Research on Online Value Checking Method of Flow Calibration System Based on Double Master Flowmeter Checking Technology

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Abstract

Whether the measurement performance of flow standard facility is normal or not directly affects the final flow measurement result, and the independent checking of quantity value is the key technical means to ensure the steady and reliable performance of flow calibration system. At present, there is a lack of quantitative verification methods for liquid flow standard facilities, and the existing researches mostly focus on expanding the range of operating parameters of facilities and improving their uncertainty level, etc, while the quantitative verification for flow facilities themselves has not been paid attention to and the relevant verification work has not been widely carried out. Based on the mutual verification of the measured values of double flowmeters, a set of intelligent online value verification method for weighing flow standard facility is designed and established. The theoretical basis of the method is described in detail, and the algorithm theoretical model and criterion are provided. Taking the weighing method micro flow standard facility of the National Institute of Metrology as the research object, the verification experiment test of the verification algorithm is carried out, and the results show that: The proposed online value verification method of flow calibration system has good adaptability and high verification accuracy, and can automatically and real-time monitor the operating status of the system in use, thus greatly improving the stability and reliability of the operation process of the facility, which is worthy of further popularization and application.

Key word：flow calibration system; weighing method; double master flowmeter; mutual check; on-line value verification

1. Introduction

The flow standard facility is the key equipment to carry out flow meter verification and calibration and ensure the unification and correct transmission of flow quantity value[1]. With the booming development of the flow industry at home and abroad in recent years, the market has become more and more stringent on the flow measurement accuracy of all kinds of flowmeters in use, and further requires that the measurement results reproduced on the flow facility should not only be more accurate and reliable, but also have good stability and repeatability[2-3]. At present, in the field of the liquid flow metering, there is still a lack of value verification methods specially for liquid flow facilities. The previous studies mostly focused on how to expand the testable pipe diameter of the flow facility, improve the pipeline flow velocity or flow rate and its uncertainty level and other technical indicators[4], but the verification of the value of the flow facility itself has been ignored. On the other hand, the flowmeter as the verification carrier is usually a relatively complex electronic instrument, which is prone to reading drift due to the influence of external factors, such as installation conditions, temperature and humidity changes, pipeline vibration, etc, and its long-term stability is difficult to ensure, which leads to the fact that the verification of flow facilities has not been widely carried out[5-6].

The self-checking of quantity value is a necessary technical means to ensure the stability and reliability of the flow calibration system in use, so it is of great significance and urgent to develop the checking method suitable for the flow standard facility. In this paper, based on the master flowmeter or the measured flowmeter by mutual check measurements, an intelligent online value verification method for the weighing method water flow standard facility has been established, which can effectively realize many functions such as value comparison, intelligent warning and fault analysis of calibration system, so that problems existing in the system during operation can be found in time and verification accuracy can be greatly improved. In addition, taking the weighing method micro flow standard facility of National Institute of Metrology as the research object, a verification experiment was carried out to improve and evaluate the accuracy and rationality of the verification algorithm, and the reliability evaluation conclusion of the measurement value of the micro-flow facility was given.

2. Theoretical Basis

The flow diagram of the weighing method flow calibration system considering dual flowmeters is shown in Figure 1:

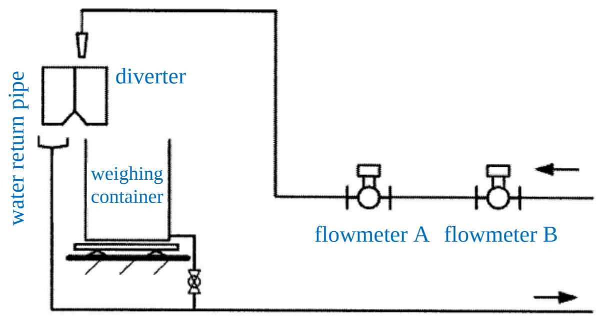


Figure 1: Schematic diagram of weighing method flow calibration system for double flowmeter

Under the same working conditions, install two flowmeters in series on the same test pipeline, start the facility and adjust the rate of flow to a stable state, test and record the measurement performance of the two flowmeters. Since the probability of failure of two flowmeters at the same time is very low, the consistent change of the measurement results of the two flowmeters under the same working condition can be considered as representing the drift of the value of the flow facility itself. Through the analysis of the consistent change, the self-verification of the whole flow calibration system of weighing method can be realized[7-8].

It is worth noting that in the selection of flow meter, the two meters should be selected as different as possible, to reduce the possibility of some uncertainty during the test process to affect the two flowmeters at the same time, thus improving the reliability of the verification results.

3. Theoretical model of algorithm

In order to ensure the accuracy and reliability of the measurement results of the flow standard facility, a set of intelligent online value verification algorithm based on the double master flowmeters mutual checking technology is established. According to the difference of the accuracy level and principle of the verification, the algorithm includes: weighing method facility + single master meter, arbitrary double meter, double master meter method and double weighing method facility + specific single meter comparison method, among which the double master meter method can be regarded as the strengthening of single master meter and arbitrary double meter method. The value of this algorithm lies in that one or more verification schemes can be flexibly selected according to the actual requirements of the site to carry out the verification of the quantity accuracy of the flow facility itself.

3.1 Weighing facility + single master meter

A schematic diagram of pipeline installation using a single master meter to verify the flow standard facility is shown in Figure 2:

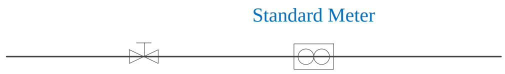


Figure 2: Schematic diagram of pipeline installation of verification scheme of weighing facility + single master meter

Verification principle: Based on the repeatability change of historical measurement results (instrument coefficient or relative error, repeatability) of a single master meter under different verification flow points, and combined with control chart method.

Implementation process: 1. Determine whether the reproducibility of the relative indication error of the master meter exceeds the set threshold; 2. Determine whether the reproducibility of the measurement repeatability of the master meter exceeds the set threshold; 3. Determine whether the local fluctuation of measurement error at a specific flow point meets the requirements by combining the control chart method.

Determination criteria: 1. The measurement error and repeatability are lower than the set threshold; 2. The control chart inspection mode: ①There is no flow point beyond the error control limit; ② There are no consecutive 9 points falling on the same side of the center line; ③There is no continuous increase or decrease of 6 points. If the first and second items above are met at the same time, the reading of the weighing facility can be regarded as reliable, otherwise, it is ignored. In mathematical form, it can be expressed as:

$$\begin{cases} F_{ci} = \left|\dfrac{E_{(i+1)} - E_i}{\delta_c}\right| \le 1、 R_{ci} = \left|\dfrac{s_{(i+1)} - s_i}{\omega_c}\right| \le 1 \\ L_{CL} = \overline{E} - A_3\overline{s} \le E_i \le U_{CL} = \overline{E} + A_3\overline{s} \\ \left(E_{i+j} - \overline{E}\right)\cdot\left(E_{i+k} - \overline{E}\right) < 0 \\ \left(E_{i+x} - E_{i+x-1}\right)\cdot\left(E_{i+x+1} - E_{i+x}\right) < 0 \\ i = 1,2,3\cdots n;\ j、k \subset [0 \quad 8];\ x \subset [0 \quad 5] \end{cases} . \quad (1)$$

Where, F_{ci} and R_{ci} are the change factors of reproducibility of relative indication error and repeatability measured for the i-th time under a certain flow point in the master meter respectively; E_i is the average indication error of the master meter measured at a certain flow rate for the i-th time, δ_c is the change threshold of error reproducibility; s_i is the repeatability of the i-th measurement result of the master meter at a certain flow rate, and ω_c is the change threshold of repeatability; U_{CL} and L_{CL} are the upper and lower control limits of the error mean control chart, $\overline{E}$ is the center line of the control chart, and A_3 is the control limit factor (The value is determined by the total number of measurements *n*, and can be provided by the GB/T 17989.2-2020[9]).

3.2 Weighing facility + arbitrary double meter

The pipeline installation schematic diagram of this verification scheme is shown in Figure 3:

Figure 3: Schematic diagram of pipeline installation of verification scheme of weighing facility + arbitrary double-meter

Verification principle: Based on the consistency of error change of measurement results of any two flowmeters at a single flow point and repeated measurement for many times.

Implementation process: 1. Determine whether the reproducibility of two adjacent measurement results in meter 1 exceeds the set threshold; 2. Determine whether the reproducibility of two adjacent measurement results in meter 2 exceeds the set threshold; 3. Judge whether the change direction of the measurement error of the double meter is consistent; 4. Judge whether the error variation amplitude of double meters exceeds the set threshold.

Determination criteria: 1. Reproducibility of two adjacent measurement results in meter 1 and meter 2 exceeds the set threshold; 2. The error variation direction of the two flowmeters is consistent and the amplitude of variation is lower than the set threshold. If the first and second items above are met at the same time, the reading of weighing facility is considered to be unreliable, otherwise, it is ignored. Its mathematical model can be expressed as follows:

$$\begin{cases} F_{1ci}=\left|\dfrac{E_{1(i+1)}-E_{1i}}{\delta_{1c}}\right|>1、F_{2ci}=\left|\dfrac{E_{2(i+1)}-E_{2i}}{\delta_{2c}}\right|>1 \\ G_i=\left(E_{1(i+1)}\text{-}E_{1i}\right)\cdot\left(E_{2(i+1)}\text{-}E_{2i}\right)\geq 0 \\ H_i=\left|\dfrac{\left(E_{1(i+1)}\text{-}E_{1i}\right)\text{-}\left(E_{2(i+1)}\text{-}E_{2i}\right)}{U_C}\right|<1 \end{cases} \quad . \quad (2)$$

Where, G_i is the judgment factor of the change direction of the two adjacent measurement errors of the double meter, H_i is the judgment factor of the change amplitude of the two adjacent measurement errors of the double meter, and U_C is the extended uncertainty of the weighing method flow facility, $i=1,2,3\cdots n$.

3.3 Weighing facility + double master meter

The pipeline installation schematic diagram of the verification scheme is shown in Figure 4:

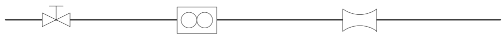


Figure 4: Schematic diagram of pipeline installation of verification scheme of weighing facility + double master meter

Verification principle: Based on the consistency change rule of relative error of historical measurement results of two master meters under different verification flow points, and combined with control chart method.

Implementation process: 1. Judge whether the reproducibility of two adjacent measurement values in meter 1 exceeds the set threshold; 2. Judge whether the reproducibility of two adjacent measurement values in meter 2 exceeds the set threshold; 3. Judge whether the change direction of the measurement error of the double meter is consistent and whether the variation amplitude of measurement error exceeds the set threshold; 4. Judge whether the local fluctuation of the measurement error of the double meter meets the consistency requirement at a specific flow point.

Determination criteria: 1. The repeatability of measurement errors in meter 1 and meter 2 exceeds the set threshold, and the change direction of errors in both meters is consistent and the change amplitude is lower than the set threshold; 2. Control chart inspection mode: ①The error data of a flow point in both meters falls outside the error limit; ②At the same time, the same 9 consecutive points fall on the same side of the center line; ③At the same time, the same 6 points increase or decrease continuously. If one of the conditions in the first and second paragraphs above is satisfied, the reading of the weighing facility is considered to be unreliable, otherwise, it is ignored. Its mathematical model can be expressed as follows:

$$\begin{cases} F_{1ci} = \left|\dfrac{E_{1(i+1)} - E_{1i}}{\delta_{1c}}\right| > 1、F_{2ci} = \left|\dfrac{E_{2(i+1)} - E_{2i}}{\delta_{2c}}\right| > 1 \\ G_i = \left(E_{1(i+1)} - E_{1i}\right)\cdot\left(E_{2(i+1)} - E_{2i}\right) \geq 0 \\ H_i = \left|\dfrac{\left(E_{1(i+1)} - E_{1i}\right) - \left(E_{2(i+1)} - E_{2i}\right)}{U_{\mathrm{C}}}\right| < 1 \end{cases} \tag{3a}$$

$$\begin{cases} \left|E_{1i} - \overline{E_1}\right| > A_3\overline{s_1}、\left|E_{2i} - \overline{E_2}\right| > A_3\overline{s_2} \\ \left(E_{1(i+j)} - \overline{E_1}\right)\cdot\left(E_{2(i+j)} - \overline{E_2}\right) > 0 \\ \left(E_{1(i+x+1)} - E_{1(i+x)}\right)\cdot\left(E_{2(i+x+1)} - E_{2(i+x)}\right) > 0 \\ i = 1,2,3\cdots n;\ j、k \subset [0 \quad 8];\ x \subset [0 \quad 5] \end{cases} \tag{3b}$$

3.4 Double weighing facility + specific single meter comparison method

The comparison is an effective and reliable means to verify the unification and reliability of the values of different facilities or different calibration stations of the facility, and also a widely used and mature verification scheme in the field of liquid flow standard facilities[10]. This scheme is used to carry out the internal comparison between stations of NIM micro-flow facility. The master flow meter with good long-term stability is used as the verification standard, and the value of E_n is used to determine the verification result. The calculation expression of E_n under each flow point is as follows:

$$E_n = \frac{\left|E_{\mathrm{A}i} - E_{\mathrm{B}i}\right|}{\sqrt{U_{\mathrm{A,C}}^2 + U_{\mathrm{B,C}}^2}} \tag{4}$$

Where, $E_{\mathrm{A}i}$、$E_{\mathrm{B}i}$ are the average indication error of the i-time measurement of the calibration system at A and B at a certain flow point respectively; $U_{\mathrm{A,C}}$、$U_{\mathrm{B,C}}$ are the extended uncertainties of the calibration system of A and B stations respectively.

Verification criteria of comparison method: if $E_n \leq 1$, indicating that the measurement results of the two stations are in good consistency and acceptable; $E_n > 1$, it indicates that the consistency of the measurement results of the two stations is greatly different, and the results are unacceptable.

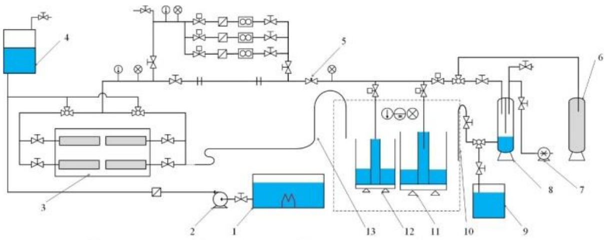
4. Flow calibration system verification experiment

4.1 Preparation for experiment

The verification experiment will be carried out on the newly established dynamic weighing method micro liquid flow standard facility of the National Institute of Metrology (NIM). The facility is designed with 2 sets of balance weighing systems (31g, 220g), 3 master meters (LF2M, LF3M, LF4M) and 2 sets of independent test pipeline systems. Its flow rate range is 100nL/min ~ 150mL/min, the overall extended uncertainty is better than 2%(k=2), and the measurement repeatability is better than 0.03%, which effectively fills the gap in the detection of micro liquid flow and improves the flow value traceability system in China. The main technical indicators are as follows:

Measurement principle: dynamic weighing method
Measuring flow range: 100nL/min ~ 150mL/min
Uncertainty: 0.6mL/min < q_v≤ 150mL/min, U_{rel}=0.1%(k=2)
10μL/min < q_v≤ 0.6mL/min, U_{rel}=0.15%(k=2)
0.1μL/min ≤q_v≤ 1μL/min, U_{rel}=(0.15+1.68)%(k=2)

The structure diagram of the facility is shown in Figure 5:



1-ultrasonic heating degassing water tank; 2-water pump; 3-injection pump; 4-water container; 5-pressure regulating valve; 6-CO_2 gas tank; 7-vacuum pump; 8-(vacuum) waste liquid tank; 9-waste liquid barrel; 10-waste liquid back to the pipette; 11-MSA225S electronic scale; 12-MCM36 electronic scale; 13-capillary inlet pipe

Figure 5: Schematic diagram of NIM dynamic weighing method micro liquid flow standard facility

4.2 Selection of verification data

Since the micro flow facility has not built a standard, repeated debugging and continuous improvement are needed to ensure that the measurement results are accurate and reliable. Here, the calibrated experimental results are filtered first, and effective data are extracted for facility verification.

Equipment involved in the experiment: 31g and 220g stations of the micro-flow facility of weighing method; Master flowmeter - LF2M, tested flowmeter - injection pump. The experimental flow point was set as Q_c=1.2mL/min, and the calibration experimental results of the master meter and the tested meter under different conditions were obtained, as shown in Figure 6:

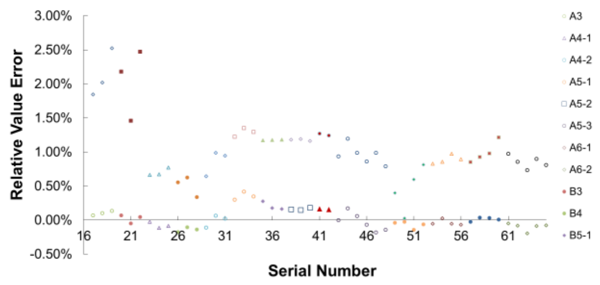


Figure 6: Experimental results of flow calibration of micro-flow standard facility (Q_c=1.2mL/min)

It can be seen from the data in Figure 6 that, with the exception of a few experimental points (serial number 17-22), the variation trend of the relative error measured by the master meter and the tested meter at different stations was generally consistent with the experimental serial number (or time order). By searching the original records, it was found that the experimental conditions of the injection pump changed (such as differences in setting of syringe, needle, beaker and overflow conditions, etc) from experimental points 17 to 22, and the results showed that the error of indication fluctuated greatly and the repeatability value was obviously high. Therefore, the data of these six experimental points were removed, and the effective data points for subsequent calculation and analysis in the whole experiment ranged from 23 to 65.

4.3 Design of verification scheme

According to the requirements, two sets of verification procedures are designed as follows. The ultimate purpose of the scheme is to judge whether the measurement results of 31g and 220g station calibration system are reliable based on the processing and analysis of the test data of NIM dynamic weighing method micro-flow facility. The general idea can be divided into two steps: 1. Process A is adopted to judge the consistency of the measurement results of the two station systems of the micro-flow facility; 2. Process B is adopted to further verify the reliability of the measurement values of the two stations.

Process A: comparison between station systems. Which is mainly to check whether the measurement results of two station systems in the facility are consistent, and the method is: determined the flowmeter as the standard for passing (master meter LF2M), the transfer standard was measured by two stations of the micro-flow facility respectively; Then, the value of E_n is calculated according to the measured error and system uncertainty to judge the verification results of the two stations.

Process B: Reliability verification of the station system. Which is mainly based on double master flowmeter mutual check technology to realize the verification of the accuracy of the reading of the system at different stations of the micro-flow facility. Comprehensive consideration has been obtained by the measuring data types and valid data, confirm verification scheme as weighing method facility + any double meters, specific 31g or 220g station calibration system +LF2M (master meter) + injection pump (tested meter).

The schematic diagram of the verification process is shown in Figure 7:

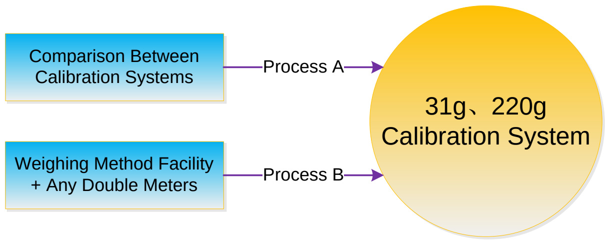


Figure 7: Schematic diagram of value verification process of micro-flow calibration system

5. The analysis of verify experimental results

5.1 Verification result of process A

According to the designed verification scheme, first of all, two stations of NIM micro-flow facility are verified by process A and judged by the value of E_n. The extended uncertainty of 31g and 220g station systems of micro-flow facility is known to be $U_{A,C}$=$U_{B,C}$=0.1%, the reproducibility threshold of indication error of master meter LF2M is set to be 0.08%, and the reproducibility threshold of indication error of tested meter (injection pump) is set as 0.11% (the mean value of measuring repeatability of two flowmeters at 1.2mL flow point is taken for both). The verification results of the comparison method of the two stations based on process A are shown in Table 1:

Table 1: Process A- the verification results of stations comparison

Comparison of Experimental Numbers	Nominal Flow Rate (mL/min)	31g Station System			220g Station System			E_n
		Relative Error	Repeatability	Uncertainty （k=2）	Relative Error	Repeatability	Uncertainty （k=2）	
23～25, 26～28	1.2	-0.08%	0.05%	0.22%	-0.14%	0.03%	0.21%	0.22

32～34, 35～37	1.2	0.35%	0.06%	0.23%	0.20%	0.06%	0.24%	0.45
38～40, 41～42	1.2	0.16%	0.02%	0.20%	0.16%	0.01%	0.20%	0.01
43～48, 49～52	1.2	-0.03%	0.13%	0.33%	-0.07%	0.05%	0.23%	0.10
53～56, 57～60	1.2	-0.04%	0.04%	0.22%	0.01%	0.03%	0.21%	0.16

As can be seen from the calculation results of E_n in Table 1, the detection results of each group at 31g and 220g stations of the facility at this flow point are consistent, indicating that the detection status of the two stations is reliable.

5.2 Verification result of process B

Then, process B, namely weighing facility + single master meter + single tested meter, was used to verify the reliability of the quantity value of the two stations of NIM micro-flow facility. The verification results are shown in Table 2 and Table 3 respectively:

Table 2: Verification results of process B (31g station)

Serial Number	Nominal Flow Rate (mL/min)	Relative Error of Master Meter	Relative Error of Measured Meter	Change in Error of Two Adjacent Measurements of Master Meter	Change in Error of Two Adjacent Measurements of Measured Meter	Change in Error Difference of Two Meters	Verification Results
23～25	1.2	-0.077%	0.700%	/	/	/	/
29～31	1.2	-0.011%	0.856%	0.07%	0.16%	0.09%	reliable
32～34	1.2	0.352%	1.287%	0.36%	0.43%	0.07%	unreliable
38～40	1.2	0.161%	1.176%	-0.19%	-0.11%	0.08%	unreliable
43～48	1.2	-0.030%	0.958%	-0.19%	-0.22%	-0.03%	unreliable
53～56	1.2	-0.039%	0.885%	-0.01%	-0.07%	-0.06%	reliable
61～65	1.2	-0.101%	0.851%	-0.06%	-0.03%	0.03%	reliable

Table 3: Verification results of process B (220g station)

Serial Number	Nominal Flow Rate (mL/min)	Relative Error of Master Meter	Relative Error of Measured Meter	Change in Error of Two Adjacent Measurements of Master Meter	Change in Error of Two Adjacent Measurements of Measured Meter	Change in Error Difference of Two Meters	Verification Results
26～28	1.2	-0.143%	0.504%	/	/	/	/
35～37	1.2	0.204%	1.175%	0.35%	0.67%	0.32%	reliable
41～42	1.2	0.157%	1.253%	-0.05%	0.08%	0.12%	reliable
49～52	1.2	-0.071%	0.457%	-0.23%	-0.80%	-0.57%	reliable
57～60	1.2	0.009%	0.989%	0.08%	0.53%	0.45%	reliable

According to the calculation results shown in Table 2 and Table 3, it is obtained that groups 32 ~ 34, 38 ~ 40 and 43 ~ 48 of 31g station of the micro-flow facility for experiment do not meet the reliability criteria of weighing method + arbitrary double meter verification scheme, that is, the detection state of 31g station is not reliable; The test data of each group at 220g station all meet this criteria, so it can be considered that the detection state at 220g station is reliable.

By integrating the verification results of process A and process B, the following conclusions can be drawn: the 31g station detection state of the micro-flow standard facility is unreliable, and the 220g station detection state is reliable.

6. Conclusion

In order to improve the measurement performance of the existing domestic flow standard facility, and improve its measuring ability and verification accuracy. In view of the current situation that the verification method of the quantity value of the flow facility is still lacking and the verification work is not paid attention to and cannot be carried out universally, the research on the value verification method of the flow calibration system based on the double master meter mutual verification technology is specially carried out, and a complete set of medium value verification solution for the flow calibration system is proposed, and the corresponding verification experiment is carried out. After the study, the main conclusions are as follows:

1) Based on the theoretical basis of double flow meter mutual check technology, a set of intelligent online value verification method for weighing method flow standard facility is designed and established. The method includes 4 sets of sub-schemes, and the algorithm realization model and discrimination criterion of each sub-scheme are given.

2) According to the test results of the verification experiment, the detection status of 31g station of

the dynamic weighing method in the micro flow facility of the National Institute of Metrology is not reliable, and that of 220g station is reliable; Meanwhile, it is proved that the on-line verification method has good adaptability and high verification accuracy, which is worthy of further popularization and application.

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