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Effect of viscoelasticity on the hold pressure of plastic pipe reinforced by cross helically wound steel wires in leak test

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ABSTRACT

Leak test is required in a number of standards to verify the leak tightness of pipelines based on the pressure drop in the pressure-hold period. However, the viscoelasticity of the matrix material polythene in plastic pipe reinforced by cross helically wound steel wires (PSP) would cause an evident pressure drop in leak test. In this study, a theoretical model was proposed to investigate the effect of viscoelasticity on the hold pressure through combining a long-term mechanical model of PSP and water state equation. Leak tests were conducted to validate the model, and a good agreement was obtained. Results showed that the pressure rapidly declined initially, and then the decreasing rate slowed until the pressure was almost stable. Finally, the principal mechanical performance of PSP was further explored, and the effects of pressurization rate and temperature on the pressure drop were also investigated.

1. Introduction

Plastic pipe reinforced by cross helically wound steel wires (PSP) is extensively used in petroleum and natural gas transportation in China [1] because of its high strength, excellent corrosion resistance, and thermal insulation. The structure of PSP is shown in Fig. 1. A two-layer steel wire mesh skeleton is sandwiched in the middle with thermoplastic high-density polyethylene (HDPE) on both sides. The inner and outer reinforcement layers are wrapped under a negative angle and a positive angle, respectively. High-strength steel wires that constitute the skeleton are integrated with HDPE by using a high-performance cohesive resin.

Pipelines and primary piping for petroleum and natural gas transportation shall be pressure-tested in place after installation but before being put into operation to demonstrate their strength and leak-tightness. In a number of standards [2–5], the hydrostatic test is referenced to determine the integrity of an in-service pipeline, including strength test and leak test, as shown in Table 1.

According to the Chinese national standard *GB 50369-2006 Code for construction and acceptance of oil and gas transmission pipeline engineering* [5], PSP is pressurized during a hydrostatic test to a fixed value at a controlled rate, and then the injection pump is stopped and isolated from the test section. Pressure should be continuously recorded during the test as the reference for acceptance criteria, as shown in Table 2. No leakage is required in the strength test, and pressure drop in the leak test is neither more than 1% of the test pressure nor more than 0.1 MPa.

Previous experimental investigation showed that a significant pressure drop is inevitable for PSP in leak test because of the viscoelasticity of HDPE. Stress and strain of PSP subjected to the internal pressure vary correspondingly during pressure-hold period because the elastic modulus of the matrix material declines over time, which leads to an expansion of its volume. Meanwhile, a rise of water volume (V) means a drop of water pressure (P) at a fixed temperature (T) [6]. In determining the leak tightness of PSP through leak test, such pressure drop caused by changing material properties is acceptable and must be obtained through calculation.

In this study, the effect of viscoelasticity on the hold pressure of PSP in leak test was studied. A prototype PSP in our previous study was modified and further extended to describe its long-term mechanical performance by considering the viscoelasticity of HDPE. Tumlirz equation was then applied to quantify the states of testing water [7]. Afterwards, a graphic method was proposed to predict the pressure drop of PSP that was induced via viscoelasticity, which is based on the continuous interaction and compatible deformation between PSP and the inner water. Experiments were subsequently conducted to verify the proposed method. Finally, the principal mechanical performance of PSP was investigated, and other influence factors on the pressure drop in leak test were also studied.

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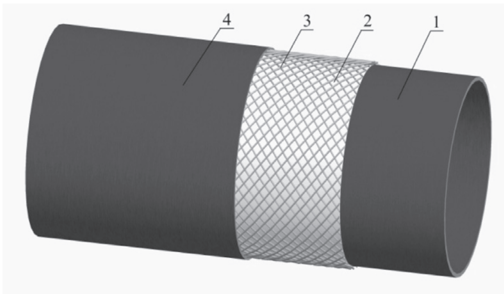

1. Inner layer, 2. Cohesive resin, 3. Steel-screen skeleton, 4. Outer layer

Fig. 1. PSP structure.

2. Theoretical analysis

2.1. Long-term mechanical model of PSP

PSP can be simplified as a three-layer cylindrical shell [8], which includes the inner HDPE layer, winding layer, and outer HDPE layer. A cross-section of PSP with dimensions is depicted in Fig. 2. The radii of the inner layer, the first and second reinforcement layers, the midplane, and the outer layer are indicated by R_i, R_j, R_k, R, and R_o, respectively.

The winding layer consists of two equivalent monolayers. Each monolayer has three symmetrical performance planes and can be modeled as an orthotropic thick-wall cylindrical shell. Fig. 3 shows the global coordinate system (z, θ, r) and the local coordinate (L, T, r). The winding angle α is defined as the angle between the z-direction (global) and the L-direction (local).

Provided that radial dispersion is continuous when PSP is subjected to the internal pressure P_i, and the axial strain of each layer is equal when PSP is unconstrained axially. Meanwhile, all deformations are assumed to be small in the case. After the aggregate elastic constants of PSP are determined, the equilibrium equation in the axial direction and deformation compatibility equations between adjacent layers can be derived. Contact pressures between layers are then obtained, and all mechanical responses of each layer can be calculated. The circumferential and axial strains of PSP at the radius of R_i, $\varepsilon_{\theta n}(R_i)$, $\varepsilon_{zn}(R_i)$, and the stress of steel wires in the direction of L, σ_{Lst}, are all proportional to the internal pressure, as follows.

$$\varepsilon_{\theta n}(R_i) = A \cdot P_i \tag{1}$$

$$\varepsilon_{zn}(R_i) = B \cdot P_i \tag{2}$$

$$\sigma_{Lst} = C \cdot P_i \tag{3}$$

where A, B, and C are positive coefficients only in the function of the material and structural parameters of PSP [8].

The viscoelasticity of HDPE determines the time-dependent nature of the mechanical properties in PSP. When the strain is stable at a constant temperature, the stress declines over time, which is defined as stress relaxation. Stress relaxation can be characterized through the relaxation modulus equation $E(t)$ [9,10].

Relaxation modulus data can be obtained from experiments. The empirical formula in the extended index form is available to most viscoelastic materials for describing relaxation modulus [10,11], as shown in Eq. (4).

$$E(t) = E_\infty + (E_0 - E_\infty)\exp\left[-\left(\frac{t}{\tau}\right)^{\beta}\right] \tag{4}$$

where coefficients $0 < \beta < 1$, $\tau > 0$, initial modulus E_0 in MPa, long-term modulus E_∞ in MPa, and time t in h.

When the relaxation modulus of HDPE at any given time is substituted into the mechanical model, the overall stress and strain of PSP at a mechanical equilibrium state can then be obtained.

2.2. State equation of water

While relaxation modulus of HDPE decreases continuously, PSP transforms from one mechanical equilibrium state to another, and the state (P, V, T) of water changes correspondingly. The P–V–T data on water have been summarized using many empirical formulas. Some of these formulas are elaborate [12]. One of the simplest but effective formulas is the Tumlirz equation, such as Eq. (5), which is entirely adequate for low temperatures and pressures, i.e., $0 \leqslant T \leqslant 40$ °C, $P \leqslant 300$ MPa [7].

Table 1
Pressure and duration required in hydrostatic test for normal petroleum pipelines.

Standard	Strength test		Leak test	
	Pressure (MPa)	Duration of pressure hold period (h)	Pressure (MPa)	Duration of pressure hold period (h)
ISO 13623	1.25 × MAOP[a]	1	1.1 × MAOP	8
ASME B31.4	1.25 × DP[b]	4	1.25 × DP	1
EN 1594	1.30 × DP	0.25	DP	24
GB 50369	1.25 × DP	4	DP	24

[a] Maximum allowable operating pressure.
[b] Design pressure.

Table 2
Requirements and acceptance criteria for oil and gas transmission pipeline in GB 50369-2006.

Type		Strength test	Leak test
Oil transmission pipeline	Pressure (MPa)	1.25/1.5 × Design pressure	Design pressure
	Duration of pressure hold period (h)	4	24
Gas transmission pipeline	Pressure (MPa)	1.1–1.5 × Design pressure	Design pressure
	Duration of pressure hold period (h)	4	24
Acceptance criteria		No leakage	Pressure drop is neither more than 1% of the test pressure nor more than 0.1 MPa.