pipeline, which is suitable for engineering applications. The findings of this study can help in better understanding of the fracture process of supercritical CO_2 pipelines.



■ INTRODUCTION

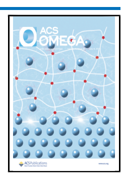
For a long time, fossil energy has been an important driving force for the world's economic development. However, the combustion of fossil energy sources such as coal and oil produces large amounts of greenhouse gases, CO_2. In recent decades, the emission of CO_2-based greenhouse gases into the atmosphere has become an increasing concern for the world.

Currently, Carbon Capture, Utilization, and Storage (CCUS) is the only technology that can significantly reduce CO_2 emissions from electricity and industry and is one of the most potential and effective solutions to the greenhouse effect in the coming decades.[1] Usually, the distance between the CO_2 capture site and the storage or use site is long, and how to transport the CO_2 from the capture site to the target site safely and efficiently is a key aspect that restricts the development of this technology.

Commonly used CO_2 transportation methods include ship, truck, rail, and pipeline transportation. At present, there is less experience on large-scale ship transportation, and the cost of high-pressure transport vessels is too high. When the transportation distance exceeds 160 km and the transportation volume exceeds 79,000 m^3/d, pipeline transportation is more economical than truck and trailer transportation.[2] CO_2 can be transported as a gas, liquid, dense phase, and supercritical phase. Since the density of CO_2 in the supercritical phase is comparable to that of the liquid phase and the viscosity is comparable to that of the gaseous phase (so, supercritical CO_2 has large density and low viscosity), the supercritical state is the best phase state for pipeline transportation of CO_2 in terms of economic efficiency.[3]

The critical temperature of CO_2 is 304.13 K, and the critical pressure is 7.38 MPa.[4] In order to ensure safe and stable operation, no phase change should be allowed during the CO_2 pipeline transportation. The operating pressure of the supercritical CO_2 pipeline needs to be greater than the critical pressure, and the pipeline maintains high-pressure operation, which may make the pipe wall material sensitive to defects and prone to leakage or even fracture accidents. Leaking of CO_2 accumulates in low-lying areas and may cause environmental

Received: March 14, 2021
Accepted: June 7, 2021
Published: June 23, 2021



damage and casualties,[5−7] so measures must be taken to inhibit pipeline cracking and fracture propagation.

The criteria for determining whether a pipeline fracture is expanding are the velocity criterion and the energy criterion.[8] The energy criterion compares the magnitude of the fracture driving force generated by the energy release inside the supercritical CO_2 with the resistance of the pipe toughness to prevent fracture propagation. When the driving force is greater than the resistance, fracture expands; otherwise, the driving force is insufficient and fracture propagation stops. The velocity criterion is to compare the propagation velocity of the decompression wave and the fracture propagation. If the velocity of the decompression wave is always greater than the fracture propagation velocity under the same pressure, the fracture propagation will stop after a certain period of time; otherwise, the crack will continue to expand until the pipe geometry or toughness changes. These two criteria are unified in nature, but the velocity criterion is more intuitive.

To avoid continued axial fracture propagation, common measures are to improve the toughness of the pipe and to install external crack arresters. Improving the toughness of the pipe can increase the arrest pressure and reduce the fracture propagation velocity. The main methods to increase the toughness of the pipeline are increasing the wall thickness and improving the Charpy impact toughness of the pipe material.[9] Measures to improve Charpy impact toughness of the pipe material include improving the heat treatment process and adding suitable alloying elements.[10] If the pipeline can rely on its own toughness to stop fracture propagation, the Charpy energy should be improved to meet the requirement of the fracture propagation velocity between the operating pressure and the arrest pressure just below the decompression wave velocity of the supercritical CO_2 decompression process and to make it minimum, required for the pipe to arrest fracture by its own toughness.

To determine the Charpy energy required to arrest fracture, the V-notch Charpy impact test,[11,12] the drop hammer tear test,[13] the crack tip opening angle,[14] and the full-scale burst test are usually required. The most commonly used method is to determine the arrest toughness of the pipeline using the Battelle two-curve model (BTC) modified by full-scale tests. The BTC model investigates the fluid−solid coupling between the decompression process and the fracture propagation process by constructing a fracture propagation curve and a decompression wave velocity variation curve.[2] At lower steel strengths, the BTC model can predict the Charpy V-notch energy required to arrest fracture of pipes better, but when applied to high-strength (X70 and above) steels, the Charpy V-notch energy calculated by the BTC model has significant deviation.[15,16] Leis et al.[17] tested the Charpy V-notch impact specimens of different steel materials with the Charpy V-notch energies ranging from 24 to 352 J. Based on the test results, the BTC model was corrected and successfully applied to the Canada−US X70 gas pipeline. In addition, Eiber[18] modified the BTC model for application to the X80 steel pipeline.

Currently, there are many studies on the fracture toughness of natural gas pipelines.[19−21] However, it has been found that pipelines transporting CO_2 in the dense phase are more prone to running-ductile fracture than natural gas pipelines.[22] This is due to the high saturation pressure reached from the dense phase or supercritical phase state and because CO_2 is prone to phase change during the decompressing process, which will result in a dramatic decrease in decompression wave velocity. Therefore, the crack arrest of the CO_2 pipeline is more difficult than that of the natural gas pipeline, and more in-depth understanding is needed for ductile fracture in CO_2 pipelines. Currently, the relationship between decompression behavior and pipeline rupture is still not very clear, and the previous models for calculating the ductile fracture propagation of the CO_2 pipeline during the decompression process are complex. In addition, to the best of the authors' knowledge, there is no research on the most difficult conditions and the minimum wall thickness and minimum Charpy V-notch energy required for toughness to ductile fracture arrest for high-pressure supercritical CO_2 pipelines, which are very important for CO_2 pipeline design

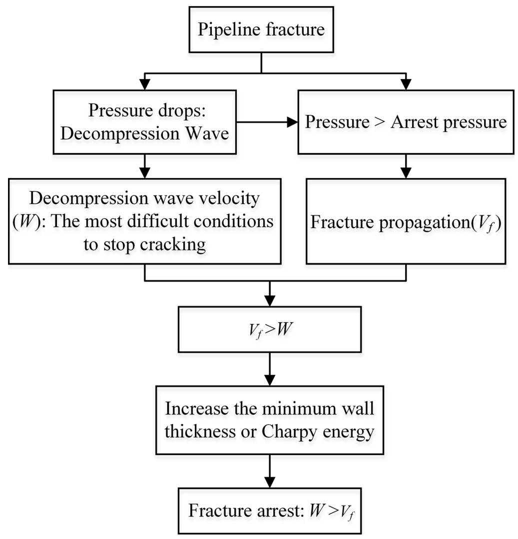


Figure 1. General sketch of this work.

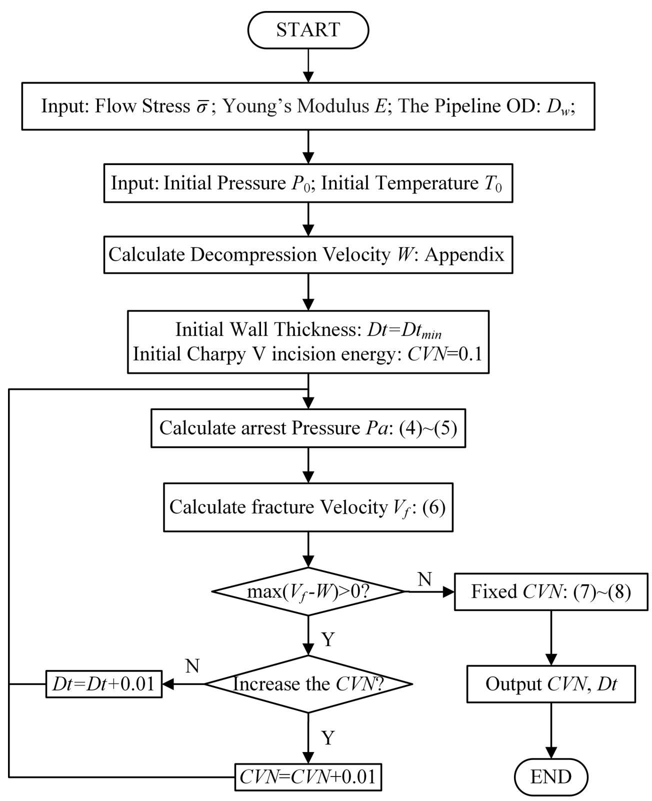


Figure 2. Calculation model for the toughness of the supercritical CO_2 pipeline to arrest fracture.

https://doi.org/10.1021/acsomega.1c01360
ACS Omega 2021, 6, 16804−16815

and pipe material selection. Since there is always a balance between accuracy and efficiency, it is necessary to develop a simpler and faster model to efficiently calculate the wall thickness and Charpy energy required for toughness to stop fracture of supercritical CO_2 pipelines.

The main objective of the present paper is to develop a simplified model to predict the toughness required for ductile fracture arrest of the supercritical CO_2 pipeline. The calculated wall thickness and Charpy energy can provide recommendations for supercritical CO_2 pipeline design and pipe material selection. The organization of this work is as follows. First, the calculation methodology of the model is presented. Second, the most difficult working conditions for fracture arrest are determined according to the supercritical CO_2 decompression wave model. Then, the decompression wave velocity and fracture propagation velocity during the decompression process of the supercritical CO_2 pipeline are compared to determine whether the pipeline toughness can arrest the fracture. Finally, the minimum wall thickness and minimum Charpy energy for toughness to fracture arrest of the supercritical CO_2 pipeline are obtained. The general sketch of this work is shown in Figure 1.

■ CALCULATION METHODOLOGY

The calculation model proposed in this work is based on the improved BTC model and a decompression wave prediction model developed by Gu etal.[23] The key to analyzing the ductile fracture arrest of the supercritical CO_2 pipeline is to determine the decompression wave velocity curve and fracture propagation velocity curve of the decompression process. When the pressure inside the pipeline is greater than the arrest pressure, the decompression wave velocity is always greater than the fracture propagation velocity and the pressure at the front end of fracture propagation keeps decreasing. When the pressure at the front end of the fracture propagation decreases to the arrest pressure, the fracture propagation stops. Figure 2 shows the diagram of the calculation model for ductile fracture arrest by toughness of the supercritical CO_2 pipeline decompression process established in this work.

The solution process of the calculation model is as follows:

(1) Steel parameter input

The calculation for the ductile fracture arrest of the supercritical CO_2 pipeline requires the input of the Young's modulus, flow stress, pipe outer diameter, and wall thickness. For different grades of steel, the modulus of elasticity does not differ much, so the Young's moduli of X65, X70, and X80 are taken to be 210 GPa. According to steel pipelines for use in pipeline transportation systems in the petroleum and natural gas industries, the minimum yield strengths of X65, X70, and X80 steel are 450, 485, and 555 MPa, respectively, and the flow stress is 69 MPa more than the minimum yield strength,[2] so the flow stresses of X65, X70, and X80 steels are taken to be 519, 554, and 624 MPa, respectively.

(2) Decompression wave velocity calculation

Since the leak of supercritical CO_2 will produce a decompression wave at the fracture to both ends of the pipeline, comparing the decompression wave velocity and the fracture propagation velocity can determine whether the pipeline fracture propagation stops or continues to expand.[2]

The equation of state is mainly used to describe the thermodynamic behavior of the CO_2 decompression process. The state equations used in the literature to predict the thermodynamic behavior of the CO_2 decompression process include GERG-2008, EOSCG-GERG, PR, Peng−Robinson−Stryjek−Vera, etc.[24−28] At present, calculation models used to predict the decompression wave characteristics of the pipeline include GASEDECOM,[24] DECOM,[26] PipeTech,[29] and other models. However, these models are too complicated in calculating the decompression wave velocity of CO_2 mixtures. In order to improve the calculation efficiency, Gu et al.[23] developed a simple model based on the GERG-2008 equation of state to predict the decompression wave behavior at the two-phase state.

Gu et al.[23] assumed that the decompression process was a one-dimensional horizontal flow, the fluid inside the pipeline was in thermodynamic equilibrium, and there was no slip between the gas and liquid phases in the adiabatic flow process. Then, they compared the model calculation data and the experimental data to verify the model in predicting the decompression wave characteristics of pure CO_2 and CO_2 with impurities. The detailed calculation process of decompression wave is shown in the Appendix A.

(3) The arrest pressure calculation

According to the BTC model, the pressure interval for calculating the fracture propagation velocity should be from the initial pressure of supercritical CO_2 pipeline fracture propagation down to the arrest pressure. To obtain the arrest pressure of the supercritical CO_2 pipeline, the arrest stress should be confirmed first.

The calculation of the arrest stress was initially proposed by Maxey and his colleagues[31] on the basis of the critical through-wall flaw size equation for initiation as shown in eqs 1−3. They deduced that the fracture arrest process is static due to the fact that the fracture velocity rapidly decreases to zero at this point, which is the reverse process of crack initiation. Therefore, the arrest stress can be calculated by the fracture initiation equation and the equivalent half-length of the extended crack and then corrected according to the results of full-scale experiments. They found that half of the effective crack length can be expressed as $3\sqrt{rDt}$, with a corresponding Folias factor M_T of 3.33, which is brought into eq 1 to yield the modified arrest stress eq 4, and then the arrest pressure of the pipe is found from the relationship between stress and pressure, as shown in eq 5.

$$\sigma_T = \frac{2\bar{\sigma}}{M_T \pi}\arccos(e^{-\pi K_c^2/8c\bar{\sigma}^2}) \tag{1}$$

$$M_T = \left[1 + 1.255\left(\frac{c^2}{rDt}\right) - 0.0135\left(\frac{c^4}{r^2Dt^2}\right)\right]^{0.5} \tag{2}$$

$$K_c = (12.5 \times CVN \times E)^{0.5} \tag{3}$$

$$-\sigma_a = \frac{2\bar{\sigma}}{3.33\pi}\arccos\left(\exp\left(\frac{-12.5\pi \times CVN \times E}{24\bar{\sigma}^2\sqrt{rDt}}\right)\right) \tag{4}$$

$$P_a = -\frac{\sigma_a Dt}{r} \tag{5}$$

(4) Calculation of the fracture propagation velocity

When the pressure at the crack tip is higher than the arrest pressure, the calculation formula for fracture velocity of the supercritical CO_2 pipeline is based on the propagation speed of the plastic strain field, and according to the existing data of the steady ductile fracture propagation, the equation is shown in eq 6:

$$V_f = C\frac{\bar{\sigma}}{\sqrt{CV}}\left(\frac{P_d}{P_a} - 1\right)^{1/6} \tag{6}$$

(5) Comparison of decompression wave velocity and fracture propagation velocity
According to the velocity criterion, it is necessary to compare the decompression wave velocity and fracture propagation velocity at different pressures during the isentropic decompression process of supercritical CO_2 leakage to determine whether the pipeline toughness can arrest the fracture. When the pressure inside the pipeline is higher than the arrest pressure, the decompression wave velocity is always greater than the fracture propagation velocity, and the toughness of the pipeline can meet the fracture arrest requirement.

(6) Calculation of the pipe wall thickness and the minimum Charpy V-notch energy
First, the minimum wall thickness of the pipeline is determined by the strength design. Without changing the pipe toughness parameters, the Charpy V-notch energies per unit area of X65, X70, and X80 pipelines are 0.96, 1.59, and 2.01 J/mm^2, respectively. Then the decompression wave velocity and fracture propagation velocity are calculated under the conditions of minimum wall thickness and minimum Charpy V-notch energy to judge whether the toughness of the pipeline can satisfy the ductile fracture arrest requirement of the supercritical CO_2 pipeline. Otherwise, it is necessary to increase the wall thickness or improve the toughness of the pipeline for arresting fracture.

As mentioned above, the calculated deviation of Charpy V-notch energy for high-strength steel calculated using the BTC model is large. Therefore, it is necessary to improve the accuracy of Charpy V-notch energy calculation for X70 and X80 pipelines by using full-scale experimental data.[17,18] The modified Charpy V-notch energy calculation equations for X70 and X80 pipelines are shown in eqs 7 and 8.

$$\begin{cases} Cv_{Arrest} = Cv_{BTCM} & Cv \leq 95\text{ J}; \\ Cv_{Arrest} = Cv_{BTCM} + 0.002Cv_{BTCM}^{2.04} - 21.98 & Cv \leq 95\text{ J} \end{cases} \tag{7}$$

$$\begin{cases} Cv_{Arrest} = Cv_{BTCM} & Cv \leq 95\text{ J}; \\ Cv_{Arrest} = Cv_{BTCM} + 0.003Cv_{BTCM}^{2.04} - 21.98 & Cv \leq 95\text{ J} \end{cases} \tag{8}$$

The purpose of calculating the wall thickness and the minimum Charpy V-notch energy required to arrest fracture is to determine the toughness of a particular pipeline. From eqs 4 and 6, it can be seen that the wall thickness and the Charpy V-notch energy of the pipeline material are related to the arrest pressure and the fracture propagation velocity of the pipeline. By increasing the wall thickness and the Charpy V-notch energy of the pipeline material, it can not only increase the arrest pressure of the pipeline but also reduce the fracture propagation velocity.

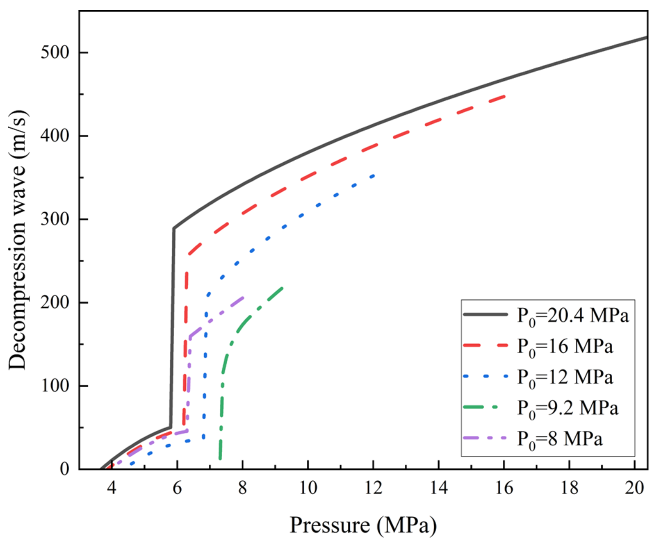


Figure 3. Decompression velocities under different initial pressures.

If the pipeline can rely on its own toughness to arrest fracture, the fracture propagation velocity should always be lower than the decompression wave velocity eqs 7 and 8, and the complete calculation process of the required minimum wall thickness of the pipeline or the minimum Charpy V-notch energy is shown in Figure 2.

RESULTS AND DISCUSSION

Since the critical pressure of CO_2 is 7.38 MPa and the critical temperature is 304.13 K, the operating pressure of the supercritical CO_2 pipeline should generally be maintained at 8−20.4 MPa and the operating temperature at 305.15−323.15 K to ensure that phase change does not occur during the supercritical CO_2 pipeline transportation.[30] The decompression wave transmission law of the supercritical CO_2 pipeline after leakage is first analyzed according to the decompression wave calculation models to determine the most difficult arrest conditions of the pipeline. In the most difficult arrest conditions, the arrest pressure of the supercritical CO_2 pipeline is higher than the saturation pressure of CO_2, which means that the supercritical CO_2 pipeline can rely on its own toughness to arrest fracture.[2] Otherwise, other methods such as crack arresters need to be used for arrest fracture.

When the supercritical CO_2 pipeline cannot meet the ductile fracture arrest toughness condition, according to eqs 4−5, it can be seen that increasing the wall thickness of the pipeline and the Charpy V-notch energy of the pipeline material can effectively increase the arrest pressure, but the cost of laying the pipeline will increase by increasing the wall thickness or improving the toughness parameter of the pipeline. Therefore, by studying the fracture propagation process of the pipeline with different wall thicknesses and Charpy V-notch energies, it can help in selecting the appropriate wall thickness and toughness parameters of supercritical CO_2 pipelines.

Decompression Wave Characteristics of the Supercritical CO_2 Leakage Process. Analyzing the decompression wave characteristics of the CO_2 leakage process with the initial pressure and temperature in the supercritical region, it can be determined that the most difficult working conditions for the pipeline to arrest fracture is when the decompression wave velocity is the smallest and the saturation pressure is the largest.

https://doi.org/10.1021/acsomega.1c01360
ACS Omega 2021, 6, 16804−16815

If the arrest pressure under these conditions is higher than the saturation pressure of CO_2, it can be considered that the supercritical CO_2 pipeline can arrest fracture by its own toughness.[2]

In order to determine the most difficult fracture arrest conditions of the pipeline, the initial temperature of the supercritical CO_2 pipeline is first assumed to be a fixed value. At this initial temperature (for example, 313.15 K), the leakage process of supercritical CO_2 is reduced under different initial pressure conditions. The relationship between the decompression wave velocity and the CO_2 saturation pressure is shown in Figure 3.

When the supercritical CO_2 pipeline operates in a certain pressure range, the initial pressure at the pipeline fracture initiation may be any pressure in the interval. In this research, the pressures at the crack initiation are chosen to be 20.4, 16, 12, 9.2, and 8 MPa. It can be seen from Figure 3 that when the leakage occurs in the supercritical CO_2 pipeline, the temperature and pressure inside the pipeline keep decreasing. When the pressure decreases to the saturation pressure, the decompression wave velocity decreases sharply due to the phase change of CO_2 inside the pipeline. Moreover, it can be seen from Figure 3 that the lower the saturation pressure is, the lower the pressure when the decompression wave is equal to zero, and the greater the overall decompression wave velocity is, which is beneficial to arrest fracture according to the BTC model. However, as shown in Figure 3, it is not that the higher the initial pressure is, the higher the saturation pressure is and the more difficult it is to arrest fracture. In the initial pressure range analyzed in this work, when the initial pressure is 9.2 MPa (initial temperature is 313.15 K), the saturation pressure of CO_2 fracture-induced during the leakage process is the largest and the pipeline cannot arrest fracture under these working conditions according to the requirement that the arrest pressure should be higher than the saturation pressure.

It is also known from Figure 3 that the saturation pressure is related to the initial pressure at the fracture port under certain temperature conditions, and the saturation pressure is maximum at an initial pressure of 9.2 MPa. Taking the initial pressure of the fracture to be 9.2 MPa, the decompression wave velocities at different initial temperatures are shown in Figure 4.

As shown in Figure 4, when the initial pressure at the fracture of the supercritical CO_2 pipeline is 9.2 MPa, the saturation pressure of CO_2 decreases with increasing temperature when the initial temperature is in the range of 313.15 to 323.15 K. However, when the initial temperature is in the range of 305.15−313.15 K, the saturation pressure of CO_2 rises with the increase of temperature. From Figures 3 and 4, it can be seen that the saturation pressure is not only related to the initial pressure of the supercritical CO_2 pipeline but also related to the initial temperature, and the saturation pressure is not linear with the initial temperature−pressure change at the fracture. So, the influence of initial pressure and temperature at the fracture on the saturation pressure should be considered comprehensively.

Figure 5 presents the relationship between the saturation pressure of CO_2 and the initial pressure at the fracture during the leakage process of the supercritical CO_2 pipeline when the initial temperatures are at 305.15, 307.65, 313.15, and 323.15 K. As shown in Figure 5, when the operating temperature of the supercritical CO_2 pipeline is higher than 307.65 K, the saturation pressure during the fracture propagation process increases and then decreases with the increase of the initial pressure at the fracture port. When the initial temperature and pressure at the fracture are 307.65 K and 8 MPa (point 1), 313.15 K and 9.2 MPa (point 2), and 323.15 K and 11.7 MPa (point 3), the maximum saturation pressure of CO_2 during the leakage process can reach the critical pressure (7.38 MPa). If the pipe relies on its own toughness to arrest fracture, it is required that the cracking pressure of the pipeline must be higher than the saturation pressure of CO_2, so the conditions of initial pressure and temperature for these three points are the more difficult conditions for the pipeline to arrest fracture. When the operating temperature is lower than 307.65 K, the saturation pressure decreases as the initial pressure increases, i.e., the lower the initial pressure for fracture propagation, the more difficult it is to arrest fracture.

When calculating the decompression wave velocity, it is assumed that the entire decompression process is an isentropic depressurization process, which means that when the initial entropy of the supercritical CO_2 is consistent with the initial entropy at the critical point, the CO_2 will inevitably undergo phase change at the critical point during the isentropic decompression process, and the decompression wave velocity also drops sharply at the critical pressure.

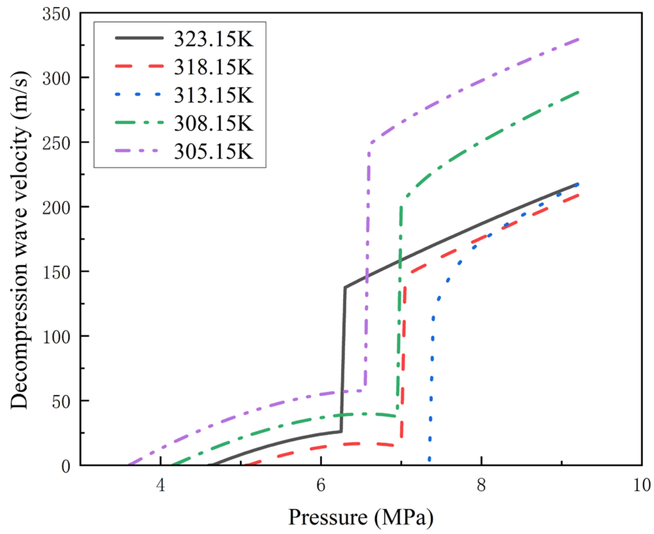


Figure 4. Decompression wave velocities at different initial temperatures.

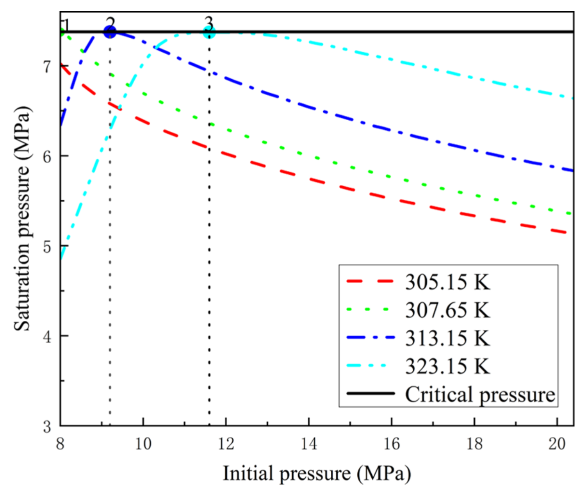


Figure 5. Saturation pressure change curves.

https://doi.org/10.1021/acsomega.1c01360
ACS Omega 2021, 6, 16804−16815

According to the equation of state, the entropy of CO_2 at the critical point (a temperature of 304.13 K and a pressure of 7.38 MPa) is $S = 1.4392$ J/kg/K. The entropies of points 1, 2, and 3 in Figure 6 (also the three points in Figure 6) are 1.4395, 1.4250, and 1.4343 J/kg/K, which are all similar to the entropy at the critical point. Therefore, when the initial entropy at the fracture port is consistent with the entropy at the critical point, the supercritical CO_2 will enter the two-phase region at the critical point during the isentropic decompression process. At this time, the saturation pressure is the critical pressure, as shown in the curve of $S = 1.4392$ J/kg/K in Figure 7. When the initial entropy at the fracture is higher than the entropy at the critical point, the supercritical CO_2 will first become gaseous and then enter the gas–liquid two-phase region. When the initial entropy at the fracture is lower than the entropy of the critical point, the supercritical CO_2 will change to a dense phase and liquid phase successively and then enter the gas–liquid two-phase region. However, whether CO_2 enters the gas–liquid two-phase state from the gas phase or the liquid phase, the saturation pressure is lower than the critical pressure, so when the initial entropy at the fracture port is the same as the critical point entropy, the saturation pressure during the decompression process is the largest and the required arrest pressure is also the largest and higher than the critical pressure.

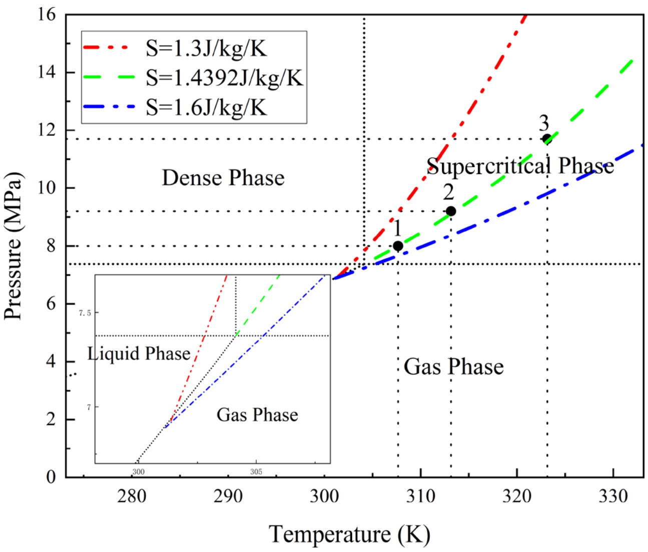


Figure 6. Supercritical CO_2 isentropic pressure drop process.

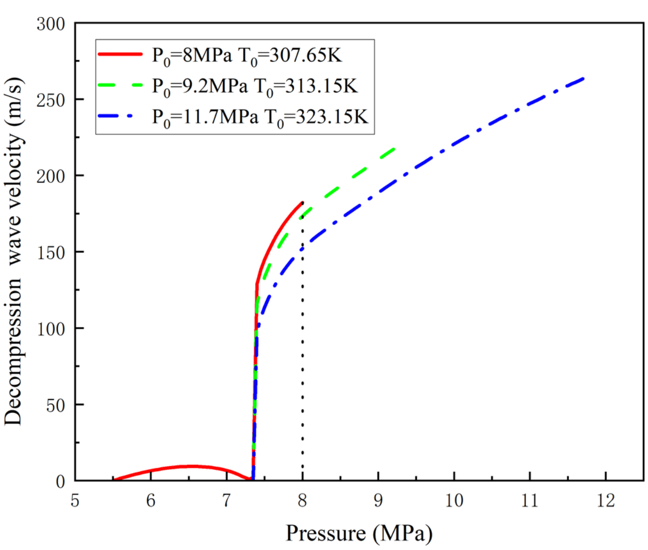


Figure 7. Decompression wave velocity diagrams at different points of the isentropic curve.

It is also known from Figure 6 that when the initial entropy of the supercritical CO_2 is the same, the saturation pressure is also the same, and the requirements for the pipeline arrest pressure are the same, but the decompression wave velocity change process is different due to the difference of initial temperature and pressure. The following analysis is performed for the decompression process of different working conditions with saturation pressure near the critical point (as shown in Figure 7) to determine the most difficult working conditions for the pipeline to arrest fracture.

According to the BTC model, the smaller the decompression wave velocity is, the smaller the allowable rupture velocity for the supercritical CO_2 pipeline is, and the more difficult it is to arrest fracture. It can be seen from Figure 7 that when the operating pressure is in the range of 8–20.4 MPa and the temperature is in the range of 305.15–323.15 K, the decompression wave velocity is the smallest and the saturation pressure is 7.38 MPa under the conditions of an initial pressure of 11.7 MPa and temperature of 323.15 K, which are the most difficult working conditions for the supercritical CO_2 pipeline to arrest fracture by its own toughness.

The Influence of Charpy V-Notch Energy on Fracture Propagation. In order to determine the ductile fracture arrest parameters and analyze the influence of Charpy V-notch energy on fracture propagation of the supercritical CO_2 pipeline, the decompression process of supercritical CO_2 leakage of different steel grades under certain pipe diameter and pressure conditions is analyzed. Three groups of supercritical CO_2 pipelines with 610 mm diameter and 13.2 MPa design pressure, 762 mm diameter and 18.6 MPa, and 1016 mm and 20.4 MPa were selected. First, the wall thickness determined according to the strength design criteria and without any toughness improvement of pipe materials, whether the pipeline can complete the crack arrest process relying on its own toughness, was studied. When the minimum wall thickness of the supercritical CO_2 pipeline is determined according to the pipeline strength design, the pipeline design factor is 0.72. The X65, X70, and X80 pipes will be analyzed below (Table 1).

In the supercritical CO_2 decompression process, an initial pressure is 11.7 MPa and a temperature is 323.15 K are the most difficult conditions for complete arrest fracture by pipeline toughness. The relationship between the supercritical CO_2

Table 1. Toughness Parameters and Minimum Wall Thicknesses of Different Pipelines

pipe material	OD (mm)	design pressure (MPa)	CV ((J/mm^2))	minimum wall thickness (mm)
X70	610	13.2	0.96	12.23
X80			1.59	11.36
X80			2.01	9.95
X65	762	18.6	0.96	21.38
X70			1.59	19.87
X80			2.01	17.41
X65	1016	20.4	0.96	31.20
X70			1.59	29.00
X80			2.01	25.41

https://doi.org/10.1021/acsomega.1c01360
ACS Omega 2021, 6, 16804–16815

decompression wave velocity and fracture propagation velocity in this situation is analyzed below to determine the ductile fracture arrest of the pipeline.

It can be seen from Figures 8–10 that the decompression wave velocity of the natural gas pipeline is much higher than fracture propagation velocity and CO_2 decompression wave velocity, and the fracture arrest process can be completed by its

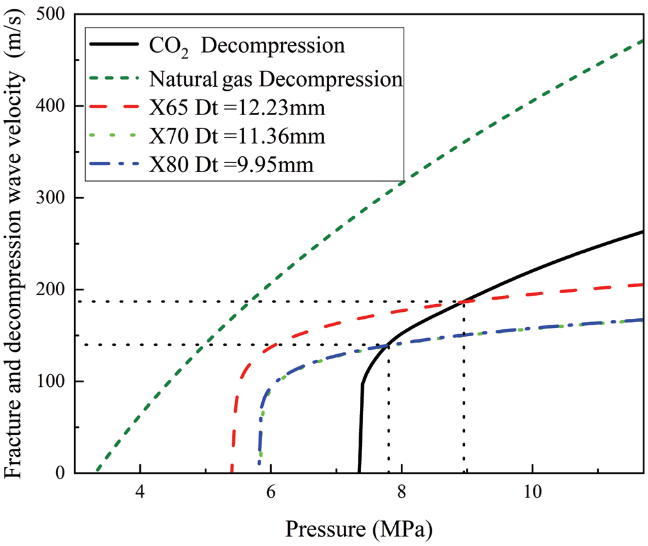


Figure 8. Fracture and decompression wave velocity curves of different material pipelines with 610 mm diameter.

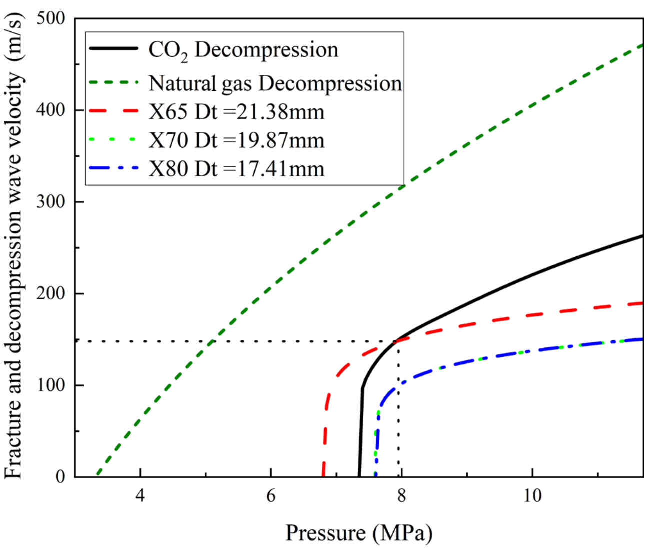


Figure 9. Fracture and decompression wave velocity curves of different material pipelines with 762 mm diameter.

own toughness. However, for the supercritical CO_2 pipeline, when the pipe diameter is 610 mm and the design pressure is 13.2 MPa, the arrest pressures of the X65, X70, and X80 pipes are less than the saturation pressure of the CO_2 decompression process when they meet the minimum wall thickness of strength requirements. During the fracture propagation process, the fracture propagation velocity is higher than the decompression wave propagation velocity, the pressure at the front of crack propagation remains unchanged, and the speed of crack propagation remains unchanged, which is about 100–150 m/s, so the fracture arrest process cannot be completed, which does

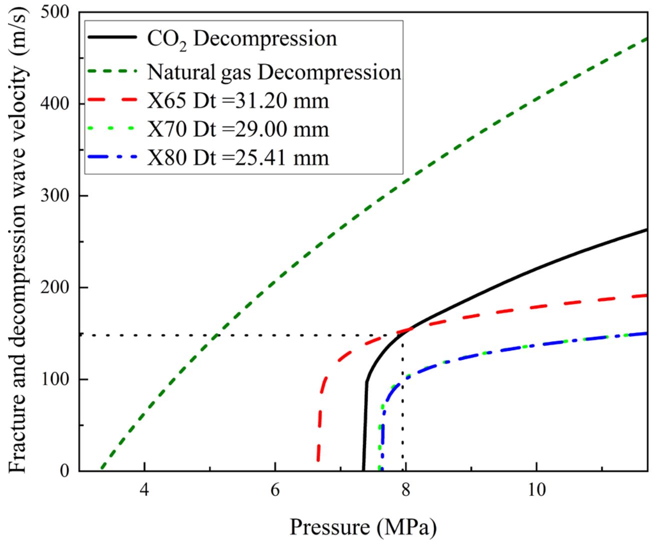


Figure 10. Fracture and decompression wave velocity curves of different material pipelines with 1016 mm diameter.

not meet the requirements of ductile fracture arrest for the supercritical CO_2 pipeline. When the pipe diameter is 762 mm and the design pressure is 18.6 MPa, and the pipe diameter is 1016 mm and the design pressure is 20.4 MPa, the minimum wall thickness of the pipeline to meet the strength design is larger due to the high design pressure of the pipeline. When using the velocity criterion to calculate the pipeline toughness, it is found that the minimum wall thicknesses of X70 and X80 pipelines meet the ductile crack arrest conditions, but the X65 pipeline cannot meet the ductile crack arrest conditions.

For the pipeline that cannot meet the requirement of ductile fracture arrest, improving the toughness of the pipeline material or increasing the wall thickness is generally adopted so that it can rely on its own toughness to stop the crack. First, the influence of improving the toughness of the pipeline material (increasing the Charpy energy of the pipeline material) on the fracture process of the supercritical CO_2 pipeline is analyzed.

According to eqs 4–6, it is known that increasing the Charpy V-notch energy of supercritical CO_2 pipelines can not only increase the arrest stress of the pipeline but also reduce the fracture propagation velocity. When the Charpy V-notch energy is taken to infinity, the arrest stress reaches the maximum value as shown in eq 9.

$$-\sigma_{amax} = \frac{2\bar{\sigma}}{3.33\pi}\arccos\left(\exp\left(\frac{-12.5\pi \times CVN \times E}{24\bar{\sigma}^2\sqrt{\frac{DwDt}{2}}}\right)\right) = \frac{2\bar{\sigma}}{3.33\pi}\arccos(0) = \frac{\bar{\sigma}}{3.33} \quad (9)$$

When the diameter and wall thickness of the pipeline are not changed, the arrest pressure corresponding to the maximum arrest stress reaches the maximum, and the maximum arrest pressure is calculated according to the following formula.

$$P_a = \frac{2\bar{\sigma}Dt}{3.33D_w} \quad (10)$$

The ductile fracture arrest of the supercritical CO_2 pipeline with 610 mm outer diameter and 13.2 MPa design pressure is analyzed. When the outer diameter of the pipe is 610 mm and the wall thicknesses of X65, X70, and X80 pipelines are 12.23, 10.94, 9.58 mm, respectively, the maximum arrest pressures achieved by increasing the Charpy V-notch energy are 6.25, 6.20, and 6.11 MPa, respectively, which are all less than the saturation pressure of 7.38 MPa for the most difficult fracture arresting conditions. Therefore, when the wall thickness of the supercritical CO_2 pipeline is taken to meet the minimum value of strength design, the fracture arrest cannot be accomplished by increasing the Charpy V-notch energy of the pipeline material in this condition. When the outer diameter of the pipe is 1016 mm and the wall thickness of X65 is 31.20 mm, the maximum arrest pressure is 9.57 MPa, so it can arrest fracture by increasing the Charpy V-notch energy of the pipeline material. Moreover, the energy of the Charpy V-notch cannot be increased infinitely for the actual pipeline material. Therefore, the minimum Charpy V-notch energies for the different wall thicknesses of X65, X70, and X80 pipelines to meet the crack-stopping toughness will be analyzed below. The specific calculation process is referred to Figure 2.

It can be seen from Figure 11 that the minimum Charpy V-notch energy required for the same wall thickness of pipelines with different strength classes is almost the same. When the pipeline wall thickness is less than d_c, increasing the pipeline wall thickness can significantly reduce the minimum Charpy V-notch energy required to arrest fracture. However, when the pipeline wall thickness is greater than d_c, it is not feasible to reduce the requirements for pipeline material toughness by increasing the pipeline wall thickness.

The minimum Charpy V-notch energy is only the basic requirement that the pipeline can arrest fracture by its own toughness. To reduce the fracture propagation velocity, the Charpy V-notch energy of the pipeline can be further increased by changing the heat treatment process of the pipeline or adding alloys. As shown in Figure 12, the effect of Charpy V-notch energy on the fracture propagation process is analyzed for the X65 pipeline with a wall thickness of 18 mm as an example.

As can be seen from Figure 12, increasing the Charpy V-notch energy of the pipeline can not only increase the arrest pressure of the pipeline and stop the fracture propagation process in advance but also can effectively reduce the fracture propagation velocity, shrink the pipeline fracture length, and effectively reduce the economic loss caused by pipeline rupture.

The Influence of Pipeline Wall Thickness on Crack Expansion of the Fracture Propagation Process of the Supercritical CO_2 Pipeline. From eq 10, it can be seen that increasing the arrest pressure by raising the Charpy V-notch energy will eventually be limited by the pipeline wall thickness condition. Therefore, in some cases, the pipeline wall thickness must be appropriately increased to meet the toughness requirement for arrest.

Under the condition that the Charpy V-notch energy per unit area remains constant, it is known from eqs 4 and 5 that increasing the wall thickness of the pipeline can increase the arrest pressure of the pipeline and reduce the fracture propagation velocity, which is beneficial to the pipeline arrest. The influence of the X65, X70, and X80 pipeline wall thicknesses on the arrest pressure will be analyzed in the following, as shown in Figure 13.

It can be seen from Figure 13 that the arrest pressure increases with the increase of pipe wall thickness under the condition of certain Charpy V-notch energy, which is basically linear. Therefore, when the toughness of the supercritical CO_2 pipeline does not meet the ductile fracture arrest requirements, the wall thickness of the pipeline can be appropriately increased to improve the arrest pressure of the pipeline. The following will combine the supercritical CO_2 decompression process to determine the minimum wall thicknesses of different material pipelines to meet the toughness requirement.

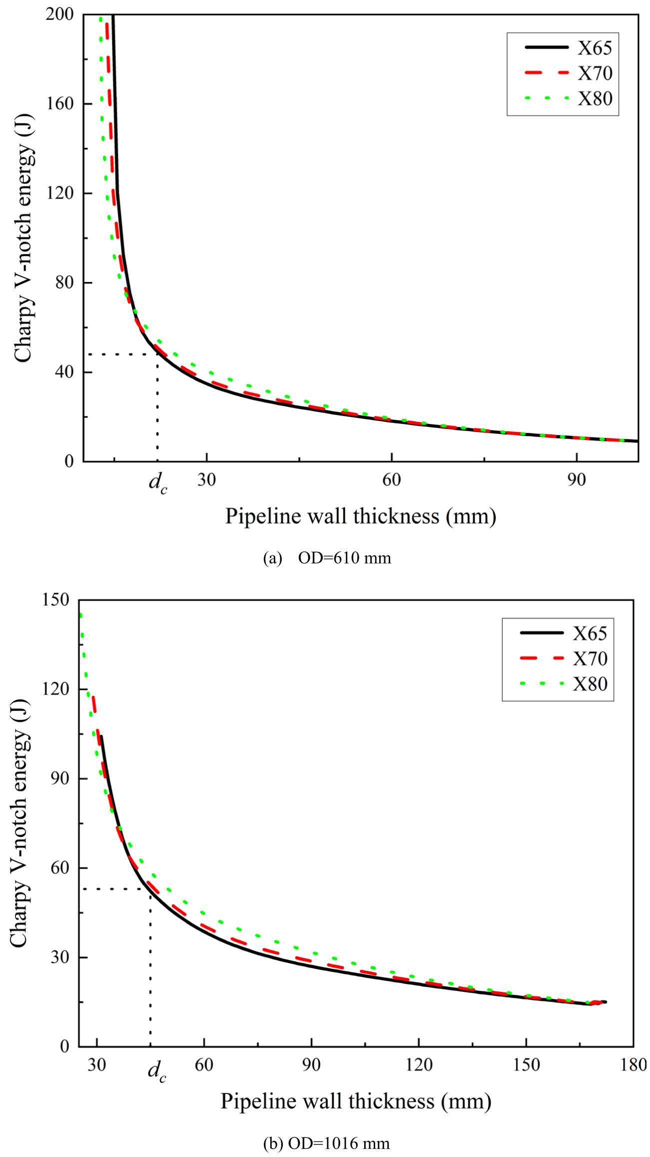


Figure 11. Minimum Charpy V-notch energies of different pipeline wall thicknesses: (a) OD = 610 mm; (b) OD = 1016 mm.

In the supercritical CO_2 decompression process, the saturation pressure of CO_2 is the highest under the initial conditions that the initial pressure is 11.7 MPa and the initial temperature is 323.15 K. This saturation pressure is close to the critical pressure and the decompression wave velocity is the slowest, which are the most difficult conditions to complete fracture arrest by relying on the toughness of the pipeline. The relationship between the supercritical CO_2 decompression wave transfer and fracture propagation in this most difficult situation is analyzed below to determine the ductile fracture arrest of the pipeline.

As shown in Figure 8, when the outer diameter of the supercritical CO_2 pipeline is 610 mm and the design pressure is 13.2 MPa, the minimum wall thickness of the pipeline determined according to the strength design cannot meet the

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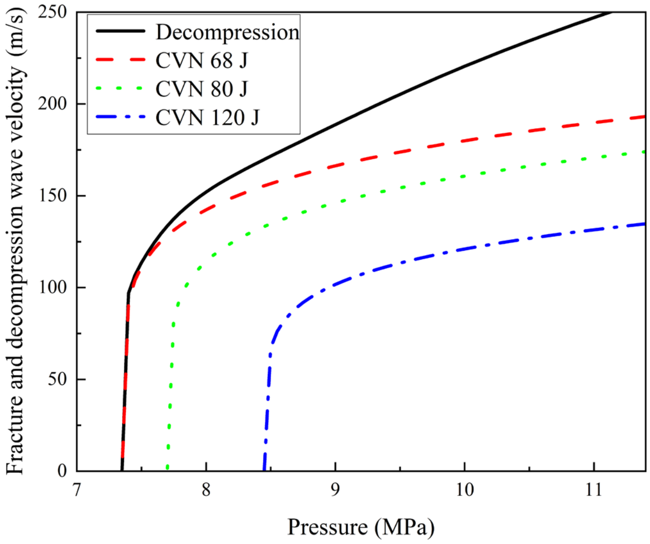

Figure 12. Effect of X65 pipeline Charpy V-notch energy on fracture velocity.

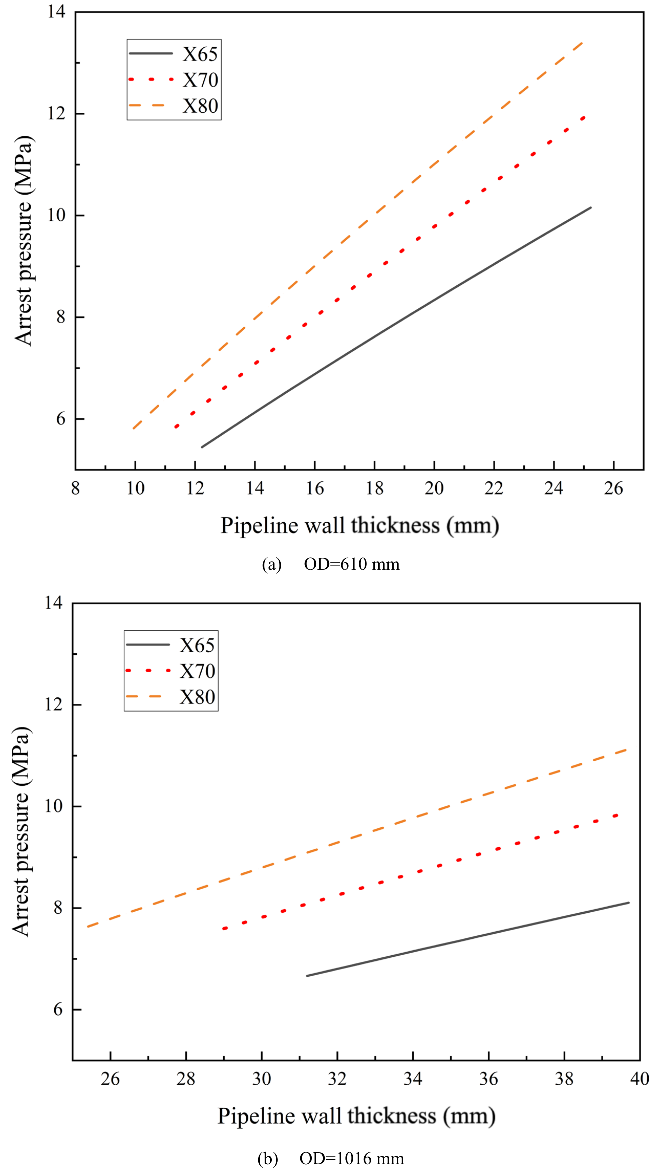

Figure 13. Relationship between fracture arrest pressure and pipeline wall thickness: (a) OD = 610 mm; (b) OD = 1016 mm.

requirements of the ductile fracture arrest of the pipeline, and if the pipeline is required to arrest fracture by its own toughness, the arrest pressure can be increased and the fracture propagation velocity can be reduced by increasing the wall thickness. Figures 14 and 15 show the analysis of the fracture propagation process and the decompression process of the supercritical CO_2 pipeline with different wall thicknesses for X65 and X80 pipelines as examples.

It can be seen from Figure 14 that the wall thickness of the X65 pipeline should not be less than 17.28 mm to prevent fracture propagation of the supercritical CO_2 pipeline without changing the Charpy V-notch energy of the pipeline material. In order to prevent ductile fracture of the supercritical CO_2 pipeline, the wall thickness of the X65 pipeline should not be less than 17.28 mm. It can also be seen from Figures 14 and 15 that increasing the pipeline wall thickness can improve the arrest pressure, but the effect of reducing the fracture propagation velocity at higher pressures is not obvious. According to this model, when the pipeline diameter is 610 mm, the minimum wall thicknesses of X70 and X80 pipelines to meet the ductile fracture arrest are 14.58 and 12.81 mm, respectively.

SUMMARY AND CONCLUSIONS

Based on the improved BTC model combined with the decompression wave calculation model of the CO_2 pipeline leakage process, the model for arrest toughness of the supercritical CO_2 pipeline is established and the following conclusions are obtained.

(1) During the decompression process of the supercritical CO_2 pipeline, when the entropy at the fracture port is the same as that of the critical point, the saturation pressure of CO_2 can reach the critical pressure, and the arrest pressure must be higher than critical pressure. The most difficult working conditions for the supercritical CO_2 pipeline to arrest fracture by its own toughness are an initial pressure of 11.7 MPa and temperature of 323.15 K.

(2) When the strength and design pressure of the supercritical CO_2 pipeline are high, the minimum wall thickness obtained according to the strength design criterion can meet the requirements of ductile fracture arrest.

(3) The arrest pressure of the pipeline can be improved by increasing the pipeline wall thickness or increasing the Charpy V-notch energy of the pipeline material. Meanwhile, the method of increasing the Charpy V-notch energy of the pipeline will ultimately be limited by the pipeline geometry, and within the scope of this paper; when the pipeline wall thickness is greater than d_c, it is difficult to reduce the minimum Charpy V-notch energy required for arrest toughness of the pipeline by increasing the pipeline wall thickness. The wall thickness of the pipeline is linearly related to the arrest pressure if other conditions are unchanged, but increasing the wall thickness will affect the economic efficiency. Therefore, a suitable wall thickness and Charpy V-notch energy should be selected to reduce the fracture propagation velocity of the pipeline.

The present work has presented a new simplified model to predict the minimum wall thickness and minimum Charpy energy required to stop fracture in the supercritical CO_2

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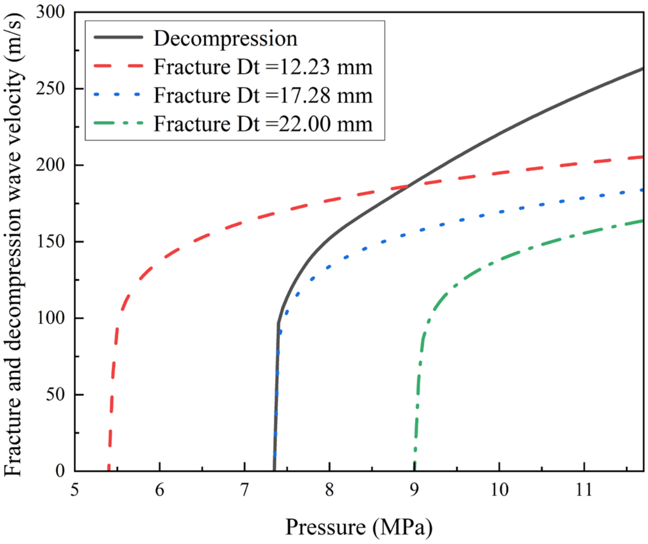

Figure 14. Fracture and decompression velocity curves of the X65 pipeline.

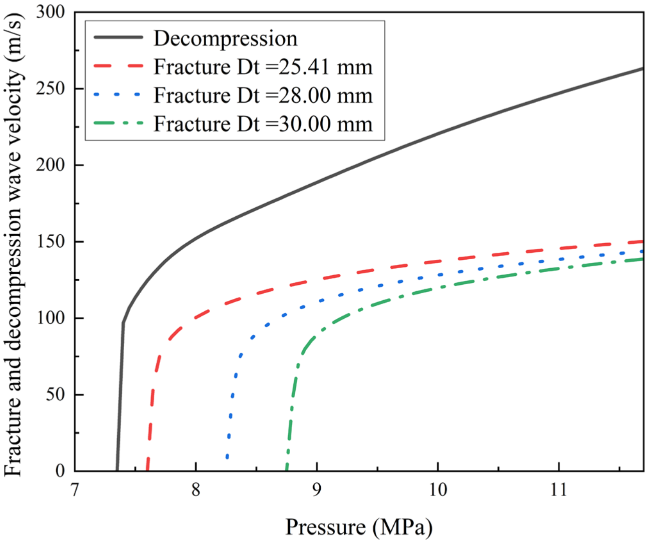

Figure 15. Fracture and decompression wave velocity curves of the X80 pipeline.

pipeline. This model is relatively simple and the program is less computationally intensive, which is suitable for engineering applications. However, the fracture velocity equation may not be accurate when the diameter of the pipeline is less than 457 mm, so this model is not suitable for small-diameter pipelines.

APPENDIX

A. Decompression Wave Velocity Calculation

The supercritical CO_2 decompression wave velocity is calculated as follows:

$$W = a - U \tag{A1}$$

As can be seen from eq A1, the decompression wave velocity is related to the sound velocity and the leakage outflow velocity, and the calculation of CO_2 sound velocity is divided into two cases, single phase and two phases.

The sound velocity that can be obtained from the equation of state (eq A2) is related to the temperature when CO_2 is in the single phase.

$$a = \sqrt{\lambda ZRT} \tag{A2}$$

CO_2 changes from the single phase to the gas–liquid two-phase with the decrease of temperature and pressure. Assuming that the pressure and temperature of both gas–liquid phases are in equilibrium, the equation for the sound velocity a_2 in pressure and temperature equilibrium is shown as eq A3

$$\frac{1}{a_2^2} = \frac{1}{a_1^2} + \frac{\rho}{T}\frac{C_{p,g}C_{p,l}(\xi_l - \xi_g)^2}{C_{p,g} + C_{p,l}} \tag{A3}$$

where $k \in \{g, l\}$, a_1 is the sound velocity in pressure equilibrium as shown in eq A4, and ξ_k and $C_{p,k}$ are determined using eq A5–A7 respectively.

$$\frac{1}{a_1^2} = \rho^2\left(\frac{x_g}{\rho_g^2 a_g^2} + \frac{1 - x_g}{\rho_l^2 a_l^2}\right) \tag{A4}$$

$$\xi_k = \left(\frac{\partial T}{\partial p}\right)_{sk} \tag{A5}$$

$$C_{p,k} = \rho_k x_k c_k \tag{A6}$$

$$c_k = T\left(\frac{\partial s}{\partial T}\right) \tag{A7}$$

The outflow velocity at the fracture of pipeline can be determined by eq A8.

$$U_i = U_{i-1} + \frac{p_{i-1} - p_i}{a_i \rho_i} \tag{A8}$$

After the calculation of sound velocity and outflow velocity at the fracture, the decompression wave velocity can be obtained by eq A1.

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https://doi.org/10.1021/acsomega.1c01360
ACS Omega 2021, 6, 16804–16815

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was supported by the Fundamental Research Funds for the Central Universities, China (20CX02405A), the Development Fund of Shandong Key Laboratory of Oil & Gas Storage and Transportation Safety, and the National Science and Technology Special Project (2016ZX05016-002).

■ NOMENCLATURE

$\overline{\sigma}$, flow stress (MPa); *E*, Young's modulus (MPa); D_w, pipeline diameter (mm); *P*, pressure (MPa); *T*, temperature (K); *W*, decompression wave velocity (m/s); *Dt*, wall thickness of the pipeline (mm); *CVN*, Charpy V-notch energy (J); *Pa*, arrest pressure (MPa); V_f, ductile fracture propagation velocity (m/s); *a*, sound speed (m/s); *U*, leakage flow velocity (m/s); *λ*, isentropic expansion coefficient (−); *Z*, compressibility factor (−); *R*, universal gas constant (8.314 J/kg/K); *ρ*, density (kg/m^3); $C_{p,k}$, extensive heat capacity (J/K/m^3); *x*, molar composition (−); c_p, heat capacity (J/kg/K); *s*, specific entropy (J/kg/K); σ_T, hoop stress at failure (MPa); M_T, Folias factor for a through-wall flaw (−); K_c, critical (plane stress) stress intensity factor (N/mm$^{1.5}$); *c*, half-length of a through-wall crack (mm); *r*, nominal radius of the pipeline (mm); σ_a, arrest stress (MPa); P_a, arrest pressure (MPa); V_f, fracture propagation velocity (m/s); *C*, constant, the backfilled pipe is 0.275 and the unbackfilled pipe is 0.379; *CV*, Charpy V-notch energy per unit area (J/mm^2); P_d, pressure at the crack tip (MPa)

Subscripts

g, gaseous phase; *l*, liquid phase

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