Energy Proceedings
Vol 35, 2023
ISSN 2004-2965

Numerical simulation of crack propagation in supercritical CO_2 pipelines

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ABSTRACT

Supercritical CO_2 pipeline is the main way to transport carbon dioxide. However, due to the decompression wave characteristics of supercritical CO_2, once the pipeline cracked, it will lead to the continuous propagation of cracks, which threatens the safety of pipeline operation. To study the crack propagation mechanism of supercritical CO_2 pipeline, the instrumented impact test is carried out, and the parameters of Cohesive Zone Model are calibrated by inversion the test results. By comparing the trapezoidal traction separation law and linear traction separation law, it is found that the simulation results of the trapezoidal constitutive are in good agreement with the experimental results, and a more accurate material model of the crack propagation region is obtained. Based on the Cohesive Zone Model, the finite element model of crack propagation in supercritical CO_2 pipeline is established to analyze the effects of pressure, wall thickness, pipe diameter on the crack propagation velocity. The results show that for supercritical CO_2 pipeline, under the given gas composition, pressure and temperature conditions, with the increase of internal pressure, the decrease of wall thickness and the increase of pipe diameter, the crack arrest pressure of pipeline decreases. It is necessary to improve the crack arrest toughness of pipeline to ensure that the pipeline can achieve crack arrest within a limited length. The research results can provide a theoretical basis for crack propagation of supercritical CO_2 pipeline and have practical engineering reference significance.

Keywords: Supercritical CO_2 pipeline, instrumented impact test, Cohesive Zone Model, crack propagation velocity

1. INTRODUCTION

Pipeline transportation of supercritical CO_2 is an important measure to control the emission of greenhouse gas such as CO_2 in the atmosphere. Among the many factors that cause pipeline failure, crack propagation is one of the most important failure modes of supercritical CO_2 pipeline. Compared with oil and gas pipelines, supercritical CO_2 pipelines are more prone to rapid fracture. During the fracture process, supercritical CO_2 will produce a longer phase transition during the depressurization process, so the driving force at the crack tip will remain relatively unchanged. At the same time, during the rapid decompression process, carbon dioxide will expand and cool due to the Joule-Thomson effect, resulting in a significant decrease in pipe wall temperature and fracture toughness, resulting in obvious local thermal stress at the crack, thereby promoting fracture propagation. Therefore, it is necessary to study the crack propagation mechanism of supercritical CO_2 pipeline to prevent and reduce the long-term crack propagation accident of supercritical CO_2 pipeline[1-3].

In view of the above problems, domestic and foreign scholars have carried out relevant research on the fracture of supercritical CO_2 pipelines. In terms of experiments, since 2012, a total of 9 full-scale CO_2 pipeline burst tests [4-7] have been carried out. The test shows that the existing Battelle Two Curve Method (BTCM) is not applicable to CO_2 pipelines, and the correction coefficient needs to be used to predict the minimum toughness requirements for crack arrest. Taking the three full-scale tests carried out by the British National Grid company as an example, the first two full-scale dense-phase CO_2 pipeline burst tests used large-diameter thick-walled pipeline steel. The test shows that the crack propagation and driving force of the two tests

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This is a paper for International CCUS Conference 2023 (ICCUSC2023), April 14-15, 2023, Beijing, China.

are higher than the predicted value. Even if the most conservative correction factor is used, the BTCM is still not conservative. The third full-scale test used pipes of different sizes. The test showed that the Battelle model can be corrected by empirical correction of the ratio of crack arrest pressure to saturation pressure. However, at present, the number of full-scale tests is small and the results are scattered, and the test cost of full-scale burst test is relatively high, the preparation period is long, and the repeatability is not strong. Therefore, the numerical simulation can make up for the situation that many working conditions cannot be obtained due to the small number of full-scale burst tests, and can analyze the crack propagation of the pipeline. In terms of simulation, Keim et al.[8] used the modified Bai-Wierzbicki model and GERG-2008 equation for numerical calculation in ABAQUS, and established a coupling model of pipeline deformation, gas decompression and crack propagation to judge the crack arrest of pipeline. At the same time, the influence of backfill soil on pipeline fracture is considered, and the law of pressure distribution after medium leakage in pipeline is shown, but the details of crack propagation are less described. Martynov et al.[9]established a dynamic fluid-solid coupling model of dense-phase and supercritical transport pipelines. The study pointed out that the presence of impurities will increase the difficulty of pipeline crack arrest, making the fracture propagation velocity and propagation distance more uncertain. Xu[10] used ANSYS to analyze the ductile crack propagation of supercritical CO_2 pipeline with impurities, and studied the influence of initial temperature, pressure and impurities, but did not consider the influence of cracks on pipeline fracture.

Based on this, the instrumented impact test is carried out and ABAQUS is used for inversion. The Cohesive Zone Model (CZM) is selected as the material model of the crack propagation area. The optimal model parameters are obtained by comparing the simulated and experimental curves through the trial algorithm. Based on the more accurate model parameters, the finite element model of supercritical CO_2 pipeline is established to simulate the crack propagation of supercritical CO_2 pipeline, and the influence of engineering parameters such as internal pressure, wall thickness and pipe diameter on the crack propagation velocity of pipeline is revealed.

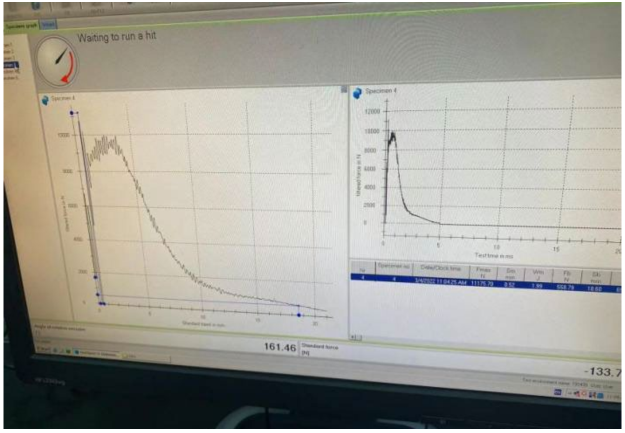
2. INSTRUMENTED IMPACT TEST

In order to obtain more accurate cohesion model parameters, the impact test analysis of X52 pipeline steel with small samples can be carried out to invert. Compared with the traditional impact test, the impact performance measured by the impact test is single, which can not be used as a toughness criterion to characterize the actual impact resistance of metal structures. The impact energy measured by the instrumented impact test can be divided into crack initiation energy and crack propagation energy, which can reflect the difficulty of crack formation and the toughness of the material. Therefore, the instrumented impact test is carried out. Because most of the cracks on the pipeline are longitudinal cracks, three sets of base metal transverse materials are selected for instrumented impact test to study the fracture toughness of X52 pipeline steel.

2.1 Sample preparation and process

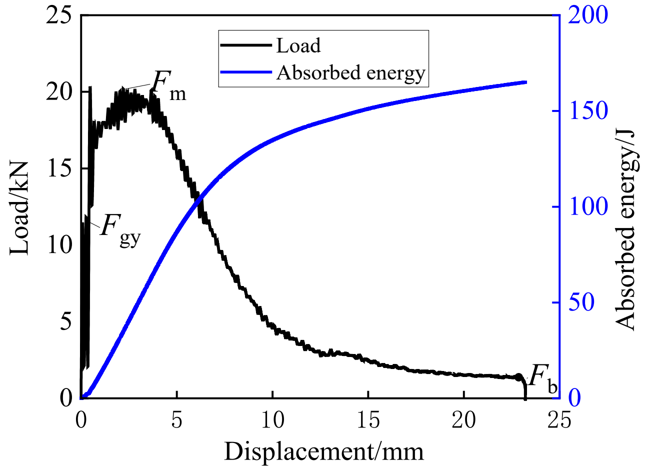
The test material is ϕ 323.9 × 8.7 mm, L360M, X52 steel grade pipeline. The impact sample is intercepted in the transverse direction of the base metal, the geometric size is 10 × 10 × 55 mm, and the test temperature is -30°C. The PSW1000 instrumented impact tester is used to test according to GB / T229-2020 " Metallic materials—Charpy pendulum impact test method"[11]. The test sample is put into the impact notch projector to

(a) Instrumented impact test

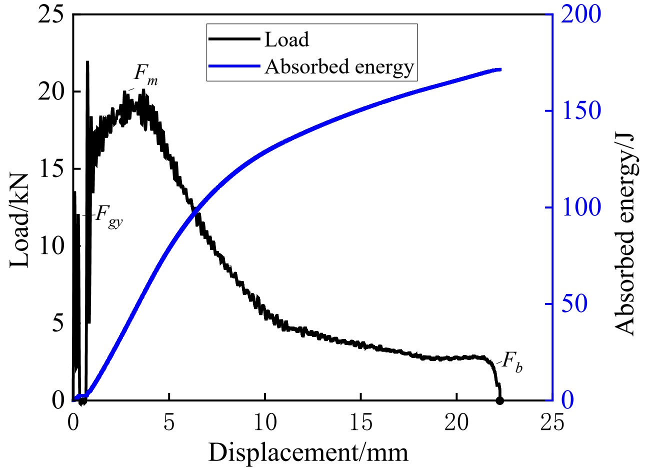


（b） Results

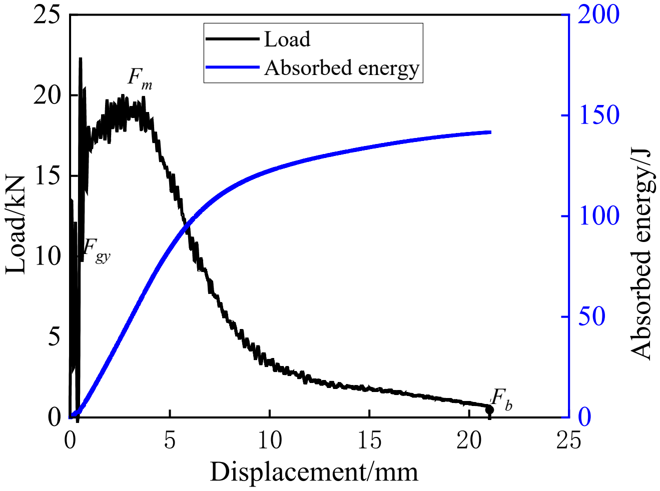
Fig. 1 Instrumented impact test and results make a notch, and then the sample is put into the instrument to cool down. After the temperature of the test sample drops to the required temperature, the impact range of the instrumented impact tester is set up to change the weight and pre elevation angle of the pendulum, and an empty pendulum is carried out. Finally, the refrigerated sample is put into the test machine to carry out the instrumented impact test. After the test is completed, the fracture of the sample is observed and the chart output by the software is read.



（a） Material 1



（b） Material 2



（c） Material 3

Fig. 2 Load-displacement curve and absorbed energy curve of X52 pipeline

2.2 Test result

As shown in Fig. 2, as far as the load is concerned, the fracture process of the sample is that the deformation displacement of the sample increases with the increase of the load, and the crack begins to expand after reaching the maximum load, forming the whole process of impact fracture. In terms of energy, the area enclosed by the instrumented impact curve, that is, the total energy, includes crack formation energy and crack propagation energy. The crack formation energy reflects the difficulty and velocity of crack formation, depending on the amount of bonding force between the atoms of the material. The crack propagation energy reflects the velocity of crack propagation of the sample with a specific crack under the action of impact force, and characterizes the ability to prevent crack propagation. The impact toughness mainly depends on the crack propagation energy. For these three groups of samples, it can be seen that their maximum load and maximum load displacement are not much different, and their impact curve types belong to plastic deformation before the maximum force, and then only stable expansion occurs. From the table, it can be seen that the crack propagation energy of material 1 is the largest, the crack propagation is relatively slow, that is, the toughness of the material is the best, and the crack propagation energy of material 3 is the smallest, because when the material produces cracks, the crack is most likely to expand. In order to make the results more conservative, the load-displacement curve of material 3 is selected as the inversion verification curve.

3. DETERMINATION OF CZM PARAMETERS

The method of determining the constitutive parameters of the CZM includes the experimental determination of the critical fracture energy of the Cohesive element and the finite element inversion curve. In this study, ABAQUS is used to establish the inversion model of the test to obtain the load displacement curve, which is compared with the results obtained from the test to calibrate the CZM. The fracture parameters can be used for pipeline fracture.

3.1 Cohesive Zone Model

When the crack-containing object is loaded, there will be a small damage zone surrounded by the upper and lower micro crack surfaces at the crack tip, that is, the cohesive zone. Because the distance between the upper and lower crack surfaces is very small, there is a molecular or atomic voluntary interaction force on the upper and lower surfaces of the cohesive zone, that is, the cohesive force. The size of the cohesive force is related to the opening displacement of the upper and lower crack surfaces. As shown in Fig. 3, the simplified model of the cohesive zone at the crack tip can be seen. The right side of the crack is the cohesive zone at the crack tip. The cohesive force model takes the cohesive force as the control parameter of crack propagation. The crack propagation is a gradual process. When the cohesive force is large, the crack does not expand, and the crack surface gradually separates when the cohesive force is small. When the cohesive force is reduced to zero, the crack propagation is realized[12].

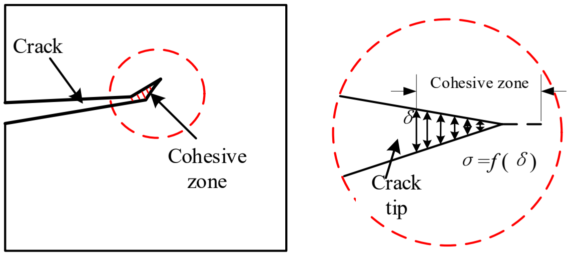


Fig. 3 The schematic diagram of cohesion and opening of cohesive force unit

In order to represent the combined effect of the entire damage and various mechanisms in the material, the damage index D is used to represent the average overall damage at the intersection of the crack surface and the edge of the crack component. Initially, D = 0. When the cohesive element satisfies the condition of damage generation, D monotonically increases from 0 to 1 when further loading after the damage begins. In order to describe the damage evolution under the combination of normal and shear separation across the interface, effective separation is defined as follow.

$$\delta_{\max}=\sqrt{(\delta_{\mathrm{n}})^2+\delta_s^2+\delta_t^2} \qquad (1)$$

For the damage variable D, the exponential model is used to describe its evolution, namely

$$D=\int_0^{\delta_{\max}}\frac{t_{\max}}{\Gamma}d\delta \qquad (2)$$

Among them, t_{max} represents cohesive stress, δ_m represents finite displacement, and Φ^c represents cohesive energy. When the supercritical CO_2 pipeline is under pressure, the main stress is the circumferential stress, which is perpendicular to the surface of the CZM. Therefore, it is feasible to simulate the crack propagation of CO_2 pipeline by this method.

From the above, it can be seen that in the CZM, the three most important material parameters are the cohesive stress t_{max}, the finite displacement δ_m and the cohesive energy Φ^c, and the relationship between the three parameters is as follows. As long as any two of the three parameters are determined, the constitutive relationship of the model can be determined.

$$\Phi^c=\int t d\delta=\int f(\delta)d\delta \qquad (3)$$

There are many forms of constitutive relations of Cohesive element, such as linear, exponential and trapezoidal constitutive relations. In this paper, linear constitutive and trapezoidal constitutive are used for inversion. The results are compared with the results of oscilloscope impact test to obtain the most reasonable CZM parameters.

The meaning of linear constitutive parameters and trapezoidal constitutive parameters is shown in Fig. 4 :

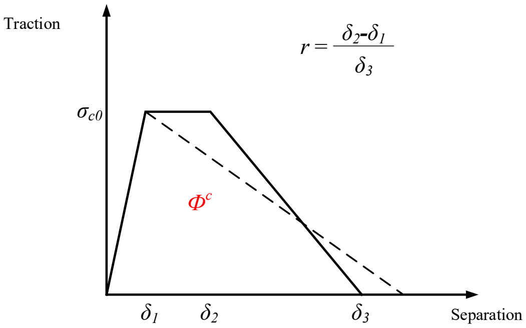


Fig. 4 CZM constitutive

In the figure: σ_{c0}—damage maximum traction, MPa ; k—stiffness, N/mm^3 ; Φ^c—fracture energy, MPa·mm; δ_1 is the initial displacement of damage, mm, $\delta_1=\sigma_{c0}/k$; δ_2 is the displacement of damage evolution stage, mm, $\delta_2=\delta_1+r\delta_3$; δ_3 is the displacement at the end of damage, mm, $\delta_3=2\cdot\Phi^c/((1+r)\ \sigma_{c0})$. Among them, r = 0 is a linear constitutive, and r belongs to (0,1] is a trapezoidal constitutive.

3.2 Finite element model

In order to obtain the appropriate CZM parameters, based on the instrumented impact test, ABAQUS is used for inversion analysis, and the unknown parameters of the numerical model are continuously adjusted to update and optimize until the optimized parameters converge, so as to ensure that the simulation results are close to the test results to the greatest extent.

The model uses ABAQUS to invert the instrumented impact test. The model consists of four parts, namely a pendulum, two supports and an instrumented impact sample. The pendulum and the support are set as rigid bodies, and the sample is set as a deformable body. Fig. 5 shows the finite element mesh of the sample and the composition view of the model, that is, the sample is placed on the support and impacted by the pendulum. Considering the stress concentration in the notch crack area, the transition grid division is used to encrypt it, and the transition grid division is also performed at the contact position between the sample and the support. In addition, Coulomb law is set to define the contact relationship between the pendulum, the sample and the support, and the downward displacement of the pendulum is set to simulate the impact process. The pendulum can only move vertically, the support is fixed, and the explicit analysis step is used for analysis.

3.3 Constitutive parameter inversion analysis

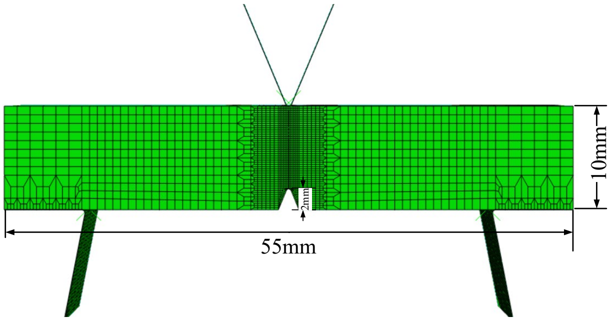


Fig. 5 Instrumented impact model

There are three parameters that affect the linear constitutive of the CZM in the material parameters, which are the loss of initial stress, failure displacement and stiffness. Due to the uncertainty of the constitutive parameters of the CZM, it is necessary to invert the parameters of the CZM. Through batch calculation and comparative analysis of the results, the working conditions with the smallest error are obtained, which provides more accurate parameter values for the subsequent crack propagation model of supercritical carbon dioxide pipeline.

The test results of X52 steel base metal transverse material 3 are selected. Since the definition of the shape of the Cohesive trapezoidal constitutive parameter shape needs to be determined by the stiffness of the material, the initial damage stress, the fracture energy of the material and the shape parameter, where the fracture energy of the material represents the total area of the trapezoid. The stiffness of the material determines the left waist slope of the trapezoid, the initial damage stress determines the height of the trapezoid, and the shape parameter determines the ratio of the upper and lower bottoms of the trapezoid. The coordinates of each point of the trapezoid are input into the model parameters, and the load-displacement curve obtained by the simulation is compared with the results obtained by the test. By continuously modifying the shape of the trapezoid, the working condition with the smallest error is analyzed, which provides a more accurate parameter value for the subsequent supercritical carbon dioxide pipeline crack propagation model. In Fig. 6, it can be seen that when the material stiffness is 1000 N/mm^3, the initial damage stress is 700 MPa, the material fracture energy is 1986.18 MPa·mm, and the shape parameter is 0.5, the error is the smallest.

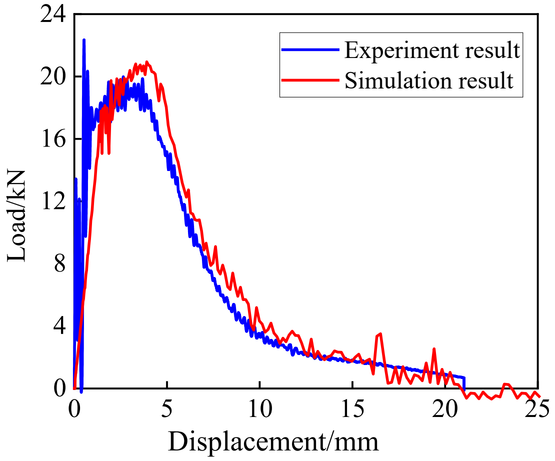


Fig. 6 The comparison of load displacement curves between simulation results and test results

Comparing the load-displacement curves obtained by the linear constitutive and trapezoidal constitutive simulation of the CZM with the experimental data, it is found that the results of the trapezoidal constitutive simulation of the CZM are closer to the experimental data and the error is smaller. Because the whole process is a dynamic simulation, the data has experienced a slight fluctuation trend, but the overall trend is consistent, and the instrumented impact test can describe the fracture behavior under dynamic load. Therefore, the crack propagation model of supercritical CO_2 pipeline is simulated by using the trapezoidal constitutive parameters of CZM.

4. RESULTS CRACK PROPAGATION SIMULATION ANALYSIS OF SUPERCRITICAL CO_2 PIPELINE

Based on the damage evolution of materials, Cohesive Zone Model controls crack propagation and can deal with the problem of ductile fracture of metals. The instrumented impact test can describe the fracture behavior under dynamic load, so the CZM parameters obtained by the inversion of the instrumented impact test can be input into the crack propagation model of the supercritical CO_2 pipeline as the crack region parameters for calculation.

4.1 Section of material and methods Establishment of pipeline model

In this section, the crack propagation model of supercritical CO_2 pipeline is calculated based on the CZM. Some simplifications are made in the modeling: the crack bending is not considered. The axial crack is considered to propagate along the axial predetermined path under internal pressure. At the same time, it is assumed that the material is an ideal elastic-plastic material independent of strain rate, and the effect of strain rate on crack dynamic propagation is not considered. Moreover, because the main stress is circumferential stress when the pipeline is compressed, and the circumferential stress is perpendicular to the surface of the CZM, it is feasible to use the CZM to simulate the crack propagation of the pipeline. In order to observe the process of crack propagation more intuitively, ABAQUS is used to establish a 1/2 model of the axial center penetrating crack of the pipeline. The crack is located in the right end of the model. The crack propagation direction along the axial path is established to simulate the crack propagation under the prefabricated path, and a 0-thickness Cohesive surface is inserted into the crack propagation plane.

Fig. 7 Geometric model of supercritical CO_2 pipeline

In the simulation, in order to prevent the pipeline model from moving in the coordinate axis direction, a fixed constraint is set on one end of the pipeline, and a Z-symmetry constraint is set on the end of the initial crack. At the same time, in order to meet the supercritical transportation of CO_2, the pressure of CO_2 in the pipeline must be kept above the critical pressure (7.38 MPa). Therefore, the high pressure inside the pipeline has a huge impact on the safe operation of the pipeline. Pressure is applied to the inner wall of the pipeline to simulate the working pressure of the pipeline. Since the propagation path of the crack on the pipeline is the focus of the analysis, it is necessary to subdivide the grid in the area near the crack propagation path. Therefore, the crack propagation surface is the center, and the minimum grid size of the ligament zone unit is 0.1 mm. The mesh of other areas is divided into coarse grids, and the two-area grids are divided into transitional grids, which not only ensures the accuracy of the calculation, but also saves the calculation time.

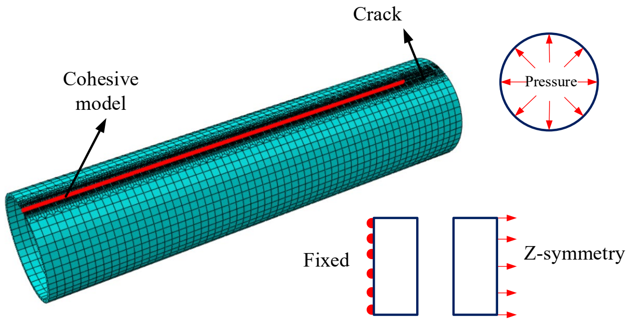


Fig. 8 Meshing and load boundary of supercritical CO_2 pipeline

4.2 Result analysis

ABAQUS cannot directly output the crack propagation velocity, but the crack propagation distance corresponding to different times can be obtained. By capturing the change of crack propagation length (the axial distance between the crack tip position and the initial prefabricated crack tip) with time, the change curve of crack propagation distance can be obtained, and the change rate of crack propagation distance to time is the crack propagation velocity.

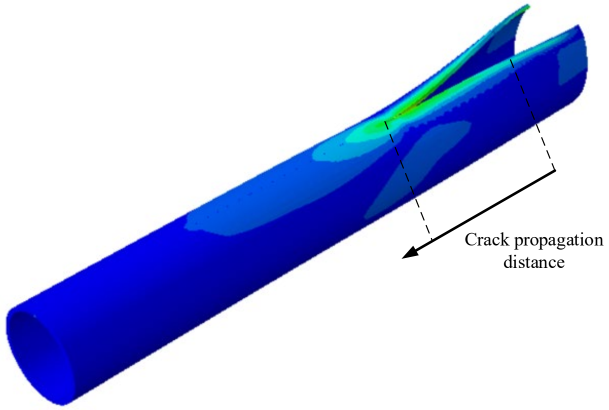
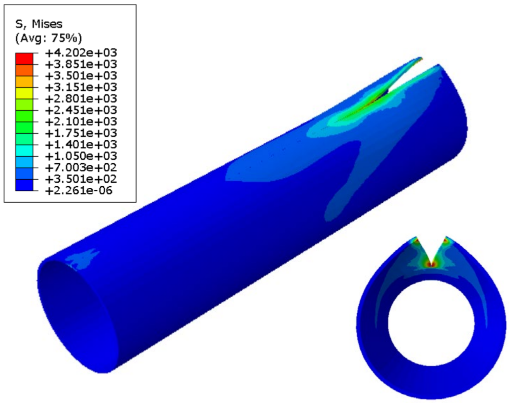
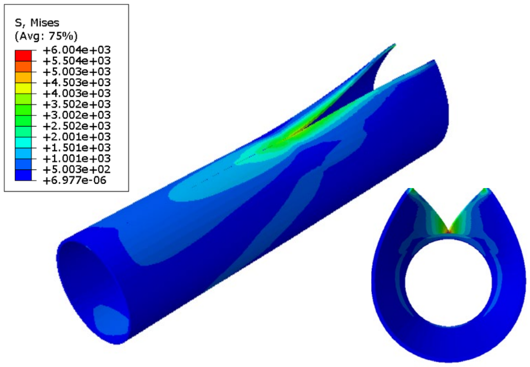


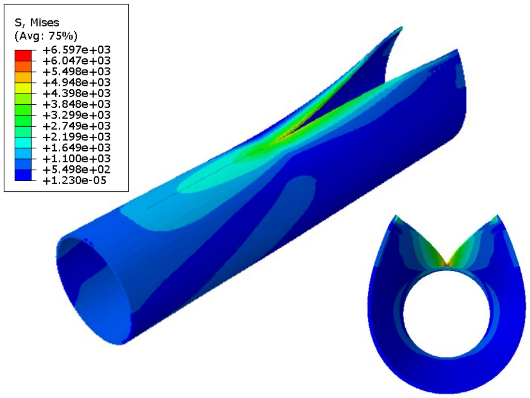
Fig. 9 Crack propagation distance of supercritical CO_2 pipeline



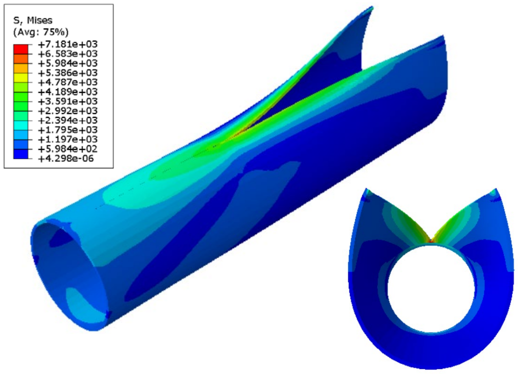
(a) 10MPa



(b) 12MPa



(c) 14MPa



(d) 16MPa

Fig. 10 Stress of pipeline under different pressures

The change of equivalent stress of supercritical CO_2 pipeline under different internal pressure is shown in Fig. 10. It can be seen from the equivalent stress cloud diagram that under the action of internal pressure, the stress of the pipeline is higher near the crack and its propagation path, and the equivalent stress is smaller in other areas. With the increase of internal pressure, the maximum equivalent stress of the pipeline increases significantly, indicating that the pipeline is prone to stress concentration when the pressure increases, and the maximum equivalent stress of the pipeline is located at the inner wall of the crack tip, that is, the influence of the internal pressure of the pipeline on the inner wall of the pipeline is greater than that of the outer wall of the pipeline. When the crack propagation is simulated by the CZM, when the crack tip stress reaches the damage condition of the material, the crack propagation makes the damage transfer to the next node, thus avoiding the large area yield at the crack tip, which can limit the stress concentration at the crack tip within a certain range.

4.3 Analysis of influencing factors

4.3.1 Internal pressure

A cracked pipe with *D* = 377 mm and *t* = 10 mm is established. The internal pressures are 8 MPa, 10 MPa, 12 MPa, 14 MPa and 16 MPa, respectively. The variation of crack propagation length with time is shown in Fig. 11. It can be seen that the crack propagation length increases with time under different internal pressure loading. Under the load of 8~16 MPa, the slope of crack propagation length increases significantly from the initial time, and then the slope remains stable, that is, the crack propagation velocity is a process from acceleration to stability.

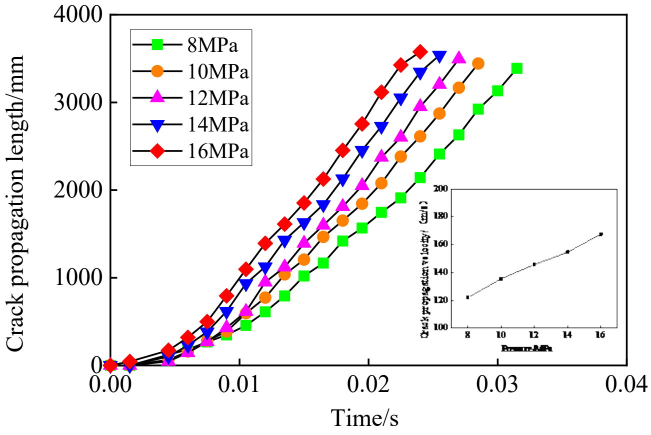


Fig. 11 Crack propagation length curves under different internal pressures

The steady-state crack propagation velocity corresponding to these internal pressures is shown in Fig. 11. It can be seen that the steady-state crack propagation velocity is positively correlated with the internal pressure, and as the internal pressure increases, the crack propagation velocity will converge.

4.3.2 Wall thickness

The crack-containing pipeline with D = 377 mm and P = 14 MPa is established, and the wall thickness are 9 mm, 10 mm, 11 mm and 12 mm respectively. The variation of crack propagation length with time is shown in Fig. 12. It can be seen that under different wall thickness conditions, the crack propagation length increases with time, and for the same crack propagation length, with the increase of wall thickness, the longer the time to reach this length, that is, the thicker the wall thickness, the slower the crack propagation.

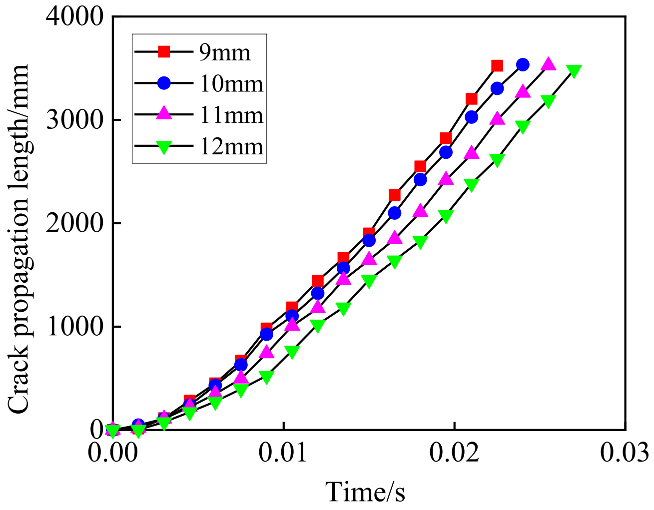


Fig. 13 Crack propagation length curves under different thickness

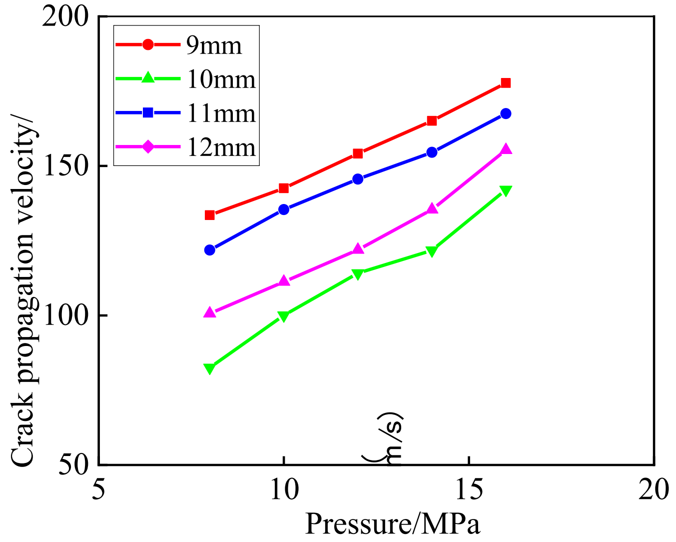


Fig. 12 Crack propagation velocity curves under different wall thicknesses and pressures

It can be seen from Fig. 12 that the crack propagation velocity first passes through an acceleration stage, and then the crack propagation velocity accelerates into the steady-state stage. The steady-state crack propagation velocity corresponding to wall thicknesses is shown in Fig. 13. It can be seen that the steady-state crack propagation velocity is negatively correlated with the wall thickness. Therefore, for a given gas composition, pressure, and temperature conditions, the driving force of crack propagation decreases with the increase of wall thickness, and the corresponding crack arrest toughness decreases, that is, increasing the wall thickness is beneficial to the crack arrest of the pipeline.

4.3.3 Pipe diameter

A crack-containing pipeline with t = 9 mm and P = 16 MPa is established, and the pipe diameters are 219 mm, 323 mm, and 377 mm, respectively. The variation of crack propagation length with time is shown in Fig. 14. It can be seen that under different pipe diameters, the crack propagation length increases with time, and at the same time, as the pipe diameter increases, the crack propagation distance is longer, that is, the larger the pipe diameter, the faster the crack propagation, and the supercritical CO_2 pipeline cracks are more prone to long-range propagation.

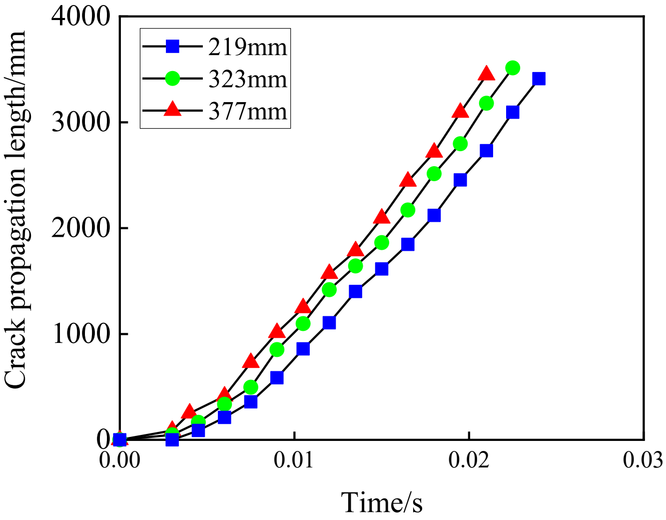


Fig. 14 Crack propagation length curves under different diameters

The steady-state crack propagation velocity corresponding to the pipe diameters is shown in Fig. 15. It can be seen that the crack propagation velocity curve moves downward in the coordinate system, that is, the steady-state crack propagation velocity is positively correlated with the pipe diameter, that is, the crack propagation velocity increases with the increase of the pipe diameter. Therefore, for a given gas composition, pressure, and temperature conditions, the driving force of crack propagation will increase with the increase of pipe diameter. It is necessary to improve the crack arrest toughness of the pipeline to ensure that the pipeline can achieve crack arrest within a limited length.

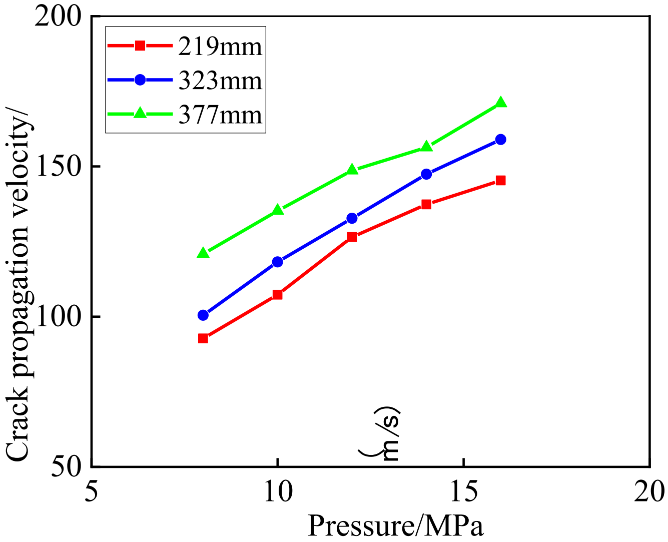


Fig. 15 Crack propagation velocity curves under different diameters and pressures

5. CONCLUSIONS

The load-displacement curve of X52 steel is obtained by the instrumented impact test, and the finite element model is established for inversion. The more accurate CZM parameters are obtained comparison experiment and the simulation curve. The material parameters are input into the crack area, and the finite element model of crack propagation in supercritical CO_2 pipeline is established. The crack propagation length and velocity of pipeline under different influencing factors are calculated and analyzed. The results show that:

(1) The instrumented impact test is carried out on the transverse material of the base metal of X52 pipeline steel. The crack propagation energy can characterize the crack propagation ability of the material structure. It is found that the crack propagation energy of material 1 is the largest and the crack propagation is relatively slow, that is, the toughness of the material is the best, while the crack propagation energy of material 3 is the smallest.

(2) The CZM parameters are calibrated by establishing the finite element model to invert the instrumented impact test. The linear constitutive and trapezoidal constitutive are compared. It is found that the results obtained by the trapezoidal constitutive simulation are consistent with the overall trend of the test results. When the material stiffness is 1000 N/mm^3, the initial damage stress is 700 MPa, the material fracture energy is 1986.18 MPa·mm, and the shape parameter is 0.5, the error is the smallest.

(3) By establishing the crack propagation model of supercritical CO_2 pipeline, the effects of internal pressure, wall thickness and pipe diameter on the crack propagation length and velocity are analyzed. It is found that under the given gas composition, pressure and temperature conditions, with the increase of internal pressure, the decrease of wall thickness and the increase of pipe diameter, it is necessary to improve the crack arrest toughness of the pipeline to ensure that the pipeline can achieve crack arrest within a limited length.

ACKNOWLEDGEMENT

This research has been co-financed by National Key R&D Program of China (Grant No.2022YFC3070100), Natural Science Foundation of China (Grant No. 52004314), Young Elite Scientists Sponsorship Program by Beijing Association for Science and Technology (Grant No. BYESS2023261), the Science and Technology Research Project of Pipechina (Grant No. WZXGL202105), the Science and Technology Research Project of Pipechina (Grant No. WZXGL202104), Science Foundation of China University of Petroleum, Beijing (No.2462023BJRC005).

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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