RESEARCH ON COLLABORATIVE CONTROL OF DOUBLE-PLUNGER GAS PROVER BASED ON EtherCAT

by

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Original scientific paper
https://doi.org/10.2298/TSCI191022002X

Piston prover has been widely used as a gas flow standard for its advantages of high accuracy in standard volume, flow stability and repeatability. It has also been employed as the primary gas flow standard in many countries to calibrate meters. However, it is difficult to ensure the uniformity of the inside dimension of the piston, thus the application of conventional piston provers are limited by the maximum calibration flow generated by the piston cylinder volume. In this paper, an improved piston gas prover that mainly consists of two uniform plungers was proposed. Their external diameter constitutes the flow standard. The plungers are driven by servo motor, and the high speed fieldbus EtherCAT has been introduced as the control unit. Hence the two pistons could work collaboratively and operate in three modes: single-piston mode, double-pistons parallel mode, and double-pistons reciprocating mode. Besides generating steady-flow rate, the double-plunger prover can even produce an unsteady-flow rate which could be used to research the dynamic characteristics of flow meters. The structure and working principle of the three modes were carefully introduced. Then experiments for calibrating critical nozzles were carried out, and the results show that the repeatability of the discharge coefficient could be better than 0.06%, and the pressure fluctuation during the process was less than 50 Pa.

Key words: *gas flow rate, standard, piston prover, double plunger, critical nozzle*

Introduction

Gas flow standard device, with the advantage of providing accurate measure airflow especially, is widely used for calibrating gas flow meter. The conventional gas flow standard system is a bell, pressure, volume, temperature, and time (pVTt) prover or a piston prover [1]. Bell provers have a long history of use and are still one of the critical methods for verification. One of the highest level bell provers in the world is located in Physikalisch-Technische Bundesanstalt Institute, Braunschweig, Germany. Its effective volume is 1 m^3 and the uncertainty is less than 0.06% [2].The pVTt prover is a standard device for indirectly measuring the gas flow rate according to pressure, *P*, and temperature, *T*, in the container, gas equation and the volume V of gas entering or leaving the container within the time, *t*.

The piston gas prover concept is widely used for primary standards in the field of gas flow measurements [3-7]. In recent years, the piston gas prover has been well developed in the world because of its simple structure, high verification accuracy, stable flow obtained

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by controllable speed, adjustable working chamber pressure [8]. The multitube small piston prover developed by METAS has an effective volume of 6~150 L, the flow range of each tube is large tube 200~20000 ml per minute, medium tube 10~1500 ml per minute and small tube 3~120 ml per minute. The maximal working pressure is 10 KPa and the uncertainty of flow measurement is 0.05% (k = 2) [9]. A novel double piston prover by PTB with a spindle stepper motor drive was developed by PTB for the calibration of micro-flow gas [10]. In this prover, the principle is the same as that of the traditional single piston calibrator existing one of the cylinders working as an instruction chamber. The IMGC has successfully created a piston gas prover in 1200 L with the flow range of 0.3~25 m^3/h. When the exhaust volume is 150~800 L, the uncertainty is 0.0048~0.0015% [11]. In China, the first piston gas flow prover is developed by the National Institute of Metrology. The flow range of the device is 0.009~0.6 m^3/h, the uncertainty is 0.05% and the maximum working pressure in the piston cylinder reaches 200 KPa, which is suitable for the verification of sonic nozzle [12].

To overcome the drawback of piston prover including the limited maximum calibration flow and the limited calibration time, a reciprocating double-pistons gas prover was developed here.

Structure and Working mode

As shown in fig.1, the piston prover involves the same two systems, each of which consists of a piston cylinder, a piston, three air inlet/outlet valves, a temperature sensor, a pressure sensor, a servo motor and a ball screw. The available capacity of single piston cylinder is 15 L, and the flow rate is from 0.005 to 1 m^3/h.

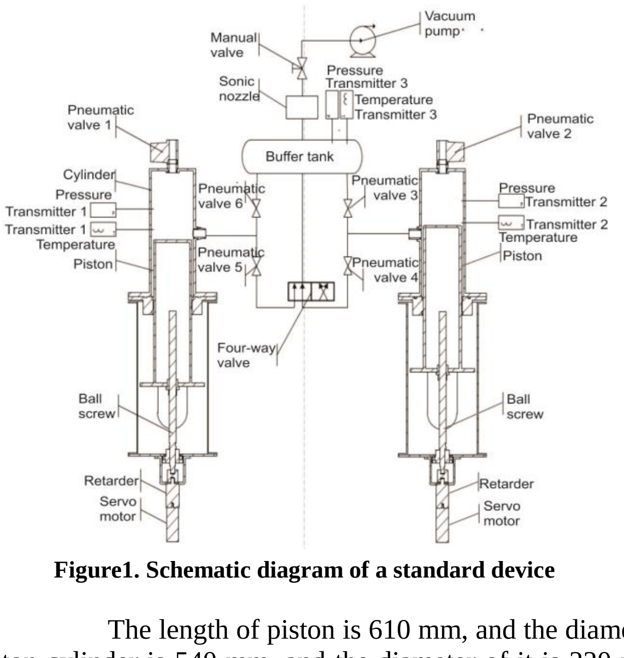

Figure1. Schematic diagram of a standard device

According to different requirements and test schemes, there are three operating modes for reciprocating double-piston gas prover: single-piston mode, double-pistons mode, and double-pistons reciprocating mode.

In order to keep the pressure of the cylinder stable as far as possible, therefore the vertical structure is chosen, which can keep sealing rings from the gravity mass of the piston, and help to prolong the service life and improve the stability. During the processing, the accuracy of the piston outer circle is easier to control than that of the inner circle. In addition, the guide of the piston structure is more stable, so this structure is adopted in the device.

The length of piston is 610 mm, and the diameter of it is 175 mm. The length of piston cylinder is 540 mm, and the diameter of it is 220 mm. The major elements of the piston system are shown in tab.1. Pipelines connect two piston cylinder devices, and electronic control system elements to join at the sonic nozzle be tested. A buffer tank is between the junction of the pipelines and the sonic nozzle to stabilize the air-flow.

Table 1. Piston system elements selection

Element	Model	Key parameter
Reducer	PS60-040	Reduction ratio 40:1
Ball screw	SFSR3205-DGC3-686-P2	Lead 5mm
Diaphragm coupling	MCGLC50-16-20	–
Inlet/outlet value	VNB601A-32A	–
Solenoid value	–	–

Single-piston mode

In single-piston mode, only one of the two cylinders is working. We take piston A for example here.

First, the inlet valve 1 is opened, and the servo motor is driven so that the piston goes down to zero position. While turning on the manual valve, the outlet valve 5, turning off the outlet valve 3, 4, and 6, and starting the vacuum pump, the air-flow in the device flows out through the pipeline, outlet valve 5, buffer tank and finally nozzle. With the running of the vacuum pump, when the upstream and downstream pressure of the nozzle reaches the critical pressure ratio, the inlet valve 1 closes and the servo motor is upward. The actual velocity curve is revealed in fig. 2(a), in which the uniform motion process is the actual verification. During this time, the speed of the piston is then dynamically adjusted to stabilize the in-cylinder temperature and pressure to ensure verification accuracy.

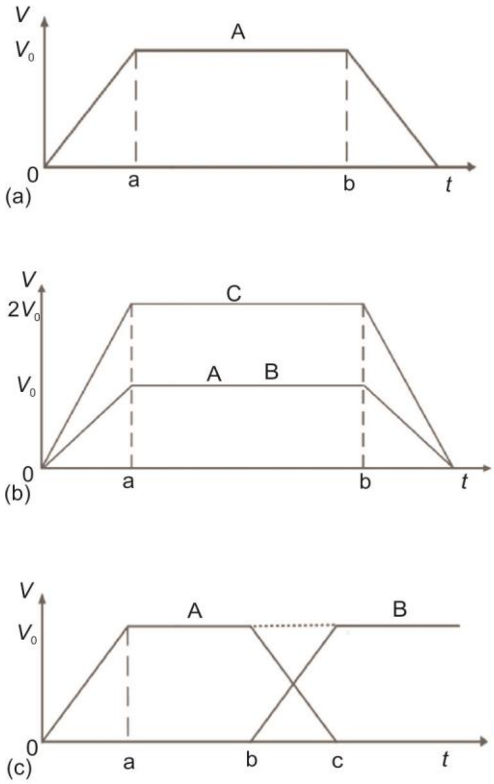

Figure 2. The *V-t* diagram of the three mode; (a) single-piston calibration mode, (b) double-pistons parallel mode, and (c) double-pistons reciprocating mode.

Double-pistons parallel mode

The state of the two-cylinder parallel mode is similar to that of the single-piston mode, but the difference lies in the simultaneous running of two-cylinders.

First, the inlet valve 1 and 2 are opened, and two servo motors are both driven so that the pistons go down to zero position. Subsequently, open the manual valve, the outlet valve 5 and 3, close the outlet valve 4 and 6, and start the vacuum pump. At this time, the air flow in the device flows out through the pipeline, outlet valve 5 or 3, buffer tank and finally nozzle. When the upstream and downstream pressure of the nozzle reaches the critical pressure ratio, the inlet valve 1 and 2 are closed and the servo motors are both driven upward with the pistons. The actual velocity curve is shown in fig. 2(b). The uniform motion process in curve C in $2V_0$ is the actual speed of verification. During this time, this speed will be dynamically adjusted to stabilize the in-cylinder temperature and pressure to ensure verification accuracy.

Double-pistons reciprocating mode

The double-pistons reciprocating mode is different from the above two, and it can run constantly.

First, two pistons are driven by servo motors down to zero position, and open inlet valve 1 and 2, close outlet valve 3~6, the open outlet valve 5. After that, the manual valve is on and the vacuum pump is started. When the upstream and downstream pressure reaches the critical pressure ratio, piston A is on. It is upward with the speed shown in fig. 2(c) from a short acceleration to uniform motion in V_0. When the piston moves close to the top, opens the outlet valve 3, and synchronously starts the servo motor B to drive the appropriate piston upward. At this time, piston A is in the deceleration stage while piston B is in acceleration from *b* to *c* in fig. 2(c). When piston A decelerates to 0 or moves to the bottom, the outlet valve 5 is closed and piston B runs separately. At this point, the piston A returns to the bottom zero position to prepare for the next operation. When piston B is about to complete the effective travel, open outlet valve 5 and start piston A at the same time. At the moment, piston A is accelerating and piston B is decelerating. When piston B slows down to 0 or runs to the bottom, the outlet valve 3 is closed. Piston A and B work alternately throughout the verification to ensure long-term uninterrupted detection.

Control system

Electrical system

At present, PLC can not meet the requirements of high real-time performance and fast response speed. It leads to insufficient coordination performance of the two motors and unable to achieve complex trajectory control. Thus, EtherCAT Ethernet technology is used instead of traditional PLC control to solve this problem. its excellent response performance and synchronization accuracy can be applied to the dynamic speed regulation of servo motor in the double piston to improve the in-cylinder pressure and keep the temperature stable, so as to improve the verification accuracy.

The electronic control system is mainly composed of electrical components, industrial personal computers, EtherCAT I/O module, servo driver, servo motor. The electronic control system is shown in fig. 3.

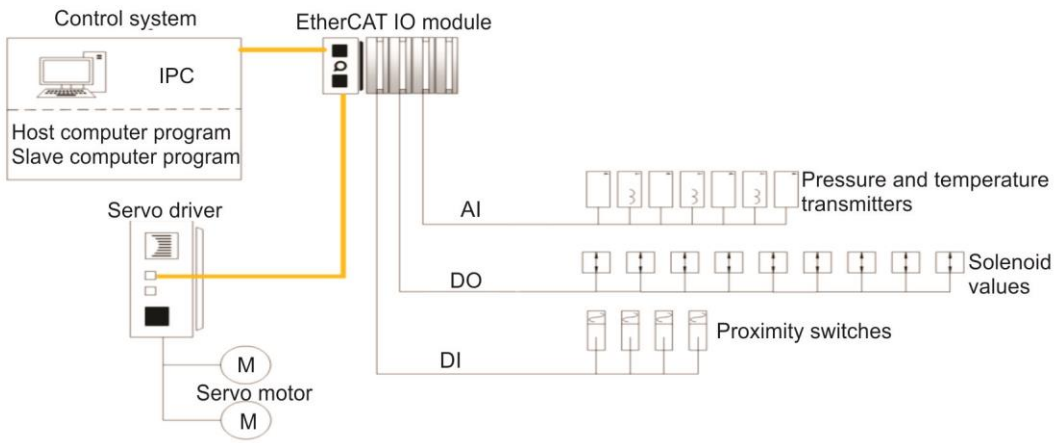

Figure 3. Electric control system

The selection of each module is shown in tab. 2. The system is composed of servo motors servo drives made by Beckhoff company, Rosemount's 3051 series pressure transmitters, thermal resistance products from JUMO and Pt100 temperature sensors.

Table 2. Electrical system components election

Component	Model	Key parameter
Servo motor	AM8021	Rated Speed: 9000 rpm Rated Torque: 0.5 Nm Rated power: 0.47 kw
Servo driver	AX5203	Rated current: 2×3 A Rated Voltage: 20~480 V
Pressure transmitter	3051DG1A62A1AB4HR5	Pressure range: –6.22～6.22 kPa The reference:accuracy 0.05%
Temperature transmitter	902120/11-402-1001-3-7-140-999/331	Temperature measurement range: –50～+400 °C Precision level: DIN EN 60751 B

Software structure

The software system is supported by Twin CAT. The human-computer interface communicates with Twin CAT through ADS. Meanwhile, as a transfer station, Twin CAT receives the data from pressure and temperature transmitters, controls servo motors and solenoid valves and processes data, shown in fig. 4.

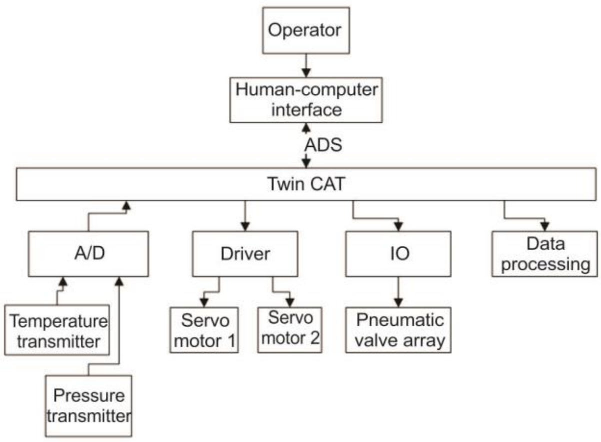

Figure 4. The structure of the device

Theoretical model

Note: See the paper ‘Development of a reciprocating double-pistons gas prover’ for the deduction process of the specific formula:

$$C_d = \frac{\dfrac{\left(\dfrac{\pi}{4}D_1^2\sum_{i=1}^{n}X_i + \dfrac{\pi}{4}D_2^2\sum_{j=1}^{m}X_j\right)\delta}{t}\,\dfrac{\sqrt{\dfrac{M}{R}T_0}}{TZ}k}{\dfrac{\pi}{4}d^2C_*\left[1 + X_{CO_2}\left(0.25 + 0.04732\varepsilon\right) + \dfrac{RH}{100}AB\right]} \tag{1}$$

where C_d is the discharge coefficient, C_* – the critical flow function, T [K] – the average absolute temperature, M [kg/k·mol] – the molecular weight (= 28.97), R – the molar gas constant, R = 8.31 J/Kmol, Z – the gas compressibility factor, k – the wet air correction coefficient, RH [%] – the gas relative humidity, δ – the pulse equivalent (the minimum distance of one pulse), d [m] – the throat diameter of the nozzle, X_{CO2} – the molar fraction of CO_2 in the air, t [s] – the set time, and $X_{1,2,3\ldots n}$, $X_{1,2,3\ldots m}$: number of pulses for the n^{th} running of piston A and the m^{th} running of piston B [13];

Test Results

Single-piston mode experiments

Nozzles with nominal flow rates of 0.06 m^3/h (numbered 1) and 0.2 m^3/h (numbered 2) were selected for testing. Firstly, a single-piston test of $1^\#$ nozzle was in 65% humidity and –64 kPa negative pressure.

The curves of in-cylinder pressure and piston position are detailed in fig. 5. At t_1, the vacuum pump downstream of the nozzle opens, and the pressure in the cylinder drops sharply (from 230 Pa to 165 Pa). During the movement of the piston, the pressure begins to rise and is stable at t_2. Thereafter, the pressure was in a continuous fluctuating state (163~173 Pa). The dynamic adjustment of the piston did keep the pressure relatively stable as a whole.

The temperature range of the single-piston test is about 0.1 °C with a general upward trend.

The parameter of the indoor environment at which $2^\#$ nozzle tests in the single-piston mode were 65% humidity and –64 kPa negative pressure.

Figure 6 is a graph of in-cylinder pressure and piston position about $2^\#$ nozzle during the test. At t_1 (0 second) moment, the downstream vacuum pump opens and the in-cylinder pressure drops. At t_2 (6 seconds) moment, the piston starts to move and the pressure rises. Because of high initial speed, the pressure has risen to about 235 Pa and keep stable, fluctuating in (235~240 Pa). Thus, the dynamic control effect of the piston is pretty good and the pressure is very stable.

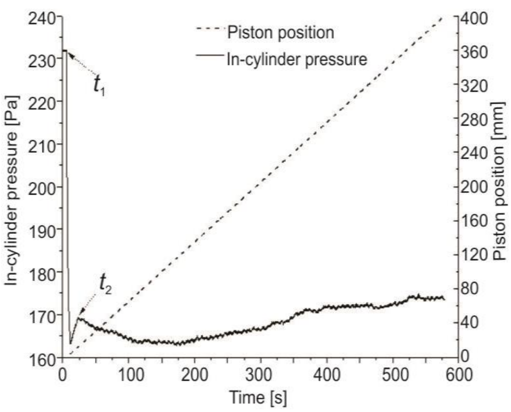

Figure 5. Result of $1^\#$ nozzle in single-piston test

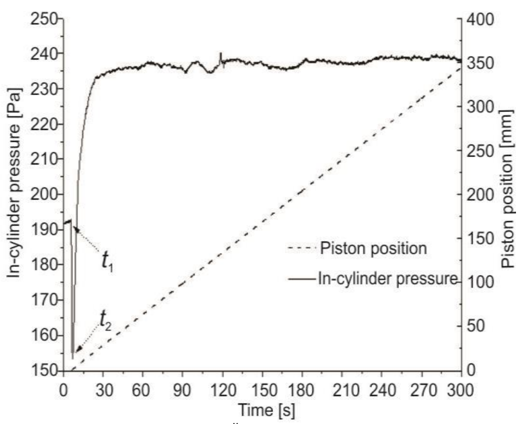

Figure 6. Result of $2^\#$ nozzle in single-piston test

The temperature is between 20.05 and 20.11 °C during the single-piston test of $2^\#$ nozzle, and the temperature is relatively stable on the whole.

Double-pistons parallel mode experiments

Two cylinders run at the same time in the double-pistons parallel mode, so under the same flow rate, the speed of the piston is reduced by half. Moreover, during the whole test process, the speed of these two pistons are necessary to be adjusted.

Firstly, the double-pistons parallel test of $1^{\#}$ nozzle was carried out in 64% humidity and downstream negative pressure –65 kPa. As shown in fig. 7, at t_1, the vacuum pump opens, and the in-cylinder pressure drops. At t_2, the two pistons start running at the same time, with the pressure declining relatively smoothly. While pistons adjustment is completed at t_3, the pressure becomes stable and fluctuates between (73~83 Pa). The temperature of the cylinder fluctuates between 20.25 and 20.31 °C.

Figure 8 is the curve of in-cylinder pressure and pistons position in the double-pistons parallel mode testing $2^{\#}$ nozzle. At t_1 (0 second), the downstream vacuum pump opens, the pressure drops. At t_2, the pistons start to run, and then the pressure in the cylinder rises rapidly to about 260 Pa because of the large initial velocity. From t_3(100 seconds), the pressure gradually stabilizes and fluctuates between (259~270 Pa).

The temperature is between 20.25 and 20.30 °C during the $2^{\#}$ nozzle test in double-pistons parallel mode.

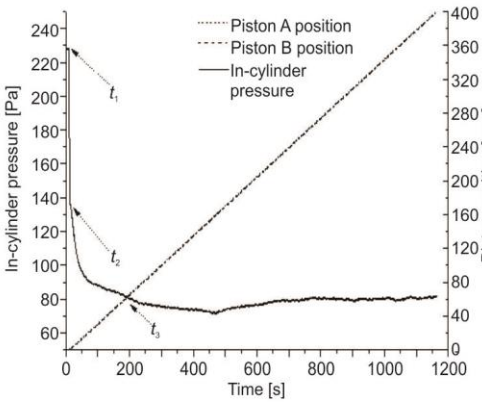

Figure 7. Result of $1^{\#}$ nozzle in double-pistons parallel mode

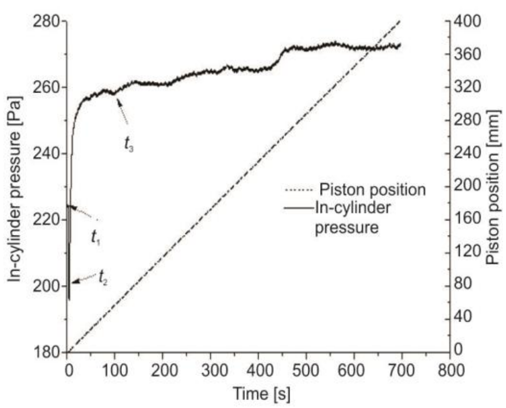

Figure 8. Result of $2^{\#}$ nozzle in double-pistons parallel mode

Double-pistons reciprocating mode experiments

The running mode of each piston in double-pistons reciprocating mode is the same as that in single piston mode, but the switch between two cylinders is more worthy of attention.

The main results of this double-piston reciprocating test of No. 1 nozzle is plotted in fig. 9. At t_1, the vacuum pump nozzle opens and the pressure in the buffer tank drops. Then at t_2, the piston A starts to run, so the pressure rises and finally tends to be stable. The piston A stops running and returns to zero while the piston B starts running. At t_3. At this time, the outlet valve 3 and 6 are switched, which causes the apparent jump of the pressure in the buffer tank. Since then, the piston B runs to the end of the travel, and these two pistons are running alternately. As shown in fig. 9, the range of pressure fluctuation is (190~220 Pa) until the system is stable.

The temperature fluctuates between (21.27~21.31 °C) during the test of 1# nozzle in double-piston reciprocating mode.

Figure 10 is the double-pistons reciprocating test of nozzle No. 2. The principle and mode are similar to those of fig. 9. The temperature fluctuates between (21.32~21.36 °C) during this test.

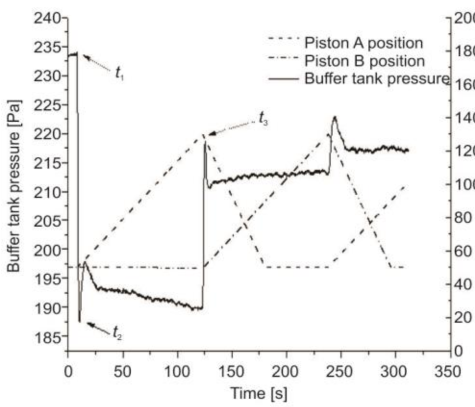

Figure 9. Result of 1# nozzle in double-pistons reciprocating mode

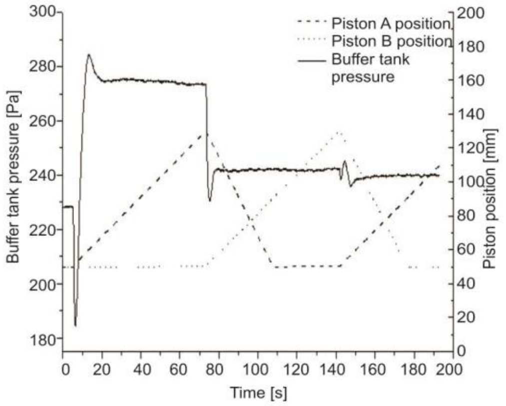

Figure 10. Result of 2# nozzle in double-pistons reciprocating mode

Tests were carried out several times on each mode to analyze the stability of process parameters better, and results data were recorded in tab. 3. In the case of non-reciprocating mode, the overall pressure fluctuation is relatively small, less than 11 Pa. However, due to the switch of solenoid valves in the double reciprocating mode, the internal pressure of the device changes greatly, about 30 Pa and 46 Pa, respectively.

Table 3. The fluctuation range of the device pressure inside

Nozzle nominal flow rate [m^3h^{-1}]	0.06				0.2			
Mode	Single (Piston A)	Single (Piston B)	Double parallel	Double reciprocating	Single (Piston A)	Single (Piston B)	Double parallel	Double reciprocating
Average range [Pa]	10.6	9.6	11.0	28.8	5.6	9.0	10.8	46.0

Repetitive experiment

Repeatability means that in the same operating environment, the same operator and the same method measure the same measured object repeatedly in a short period of time, so as to obtain the consistency of measurement results. Repeatability can be calculated by relative standard deviation RSD and sample average value, *i. e*. standard deviation/average value ×100%. In general, the true value of the measurement is unknown, then the standard deviation can be calculated according to the Bessel formula, and then the repetition rate can be calculated:

$$S = \sqrt{\frac{\sum_{i=1}^{n}(X_i - \overline{X})^2}{n-1}} / \overline{X} \times 100\% \tag{2}$$

where n is the number of measurements, X_i – the value for the i^{th} measurement, and X – the arithmetic mean value of n measurements.

Two nozzles with nominal flow rate of 0.06 m^3/h and 0.2 m^3/h were selected for the repeatability test. The three mode experiments were adopted for each of them. According to the requirement of repeatability test, five successive tests were carried out on each nozzle under each mode, and the repeatability was shown in tab.4.

Table 4. The result of the repeatability test

Mode	Nominal flow rate [m^3h^{-1}]	Discharge coefficient (Cd)					Repeata-bility [%]
Single (Piston A)	0.06	0.94972	0.95003	0.94992	0.94979	0.94988	0.0123
	0.2	0.96484	0.96519	0.96490	0.96495	0.96492	0.0142
Single (Piston B)	0.06	0.94974	0.94979	0.94989	0.95008	0.94999	0.0153
	0.2	0.96483	0.96514	0.96496	0.96485	0.96485	0.0135
Double-piston parallel	0.06	0.94948	0.94966	0.94954	0.94984	0.94953	0.0152
	0.2	0.96444	0.96451	0.96441	0.96466	0.96443	0.0106
Double-piston reciprocating	0.06	0.94903	0.94918	0.94910	0.94948	0.94932	0.0193
	0.2	0.96524	0.96559	0.96526	0.96526	0.96558	0.0191

According to the data in tab. 4, the repeatability of the double-piston reciprocating mode is relatively high in these three modes, reaching 0.0193% and 0.0191%, respectively. It is due to the fluctuation of pressure caused by the switch of solenoid valves in this mode. However, overall, the whole repeatability is less than 0.05% reaching the device requirement.

Contrast experiment

Here we take five experiments for each sonic nozzle under different modes. The average discharge coefficient was obtained and compared with the verification results obtained by the Zhejiang Institute of Metrology. The results are pictured in tab.5.

Table 5. The results of average discharge coefficient

Nominal flow rate	Mode	Average discharge coefficient	Result	Error [%]
0.06 [m^3h^{-1}]	Single (Piston A)	0.94987	0.94971	0.0164
	Single (Piston B)	0.94989		0.0196
	Double-piston parallel	0.94961		0.0107
	Double-piston reciprocating	0.94922		0.0516
0.2 [m^3h^{-1}]	Single (Piston A)	0.96496	0.96483	0.0135
	Single (Piston B)	0.96493		0.0010
	Double-piston parallel	0.96449		0.0353
	Double-piston reciprocating	0.96539		0.0576

The accuracy under these three modes is all less than 0.06%. Combined with the data in tab. 5, the accuracy of single-piston mode is relatively high and the repeatability is good. This is because the control of this mode is relatively simple. In the double-piston reciprocating mode, the accuracy is relatively poor, reaching 0.0516% and 0.0576%, respectively. The overall results meet the design requirements.

Conclusion

A reciprocating double piston gas prover was developed based on EtherCAT. It can operate in three different modes and provide a continuous standard flow to calibrate gas flow meters. The critical flow nozzles with different diameters were selected for verification and repeatability experiment under these three working modes. The repeatability of the device is less than 0.05% and the accuracy is less than 0.06%. The results show that the device reaches the requirement of gas flow rate standard and EtherCAT could be popularized for other piston provers.

Acknowledgment

This work was supported by supported by the Natural Science Foundation of Zhejiang Province(No.LY18E050009 and No.Q19E060008).

Nomenclature

C_d – discharge coefficient
C_* – critical flow function
d – throat diameter of the nozzle, [m]
k – wet air correction coefficient
M – molecular weight, (= 28.97), [kgk^{-1}mol^{-1}]
R – Molar gas constant, R = 8.31[JK^{-1}mol^{-1}]
RH – gas relative humidity, [%]
T – average absolute temperature, [K]
t – set time, [s]
X – arithmetic mean value of n measurements
X_i – value for the i^{th} measurement
X_{CO2} – molar fraction of CO_2 in the air
Z – gas compressibility factor

Greek synbol

δ – pulse equivalent (the minimum distance of one pulse)

Acronyms

ADS – automation device specification
A/D – analog to digital
AI – analog input
DI – digital input
DO – digital output
IO – input and output
IPC – industrial personal computer

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Paper submitted: October 22, 2019
Paper revised: November 26, 2019
Paper accepted: December 10, 2019