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Study on validation for accelerated life tests of pneumatic cylinders based on the test results of normal use conditions †

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Abstract

This paper presents a validation method for Accelerated life tests (ALTs) of pneumatic cylinders. Two ALTs using each temperature and pressure stress were performed. Weibull analyses for these ALTs and their combination data were conducted. The comparison analysis was carried out between predictions based on ALTs and results obtained from normal use conditions. In other words, the validation of ALTs was conducted by applying hypothesis tests and confidence intervals for Weibull parameters. Finally, the Weibull shape parameter, the acceleration index of pressure, the activation energy for temperature, and the life cycles (B_{10} and characteristic) under normal use conditions for pneumatic cylinders were obtained.

Keywords: Pneumatic cylinder; Accelerated life test; Validation of accelerated life test; Weibull shape parameter; Temperature-nonthermal model; Hypothesis test

1. Introduction

ALTs are widely used in industry to assist in product development. Overstressing, increasing usage rates and tightening the failure threshold are widely utilized as acceleration methods [1]. The overstressing method is the most common acceleration method. This method is accomplished by applying the higher stress level than the level a product will encounter under normal use conditions. The lifetime under normal use conditions is predicted by an extrapolation method using ALTs results.

Practical methodologies, basic theories, references list and examples of the ALTs are provided in several studies [2-6]. Park et al. [7] examined three types of acceleration methods in ALTs for secondary rechargeable batteries.

The pneumatic cylinder is a major mechanical component which is used in various fields such as automobile production line, semiconductor inspection devices, robots and medical devices. Chang et al. [8, 9] estimated the life cycle and proposed reliability qualification test method based on performance degradation data of pneumatic cylinders. Existing studies on reliability testing of pneumatic cylinders have mainly focused on ALTs. Han and Fu [10] performed ALTs with pressure and velocity acceleration stress factors at a temperature of 65 °C and came to the conclusions that pressure stress is more influential than velocity on the lifetime of pneumatic cylinders. Chen et al. [11] and Bai et al. [12] applied a general log-linear model including four acceleration stress factors for temperature, frequency, pressure and velocity. Chen et al. [13] considered temperature, frequency, and velocity as acceleration stress factors for ALTs of pneumatic cylinders. Chen et al. [14] implemented double crossed step-down-stress ALTs for pneumatic cylinders by switching down the double stresses alternatively. In the above studies, the accelerated stress levels of frequency and pressure were not largely different compared to normal use conditions.

This paper presents a validation method for ALTs of pneumatic cylinders. For this purpose, Sec. 2 introduces the specification of the used test item and its failure analysis results. Pressure and temperature are selected as acceleration stress factors. In Sec. 3, the life distribution and ALTs models for pneumatic cylinders are presented. Weibull analyses for two ALTs datasets (pressure and temperature) and their combination are conducted. In Sec. 4, ALTs analysis results are compared with those from normal use conditions. In other words, the validation of ALTs was conducted by applying hypothesis tests and confidence intervals for Weibull parameters. Finally, the shape parameter of Weibull distribution, the acceleration index of pressure, the activation energy for temperature and the life cycles (B_{10} and characteristic) under normal use conditions for pneumatic cylinders are calculated. We conclude this paper with some brief remarks in Sec. 5.

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Table 1. Failure modes and failure mechanisms for pneumatic cylinders.

Part	Function	Failure mode	Failure mechanism
Piston seal	Prevents the inner leakage in the head and rod parts	Leakage	Friction wear
		Friction increase	Lubrication decline
		Impossible of pressure retaining	Fatigue fracture
Rod seal	Prevents the air and dust inflow from outside	Leakage	Friction wear
		Friction increase	Lubrication decline
		Impossible of pressure retaining	Fatigue fracture
Cylinder tube	Maintains the structure and stiffness of cylinder, performs a role of pressure chamber in forward or backward rod	Fracture	Fatigue fracture
		Deformation	Alternative load
Head/rod cover	Maintains the airtightness inside the tube	Fracture of assembled bolt	Over pressure

Table 2. Decision matrix for acceleration stress factors.

		Acceleration stress factor				
Failure mode	Weight	Temperature	Pressure	Velocity	Contamination	Load
Leakage through piston seal wear	5	◎	◎	O	O	O
Leakage through rod seal wear	3	O	O			
Blockage of internal air cushion	3	△	△	△	◎	
Rod fracture	1		O	O		O
Deformation of the cylinder tube	1		△			O
Aberration of rod seal	1	◎	◎	△		◎
Total		42	46	22	30	26

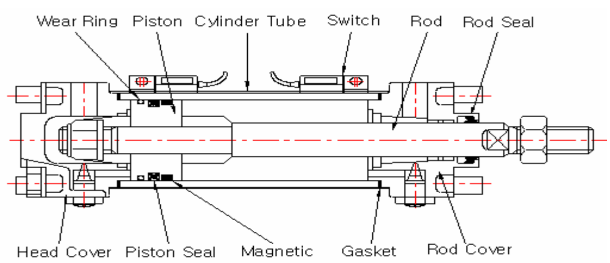
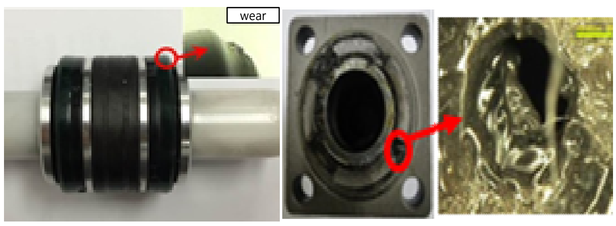


Fig. 1. Structure of a pneumatic cylinder.



(a) Wear of the piston seal (b) Blockage of air cushion

Fig. 2. Failure modes of pneumatic cylinders.

2. Failure analysis of pneumatic cylinder

The pneumatic cylinder is mainly composed of the cylinder tube, piston, piston rod, piston seal and rod seal. The cylinder tube guides a reciprocating operation, and the piston transforms into mechanical rectilinear motion by sliding inside the tube. The piston rod transfers weights, the piston seal prevents the inner leakage, and the rod seal prevents the air and dust inflow from outside. The cylinder used for tests is a double acting pneumatic cylinder with the piston having a diameter of 32 mm and a stroke of 160 mm. Fig. 1 shows the structure of the used pneumatic cylinder.

The cylinder acts as an actuator that transforms pressurized air into rectilinear motion. Mechanical failures are induced by temperature, pressure, velocity, contamination and load. The main failure mode of the pneumatic cylinder is leakage caused by wear of seals. The wear occurs as a result of seal hardening caused by reciprocating operations. This problem occurs at the piston seal rather than the rod seal. In order to check the piston seal leakage, Minimum operating pressure (MOP) tests and leakage tests are conducted. There are several failure modes of the pneumatic cylinder in normal use conditions: Leakage by wear of piston and rod seals, blockage of internal air cushion, rod fracture, deformation of the cylinder tube and aberration of rod seals. Failure modes and failure mechanisms of the pneumatic cylinder are shown in Table 1 and Fig. 2.

Table 2 represents a decision matrix that assesses the influence of each acceleration stress factor on failure modes of the pneumatic cylinder. The weight of the failure mode is determined by a factor (1, 3, or 5) considering the occurrence frequency of each failure mode under normal use conditions. Therefore, the weight of the main failure mode, leakage by wear of piston seal, was set as 5 points. The relationship between failure modes and acceleration stress factors is rated depending on how well the acceleration stress factor can accelerate the corresponding failure mode. When they are closely related, it is marked with ◎(5); if less related, it is marked with O(3); when only remotely connected, it is marked with △(1); the cell is left blank in case of no relation. Total values of each acceleration stress factor are calculated by adding up the products of weight and value of the respective relationship. As a result of Table 2, pressure and temperature are the predominant acceleration stress factors of pneumatic cylinders.

The one stroke time of the ALTs was used as 0.5 seconds to keep air resistance in the cylinder constant according to ISO 19973-3 [15]. The conducted performance tests for checking the failure of pneumatic cylinders include a minimum operating pressure test, a leakage test, and a stroke time test; all tests were conducted in accordance with ISO 19973-3 [15] standard. The pneumatic cylinders were considered to have failed the ALTs if the leakage rate exceeded 12 dm^3/h according to ISO 19973-3 [15] and ISO 10099 [16] standards. The quality of operating air follows ISO 19973-1 [17] standard.

3. Weibull analysis of ALTs data

3.1 Life distribution and ALTs models

Weibull distribution is a commonly used distribution in reliability engineering and is the most common distribution in general mechanical engineering [18, 19]. Also, we know that life cycles of pneumatic cylinders follow Weibull distribution [8]. The reliability function $R(t)$ and failure probability $F(t)$ of Weibull distribution are written in Eqs. (1) and (2).

$$R(t) = \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right], \qquad t > 0. \tag{1}$$

$$F(t) = 1 - \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right], \qquad t > 0. \tag{2}$$

β and η are the shape parameter and the scale parameter of Weibull distribution; both are positive. η is also called the characteristic life. The shape parameter may provide an indication to the physics of failure, and the scale parameter represents the typical life to failure in Weibull analysis [18].

The Arrhenius model (or relationship) is the most common model used in ALTs when the acceleration stress factor is temperature. The Arrhenius model [20] is expressed as Eq. (3).

$$L(T) = Ce^{\frac{E_a}{k \cdot T}}, \qquad C > 0. \tag{3}$$

The L and T represent the characteristic life of Weibull distribution and the absolute temperature in Kelvin (K = °C + 273.15). E_a and C are model parameters to be determined. k is the Boltzmann constant ($k = 8.6171 \times 10^{-5}$ eV/K) and E_a is the activation energy in electron-volt (eV) [1].

The inverse power law model is commonly used for non-thermal acceleration stress factors such as voltage, current intensity, pressure, humidity, vibration, and load. The inverse power law model [20] is shown in Eq. (4).

$$L(P) = \frac{1}{A \cdot P^n}, \qquad A > 0. \tag{4}$$

P is the pressure stress; A and n are model parameters to be calculated. n is a measure of the effect of the non-thermal stress on the lifetime and is called acceleration index of non-thermal stress [20, 21].

The temperature-nonthermal model is used when temperature stress and pressure stress are considered simultaneously in a test. This model [20] is expressed as Eq. (5).

$$L(P,T) = \frac{C}{P^n \cdot \exp\left(-\frac{E_a}{k \cdot T}\right)}, \qquad C > 0. \tag{5}$$

One of the important concepts in ALTs is the Acceleration factor (*AF*), can be obtained by the ratio of lifetimes at two different stress levels. The *AF* is represented as $AF = L_{use} / L_{test} = \eta_{use} / \eta_{test}$, where η_{use} and η_{test} are the characteristic lives of Weibull distribution under normal use conditions and at the accelerated stress level [21].

Table 3. Test conditions and sample size of ALTs for pneumatic cylinders.

		Pressure stress (kPa)		
		630	800	1200
Temperature stress (°C)	23	8	10	5
	80	7		
	100	7		
	110	6		

3.2 ALTs plans of pneumatic cylinders

The main failure mode of pneumatic cylinders was identified as leakage through piston seal wear. Based on our experiences and Refs. [10-13], the acceleration stress factors of pneumatic cylinders were determined as temperature and pressure. The normal use conditions are 23 °C and 630 kPa. The highest stress levels are 110 °C and 1200 kPa. The highest level of applied stress should not induce failure modes (or failure mechanisms) which do not occur under normal use conditions [3, 8]. The stress levels of temperature were set as 80, 100 and 110 °C. For pressure, 800 and 1200 kPa were selected as stress levels.

The sample size of each condition was determined to be 5~10 in regards to the situation. Test conditions regarding pneumatic cylinders and sample size of each condition are given in Table 3. Two samples of the condition (80 °C, 630 kPa) are censored since their lives exceeded the test time. The

Table 4. Life cycles of case A.

Sample size	Temperature (°C)	Pressure (kPa)	Start cycles	End cycles
7	80	630	3000000	3300000
			3600000	3900000
			2000000	2500000
			3900000	Censored
			3900000	Censored
			3600000	3900000
			2500000	3000000
7	100	630	400000	600000
			2200000	2400000
			600000	800000
			2400000	2600000
			1800000	2000000
			1600000	1800000
			1200000	1400000
6	110	630	800000	1000000
			400000	600000
			800000	1000000
			600000	800000
			400000	600000
			200000	400000

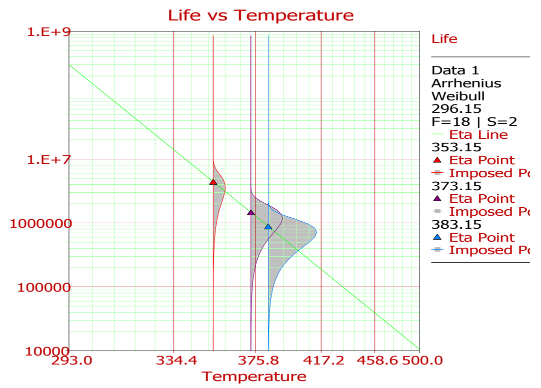


Fig. 3. Relationship plot between life cycles and temperature stress-Case A (from ALTA 7).

life of pneumatic cylinders is commonly represented as the number of cycles. The periodic performance test was performed to check for failures. The test cylinder was considered as failed, if the failure criteria, such as minimum operating pressure, leakage, stroke time, were reached. The life cycles of pneumatic cylinders are called interval censored data and it represents the cylinders fail within an interval. The life cycles in this paper represent the interval censored data practically.

3.3 Case A: ALTs using temperature stress

Table 4 shows the life cycles obtained from the three different temperature stress levels. The pressure level of case A is set to 630 kPa (normal use conditions). Start and end cycles in Table 4 represent the interval in which the failure of the cylinder occurred.

We performed the Weibull analysis of life cycles for case A. The Maximum likelihood estimates (MLEs) of β, C and E_a using ALTA software were 2.4858, 0.0053 and 0.6254, respectively. Fig. 3 shows the relationship plot between life cycles and temperature stress for case A. The scale parameter (or characteristic life) under normal use conditions was 230760000 cycles. This value is obtained by substituting T = 296.15 K (23 °C+273.15) into Eq. (3). The B_{10} life cycles of pneumatic cylinders under normal use conditions is calculated as follows.

Table 5. Life cycles of case B.

Sample size	Temperature (°C)	Pressure (kPa)	Start cycles	End cycles
10	23	800	14000000	16000000
			14000000	16000000
			16000000	18000000
			10000000	12000000
			14000000	16000000
			6000000	8000000
			10000000	12000000
			20000000	22000000
			10000000	12000000
			12000000	14000000
5	23	1200	10000000	12000000
			1000000	2000000
			8000000	10000000
			4000000	6000000
			4000000	6000000

$$B_{10} = \eta \times \left(-\ln(1-0.1)\right)^{\frac{1}{\beta}}$$
$$= 230760000 \times \left(-\ln(1-0.1)\right)^{\frac{1}{2.4858}} = 93325113.$$

ALTs should not use stress levels that cause failure modes never seen in normal use conditions. Thus, failure mode occurring in ALTs and normal use conditions should be the same. Since the shape parameter represents the failure mode of the product, it is necessary to confirm whether it is the same at each stress level or not. An equality test for shape parameters is used to verify this assumption.

The Likelihood ratio (LR) test was used to assess the shape parameters obtained at the m stress levels. If the LR statistic T is less than or equal to the $\chi^2(1\text{-}\alpha, m\text{-}1)$, the m shape parameter estimates do not differ statistically significantly at 100α % level [20]. The m is the number of stress levels, whereas α stands for the significance level.

The values of the LR test statistic T and the $\chi^2(0.95, 2)$ for case A are 2.3048 and 5.9915. Therefore, the shape parameter estimates for case A do not differ statistically at 5 % significance level.

3.4 Case B: ALTs using pressure stress

Table 5 shows the life cycles obtained from the two different pressure stress levels. The temperature level of case B is set to 23 °C (normal use conditions).

We also performed Weibull analysis and LR test of life cy-

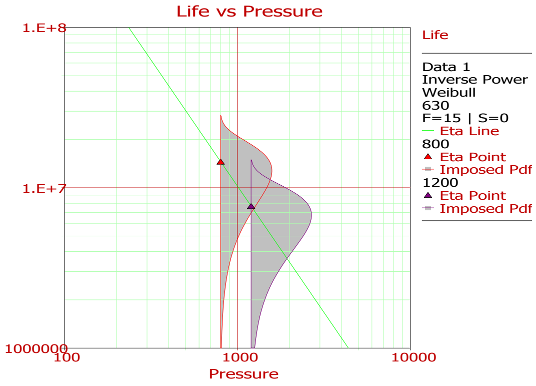


Fig. 4. Relationship plot between life cycles and pressure stress-Case B (using ALTA 7).

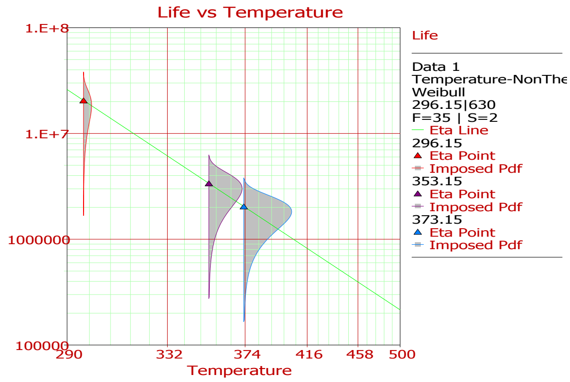


Fig. 5. Relationship plot between life cycles and temperature stress-Case C (using ALTA 7).

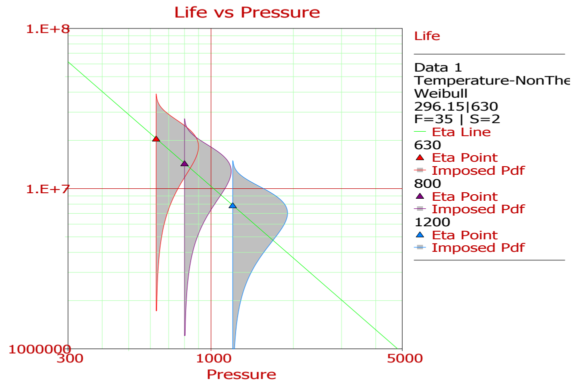


Fig. 6. Relationship plot between life cycles and pressure stress-Case C (using ALTA 7).

cles for case B. The values of the LR test statistic T and the $\chi^2(0.95, 1)$ for case B are 2.7986 and 3.8415. Therefore, the shape parameter estimates for case B do not differ statistically at 5 % significance level.

The MLEs of β, A and n using ALTA software were 3.0383, 1.8556×10^{-12} and 1.5736, respectively. Fig. 4 shows the relationship plot between life cycles and pressure stress for case B. The characteristic life under normal use conditions was 21202000 cycles. This value is obtained by substituting P = 630 kPa into Eq. (4). The B_{10} life of pneumatic cylinders under normal use conditions was 10109000 cycles.

3.5 Case C: ALTs using temperature and pressure stresses

In this case C, the life cycles of cases A and B are combined to consider two acceleration stress factors such as temperature and pressure. To balance sample size at each stress, life cycles of the most severe condition (110 °C, 630 kPa) in case C were excluded.

Weibull analysis and LR test of life cycles were also performed for case C. The values of the LR test statistic T and $\chi^2(0.95, 3)$ for case B are 5.0607 and 7.8147. Therefore, the shape parameter estimates for case C do not differ statistically at 5 % significance level.

The MLEs of β, C, E_a and n using ALTA software were 3.0425, 1.0350×10^7, 0.2982 and 1.6926, respectively. Figs. 5 and 6 show the relationship plot between life cycles and acceleration stresses, pressure and temperature, for case C. The characteristic life under normal use conditions was 22436000 cycles. This value is obtained by substituting T = 296.15 K (23 °C) and P = 630 kPa into Eq. (5). The B_{10} life of pneumatic cylinders under normal use conditions was 10708000 cycles.

4. Validation for ALTs

4.1 Weibull analysis of normal use conditions

The life cycles obtained from normal use conditions (23 °C, 630 kPa) were used to validate the ALTs of pneumatic cylinders. The life test under normal use conditions was performed for about 16.5 months. Table 6 shows the life cycles of normal use conditions. Weibull probability plot for life cycles of normal use conditions is shown in Fig. 7. The MLEs of shape parameter and characteristic life were 4.1189 and 20218409 cycles, respectively. The 95 % confidence intervals of the shape parameter and characteristic life were (2.2520, 7.5336) and (16933000, 24141000). The point estimate and 95 % confidence intervals for the B_{10} life were 11708000 cycles and (7716900, 17762000) cycles.

4.2 Validation of the conducted ALTs

A hypothesis test was conducted to validate the ALTs results by the test results at normal use conditions. The confidence intervals of parameters also can be used for the validation of ALTs. The hypothesis test uses two statements, called the null hypothesis (H_0) and the alternative hypotheses (H_1). The null and alternative hypotheses for validation are as follows.

$$H_0: \theta = \theta_{ALT} \quad \text{vs.} \quad H_1: \theta \neq \theta_{ALT}.$$

θ is the shape or scale parameter of the normal use conditions. θ_{ALT} is the predicted values of shape or scale parameter

Table 6. Life cycles of normal use conditions.

Sample size	Temperature (°C)	Pressure (kPa)	Start cycles	End cycles
8	23	630	24000000	26000000
			20000000	22000000
			10000000	12000000
			8000000	10000000
			20000000	22000000
			14000000	16000000
			22000000	24000000
			20000000	22000000

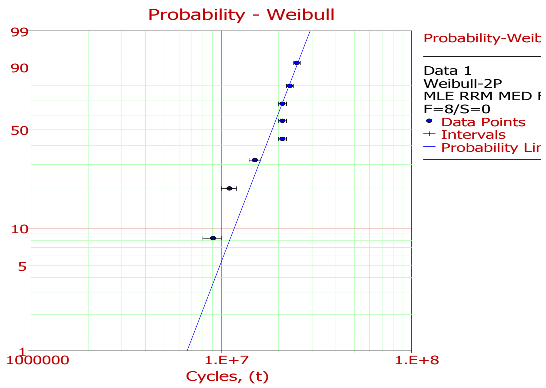


Fig. 7. Weibull probability plot for life cycles of normal use conditions (using Weibull++7).

obtained from each ALTs. For example, the null and alternative hypotheses of shape parameter under normal use conditions for the validation of case A are as follows.

$$H_0: \beta = 2.4858 \quad \text{vs.} \quad H_1: \beta \neq 2.4858.$$

The hypothesis test is used to determine whether to reject the null hypothesis or not, based on the sample data (data of normal use conditions). The p-value is the probability of obtaining the observed sample data under the assumption that the null hypothesis is true. The smaller the p-value becomes, the more compelling is the evidence that the null hypothesis should be rejected [22]. Thus, the larger the p-value is, the higher the validity of each ALTs is.

Based on analysis results, p-values for the hypothesis test of shape and scale parameters can be seen in Table 7. These p-values were calculated with the help of the Wald test of Minitab software. As a result, predicted shape and scale parameters of cases 2 and 3 were not significantly different from the results of normal use conditions at 5 % significance level. However, there was a big difference between the predicted scale parameter of case A and the parameter for normal use conditions.

In addition to the hypothesis test, confidence intervals of parameters were calculated for the validation of ALTs. Table 8 shows 95 % confidence intervals of parameters under normal use conditions and the predicted values of parameters for ALTs. We do not reject H_0 (β = 2.4858, shape parameter of case A) if the 95 % confidence intervals of shape parameter

Table 7. The p-values for each case.

Parameter	Case A	Case B	Case C
Shape	0.101	0.324	0.326
Scale	0.000	0.597	0.248

Table 8. The shape and scale parameters estimated from normal use conditions and ALTs.

Condition		Shape parameter	Scale parameter
Normal use conditions	95 % lower confidence limit	2.2520	16933000
	Point estimate	4.1189	20218409
	95 % upper confidence limit	7.5336	24141000
Case A	Point estimate	2.4858	230760000
Case B	Point estimate	3.0383	21202000
Case C	Point estimate	3.0425	22436000

under normal use conditions includes H_0 [22]. Thus, the conclusions are equal to those of the hypothesis test.

4.3 Final reliability characteristics of pneumatic cylinders

Finally, the life cycles of cases C and normal use conditions were combined to calculate the various parameters of pneumatic cylinders.

The MLEs of β, E_a and n were 3.2233, 0.2854 and 1.4873, respectively. The 95 % confidence intervals for each parameter were (2.4243, 4.2856), (0.2494, 0.3214) and (0.9173, 2.0573). The characteristic life of pneumatic cylinders under normal use conditions was obtained as η_{use} = 20546000 life cycles by substituting T = 296.15 K (23 °C) and P = 630 kPa into Eq. (5). The B_{10} life of pneumatic cylinders under normal use conditions was 10222000 cycles.

5. Conclusions

The major conclusions of this paper are as follows:

- The main failure mode of pneumatic cylinders was identified as leakage through piston seal wear.
- The acceleration stress factors affecting the life cycles of pneumatic cylinders were selected as temperature and pressure.
- Based on ALTs results, pressure is a more significant acceleration stress factor than temperature.
- By combining the test data of single stress ALTs, more meaningful results were provided.
- Validation for ALTs was performed by using the hypothesis test and confidence intervals for parameters between ALTs and normal use conditions. The ALTs results of cases B and C appeared to be effective based on the validation methods.
- Weibull shape parameter of pneumatic cylinders is 3.2.

- The final ALTs parameters of pneumatic cylinders including data of normal use conditions are as follows:
  • Acceleration index of pressure (*n*): 1.5.
  • Activation energy on the temperature (E_a): 0.29 eV.
- The scale parameter and the B_{10} life under normal use conditions (23 °C and 630 kPa) are 20546000 and 10222000 cycles, respectively.

Nomenclature

$R(t)$: Reliability function
$F(t)$: Failure probability
β : Shape parameter of Weibull distribution
η : Scale parameter (or characteristic life) of Weibull distribution
L : Quantifiable life (characteristic life of Weibull distribution)
A, C : Parameters of ALTs model
V : Nonthermal stress (pressure)
T : Absolute temperature (K)
n : Acceleration index of pressure
E_a : Activation energy (eV)
k : Boltzmann constant (8.6171×10^{-5} eV/K)
AF : Acceleration factor
B_{10} *Life* : The lifetime by which 10 % of a population of a product will have failed

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