

Article

Hydrogen Diffusion Behavior of Steel-Wire-Reinforced Thermoplastic Pipes with Stress–Hydrogen Coupled Finite Element Method

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Abstract

Hydrogen embrittlement of the steel reinforcement layers poses a critical threat to the safe operation of steel-wire-reinforced thermoplastic pipes (SRP) in hydrogen transport. However, the mechanisms governing hydrogen diffusion in SRP under stress conditions remain poorly understood. This study develops a two-dimensional finite element model based on the theory of hydrogen diffusion under stress conditions. The model systematically examines the influence of four parameters on hydrogen diffusion in SRP: hydrogen pressure (1–20 MPa), steel wire diameter (1.0–2.0 mm), radial distance from the steel wire layer to the inner pipe wall (3.2–4.8 mm), and steel wire winding angle (8–15°). The key findings are as follows: (1) Increasing hydrogen pressure proportionally accelerates hydrogen diffusion and raises the local hydrogen concentration around the steel wires, thereby promoting hydrogen-induced crack initiation. (2) The effect of steel wire diameter is non-monotonic. Increasing the diameter from 1.0 mm to 1.2 mm lengthens diffusion paths and suppresses the local hydrogen concentration, whereas a further increase to 2.0 mm intensifies steric hindrance and hydrogen retention. Optimal hydrogen barrier performance is achieved at diameters of 1.2–1.4 mm. (3) Increasing the radial distance from the steel wire layer to the inner pipe wall strengthens the hydrogen concentration gradient across the inner and outer high-density polyethylene layers. This accelerates hydrogen diffusion and reduces the hydrogen concentration adjacent to the wires. (4) A winding angle of 9–10° minimizes the hydrogen concentration within the steel wire layer, thereby significantly improving resistance to hydrogen embrittlement. These findings elucidate the mechanisms governing hydrogen diffusion in SRP and provide quantitative design guidelines for mitigating hydrogen-induced damage in composite pipeline systems.

Keywords: hydrogen embrittlement; steel-wire-reinforced thermoplastic pipes (SRP); FEM; hydrogen diffusion



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1. Introduction

With global energy demand continually rising, the safe operation of oil and gas transmission pipelines faces increasingly severe challenges [1–4]. Traditional carbon steel

pipelines are highly susceptible to corrosion-induced leakage in aggressive environments, a vulnerability that has severely constrained the development of oil and gas resources. Statistics indicate that corrosion accounts for over 60% of pipeline failures in the oil and gas industry [5–8]. In this context, non-metallic composite pipes, particularly steel-wire-reinforced thermoplastic pipes (SRP), have emerged as a promising alternative [9,10]. These pipes feature a unique metal–polymer hybrid structure that combines excellent corrosion resistance with high pressure-bearing capacity. Moreover, their flexible nature enables coiled transportation and rapid installation, reducing overall construction costs by more than 30% [11–13]. Nevertheless, recent field experience has revealed that hydrogen embrittlement of the steel wire reinforcement layer is becoming a critical technical bottleneck that hinders the large-scale deployment of SRP [14,15].

An SRP typically comprises inner and outer high-density polyethylene (HDPE) protective layers, a spirally wound galvanized steel wire mesh skeleton, and interfacial bonding layers [16,17]. Although the HDPE layers effectively block external corrosive media, acidic components in oil and gas, such as H_2S and CO_2 , can still permeate through the intermolecular gaps of the polymer [18]. Experimental studies have shown that the permeation coefficient of HDPE for H_2S can reach $10^{-13} \text{ m}^2/\text{s}$ at 60°C [19]. Acidic components such as H_2S dissociate to produce hydrogen ions (H^+) in the presence of trace water, and these ions permeate through the HDPE layer to the steel wire surface, where they are reduced to atomic hydrogen. Atomic hydrogen then diffuses into the steel matrix and induces hydrogen embrittlement of the steel wire. More critically, the residual stress generated during pipe coiling and transportation can act synergistically with hydrogen embrittlement, accelerating the degradation of material properties.

Existing studies on SRP have predominantly focused on characterizing short-term mechanical properties. Zheng et al. [20,21] established a burst pressure–temperature correlation model and systematically analyzed the basic short-term mechanical properties of cross helically wound steel-wire-reinforced pipes. Bai et al. [22,23] proposed the combined bending–internal pressure failure criterion and further clarified the mechanical response behavior of SRP under external pressure conditions. For the structural response under multi-factor coupling, the temperature–bending moment interaction law revealed by Shi et al. [17], and subsequent work by Shi et al. [24] extended the investigation to the mechanical properties of SRP under combined internal pressure and bending moment across various service temperatures. Scholars such as Longva and Yuan et al. [25,26] have started to examine the mechanical response during pipe coiling; however, systematic investigations of material degradation mechanisms under the synergistic effects of hydrogen permeation and stress are still lacking. Elkhodbia et al. [27] comprehensively evaluated the failure of steel-reinforced flexible thermoplastic composite pipes in H_2S -containing acidic environments and attributed the failure to hydrogen embrittlement of the steel wires within the reinforcement layer.

Despite these advances, three critical knowledge gaps remain unsolved. First, existing SRP hydrogen embrittlement studies are mostly limited to post-failure phenomena analysis; no coupled model for hydrogen diffusion has been established for this metal–polymer composite structure to date, and the mechanisms of hydrogen migration and enrichment in HDPE–steel wire multilayer structures remains unclear. Second, the quantitative influences of core design and service parameters hydrogen pressure, steel wire diameter, radial position of the steel wire layer, and winding angle on hydrogen concentration in the reinforcement layer have not been systematically explored, leaving the underlying regulatory mechanisms unknown. Third, there is a lack of quantitative design guidelines for mitigating SRP hydrogen embrittlement through structural optimization, which cannot support the safe engineering application of SRP in hydrogen transport [28].

To fill these gaps, this study develops a two-dimensional finite element model of SRP based on stress-assisted hydrogen diffusion theory, and systematically investigates hydrogen diffusion behavior and concentration distribution under stress conditions. This work advances the state of the art in three core aspects. It first establishes a hydrogen diffusion coupling model tailored to SRP composite structures under stress conditions, which incorporates normalized concentration continuity and diffusion flux continuity at the steel–HDPE heterogeneous interface to enable accurate simulation of hydrogen transport in multilayer composite pipes. On this basis, it quantitatively characterizes the effects and underlying mechanisms of four key parameters hydrogen pressure (1–20 MPa), steel wire diameter (1.0–2.0 mm), radial distance from the steel wire layer to the inner wall (3.2–4.8 mm), and winding angle (8–15°) on hydrogen concentration and diffusion flux. The study further identifies optimal structural parameter intervals that minimize hydrogen concentration in the steel wire layer, providing quantitative theoretical guidance for the hydrogen embrittlement resistance design and safe operation of hydrogen-transport SRP.

2. Governing Equations

2.1. Governing Equation for Hydrogen Diffusion

Hydrogen diffusion in SRP is simulated using the mass diffusion model. The mass diffusion governing equation, an extension of Fick's law, accounts for the non-uniform solubility of hydrogen in the base material. The basic variable is the normalized concentration, which serves as the nodal degree of freedom and is defined as $\Phi = c/s$, where c is the mass concentration of hydrogen and s is its solubility in the base material. Consequently, the normalized concentration remains continuous across material interfaces [29].

First, hydrogen diffusion follows the law of mass conservation [30]:

$$\frac{\partial C}{\partial t} + \nabla \cdot J = S \quad (1)$$

where J is the diffusion flux, S is the source term ($S = 0$ in the absence of an external hydrogen source), t is the hydrogen diffusion time, and C is the total hydrogen concentration.

$$C = C_L + C_T \quad (2)$$

where C_L and C_T denote the diffusible and trapped hydrogen concentrations, respectively. Since no external hydrogen source is considered, the mass conservation equation reduces to:

$$\frac{\partial C}{\partial t} + \nabla \cdot J = 0 \quad (3)$$

To model stress-assisted hydrogen diffusion, Fick's law is extended to incorporate both the concentration gradient and the stress gradient. Hence, the expression for the diffusion flux J is:

$$J = -D \nabla C_L + \frac{D C_L V_H}{RT} \nabla \sigma_H \quad (4)$$

where D , V_H , R , T , and σ_H denote the diffusion coefficient, partial molar volume of hydrogen, gas constant, absolute temperature, and hydrostatic stress, respectively. Combining the mass conservation equation with the modified diffusion flux yields the governing equation for hydrogen diffusion:

$$\frac{\partial (C_L + C_T)}{\partial t} = \nabla \cdot \left[D \left(\nabla C_L - \frac{C_L V_H}{RT} \nabla \sigma_H \right) \right] \quad (5)$$

2.2. Mass Conservation Across Material Interfaces

At the interface between the steel wire layer and the high-density polyethylene layer in the steel-wire-reinforced thermoplastic pipes, the hydrogen diffusion behavior must satisfy the following conditions:

- (1) Continuity of normalized concentration:

According to the Larche-Cahn theory [31], hydrogen activity (i.e., normalized concentration) remains continuous across the interface:

$$\Phi_1 = \Phi_2 \Rightarrow \frac{c_1}{s_1} = \frac{c_2}{s_2} \quad (6)$$

where Φ_1 and Φ_2 are the hydrogen activities in the steel wire and HDPE, respectively; s_1 and s_2 are the hydrogen solubility coefficients in the steel wire and HDPE, respectively; and c_1 and c_2 are the hydrogen concentrations in the steel wire and HDPE, respectively. This condition ensures chemical potential equilibrium across the interface and serves as the core constraint for modeling hydrogen diffusion across dissimilar materials.

- (2) Continuity of diffusion flux:

Mass conservation requires that the normal component of the diffusion flux be continuous across the interface [32]:

$$J_1 \cdot n = J_2 \cdot n \quad (7)$$

where J_1 and J_2 are the hydrogen diffusion fluxes in the steel wire and HDPE, respectively, and n is the outward normal to the interface. Combining this continuity condition with the modified Fick's law (Equation (4)) yields:

$$\left[D_1 \left(\nabla C_{L1} - \frac{C_{L1} V_H}{RT} \nabla \sigma_{H1} \right) \right] \cdot n = \left[D_2 \left(\nabla C_{L2} - \frac{C_{L2} V_H}{RT} \nabla \sigma_{H2} \right) \right] \cdot n \quad (8)$$

This expression captures the effect of abrupt changes in the diffusion coefficient D and stress gradient $\nabla \sigma_H$ at the interface on the diffusion flux.

- (3) Treatment of hydrogen diffusion under stress condition at the interface:

The hydrostatic stress σ_H is coupled to the hydrogen concentration field through the Sofronis–McMeeking model [33]:

$$\sigma_H = \frac{1}{3} \text{tr}(\sigma) + \frac{E V_H C_L}{3(1-\nu)} \quad (9)$$

where E is the elastic modulus, ν is Poisson's ratio, $\text{tr}(\sigma)$ is the trace of the stress tensor, and σ denotes the stress tensor. This model integrates hydrogen concentration into the stress calculation, while displacement and stress continuity across the interface are enforced through the mechanical equilibrium equations.

2.3. Governing Equation for Hydrogen Diffusion in the Composite Material

Combining Equations (5)–(9) and incorporating the interfacial Dirac delta function δ_Γ yields the governing equation for hydrogen diffusion in the composite material:

$$\frac{\partial(C_L + C_T)}{\partial t} = \nabla \cdot \left[D \left(\nabla C_L - \frac{C_L V_H}{RT} \nabla \sigma_H \right) \right] + \delta_\Gamma \cdot \left[\frac{D_1 s_1}{s_2} \nabla C_{L2} - D_2 \nabla C_{L1} \right] \quad (10)$$

where D_1 and D_2 are the hydrogen diffusion coefficients in the steel wire and HDPE, respectively; C_{L1} and C_{L2} are the diffusible hydrogen concentrations in the steel wire and HDPE, respectively. The second term on the right-hand side accounts for the additional diffusion contribution arising from the discontinuity in material parameters across the interface.

3. Model Establishment

3.1. Geometric Model

The hydrogen diffusion model is presented in Figure 1. The model consists of high-density polyethylene (HDPE) layers and a steel wire layer, with the inner and outer layers being HDPE layers and the middle layer being the steel wire layer. The inner boundary of the inner layer serves as the hydrogen charging boundary, where hydrogen pressure is applied. The inner pipe diameter is set to 8 mm. The main dimensional parameters of the model were designed based on the steel-wire-reinforced thermoplastic pipes parameters studied by Shi et al. [24], as listed in Table 1.

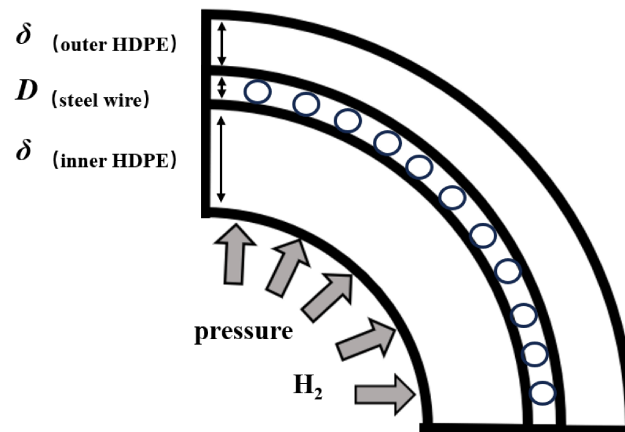


Figure 1. Hydrogen diffusion model.

Table 1. Model parameters [24].

Model	D (Steel Wire)/mm	δ (Inner HDPE)/mm	δ (Outer HDPE)/mm	Angle/ $^{\circ}$	Pressure/MPa
1	1.2	4.2	2.6	10	1/2/3/4/5/10/15/20
2	1.0/1.2/1.4/1.6/1.8/2.0	4.2	2.6	10	2
3	1.2	3.2/3.4/3.8/4.2/4.4/4.8	3.6/3.4/3.0/2.6/2.4/2.0	10	2
4	1.2	4.2	2.6	8/9/10/12/13/15	2

3.2. Model Assumptions

- (1) The material within each layer is assumed to be homogeneous, and the layers are perfectly bonded.
- (2) In SRP, the steel wire reinforcement layer is bonded to the inner and outer HDPE layers via a resin or hot-melt adhesive layer. The key properties of the bonding medium, including mechanical performance, hydrogen diffusion coefficient and hydrogen solubility, are on the same order of magnitude as those of the HDPE matrix. For simplicity, the bonding medium is idealized to adopt the material parameters of HDPE in the model.
- (3) This macroscopic model is established for general mechanistic analysis with corresponding simplifying assumptions. The galvanized zinc coating on steel wires is neglected, and general carbon steel parameters are adopted rather than the material data of a specific galvanized steel grade. Microscale grain boundary hydrogen diffusion and intergranular embrittlement are not included in the modeling framework.

3.3. Material Parameters

Based on previous studies, the material parameters used in the model are all widely recognized general properties for hydrogen diffusion simulation at the structural scale. The key hydrogen diffusion, solubility and mechanical parameters of steel wire and HDPE adopted in the simulation are systematically summarized in Table 2. It should be noted

that the hydrogen diffusion and solubility parameters adopted in the model are general properties of carbon steel rather than parameters of a specific steel grade, to suit the mechanistic parametric analysis of this work [30]. For the steel wire, the hydrogen diffusion coefficient D_1 and solubility s_1 are $1.97 \times 10^{-4} \text{ mm}^2/\text{s}$ and $3.88 \times 10^{-4} \text{ ppm}$, respectively. These values are general properties of carbon steel for stress-assisted hydrogen diffusion analysis, directly cited from our previous study [30], and are not tied to a specific steel grade or microstructure. The elastic modulus E_1 and Poisson's ratio ν_1 are $2 \times 10^5 \text{ MPa}$ and 0.3, respectively, which correspond to the typical mechanical properties of galvanized carbon steel wires commonly used in SRP reinforcement layers. For HDPE, the hydrogen diffusion coefficient D_2 and solubility s_2 are $0.032 \text{ mm}^2/\text{s}$ and 0.17 ppm, respectively, which are consistent with the molecular simulation results of hydrogen permeation behavior of common polymers reported by Zhang et al. [34]; the elastic modulus E_2 and Poisson's ratio ν_2 are 1439.7 MPa and 0.45, respectively, which are taken from the SRP mechanical parameter setting in the study by Shi et al. [24]. This set of general material parameters can accurately reflect the macroscopic influence law of structural and service parameters on hydrogen diffusion in SRP, and is fully applicable to the mechanism-oriented parametric analysis in this work.

Table 2. Material parameters.

Materials	$D \text{ (mm}^2/\text{s)}$	$s \text{ (ppm)}$	$E \text{ (MPa)}$	ν
Steel	1.97×10^{-4}	3.88×10^{-4}	2×10^5	0.3
HDPE	0.032	0.17	1439.7	0.45

3.4. Mesh and Boundary Conditions

The steel wire layer is discretized with two-dimensional triangular elements, and the inner and outer HDPE layers are meshed with quadrilateral elements, using a uniform element size of 0.4 mm. The resulting mesh is presented in Figure 2. All hydrogen diffusion simulations are carried out under the internal hydrogen pressure condition only, using three-node linear axisymmetric diffusion triangular elements (DCAX3) in a transient analysis. A constant hydrogen concentration of 10 mol/m^3 [35] (1.3 ppm) [36], corresponding to a hydrogen pressure of 2 MPa, is applied to the charging boundary, while a zero concentration is imposed on the hydrogen escape side.

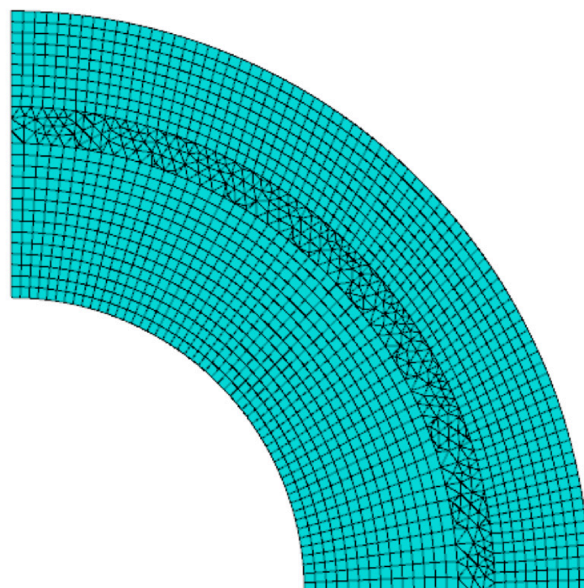


Figure 2. Mesh in the model.

3.5. Model Validation

First, to ensure that the numerical results are not affected by mesh density, a mesh sensitivity analysis was performed on the SRP model using the maximum hydrogen concentration during hydrogen diffusion, as shown in Table 3. As the mesh was refined, the maximum hydrogen concentration gradually stabilized, varying from 2.216×10^{-4} ppm to 2.233×10^{-4} ppm as the element number increased from 1922 to 7495, with a variation of approximately 0.8%, indicating adequate accuracy. Refining the mesh from 4352 to 7495 elements changed the result by only 0.18% (from 2.229×10^{-4} to 2.233×10^{-4} ppm) but substantially increased the computation time. The model with 1922 elements differed by only 0.76% from the 7495-element model while requiring much less computation time. Therefore, considering both efficiency and accuracy, the mesh with 1922 elements was ultimately adopted for the simulations.

Table 3. Results of mesh verification.

Mesh Quantity	720	1057	1922	4352	7495
Maximum hydrogen concentration (10^{-4} ppm)	1.832	2.197	2.216	2.229	2.233

The two-dimensional hydrogen diffusion finite element model developed in this study was validated against the mechanical behavior and failure modes reported by Bai et al. [22] from full-scale tests and finite element modeling of SRP under combined bending and internal pressure. The model geometry and loading configuration are illustrated in Figure 3. In the two-dimensional model, internal pressure is applied on the inner pipe wall, and the pre-applied bending moment is simulated via equivalent boundary loads on the outer pipe wall. Simulations were performed under various internal pressures, and the resulting change in pipe ovality was extracted. The ovality is calculated as follows:

$$Ovality = \frac{R_{\max} - R_{\min}}{R_{\max} + R_{\min}} \quad (11)$$

where $R_{\max}$ and $R_{\min}$ are the maximum and minimum diameters of the cross section, respectively.

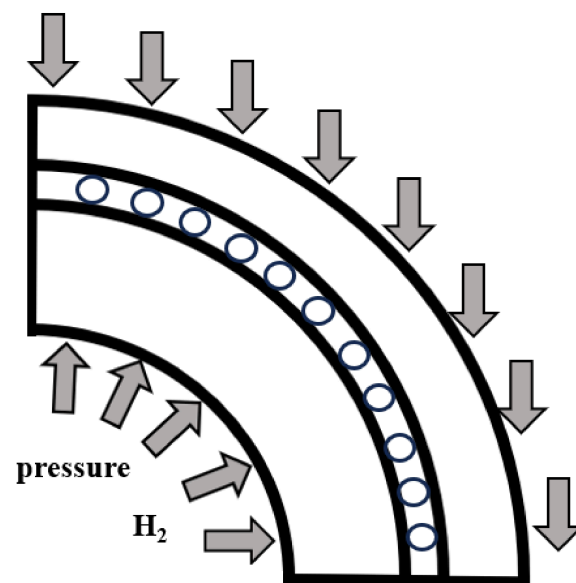


Figure 3. Mechanical verification model.

As shown in Figure 4, the ovality decreases gradually with increasing internal pressure and approaches zero. This indicates that internal pressure enhances the bending resistance of the pipe when it is subjected to curvature. These results agree well with those reported by Bai et al. [22], confirming that the mechanical behavior of the present model is consistent with the published findings. Furthermore, this study extends the hydrogen diffusion model developed in our previous study [30] for stress-driven diffusion in steel inclusions to SRP, thereby validating the two-dimensional SRP model.

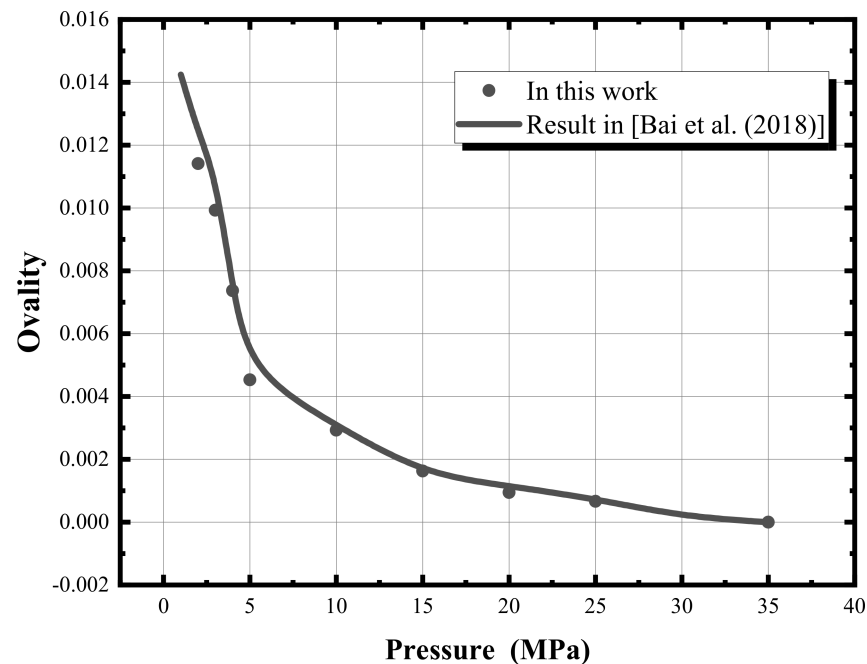


Figure 4. Comparison of the simulation in this work with the result in [22].

4. Results and Discussion

4.1. Effect of Hydrogen Pressure

The application of hydrogen pressure profoundly perturbs hydrogen diffusion within an SRP. In this context, the stress field distribution plays a decisive role in governing hydrogen migration and segregation. Figure 5 shows that, in the absence of stress, the hydrogen concentration exhibits a pronounced gradient. Figure 6 indicates that the maximum stress within the pipe occurs in the upper-middle region of the steel wire layer, forming a characteristic stress concentration zone. By examining the stress field distribution, this study elucidates the stress-driven evolution of hydrogen segregation.

Under hydrogen transport conditions, variations in internal pressure alter the stress state within the pipe, thereby modulating hydrogen diffusion in the SRP. This study simulates hydrogen diffusion through the pipe wall by applying hydrogen pressures of 1–20 MPa on the inner wall (equivalent to 0.65–13 ppm hydrogen concentration). Figure 7 shows pronounced hydrogen enrichment within the steel wire layer, with the peak concentration coinciding with the stress concentration zone. Compared with the stress-free diffusion case (Figure 5), the stress-coupled model yields a higher steady-state peak hydrogen concentration due to the stress gradient. This confirms that the presence of stress accelerates hydrogen diffusion and elevates the local hydrogen concentration. Figure 8 shows that the hydrogen concentration at the steel wire–HDPE interface increases linearly as hydrogen pressure rises from 1 to 20 MPa. Under high pressure, hydrogen atoms preferentially segregate at stress concentration sites, forming high-concentration traps. This accumulation exacerbates hydrogen-induced damage. This synergistic effect increases the material's

susceptibility to hydrogen embrittlement with rising hydrogen pressure, promoting crack initiation and propagation and ultimately degrading mechanical properties.

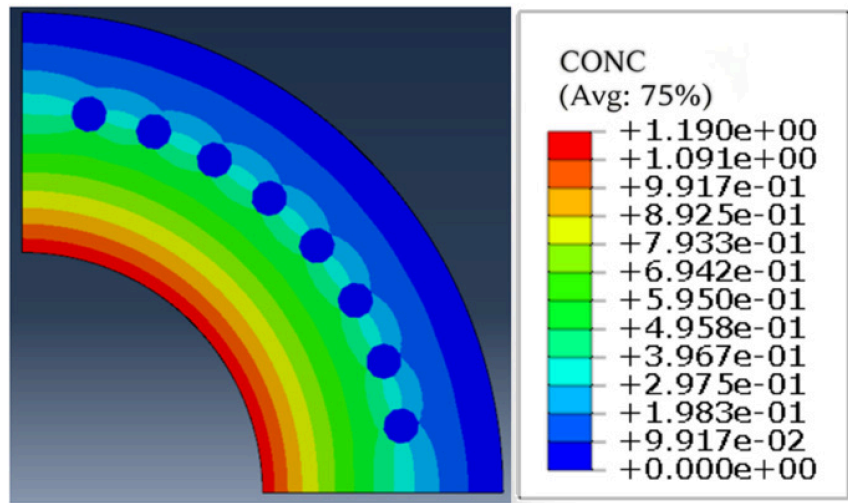


Figure 5. Hydrogen distribution without stress conditions.

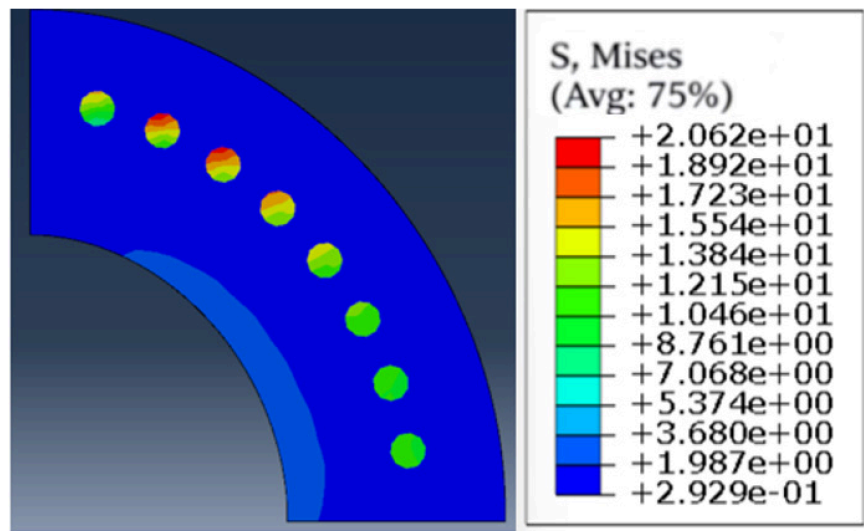


Figure 6. Stress distribution in SRP under stress conditions.

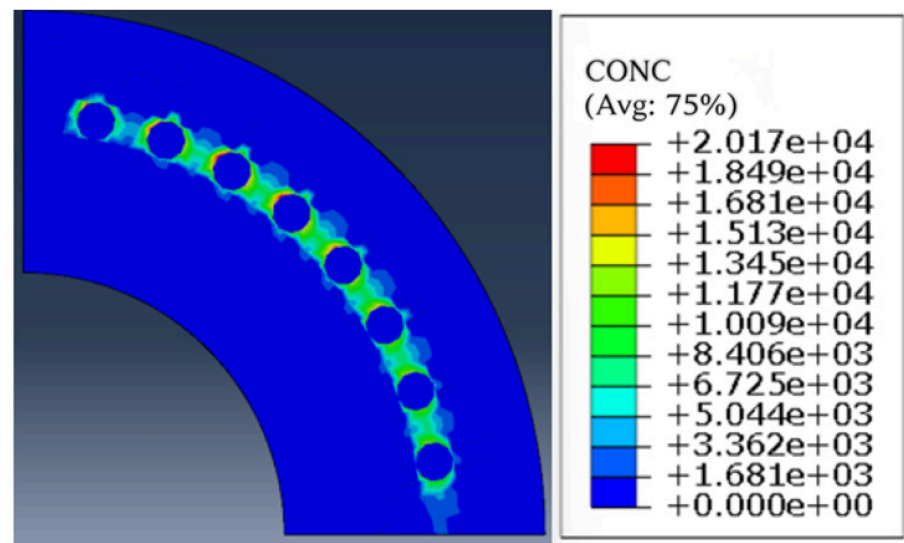


Figure 7. Hydrogen distribution under stress conditions.

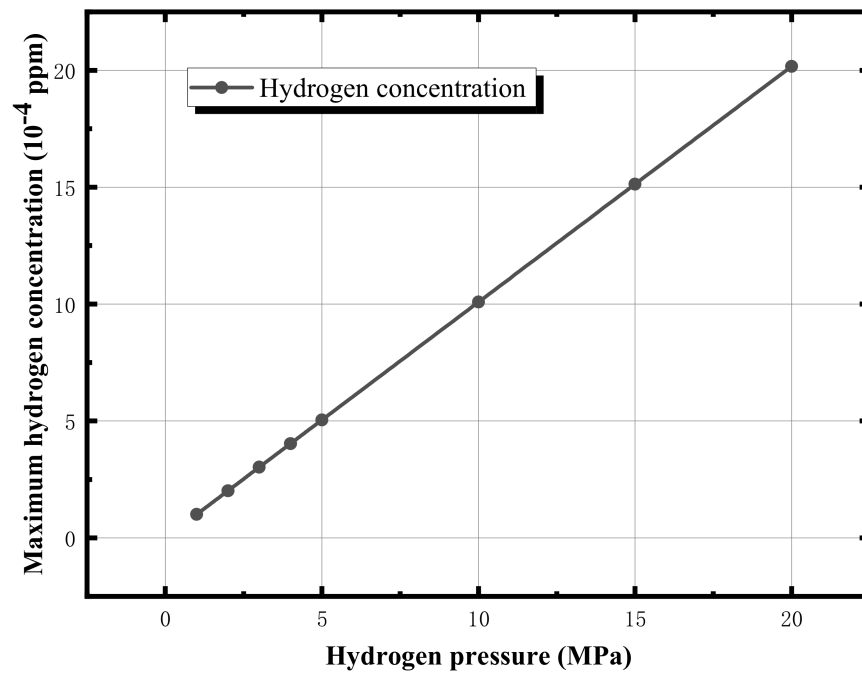


Figure 8. Relationship between hydrogen pressure change and the maximum hydrogen concentration.

4.2. Effect of the Steel Wire Diameter

In an SRP, the steel wire layer is embedded between the inner and outer HDPE layers. This forms a sandwich composite structure that enhances the pipe's mechanical strength, tensile performance, and compressive stability, thereby extending its service life. Under hydrogen exposure, atomic hydrogen readily permeates the steel wire, causing hydrogen embrittlement. In stress concentration regions, stress-driven hydrogen enrichment further increases this susceptibility. This severely threatens the structural integrity of the pipeline.

This paper systematically analyzes the effect of steel wire diameter, D (1.0–2.0 mm), on hydrogen diffusion behavior. The effect of steel wire diameter is non-monotonic: neither the maximum hydrogen concentration around the wires nor the diffusion flux on the hydrogen escape side changes unidirectionally with increasing diameter, and both parameters show an inflection point at a diameter of approximately 1.2 mm.

Figure 9 shows that, during hydrogen diffusion under stress conditions, increasing the steel wire diameter reduces the spacing between adjacent wires. From the perspective of hydrogen diffusion under stress conditions, the stress fields generated by each loaded steel wire superimpose on each other in the gap between adjacent wires, forming a local region with significantly elevated hydrostatic stress. In accordance with the governing mechanism of hydrogen diffusion under stress conditions adopted in this study, hydrogen atoms spontaneously migrate from regions with low hydrostatic stress to regions with high hydrostatic stress driven by the stress gradient. As a result, hydrogen atoms continuously accumulate in the high-stress gap between wires; the stronger the mutual stress interaction, the higher the peak hydrostatic stress in the gap, and the more significant the local hydrogen enrichment effect. Their close proximity generates strong mutual stress interactions, promoting high-concentration hydrogen accumulation between the wires. Figures 10 and 11 show that as the wire diameter increases from 1.0 to 2.0 mm, the maximum hydrogen concentration around the wires first decreases and then increases, while the hydrogen escape side diffusion flux first increases and then decreases. When the diameter increases from 1.0 mm to 1.2 mm, the longer diffusion path forces hydrogen atoms to follow a more tortuous route, thereby lowering the maximum hydrogen concentration and increasing the hydrogen escape side diffusion flux. When the wire diameter further

increases from 1.2 mm to 2.0 mm, the steric hindrance of the wires on hydrogen diffusion intensifies. This effect describes the physical blocking caused by the enlarged wire volume and narrowed gap between adjacent wires: it forces hydrogen atoms to follow more tortuous diffusion paths, prolongs the residence time of hydrogen atoms around the wires, and accordingly increases the maximum local hydrogen concentration. Simultaneously, the increased tortuosity of the diffusion path lowers the efficiency of hydrogen transport into the outer HDPE layer, leading to a lower hydrogen escape side diffusion flux. These findings indicate that increasing the wire diameter raises the hydrogen concentration by altering the diffusion path, while the barrier effect simultaneously modulates the hydrogen diffusion flux. At a diameter of 1.2–1.4 mm, the hydrogen concentration in the steel wire layer remains relatively low, effectively suppressing hydrogen segregation and improving barrier performance.

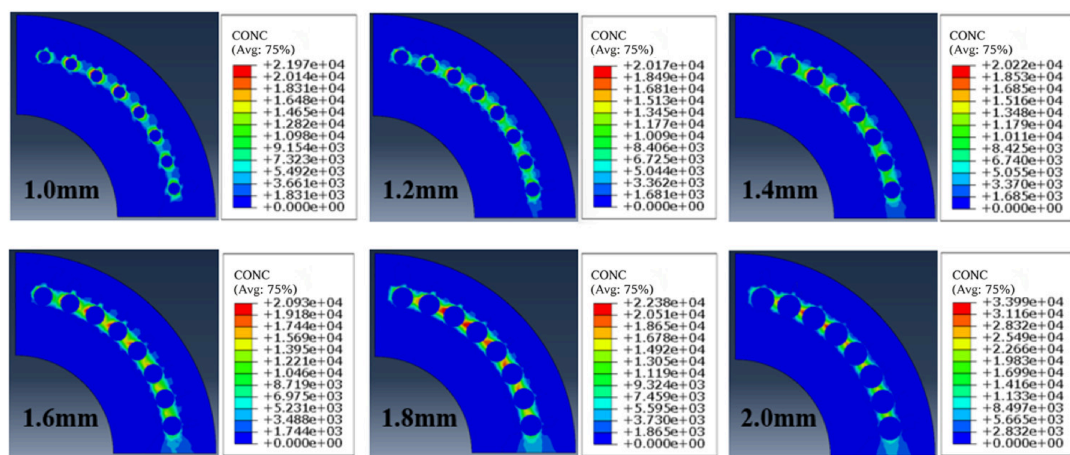


Figure 9. Hydrogen distribution with different $D_{(\text{steel wire})}$ under stress conditions.

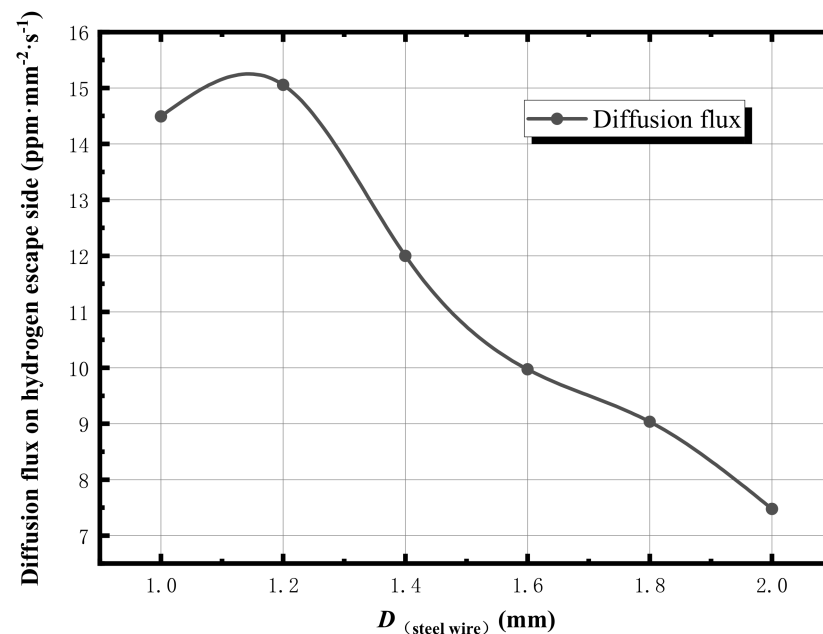


Figure 10. Relationship between diffusion flux on the hydrogen escape side and $D_{(\text{steel wire})}$ under stress conditions.

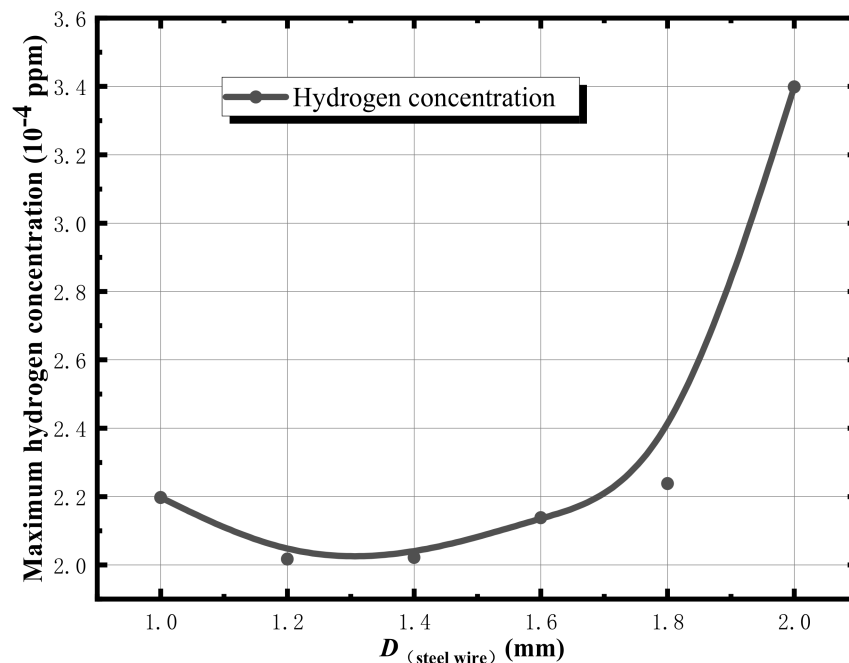


Figure 11. Relationship between the maximum hydrogen concentration and the $D_{(\text{steel wire})}$ under stress conditions.

4.3. Effect of the Radial Distance from the Steel Wire Layer to the Pipe Wall

In an SRP, the inner and outer HDPE layers act as a composite barrier. The inner layer limits hydrogen contact with the steel wire by reducing the inward diffusion flux, while the outer layer resists environmental corrosion and prevents hydrogen leakage. This synergy reinforces the pipe structure and optimizes the hydrogen migration path. This study controls hydrogen diffusion by varying the radial distance from the steel wire layer to the inner pipe wall, which consequently alters the thicknesses of the inner and outer HDPE layers. Figure 12 shows that as the radial distance from the steel wire layer to the inner pipe wall increases from 3.2 mm to 4.8 mm, the inner HDPE layer thickness increases from 3.2 mm to 4.8 mm, while the outer layer thickness decreases from 3.6 mm to 2.0 mm. This change significantly reduces the hydrogen concentration in the steel wire layer.

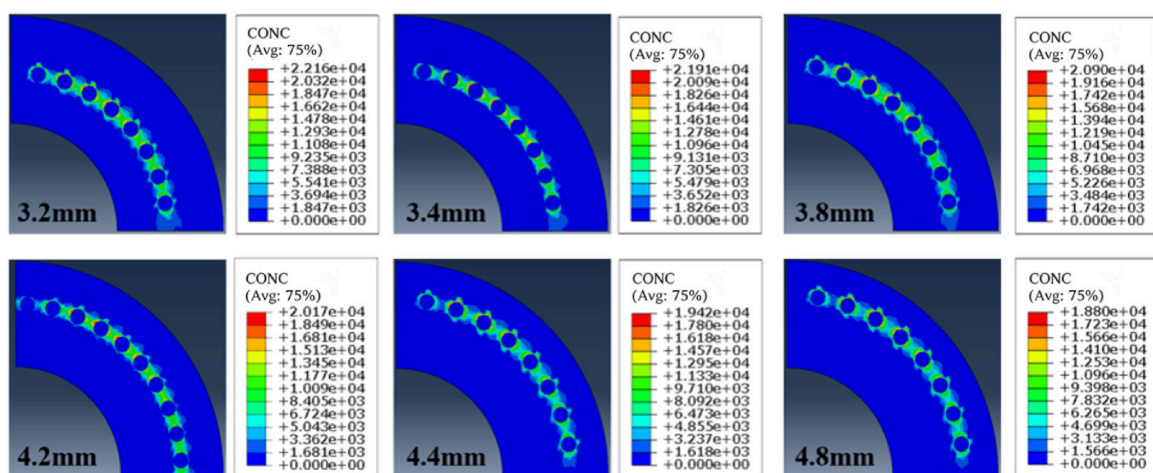


Figure 12. Hydrogen distribution for different wire layer pipe radial spacing under stress conditions.

Figures 13 and 14 illustrate the variation in hydrogen escape-side diffusion flux and maximum local hydrogen concentration with the radial distance from the steel wire layer to the inner pipe wall. As the radial distance increases, the escape-side flux rises monotonically.

ically, while the peak hydrogen concentration around the steel wires shows a consistent decreasing trend. Notably, the flux does not conform strictly to the ideal scaling law expected for homogeneous Fickian diffusion, such as a linear or square-root dependence on diffusion length. This deviation originates from the stress–hydrogen coupling effect and the structural characteristics of the multilayer composite system. In the proposed model, hydrogen transport is driven by both the concentration gradient and the hydrostatic stress gradient, as expressed in Equation (4). The magnitude and distribution of the local stress field around the steel wire layer change continuously with its radial position, and the superimposed stress-driven term modifies the total diffusion driving force, breaking the simple scaling relation derived for homogeneous concentration-only diffusion systems. Meanwhile, adjusting the radial position of the steel wire layer induces opposite thickness variations in the inner and outer HDPE layers under a constant total wall thickness: the thickening inner layer increases diffusion resistance, whereas the thinning outer layer reduces it. The combined effect of these two opposing resistance changes introduces inherent nonlinearity to the flux evolution. The geometric barrier imposed by the steel wire layer further contributes to this non-ideal behavior, as hydrogen atoms follow tortuous diffusion paths around the wires rather than propagating along an ideal one-dimensional route, and the path tortuosity also varies slightly with the radial position of the reinforcement layer.

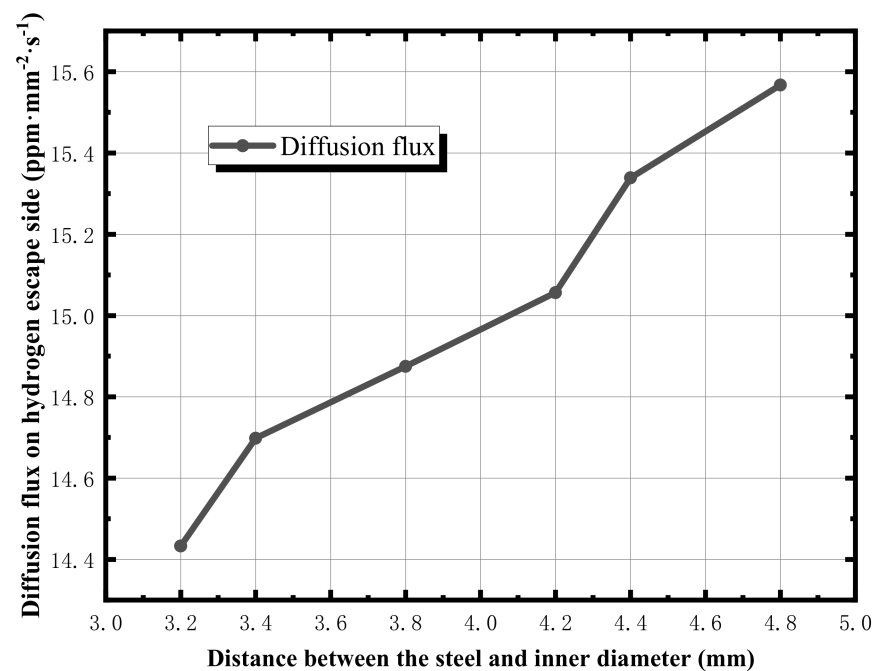


Figure 13. Relationship between the diffusion flux on the hydrogen escape side and the radial distance between the steel wire layer and the inner pipe wall under stress conditions.

The growth rate of the escape-side flux exhibits a moderate slowdown in the range of 3.4–4.2 mm, which reflects a relative equilibrium among the multiple influencing factors described above. When the radial distance is below 3.4 mm, the steel wire layer is located close to the inner charging boundary, resulting in a steeper concentration gradient across the inner HDPE layer and a more prominent stress-driven enhancement effect; thus, the flux increases rapidly with the radial distance. Within the 3.4–4.2 mm interval, the increasing resistance from the thickening inner layer, the decreasing resistance from the thinning outer layer, and the stress-driven diffusion promotion around the steel wires gradually reach a balanced state, leading to the decelerated flux growth. As the radial distance exceeds 4.2 mm, the outer HDPE layer becomes sufficiently thin, and the reduction in outer-layer diffusion resistance gradually dominates the process, causing a slight recovery in the flux

growth rate. From the perspective of the overall regulatory mechanism, increasing the radial distance extends the hydrogen diffusion path through the inner HDPE layer and intensifies the concentration attenuation from the inner pipe wall to the steel wire layer, which strengthens the concentration gradient across the two HDPE layers. The enhanced concentration gradient provides a greater driving force for hydrogen diffusion, accelerates the overall hydrogen transport within the SRP structure, elevates the escape-side flux, and ultimately reduces the hydrogen accumulation in the steel wire reinforcement layer.

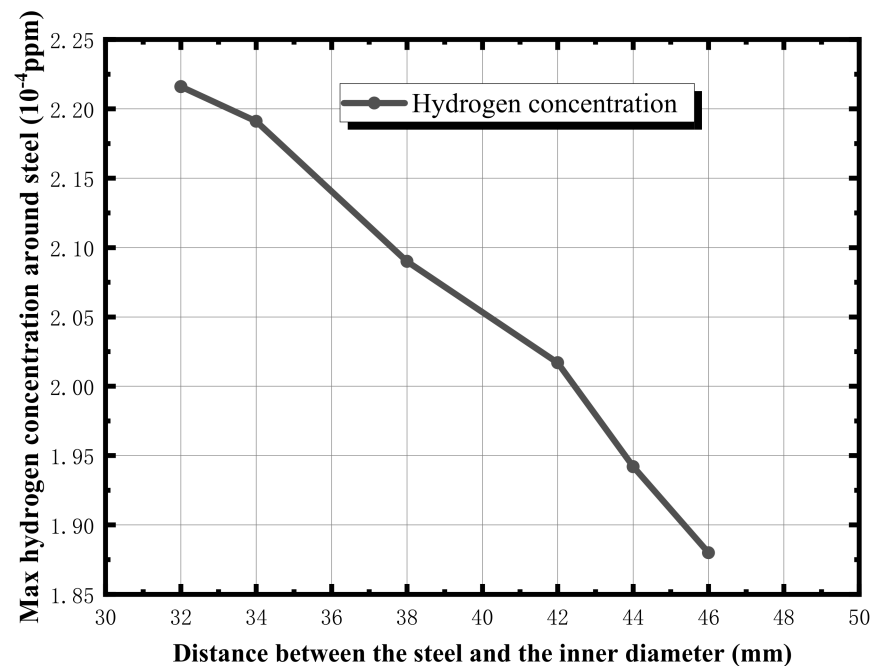


Figure 14. Relationship between the maximum hydrogen concentration and the radial distance between the steel wire layer and the inner pipe wall under stress conditions.

4.4. Effect of the Steel Wire Winding Angle

Varying the steel wire winding angle in an SRP significantly affects the hydrogen diffusion path and resistance. From a geometric point of view, this effect is intrinsically linked to the spacing between adjacent steel wires, and shares the same physical logic with the influence of steel wire diameter on inter-wire stress interaction. For an SRP with fixed pipe diameter and total number of steel wires, the winding angle is defined as the angle between the steel wire axis and the axial direction of the pipe. A smaller winding angle corresponds to a smaller spiral pitch of the steel wires, resulting in denser arrangement and smaller spacing between adjacent wires in the pipe wall; as the winding angle increases, the spiral pitch enlarges and the inter-wire spacing increases accordingly. This geometric change regulates the intensity of mutual stress interaction between adjacent steel wires, and further affects hydrogen transport and accumulation during hydrogen diffusion under stress conditions. An excessively large winding angle will lead to local hydrogen retention around the wires and thus increase the local hydrogen concentration. The hydrogen concentration distribution in the pipe wall under different winding angles is presented in Figure 15.

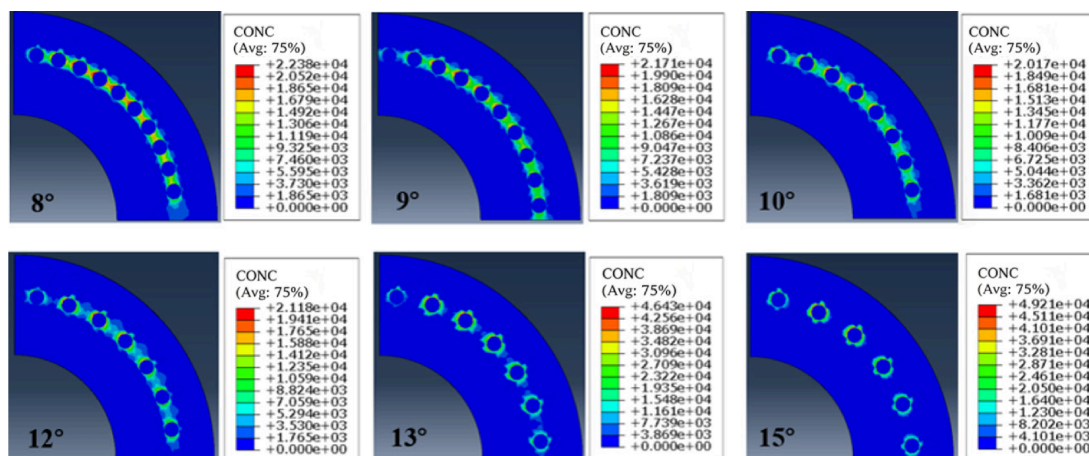


Figure 15. Hydrogen distribution of the angle between different steel wire under stress conditions.

Figures 16 and 17 show that, under stress induction, as the winding angle increases from 8° to 15°, the maximum hydrogen concentration around the steel wires first decreases and then increases, while the hydrogen escape side diffusion flux first increases and then decreases. When the angle exceeds 12°, the maximum hydrogen concentration increases markedly. At small winding angles, the close packing of steel wires restricts the diffusion path, elevating the local hydrogen concentration while the hydrogen escape side diffusion flux remains low. A further increase in angle creates excessive wire spacing, allowing hydrogen to accumulate locally around the wires and form high-concentration regions. Consequently, the hydrogen escape side diffusion flux decreases again. These findings indicate that the winding angle can be optimized to effectively control the hydrogen diffusion path and resistance. At a winding angle of 9–10°, the hydrogen concentration in the steel wire layer is minimized, demonstrating excellent hydrogen barrier performance.

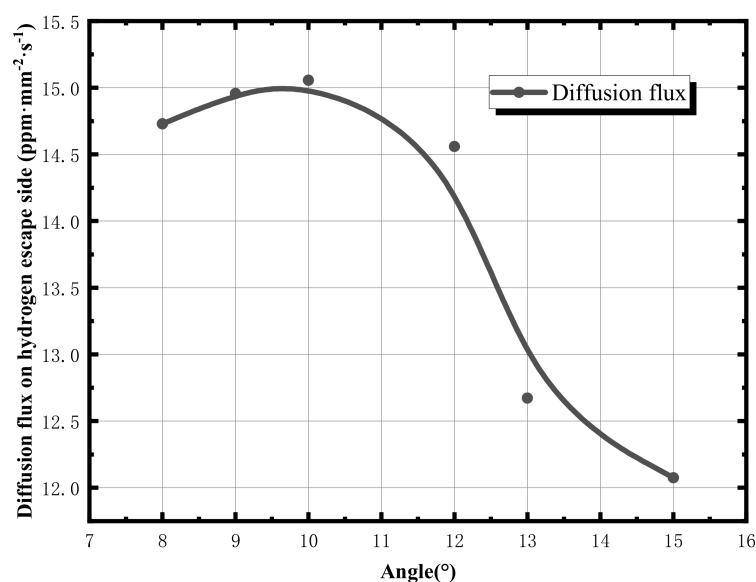


Figure 16. Relationship between the diffusion flux on the hydrogen escape side and the angle between the steel wire under stress conditions.

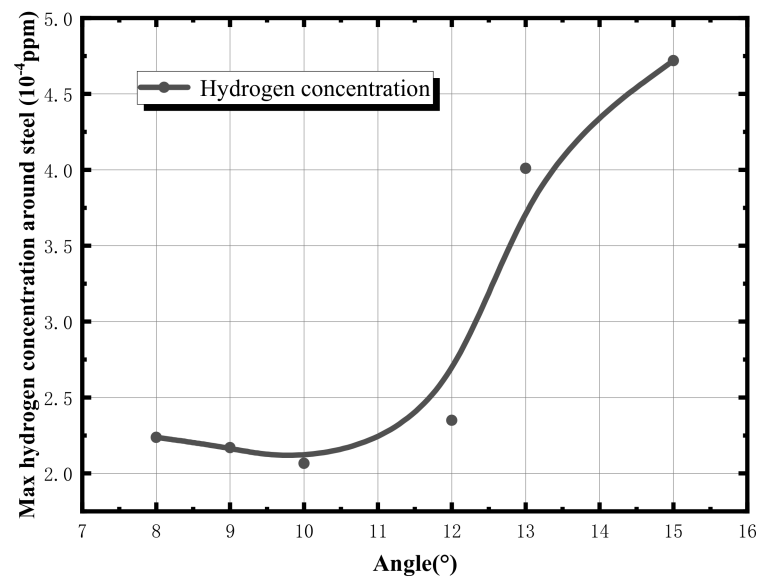


Figure 17. Relationship between the maximum hydrogen concentration and the angle between the steel wire under stress conditions.

5. Conclusions

Within the parameter ranges investigated in this work (hydrogen pressure: 1–20 MPa; steel wire diameter: 1.0–2.0 mm; radial distance from the steel wire layer to the inner pipe wall: 3.2–4.8 mm; winding angle: 8–15°), the following numerical observations are obtained based on finite element simulations of hydrogen diffusion under stress conditions:

- (1) Within the studied hydrogen pressure range, increasing hydrogen pressure tends to accelerate hydrogen diffusion in SRP and raise the hydrogen concentration in the steel wire layer in an approximately proportional manner. Under higher pressure, hydrogen atoms are more likely to segregate at stress concentration sites and form local high-concentration zones. The elevated local hydrogen concentration may increase the risk of hydrogen-induced damage, and the synergistic effect inherent in hydrogen diffusion under stress conditions may increase the susceptibility of steel wires to hydrogen embrittlement, which may further raise the risk of crack initiation and propagation and degrade mechanical performance.
- (2) For hydrogen diffusion under stress conditions, increasing the steel wire diameter from 1.0 mm to 1.2 mm lengthens the hydrogen diffusion path, which reduces the local hydrogen concentration around the wires and increases the hydrogen escape-side diffusion flux. As the diameter further increases from 1.2 mm to 2.0 mm, the physical barrier effect of steel wires is intensified, prolonging the residence time of hydrogen atoms around the wires and increasing the local hydrogen concentration, while the increasingly tortuous diffusion path reduces the hydrogen escape side diffusion flux. Within the studied diameter range of 1.0–2.0 mm, steel wires with diameters of 1.2–1.4 mm maintain a relatively low hydrogen concentration in the reinforcement layer, which indicates favorable hydrogen barrier performance under the simulation conditions.
- (3) Increasing the radial distance from the steel wire layer to the inner pipe wall increases hydrogen retention in the inner HDPE layer and forms a more significant concentration gradient across the inner and outer HDPE layers, which accelerates the overall hydrogen diffusion in SRP and reduces the hydrogen concentration around the steel wires. Within the investigated range, these results suggest that appropriately increas-

ing this radial distance may help mitigate the risk of hydrogen-induced damage and improve the hydrogen barrier performance of the SRP structure.

- (4) The steel wire winding angle has a notable influence on the hydrogen diffusion path and diffusion resistance. A smaller winding angle leads to closely arranged steel wires, which restricts hydrogen diffusion and increases local hydrogen concentration. As the winding angle increases, the effective diffusion area expands, which reduces the hydrogen concentration and increases the diffusion flux. However, an excessively large winding angle may cause local hydrogen accumulation between adjacent wires, leading to a decrease in diffusion flux again. Within the studied winding angle range of 8–15°, a winding angle of 9–10° corresponds to the lowest hydrogen concentration in the steel wire layer in our simulations, showing favorable hydrogen barrier performance under the given conditions.

In summary, all findings presented in this work are trend predictions derived from the proposed stress–hydrogen coupled finite element model within the specified parameter ranges. All hydrogen diffusion behavior and local hydrogen concentration results are obtained purely from numerical simulation, and no corresponding physical measurement experiments have been conducted in the current stage. The quantitative hydrogen concentration values are simulation outputs corresponding to the adopted general material parameters and macroscopic modeling assumptions, and should not be overinterpreted as absolute engineering design results. The numerical findings can provide theoretical reference for the structural design and parameter optimization of SRP used in hydrogen transport, and the applicability of the model is mainly oriented to mechanistic analysis and parametric comparison at the structural scale.

Experimental validation of hydrogen diffusion behavior and local hydrogen concentration in steel-wire-reinforced thermoplastic pipes remains an important topic for future research. Subsequent work will also include the evaluation of long-term service effects, and the development of multi-scale models incorporating microstructural heterogeneity and hydrogen trapping dynamics.

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Abbreviations

The following abbreviations are used in this manuscript:

SRP	Steel-Wire-Reinforced Thermoplastic Pipes
HDPE	High-Density Polyethylene
FEM	Finite Element Method

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