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Online Gas Metering System for Laboratory Scale Anaerobic Fermentation Based on LabVIEW

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Abstract: Biogas yield represents a key parameter for evaluating the stability of fermentation process. In laboratory scale anaerobic fermentation experiments, the gas flow rate is generally low and the experimental period lasts long. In order to solve the problems of labor intensity and low efficiency caused by manual measurement, a system for online gas metering for low gas flow rate with high resolution and friendly interface was developed following the principle of liquid displacement. The system was designed based on the LabVIEW software. Various functions were achieved, including automatic calibration, automatic refilling the displaced liquid to compensate the loss from evaporation, real-time pressure and temperature compensation for volume, generating, displaying, storing accumulated gas production curve and data in real-time, etc. Finally, fermentation experiment was conducted to validate the system's performance. Test results showed an average relative error of −2.30% and a maximum relative error of −3.03% compared with manual measurement, which indicated a high measurement accuracy of the system. Moreover, the results were stable even in the continuous long run for 80 h, indicating a good performance at operational stability. In conclusion, the system can satisfy the need of real-time gas metering for laboratory scale anaerobic digesters, and it had great practical value.

Key words: anaerobic fermentation; low gas flow rate; online monitoring; LabVIEW

0 Introduction

Anaerobic fermentation is one of the effective methods of utilization of organic waste[1-3]. Gas production is an important target variable of anaerobic fermentation. It can reflect the biodegradability of substrate[4-5] and evaluate the efficiency of methanogens[6-7]. The volume of laboratory scale anaerobic reactor is low. The daily gas production is often between several hundred milliliters and several liters. Traditional gas flow meters can not meet the needs of accurate measurement of low gas flow rate[8]. Biogas produced in anaerobic fermentation is usually determined by manual gasometric methods. The sampling sites are scattered and gas production can not be continuously monitored during the fermentation process. It is easy to miss those important points of fermentation[9]. In addition, manual measurement also has other shortcomings, such as time and labor consuming, low efficiency. The research and development of online gas metering system for laboratory scale anaerobic fermentation is of great importance.

The measurement of low gas flow rate from laboratory scale reactors is mainly based on the liquid displacement method[10-12] and the manometric method[13-14]. LIU[15] designed a gas metering system for methane production potential research. The system determined the cumulative biogas production by liquid displacement method. A small quantity of biogas is not measured during the time taken for the flow cell to tip[16] and the gas can not be released completely when the gravity of the flow cell is greater than the buoyancy. KUSS et al[17] designed a kind of optical bubble counter device to calculate gas accumulation during anaerobic fermentation process. It was found that the volume of the bubbles was relatively stable only when gas flow rate was low. TAUBER et al[18]

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designed a system for measurement of gas production in bioreactors based on image recognition technology and the values of measurement were easily affected by the pattern recognition error of the bubble. SHEN et al[19] developed an automatic gas recording system for in vitro fermentation based on manometric method. It makes use of electronic pressure switch to monitor the pressure inside fermentation bottle. When the pre-set pressure is reached, the electromagnetic valve is triggered to release biogas. The volume of each vent has greater volatility.

Based on the principle of liquid displacement, a new system was designed for online metering of low gas flow rate which can apply to anaerobic fermentation at laboratory scale.

1 System constitution and principle

The system was composed of computer, barometric pressure transmitter, temperature sensor, liquid level sensors, data acquisition card, peristalsis pump, step motor controller, pinch valve, U-shaped measuring vessel, etc., as shown in Fig. 1.

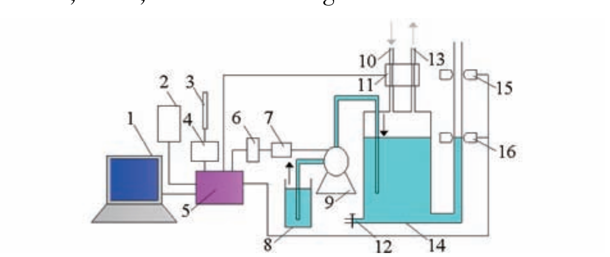

Fig. 1 Schematic diagram of online gas metering system for low gas flow rate

1. Computer 2. Barometric pressure transmitter 3. Temperature sensor 4. Temperature transmitter 5. Data acquisition card 6. Stepper motor controller 7. Stepper motor driver 8. Liquid storage bottle 9. Peristaltic pump 10. Gas inlet 11. Pinch valve 12. Liquid discharge port 13. Gas outlet 14. U-shaped measuring vessel 15. Liquid level sensor 1 16. Liquid level sensor 2

The volume of U-shaped measuring vessel was about 130 mL. The inner diameter of the left and right vessels were 50 mm and 6 mm, respectively. The liquid storage bottle was a reagent bottle of 250 mL.

Pinch valve is two-position three-way magnetic valve. Electronic signal controls extrusion or release of flexible tube to complete the switch of intake and exhaust. Before measurement, the initial liquid adding program was started to add liquid to the measuring vessel until the liquid level reached sensor 2. In the normal situation, the pinch valve is inactivated. Gas flows to the measuring vessel through gas inlet. The sensor 1 outputted high-level signal when the liquid level reached it. When the signal was detected by the acquisition card, the computer started to calculate, display and save the cumulative gas production. At the same time, the pinch valve was activated for a period of several seconds, allowing the gas to be released from the gas outlet competently. Then the pinch valve was deactivated and the measurement cycle repeated. Ambient temperature and pressure were real-timely monitored by temperature sensor and barometric pressure transmitter, respectively. The computer collected the data when the pinch valve was activated and the gas volume was normalized by it. After the gas was discharged competently, system judged the fluid should be added or not based on the signal of liquid level sensor 2. When the signal was low-level, the acquisition card outputed a single pulse signal to start the peristalsis pump to compensate the loss from evaporation. The liquid discharge port was opened in order to empty liquid at the end of measurement.

2 System hardware design

The system was built by host-guest model. The host selected computer as a platform for completing the data collection, display and conserve, etc. The guest selected data acquisition card and step motor controller, which can realize data acquisition and control on actuators. The host-guest maintained real-time communication through the USB interface. The hardware diagram of system is shown in Fig. 2.

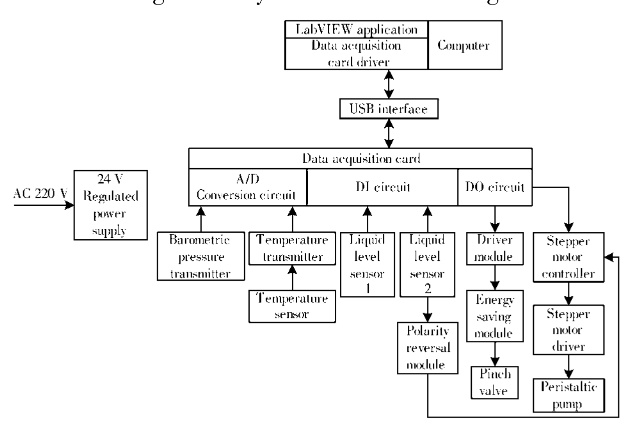

Fig. 2 Hardware diagram of online gas metering system for low gas flow rate

2.1 Signal detection

PT100 resistance thermometer was selected as temperature measuring element. The output signal was converted to 4 ~ 20 mA standard signal by the temperature transmitter. The barometric pressure was measured by DQY – T5 barometric pressure transmitter, which covers a pressure range of 800 ~ 1 100 hPa with 4 ~ 20 mA output. HPQ – T2 liquid level sensors with PNP output were used to detect the liquid level.

2.2　Data acquisition card

The data acquisition card selected was USB – 7660DN DAQ board made by Zhongtai Yanchuang Company. It offers 24 differential analog inputs, 12-bit resolution, up to 50 kHz sampling rate, 16 digital I/O lines, 50 mA output drive capability.

2.3　Output control

The pinch valve selected was Baike 100P3 typed solenoid valve with operating current of 300 mA. Energy saving module was CC24060L, which is an energy-saving temperature-reducing device. It dropped the current to "hold" current automatically after the pinch valve was activated. The stepper motor controller was CS20 – 1 single axis controller with 4 programmable NPN inputs. The output signal polarity of the liquid level sensor 2 needs to be reversed first and then connected to the controller.

3　System software design

The software of system was developed based on LabVIEW platform, which consisted of front panel and block diagram. Front panel was the man-machine interface of the system, which had the function of input and output. Block diagram was the implementation process of the system function, and it was a kind of graphical programming structure.

3.1　Front panel

The front panel was shown in Fig. 3, including functions such as parameters setting, real-time display of execution state, monitoring data and cumulative gas production curve, path selection of calibration file, start and stop. The front panel could be accomplished by input and output controls.

3.2　System program

Functional modules were designed based on modular thinking. The major functions of the system were equipment initialization, system calibration, data acquisition, output control, data management, etc. The flow chart of main program was shown in Fig. 4.

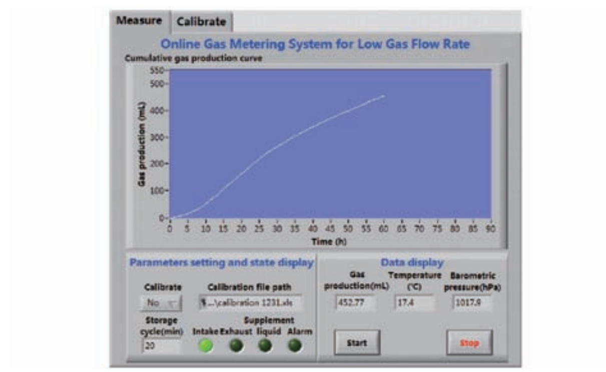

Fig. 3　Front panel interface

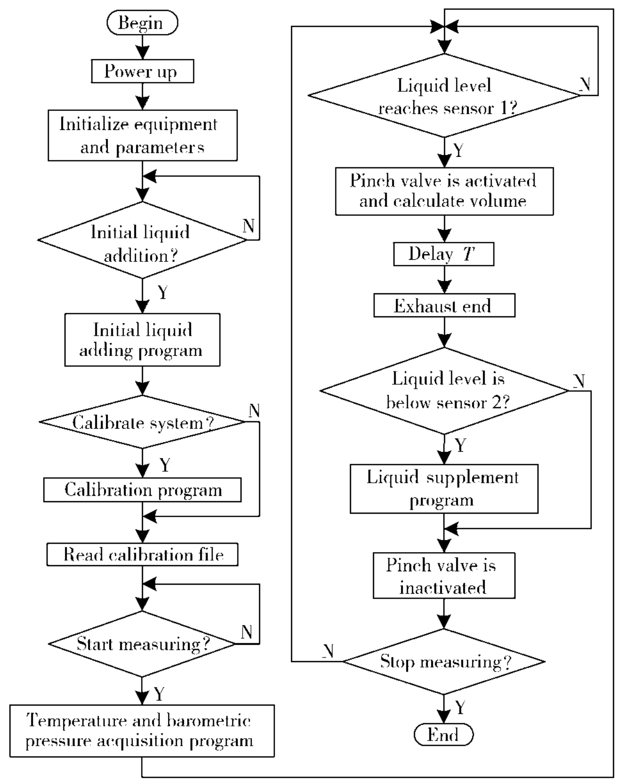

Fig. 4　Flow chart of main program

3.2.1　Module of equipment initialization and system calibration

Equipment initialization included establishing the communication connection between computer and data acquisition card and starting the stepper motor controller. The OpenDevice function was called to determine whether the communication between computer and the acquisition card was normal. The function return value was – 1, indicating that the communication was fault and alarm indicator was lighted. The system called GetLastErr function to query reasons and terminate running. The function return value was 0, indicating that the communication was succeed. Then using the digital output function of the acquisition card, the single pulse was input to the starting port of the stepping motor controller and the controller was started.

The system was calibrated by means of injecting air to the U-shaped measuring vessel. Because the injected volume was usually not integer multiple of calibration value so that a small amount of gas could not be included and it needed to subtract the volume and then calculate the calibration value. When calibrating, the main VI statically called calibration sub VI. Sub VI automatically recorded the activated times of the pinch valve and transferred it to the main VI in real time by means of global variable. After calibration, the prompt user input express VI was called, dialog box popped up on the front panel to prompt the user to input the height of liquid column in the thin tube and the volume of injected gas. The program could automatically calculate the calibration value. After 6 calibrations, the results could be calculated by using standard deviation and variance VI. The results were stored in the Excel file with the write to spreadsheets file VI. The calibration program was shown in Fig. 5.

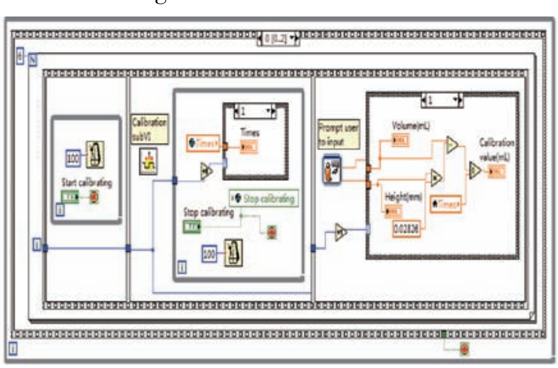

Fig. 5 Block panel of calibration program

3.2.2 Data acquisition module

Driver library USB7660.dll of the data acquisition card contains all the functions of data collection. Using the call library function node in LabVIEW, the DLL could be called to achieve the function of data collection. Before temperature and barometric pressure were collected, the acquisition parameters were set first, including channel mode, sample rate, acquisition range and so on. Output signals of transmitters were conversed to digital form by the acquisition card. Then it was transferred to the buffer. The data in the buffer could be read in chunks by calling AIFifoEx function and then converted to the corresponding temperature and pressure values by a series of array functions and formula node. Liquid level sensor output digital signal and the level could be read by the DIBit function to judge whether the liquid level reached the measuring position of sensor. Fig. 6 showed the block panel of temperature and barometric pressure real-time acquisition and display program.

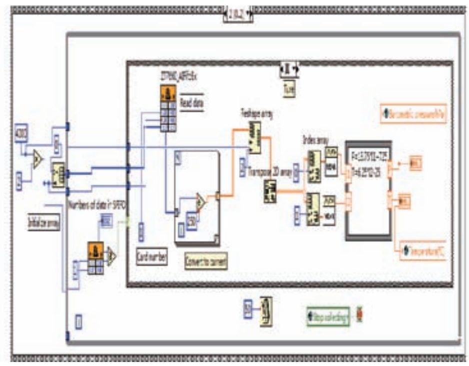

Fig. 6 Block panel of temperature and barometric pressure real-time acquisition and display program

3.2.3 Output control module

The output control included two parts: the control of pinch valve and liquid addition. The DOBit function was called to set output state of the corresponding channel and control the on-off of pinch valve to realize switch of intake and exhaust. The stepper motor had advantages of easy control, no accumulated error, quick start and stop and so on[20]. It was used as power source of peristaltic pump. The control system of peristaltic pump consisted of computer, data acquisition card and stepper motor controller. Subroutines of initial liquid adding and liquid supplement in the later could be edited by shift, speed assignment, automatic stop and other instructions of the controller. When the liquid should be added, the control instruction came from the computer was converted to digital signal by acquisition card and sent to programmable input port of controller. After the signal was scanned, the corresponding subroutine was called to realize the function of adding liquid, as shown in Fig. 7.

3.2.4 Data management module

(1) Data processing: a variety of noise existed in the test environment. In order to improve the accuracy of test results, it was necessary to make filtering. The mean VI was called in LabVIEW to carry out arithmetic mean filter processing to collect data. This method could make results smooth and eliminate the effect of random disturbance signal[21].

Temperature and pressure influence the volume of

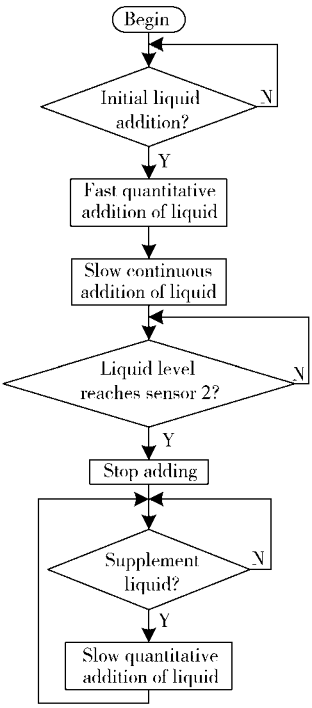

Fig. 7 Flow chart of liquid adding program

gas. The content of saturated water vaporin biogas is different at different temperatures. For easy to compare, the measured value should be adjusted to standard condition (1 atm, 0℃ and zero water content)[22]. It could be assumed that the gas had been cooled to room temperature when measured, because the measuring vessel was small and had no heat preservation. The equation for adjusting the measured gas volume to standard condition based on the ideal gas law as

$$V_s = V_m \frac{p_g}{p_s} \frac{T_s}{T_s + T_a} \tag{1}$$

The pressure of gas at the moment when pinch valve was activated could be calculated as[23-24]

$$p_g = p_a + \rho g h - p_v \tag{2}$$

$$p_v = 6.112\,1 \exp\left(\left(18.678 - \frac{T_a}{234.5}\right)\frac{T_a}{257.14 + T_a}\right) \tag{3}$$

where V_s is gas volume adjusted to standard condition, mL; V_m is measured gas volume, mL; p_g is pressure of gas at the moment when pinch valve was activated, kPa; p_a is ambient pressure, hPa; T_a is ambient temperature, ℃; p_s is standard pressure, 101.325 kPa; T_s is standard temperature, 273.15 K; ρ is liquid density, kg/m^3; g is acceleration of gravity, 9.8 N/kg; h is height difference of liquid level between left and right tubes at the moment when pinch valve was activated, m; p_v is saturated water vapor pressure, hPa.

(2) Data display: the display module could present the execution state and measuring results. Execution state could be displayed by using the LED control. The measuring results were displayed on the front panel in the form of values and curves by means of numeric indicator and waveform chart control.

(3) Data storage: the data needed to be stored for subsequent analysis. The storage cycle could be set on the front panel. The data storage program was placed in a separated loop, running in parallel with the acquisition program. The data was transmitted between them by global variable. Time and data were converted to strings with string functions. Using the build array function and the write to spreadsheets file VI, strings would be integrated into a two-dimensional array and stored in the excel file. The file path sub VI was designed. Its input was a string and output was a path. New file could be created in the specified folder by calling it. Fig. 8 showed the block panel of data display and storage program.

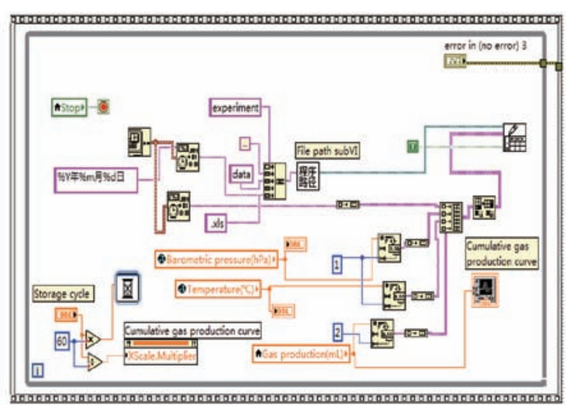

Fig. 8 Block panel of data display and storage program

4 System performance test

4.1 Calibration experiment

(1) Experimental equipment: single syringe infusion pump (KDS100, KD Scientific Inc.) and the designed online gas metering system for low gas flow rate.

(2) Experimental method: the syringe was fixed to the syringe holder of infusion pump. The outlet of syringe was connected to gas inlet of metering system. Injection volume (total amount of gas injection) and flow rate were set up before each calibration and started infusion pump to inject air to the measuring vessel. The calibration value (gas volume measured per measuring cycle) was calculated according to 3.2.1

section. Injection volume was set to 50 mL in all experiments and flow rates were 5 mL/h, 25 mL/h, 50 mL/h, 75 mL/h, 100 mL/h, 125 mL/h, 150 mL/h, 175 mL/h and 200 mL/h, respectively. Repeated 6 times with the same flow rate and the data were shown in Tab. 1.

Tab. 1 Calibration data

Flow rate/	Calibration values/mL						Average/	Relative standard
($mL \cdot h^{-1}$)	1	2	3	4	5	6	mL	deviation/%
5	0.991	0.985	0.983	1.001	0.995	0.992	0.991	0.66
25	0.998	1.001	0.986	0.991	0.995	1.001	0.995	0.60
50	1.001	1.011	0.995	0.996	0.998	1.006	1.001	0.62
75	1.005	0.998	0.994	1.007	0.991	1.005	1.000	0.66
100	1.000	0.997	0.993	1.012	1.010	1.008	1.003	0.77
125	1.010	1.005	1.002	1.011	1.006	1.014	1.008	0.44
150	1.014	1.021	1.012	1.007	1.012	1.013	1.013	0.45
175	1.014	1.013	1.008	1.027	1.025	1.017	1.017	0.72
200	1.024	1.028	1.014	1.017	1.021	1.012	1.019	0.60

The calibration values of online metering system were between 0.991 mL and 1.019 mL when flow rate was from 5 mL/h to 200 mL/h, as shown in Tab. 1. The relative standard deviation was less than 1%, indicating that the system had good reproducibility and data was reliable. The calibration values were increased with the increase of flow rate. By analysis, the main reason was that there was a certain response time from the high level output signal of liquid level sensor was detected to the pinch valve acted. At the same time, the actual injected gas was increased with the increase of flow rate.

4.2 Verification experiment

In order to verify the performance and reliability of the online gas metering system, anaerobic fermentation experiment was carried out. The measured values were compared with the manual measuring results.

4.2.1 Experimental material

Glucose was used as the substrate. The inoculum sludge was obtained from the laboratory scale continuous stirred tank reactor (CSTR). pH value, total solids (TS) and volatile solids (VS) were (8.23 ± 0.21), (7.25 ± 0.01)% and (3.47 ± 0.01)%, respectively.

4.2.2 Experimental method

Batch anaerobic fermentation experiment was conducted. Totally 160 mL sludge and 8 mL glucose solution with concentration of 0.1 g/mL were added to the 250 mL serum bottles. The bottles were flushed for 2 min with N_2 to remove air and then incubated at (35 ±1)℃ in electrothermal water bath for 80 h. Shaking the bottles every 1 ~ 2 h to ensure that the substrate was fully contacted with sludge. Quadruplicate bottles were used in the experiment. Gas production from three of those bottles was manually measured with glass syringe every 4 h[25] and the data were modified according to the following equation

$$V_s = V_m \frac{p_a - p_v}{p_s} \frac{T_s}{T_s + T_a} \tag{4}$$

Three replicates were set and the average was taken as the result. Gas produced from the other one through the water-sealed bottle entered into the online system for metering. In order to reduce the diffusion of CO_2, acidified saturated NaCl solution (pH value was less than or equal to 3.00) was used as the filled liquid[26].

4.2.3 Analysis method

TS was determined by drying to constant weight in an oven at 105℃. VS was determined by igniting to constant weight at 550℃. pH value was determined by FE20 pH meter (Mettler-Toledo instruments (Shanghai) Co., Ltd.).

4.2.4 Results and discussion

Cumulative gas production data during the fermentation process was shown in Tab. 2. Compared with the manual measured results, the average relative error was −2.30% and maximum relative error was −3.03%. It showed that the system had higher accuracy and could meet the requirement of real-time gas metering for low gas flow rate. The result of the system was lower compared with that measured by manual method. It might be because a small amount of gas leaked out from the hose connection. The relative error was large at early stage of the experiment. It might be because a small amount of CO_2 in the biogas dissolved in the liquid. The results were stable in the continuous long run for 80 h, which indicated that the system had high stability.

Tab. 2 Fermentation experiment data

Time/h	Manually measured cumulative gas production/mL	System measured cumulative gas production/mL	Relative error/%
4	11.63	11.28	-3.03
8	34.59	33.70	-2.58
12	76.58	74.50	-2.72
16	121.43	118.00	-2.83
20	167.77	162.93	-2.88
24	213.09	206.86	-2.92
28	253.89	247.09	-2.68
32	286.46	279.26	-2.51
36	317.19	309.68	-2.37
40	346.15	337.34	-2.55
44	372.20	364.48	-2.08
48	395.79	388.01	-1.97
52	418.99	409.45	-2.28
56	441.90	432.92	-2.03
60	461.76	452.77	-1.95
64	481.98	474.23	-1.61
68	499.53	490.70	-1.77
72	513.22	503.45	-1.90
76	523.83	515.11	-1.66
80	528.28	519.18	-1.72

5 Conclusions

(1) Online gas metering system could realize high sensitivity measurement with a resolution of about 1 mL. It could satisfy the requirement of precise measurement of gas production from laboratory scale digester. The system could collect the ambient temperature and barometric pressure in real time and the measured volume could be adjusted to standard condition, which ensured the normalization and accuracy of the data.

(2) The system could continuously and automatically collect, display and store the data. It had the characteristics of good real-time performance and high automation. It effectively avoided tedious manual measurement process.

(3) The results of anaerobic fermentation experiment showed that the average relative error was -2.30% and the maximum relative error was -3.03%. It showed that the system had high accuracy and good stability. The system could be used as an online gas metering device for laboratory scale anaerobic fermentation.

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基于 LabVIEW 的实验室厌氧发酵产气在线监测系统

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摘要: 针对实验室厌氧发酵试验周期长、产气速率低、人工测量产气量劳动强度大的问题,根据排水法原理,设计了基于 LabVIEW 软件平台的微量产气在线监测系统,实现了系统标定、测量液体自动添加和补充、产气量实时测量、累积产气曲线实时显示和监测数据自动存储等功能。厌氧发酵试验测试结果表明:在线监测数据与人工测量数据对比,相对误差平均值为 -2.30%,相对误差最大值为 -3.03%,该系统具有良好的准确度和稳定性,可满足实验室厌氧发酵试验微量产气实时监测的需求。

关键词: 厌氧发酵; 微量产气; 在线监测; LabVIEW

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Online Gas Metering System for Laboratory Scale Anaerobic Fermentation Based on LabVIEW

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Abstract: Biogas yield represents a key parameter for evaluating the stability of fermentation process. In laboratory scale anaerobic fermentation experiments, the gas flow rate is generally low and the experimental period lasts long. In order to solve the problems of labor intensity and low efficiency caused by manual measurement, a system for online gas metering for low gas flow rate with high resolution and friendly interface was developed following the principle of liquid displacement. The system was designed based on the LabVIEW software. Various functions were achieved, including automatic calibration, automatic refilling the displaced liquid to compensate the loss from evaporation, real-time pressure and temperature compensation for volume, generating, displaying, storing accumulated gas production curve and data in real-time, etc. Finally, fermentation experiment was conducted to validate the system's performance. Test results showed an average relative error of -2.30% and a maximum relative error of -3.03% compared with manual measurement, which indicated a high measurement accuracy of the system. Moreover, the results were stable even in the continuous long run for 80 h, indicating a good performance at operational stability. In conclusion, the system can satisfy the need of real-time gas metering for laboratory scale anaerobic digesters, and it had great practical value.

Key words: anaerobic fermentation; low gas flow rate; online monitoring; LabVIEW

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引言

厌氧发酵是有机废弃物资源化利用的有效方式之一[1-3]，产气量是其重要的目标变量，可以反映底物的生物降解性能[4-5]，评估产甲烷菌群工作效率[6-7]。实验室小试的厌氧反应器体积较小，日产气量一般在几百毫升到几升之间，传统的气体流量计不能满足微量气体精确计量的需求[8]，所以产气量的测量仍以人工操作为主。人工测量数据采样点比较分散，无法对发酵过程的产气连续监测，容易错失发酵过程中的重要反应点[9]。此外，人工测量还存在耗时费力、工作效率低等问题。因此，研究开发微量产气在线监测系统具有重要意义。

国内外对微量气体的测量主要基于排水法[10-12]和压力法[13-14]。刘京[15]设计了一套用于物料产甲烷潜力研究的产气量测量系统，该系统利用排水法测量累积产气量，存在无法计量翻转瞬间产生的气体[16]、容器重力大于气体浮力时气体排不净的问题。KUSS 等[17]设计了一种光学气泡计数装置测量厌氧反应过程中的产气量，应用时发现气泡体积只有在产气率较低的情况下保持相对稳定。TAUBER 等[18]基于图像识别技术设计的生物反应器产气测量系统，测量结果易受气泡图像识别误差影响。沈英等[19]基于压力法设计的体外发酵产气自动记录系统，通过发酵瓶内气体压力控制差压开关触发电磁阀导通排气，排出气体体积波动较大。

本文以排水法为测定依据，设计一种适用于实验室规模厌氧发酵试验微量产气在线监测系统。

1　系统组成及工作原理

系统主要由计算机、大气压力变送器、温度传感器、液面传感器、数据采集卡、蠕动泵、步进电动机控制器、夹管阀、U 型测量容器等组成，如图 1 所示。

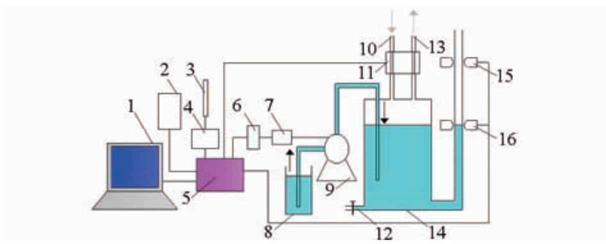

图 1　微量产气在线监测系统示意图

Fig. 1　Schematic diagram of online gas metering system for low gas flow rate

1. 计算机　2. 大气压力变送器　3. 温度传感器　4. 温度变送器　5. 数据采集卡　6. 步进电动机控制器　7. 步进电动机驱动器　8. 储液瓶　9. 蠕动泵　10. 进气口　11. 夹管阀　12. 排液口　13. 排气口　14. U 型测量容器　15. 液面传感器 1　16. 液面传感器 2

U 型测量容器总体积约 130 mL，左侧容器内径为 50 mm，右侧细管内径为 6 mm。储液瓶选用体积为 250 mL 的试剂瓶。

夹管阀为两位三通电磁阀，由电控信号控制软管的挤压或松开，完成进排气切换。测量前，启动初始加液程序向测量容器内加液至液面与传感器 2 测量位置平齐。测量时，夹管阀断电，气体由进气口进入测量容器。当液面升至传感器 1 测量位置时，传感器 1 输出高电平信号，采集卡检测到信号后利用计算机中的应用程序计算、显示及保存累积产气量，同时触发夹管阀通电，气体由排气口释放。延长通电时间，待气体排净后，夹管阀断电，开始下一次测量。环境温度和压力分别由温度传感器和大气压力变送器实时监测，计算机在夹管阀通电瞬间读取采集的数据，并对测量值进行标准化修正。每次排气结束后，系统会根据传感器 2 的输出信号判断是否补液，当信号为低电平时，采集卡输出单脉冲信号启动蠕动泵，补偿因蒸发损失的液体。测量结束后，打开排液口将液体排空。

2　系统硬件设计

系统采用上、下位机模式搭建，上位机选用计算机以 LabVIEW 为平台完成采集数据的处理、显示和保存等操作，下位机选用数据采集卡和步进电动机控制器实现数据采集和执行机构控制，上、下位机通过 USB 总线接口实时通讯。图 2 为系统硬件框图。

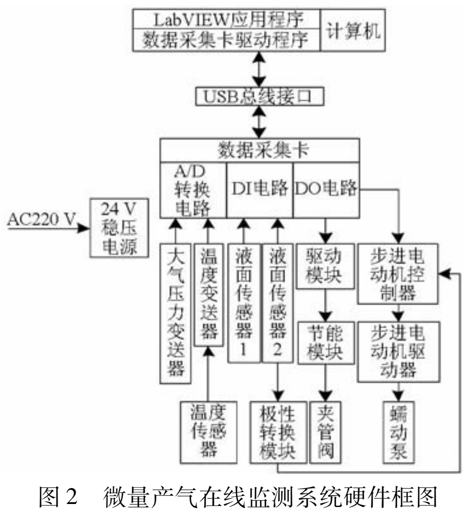

图 2　微量产气在线监测系统硬件框图

Fig. 2　Hardware diagram of online gas metering system for low gas flow rate

（1）信号检测：测温元件选用 PT100 铂电阻，输出信号经温度变送器转换成 4～20 mA 标准信号。大气压选用 DQY－T5 型大气压力变送器测量，输出为 4～20 mA 标准信号，量程为 800～1 100 hPa。液面位置选用 HPQ－T2 型液面传感器检测，输出为

PNP 型。

（2）采集卡：中泰研创 USB－7660DN，24 路差分 AI 通道，分辨率为 12 位，最高采样频率 50 kHz；16 路 DI/O 通道，单通道驱动能力为 50 mA。

（3）输出控制：夹管阀为百柯流体 100P3 型电磁阀，工作电流为 300 mA。节能模块为 CC24060L 型节能降温器，可在启动夹管阀后自动将电流降至保持电流。步进电动机控制器为 CS20－1 型单轴控制器，具有 4 个可编程 NPN 型输入口，液面传感器 2 的输出信号需极性转换后再接入控制器。

3　系统软件设计

系统软件基于 LabVIEW 平台开发，由前面板和程序框图两部分组成。前面板是系统的人机交互界面，具有输入输出功能。程序框图是系统功能的实施流程，是一种图形化的程序结构。

3.1　前面板界面

前面板界面如图 3 所示，包括参数设置、执行状态和监测数据的实时显示、累积产气曲线的显示、标定文件路径的选择、开始停止等功能，可借助具有输入输出功能的控件设计。

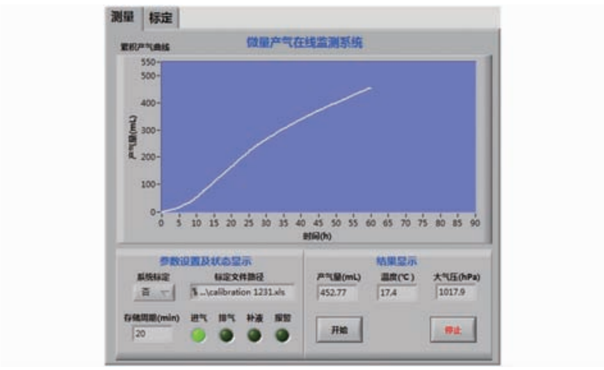

图 3　前面板界面

Fig. 3　Front panel interface

3.2　系统程序

采用模块化思想设计各功能模块，主要包括设备初始化、系统标定、数据采集、输出控制、数据管理等功能，主程序流程如图 4 所示。

3.2.1　设备初始化和系统标定模块

设备初始化主要是指建立计算机与采集卡的通讯连接及步进电动机控制器的启动。通过调用 OpenDevice 函数判断计算机与采集卡通讯是否正常，函数返回值为－1 表示通讯失败，报警指示灯点亮，同时调用 GetLastErr 函数查询原因，并终止程序运行；返回值为 0 表示通讯成功，之后利用采集卡的数字量输出功能，将单脉冲信号输入到步进电动机控制器的启动端口，启动控制器。

系统采用向测量容器内注入空气的方式进行标

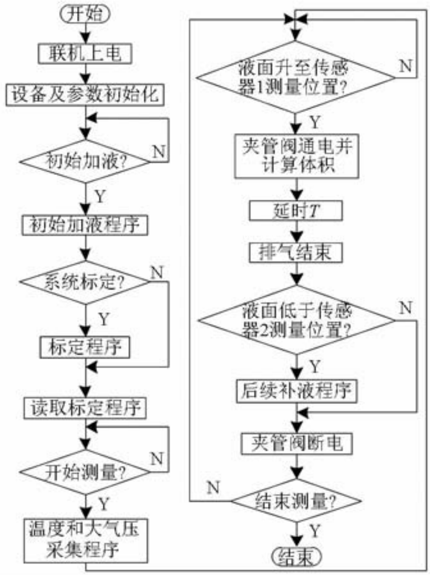

图 4　主程序流程图

Fig. 4　Flow chart of main program

定，由于注入的体积通常不是标定值的整数倍，会有少量气体无法计入，因此需先减去该部分体积再计算标定值。标定时，主 VI 静态调用标定子 VI，子 VI 自动记录夹管阀通电次数并通过全局变量将数据实时传递到主 VI。标定结束后，调用提示用户输入函数，前面板弹出对话框，用户输入细管内液柱高度和注入的气体体积后程序可自动算出标定值。重复标定 6 次后，使用标准差和方差 VI 计算及显示标定结果，并利用写入电子表格文件 VI 将结果存储到 EXCEL 文件。图 5 为标定程序框图。

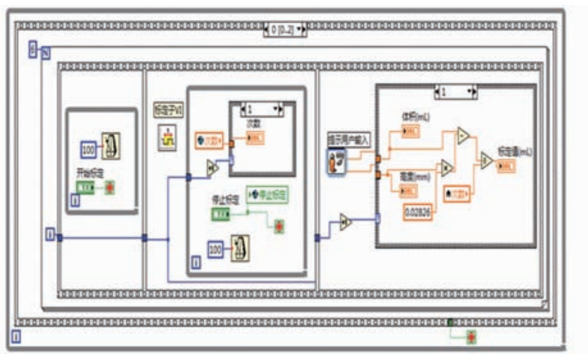

图 5　标定程序框图

Fig. 5　Block panel of calibration program

3.2.2　数据采集模块

数据采集卡自带的驱动程序库 USB7660. dll 包含数据采集的所有函数，利用 LabVIEW 的调用库函数节点（Call library function node，CLF）可调用动态链接库（Dynamic link library，DLL），实现数据采集功能。温度和大气压采集前，先要设置相应采集参数，包括通道模式、采集速率、采集量程等。变送器输出的信号经采集卡 A/D 转换后进入缓冲区，通过调用 AIFifoEx 函数成批读取缓冲区数据，然后利用

一系列的数组函数和公式节点将其转换为对应的温度和气压。液面传感器输出数字量信号,利用 DIBit 函数读取输出的电平状态,判断液面是否到达传感器测量位置。图 6 为温度和大气压实时采集与显示程序框图。

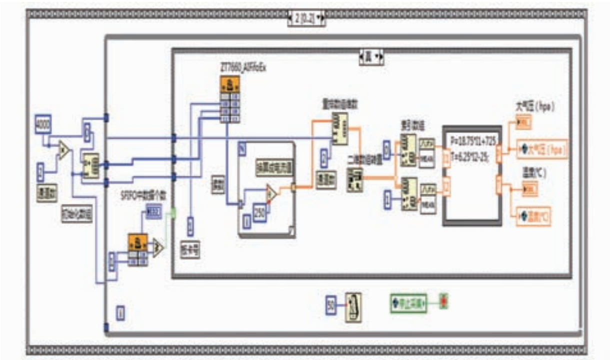

图 6 温度和大气压实时采集与显示程序框图

Fig. 6 Block panel of temperature and barometric pressure real-time acquisition and display program

3.2.3 输出控制模块

输出控制包括夹管阀控制和加液控制两部分。调用 DOBit 函数设置对应通道输出状态,控制夹管阀的通断,实现进排气切换。步进电动机具有易于控制、无累积误差、启停迅速等优点[20],选用它作为蠕动泵的动力源,计算机、数据采集卡、步进电动机控制器组成蠕动泵的控制系统,使用控制器位移、速度赋值、自动停止等指令可编辑初始加液和后续补液子程序。需要加液时计算机发出控制指令,由采集卡转换成数字量信号输出给控制器的可编程输入口,控制器扫描到该信号后调用对应的子程序实现加液功能。加液程序流程如图 7 所示。

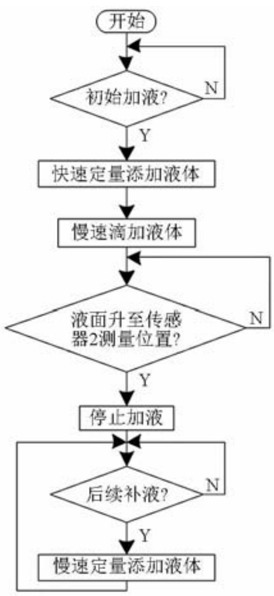

图 7 加液程序流程图

Fig. 7 Flow chart of liquid adding program

3.2.4 数据管理模块

(1)数据处理:测试环境中混杂着多种噪声,为了提高测试结果的精准性,需对采集的信号进行滤波处理。系统通过 LabVIEW 中的均值 VI 对数据进行算术平均值滤波,该方法处理的数据结果平滑度较高,可消除随机性的干扰信号[21]。

气体体积受温度和压力影响,且不同温度下沼气中饱和水蒸气的含量也不同,为了方便比较,需将测量值换算为标准状态(1 个大气压、0℃、零含水率)下的数值[22]。由于测量容器体积小、无保温,可假定测量时气体温度已降至室温,根据理想气体状态方程可知

$$V_s = V_m \frac{p_g}{p_s} \frac{T_s}{T_s + T_a} \tag{1}$$

夹管阀通电瞬间气体的压力[23-24]为

$$p_g = p_a + \rho g h - p_v \tag{2}$$

其中

$$p_v = 6.1121\exp\left(\left(18.678 - \frac{T_a}{234.5}\right)\frac{T_a}{257.14 + T_a}\right) \tag{3}$$

式中 V_s——标准状态下的体积,mL

V_m——实际测量的体积,mL

p_g——夹管阀通电瞬间气体压力,kPa

p_a——环境压力,hPa

T_a——环境温度,℃

p_s——标准状态下压力,101.325 kPa

T_s——标准状态下温度,273.15 K

ρ——测量液体密度,kg/m^3

g——重力加速度,9.8 N/kg

h——夹管阀通电瞬间左右两管液面高度差,m

p_v——饱和水蒸气分压力,hPa

(2)数据显示:显示模块包括执行状态和测量结果的显示。执行状态可利用指示灯控件显示。测量结果分别借助数值显示控件和波形图表控件以数值和曲线的形式显示在前面板上。

(3)数据存储:为了后续分析试验数据,需要对数据进行存储,存储周期可在前面板中设定。数据存储程序放在独立的循环中,与采集程序并行运行,二者利用全局变量传递数据,使用字符串处理函数将时间和数据转换成字符串,再通过创建数组等函数及写入电子表格文件 VI 将字符串整合成二维数组后存储到 EXCEL 文件。本文设计了程序路径子 VI,输入为字符串,输出为路径,调用该子 VI 可自动在指定文件夹内新建以测量日期命名的文件。图 8 为数据显示及存储程序框图。

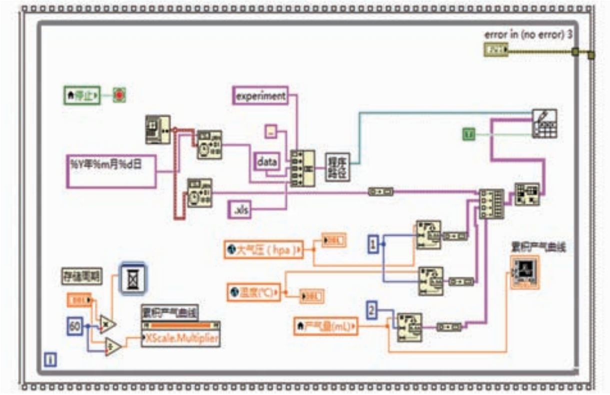

图 8　数据显示及存储程序框图

Fig. 8　Block panel of data display and storage program

4　系统性能测试

4.1　标定试验

试验设备：单通道微量注射泵（KDS100，美国 KD Scientific 公司）和本文设计的微量产气在线监测系统。

试验方法：将注射器安装在单通道微量注射泵上，注射器出口与监测系统进气口连接。每次标定试验前，设定注射泵的注射体积（向测量容器内注入的空气总量）和注射流量，然后启动注射泵向测量容器内注入气体，依据 3.2.1 节所述方法计算标定值（系统一次测量的气体量）。试验中注射体积设为 50 mL，流量选取 9 个梯度，分别为 5、25、50、75、100、125、150、175、200 mL/h，同一流量重复 6 次，试验数据如表 1 所示。

由表 1 可知，流量在 5 ~ 200 mL/h 范围内，在线监测系统的标定值介于 0.991 ~ 1.019 mL 之间，平均值为 1.005 mL，相对标准偏差在 1% 以内，结果重复性好，数据可靠。随着流量的增加，标定值整体呈上升趋势，分析其原因主要在于系统从检测到液面传感器输出的高电平信号到夹管阀动作存在着一定的响应时间，在同样的时间内，流量越大，实际进气量越多。

表 1　标定数据

Tab. 1　Calibration data

流量/ ($mL \cdot h^{-1}$)	标定值/mL						平均值/ mL	相对标准 偏差/%
	1	2	3	4	5	6		
5	0.991	0.985	0.983	1.001	0.995	0.992	0.991	0.66
25	0.998	1.001	0.986	0.991	0.995	1.001	0.995	0.60
50	1.001	1.011	0.995	0.996	0.998	1.006	1.001	0.62
75	1.005	0.998	0.994	1.007	0.991	1.005	1.000	0.66
100	1.000	0.997	0.993	1.012	1.010	1.008	1.003	0.77
125	1.010	1.005	1.002	1.011	1.006	1.014	1.008	0.44
150	1.014	1.021	1.012	1.007	1.012	1.013	1.013	0.45
175	1.014	1.013	1.008	1.027	1.025	1.017	1.017	0.72
200	1.024	1.028	1.014	1.017	1.021	1.012	1.019	0.60

4.2　验证试验

为验证在线监测系统的性能及可靠性，开展厌氧发酵试验，将系统监测值与人工测定结果进行比较。

4.2.1　试验材料

试验采用葡萄糖为基质，接种污泥取自实验室 CSTR 反应器出料，经测定其 pH 值为 8.23 ± 0.21，总固体（TS）质量分数为（7.25 ± 0.01）%，挥发性固体（VS）质量分数为（3.47 ± 0.01）%。

4.2.2　试验方法

采用批式试验，将 160 mL 污泥和 8 mL 质量浓度为 0.1 g/mL 的葡萄糖溶液混合后加入到 250 mL 发酵瓶中，用 N_2 吹扫 2 min 以排除空气，然后置于电热水浴锅（35 ± 1）℃恒温发酵 80 h。每隔 1 ~ 2 h 晃动发酵瓶一次，保证基质与污泥充分接触。使用玻璃注射器每隔 4 h 对产气量进行人工测定[25]，测量值按式（4）修正。

$$V_s = V_m \frac{p_a - p_v}{p_s} \frac{T_s}{T_s + T_a} \tag{4}$$

共设置 3 个重复，取其均值作为结果。另设置一个发酵瓶，产气经水封瓶后进入本文设计的系统进行在线监测。为减少 CO_2 溶解，水封瓶和测量容器中用水选择酸性（pH 值小于等于 3）的饱和食盐水[26]。

4.2.3　分析方法

TS 测定：在 105℃ 干燥箱内干燥至质量恒定；VS 测定：550℃ 灼烧至质量恒定；pH 值测定：FE20 型 pH 计（梅特勒-托利多仪器（上海）有限公司）。

4.2.4　结果与讨论

发酵过程中累积产气数据如表 2 所示，系统测量结果与人工测量结果相比，相对误差平均值为 −2.30%，相对误差最大值为 −3.03%，准确度较高，可满足微量产气实时监测的功能需求和精度要

表 2 发酵试验数据

Tab. 2 Fermentation experiment data

时间/h	人工测量累积产气量/mL	系统测量累积产气量/mL	相对误差/%
4	11.63	11.28	-3.03
8	34.59	33.70	-2.58
12	76.58	74.50	-2.72
16	121.43	118.00	-2.83
20	167.77	162.93	-2.88
24	213.09	206.86	-2.92
28	253.89	247.09	-2.68
32	286.46	279.26	-2.51
36	317.19	309.68	-2.37
40	346.15	337.34	-2.55
44	372.20	364.48	-2.08
48	395.79	388.01	-1.97
52	418.99	409.45	-2.28
56	441.90	432.92	-2.03
60	461.76	452.77	-1.95
64	481.98	474.23	-1.61
68	499.53	490.70	-1.77
72	513.22	503.45	-1.90
76	523.83	515.11	-1.66
80	528.28	519.18	-1.72

求。与人工测量结果相比,系统的测量值偏低,可能是试验过程中微量的气体从软管连接处渗漏出去所致。前期相对误差较大,可能是由于沼气中少量的 CO_2 溶解到测量液体中。连续运行 80 h 的测定结果稳定,表明系统稳定性能良好。

5 结论

(1)基于 LabVIEW 设计了微量产气在线监测系统,实现了 1 mL 分辨率下的高灵敏度检测,能够满足实验室厌氧发酵试验微量产气精准测量的需求。系统可以实时采集环境温度和大气压,将体积自动校正为标准状态下的数值,保证了数据的规范性及准确性。

(2)本系统能够连续自动地采集、显示和存储测试数据,实时性好,自动化程度高,有效避免了繁琐的人工测定过程。

(3)厌氧发酵试验结果显示,产气量测定的相对误差平均值为 -2.30%,相对误差最大值为 -3.03%,表明该系统测定结果准确度高,稳定性好,可作为厌氧发酵试验微量产气在线监测装置使用。

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