Paper:

Design and Realization of a Closed-loop Constant Flow Rate Air Sampler Using Differential Pressure Sensor

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In order to improve the accuracy of detection of a certain pollutant in the air, a digital air sampler based on flow rate feedback is designed and realized. Compared with the previous generation air sampler, orifice plate is used as basic measurement mechanism, instead of float flowmeter. A differential pressure sensor based on thermal micro-flow measurement is used to measure the pressure difference of the orifice plate and calculate the flow rate. This air sampler is designed as a closed-loop system and the flow rate is measured digitally. Experiments show that the accuracy of the air sampler meets the needs of the client.

Keywords: Differential Pressure Flowmeter, Orifice Plate Flowmeter, Flow Measurement, Air Sampler

1. Introduction

In order to detect the content of a certain pollutant in the air, a certain amount of gas needs to be sampled by an air sampler firstly. The sampling method is to use an air pump to let a certain volume of air flow through a specific collection device, then the collection device adsorbs a certain substance in the air, and the content of the substance can be determined by it in the collection device[1]. The accuracy of gas sampling greatly affects the detection results. How to design an air sampler for gas sampling with high accuracy is a very important issue[2, 3, 4].

The float flowmeter air sampler is one of the most common and cheap air sampler. This kind of sampler achieves the desired working flow rate by manually observing the indication of the float flowmeter and adjusting the speed of the air pump. There are some disadvantages. Firstly, the control system does not measure the actual flow rate, which is open-looped[5]. Secondly, the flow rate measurement depends on manually reading, which could result in a certain error. In addition, the volume of the gas that has been sampled is different when temperature and atmospheric pressure change.

The client hope to solve these problems and develop a new generation air sampler of which the flow rate error is less than 2.5% and the stability error is less than 2%. A digital constant flow rate air sampler using closed-loop control is designed and realized. It is based on orifice plate flowmeter with differential pressure sensor. It measures flow rate digitally. Temperature, humidity and atmospheric pressure sensors are added to the air sampler to calculate volume under different conditions.

In the following, the measurement principle of the air sampler is introduced in 2. Next, the design of the air sampler including hardware and software is proposed in 3. Then some experiments and analyses are done in 4 to verify the performance of the air sampler.

2. Measurement Principle of the Air Sampler

The accuracy of flow rate measurement determines the performance of the air sampler. The differential pressure flowmeter is widely used in various industrial production[6]. Therefore, the differential pressure flowmeter is tried to be put on the air sampler to measure the flow rate.

The differential pressure flowmeter uses the pressure difference generated by the fluid flowing through the throttling device to measure the flow rate. Common differential pressure flowmeters include Venturi tube flowmeter, orifice plate flowmeter, nozzle flowmeter and so on[7]. The basic structure[8] of orifice plate flowmeter is shown in **Fig. 1**.

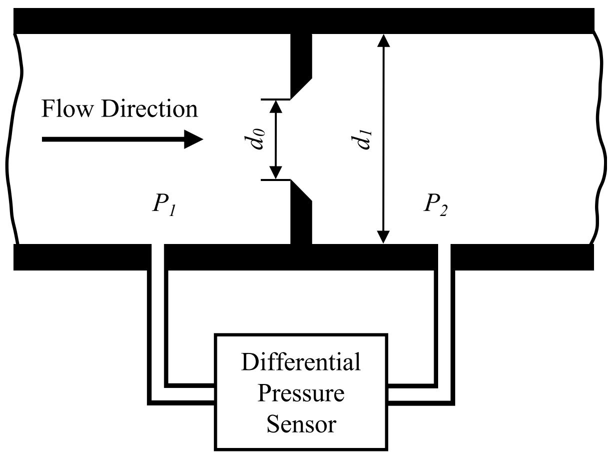

Fig. 1. Basic structure of orifice plate flowmeter

The flow rate can be calculated according to the pressure difference between two sides of the orifice plate $\Delta P = P_1 - P_2$. Without considering energy loss, the theoretical volume flow rate calculation formula of the orifice plate flowmeter is

$$Q_v = \frac{\pi (C_0 d_0)^2}{4} \cdot \sqrt{\frac{2}{1-(\frac{C_0 d_0}{d_1})^4}} \cdot \sqrt{\frac{\Delta P}{\rho}} = C_1 \sqrt{\frac{\Delta P}{\rho}}, \tag{1}$$

where ρ is the density of fluid, C_0 is the coefficient of contraction which depends on the geometric size of the orifice plate, and C_1 is a constant[9, 10, 11]. Under the same other conditions, the pressure difference is proportional to the square of the volume flow rate multiplied by the density. That is

$$\Delta P \propto Q_v^2 \cdot \rho. \tag{2}$$

In order to eliminate the influence of gas density on the measurement, a differential pressure sensor based on thermal micro-flow measurement is selected, and its output characteristic is

$$V_{out} \propto \Delta P \cdot \rho. \tag{3}$$

Combining (2) and (3), the sensor's output is proportional to the square of the mass flow rate, that is

$$V_{out} \propto Q_v^2 \cdot \rho^2 = Q_m^2. \tag{4}$$

Through the Ideal Gas Law

$$PV = nRT \tag{5}$$

or

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}, \tag{6}$$

the volume under different conditions can be obtained.

3. Design of the Closed-loop Air Sampler

3.1. Hardware

A single-chip microcomputer is used to read the pressure difference data from the differential pressure sensor. The hardware is mainly divided into two parts: gas path and single-chip microcomputer system.

3.1.1. Gas Path

The air to be sampled is drawn into the collection device. Compared with blowing air into the collection device, this method can avoid the pipes from polluting the air to be sampled. The diagram of the gas path is shown in **Fig. 2**.

The gas path system is composed of five parts mainly: collection device (load), air pump, buffer bottle, orifice plate and differential pressure sensor. The pump is a direct current micro-diaphragm air pump. The function of the buffer bottle is to reduce the pulsation of the air flow in the pipes when the air pump is working, so that the data read from the differential pressure sensor is more effective.

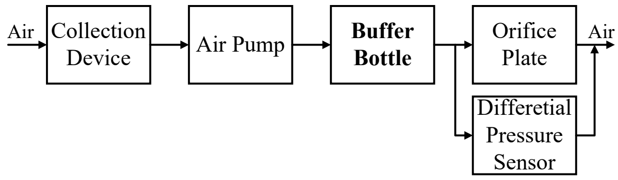

Fig. 2. Diagram of the gas path

3.1.2. Single-chip Microcomputer System

The single-chip microcomputer system is mainly composed of STM32 MCU, differential pressure sensor, air pump, temperature, humidity and atmospheric pressure sensors and human-computer interaction system, which is shown in **Fig. 3**. The function of temperature, humidity and atmospheric pressure sensors is to record current working condition and calculate flow rate and volume under different conditions. The human-computer interaction is composed of several buttons and a screen.

3.2. Software

The software is mainly divided into three parts: information transmission between the microcomputer and user, reception and processing of the sensor's data and control of the air pump. First, user sets the flow rate and volume of the gas to be sampled. Next, the microcomputer reads the pressure difference data from the sensor and calculate current flow rate and volume. Then the microcomputer controls the air pump to a constant flow rate when sampling air. Current flow rate, volume of the gas which has been sampled, temperature, humidity, atmospheric pressure and elapsed time are displayed on the screen. The flow chart is shown in **Fig. 4**.

4. Experiment

4.1. Sensor Noise Analysis

Before performing the control on the air pump, it is necessary to read sensor's data for analysis. When there is no buffer bottle, let the air pump run at a constant flow rate about 0.5 L/min. Then read one value every 15 ms according to the response time of the sensor. The data are shown in **Fig. 5**.

The flow pulsation and the noise of the sensor are very serious, and there are even negative values. These data cannot be used for controlling the air pump[13, 14]. In order to make the air flow evenly through the sensor to make the data usable, a buffer bottle with appropriate volume is added in the gas path. Considering the volume of the air sampler and the buffering effect, the volume of the bottle is 500 mL. After adding the buffer bottle, the sensor's data are shown in **Fig. 6**.

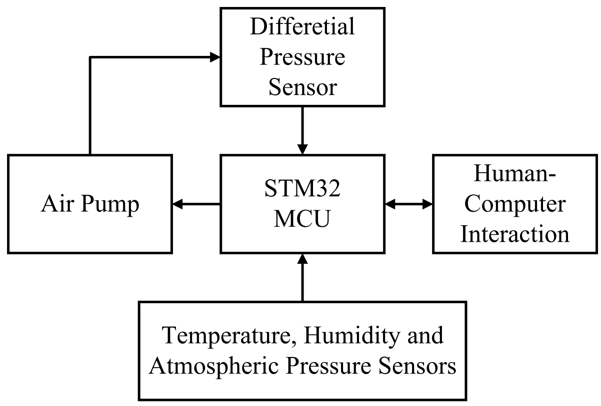

Fig. 3. Diagram of the single-chip microcomputer system

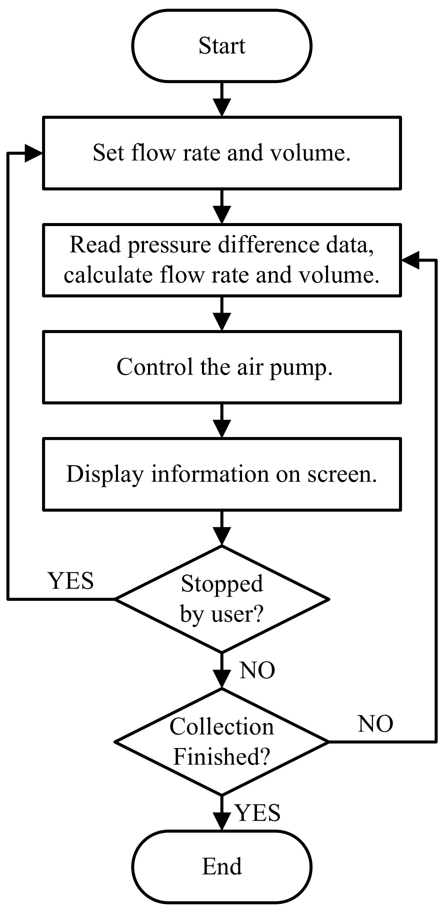

Fig. 4. Flow chart of the software

Now the difference between the maximum value and the minimum value is less than 10 Pa. The values fluctuate in a small range periodically. In order to obtain the frequency characteristics of the noise, Fast Fourier Transform(FFT) is performed on the data of different air pump speeds[15], and the frequency domain results obtained are shown in **Fig. 7**.

When the air pump runs at different speeds, there are

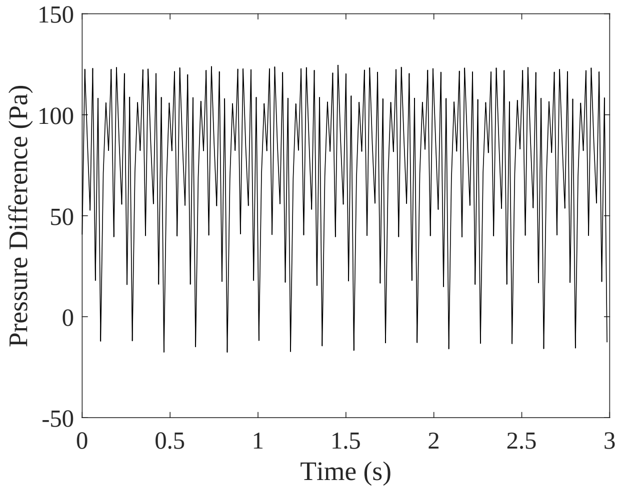

Fig. 5. Pressure difference data without buffer bottle

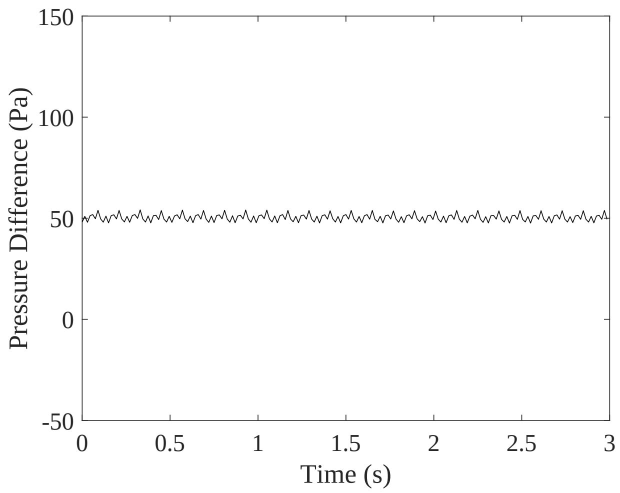

Fig. 6. Pressure difference data with buffer bottle

several peaks in the spectra, and the frequencies and amplitudes of these peaks are different. It can be inferred that the periodic fluctuation and the peaks are caused by the air pump.

Considering running speed of the single-chip microcomputer and time interval between every two controls, the average of every 20 values is taken as a new pressure difference value. The pressure difference data averaged are shown in **Fig. 8**, **Fig. 9** and **Fig. 10**.

The pressure difference values are much more steady. When the flow rate is 0.5 L/min or 0.8 L/min, the difference between the maximum value and the minimum value is about 1 Pa. When the flow rate is 1.5 L/min, the difference is about 3 Pa, which is slightly larger. Continue to perform FFT on the data averaged and analyze the frequency characteristics of the noise. The spectra graphs are shown in **Fig. 11**.

Compared with the spectra in **Fig. 7**, the peaks have

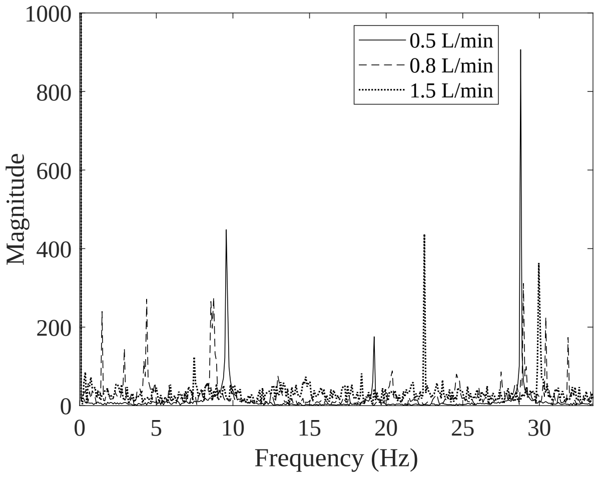

Fig. 7. FFT on the data of different flow rates

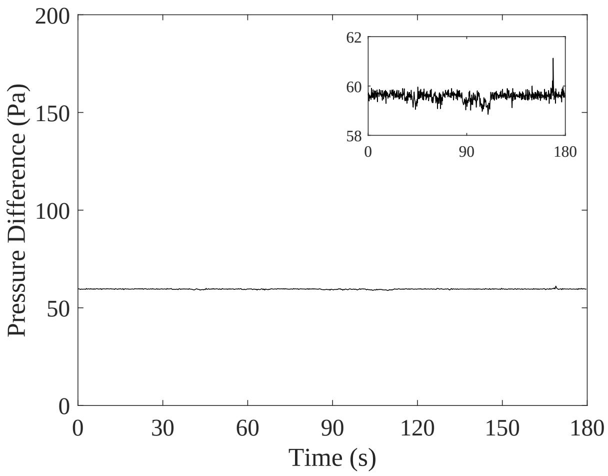

Fig. 8. Pressure difference data averaged at 0.5 L/min

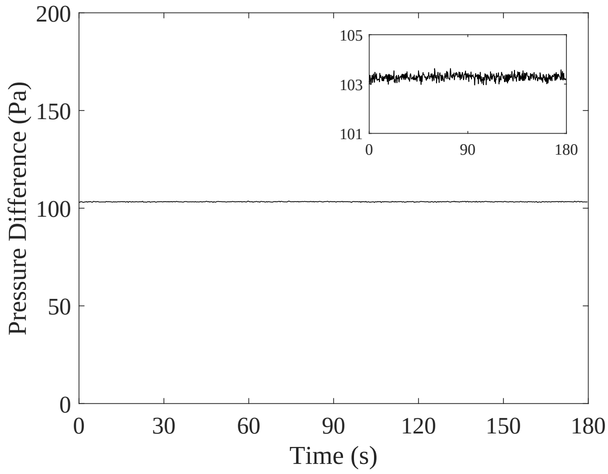

Fig. 9. Pressure difference data averaged at 0.8 L/min

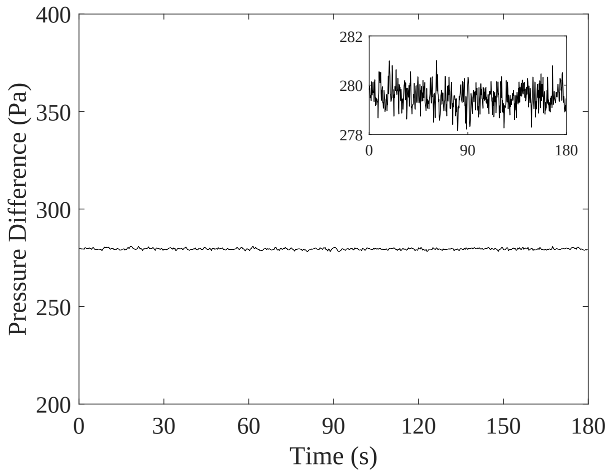

Fig. 10. Pressure difference data averaged at 1.5 L/min

almost disappeared. The amplitudes of other frequencies are also reduced. The filtering effect is obvious and satisfactory. These data can be used for calculating flow rate and controlling the air pump.

4.2. Calibration and Fitting of Flow Rate and Pressure Difference

From (3), sensor's output is proportional to the square of mass flow rate. When the temperature and atmospheric pressure are constant, the output is proportional to the square of the volume flow rate. Several points are selected for fitting by measuring the actual flow rate, which are shown in **Table 1**. The actual flow rate is measured by a soap film flowmeter with error less than 1.0%.

Perform a quadratic fitting. The result is

$$\Delta P = 8.512 \times 10^{-5} Q_v^2 + 6.504 \times 10^{-2} Q_v - 8.638 \times 10^{-1}, \tag{7}$$

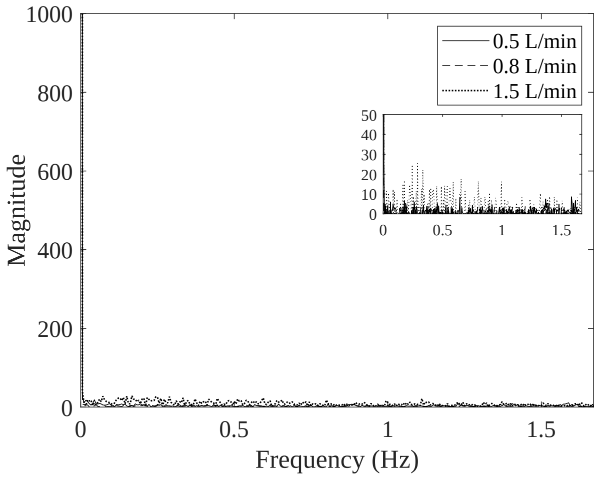

Fig. 11. FFT on the data averaged

where the unit of ΔP is Pa, and the unit of Q_v is mL/min. The pressure difference corresponding to other flow rates can be calculated by (7). Then the actual flow rates are measured to determine the accuracy of the fitting. The results are shown in **Table 2**.

Table 1. Data points used for fitting

Q_v (mL/min)	ΔP (Pa)
200	16
500	52
1000	150
1500	288
Temperature: 27.6 °C, Atmospheric Pressure: 1001 hPa	

Table 2. Fitting and test results of different flow rates

Q_v (mL/min)	$\Delta\hat{P}$ (Pa)	Q_v' (mL/min, Measured)
500	52.94	501.9
600	68.80	599.5
700	86.37	700.6
800	105.65	801.3
900	126.62	902.5
1000	149.30	1005
1100	173.68	1109
1200	199.76	1207
1300	227.54	1312
1400	257.03	1417
1500	288.22	1529
Temperature: 27.6 °C, Atmospheric Pressure: 1001 hPa		

It can be seen form the table that when the flow rate is between 500 mL/min to 1000 mL/min, the accuracy of the fitting is high. When the flow rate continues to increase, the fitted value is gradually smaller than the actual value. This may be caused in part by energy loss. The error is the largest at 1500 mL/min, which is about 2.0%.

4.3. Resistance to Load Changes Test

The load is described by the pressure difference between the air and the inside of the pipe between the collection device and the air pump. The load is positively related to the resistance when sampling air. The test results are shown in **Table 3**.

Since the collection device and the differential pressure sensor are on different sides of the air pump, the load changes hardly affect the flow rate measurement theoretically. Under different loads, the flow rate changes little. The air sampler has the ability to resist load changes.

4.4. Stability Test

Let the air sampler work continuously for one hour at the same flow rate. Measure the actual flow rate every 10 minutes. The test results are shown in **Table 4**.

During the hour, the difference between the maximum flow rate and the minimum flow rate is less than 0.6%. It shows that the air sampler has the stability of long-time working.

Table 3. Test results of resistance to load changes

Load (kPa)	0.5	5	10
Q_v (mL/min)	508.7	508.4	506.7
	1013	1013	998.2
	1477	1474	1466
Temperature: 28.3 °C, Atmospheric Pressure: 998 hPa			

5. Conclusion

A digital constant flow rate air sampler based on closed-loop control has been designed and realized. The orifice plate with a differential pressure sensor is the basic flow rate measurement mechanism. It has the advantages of high sampling accuracy, strong resistance to load changes and low cost after experimental verification. After calibration and fitting, its flow rate error is less than 2.0%. When the sampler works for one hour continuously, the flow rate stability error is less than 0.6%. The flow rate is almost unaffected when the load changes. The performance of the air sampler meets the needs of the client.

Future work includes improvement of fitting, analysis of the influence of air pump on measurement and selection of the orifice plate and the pipes. First, the fitting can be improved to make the result more accurate. Next, research on the characteristics of the air pump and adoption of a better filter could be carried out. In addition, selection of sizes and materials of the orifice plate and the pipes according to actual needs is also worth researching.

Acknowledgements

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Table 4. Test results of stability

Pressure Difference	140 Pa						
Time	1 min	10 min	20 min	30 min	40 min	50 min	60 min
Actual Flow Rate (mL/min)	969.0	964.8	967.8	968.4	967.8	966.0	970.2
Temperature: 31.0 °C, Atmospheric Pressure: 992 hPa							

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Appendix A. Requirements for Gas Sampling by Different Standard Documents

Some requirements for gas sampling by different standard documents are shown in **Table 5**.

Appendix B. Performance Requirements for Air Sampler by JJG 956-2013 and JJF 1404-2013

Performance requirements for air sampler by documents JJG 956-2013 *Verification Regulation of Air Samplers* and JJF 1404-2013 *Program of Pattern Evaluation of Air Samplers* are shown in **Table 6**.

Table 5. Some requirements for gas sampling by different standard documents

Standard No.	Substance	Flow Rate (L/min)	Volume (L)	Error
GB 50325 (GB/T 18204.2)	Formaldehyde	0.5	10	≤5%
GB 50325	Benzene, Toluene, Xylene and TVOC	0.5	10	≤5%
GB 50325 (GB/T 18204.2)	Ammonia	0.5	5	≤5%
GB/T 18883 (GB/T 18204.2)	Formaldehyde	0.5	10	≤5%
GB/T 18883	Benzene	0.5	20	≤5%
GB/T 18883	TVOC	Not Specified	1∼10	≤5%
The document inside the parentheses is cited by the document outside in the same row.				

Table 6. Performance requirements for air sampler by JJG 956-2013 and JJF 1404-2013

Item	Performance Requirement
Flow Rate Indication Error	±5%
Flow Rate Repeatability	≤2%
Flow Rate Stability	≤5%
Timing Error	±0.2%
Temperature Control Stability*	≤2°C
Temperature Indication Error*	±2°C
*Exempt form test if without temperature control function.	