Application of Weighted Fusion Algorithm in Air Tightness Detection Device

Yang Liu, Jie Gao, Linggai Zhang
Chengyi University College, Jimei University, Xiamen, Fujian, 361021, China
*Corresponding author’s e-mail: 11872130@qq.com

Abstract. Gastightness testing plays an increasingly important role in ensuring the quality and performance of sealed products and the safety of their use. In this paper, a gas tightness detection scheme based on carbon dioxide gas sensor is proposed. The adaptive weighted fusion algorithm is used to fuse the weighted data collected by multiple carbon dioxide sensors to compensate for the error of single sensor test. The method is applied to leak detection of tracer gas, with high detection accuracy and wide range to meet production demand.

1. Introduction
With the continuous progress of industrial technology, the application field of air tightness detection device is more and more extensive. From aerospace to production and life, any potential minor leakage may lead to unqualified products or even lead to safety accidents. At present, there are many kinds of leak detection devices in the market, their principles and methods of use are different, and the results obtained by optimizing the information obtained are different, thus affecting the detection efficiency. In this paper, a multi-sensor weighted fusion algorithm is proposed. This method is applied to tracer gas leak detection, which has high detection accuracy and wide range, and meets the production requirements.

There are many factors affecting the accuracy of air tightness detection. It is difficult to determine the exact functional relationship between leakage and each factor. With the development of modern control technology, people apply various intelligent algorithms to data processing to improve the accuracy of air tightness detection. In this paper, a multi-sensor adaptive weighted fusion algorithm is proposed. Carbon dioxide is used as a tracer gas, and then the information collected by multiple carbon dioxide sensors is fused with weighted data to compensate for the test error of a single sensor.

2. System scheme
The air tightness testing experimental system is controlled and processed by computer. The controller is composed of a data acquisition card for signal acquisition, transmission and processing. The AI channel of the data acquisition card is used to transmit the signal value collected by the gas pressure sensor and the carbon dioxide sensor. The AO channel outputs the voltage to the electric proportional valve for regulation. Detection of air pressure, DO signal is used to control the opening and closing of the external solenoid valve and control the indicator light for sound and light alarm [57]. The control block diagram of the detection system is shown in Figure 1. Considering the number of test channels and the performance of data acquisition card, Yanhua High Precision Multifunctional PCI-1711 data acquisition card is selected to complete the signal acquisition and control.
Figure 1 System structure diagram

The principle of gas tightness detection based on carbon dioxide sensor is to calculate the leakage rate by measuring the change of carbon dioxide concentration in the container. According to the experimental purpose and requirement of the gas tightness testing scheme based on carbon dioxide sensor, the software flow of automatic testing is determined, which includes initialization of data acquisition card, zero adjustment of sensor calibration, gas path control, data acquisition and processing, display and storage of test results, etc.

3. Principle of leakage test

3.1. Leakage rate formula

The content of each component in the atmosphere is usually expressed as volume concentration and mass volume concentration. When carbon dioxide is used as tracer gas, the leak rate detected cannot be equivalent to the air leak rate, so the results need to be converted equivalently. The equivalent leakage rate of the air tightness detection scheme designed in this paper is shown in formula (1):

\[
Q' = \sqrt{\frac{M_1}{M_2}} \frac{(C_2-C_1)(V_2-V_1) \times 60}{t \times 10^6}
\]

(1)

In the formula, \(M_1\) is the molar mass of some gas component. 
\(M_2\) is the average molar mass of air. 
\(V_1, V_2\) indicates the volume of the container and the volume of the detected parts. 
\(C_2, C_1\) indicates the initial concentration value of tracer gas in the container and the final concentration value at the end of detection, unit ppm; 
\(t\) indicates detection time, unit s.

3.2. Leakage diffusion model analysis

The air tightness detection scheme designed in this paper is aimed at the micro leakage situation, that is, the uniform continuous leakage model with small change of air pressure. Therefore, the Gauss plume diffusion model is used for theoretical analysis. The Gauss plume diffusion model can be used to describe the concentration distribution of gas diffusion released from a persistent gas leakage point. In a stable detection environment, the leak point is taken as the virtual coordinate origin and the right-hand coordinate system is established. The horizontal (main direction) of gas diffusion is x-axis, the vertical (y-axis) is Y-axis and the vertical (z-axis) is z-axis. Without considering the spatial obstacles, noise and airflow, the expressions of concentration function at each point of the Gauss plume diffusion model can be obtained, as shown in equation (3):

\[
C(x, y, z) = \frac{Q}{2\pi \sigma_x \sigma_y} \exp \left[ -\frac{1}{2} \left( \frac{y^2}{\sigma_y^2} + \frac{z^2}{\sigma_z^2} \right) \right]
\]

(2)
\[ C(x, y, z) = \frac{Q}{2\pi\sigma_x \sigma_y \sigma_z} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \exp\left(-\frac{(z-H)^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(z+H)^2}{2\sigma_z^2}\right) \]  

(3)

In the formula, \( H \) : the height of the leakage source is m.

\( C(x, y, z) \): gas concentration at coordinate point \((x, y, z)\), unit \( mg/m^3 \);

\( Q \): gas leakage rate, unit \( m^3/s \);

\( \sigma_y, \sigma_z \): diffusion coefficient of gas in Y and Z directions, unit m.

4. Weighted data fusion algorithm

When the measured part leaks, the gas diffuses through the leak hole into the detection vessel to form an uneven concentration field. The carbon dioxide concentration curve obtained by a single sensor cannot reflect the change of carbon dioxide concentration in the detection unit, but reflects the change of carbon dioxide concentration in the local space, so it cannot reflect the change of the leakage rate of the detected system. In this paper, several carbon dioxide gas sensors are distributed in different locations of the detection container to collect data, and then weighted data fusion is carried out on the multi-sensor information. Finally, a difference in concentration representing the change in the concentration of the entire test vessel is obtained, thereby making up for the deficiency of the single gas sensor being susceptible to other environmental gases, and optimizing the experimental scheme.

In this paper, the optimal weighted data fusion algorithm is used, that is, the optimal fusion value \( \hat{X} \) is obtained when the total mean square error is the smallest and the corresponding weighted values of carbon dioxide gas sensors in \( n \) different locations are different. Assuming that the measurement value of sensor \( S_1, S_2, \ldots, S_n \) is \( X_1, X_2, \ldots, X_n \) and the detection results are independent of each other, the corresponding detection results of sensor \( P \) at the first time can be recorded as \( x_P(i) \).

According to the measured data provided by the sensor, the standard deviation corresponding to each single measurement of the sensor is \( \sigma_1, \sigma_2, \ldots, \sigma_n \), and the corresponding weights are \( W_1, W_2, \ldots, W_n \), respectively. Weighted data fusion can get the optimal data fusion value \( \hat{X} \) with a minimum mean square error of \( \sigma^2 \). In this paper, the weight of each sensor's measurement value is calculated by the actual measurement results. From the analysis of the actual measurement results, the influence of sensor placement on the experimental results has been solved. The model structure of the optimal weighted data fusion algorithm is shown in Figure 2.

![Figure 2. optimal weighted data fusion algorithm](image)

In weighted data fusion, the state estimation and weight of the measured objects meet the requirements of formula (4) respectively.

\[ \hat{x} = \sum_{i=1}^{n} W_i x_i, \quad \sum_{i=1}^{n} W_i = 1 \]  

(4)

The total mean square error is:
\[ \sigma^2 = \mathbb{E}[(x - \hat{x})^2] = \mathbb{E} \left[ \sum_{i=1}^{n} w_i (x - x_i)^2 \right] \]

\[ \quad = \mathbb{E} \left[ \sum_{i=1}^{n} w_i^2 (x - x_i)^2 + 2 \sum_{i=1, j=1}^{n} w_i (x - x_i) w_j (x - x_j) \right] \]  

(5)

Because \( X_i \) is independent of each other and is unbiased for \( X \), so:

\[ \mathbb{E}[(x - x_i)(x - x_j)] = 0 \quad (i, j = 1, 2, ..., n, i \neq j) \]  

(6)

Therefore, the total mean square error is:

\[ \sigma^2 = \mathbb{E} \left[ \sum_{i=1}^{n} w_i^2 (x - x_i)^2 \right] = \sum_{i=1}^{n} w_i^2 \sigma_i^2 - \lambda (\sum_{i=1}^{n} w_i - 1) \]  

(7)

When the total mean square error \( \sigma^2 \) is the smallest, the Lagrangian conditional extremum algorithm is used to construct an auxiliary function to calculate the value of \( W_i \):

\[ \sigma^2 = \mathbb{E} \left[ \sum_{i=1}^{n} w_i^2 (x - x_i)^2 \right] = \sum_{i=1}^{n} w_i^2 \sigma_i^2 - \lambda (\sum_{i=1}^{n} w_i - 1) \]  

(8)

Set up equations:

\[ \begin{align*}
\frac{\partial f}{\partial w_i} &= 2w_i \sigma_i^2 - \lambda = 0 \quad (i = 1, 2, ..., n) \\
\frac{\partial f}{\partial \lambda} &= 1 - \sum_{i=1}^{n} w_i = 0
\end{align*} \]  

(9)

The required conditions can be obtained:

\[ w_i = -\frac{\lambda}{2\sigma_i^2}, \quad \sum_{i=1}^{n} w_i = 1 \]  

(10)

From the formula (10), the total mean square error \( \sigma^2 \) value can be obtained at the minimum, and the corresponding weights of each sensor are:

\[ W_i = \frac{\sigma_i^{-2}}{\sum_{i=1}^{n} \sigma_i^{-2}} \]  

(11)

The resulting fusion output value is:

\[ X = \sum_{i=1}^{n} w_i * X_i \]  

(12)

5. Analysis of experimental results

In this paper, three carbon dioxide sensors are used to collect data at different locations in the detection container. The standard deviation and weight of each sensor are calculated by calling the standard deviation sub-VI and weight sub-VI which are independently compiled. The weighted data
fusion is carried out. Finally, the leakage rate is calculated by using the carbon dioxide concentration value obtained from the fusion. In the sequence of equal precision test results, the formula for calculating the standard deviation of single measurement of the sensor is shown in equation (13):

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} v_i^2}{n - 1}}$$

(13)

In this paper, the experimental conditions are designed to meet the experimental ambient temperature of (20 ± 5°C) and the output pressure of the electric proportional valve is set to 100 kPa. The volume of the test vessel is 600 ml, the volume of the tested piece is 100 ml, the time of pumping is 10 seconds, the time of charging is 10 seconds, and the time of stabilization is 50 seconds. Three carbon dioxide sensors were placed in different positions in the detection container, and the sampling period was 0.01s. The results of the three sensors are measured every 25s, and the test data are shown in Table 1. According to the weighted fusion algorithm, the standard deviations of each sensor are 108.2, 113.7 and 112.8, and the corresponding weights are 0.36, 0.33 and 0.34, respectively. The synthetic concentration is shown in Table 1.

| time/s | S1/ppm       | S2/ppm       | S3/ppm       | Synthesis/ppm |
|--------|--------------|--------------|--------------|---------------|
| 0      | 483.59       | 482.91       | 483.31       | 483.28        |
| 25     | 542.87       | 519.95       | 522.49       | 528.42        |
| 50     | 665.23       | 660.40       | 657.69       | 661.11        |
| 75     | 730.27       | 727.29       | 727.34       | 728.30        |
| 100    | 762.01       | 765.01       | 762.22       | 763.08        |
| 125    | 774.90       | 779.84       | 778.82       | 777.86        |
| 150    | 785.74       | 787.40       | 789.68       | 787.61        |
| 175    | 796.72       | 800.58       | 799.31       | 798.87        |
| 200    | 796.48       | 799.60       | 798.29       | 798.13        |
| 225    | 797.92       | 802.83       | 799.32       | 800.03        |

| Concentration difference/ppm | 314.33 | 319.92 | 316.01 | 316.77 |

| Leakage rate ml/min | 0.184 | 0.185 | 0.184 | 0.184 |

The output value $C_i$ of the carbon dioxide sensor shown in Table 1 shows that after 20 seconds, the concentration value of the carbon dioxide sensor in the detection container rises rapidly, and the growth rate decreases with time. The sensor value tends to be stable around 180 seconds. After the detection, the standard of the carbon dioxide concentration difference $\Delta C$ is found in the formula (1). The leakage rate of leakage is 0.184ml/min. The relative error is 2.95% compared with the standard leakage rate of the standard leak rate of 0.19 ml/min under the test conditions.

50 repeated tests were carried out according to the above test conditions. The results of CO$_2$ concentration difference $\Delta C$ are shown in Table 2.

| Serial number | Difference value/ppm | Serial number | Difference value/ppm | Serial number | Difference value/ppm | Serial number | Difference value/ppm | Serial number | Difference value/ppm |
|---------------|----------------------|---------------|----------------------|---------------|----------------------|---------------|----------------------|---------------|----------------------|

Table 2. reproducibility test results of 100k Pa
Table 2: Test Results

|   | ppm | ppm | ppm | ppm | ppm | ppm |
|---|-----|-----|-----|-----|-----|-----|
| 1 | 361.77 | 320.66 | 315.17 | 326.46 | 325.32 |
| 2 | 319.28 | 318.38 | 330.81 | 319.65 | 317.66 |
| 3 | 325.66 | 317.65 | 316.26 | 325.15 | 320.28 |
| 4 | 318.12 | 315.45 | 315.56 | 324.24 | 324.14 |
| 5 | 315.24 | 319.52 | 318.16 | 314.65 | 329.45 |
| 6 | 324.06 | 315.61 | 320.47 | 324.53 | 315.08 |
| 7 | 315.14 | 320.24 | 320.24 | 321.78 | 320.29 |
| 8 | 319.69 | 318.74 | 327.85 | 320.60 | 320.69 |
| 9 | 317.16 | 316.87 | 317.88 | 320.17 | 318.98 |
| 10 | 318078 | 323.23 | 315.25 | 319.16 | 322.58 |

According to the test data shown in Table 2, the average \( \bar{x} = 318.93 \) ppm, total standard deviation 3.499, sample standard deviation \( S = 3.5354 \) and relative standard deviation less than 10% can be calculated, which shows that the repeatability of the experiment is guaranteed, and fully verifies the practical feasibility of the detection method proposed in this paper.

6. Conclusion

In this paper, the weighted data fusion algorithm is applied to the gas tightness detection technology, and a gas tightness detection scheme based on carbon dioxide sensor is proposed. The test piece filled with carbon dioxide gas is sealed in the test container. When the test piece leaks, the leakage rate of the test piece is detected by measuring the change of carbon dioxide gas concentration in the test container. In this paper, a multi-sensor weighted data fusion algorithm is proposed. Without any prior knowledge of sensor measurement data, the minimum variance data fusion value can be fused using the measurement data provided by sensors, thus improving the accuracy of measurement data.

**Fund projects:** Research Projects for Young and Middle-aged Teachers in Fujian Province; Item number: JA15652;

**entry name:** Development of QM100 Series Intelligent Air Tightness Testing Machine

**References**

[1] Zeng Cheng-zhou. Research and Development of Leak Detecting System Based on Different Pressure Principle[D]. Hangzhou: Zhejiang University, 2012.

[2] Peng Guang-zheng, Ji Chun-hua, Ge Nan. Current Statues and Future Development of Air Tightness Detection Technique[J]. Machine tools and hydraulic pressure, 2008, 36(11): 172-174.

[3] Ji Zeng-lian. Research and Design of Air Leak Testing System[D]. Dalian: Dalian Jiaotong University, 2008.

[4] Yan Shi-ping. Real Time Monitoring Method of CO2 Concentration and Its Experimental Research[D]. Changsha: Hunan University, 2011.

[5] Zhang Yuan-yuan, Zhang Ju-wei, Shang Si-si et al. Research and Application on Diffusion Model of Leakage gas[J]. Contemporary chemical industry, 2013, 42(4): 507-509.

[6] Xiao Jian-ming, Chen Guo-hua, Zhang Rui-hua. Research on Algorithm of Diffusion Area for Gauss Plume Model[J]. Computer and Applied Chemistry, 2010, 23(6): 559-564.
[7] Wen Hao, Dong Xiao-rui, Ma Yu-cheng. The Research of the Database Connecting Methods in Lab VIEW based on ADO[A]. In: 2010 International Conference on Computer Application and System Modeling[C]. Taiyuan, China, 2010: 229-233.