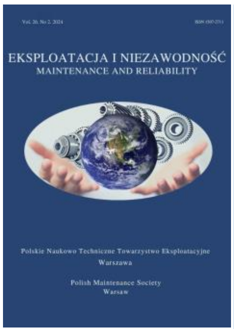

Eksploatacja i Niezawodnosc – Maintenance and Reliability

Volume 26 (2024), Issue 2

journal homepage: http://www.ein.org.pl

Article citation info:
Li W, Qian X, Chen X, Li F, Lu Y, Validation research of pressure decay test method for internal leakage detection of hydraulic cylinder, Eksploatacja i Niezawodnosc – Maintenance and Reliability 2024: 26(2) http://doi.org/10.17531/ein/184039

Validation research of pressure decay test method for internal leakage detection of hydraulic cylinder

Indexed by: Web of Science Group

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Highlights

- Identify the key influencing factors for internal leakage in hydraulic cylinders.
- Analyzing the correlation between pressure decay rate and internal leakage rate.
- Identify the effective range of application of the pressure decay test method.

Abstract

Leakage test is one of the acceptance tests to ensure hydraulic cylinder reliability. Under the consideration of economic and technical maturity conditions, the existing internal leakage detection methods may be difficult to achieve rapid screening. After research, the pressure decay test method is a common method of quickly testing hydraulic cylinders for internal leakage in the manufacturing industry. However, the validity of the pressure decay test method has not been theoretically verified, limiting the versatility of the method. This paper will theoretically validate the effectiveness of the pressure decay test method and provide important theoretical support for its use as a general rapid screening method for internal leakage, thereby improving the reliability and safety of hydraulic systems. Both simulation and experimental results show that there is a linear relationship between the pressure decay rate and the internal leakage rate. Especially for working pressures greater than 16 MPa, the pressure factor has an insignificant impact on the application of this method.

Keywords
hydraulic cylinder, simulation and experiment, internal leakage, pressure decay test, validation of effectiveness

1. Introduction

Hydraulic cylinder is one of the most important executive components in modern industrial equipment [32]. Hydraulic cylinders have been widely used in various fields due to their simple structure, fast response and high load capacity [23]. Hydraulic cylinder leakage is one of the important performance indicators to judge whether the hydraulic cylinder is qualified, and is a mandatory item in the hydraulic cylinder acceptance test [17]. Generally, it can be divided into internal leakage and external leakage according to the location. Internal leakage [8] can be caused by the variability of material, manufacturing and assembly processes or the failure of sealing, resulting in hydraulic fluid leaking from the working chamber into the low-pressure chamber. External leakage is mainly to check whether there is leakage at the static seal of the cylinder, at the joint surface, at the welding and at the adjustable mechanism. It is easy to find by careful observation. Internal leakage is common but hidden [43]. It is difficult to evaluate the sealing condition by visual inspection before the fault occurs. If the presence of internal leakage can be detected in the acceptance test, damage due to internal

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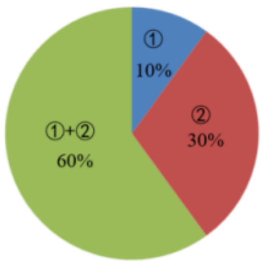
leakage failure can be avoided. Reduce downtime and maintenance costs [6]. Therefore, the internal leakage detection of hydraulic cylinders in the acceptance test is particularly important.

Currently, the acceptance test of hydraulic cylinder internal leakage detection method is usually divided into direct measurement method and indirect measurement method [20]. Direct measurement method, including measuring cup measurement method [9], is a common method for hydraulic cylinder leakage detection in the national standard at present. This method measures the rate of oil leakage in a certain period of time by measuring cup. The overall structure of the test bench of the measuring cup measurement method is simple and low cost, and the measurement is inefficient and time-consuming. However, in the case of very small internal leakage, it may not be possible to guarantee the accuracy of measurement. Indirect measurement methods include the piston settling method, the compensating oil pump method [25] and the pressure decay test method. The piston settling method [44] can measure the internal leakage of the hydraulic cylinder at any stroke by collecting the piston displacement signal. However, an additional loading test bench needs to be built and the experimental cost is high. Compensating oil pump method can restore the hydraulic cylinder to its rated pressure through metering pump, so that it can detect tiny leakage in the hydraulic cylinder. This method is very accurate and effective, but it can be affected by leakage from other parts of the system. The pressure decay test method [37] collects the pressure signal of the high pressure chamber and determines whether there is a leak by the pressure decay rate during the pressure holding time. This method is easy to measure pressure signals, with high detection efficiency, and does not need to convert the measured values into internal leakage. It can visually judge whether there is internal leakage in the hydraulic cylinder by the pressure decay rate. Therefore, most manufacturers currently use the pressure decay test method to perform leakage acceptance testing of hydraulic cylinders. Table 1 shows the results of the research on the methods used for internal leakage detection in companies. There are ten companies in this research and they are presented in anonymous form. Ten percent of the surveyed companies use the measuring cup method, 30% use the pressure decay test method, and 60% use both methods. In summary, 90% of the companies support the use of the pressure decay test method. However, there are many difficulties in the use of the pressure decay test method, and there is no relevant specification to support it. This leads to the pressure decay test method is still difficult to recommend for use in industry or international standards.

Table 1. Questionnaire on the application of leakage detection methods in hydraulic cylinders.

Research time: 2021.11.26-2022.2.27				Detection method: ①Measuring cup measurement method
Research method: questionnaire + offline				②Pressure decay test method
Enterprise name	①	②	①+②	Survey Statistics
1. Company A			●	
2. Company B			●	
3. Company C		●		
4. Company D			●	
5. Company E			●	
6. Company F		●		
7. Company G		●		
8. Company H	●			
9. Company I			●	
10. Company J			●	
Conclusion: The pressure decay test method is widely used in the enterprise and has a high percentage.				

In the hydraulic cylinder acceptance test of the internal leakage performance test mainly has the above methods. At present, the leakage detection about hydraulic cylinder is mainly for the operation and maintenance aspect. In recent years, a large number of theoretical and applied methods have been proposed by scholars from various countries regarding the detection of the internal leakage rate of hydraulic cylinders by various signal characteristics [29,45]. An and Sepehri [2] used an Extended Kalman Filter (EKF) to identify internal leaks at the piston seal of a hydraulic cylinder and external leaks occurring at the piston rod seal. The results show that different types of leakage can be identified by calculating the residual between the measured pressure and predicted pressure. Goharrizi et al [11-13] used wavelet transform to monitor and diagnose the fluid leakage inside and outside the hydraulic cylinder. A multi-resolution decomposition technology is used to decompose the pressure signal into details and approximate wavelet coefficients. It was shown that the root mean square features extracted from the level two detail coefficients can be used to identify the presence of leak faults. Tang et al [33] applied wavelet transform and back propagation neural network to the pressure signal. The results show that this method can effectively identify the extent of leakage. Qiu et al. [26] used the analysis by computational fluid dynamics technique to find the energy characteristics of the pressure signal related to internal leakage. Statistics on energy characteristics can be used to detect internal leaks. The results show that the method has a better accuracy compared to other classical detection methods. Tan [34,35] and Yunbo [41] proposed a method based on time domain and frequency domain features to diagnose the leakage status of water hydraulic cylinders by acquiring vibration signals. Chen [5] used acoustic emission (AE) signals for the detection of hydraulic cylinder leakage less than 1.0 l/min and showed that the root mean square (RMS) value could explain the AE signals due to leakage. As mentioned above, in most cases, leakage faults are detected using classification algorithms after extracting features by means of signal processing. As shown in Table 2, these methods are effective for modelling complex faults and are highly accurate in detecting internal leaks. However, most methods require large data sets and higher economic costs. Therefore, the existing methods are difficult to be applied to the internal leakage rapid detection of hydraulic cylinders in acceptance test.

Table 2. Internal leakage detection method literature research table.

Research Subjects	Signal	Technique	Paper	Advantages and Shortcomings
Hydraulic cylinder	Pressure	EKF	[1],[2]	● It has high detection accuracy. ○ Requires higher economic costs. ○The maturity of the technology needs further verification.
		HHT	[10]	
		Wavelet Transform	[11-13],[21,22],[33]	
	Displacement		[43]	
		PNN	[14]	
	Vibration	Time-domain and frequency-domain features	[34,35],[41]	
	AE		[5],[30,31]	

According to the above mentioned enterprise application survey and literature research, the existing data-driven internal leakage detection methods have high detection accuracy, but the maturity of the technology for industrial applications needs further study. However, there is an urgent need for an rapid and convenient testing method to be applied to the acceptance leakage test of hydraulic cylinders to determine whether they are qualified. The pressure decay test method is a common method of quickly testing hydraulic cylinders for internal leakage in the manufacturing industry. Therefore, this paper proposes a validation test scheme for the internal leakage detection method based on the pressure decay test method, and investigates the validity and effective application range of the method. Compared to existing researches, the main points of innovation in this paper are as follows:

(1) The various factors influencing internal leakage are studied and analyzed, which provides theoretical guidance for simulation verification and experimental tests.

(2) The validity and effective range of the pressure decay test method are verified by simulation and experiment respectively. It provides theoretical basis for promoting and applying the pressure decay test method for leakage detection in engineering practice.

2. Analysis of internal leakage models for hydraulic cylinders

The overall research idea of this paper is shown in Fig. 1. Firstly, various types of key factors affecting the internal leakage of hydraulic cylinders are derived through research and analysis. Then, an effectiveness verification test scheme based on the pressure decay test method is proposed and simulated using AMESim. Finally, the simulation results are further verified by a test bench.

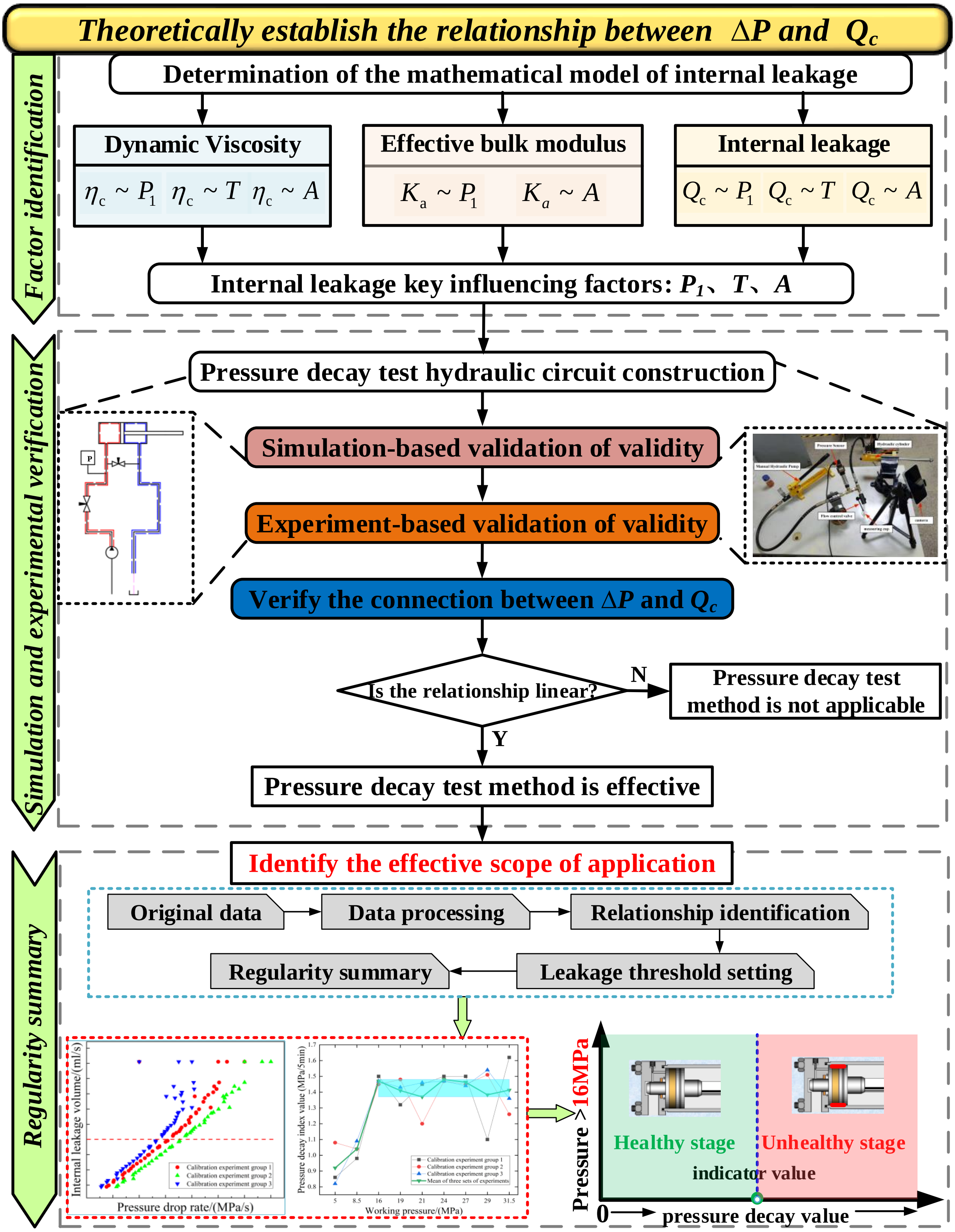


Fig. 1. Schematic of the overall research scheme of the pressure decay test method.

2.1 Hydraulic cylinder internal leakage mathematical model

Internal leakage is the flow of hydraulic fluid from the working chamber to the low pressure chamber during operation. External leakage means that the fluid flows into the external environment. Combined with the actual hydraulic engineering, the main consideration in this thesis is the internal leakage. It is considered as eccentric ring leak gap flow. The simplified model of internal leakage is shown in Fig. 2.

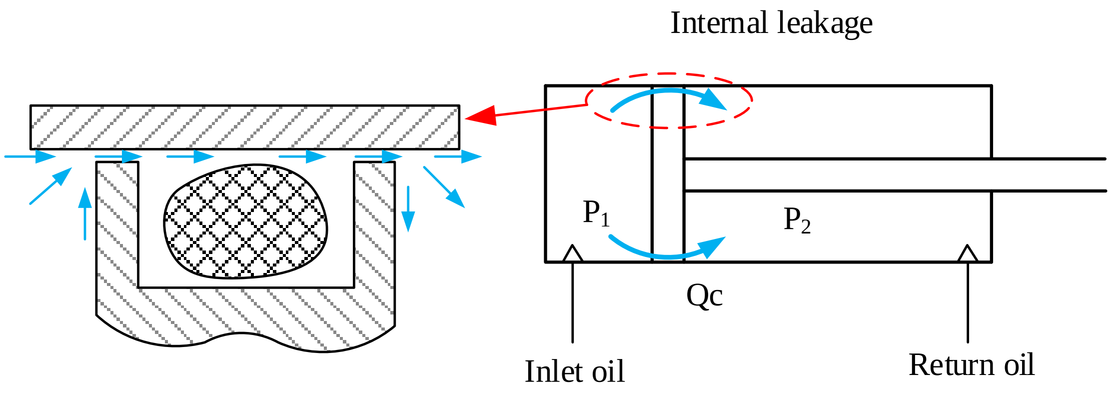


Fig. 2. Diagram of internal leakage of the hydraulic cylinder.

According to the eccentric ring leak gap flow model [40], the hydraulic cylinder leakage rate Q_C can be calculated according to equation (1).

$$Q_c = \pi d h^3 \frac{(1+1.5\varepsilon^2)(P_1-P_2)}{12\eta l} \quad (1)$$

Where, Q_c is the internal leakage rate , P_1 is the pressure on the high pressure side of the gap, P_2 is the pressure on the low pressure side of the gap, d is the diameter of the cylinder, ε is the relative eccentricity, $\varepsilon = e/h$ where e is the eccentricity, h is the size of the gap, η is the dynamic viscosity of the fluid, and l is the gap length. The leakage rate Q_c is related to the testing time.

In this paper the physical parameters of the hydraulic cylinder are integrated as structural coefficients, which can be expressed as shown in equation (2). The structural coefficient K_s is related to the structure size of the cylinder.

$$K_s = \pi d h^3 \frac{(1+1.5\varepsilon^2)}{12l} \quad (2)$$

In engineering practice, the internal leakage of hydraulic cylinders varies with the working pressure, temperature, and air content of the system. Therefore, the internal leakage of the system can be influenced by many factors. The influence of working pressure, working temperature and air content on internal leakage can be attributed to the influence on dynamic viscosity and compressibility of hydraulic fluid. In this paper, the effect of working pressure on the hydraulic fluid dynamic viscosity is chosen from the Barus model as in equation (3). The effect of temperature on the hydraulic fluid dynamic viscosity is chosen from the Reynolds model as in equation (4). According to Equation (5), the influence of air content on the dynamic viscosity of hydraulic fluid is calculated [40].

$$\eta_P = \eta_0 \exp \alpha P \quad (3)$$

$$\eta_T = \eta_0 \exp\left(-\beta(T - T_0)\right) \quad (4)$$

$$\eta_A = \eta_0(1 + 0.015A_1) \quad (5)$$

Thus the integrated dynamic viscosity can be calculated according to equation (6).

$$\eta_c = \eta_0(1 + 0.015A_1)\exp[\alpha P_1 - \beta(T - T_0)] \quad (6)$$

Where, η_0 is the dynamic viscosity of the fluid at atmospheric pressure, A_1 is the rate percentage occupied by air bubbles in the hydraulic fluid, β is the viscosity-temperature coefficient, α is the viscosity-pressure coefficient, T is the working temperature , T_0 is the initial temperature of the hydraulic fluid, and η_c is the integrated dynamic viscosity. A_1 detailed computational modeling is shown in Ref. 40.

The effect of working pressure on the compressibility of hydraulic fluid [40], the model as in equation (7) is chosen in this paper. The effect of temperature on the compressibility of hydraulic fluid is modeled as in equation (8). The effect of air content on the compressibility of hydraulic fluid is calculated according to equation (9).

$$Q_P = Q_0[1 + (P_1 - P_2)/K_0] \quad (7)$$

$$Q_T = Q_0[1 + \gamma(T - T_0)] \quad (8)$$

$$Q_A = Q_0[1 + (P_1 - P_2)/K_a] \quad (9)$$

Where, Q_0 is the theoretical internal leakage of the hydraulic cylinder, γ is the coefficient of thermal expansion, and K_a is the bulk modulus of elasticity of the hydraulic fluid after mixing with air.

2.2 Analysis of the bulk modulus model

The bulk modulus of elasticity is an inherent property of the fluid. It can characterize the compression characteristics of hydraulic fluid during operation. It is generally considered that the bulk modulus of elasticity is constant. However, in the analysis of hydraulic system working conditions change greatly or dynamic characteristics. In order to better reflect the compression characteristics in the actual work process, it is necessary to introduce the effective bulk elastic modulus. Its value is mainly related to the working pressure, working temperature and air content. In practice the temperature is usually kept within a small enough variation that temperature fluctuations can be ignored. Therefore, a suitable model needs to be introduced to describe the effect of pressure and air content on internal leakage. There are four commonly used models for the effective bulk modulus of elasticity of hydraulic fluid: the Wylie model [19], the Yu model [18], the Nykanen model [24], and the Ruan model [27], which is shown in equation (10).

$$K_a = \begin{cases} \frac{K_0}{AP_2K_0\left(\frac{1}{P_1^2}-\frac{1}{P_c^2}\right)+1}, & P_2 < P_1 < P_c \\ K_0, & P_1 \geq P_c \end{cases} \tag{10}$$

Where P_2 is the atmospheric pressure; P_c is the critical pressure; K_0 is the pure oil bulk modulus of the hydraulic fluid; and A is the relative amount of entrained air at atmospheric pressure.

The portion of air in the fluid in the form of bubbles has a great effect on the bulk modulus of the hydraulic fluid. On the other hand, air dissolved in fluid has little effect. The two forms of existence reach equilibrium under certain pressure conditions. Wylie, Yu and Nykanen models assume that the air content in fluid is constant, while Ruan model holds that the solubility of air in the fluid is a dynamic process. It takes into account the transformation of the undissolved air with pressure changes and thus the effect on the effective bulk modulus of the hydraulic fluid. The Ruan model is more in line with the engineering reality and is used in the studies in the literature [38,7,15,16], so it is chosen to express the effect of pressure and air content on the effective bulk modulus of the hydraulic fluid.

Regarding the critical pressure value for the equilibrium state of air dissolved in the fluid, Yang et al [42] conducted test experiments and theoretical simulations by testing the bulk modulus of elasticity of hydraulic fluids. It was found that the bulk modulus of elasticity of hydraulic fluid tends to stabilize at more than 8.5 MPa, which is close to the value of elastic modulus of pure fluid. By comparing the trends of the bulk modulus at 25℃ and 45℃, it was found that the bulk modulus is similar when the working pressure is greater than 8.5 Mpa, and tended to be constant at the two temperatures. This value was also used in the literature [4,36,39] when studying the effective bulk modulus of elasticity of hydraulic fluids. Therefore, in this paper, the critical pressure P_c is determined to be 8.5 MPa.

Therefore, after taking into account the influence of working pressure, temperature and air content. The internal leakage rate Q_c for the hydraulic cylinder eccentric ring leakage gap flow model can be derived from Eq. (1)-Eq. (10) as shown in Eq. (11). The parameters of the variables in the mathematical model of internal leakage are shown in Table 3.

$$Q_c = K_s(P_1 - P_2)[1 + \gamma(T - T_0)]\frac{[1+(P_1-P_2)/K_a]}{\eta_c} \tag{11}$$

Table 3. Variables in the internal leakage rate calculation model.

Variable	Value	Description
η_0	0.5[Pa·s]	Dynamic viscosity of the fluid at atmospheric pressure
β	0.02[K^{-1}]	Viscosity-temperature coefficient
α	1.2×10-8[m^2/N]	Viscosity-pressure coefficient
K_s	4.9765×10-14[m^3]	Structural coefficient
P_1	0-50[MPa]	High pressure side pressure
P_2	0.1[MPa]	Atmospheric pressure
γ	6.2×10-4[K^{-1}]	Coefficient of thermal expansion
T	20-60[℃]	Working temperature
T_0	15[℃]	Initial temperature
K_0	1.5[GPa]	Bulk modulus of pure oil
P_c	8.5[MPa]	Critical pressure
A	3-15[%]	Relative amount of entrained air at atmospheric pressure
K_a	—[GPa]	Bulk modulus of entrained air
η_c	—[Pa·s]	Integrated dynamic viscosity
A_1	—[%]	Percentage of air bubbles in hydraulic fluid

3. Analysis of influencing factors of hydraulic cylinder leakage

This section analyzes the factors influencing the internal leakage of the hydraulic cylinder. Based on the mathematical model of internal leakage in Section 2.1, this paper considers the influencing factors of internal leakage as three kinds of influencing factors: high pressure side pressure, working temperature and air content. The analysis steps are shown in Fig. 3.

This chapter on the hydraulic cylinder of the internal leakage of factors affecting the consideration of the high-pressure side pressure P_1, operating temperature T and gas content A. According to the actual enterprise research and standard regulations [9,17], it is found that the internal leakage test of the hydraulic cylinder pressure is generally below 31.5 MPa. Therefore, this paper expands to 50 MPa and is divided into low pressure (5 MPa -8 MPa), medium pressure (8 MPa -16 MPa) and high pressure (16 MPa -50 MPa). The working temperature is determined as 20℃, 40℃, 60℃ three levels, and the temperature increase is controlled within 5℃. The air content was determined as five levels of 3%, 6%, 9%, 12% and 15%. Research scope of the above variables has been able to cover most working conditions, which is close to engineering practice.

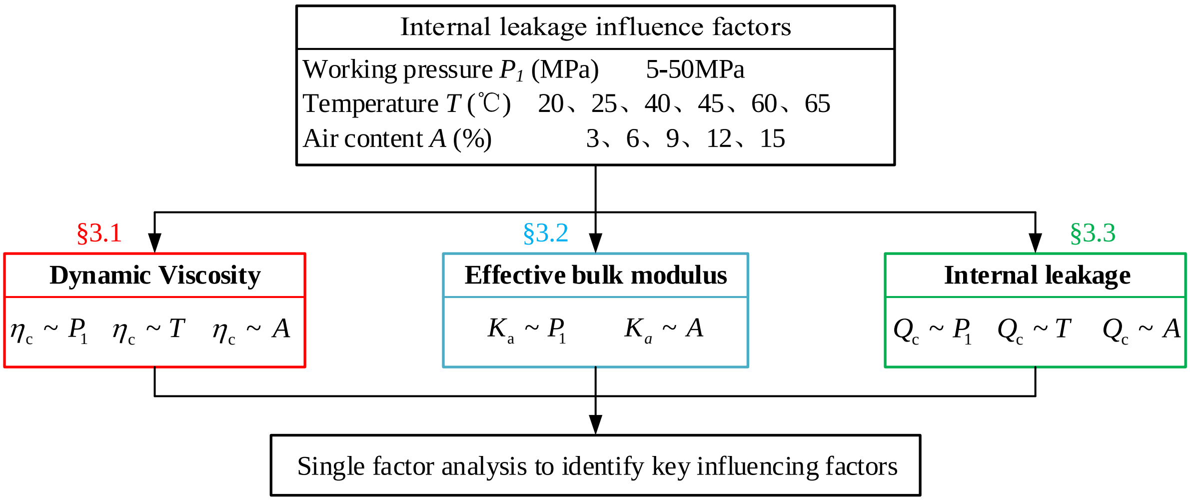


Fig. 3. Diagram of internal leakage of the hydraulic cylinder.

3.1 Analysis of the effect of air content, temperature and pressure on dynamic viscosity

Fig. 4 shows the trend of dynamic viscosity with pressure and air content at different working temperatures.

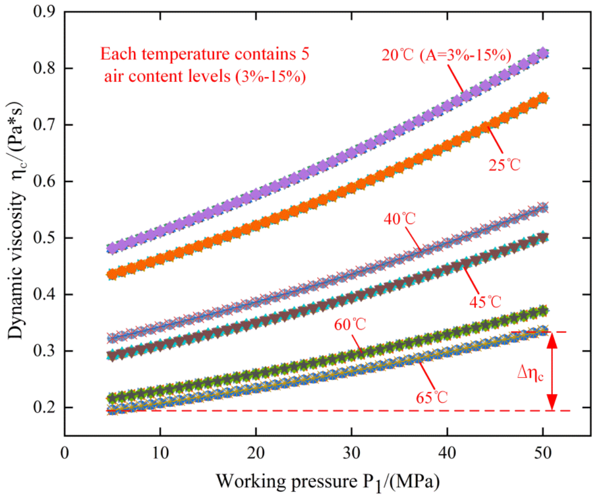


Fig. 4. Trend of dynamic viscosity with temperature and air content at different pressure.

The dynamic viscosity of the initial air content A at 3%, 6%, 9%, 12% and 15% are analyzed respectively, while the initial working temperature T=20℃, 40℃ and 60℃ is controlled, and the allowed fluctuation range is 5℃. The effect of high-pressure chamber pressure P_1 on the dynamic viscosity (η_c~P_1) was analyzed by the Single factor analysis method. It can be seen from the graph that when the air content and working temperature T are certain, the dynamic viscosity of hydraulic oil increases gradually (71.68%) as the pressure level increases (5 MPa-50 MPa). When the pressure and air content are certain, the dynamic viscosity gradually decreases with the increase of temperature.

The effect of the working temperature T on the dynamic viscosity (η_c~T) was analyzed by the Single factor analysis method. According to Fig. 4, when the working temperature T = 20 °C becomes T = 60 °C at a certain air content, the rate of change of dynamic viscosity at each pressure level and each air content level is -55.0681% to -55.4188%. The rates of change at different pressure levels are shown in Table 4. With the increase of pressure level, the effect of air content on the dynamic viscosity is gradually smaller. The effect of working temperature T on the dynamic viscosity ($\eta_c \sim A$) was analyzed by the Single factor analysis method. When the working temperature is certain, different air content (3%-15%) at each pressure level has almost no effect on the change of dynamic viscosity.

Table 4. Effect of temperature and air content on dynamic viscosity.

Working pressure P_1/Mpa	Effect of temperature on dynamic viscosity $d\eta_T$/%	Effect of air content on dynamic viscosity $d\eta_A$/%
	$d\eta_T = \frac{\eta_{T_{i,j,60℃}} - \eta_{T_{i,j,20℃}}}{\eta_{T_{i,j,20℃}}}$	$d\eta_A = \frac{\eta_{T_{i,15\%,k}} - \eta_{T_{i,3\%,k}}}{\eta_{T_{i,3\%,k}}}$
Low Pressure（5-8）	-55.0725< $d\eta_T$<-55.4188	0.1798< $d\eta_A$<0.1799
Medium pressure（8-16）	-55.0699< $d\eta_T$<-55.0725	0.1798
High Pressure（16-50）	-55.0681< $d\eta_T$<-55.0699	0.1797< $d\eta_A$<0.1798

Where, i represents a certain working pressure; j is a certain air content level; k is a certain temperature level ; $\eta_{T_{i,j,20℃}}$ represents the dynamic viscosity at working pressure of i MPa, air content of j %, and temperature T=20°C ; $\eta_{T_{i,3\%,k}}$ represents the dynamic viscosity at working pressure of i MPa, temperature of k°C, and air content of j = 3%.

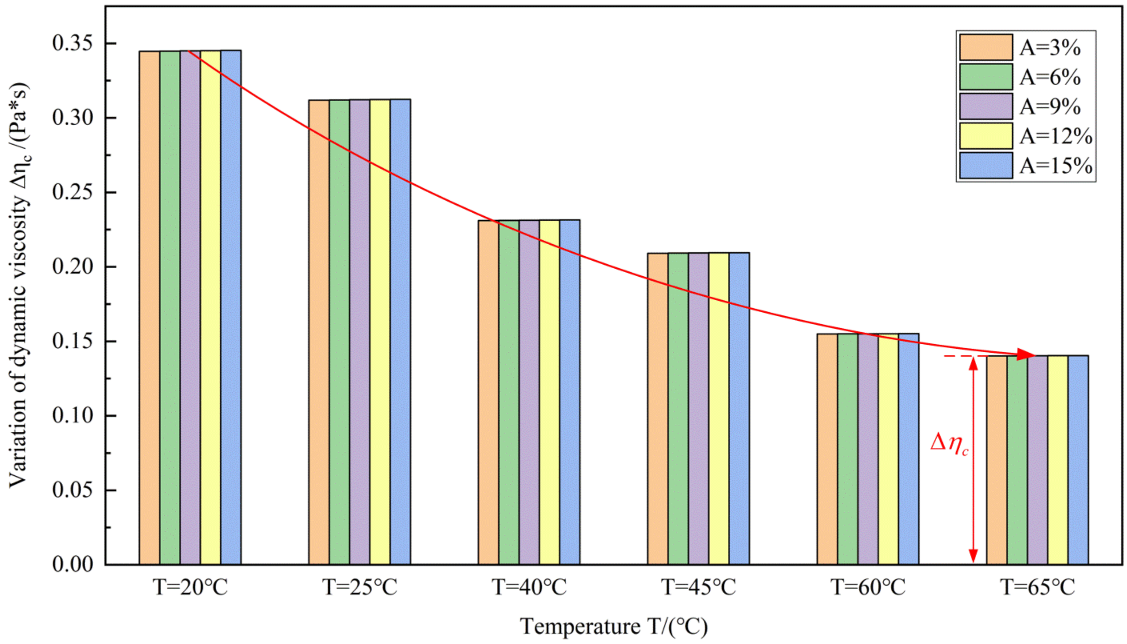


Fig. 5. Effect of different temperatures on dynamic viscosity with pressure and air content.

Fig. 5 shows the analysis of the effect of different air content and temperature on the degree of variation of dynamic viscosity in the range of 5 MPa to 50 MPa. The analysis results in Table 4 are further demonstrated and verified. When the air content is certain and the working temperature T fluctuates from 20℃-25℃, 40℃-45℃ and 60℃-65℃, the corresponding dynamic viscosity change rate is roughly -9.5% at each pressure level and air content. Therefore, when the working temperature fluctuation is not less than 5℃ will lead to a large change in dynamic viscosity. Table 5 analyzes the rate of change of dynamic viscosity when the working temperature fluctuates at 3℃, 2℃ and 1℃ respectively. The results show that the rate of change of dynamic viscosity is less than 5% when the maximum working temperature fluctuation is less than 2℃ at constant temperature. It is within the acceptable error range of engineering practice.

Table 5. Influence of different temperature fluctuation levels on dynamic viscosity.

Temperature T fluctuation range(°C)	Effect of temperature fluctuations on dynamic viscosity $d\eta_{\triangle T}$/% $d\eta_{\triangle T}=\frac{\eta_{T_{i,j,k_2}}-\eta_{T_{i,j,k_1}}}{\eta_{T_{i,j,k_1}}}$
20-25、40-45、60-65	-9.5165~-9.5185
20-23、40-43、60-63	-5.8249~-5.8237
20-22、40-42、60-62	-3.9220~-3.9212
20-21、40-41、60-61	-1.9806~-1.9802

Where, i represents a certain working pressure; j is a certain air content level; k_i is a certain temperature level ; $\eta_{T_{i,j,k_1}}$ represents the dynamic viscosity at working pressure of i MPa, air content of j%, and temperature k_1℃.

3.2. Analysis of the effect of air content and pressure on bulk modulus

According to the research analysis in section 2.2, this paper assumes that the effect of temperature on the effective bulk modulus of hydraulic fluid is not considered. Fig. 6 shows the effect of different pressure and air content levels on the effective bulk modulus. As can be seen from the figure, before reaching the air separation pressure (8.5 MPa), the effective bulk modulus of hydraulic fluid becomes significantly larger as the air bubbles in the fluid gradually dissolve with the increase of pressure. After reaching the air separation pressure, the air bubbles have all been dissolved in the fluid as the pressure increases, and the bulk modulus remains constant. The value is the bulk modulus of pure fluid.

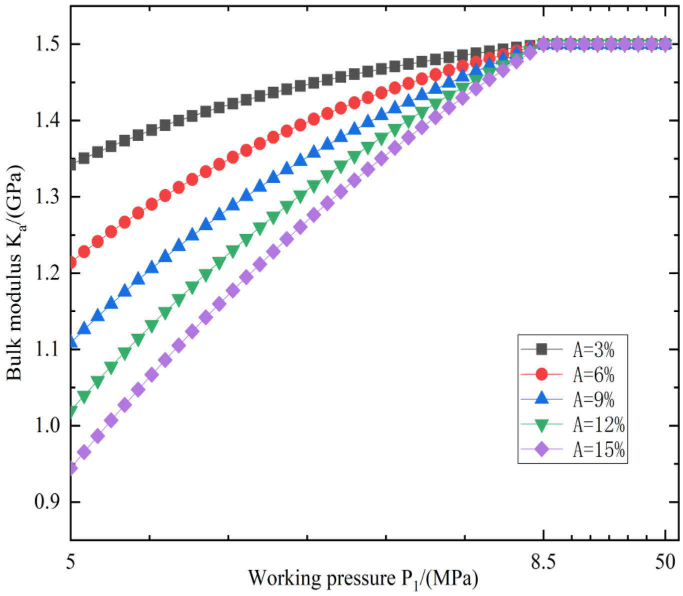


Fig. 6. Trend of bulk modulus with pressure and air content.

From Fig. 6, it can be seen that at pressures below 8.5 MPa, different air contents have different degrees of influence on the effective bulk modulus as the pressure increases. When the air content increased from 3% to 15%, the rate of change of the bulk modulus caused by the pressure change (5 MPa-8.5 MPa) changed from 6.99% to 34.7%. The lower the air content, the smaller the degree of influence of pressure change on the effective bulk modulus.

3.3. Analysis of the effect of air content, pressure and temperature on the rate of internal leakage

Fig. 7 shows the trend of internal leakage rate with pressure and air content at different working temperatures. The leakage rate at 3%, 6%, 9%, 12% and 15% of the initial air content A are analyzed respectively, while the working temperatures T=20℃, 40℃ and 60℃ are controlled, and the allowable fluctuation range is 5℃. The effect of high-pressure chamber pressure P_1 on the leakage rate was analyzed by the Single factor analysis method (Q_c~P_1). It can be seen from the graph that when the air content and working temperature T are certain, the internal leakage rate will gradually increase (about 500%) as the pressure level increases (5 MPa-50 MPa). When the pressure and air content is certain, the internal leakage rate gradually increases with the increase of temperature.

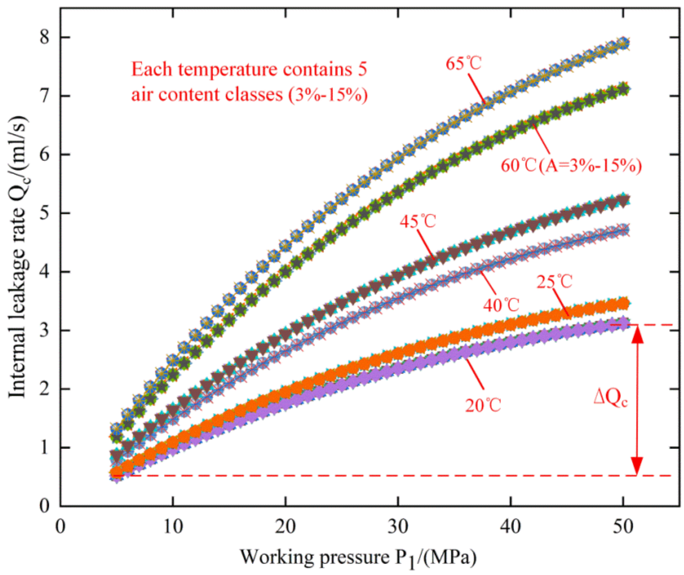


Fig. 7. Trend of internal leakage rate with temperature and air content at different pressure.

The effect of the working temperature T on the leakage rate (Q_c ~T) was analyzed by the Single factor analysis method. As shown in Fig. 7, the working temperature has a large effect on the leakage rate. Under the condition of a certain air content, the rate of change of leakage rate from T = 20 °C to T = 60 °C is 128.0612% to 129.8552% at each pressure level and each air content level. The rates of change at different pressure levels are shown in Table 6. By analyzing the effect of air content on the leakage rate through the Single factor analysis method (Q_c~A), the effect of air content on the internal leakage rate is gradually smaller as the pressure level increases. When the working temperature is certain, different air content (3%-15%) at each pressure level has almost no effect on the leakage rate.

Table 6. Effect of temperature and air content on leakage rate.

Working pressure P_1/Mpa	Effect of temperature on leakage rate dQ_T/%	Effect of air content on leakage rate dQ_A/%
	$dQ_T = \frac{Q_{T_{i,j,60°C}} - Q_{T_{i,j,20°C}}}{Q_{T_{i,j,20°C}}}$	$dQ_A = \frac{Q_{T_{i,15\%,k}} - Q_{T_{i,3\%,k}}}{Q_{T_{i,3\%,k}}}$
Low pressure（5-8）	128.0835< dQ_T<129.8552	-0.0234< dQ_A<-0.1625
Medium pressure（8-16）	128.0705< dQ_T<128.0837	-0.1625< dQ_A<-0.1794
High pressure（16-50）	128.0612< dQ_T<128.0705	-0.1794

Where, i represents a certain working pressure; j is a certain air content level; k is a certain temperature level ; $Q_{T_{i,j,20°C}}$ represents the leakage rate at working pressure of i MPa, air content of j %, and temperature T=20°C and $Q_{T_{i,3\%,k}}$ represents the leakage rate at working pressure of i MPa, temperature of k°C, and air content of j = 3% .

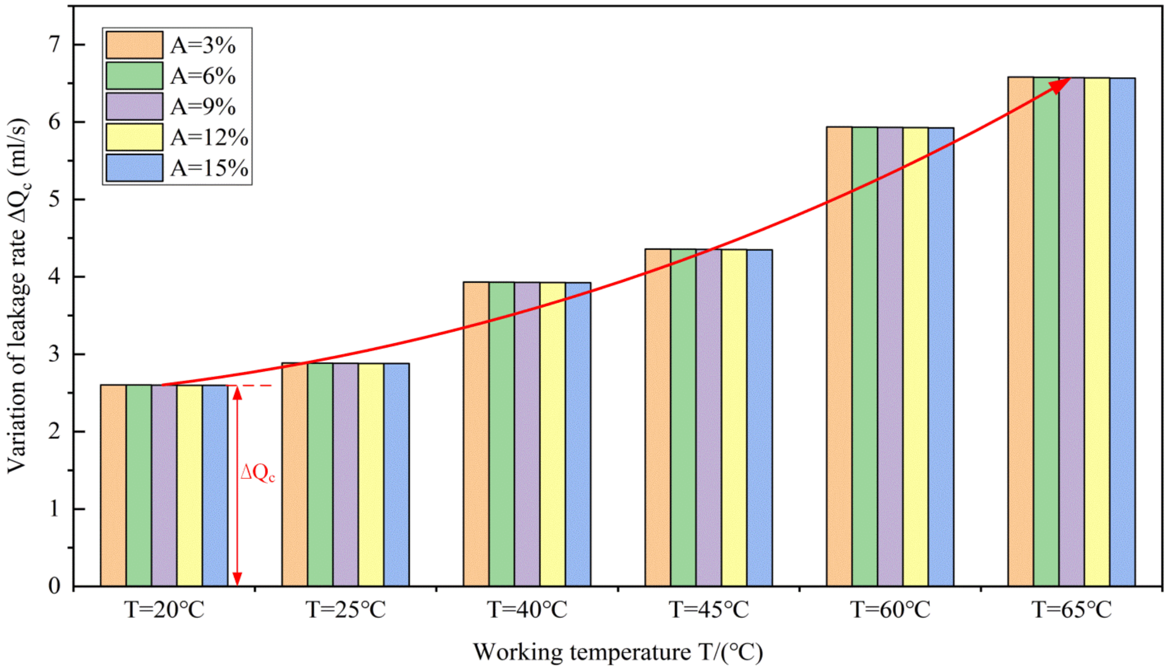


Fig. 8. Trend of leakage rate with temperature and pressure at different air content.

Fig. 8 shows the analysis of the effect of different air content and temperature on the degree of variation of the internal leakage rate in the range of 5 MPa to 50 MPa. When the air content is certain, the leakage rate increases significantly at each pressure level as the working temperature T increases. As shown in Table 7, when the working temperature T is certain, the different air content at each pressure level has basically no effect on the leakage rate. When the air content is certain and the working temperature T fluctuates at 20℃-25℃, 40℃-45℃ and 60℃-65℃, the corresponding leakage rate change rate is 10.8604%-10.8507% at each pressure level and each air content case. Therefore, when the working temperature fluctuation is not less than 5℃ leakage rate changes more. The results show that the thermostatic working conditions allow the maximum working temperature fluctuations of less than 2 ℃, the rate of change of internal leakage rate is less than 5%.

Table 7. Effect of different temperature fluctuation levels on leakage rate.

Temperature T fluctuation range(°C)	Effect of temperature fluctuations on leakage rate $dQ_{\triangle T}$/%
	$dQ_{\triangle T}=\frac{Q_{T_{i,j,k_2}}-Q_{T_{i,j,k_1}}}{Q_{T_{i,j,k_1}}}$
20-25、40-45、60-65	10.8604-10.8507
20-23、40-43、60-63	6.3813-6.3760
20-22、40-42、60-62	4.2100-4.2067
20-21、40-41、60-61	2.0830-2.0817

Where, i represents a certain working pressure; j is a certain air content level; k_i is a certain temperature level ; $Q_{T_{i,j,k_1}}$ represents the leakage rate at working pressure of i MPa, air content of j %, and temperature k_1℃.

Based on the above discussion and analysis the following conclusions are drawn. When analyzing the internal leakage rate, it is necessary to focus on the influence of high pressure chamber pressure P_1 and working temperature T. In the low pressure case (less than 8.5 MPa) need to consider the influence of the air content.

4. Simulation-based analysis of the validation results of the pressure decay test method

In this section, a validation scheme based on the pressure decay test method is proposed. The validity of the pressure decay test method is verified by simulation analysis. The principle of simulation analysis is shown in Fig. 9.

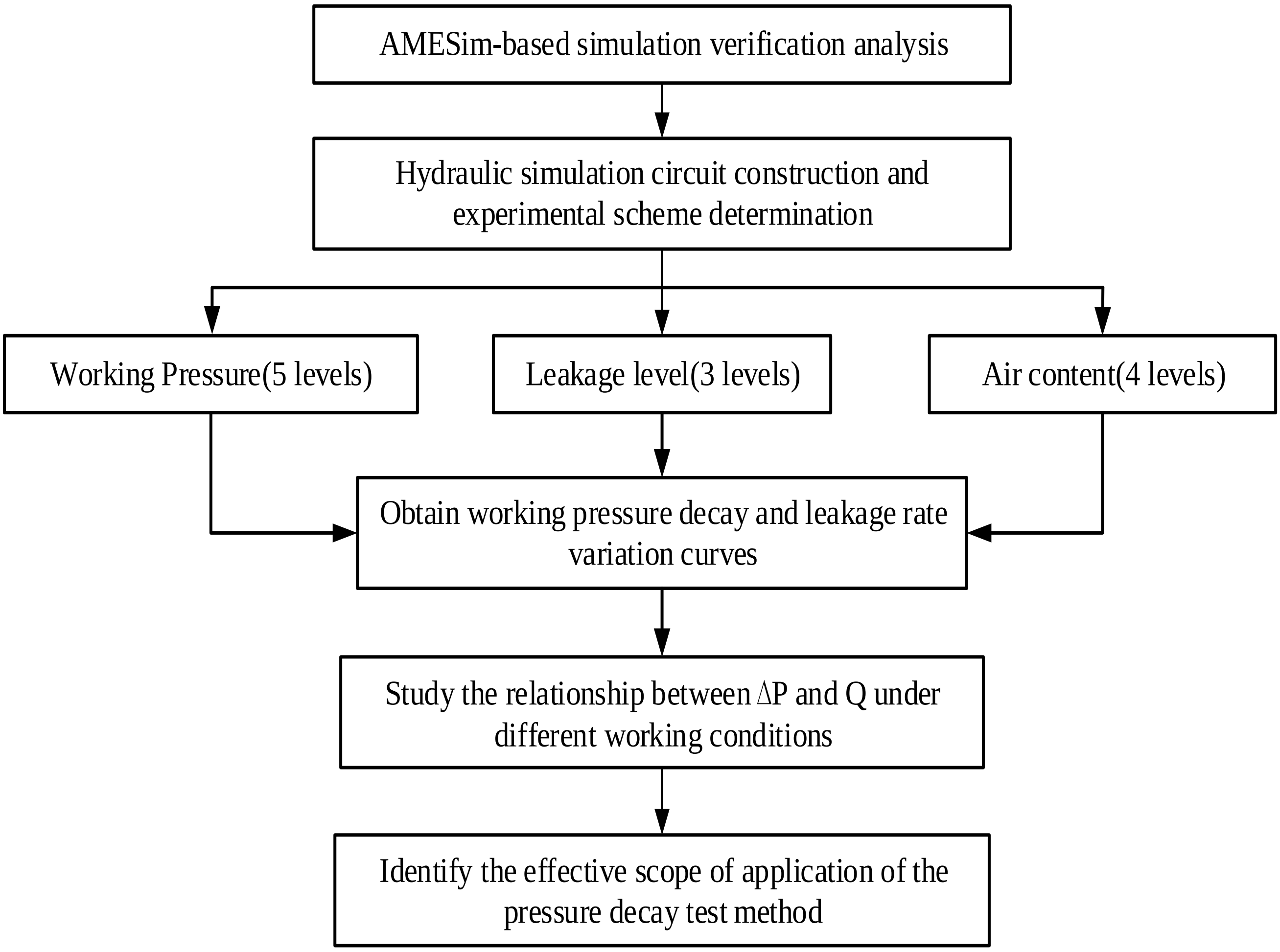
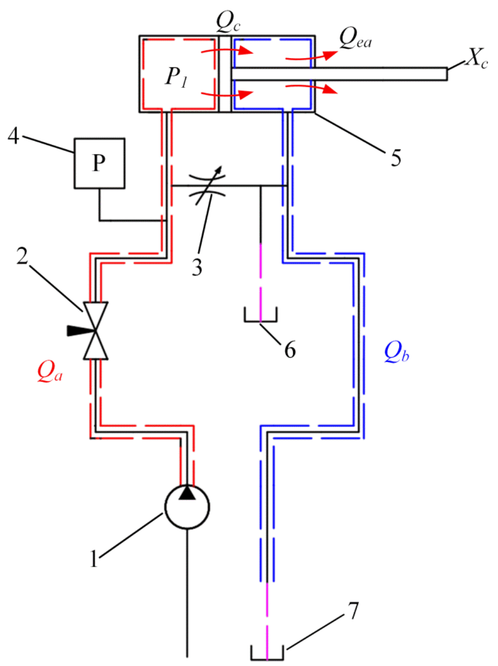


Fig. 9. Schematic diagram for simulation verification of the pressure decay test method.

4.1 Hydraulic cylinder internal leakage detection model and framework based on pressure decay test method

The schematic diagram of the hydraulic circuit for the leakage detection test inside the hydraulic cylinder is shown in Fig. 10, where the high pressure side circuit (red dashed box) and the low pressure side circuit (blue dashed box) are the two control volumes.



1-Hydraulic pump; 2-Globe valve; 3-Flow control valve
4-Pressure sensor; 5-Experimental hydraulic cylinder; 6,7-Tank;

Fig. 10. Hydraulic circuit schematic.

The basic principle behind the continuity equation is conservation of mass. Since this paper focuses on the flow in the high pressure side circuit, the continuity equation of the high pressure side control rates are derived [3]. The mass flow rate Q_a in the high pressure side circuit is not equal to the Q_b in the low pressure side circuit, it leads to piston displacement due to pressure increase. As shown in equation (12):

$$Q_a - Q_c - Q_{ea} = S_p \cdot \dot{x}_c + \frac{S_p \cdot x_c + V_h}{K_a} \cdot \dot{P}_1 \tag{12}$$

Where Q_a is the input flow rate, Q_c is the internal leakage flow rate, Q_{ea} is the external leakage flow rate, S_p is the piston rod cross-sectional area, x_c is the piston displacement, V_h is the volume of the high pressure side tubing, and $\dot{P}_1$ is the pressure change rate of the high pressure chamber. When the leakage experiment is conducted, assuming that the external leakage Q_{ea} is 0, the input flow rate Q_a is 0 during the pressure holding process, and the same piston rod displacement x_c is 0, equation (12) can be reduced to equation (13):

$$Q_c = -\frac{V_h}{K_a} \cdot \dot{P}_1 \tag{13}$$

The relationship between the leakage rate Q_c and the rate of change of the pressure in the high pressure chamber can be expressed as in equation (14):

$$Q_c \sim -\frac{1}{K_a} \dot{P}_1 \tag{14}$$

The pressure retention curve of the high pressure side capacitor cavity based on the pressure decay test method is shown in Fig. 11. By monitoring the pressure values $P(t_1)$ and $P(t_2)$ at moments t_1 and t_2 during the pressure decay, equation (14) can therefore be reduced to equation (15). t_1 and t_2 represent the start time and end time of pressure data monitoring after the start of the pressure holding process, respectively.

$$Q_c \sim -\frac{1}{K_a} \frac{[P(t_1) - P(t_2)]}{(t_2 - t_1)} \tag{15}$$

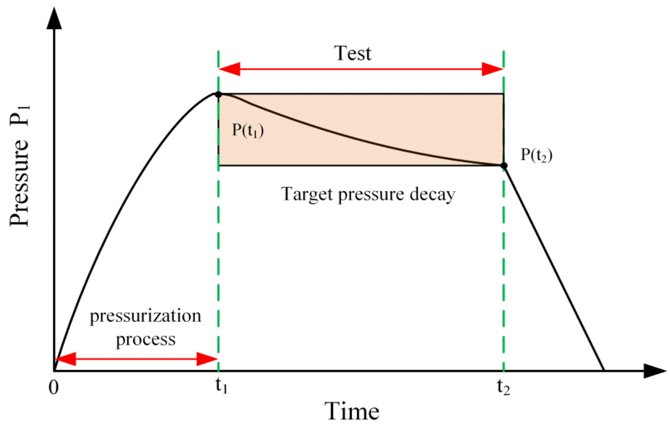


Fig. 11. Schematic of pressure holding curve of high pressure chamber.

Therefore, the pressure decay in the high pressure chamber and the leakage rate can be considered as a nearly linear relationship. The rationality of the application of the pressure decay test method is initially verified.

Since the internal leakage and pressure decay of a hydraulic cylinder is a dynamic process. In order to better simulate the process of internal leakage, a simulation-based dynamic study is conducted. In this paper, we propose a validation test scheme based on the pressure decay test method, which has the following five specific steps, as shown in Fig. 12.

Step 1: Through research and analysis, the test levels of various working conditions are obtained and the overall test plan is determined.

Step 2: The rod-less chamber of the hydraulic cylinder is pressurized to the determined pressure level. Starts the pressure holding process when the piston rod of the hydraulic cylinder fully extends to the maximum stroke position.

Step 3: Measure and record the pressure change curve $P(\mathrm{t})$ and the internal leakage change curve $V(\mathrm{t})$ in the high-pressure chamber during the pressure holding time Δt. The pressure change $P(\mathrm{t})$ and leakage rate $Q(\mathrm{t})$ are related to the testing time.

Step 4: According to the overall test scheme determined in Step 1, repeat the test under different working conditions.

Step 5: As shown in Fig. 13, calculate the average pressure decay rate and the internal leakage rate at different moments during the holding time, and summarize the relationship between pressure decay rate and internal leakage rate under different working conditions.

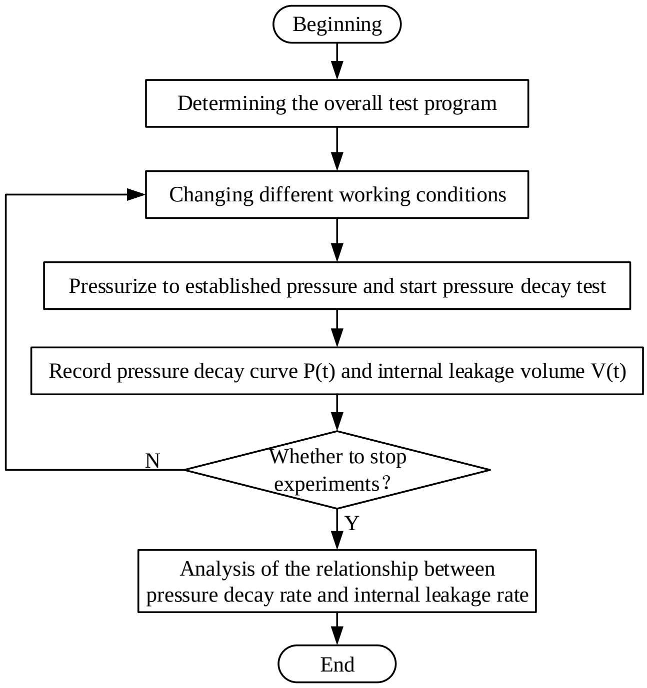


Fig. 12. Flow chart of the verification scheme based on the pressure decay test method.

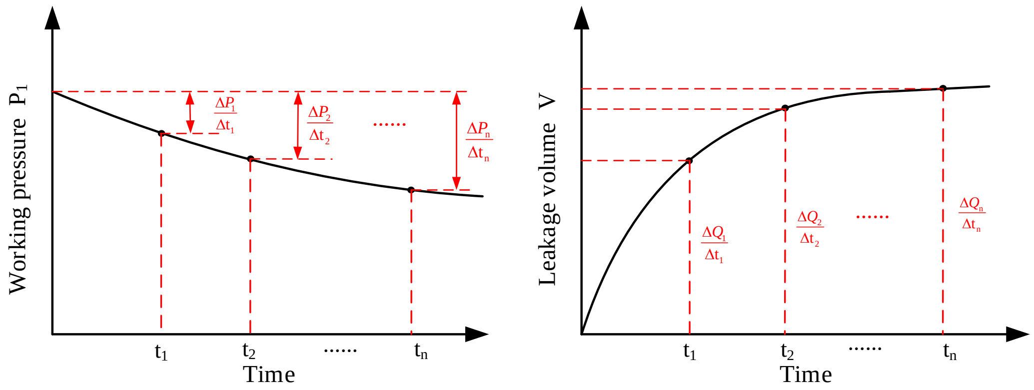


Fig. 13. Schematic of the data processing scheme

(a) Pressure change data (b) Internal leakage volume change data.

The tests were conducted according to the above validation test scheme based on the pressure decay test method. Since the internal leakage can be equated to the eccentric ring leak gap flow, the actual internal leakage rate can be approximated as a nearly linear relationship with the pressure decay rate. Based on the above analysis if the test results of internal leakage rate and pressure decay rate show an approximately regular linear relationship as shown in Fig. 14, the pressure decay test method can be considered feasible. Pressure decay rate can be used to characterize the rate of internal leakage, so as to determine whether the internal leakage of the hydraulic cylinder is qualified. Otherwise, the pressure decay test method is not applicable to the internal leakage detection.

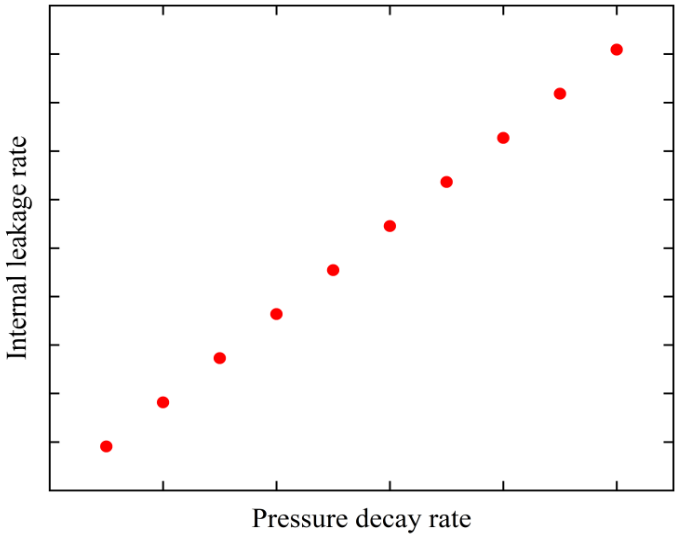
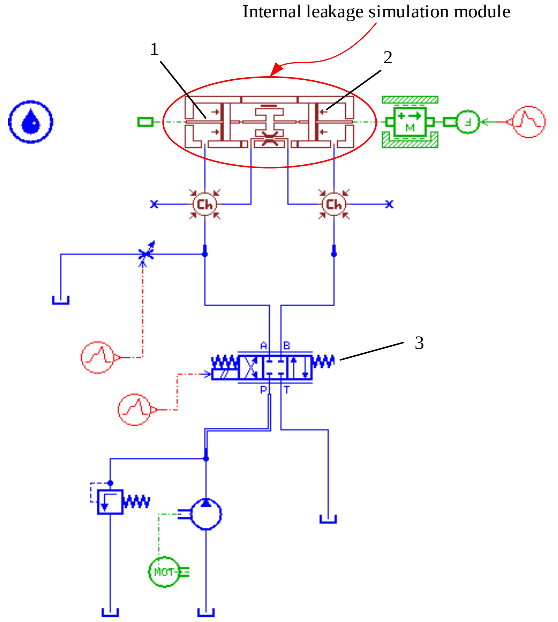


Fig. 14. Diagram of the relationship between pressure decay rate and internal leakage rate.

4.2 Experimental setup and protocol

AMESim is dedicated to the modeling, simulation and dynamics analysis of hydraulic mechanical systems. It is suitable for modeling in the field of machinery and hydraulics, and can well simulate the real situation in hydraulic engineering practice. In this case, the hydraulic circuit shown in Fig. 15 is used as the object of the simulation of internal leakage of a hydraulic cylinder.



1、Hydraulic cylinder without rod chamber 2、Hydraulic cylinder with rod chamber
3、Three-way four-way reversing valve

Fig. 15. Hydraulic cylinder internal leakage simulation working circuit model.

The hydraulic circuit consists of hydraulic cylinders, reversing valves, relief valves and other hydraulic components. In order to simulate the internal leakage of the hydraulic cylinder more realistically, the leakage module in the AMESim hydraulic component design library is used. The hydraulic oil flowing through the leakage module is the internal leakage during the pressure holding period.

In the simulation verification, the working chamber is first pressurized to the established pressure level by the hydraulic pump, and then the reversing valve is closed in the neutral position to realize the whole pressure-holding process. The pressure change curve $P(t)$ of the working chamber of the hydraulic cylinder and the rate of internal leakage flowing through the leakage module can be obtained. By studying the relationship between the pressure decay rate and the internal leakage rate in the working chamber during the pressure holding process, the validity of the pressure decay test method for detecting the internal leakage rate can be verified.

Based on the hydraulic simulation model in Fig. 15, a sub-model is selected for each component of the completed hydraulic system to simulate the whole pressure-holding process of the internal leakage test in accordance with the engineering reality. The parameter settings of the main components are shown in Table 8.

Table 8. Hydraulic simulation circuit main component parameters.

Variables	Value
Motor speed/(r/min)	1500
Pump rated displacement/(ml/r)	40
Hydraulic cylinder bore/(mm)	100
Piston rod inner diameter / (mm)	63
Hydraulic cylinder stroke/(mm)	300
Leakage module gap length/(mm)	10
Temperature/(℃)	50
Hydraulic oil dynamic viscosity /(Pa*s)	0.041

As shown in Fig. 15, the simulation verification of the internal leakage is set for a pressurization time of 5 s. The solenoid reversing valve closing time is 900 s. Therefore, the start time of the pressure-holding experimental process $t_1 = 5s$, the termination time of the pressure holding experiment $t_2 = 905s$, and the total of the whole process of the experiment is 905 s. And the communication interval is 0.05 s.

Different leakage levels are simulated by changing the leak gap height in the leakage module. According to the test protocol, three leak levels will be selected as test samples. It is assumed that the leakage level is defined as three levels. They are 0.015 mm micro-leakage, 0.020 mm moderate leakage and 0.025 mm severe leakage. In engineering practice, hydraulic fluids typically contain 5-7% air at ambient temperature and atmospheric pressure [28]. Therefore, four grades with air content of 3%, 6%, 9% and 12% were selected for the simulation test. The working pressure was determined as five levels of 5 MPa, 8.5 MPa, 16 MPa, 31.5 MPa, and 50 MPa. According to the test scheme shown in Table 9, a total of 60 full simulation tests were conducted.

Table 9. Simulation experiment variable level setting.

Influence factors	Experimental level
Working pressure P_1 (MPa)	5、8.5、16、31.5、50
Leakage level d（mm）	Micro-leakage(0.015)、Moderate leakage(0.02)、Severe leakage(0.025)
Air content A (%)	3、6、9、12

4.3 Simulation results analysis

Simulation tests with full working condition coverage were conducted based on the various types of different working condition classes shown in Table 9. Among them, the air content is 12%, the pressure level is 5 Mpa, and the pressure variation under the leakage level of micro-leakage is shown in Fig. 16.

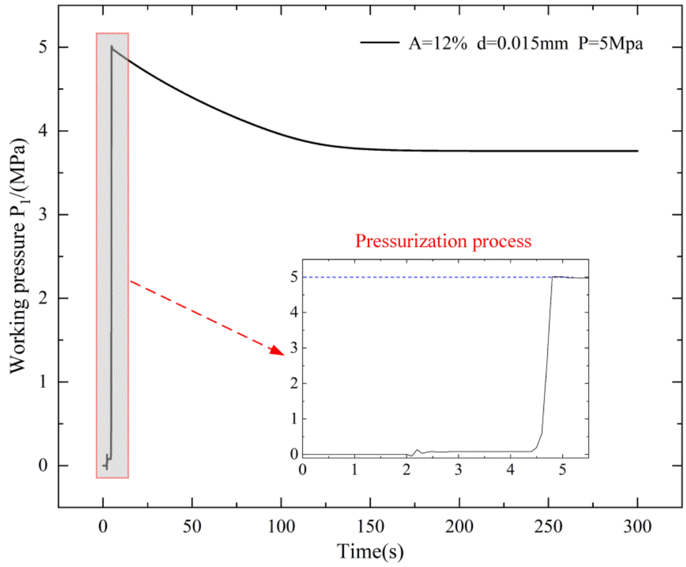
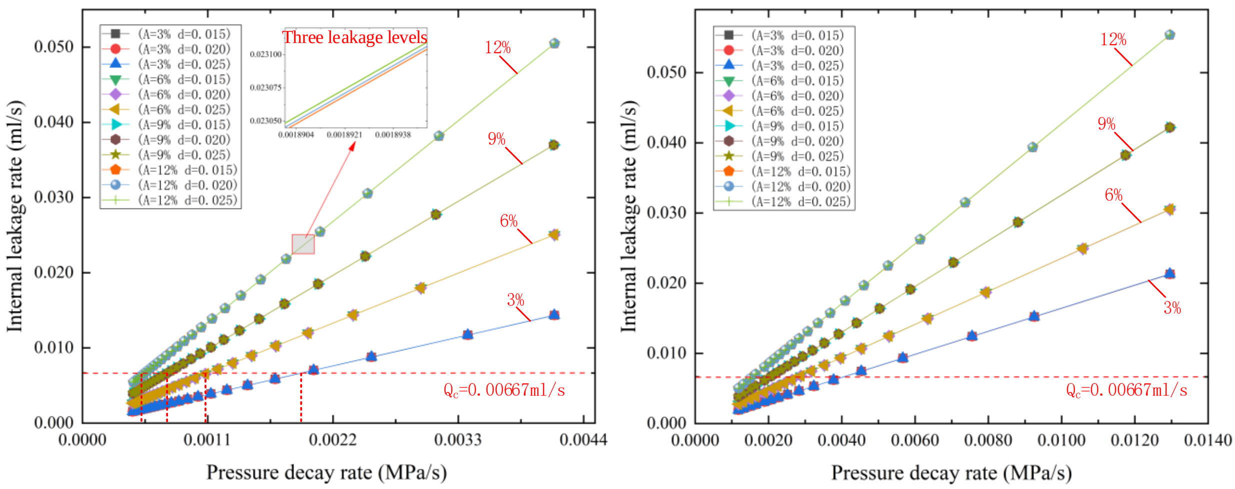
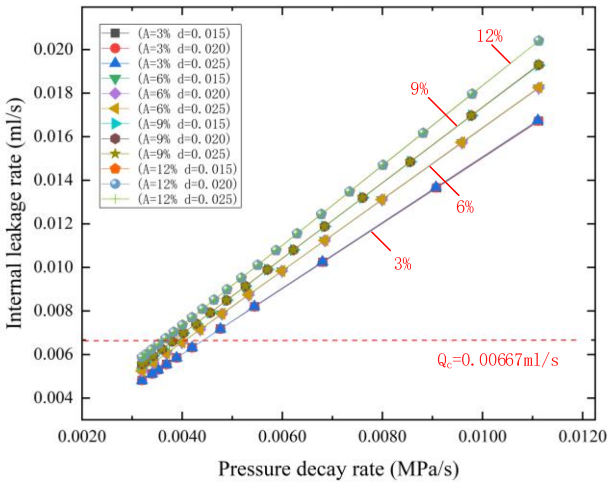


Fig. 16. Pressure variation curve for pressure decay test at 12% air content, 5 Mpa and micro-leakage.

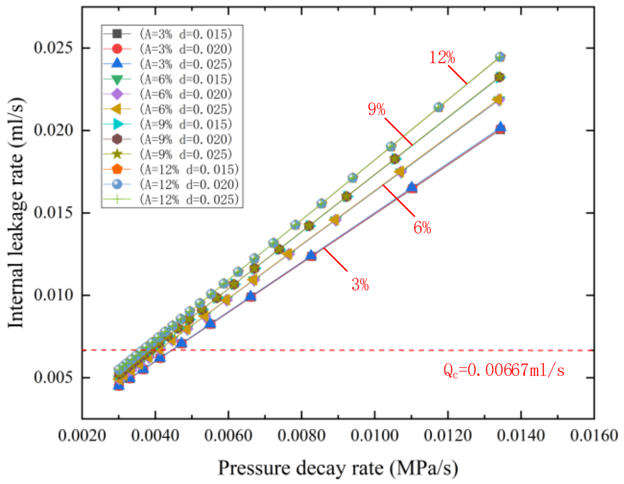
As shown in Fig. 16, the pressure variation of the working chamber under the condition of 12% air content, 5 Mpa pressure level and small leakage. It roughly contains three stages, which are the pressure boosting stage, pressure decay stage, and stabilization stage. First, the working chamber is pressurized to 5 MPa by the hydraulic pump, and the piston rod is already at the maximum stroke. Then the valve is closed to realize the pressure holding process. Due to the presence of leakage, the pressure in the working chamber will undergo decay and eventually stabilize. This process is in line with the practical application of the pressure decay test method for detecting internal leakage in engineering practice.



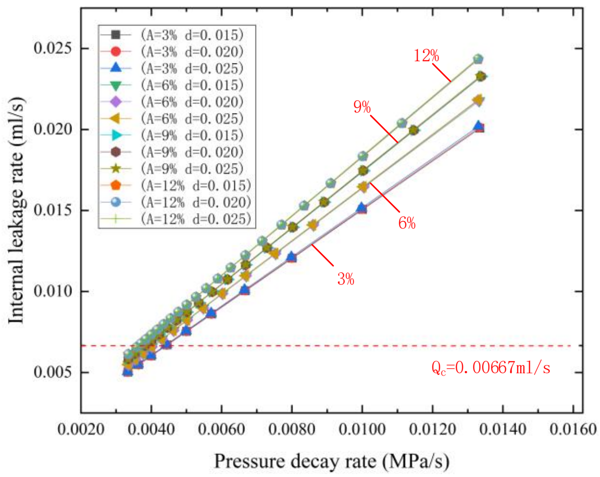
(a) P_1=5 MPa (b) P_1=8.5 MPa



(c) P_1=16 MPa



(d) P_1=31.5 MPa



(e) P_1=50 MPa

Fig. 17. Effect of air content and leakage level on the relationship between pressure decay rate and internal leakage at different pressure levels.

In Fig. 17, (a)-(e) show the effects of air content and leakage level on the relationship between pressure decay rate and internal leakage rate at different pressure levels, respectively. From Fig. 17, it can be seen that under different working conditions, the leakage volume and pressure decay obey the nearly linear relationship, which initially verifies the effectiveness of the pressure decay test method. When the working pressure and air content is certain, different leakage levels basically obey the same linear distribution. When the working pressure and the leakage level are certain, the slope between the internal leakage rate and the pressure decay rate increases with the increase of the air content. This change is especially obvious in the case of low and medium pressure. This result is consistent with the conclusion that the air content has a greater effect on the internal leakage in the low and medium pressure cases.

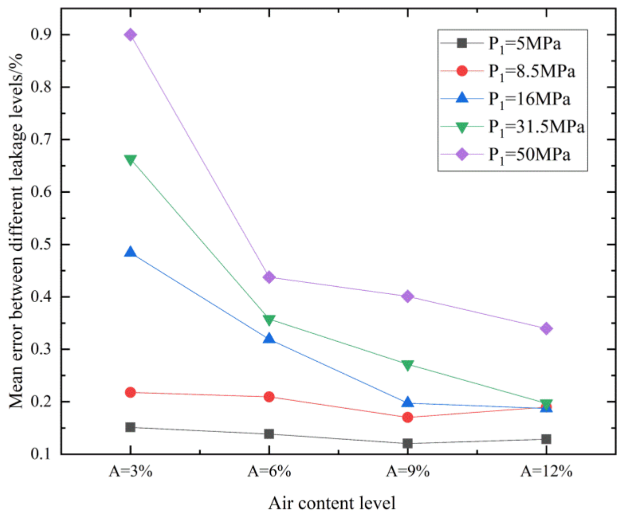


Fig. 18. Mean error between different leakage levels.

The average error between the different leakage levels is shown in Fig. 18. The average error between the different leakage levels is small (<1%) in all types of working conditions. This indicates that the leakage level has no effect on the application of the pressure decay test method. When the air content is certain, the error between different leakage levels gradually increases with the increase of working pressure. This may be due to the increase in the flow rate per unit time through the leakage module as the working pressure increases.

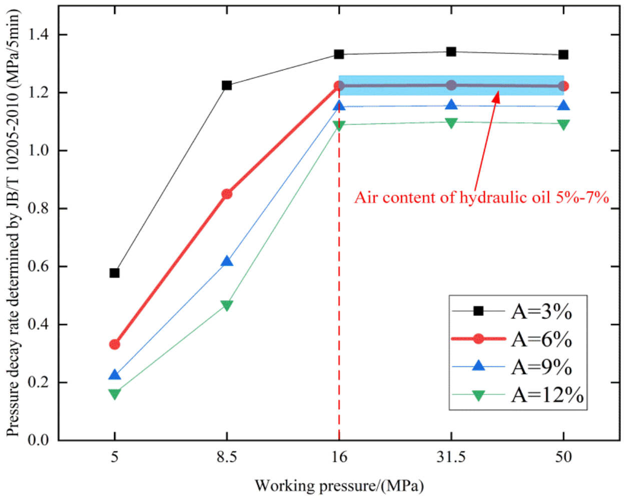


Fig. 19. The average pressure decay rate determined by JB/T 10205-2010.

According to JB/T 10205-2010, the maximum internal leakage of double-acting hydraulic cylinder with 100 mm bore is not more than 0.00667 ml/s when using slip ring combination seal. The leakage index value corresponds to the red dashed line in Fig. 17. Fig. 19 shows the average pressure decay rate determined by JB/T 10205-2010 under different working conditions. The average pressure decay rate refers to the average value of the pressure decay rate of the three leakage levels under the determined working pressure and air content.

As shown in Fig. 19, when the leakage level is certain and the working pressure is below 16 MPa, the rate of pressure decay per unit time decreases significantly with the increase of air content in the fluid. When the air content and leakage level are certain and the working pressure is higher than 16 MPa, the pressure decay rate per unit time is basically unchanged (<0.9%). This is due to the fact that when the oil contains a certain amount of air, the effective bulk modulus tends to be constant as the working pressure rises. Therefore, for this kind of hydraulic cylinder, when the working pressure is high (>16 Mpa), a defined pressure decay rate indicator can be set to visually determine if the cylinder has an internal leakage.

5. Experiment-based validation analysis of the pressure decay test method

In this section, the effectiveness of the pressure decay test method is studied through the internal leakage test bench of hydraulic cylinder. By analyzing the relationship between pressure decay rate and internal leakage rate under different operating conditions, the results are compared with those verified by simulation.

5.1 Experiment set

The hydraulic cylinder internal leakage test rig used in this study is shown in Fig. 20. It mainly consists of hydraulic power and hydraulic control components. Oil is supplied to the circuit through a manual pressure pump and the hydraulic cylinder moves under pressure.

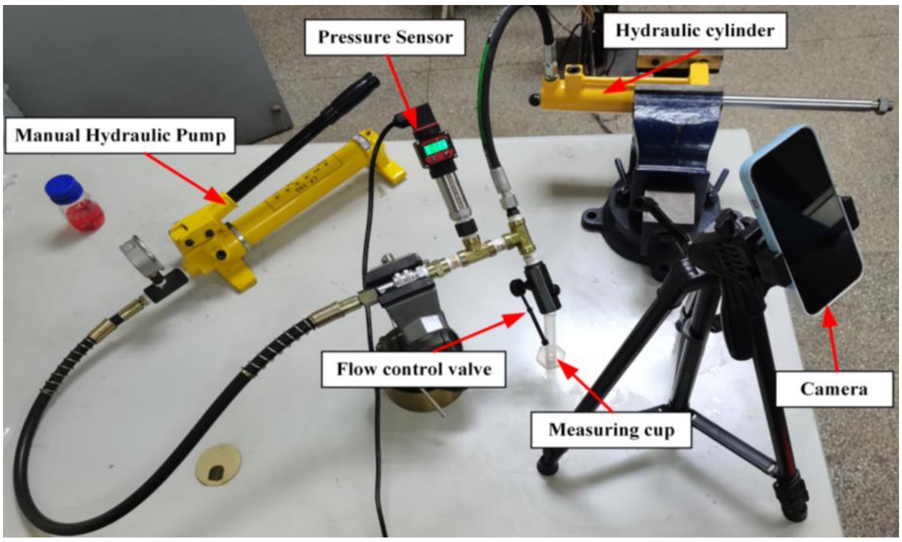


Fig. 20. Hydraulic cylinder internal leakage test bench.

The internal leakage of the hydraulic cylinder is usually small and the internal structure of the cylinder is complex. Part of the leaking fluid will adhere to the cylinder wall and the oil port, which seriously affects the results of the internal leakage measurement. In order to simulate the internal leakage of hydraulic cylinder more truly, so as to accurately investigate the relationship between pressure decay rate and internal leakage rate, flow control valve is used to simulate the internal leakage of hydraulic cylinder in this paper. As shown in Figure 21, by improving the knob of the flow control valve, the opening of the flow control valve can be better adjusted to simulate different leakage levels. The pressure transducer was mounted directly on the main circuit to capture the pressure variations within the experimental circuit, and the camera was used to record the pressure and oil dripping. The parameters of the experimental equipment are shown in Table 10.

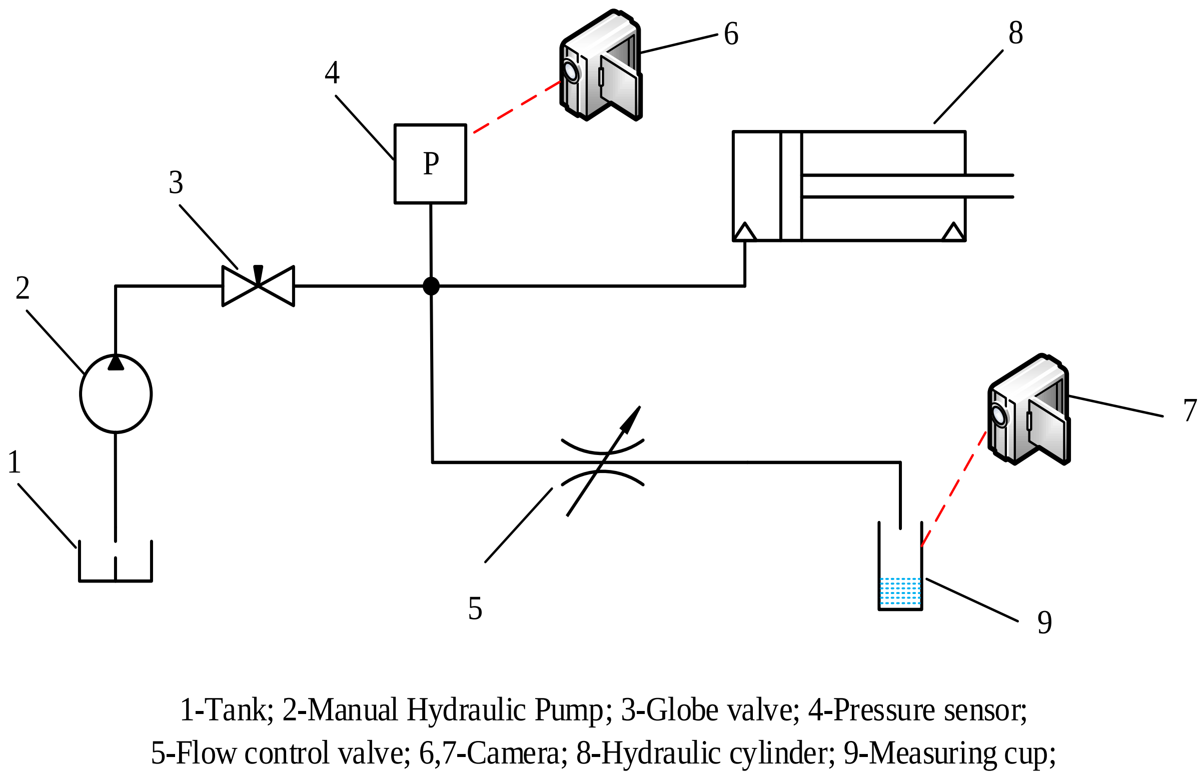


Fig. 21. Experimental circuit schematic diagram.

Table 10. Parameters of experimental equipment.

Equipment	Parameter
Manual Hydraulic Pump	Nominal pressure 60 MPa
Hydraulic cylinder	Cylinder/rod diameter 40/20 mm, stroke 180 mm
Flow control valve	Nominal pressure 50 MPa
Pressure Sensor	Measurement range 0-50 MPa, measurement accuracy 0.5%
Measuring cup	Measurement range 0-10 ml

5.2 Measurement of pressure and internal leakage signals

The hydraulic cylinder internal leakage test bench collects the pressure data from the rod-less cavity of the hydraulic cylinder by QDW90A-S pressure sensor, the accuracy of the pressure sensor is 0.5% FS. The experiment is recorded with a camera instead of a data acquisition system because the value of the pressure at the moment of oil drop corresponds to the internal leakage volume. As shown in Fig. 22(b), the pressure value at the moment of oil dropping was recorded at that moment.

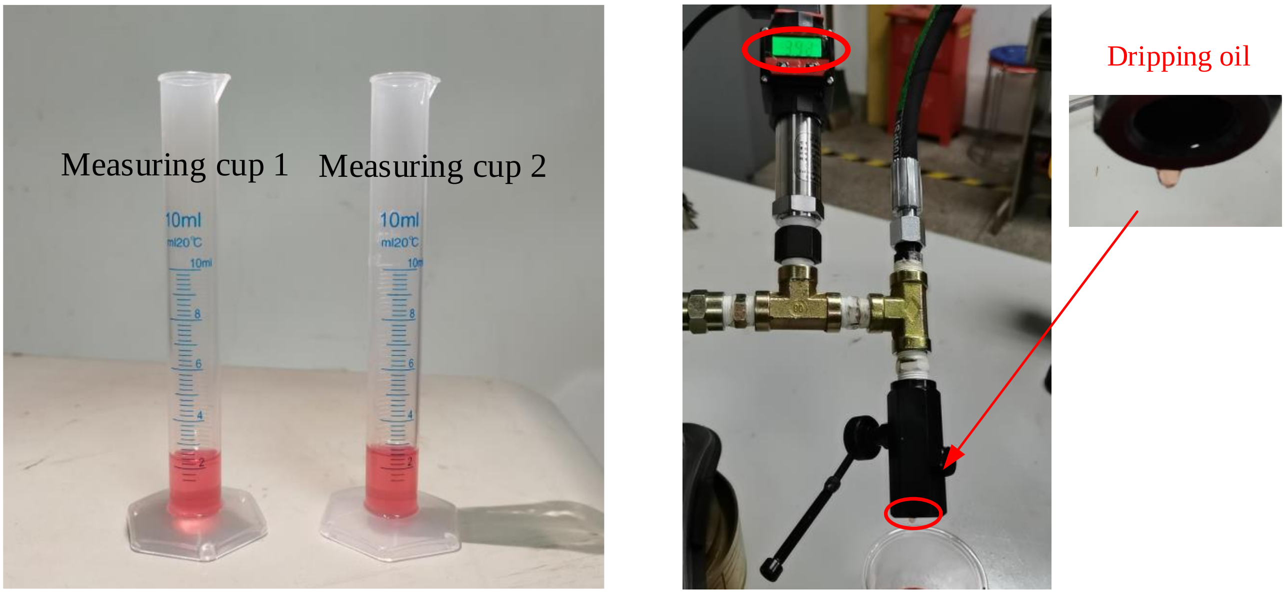


Fig. 22. Schematic diagram for pressure and leakage measurement
(a) Leakage calibration experiment (b) Schematic diagram of pressure and leakage monitoring.

Since the volume of internal leakage in hydraulic cylinders is usually small, this paper adopts counting the volume of internal leakage according to the number of oil drops falling. As shown in Fig. 22(a), the number of oil drops needed to measure 1 ml of oil is measured using a standard measuring cylinder, and the results are shown in Table 11. The experiment was carried out under the pressure of 5 MPa. Other pressure levels have essentially no effect on the volume of oil droplets. The results show that the volume of each drop of oil is about 0.04 ml, and the effects of other factors on the measurement results were neglected in this experiment.

Table 11. Experimental results of oil volume measurement.

Number of experiments	1	2	3	4	5
Number of oil droplets in 1 ml of fluid	25	25	26	25	25

In order to determine the correspondence between the pressure decay rate and the internal leakage rate in the hydraulic cylinder internal leakage simulation experiment, the time of leakage start is defined as the time when the first drop of oil is observed from the valve port of the flow control valve. The internal leakage simulation was carried out for 5 minutes. Due to the limitation of the experimental conditions and the safety of the experiment, the experimental pressure range was taken to be 5 MPa-31. 5 MPa. The leakage rate is slower in the low-pressure condition (5 MPa), so the experimental time was extended by about 5 minutes in order to collect enough data points.

5.3 Analysis of pressure and internal leakage data

Hydraulic components in the normal state there will be a slight leakage. In order to exclude the influence of leakage from other components of the system on the experimental results during the experiment, a calibration experiment is carried out. At this time, the flow control valve is closed. Specific processes are as follows:

Step 1: Close the flow control valve and pressurize to the established pressure level with a hand pump, hold the pressure for 5 minutes, and record the pressure change curve.

Step 2: Repeat step 1 after unloading and perform three sets of calibration experiments at this pressure level. The pressure change curves are noted as $P_0(\mathrm{t})$, $P_1(\mathrm{t})$, and $P_2(\mathrm{t})$, and the pressure decay is $\triangle P_i$.

Step 3: Change the working pressure level and repeat steps 1 and 2.

Step 4: After loading to the established pressure level by means of a hand pump, open the flow control valve and hold the pressure for 5 min. Pressure changes and leakage of oil are recorded by camera and are noted as $P(\mathrm{t})$, $V(\mathrm{t})$, and the pressure decay is $\triangle P$, as shown in Fig. 24.

Step 5: Change the working pressure level, repeat step 4. At this time the actual pressure decay caused by the leakage is $\triangle P - \triangle P_i$.

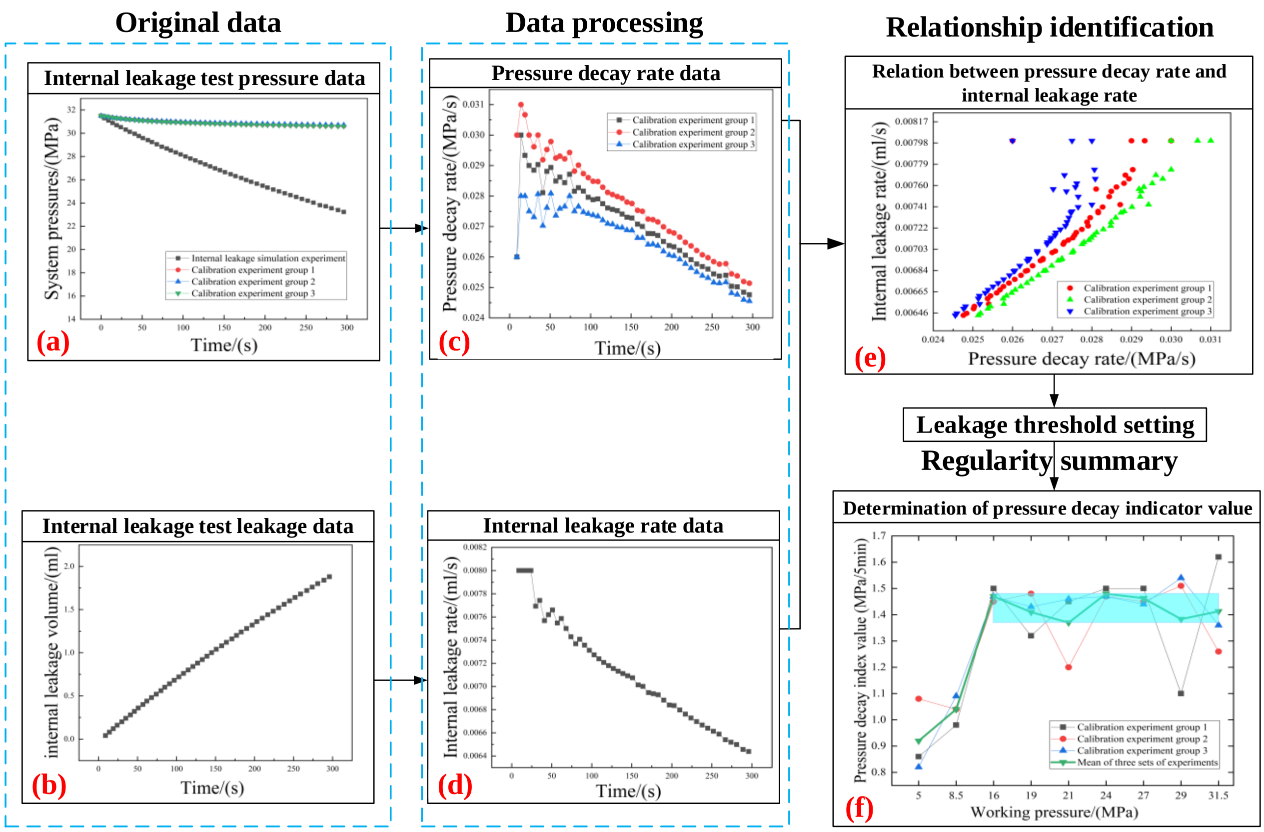


Fig. 23. Data processing schematic diagram.

The process of analyzing and processing the pressure and internal leakage volume data is shown in Fig. 23. Firstly, the raw data of pressure and leakage volume are collected, which contains three sets of pressure data from calibration experiments, as shown in Fig. 23 (a)-(b). Then, the pressure decay rate and average leakage rate are calculated as shown in Fig. 23 (c)-(d). Fig. 23 (e) shows the relationship between pressure decay rate and leakage. Finally, according to JB/T 10205-2010 to determine the value of the pressure decay rate indicator to determine the type of hydraulic cylinder leakage or not, as shown in Fig. 23 (f).

5.4 Analysis of experimental results

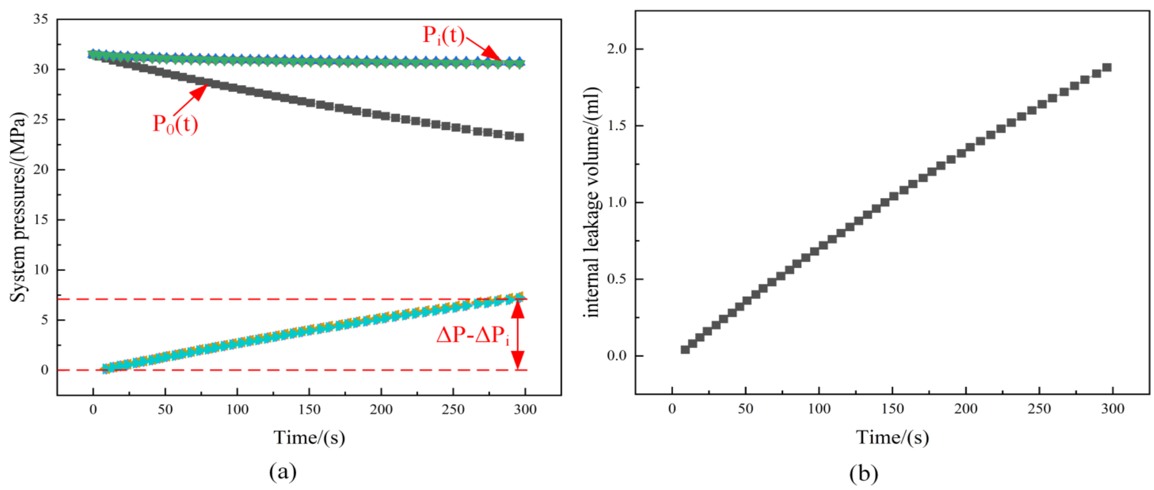
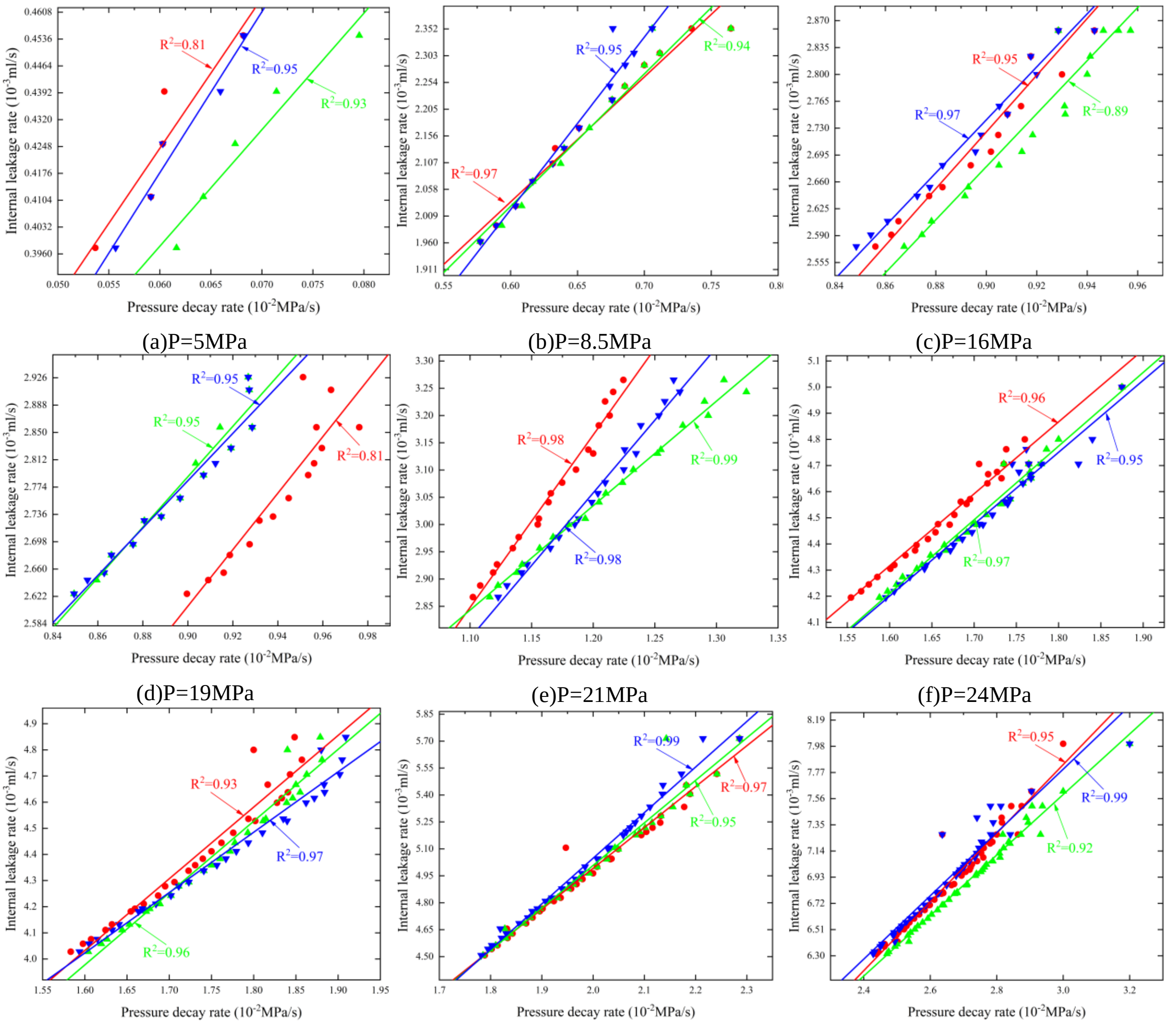


Fig. 24. Pressure change and leakage original data

(a) Pressure change curve (b) Leakage volume change curve.

Fig. 24 shows the original data of pressure and leakage changes under the pressure level of 31.5 MPa in the hydraulic cylinder leakage test.



(a)P=5MPa (b)P=8.5MPa (c)P=16MPa

(d)P=19MPa (e)P=21MPa (f)P=24MPa

(g)P=27MPa (h)P=29MPa (i)P=31.5MPa

Fig. 25. Linear fitting results of pressure decay rate-internal leakage at different pressure levels.

The results of the linear fitting of the relationship between pressure decay rate and internal leakage rate at different pressure levels are shown in Fig. 25, respectively. The three lines in the figure represent three sets of calibration experiments, respectively. As shown in Fig. 25(a)-(i), the dispersion of the data points in the initial stage of the experimental results under different pressure levels is high, which is due to the fact that the pressure change of the circuit and the decay of leaking fluid will present a certain hysteresis.

In most cases, the linear regression model has a high goodness of fit (R^2 > 0.9). The relationship between the pressure decay rate and the internal leakage rate can be considered as linear under different operating conditions. The experimental results further verified the validity of the pressure decay test method.

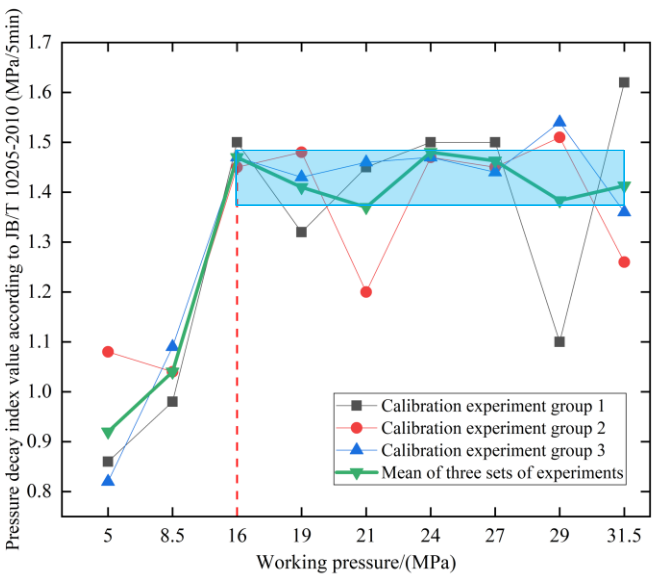


Fig. 26. The average pressure decay rate determined by JB/T 10205-2010.

According to JB/T 10205-2010, the leakage of 40 mm bore hydraulic cylinder is less than 0.06 ml/min, which is regarded as qualified for internal leakage test. Fig. 26 shows the pressure decay rate index value determined by JB/T 10205-2010 under different working conditions. When the working pressure is lower than 16 MPa, the pressure decay rate index value increases with the increase of pressure in all test cases. When the working pressure is greater than 16 MPa, the mean values of the three sets of calibration test results fluctuate within a constant range. This fluctuation may be caused by the expansion of the pipeline and the fluctuation of the air content during the test.

Comparing the simulation verification results with the experimental results, as shown in Figs. 19 and 26, the pressure decay rate index values calculated by the two verification methods have the same trend under different pressure levels. The effective application range of the pressure decay test method is further verified.

6. Conclusion and Prospect

This paper focuses on the effectiveness of the hydraulic cylinder internal leakage detection method based on the pressure decay test method. The research content mainly includes three parts. Firstly, various types of key factors affecting the internal leakage of hydraulic cylinders are derived through research and analysis. Then, an effectiveness verification test scheme based on the pressure decay test method is proposed and simulated using AMESim. Finally, the simulation results were further verified by the test bench. The results fill a research gap in the literature in this area, showing a linear relationship between pressure decay rate and internal leakage rate. Especially for working pressures greater than 16 MPa, the pressure factor has an insignificant impact on the application of the pressure decay test method. It is effective to quickly detect the leakage in hydraulic cylinder by pressure decay test method.

At present, due to the limitations of the experimental conditions, the experiments of hydraulic cylinders with ultra-high pressure and high temperature working conditions can not be carried out. But for the online monitoring and intelligent operation and maintenance stage, this part of the research content is still necessary to continue. The general idea and method of research can be based on this paper. Regarding the applicability of the pressure decay test method in the low-pressure case, further investigation can be carried out by exploring the mechanism and law of the effect of pressure and temperature on bulk modulus. The work done in this paper provides a theoretical basis for detecting internal leakage in hydraulic cylinders using the pressure decay test method. In the future, the currently studied data-driven detection method can be combined with the pressure decay test method to explore a more rapid and efficient method for internal leakage detection. The pressure decay test method can also be extended to leakage detection of other components.

Acknowledgments

This research was supported by the National Key Research and Development Program of China “Manufacturing Basic Technology and Key Components” key project (Grant No. 2021YFB2011200). This research was also supported by the Hubei Provincial Department of Education (Grant No. D20221105).

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