

# CHARACTERISTICS OF LEAK DETECTION BASED ON DIFERENTIAL PRESSURE MEASUREMENT

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## ABSTRACT

This paper presents the first study on how the unbalance of temperature recovery after air charged has a significant effect on the accuracy and repeatability of air leak detection. From this viewpoint, temperature recovery time is derived and affecting parameters are investigated. In a leak detection based on differential pressure measurement, the leak is detected by measuring pressure difference between a reference component, which is leak tight, and a tested component using a differential pressure sensor. When the tested component is leaking, the pressure inside it decreases and the pressure difference with the reference is measured. However, when the required temperature recovery time is not satisfied, unbalance of temperature recovery due to a possibly small difference of heat transfer coefficient between the reference and tested component can produce pressure difference that is similar in size as a real leak and larger uncertainty. This phenomenon is described theoretically and the experimental data are in satisfactory agreement with the calculated results.

## KEY WORDS

Air leak detection, Differential pressure, Temperature recovery

## NOMENCLATURE

$b$	: Critical pressure ratio	[]	$P$	: Differential pressure	[Pa]
$C$	: Sonic conductance	[m <sup>3</sup> /(s.Pa)]	( $P=P_r-P_m$ )		
$C_p$	: Specific heat at constant	[J/(kg · K)]	$q$	: Volume flow rate	[m <sup>3</sup> /s]
	pressure		$Q_L$	: Leak rate	[cc/min]
$C_v$	: Specific heat at constant	[J/(kg · K)]	$Q_{LG}$	: Generated leak rate	[cc/min]
	volume		$R$	: Ideal gas constant	[m <sup>2</sup> /(s <sup>2</sup> · K)]
$G$	: Mass flow rate	[kg/s]	$S_h$	: Heat effective area	[m <sup>2</sup> ]
$h$	: Heat transfer coefficient	[W/(m <sup>2</sup> · K)]	$T_h$	: Thermal-time constant	[s]
$\kappa$	: Ratio of specific heat	[]	$T_r$	: Temperature recovery time	[s]
$m$	: Mass	[kg]	$T_{rr}$	: Required temperature	[s]
$P$	: Pressure	[kPa]		recovery time	
			$V$	: Volume	[cc]

	: Temperature	[K]
	: Differential temperature	[K]
$e$	: Measurement error	[cc/min]
$\sigma$	: Standard deviation	[cc/min]
$\rho_o$	: Air density	[kg/m <sup>3</sup> ]

**Subscripts**

$m$	: Master
$t$	: Tested

**INTRODUCTION**

The growing need for leak tight products has made researchers as well as leak tester manufacturer competing to develop a better leak tester. Various leak detection methods have been developed to satisfy the wide range of leak size down to 10<sup>-12</sup>cc/min depending on the application. In a leak detection based on differential pressure measurement, leakage is detected by measuring pressure difference between a reference and a tested component using a differential pressure sensor. As compared with only measurement of pressure inside the tested component chamber, measurement of differential pressure between the dual chambers, in which a leak-tight master is used as a reference, has several advantages. The waiting time for detection can be shortened, thermal instability can be reduced and influence of external environment change can be counterbalanced.

E.B. Arkilic described in his paper that temperature stability of the environment surroundings the low flow system and temperature stability within it influences the result. The more accurate the detection result and the smaller the leak size to be detected the higher the temperature stability requirement [1].

During the charging process in to a chamber, T. Kagawa demonstrated in his paper that pressure response within the chamber is affected by the heat transfer between the air in the chamber and the chamber wall [2]. Higher tested pressure takes longer temperature recovery time and bigger chamber volume also needs longer temperature recovery time. This must be considered when differential pressure measuring technique is going to be utilized for leak tester.

When two chambers are charged simultaneously, unbalance of temperature recovery due to a small difference of heat transfer coefficient occurs and produces differential pressure that is similar in size as a real leak and uncertainty to the air leak detection. In this paper, these phenomena are analyzed theoretically and verified experimentally.

**MODEL AND ANALYSIS**

When a chamber is charged as illustrated in Figure 1, temperature inside the chamber increases to a certain level and recovers to atmosphere temperature due to

heat transfer. And when the charging process is stopped during temperature recovery, the pressure inside the chamber decreases proportionally to the temperature change within the chamber [3]. To describe this phenomenon, first, the ideal-gas equation of state is derived as follow:

$$\frac{dP}{dt} = \frac{P}{\theta} \frac{d\theta}{dt} + \frac{R\theta}{V} G \tag{1}$$

From the conservation of energy, the following equation is obtained:

$$C_v m \frac{d\theta}{dt} = C_v G_u (\theta_a - \theta) + R G_u \theta_a + Q \tag{2}$$

As the atmosphere temperature is maintained constant at a certain level  $\theta_a$ , the heat transfer rate passing through the chamber wall can be expressed as:

$$q = h S_h (\theta_a - \theta) \tag{3}$$

Based on Eq. (1), Eq. (2) and Eq. (3), the pressure and temperature change inside the chamber after charging process, can be expressed utilizing the following equations:

$$\frac{dP}{dt} = \frac{P}{\theta} \frac{d\theta}{dt} + \frac{R\theta}{V} G \tag{4}$$

$$\frac{d\theta}{dt} = \frac{R\theta}{C_v P V} [G(C_p \theta_a - C_v \theta) + h S_h (\theta_a - \theta)] \tag{5}$$

Where the mass flow rate to the chamber is expressed as [4]:

$$G = \begin{cases} C \rho_o P \sqrt{1 - \left(\frac{P/P_s - b}{1-b}\right)^2} \dots\dots \frac{P}{P_s} > b \\ C \rho_o P \dots\dots\dots \frac{P}{P_s} \leq b \end{cases} \tag{6}$$

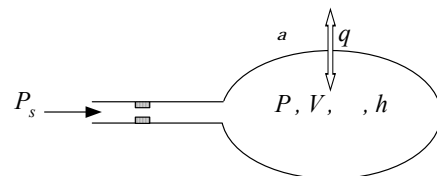


Figure 1 Air charged in to a chamber

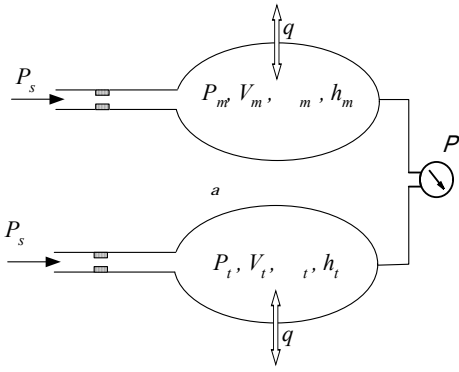


Figure 2 Air charged simultaneously to two chambers

The simulated results of pressure and temperature change within the chamber after stop charging at 6s, under pressure 500kPa and chamber volume 140cc are shown in Figure 3. As illustrated in the figure, the pressure within the chamber decreases as a result of temperature recovery.

In a differential pressure type air leak tester as displayed simply in Figure 2, two chambers are charged simultaneously to supply pressure before starting leak detection.

After charging process is stopped at  $T_r = 6s$ , to start leak detection, temperature difference due to inadequate temperature recovery produces differential pressure that is similar in size as a real leak even though tested chambers is leak-tight.

These phenomena are demonstrated theoretically in Figure 4. As illustrated in the figure, although the heat transfer coefficient is only 0.26% different between master and tested chamber, a 0.01K remaining unbalance of temperature recovery occur at this point due to inadequate temperature recovery time and this produces a pressure difference of 6Pa even though tested tank is leak-tight. When the charging is stopped at a longer time (i.e. 10s), the pressure difference becomes about 3.5Pa. It is clear that longer waiting time is necessary to create adequate temperature recovery and to eliminate the pressure difference not due to leak.

Leak size for dual chamber method is simply calculated based on the derivation of ideal gas equation:

$$\frac{V_t}{R\theta_t} \frac{dP_t}{dt} - \frac{V_m}{R\theta_m} \frac{dP_m}{dt} = \rho Q_L + \frac{P_t V_t}{R\theta_t^2} \frac{d\theta_t}{dt} - \frac{P_m V_m}{R\theta_m^2} \frac{d\theta_m}{dt} \quad (7)$$

If the two chambers are equal in temperature, volume and undergo identical thermal fluctuations, then the leak rate is given by:

$$Q_L = \frac{V}{R\theta} \frac{d\Delta P}{dt} - \frac{\Delta P V}{R\theta^2} \frac{d\theta}{dt} \quad (8)$$

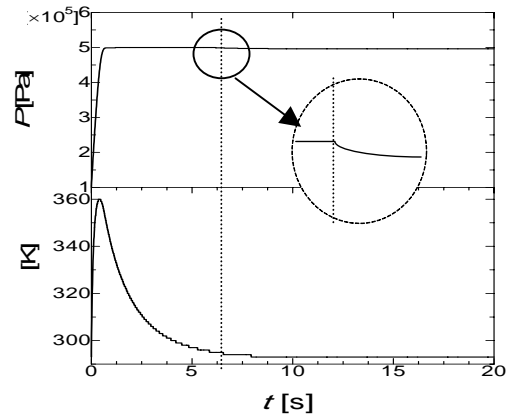


Figure 3 Pressure and temperature inside the chamber [Charging is stopped at 6s]

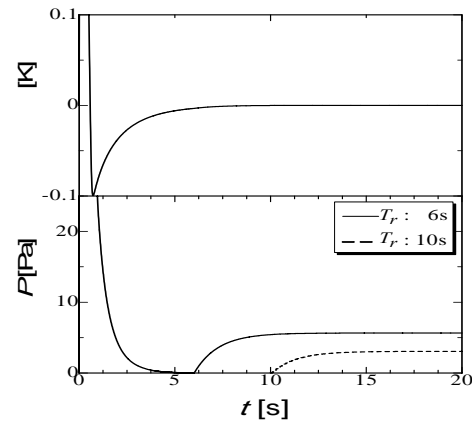


Figure 4 and  $P$  change between the two chambers [ $h_m = 30W/(m^2K)$ ,  $h_t = 30.08W/(m^2K)$ ]

Generally, the last part of Eq. (8) can be neglected since  $P$  and  $\frac{d\theta}{dt}$  is very small as compared with  $\frac{d\Delta P}{dt}$ .

## LEAK DETECTION

### The developed leak tester

The developed leak tester as illustrated in Figure 5 consists of 5 main elements: PLC (Programmable Logic Controller), PC (Personal Computer), a reference and tested component, a differential pressure sensor and valves. The valves are controlled by the PLC based on the sequence as displayed in Figure 6. The room temperature is maintained constant at 20° C.

The applicability under high pressure and the leak-tightness of the leak tester before utilizing for leak detection are important to be guaranteed. By disassembling both master and tested chamber, the leak tester is charged up to 800kpa.

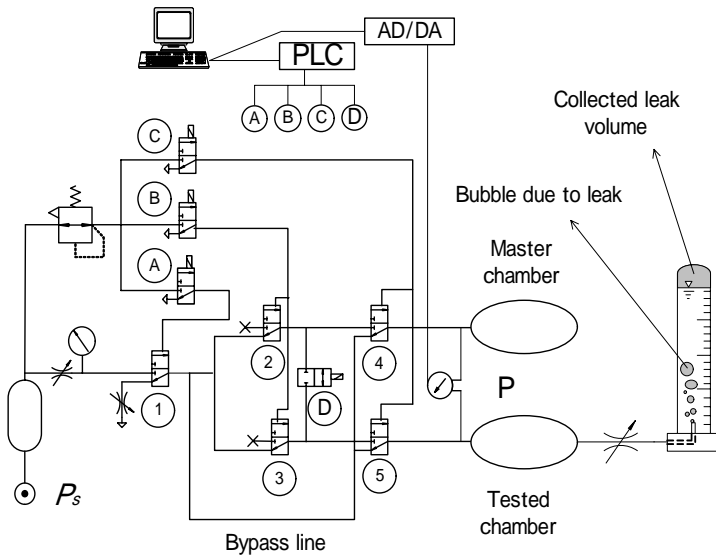


Figure 5 Developed leak tester

At the possible shortest temperature recovery time  $6s$ , the charging is stopped and the differential pressure response between reference and tested circuit is recorded, and repeated 5 times under the same experimental condition to guarantee the repeatability of the leak tester. As illustrated in Figure 7, the differential pressure responses after the charging process is stopped at  $6s$  are stable, constant at zero level and high repeatability. The experimental result demonstrates the applicability of the developed leak tester under high pressure, pressure balance between reference and tested circuit, and the leak-tightness of the leak tester.

#### Characteristics of leak-tight chamber

As demonstrated in the simulated results that inadequate temperature recovery can produce pressure difference that is similar in size as the real leak although tested chamber is leak-tight. The experimental results, as displayed in Figure 8(a) and 8(b), are carried out under leak-tight tested chamber, 5 times repetitions and in two different  $T_r$  (i.e.  $6s$  and  $10s$ ). The results are in satisfactory agreement with the simulated results.

Since the charging process passing through a sudden enlargement from the pipe to the chamber, the experimental results also show the effect of inadequate temperature recovery to the range of uncertainty as demonstrated in Figure 8. Within 5 sample data, the range of uncertainty of the differential pressure response due to inadequate temperature recovery is larger when shorter  $T_r$  is applied.

#### Leak generation and detection results

As displayed in Figure 5, leakage is generated by a variable restrictor attached to the tested chamber. The generated air leak is measured by a mess cylinder filled with water connected at the end of the pipe.

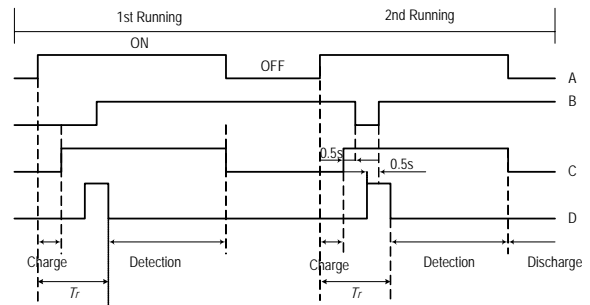


Figure 6 Valve control sequence

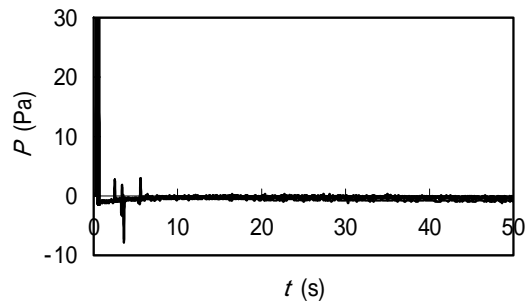


Figure 7  $P$  response of leak tester

Based on the JPAS002-1984 standard for air leak measurement, the generated leak rate is the ratio of the collected air volume due to leakage in the top of the mess cylinder to time consumption  $t$  during leak detection.

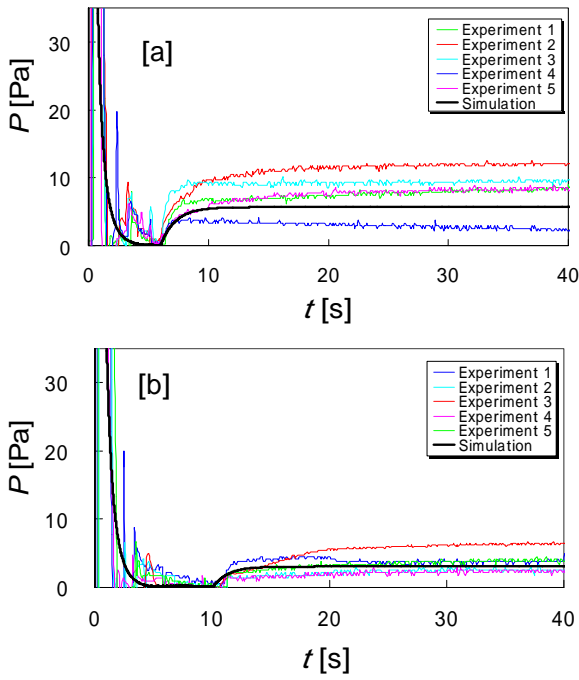


Figure 8 Simulated and experimental results of the  $P$  responses for leak-tight tested chamber, Experiment is carried out 5 times,  $P=500\text{kPa}$  and  $V=140\text{cc}$ : [a]  $T_r=6\text{s}$  and [b]  $T_r=10\text{s}$

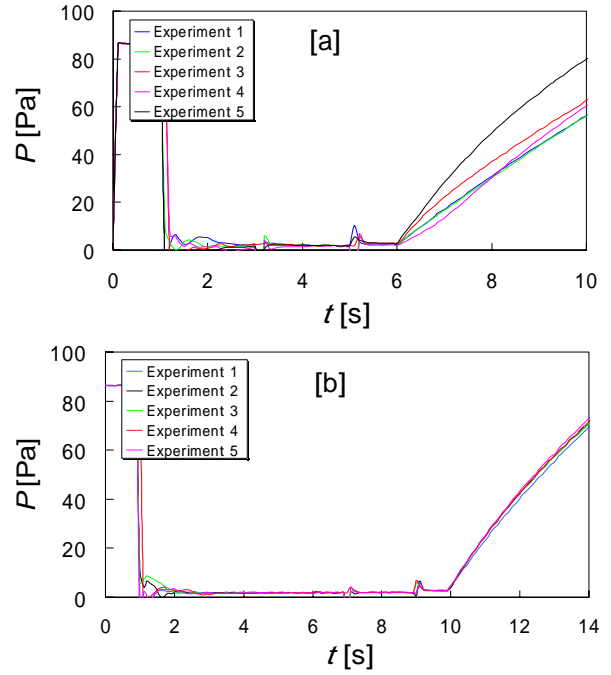


Figure 9 Differential pressure change under 5 times repetitions for  $0.3\text{cc}/\text{min}$  generated leak from tested chamber for  $P=500\text{kPa}$  and  $V=140\text{cc}$ : [a]  $T_r=6\text{s}$  and [b]  $T_r=10\text{s}$

The experiment on leak tested chamber was carried out by generating  $0.3\text{cc}/\text{min}$  leakage from the tested chamber and five sample data were recorded at each temperature recovery time to investigate the repeatability of the detection results. The experimental results are summarized in Figure 9(a) and 9(b) for  $T_r=6\text{s}$ , and  $10\text{s}$  respectively.

Figure 9(a) demonstrates that inadequate temperature recovery produces larger uncertainty or low repeatability which is shown by about  $24\text{Pa}$  range of uncertainty of the differential pressure  $P$  change within 5 sample data due to  $0.3\text{cc}/\text{min}$  generated leak. However, when the temperature recovery time  $T_r$  is set to be longer ( $T_r=10\text{s}$ ), the differential pressure  $P$  response varies narrowly about  $4\text{Pa}$  as demonstrated in Figure 9(b).

Table 1 displays the summary of the precision and accuracy of the detection results in various  $T_r$  and leak sizes which are indicated by the measurement error  $e$  and the standard deviation  $\sigma$  respectively.

### REQUIRED TEMPERATURE RECOVERY

The uncertainty of the differential pressure responses for leak-tight tested chamber in various pressures and volumes are summarized in Figure 10.

Table 1 Measurement error and deviation  
(a)  $P=500\text{kPa}$  and  $Q_{LG}=0.3\text{cc}/\text{min}$

$T_r$	$e$	$\sigma$
6	0.04	0.01
10	0.02	0.002
14	0.01	0.001

(b)  $P=500\text{kPa}$  and  $Q_{LG}=0.05\text{cc}/\text{min}$

$T_r$	$e$	$\sigma$
14	0.004	0.01
18	0.001	0.006
22	0.001	0.002

The experiments were carried out by taking the maximum range of uncertainty within five sample data for various pressures (i.e.  $200\text{kPa}$ ,  $500\text{kPa}$  and  $800\text{kPa}$ ), various volumes (i.e.  $140\text{cc}$  and  $400\text{cc}$ ) and  $4\text{s}$  time increment (i.e.  $6\text{s}$ ,  $10\text{s}$ ,  $14\text{s}$  and  $18\text{s}$ ).

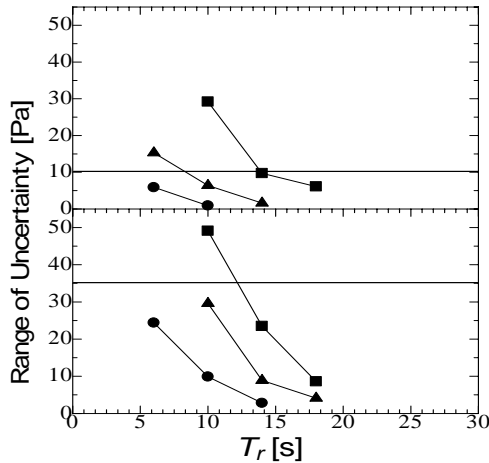


Figure 10 Range of uncertainty in various pressures

Higher accuracy requires lower uncertainty and a 0.001cc/min of accuracy requires less than 10Pa and 35Pa tolerable range of uncertainty of the differential pressure response for chamber volume 140cc and 400cc respectively. The required temperature recovery time  $T_{rr}$  is defined as the minimum temperature recovery time that can produce range of uncertainty less than 10Pa and 35Pa for chamber volume 140cc and 400cc respectively which is shown by the solid line in Figure10. And the experimental results of the  $T_{rr}$  are summarized in Figure 11 upper side.

It is clear that  $T_{rr}$  depends on the charged pressure and chamber volume. However, it is difficult to determine it by drawing the curve of uncertainty as shown in Figure 10, since it takes long time to conduct experiments under different  $T_r$ .

Here, we discuss the relation between  $T_{rr}$  and the thermal time constant. The thermal time constant is defined in the following equation [5].

$$T_h = \frac{C_v W}{S_h h} = \frac{C_v P V}{S_h h R \theta} \quad (9)$$

Because  $T_{rr}$  is also a parameter proportional to the charged pressure and related to chamber volume as shown in Figure 11 upper side, we calculate their ratio and show the result in Figure 11 lower side. It can be seen that the ratio is less than 6. Therefore, as a practical determination method, the required temperature recovery time can be approached by setting 6 times of the calculated thermal time constant for various pressures and volumes.

## CONCLUSIONS

A differential pressure type air leak tester is studied.

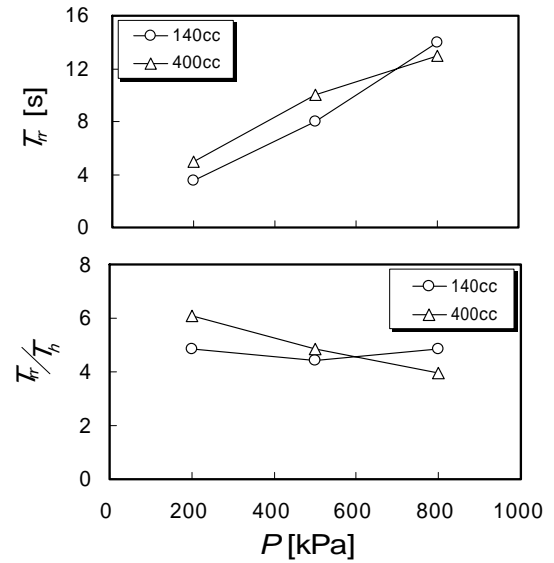


Figure 11 Required temperature recovery and thermal-time constant

Temperature recovery and its unbalance due to a small difference of heat transfer are discussed. This unbalance and inadequate temperature recovery produces differential pressure between master and tested chamber though the tested chamber is leak tight. Furthermore, this differential pressure is uncertain due to uncertainty of heat transfer. Due to the difficulty of determining the required temperature recovery time experimentally, its relation with thermal time constant has been investigated and proposed in this research to be utilized to estimate the required temperature recovery time that is very meaningful in leak detection field.

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