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Study on the aging rate of polyethylene gas pipelines with different diameters in urban areas

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Abstract: Under the same standard dimension ratio (SDR), there are differences in the aging rate of polyethylene gas pipelines with different diameters. To investigate the relationship between the aging rate of polyethylene pipes and pipe diameter, and to consider the influence of pipe diameter on aging life in existing polyethylene(PE) pipe aging prediction models, this paper conducted thermal oxygen accelerated aging tests on polyethylene pipes of multiple pipe diameters (with the same SDR and material). The aging rate of the pipelines was calculated by measuring the oxidation induction period (OIT) of the aged PE pipelines. The study found that under the same SDR, the aging rate of pipes made of the same material decreases with increasing wall thickness due to the influence of pipe diameter, and the aging rate is exponentially related to the reciprocal of pipe diameter. This functional relationship can be substituted into the Arrhenius equation to establish the relationship equation between aging rate, pipe diameter, and temperature.

1. Introduction

In recent years, non-metallic pipelines have continued to expand their application scale in gas, chemical and other fields due to their advantages of corrosion resistance, lightweight, easy connection, and low operation and maintenance costs. At present, non-metallic pipelines account for 70% of gas pressure pipelines, all of which are buried polyethylene pipelines. Polyethylene pipes, as a type of polymer material, are inevitably subject to aging and degradation due to environmental factors such as temperature, pressure, and microorganisms[1]. The aging behavior of buried polyethylene pipelines is mainly thermal oxidative aging, and its failure is a complicated process mainly characterized by material aging and stress crack propagation. The creep mechanical failure modes can be roughly divided into three categories: ductile failure, brittle failure, and transitional state between the two (quasi brittle failure)[2-5]. The critical threshold for the transition from ductile failure to brittle failure is difficult to accurately define. In the quasi brittle stage, the failure behavior of polyethylene (PE) pipes is mainly controlled by the slow crack propagation (SCG) process; In the brittle failure stage, the failure is mainly dominated by material aging mechanisms that are independent of stress[6]. The ultimate failure mode of polyethylene pipes is manifested as overall brittle failure caused by material aging. Currently, research on the aging characteristics of polyethylene pipes mainly involves simulating actual service and environmental conditions, conducting accelerated aging tests, and analyzing related mechanisms. In previous studies, it was found that under the same SDR, pipelines made of the same polyethylene material were affected by the pipe wall thickness, and the aging rate of pipelines with different diameters varied. In actual PE gas pipeline laying, there are various pipe diameters. In order to study the difference in aging rate between different pipe diameters and construct a life prediction method for PE pipes suitable for different pipe diameters and operating conditions, this paper used existing accelerated aging experimental platforms[7] to conduct accelerated thermal oxygen aging tests on PE pipes of different pipe diameters, and calculated the aging rate of pipes of different pipe diameters by testing the remaining antioxidant content of the pipes.

In order to extend the service life of polyethylene pipes, manufacturers add antioxidants to polyethylene pipes during the production process. The pipeline will not undergo significant degradation until the antioxidant is consumed to a certain extent. Therefore, the aging process of polyethylene pipes can generally be divided into the consumption of antioxidants and the degradation of the polyethylene material itself. Hoang et al. [8] used differential scanning calorimetry to detect the changes in OIT of polyethylene pipes during aging to characterize the remaining antioxidant content in the pipes, and determined its effectiveness using iodine titration. Therefore, this article characterizes the aging rate by detecting the OIT of polyethylene pipelines after aging, in

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order to study the effect of pipe diameter on the aging of gas polyethylene pipelines.

2. Accelerated aging test

This article uses thermal oxygen accelerated aging experiments for research. In order to investigate the differences in antioxidant consumption rates of polyethylene pipes with different diameters, SDR11 PE80 produced by Yada Group, which is widely used, was selected with diameters of dn 63, 90, 110, 160, and 200. Considering that the Vicat softening point of polyethylene pipes is 120 °C, in order to accelerate the pipeline speed and prevent differences from the aging mechanism under normal working conditions, the temperature of the aging chamber is set to 100 °C. The aging box is shown in Figure 1.The specific experimental arrangement is shown in the table below. During the experiment, samples were taken from the aged PE test pipe according to the time in Table 1. The aged PE pipe sample taken out should be placed in a place that is not directly exposed to sunlight at room temperature, and allowed to stand for 1 day to adjust its state before further testing and analysis.

Figure 1. Aging experimental platform.

Table 1. Aging time of polyethylene pipes.

pipeline	Pipe diameter dn	First batch /h	Second batch/h	Third batch/ h	Fourth batch/ h	Fifth batch/ h
PE 80 SDR11	63	24	48	96	200	384
	90	24	48	96	200	384
	110	24	48	96	200	384
	160	24	48	96	200	384
	200	24	48	96	200	384

3. Pipeline aging rate detection

According to GB/T43922-2024 "Inspection and evaluation of in-service polyethylene gas pipeline"[9], the external surface damage shall not exceed 10% of the wall thickness. When the damage or degradation depth of the pipe outer surface exceeds 10% of the wall thickness, the pipeline needs to be repaired or replaced. According to research, the loss of antioxidants mainly occurs on the outer surface of pipelines. And when the antioxidant content is below a certain value, polyethylene materials will degrade rapidly[7]. The consumption rate of antioxidants on the outer surface of pipelines is the fastest, and the outer surface will lose protection due to low antioxidants and undergo aging degradation first. When the aging and powdering depth of the outer surface exceeds the standard value, the pipeline must be replaced. Therefore, the remaining antioxidant content in a certain thickness area on the outer surface of the pipeline can determine the remaining life of the pipeline. Therefore, this article believes that when 10% of the thickness of the pipe outer surface loses its antioxidant protection and begins to age rapidly, the pipeline already needs to be replaced. Considering that sampling during the OIT may cause slight damage to the tube body, in order to prevent serious impact on the mechanical properties of the tube body and lay the foundation for future micro damage detection, the sampling thickness in this article shall not exceed the provisions of GB/T43922.In order to reduce the influence of sample differences on the detection results, the samples were uniformly cut on the outer surface with a thickness of 9% of the wall thickness, and samples were avoided from being taken at the color bar position.During the testing process, the heating rate was set to 20 °C/min, the test temperature was 200 °C, and the nitrogen and oxygen flow rates were 50mL/min[10]. The minimum value of the three tests was taken as the test result. To reduce detection errors, the difference between the three detection results cannot exceed 3 minutes. When the difference between the detection results exceeds 3 minutes, retesting is required. The instrument used for detecting the OIT is the DSC 200 F3 Maia® (Figure 2). The results of the OIT detection are shown in Figure 3. As shown in the figure, there are significant differences in the OIT reduction rate among pipes of different diameters. In the experiment, the pipe with the smallest PE diameter (dn63) showed the fastest decline in aging performance, while the pipes with diameters ranging from dn110 to dn200 showed similar decline rates. The pipe with diameter dn200 showed the slowest decline in aging performance. It can be seen that in the case of the same SRD, large-diameter PE pipes have relatively strong resistance to material aging due to their high antioxidant content. Therefore, when predicting the aging life of in-service PE pipes, it is necessary to consider the influence of pipe diameter on the aging rate.

Figure 2. Differential scanning calorimete.

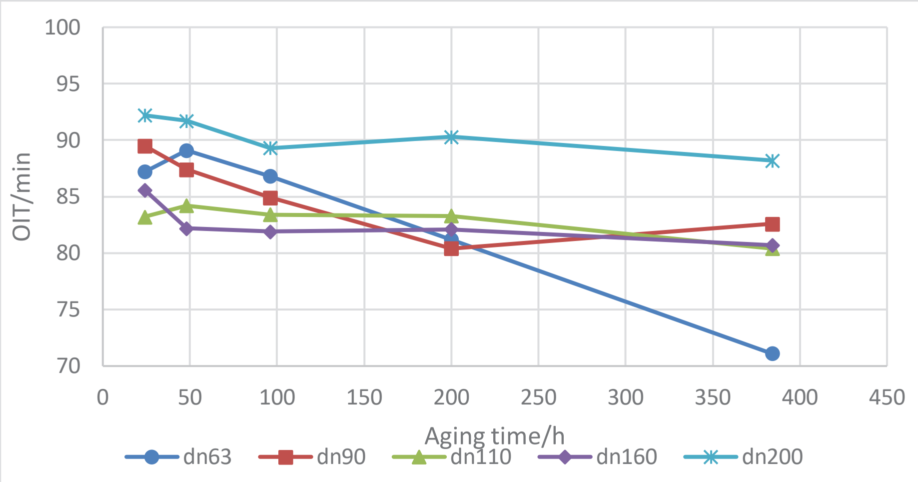

Figure 3. Decrease in OIT for different pipe diameters

4. Analysis of the influence of pipe diameter on aging rate

4.1. Reaction rate varies with pipe diameter

Considering the instability of materials in the production process of PE pipes, the reduction rate of OIT for different pipe diameters was compared based on the initial OIT of each pipe diameter. According to the Arrhenius equation, the induction period of pipeline oxidation is linearly related to aging time, which can be expressed as

$$ln\,Q = ln\,A - Kt \quad (1)$$

Where:

Q - Remaining performance of the pipe, expressed in this article as the OIT;

T - Expected lifespan, h;

K - Chemical reaction rate constan;

A - Material constant.

K is the rate constant of a chemical reaction in the Arrhenius equation, which characterizes the reaction rate of the chemical reaction itself. Therefore, in this study, K can reflect the consumption rate of antioxidants, i.e. the aging rate of pipelines.

Plot the logarithm of the OIT for each pipe diameter against the aging time and perform a linear fit as shown in Figure 4. The aging rate of PE pipes with different diameters can be determined by fitting the slope of the dashed line.

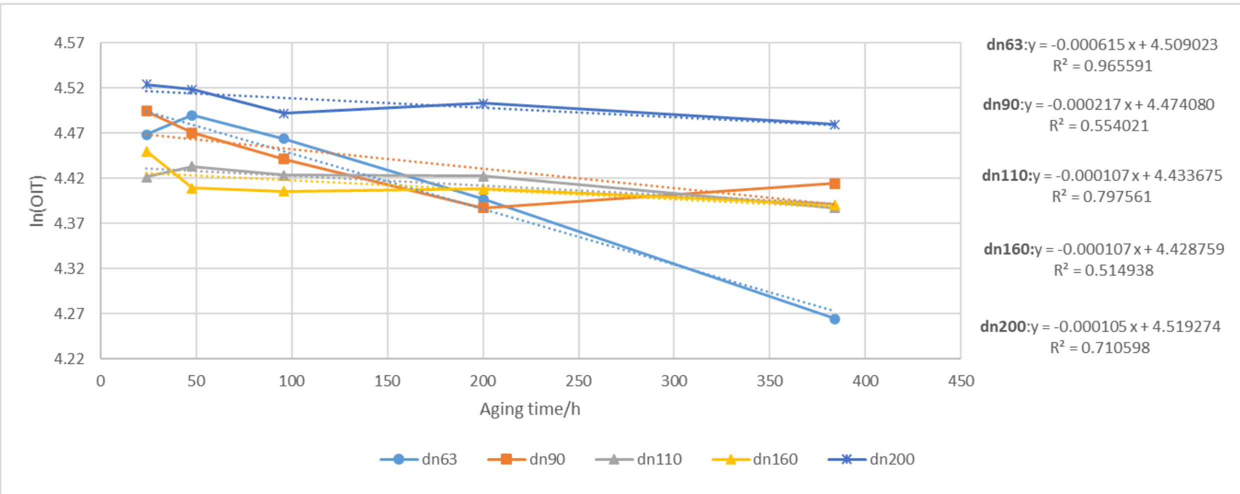

Figure 4. Fitting of aging rate curves for different pipe diameters.

Comparing different pipeline diameters and aging rates (Figure 5), it can be seen that as the diameter increases, the aging rate (antioxidant consumption rate) of the pipeline decreases, and the antioxidant capacity of the pipeline increases.In the experiment, when the diameter of the pipe increased to dn110, the difference in aging rate decreased. It is recommended that when evaluating the aging performance of in-service PE pipes, special attention should be paid to the poor performance of small diameter pipes.

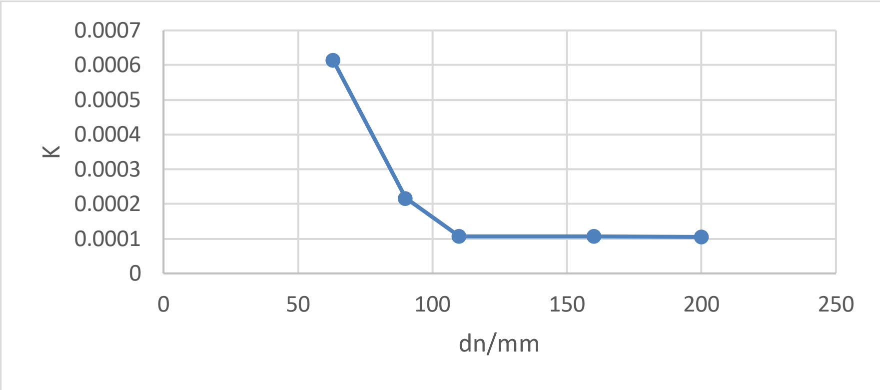

Figure 5. Relationship between Pipe Diameter and Aging Rate.

4.2. Prediction formula for reaction rate of different pipe diameters

According to research, there is a phenomenon of antioxidant migration. Antioxidants will first be lost from the surface of the material, while antioxidants in the middle of the material will migrate to the surface and then be lost [11-16]. In actual operation, the pipeline is buried underground, and oxygen exists in the soil but not in the transport medium. Therefore, the consumption of antioxidants in polyethylene gas pipelines mainly occurs on the outer surface. In previous study[17], it was found that when only the outer wall of the pipeline comes into contact with oxygen, the OIT reduction rate of the inner wall and the interior of the pipeline is consistent, lower than that of the outer surface of the pipeline. Prove that the consumption of antioxidants mainly occurs on the surface in contact with oxygen, and the decrease in OIT in other areas is mainly affected by the migration of antioxidants, and the rate is consistent. Under the same operating conditions, the consumption rate of antioxidants per unit surface area is the same. According to the production process of polyethylene pipes, the base material particles of the pipes already contain antioxidants and do not require additional addition. Therefore, the larger the volume of the pipeline produced using the same batch of base material particles, the more antioxidants are contained in the material. As the ratio of pipeline volume (antioxidant content) to surface area (reaction area) is related to wall thickness, i.e. $V/S = \frac{\frac{\pi}{4}(D^2-d^2)L}{\pi(D+d)L} = \frac{D-d}{4} = \frac{e}{4}$, when SDR (e=dn/SDR) is constant, this ratio also increases with the increase of pipeline diameter. Therefore, large-diameter PE pipes consume more antioxidants per unit surface area and have strong antioxidant capacity under the same usage environment.

According to the Arrhenius equation extrapolation method, the change in aging rate K follows the Arrhenius equation (equation 2) [18-19]

$$K = Ze^{-E/RT} \tag{2}$$

Where:

T - absolute temperature, K;

E - Material activation energy, $J\cdot mol^{-1}$:;

Z - Material frequency factor, d^{-1};

R - gas constant, $8.31 J\cdot K^{-1}\cdot mol^{-1}$.

The Arrhenius equation describes the rate law of homogeneous reactions with fully contacted reactants and unrestricted mass transfer; But the thermal oxidation aging of PE gas pipelines is a heterogeneous reaction in which oxygen diffuses from the outer surface of the pipeline inward and reacts with antioxidants inside the pipeline. Therefore, calculating the aging rate of pipelines requires modifying the equation. Fit the reaction rate constant K to the reciprocal 1/dn of the pipe diameter, and the curve will be exponential. The exponential fitting of the reaction rate constant K obtained from the experiment and the reciprocal 1/dn of the pipe diameter is shown in Figure 6, and the fitting result can be obtained $K = 0.000004e^{\frac{167.88}{dn}}$.Among them, R2=0.9658>0.95.

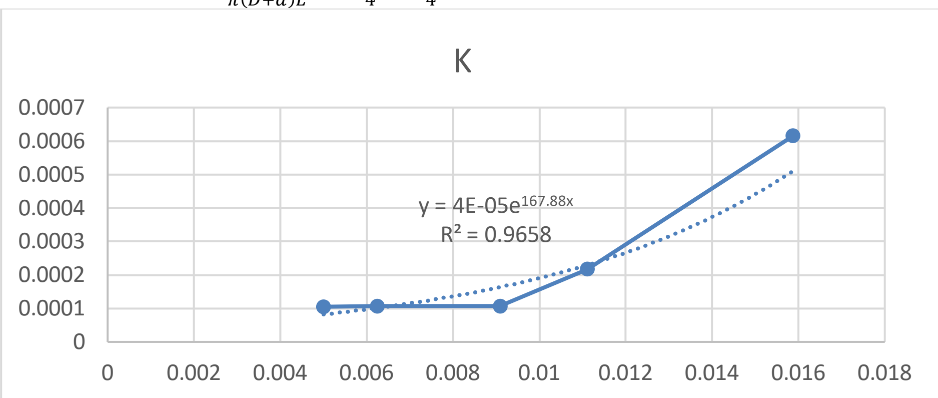

Figure 6. Relationship between reciprocal of pipe diameter and aging rate.

Therefore, for the SDR11 PE80 pipes studied in this article, the aging rate of pipes with different diameters can be converted using $K = 0.000004e^{\frac{167.88}{d_n}}$. By substituting this result into equation 2, equation 3 can be obtained, which is used to calculate the reaction rate constant K of pipes with different diameters based on diameter and temperature at the same diameter ratio.

$$K = \beta Z e^{-\alpha E/RT d_n} \tag{3}$$

Where:
T - absolute temperature, K;
E - Material activation energy, $J\cdot mol^{-1}$:;
Z - Material frequency factor, d^{-1};
R - gas constant, $8.31J\cdot K^{-1}\cdot mol^{-1}$;
dn - pipe diameter,,mm;
α - calculation constant;
β - calculation constant.

5. Conclusion

This article conducted aging tests on PE pipes with different diameters, and based on the results, the following conclusions were drawn:

(1) When SDR remains constant, as the diameter of the pipeline increases, the rate of decrease in the antioxidant content on its outer wall slows down, and the aging rate of the pipeline material also decreases. Under the same SDR conditions, the aging process of large-diameter polyethylene pipes is slower compared to small-diameter pipes.

(2) According to the experimental results, there is an exponential relationship between the rate and the reciprocal of the pipe diameter. After calculating the constant, the relationship between the aging rate constant K and the pipe diameter and temperature was established. However, the temperature dependent part of the current model adopts the classical Arrhenius hypothesis and mature literature conclusions, without direct multi temperature experimental verification. Therefore, gradient temperature experiments will be supplemented in future work to optimize and validate the coupled model.

(3) According to the prediction method provided in this article, when SDR and operating conditions are the same, the aging rate of one pipe diameter can be used to calculate the aging rate of other pipe diameters.

(4) Subsequent research suggests conducting multi factor coupled aging tests on different types of materials, pipe diameters, internal pressures, and temperature conditions, and constructing a multi factor related aging life characterization model to provide theoretical basis and technical support for predicting the aging life of in-service natural gas polyethylene pipelines.

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