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The Error Analysis of Leak Measurement for Pneumatic Cylinder Using Isothermal Chamber

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Key Words : Leakage Measurement, Compressible Fluid, Isothermal Chamber, Pneumatic Cylinder, Reliability Test

Abstract: ISO pneumatic cylinder reliability test requires air leakage measurement. Air cylinder has many parts and the leakage shall be measured before, during and after endurance test, and, the leakage should smaller than the specified value. The existing measurement method needs complex operation and the calibration of leak detector, and, has to separate the testing cylinder from endurance test device, which causes the change of contact condition of seal in the cylinder. Therefore, it is hard to evaluate the air leakage during endurance test, and guarantee the reliability of the conventional measurement method. In this paper, a new method for air leakage measurement using isothermal chamber, which does not requires calibration or temperature compensation, and, can measure air leakage accurately with quite simple operations, is proposed. As a result, reliability of air leakage measurement can be improved because the proposed method does not have to separate the testing cylinder from the endurance test device for air leakage measurement. The effectiveness of the proposed method is proved by error analysis of leak measurement from experimental result.

NOMENCLATURE

G : Mass flow-rate of leakage [kg/s]
M : Air mass in the measuring volume [kg]
P : Pressure in the measuring volume [Pa]
δP : Measurement error of pressure [Pa]
ΔP : Range of pressure change [Pa]
Q : Volume flow-rate of leakage [m^3/s] (under 0[℃] and 1 atmosphere)
ΔQ : Range of leakage flow-rate [m^3/s] (under 0[℃] and 1 atmosphere)
δQ : Measurement error of leakage flow-rate [m^3/s] (under 0[℃] and 1 atmosphere)
R : Gas constant, where 287 [J/kg·K]
T : Temperature of measuring room [K]
δT : Measurement error of temperature [K]
V : Measurement volume [m^3]
δV : Measurement error of volume [m^3]

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1. INTRODUCTION

Pneumatic cylinder, which is the major component of pneumatic system, is pneumatic apparatus using compressed air as working fluid. Pneumatic cylinder goes through leakage by the reciprocating motion of piston which results from the wear of seal equipped in piston and rod. Such leakage degrades the performance of cylinder and being the major cause for the life reduction of cylinder.

However, precise measurement of flow-rate is not easy considering the characteristics of compressible fluid. In particular, extremely infinitesimal flow-rate such as leakage flow-rate cannot be measured by the measuring method of ISO 6358[1)] and the measuring method of JIS B 8390[2)]. Therefore, indirect method such as Bubble test has been used to check whether leakage is occurring or not, and leakage flow-rate has been measured by the expensive digital mass flow-meter for leakage measurement. On the other hand, Bubble tests cannot be performed if any of the part should avoid being wet and have trouble in quantitative analysis of leakage flow-rate.

Accordingly, leakage of cylinder has been measured by the expensive digital mass flow-meter for leakage measurement. But, this method requires separating the equipped cylinder from life tester, which causes the possibility of change for contact part of cylinder wall and piston seal in the course of attachment and detachment of cylinder. As a result, it is hard to evaluate the accurate leakage flow-rate occurred by life test.

2. ISOTHERMAL CHAMBER

Isothermal chamber[3~5], in this paper, keeps the temperature changes of air to be isothermal in case of providing the compressed air inside of chamber by extending the heat transfer coefficient and heat transfer area with stuffing the steel wool inside of chamber and in case of emitting the compressed air inside of chamber.

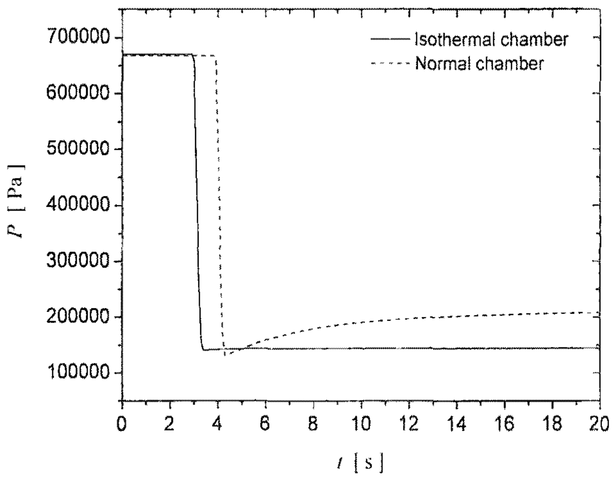


Fig. 1 Pressure change after stopping air discharge in an each isolated chamber

Fig. 1 shows the result of experiment in case of discharging compressed air inside of pressurized and isolated normal chamber and isothermal chamber. Fig. 2 provides the result of experiment in case of discharging compressed air inside of pressurized normal chamber connected with isothermal chamber. The solid line in Fig. 1 represents the experiment result in case of discharging compressed air inside of pressurized normal chamber, for random time, applying random reduce pressure, and blocking the coming and going of compressed air. The dotted line in Fig. 1 represents the experiment result in case of performing the same method with normal chamber. In Fig. 1, the horizontal axis shows the time, while the axis of ordinates shows the pressure inside of vessel. In case of normal chamber that was not stuffed with steel wool, the pressure inside of chamber changed shortly after blocking the coming and going of compressed air by the temperature rising of compressed air but, in case of isothermal chamber that was stuffed with steel wool, pressure scarcely changed after blocking the coming and going of compressed air that we can interpret this situation as the restraint state of temperature change inside of chamber.

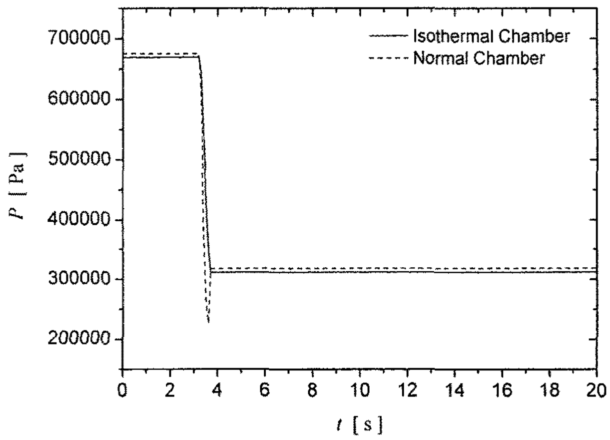


Fig. 2 Pressure change after stopping air discharge in isothermal chamber connected with normal chamber

Fig. 2 shows the temperature effect in the each chamber. In Fig. 2, solid line and dotted line denotes pressure change inside of the normal chamber and isothermal chamber which, the same method with Fig. 1. In the isothermal chamber, keep up the isothermal condition, on the other hand, in the normal chamber, rapidly changing of pressure immediately after isolated flow-rate. But, in the normal chamber, it can be quick stabilization of pressure under the influence of isothermal chamber.

3. The Principle of Flow-Rate Measurement Using Isothermal Chamber

The relationship between the change of temperature or pressure and flow-rate of air can be expressed as follows.

$$G = \frac{1}{RT}\left(V\frac{dP}{dt} - MR\frac{dT}{dt}\right) \qquad (1)$$

In isothermal condition, we can express the flow-rate as the function of pressure change as follows because the second term on the right side of equation (1) can be ignored.

$$G = \frac{V}{RT}\frac{dP}{dt} \qquad (2)$$

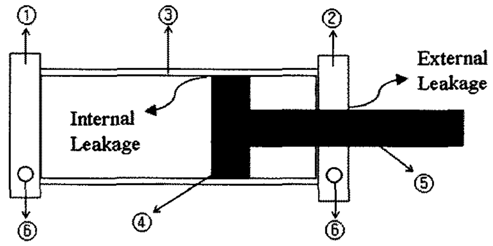
In equation (2), if we assume that we are aware of the volume of chamber and the temperature of measuring room, we can find that it is possible to measure the mass flow-rate of air by the pressure change inside of chamber. Also, by applying equation (2), we can measure relatively wide range of mass flow-rate including infinitesimal leakage flow-rate because the change of pressure can be readily measured up to high frequency area.

4. MEASUREMENT OF LEAKAGE FLOW-RATE USING ISOTHERMAL CHAMBER

4.1 Measurement method of leakage flow-rate using isothermal chamber

In this paper, the result of flow-rate measurement is expressed by converting mass flow-rate into the volume rate of flow under 0[℃] and 1 atmosphere.

The pneumatic cylinder in Fig. 3 is a double-acting cylinder which is mainly used in the factory automation line. The main leakage from this kind of cylinder can be divided into internal leakage which occurs at the gap between piston seal and guide tube and external leakage which occurs at the gap between rod seal and rod.



①end cap, ②rod cap, ③cylinder wall, ④piston head, ⑤piston rod, ⑥inlet or outlet port

Fig. 3 Typical leakage flow-rate of pneumatic cylinder

According to ISO 19973-3[6] which is progressing for the establishment of international standard on the reliability of pneumatic component, the tolerance of leakage flow-rate is prescribed as an important failure criteria and both end position of cylinder(end cap, rod cap) is specified as the place to measure the leakage. But, there exist no prescription in detail for the method of leakage measurement. However, if we select the method that measures the leakage at both end of cylinder with existing digital mass flow-meter for leakage measurement, internal leakage flow-rate occurring at piston seal can relatively be measured with ease but external leakage flow-rate occurring at rod seal cannot be measured simply. Thus, it is hard to estimate actual total leakage flow-rate that improvement of reliability through failure mode analysis is not simple.

In this paper, we are to propose the method of quantitatively measuring the internal leakage flow-rate and external leakage flow-rate by attaching the measuring apparatus for leakage flow-rate using the isothermal chamber to the life tester as shown in Fig. 4. The measuring method of internal leakage flow-rate occurring at piston seal is as follows.

1) Set the upper-side supply pressure of cylinder as 0.63(or 0.15)[MPa] and set the pressure inside of lower-side isothermal chamber to be atmospheric pressure.

2) Advance the piston head to the rod cap direction of cylinder by applying set pressure 0.63(or 0.15)[MPa] to isothermal chamber and cylinder room through control valve.

3) Block the coming and going of compressed air between isothermal chamber and control valve by using isolation valve.

4) Calculate the internal leakage flow-rate using equation (2) after measuring the pressure change inside of isothermal chamber.

The measuring method for the total leakage flow-rate occurring at the piston seal and rod seal of cylinder is as follows.

1) Set the upper-side supply pressure of cylinder as 0.63(or 0.15)[MPa] and set the pressure inside of lower-side isothermal chamber to be atmospheric pressure.

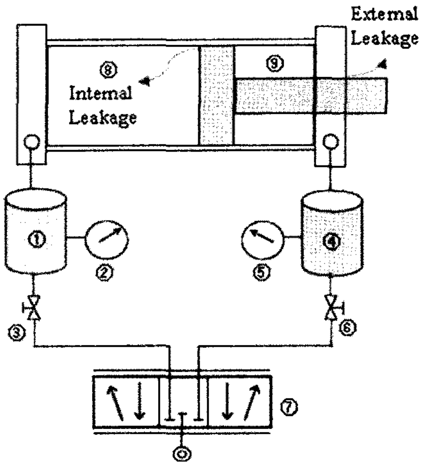
2) Advance the piston head to the end cap direction of cylinder by applying set pressure 0.63(or 0.15)[MPa] to isothermal chamber and cylinder room through control valve.

3) Block the coming and going of compressed air between isothermal chamber and control valve by using isolation valve.

4) Calculate the total leakage flow-rate of cylinder using equation (2) after measuring the pressure change inside of isothermal chamber.

Where, supply pressure is 0.15 and then 0.63[MPa], allowable error is ± 0.03[MPa]. The external leakage flow-rate occurring at the rod seal of cylinder is estimated by using the measured internal leakage flow-rate and total leakage flow-rate.

The volume of isothermal chamber which is used in this experiment is 1.616×10^{-3}[m^3], and the inside of chamber is charged with the steel wool of 0.165×10^{-3}[m^3]. Copper tube with the diameter of 6[mm] and length of 150 [mm] is used as the pneumatic pipeline. The pressure inside of chamber was measured by using the pressure transducer of piezo type, with setting the sampling time as 10[ms] and total experiment time as 60[s]. The pneumatic cylinder used in this experiment was single rod double-acting pneumatic cylinder which was applied with vertical load of 10[kg] to drive over 1×106[cycle], with the diameter of 50[mm] and the stroke of 300[mm].



①, ④isothermal chamber, ②, ⑤pressure sensor, ③, ⑥isolation valve, ⑦adjustable flow control valve, ⑧, ⑨ cylinder chamber

Fig. 4 Measurement apparatus of leakage flow-rate using isothermal chamber

4.2 Measurement error of leakage flow-rate using isothermal chamber

According to the ISO 19973-3[6] and ISO 10099[7], the maximum permissible leak flow-rate of a new cylinder is equal to Table 1. During or after the endurance test, it must not exceed 10 times the value specified in Table 1.

Table 1 Permissible leakage of a cylinder chamber (Before the endurance test)

bore [mm]	leak [m^3/s]	bore [mm]	leak [m^3/s]
8~12	1.66×10^{-7}	63~100	5.55×10^{-7}
16~25	2.22×10^{-7}	125~200	8.33×10^{-7}
32~45	3.33×10^{-7}	250~320	13.83×10^{-7}

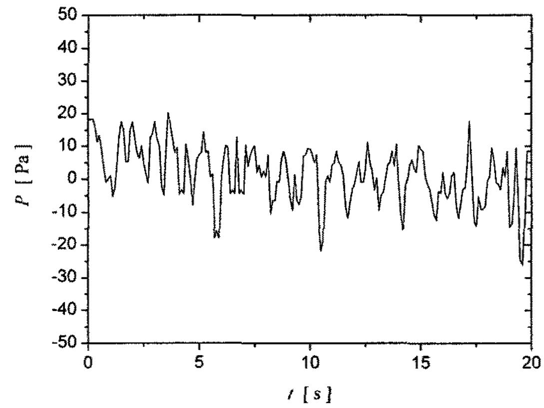


Fig. 5 The change of pressure in the isothermal chamber under atmosphere condition

Fig. 5 shows the result of pressure change in the isothermal chamber under 20 [℃] and 1 atmosphere. As shown in Fig. 5, a change of pressure is about 45 [Pa].

The leak Measurement error can be calculated by equation (3). In isothermal condition, first and second term on the right side of equation (3) can be ignored. Thus, equation (3) is converted to equation (4).

$$\frac{\delta Q}{\Delta Q}=\sqrt{\left(\frac{\delta V}{V}\right)^2+\left(\frac{T}{\delta T}\right)^2+\left(\frac{\delta P}{\Delta P}\right)^2} \quad (3)$$

$$\delta Q=\frac{\delta P}{\Delta P}\times \Delta Q \quad (4)$$

Therefore, leak measurement error can be estimated by the equations (2), (4) and Fig. 5. In this applications, estimated leak measurement error is about 0.13×10^{-7}[m^3/s](0.8[cc/min]), and this result is applicatory value compare to Table 1.

4.3 Experimental results of leakage flow-rate using isothermal chamber

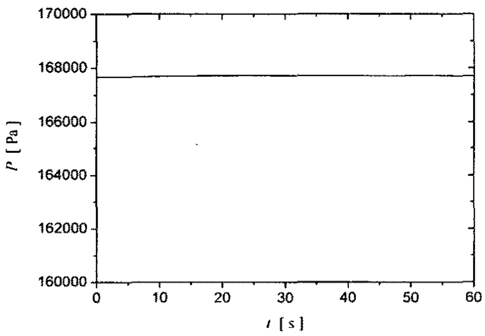


Fig. 6 Pressure response of internal leakage with supply pressure 0.15[MPa]

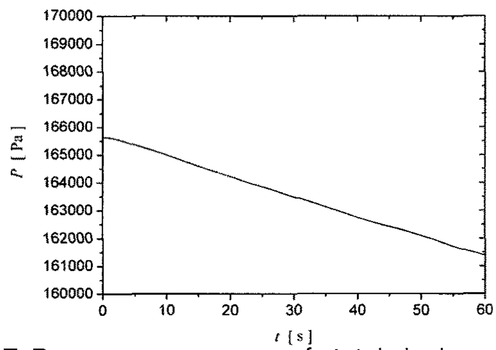


Fig. 7 Pressure response of total leakage with supply pressure 0.15[MPa]

Fig. 6 and Fig. 7 show the result of observation for the pressure response by connecting isothermal chamber at the supply 0.15[MPa],on the direction of end cap and rod cap respectively. In case of infinitesimal leakage flow-rate, pressure change by leakage flow-rate is not notable as shown in Fig. 6 that being affected by noise.

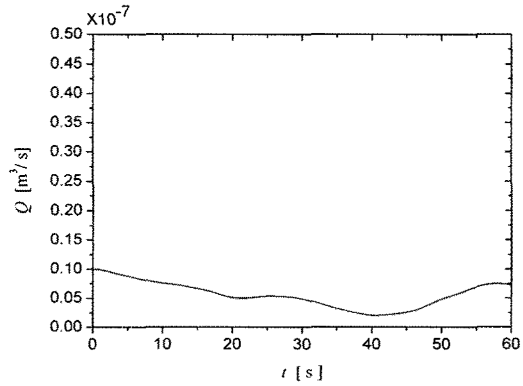


Fig. 8 Internal leak with supply pressure 0.15[MPa]

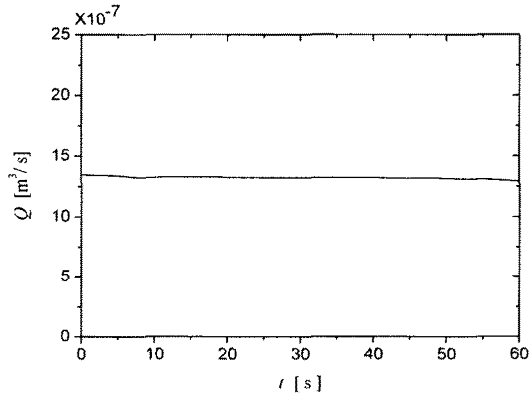


Fig. 9 Total leak with supply pressure 0.15[MPa]

Fig. 8 and Fig. 9 shows the results converting the pressure response in Fig. 6 and Fig. 7 into the leakage flow-rate at end cap and rod cap by using equation (2). From Fig. 8, the average internal leakage flow-rate measured at end cap is about 0.07×10^{-7}[m^3/s], and the measured leak value smaller than the allowable error. Therefore, internal leak is almost zero or infinitesimal value. On the other hand, the average total leakage flow-rate measured at rod cap is about 13.4×10^{-7}[m^3/s], which make it possible to estimate the average external leakage flow-rate as about 13.4×10^{-7} [m^3/s].

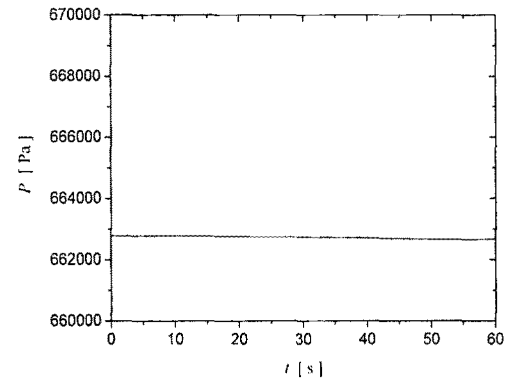


Fig. 10 Pressure response of internal leakage with supply pressure 0.63[MPa]

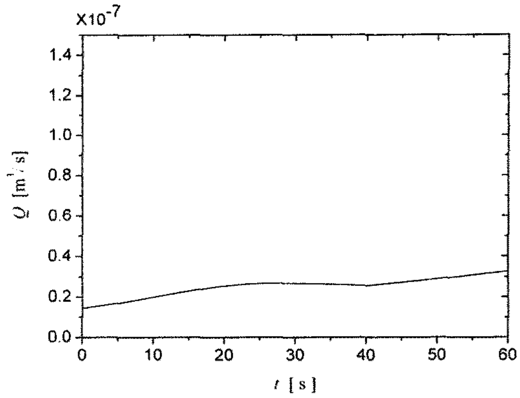


Fig. 12 Internal leakage with supply pressure 0.63[MPa]

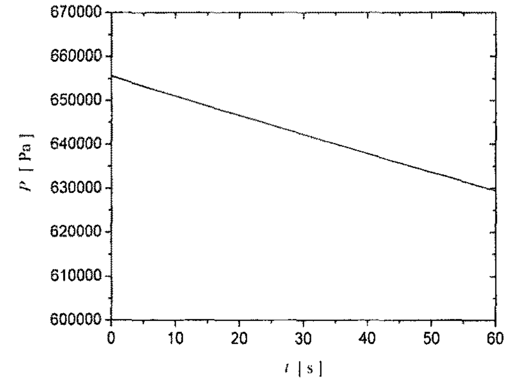


Fig. 11 Pressure response of total leakage with supply pressure 0.63[MPa]

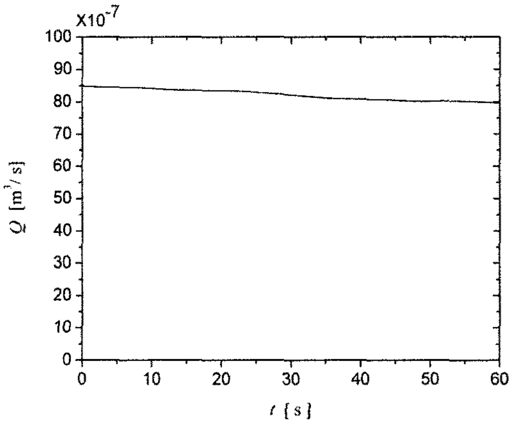


Fig. 13 Total leakage with supply pressure 0.63[MPa]

Fig. 10 and Fig. 11 show the result of observation for the pressure response by connecting isothermal chamber at the supply 0.63[MPa], on the direction of end cap and rod cap respectively.

Fig. 12 and Fig. 13 show the results converting the pressure response in Fig. 10 and Fig. 11 into the leakage flow-rate at end cap and rod cap by using equation (2). From Fig. 12, the average internal leakage flow-rate at end cap is about 0.25×10^{-7}[m^3/s]. But, if consider to measurement error(0.07×10^{7}[m^3/s]), minimum value is 0.18×10^{7} [m^3/s] and maximum value is 0.32×10^{7}[m^3/s] of internal leak. Furthermore, the average total leakage flow-rate measured at rod cap is about 82.5×10^{-7}[m^3/s], which make it possible to estimate the average external leakage flow-rate about 82.25×10^{-7}[m^3/s].

In Fig. 12, pressure variation inside of chamber according to the leakage is infinitesimal for the total experiment time that the change of leakage flow-rate is not very huge. But, in case of relatively large amount of leakage flow-rate as shown in Fig. 13, the pressure inside of chamber reduces below rated pressure by leakage flow-rate and flow-rate also reduces by reduced pressure. Therefore, for the precise evaluation of the leakage flow-rate, it is desirable to express it based on the pressure.

Fig. 14 show the result of total leakage flow-rate at rod cap based on the pressure. From Fig. 14, which is in the case of relatively large amount of leakage flow-rate, we can see that the pressure in chamber is changing according to the leakage flow-rate. So, if we measure pressure after deciding the limit that the pressure in chamber which can be changed according to the leakage, we can decide whether the leakage characteristics of equipment under measurement can meet the criteria or not by only the pressure after specific time.

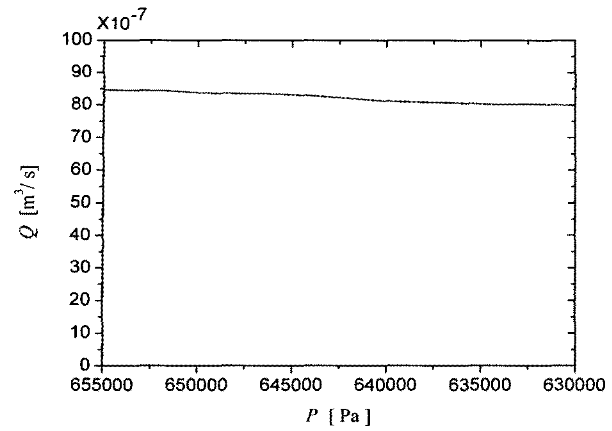


Fig. 14 Total leakage by pressure response at 0.63[MPa]

According to the JIS standard[8)] for the leakage of pneumatic cylinder, internal leakage of 2×10^{-7}[m^3/s] (12[cc/min]) and external leakage of 1.33×10^{-7}[m^3/s] (8[cc/min]) is permitted in case of single rod double-acting cylinder with the diameter of 50[mm] which is used in this experiment. And, according to the ISO standard[6~7)] for the leakage of pneumatic cylinder, total leakage flow-rate of carried out the endurance test cylinder is permitted up to 33.3×10^{-7}[m^3/s] (200[cc/min]) irrespective of internal or external leakage. Therefore, we can see that the cylinder which is used in this experiment exceeds the leakage tolerance of both JIS and ISO standard.

CONCLUDING REMARKS

In this study, we proposed a new method to measure the leakage flow-rate of pneumatic cylinder which is the representative pneumatic apparatus by using the pressure change inside of chamber.

The measuring method for the leakage flow-rate proposed in this paper is the method that converting the pressure change inside of chamber occurring by leakage into flow-rate by pressurizing the chamber which was connected with cylinder without separating the cylinder equipped in life tester. If we measure leakage flow-rate using the suggested method, we can evaluate the leakage flow-rate during life test quantitatively because we do not need to detach or attach the cylinder from life tester to measure leakage. In addition, proposed measurement method needs not temperature compensation and calibration. Based on this fact, reliability improvement through the failure analysis of pneumatic cylinder becomes easier. Also, measuring method for the leakage flow-rate suggested in this paper can measure the internal and external leakage flow-rate with only chamber and pressure sensor without requiring extra apparatus for the measurement of leakage. As a result, it can reduce the time and cost for the configuration of measuring apparatus for leakage flow-rate comparing with conventional method.

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