Investigation of the pVTt Gas Flow Standard with Active Thermal Compensation

Hu Wenqing*, Xu Zhipeng, Zhang Gaoming，Guo Jing

College of metrology & measurement engineering, China Jiliang University,
Xueyuan Street, Xiasha Higher Education District, Hangzhou, P. R. China, 310018

Abstract

pVTt has been employed as the primary gas flow standard in many countries due to its unique advantages like high accuracy, simple structure, low maintenance, etc. However, its calibration efficiency is relatively low because of the long stabilization time of intake and outtake procedures. To reduce the stabilization time, a novel pVTt gas flow standard with active thermal compensation was proposed. Above all, structure and principle of the new pVTt standard device was introduced. Subsequently, the numerical simulation was performed to investigate the influence of thermal compensation. Finally, experiments were carried out, and results showed that the stabilization time after intake completion could be reduced from ten minutes to one minute,which means calibration efficiency was improved a great deal.

1 Introduction

pVTt has been employed as the primary gas flow standard for more than 40 years in many countries such as China, the United States, and Japan [1]. The unique advantages of the pVTt gas flow standard are high accuracy, simple structure, and low maintenance. It is usually used for the calibration of critical flow sonic nozzles or other secondary standards [2]. The schematic diagram of the entire pVTt method device is shown in Figure1. The principle can be summarized as follows. Within a certain time-interval t, gas enters and exits a standard container with a volume of V. By calculating the average density of the gas before and after the inlet according to the pressure p and temperature T, the average mass flow of gas during the verification process can be calculated. However, due to the long stabilization time of intake and outtake procedures of the calibration, the efficiency of pVTt is relatively low. Sometimes the calibration time could be more than 1 hour for just one single cycle.

So far, the number of pVTt gas flow standard devices is small, and the flow range for verification is limited. In order to cope with more complex industrial production situations, improving the calibration efficiency and expanding the flow range are still the focus of future research.

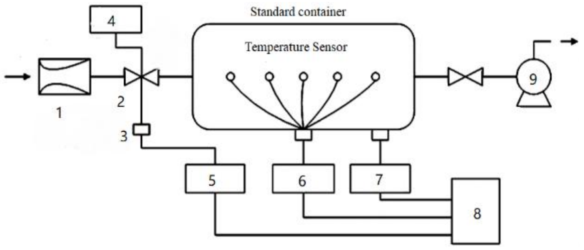
In recent years, great progress has been made in establishing a new pVTt standard and reducing its uncertainty. NIST Fluid Flow Group has given a description of the gas flowmeter calibration services that use the 34 L and 677 L pVTt primary standards. These pVTt standards were designed to calibrate flowmeters with measuring range from 1 L/min to 2000 L/min and with uncertainties between 0.02 % and 0.05% [3]. In 2003, NIST upgraded the temperature-averaging scheme used in its 26 m^3 pVTt system. Applying the new temperature-averaging scheme, the flow uncertainty of the NIST 26 m^3 pVTt system has decreased from 0.22% to 0.13% (with a coverage factor of 2) [4]. At the 2009 Measurement Science Conference, related papers pointed out that NIST has reduced the uncertainty of its 34 L and 677 L Pressure-Volume-Temperaturetime (pVTt) primary flow standards from 0.05 % to 0.025 % (k = 2) for air flow in the range from 0.01 slm to 2000 slm. Over the restricted range from 0.1 slm to 1000 slm, the uncertainty was reduced to 0.015% [5]. In Japan, a new pVTt system has been constructed to establish a standard for gas flow rate less than 5 mg/min. In this pVTt system, a realistic relative standard uncertainty at a flow rate of 0.01 mg/min is 0.21% when the collection time is 40 h and a realistic relative standard uncertainty is 0.0001% at a flow rate of 5 mg/min with the collection time of one hour [6]. In 2019, a new pVTt standard for gas flow has been commissioned at NMIA. The main aim of developing this new standard was to reduce the measurement inaccuracy of NMIA’s bell and mercury-sealed piston provers with an uncertainty of ±1000 ppm (±0.10%)[7].

To improve the pVTt calibration efficiency, different methods have been taken out. For example, In the 1990s, Japan established a set of medium-flow pVTt method gas flow standard devices, which used a water bath constant temperature measure. The uncertainty was less than 0.1% (k=2). In 2002, the container structure was updated, and a sandwich water bath was used to improve its ability to work under pressure, so its uncertainty was better than 0.05% (k=2) [8]. In 2003, NIST announced a set of small and medium flow pVTt method gas flow standard devices, including 34L and 677L standard containers, the flow range is (1~2000) L/min, and the uncertainty is better than 0.025% (k=2). In 2004, Researchers established a large-flow pVTt method gas flow standard device. It adopts a high-pressure intake method with a flow range of 200~77000 L/min, and its uncertainty is better than 0.09% (k=2).

According to its device principle, it is mainly used to verify sonic nozzles [9], of course, it can also be used to verify other secondary standards. The schematic diagram of the entire pVTt method device is shown in Figure1.

According to the current research status, the fundamental reason that affects the verification efficiency of the device is the long stabilization time of intake and outtake process, which is usually more than half an hour. The specific reasons include three aspects. Firstly, temperature inside the container increases a lot due to the high temperature gas at the inlet.Secondly,the area of the container is limited,which means the area of natural convection heat transfer is limited; Thirdly, the heat transfer coefficient of natural convection is low.

In this work, to improve the calibration efficiency, a novel pVTt gas flow standard with active thermal compensation was proposed. Firstly, the structure and principle of the new pVTt standard device was introduced. Subsequently, numerical simulation on temperature distribution in the container was conducted to investigate the influence of thermal compensation. Finally, experiments were carried out to validate the theoretical results and the feasibility of the proposed pVTt standard device.



1.Critical Venturi nozzle 2. On-off valve
3. Photoelectric pulse signal converter 4. Air compressor
5.Timer 6.Temperature Sensor 7.Pressure gauge
8.Console 9.Vacuum pump

Figure 1: Schematic diagram of pVTt gas flow standard device.

2 Description of the pVTt system

The nozzle verification using the pVTt method is mainly considered from three aspects: structural design and installation, measurement performance requirements,and general technical requirements[10-11]. The schematic and picture of the proposed pVTt system are displayed in Figure 2 and Figure 3 respectively. As shown in Figure2, the new-type pVTt gas flow standard device includes a sonic nozzle, an air compressor, a standard container, an active thermal compensation module, a vacuum pump and two on-off valves.The nozzle verification module is a key part of the entire system.The function of the air compressor is to compress gas under negative pressure.The active thermal compensation module is the focus and novelty of this work. It is mainly composed of a stainless-steel coil (shown in Figure 4), a water cooler, and pipes connectd to the standard container. A coil is inserted into the standard container to enhance heat transfer. The water cooler provides cold water which flows through the stainless-steel coil in the standard container through the connecting pipe to cool the gas inside the standard container.The upstream and downstream temperatures in the container are measured by temperature sensors T1 and T2 respectively, the pressure inside the container is measured by the pressure sensor P0 and the ambient temperature is measured by the temperature sensor T0.

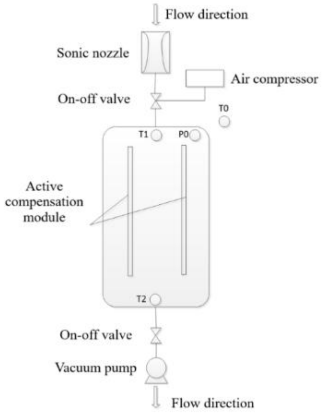


Figure 2: Schematic of the active thermal compensation pVTt.

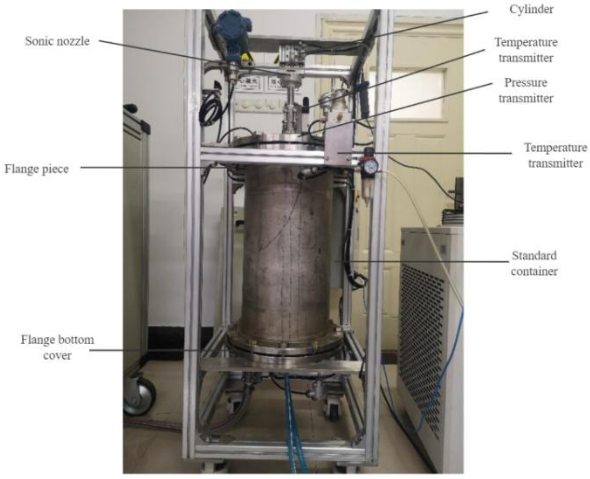


Figure 3: Picture of pVTt gas flow standard device.

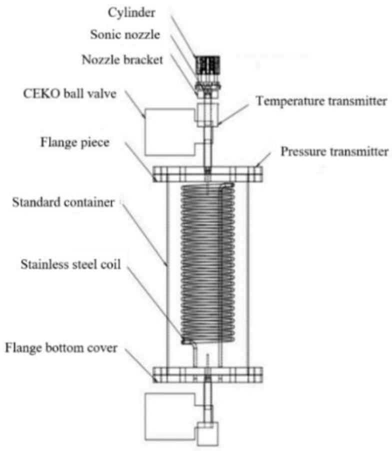


Figure 4: Structure detail of the pVTt container.

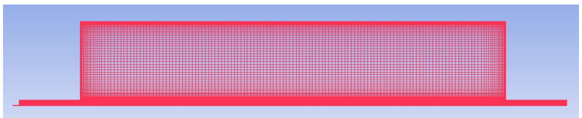
3 Numerical simulation on temperature field

Based on the designed pVTt verification system, a two-dimensional model of the system is established to simplify the calculation. The CFD method is carried out to simulate the process of inflation,and compare the temperature field inside the standard container under the conditions of natural state, passive compensation, and active compensation, which is to verify the feasibility of this pVTt device[12].

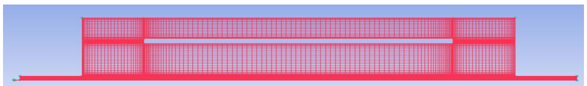
To simulate the temperature field inside the standard container, it is the first step to determine the geometric model. The simplified three-dimensional model of pVTt device includes the critical flow nozzle, an inlet pipe, the standard container and an outlet pipe as shown in Figure5.

Figure 5: The simplified three-dimensional model.

The second step is grid generation and grid independence verification. In this work, ANSYS ICEM CFD is uesd to generate the grid.The generated grid is shown in Figure6. More than 90% of the grid quality parameters are less than 0.4, which can meet the needs of this simulation.



(a) No active thermal compensation model



(b) Active thermal compensation model

Figure 6: Schematic of the generated grid.

The next step is to set the boundary conditions.The inlet boundary condition is set to flow inlet with the mass flow rate of 0.00017323 kg/s, which is the value collected after the formation of the critical flow. To ensure calculation accuracy and reduce calculation time, the time step is set to 10^{-5} s.

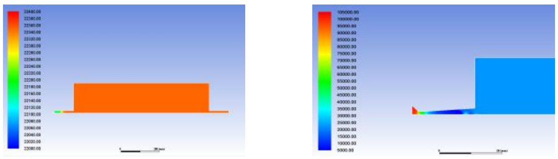
4 Results and discussion

4.1 Simulation results

4.1.1 Temperature and pressure distribution in the process of intake

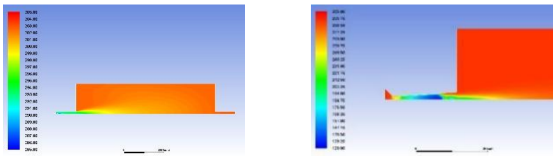
Firstly, we set the intake time to 10s and qualitatively analyze the temperature and pressure distributions inside the whole system with and without active thermal compensation at the end of the intake process. For the cases with and without active thermal compensation, both the temperature and pressure in the standard container rise linearly A critical flow has formed at the nozzle at the end of intake.

At the end of intake, the temperature and pressure distributions inside the whole system without active thermal compensation are shown in Figure 7 and Figure 8.



(a) The whole system (b) Partially enlarged nozzle

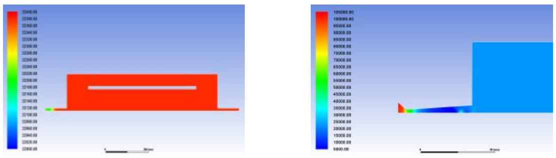
Figure 7: Pressure distribution in the case without active thermal compensation at the end of intake.



(a) The whole system (b) Partially enlarged nozzle

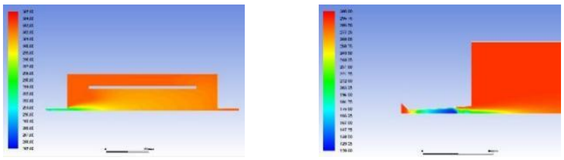
Figure 8: Temperature distribution in the case witout active thermal compensation at the end of intake.

At the end of intake, the temperature and pressure distributions inside the whole system with active thermal compensation are shown in Figure 9 and Figure 10.



(a) The whole system （b）Partially enlarged nozzle

Figure 9: Pressure distribution in the case with active thermal compensation at the end of intake.



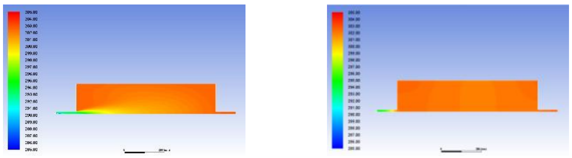
(a) The whole system (b) Partially enlarged nozzle

Figure 10: Temperature distribution in the case with active thermal compensation at the end of intake.

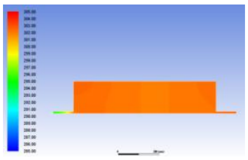
From Figure 7 and Figure 9, it can be seen that pressure distribution inside the whole system in the cases with and without active thermal compensation is similar at the end of intake.In both cases, the pressure distribution in the standard container is uniform and the pressure in the expansion section of the nozzle decreases. From Figure 8 and Figure 10, it can be observed that for the two cases, the temperature distribution is similar as well. The temperature in the container is significantly non-uniform for the reason that the gas moves violently after entering the standard container and gas molecules collide with each other. There exists a low-temperature area in the nozzle expansion section, after which the temperature gradually rises.

4.1.2 Temperature distribution inside the container after intake completion

To simulate the temperature distribution after intake completion, we change the pressure inlet to the wall when the process of intake has completed. Figure 11 displays the temperature distribution inside the standard container without thermal compensation 0 second, 30 seconds and 60 seconds after intake completion.



(a) 0s after intake completion (b)30s after intake completion

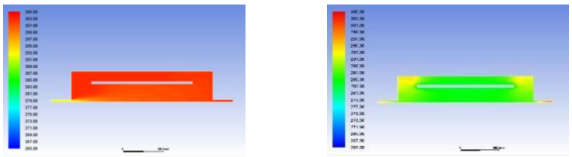


(c) 60s after intake completion

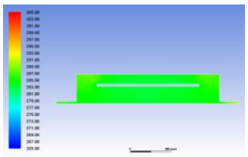
Figure 11: The temperature distribution inside the container without thermal compensation after intake completion.

From Figure11(a), when the intake process has just completed， there is a temperature gradient along the axis of the container. At this time, the temperature at the center of the standard container is 300.69K. As shown in Figure11(b), the temperature gradient in the standard container decreases thirty seconds after intake completion,,indicating that the temperature field tends to stabilize. Sixty seconds after intake completion, the temperature distribution in the container shows little difference from that of thirty seconds after intake completion. At this time, the center temperature in the container is 301.99K.

To simulate the process of active thermal compensation, we set the wall temperature of the stainless-steel coil to 283.15K. Figure 12 illustrates the temperature distribution inside the standard container with active thermal compensation 0 second, 30 seconds and 60 seconds after intake completion.



(a) 0s after intake completion （b）30s after intake completion



（c）60s after intake completion

Figure 12: The temperature distribution inside the container with active thermal compensation after intake completion.

As shown in Figure12 (a),when the intake process has just completed,the temperature inside the standard container exhibits zonal distribution along the axis, and the temperature near the inlet is low,while the temperature away from the inlet is high. From Figure 12 (b),,the temperature in the container decreases obviously and tends to be uniform thirty seconds after intake completion. However, due to the distance from the active compensation module, the temperature at inlet and outlet is a bit higher than that in the bulk of the container. It can be seen from Figure12 (c) that temperature inside the container is quite uniform sixty seconds after intake completion, indicating that the temperature field in the container is stable at this time. Thus adding the active thermal compensation module to the standard container enhances the heat transfer inside the container and,accelerates the stabilization of the temperature field, which can greatly improve the verification efficiency of pVTt method.

4.2 Experimental results

4.2.1 Temperature distribution in the container with and without active thermal compensation

Tables 1 and 2 illustrate variations in tested temperture and mass of gas in the container without and with active thermal compensation after intake completion respectively. From Table 1, in the case without thermal compensation, the temperatures upstream and downstream are still rising slowly within one minute after intake completion owing to intense airflow. Due to the vertical placement of the container, there is a difference between the upstream and downstream temperatures. Within five minutes after intake completion, the mass of gas fluctuates in a small range, indicating the gas distribution in the container is still uneven. As time progresses, the gas in the container gradually stabilizes.Ten minutes after intake completion, the mass of gas is basically stable at 17.171 g, which means the temperature field in the container is basically stable.

From Table 2, it can be seen that the temperatures upstream or downstream decrease gradually 20 s after intake completion in the case with active thermal compensation. The temperature sensor upstream is closer to the air inlet, and the airflow in this area changes drastically during intake. Therefore, the temperature upstream is higher than that downstream. Due to the uneven distribution of the gas in the container, measurement inaccuracy of temperature and pressure exists, causing the mass of gas fluctuates in a small range. As time progresses, the mass of gas stabilizes at 17.140 g one minute after the intake completion. Compared to the case without thermal compensation, the stabilization duration of temperature in the container reduces from ten minutes to one minute in the case with active thermal compensation, indicating that calibration efficiency of pVTt can be greatly improved resulting from the cooling effect of active thermal compensation module.

4.2.2 Nozzle verification experiment

To validate the feasibility of the proposed pVTt device, a set of nozzles with a nominal flow rate of $1m^3/h$ and a throat diameter of 1.37mm are used to perform verification experiments. According to the verification regulations, different intake durations are set to observe the repeatability of the outflow coefficient. The experimental results are shown in Table 3. From Table 3, the repeatability of the nozzle outflow coefficient for different intake durations is within 0.1%, indicating that this device meets the design requirements. Moreover, as the intake duration increases, repeatability decreases. When the intake duration is 30s, the nozzle repeatability can reach 0.0361%, indicating that prolonging the intake duration can improve nozzle verification accuracy.

Table 1: Test results without active thermal compensation module.

Time (min)	Temperature upstream (℃)	Temperature downstream (℃)	Average temperature (℃)	Pressure (Pa)	Mass of gas (g)
Initial state	25.8417	25.6375	25.7396	19983.25	14.976
1	25.8917	25.7083	25.8000	22895.50	17.135
2	25.8750	25.7125	25.7938	22903.75	17.142
3	25.8500	25.6917	25.7708	22905.25	17.154
4	25.8542	25.6917	25.7729	22907	17.166
5	25.8542	25.6792	25.7667	22907	17.169
6	25.8394	25.6792	25.7593	22912	17.170
7	25.8377	25.6833	25.7605	22912	17.170
8	25.8150	25.6750	25.7450	22912	17.171
9	25.8193	25.6667	25.7430	22912	17.171
10	25.8191	25.6667	25.7429	22912	17.171

Table 2: Test results with active thermal compensation module.

Time (s)	Temperature upstream （℃）	Temperature downstream （℃）	Average temperature （℃）	Pressure (Pa)	Mass of Gas （g）
Initial state	25.0625	22.8791	23.9708	20008	15.084
10	25.1125	22.9000	24.0063	22788.25	17.178
20	25.0875	22.8125	23.9500	22738.75	17.144
30	25.0809	22.7875	23.9342	22732.25	17.140
40	25.0741	22.7833	23.9287	22730.50	17.139
50	25.1188	22.6458	23.8823	22728.25	17.140
60	25.1838	22.5792	23.8815	22728.25	17.140

Table 3: Repeatability of outflow coefficient for $1m^3/h$ nozzle with different intake durations

Intake duration(s)	Outflow coefficient					Repeatability
10	0.9708	0.9718	0.9692	0.9713	0.9696	0.000982
20	0.9704	0.9716	0.9688	0.9709	0.9693	0.000748
30	0.9710	0.9699	0.9708	0.9694	0.9706	0.000361

5 Conclusions

In this work, a novel pVTt gas flow standard with active thermal compensation was proposed to improve the calibration efficiency, the CFD simulation was conducted to investigate the effect of thermal compensation, and experiments were carried out to verify the theoretical results. Corresponding conclusions are summarized as follow.

1) In the light of the simulation results, the average temperature in the standard container with active thermal compensation will be reduced from 301.99k to 284.28k within one minute after intake completion.compared to the case without thermal compensation. Furthermore, by applying active thermal compensation, temperature inside the container becomes uniform and stable sixty seconds after intake completion.

2) Based on the tested results,.when an active compensation module is added to the pVTt device, the stabilization duration of temperature in the container is reduced from ten minutes to one minute, which means that calibration efficiency of pVTt can be greatly improved.

3) According to the nozzle verification experiment, the repeatability is within 0.1%, which meets the design requirement of the pVTt device and validates the feasibility of the pVTt device with active thermal compensation.

Acknowledgements

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

References

[1] WANG X Y, LUO X X, XU Z P. Study of polytropic exponent based on high pressure switching expansion reduction journal of thermal science[J]. 2011, 20(5): 435-441.

[2] JJG 619-2005, pVTt Method Gas Flow Standard Device [S].

[3] Wright J D , Johnson A N , Moldover M R , et al. Gas Flowmeter Calibrations with the 34 L and 677 L pVTt Standards[J]. NIST SP -, 2004.

[4] Temperature characterization in the collection tank of the NIST 26 m3 pVTt gas flow standard[J]. Metrologia, 2003, 40(5):211.

[5] Wright J D , Johnson A N . Lower Uncertainty (0.015 % TO 0.025 %) OF NIST S Standard For Gas Flows From 0.01 TO 2000 Standard Liters/Minute[J].

[6] Nakao S I , Terao Y , Takamoto M . Development of the pVTt system for very low gas flow rates. 2003.

[7] Chahine, K. and Wang, Z., Establishment of an Ultra-High Accuracy 670L pVTt Gas Flow Primary Standard at NMIA, FLOMEKO, Lisbon, Portugal, June 26 to 28, 2019.

[8] Masahiro I, Toshihiro M. The renewed airflow standard system in Japan for 5-1000 m3/h [J]. Flow Measurement and Instrumentation, 2006, 17(3): 153-161.

[9] D. Ma, Research on pVTt gas flow calibration facility [J], Metrology & Measurement Technique 43 (12) (2016) 83–84.

[10] JJG 619-1989, p.V.T.t method gas flow standard device trial verification regulations [S].

[11] JJG 620-2008, Critical flow venturi nozzle [S].

[12] Davis J A, Stewart M. Predicting Globe Control Valve Performance Part I: CFD Modeling[J]. Journal of Fluids Engineering ,2002,124(3) :772 -777.