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RESEARCH ARTICLE

Design of a Flow Automatic Calibration System Based on the Master Meter and Dynamic Weighing Methods

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ABSTRACT To address the issue of measurement errors in ultrasonic water meters caused by various interfering factors during the flow calibration process, this study proposes a highly automated and intelligent ultrasonic water meter flow calibration system design. Firstly, by analyzing and studying the working principle of the water flow calibration device, and considering the actual flow calibration range, the calibration method that combines the master meter method and the dynamic weighing method is determined. To enhance the automation level of the flow calibration system, the flow calibration control algorithm is thoroughly analyzed and designed. Finally, a flow correction algorithm based on linear interpolation was designed and utilized for water meter flow calibration. Test data show that after the flow correction, the value error of the ultrasonic water meter in the "high area" is not more than 2%, in the "low area" it is not more than 3%, and the repeatability is less than 0.05%. Compared with manual calibration, the flow calibration system designed in this paper enables high-precision automated flow calibration of ultrasonic water meters, significantly enhancing detection efficiency and accuracy.

INDEX TERMS Automatic control, dynamic weighing method, flow calibration, master meter method.

I. INTRODUCTION

Compared to traditional mechanical water meters and mechanical water meters with electronic devices [1], the emerging intelligent ultrasonic water meters are characterized by the absence of mechanical moving parts. The aforementioned devices exhibit exceptional metering performance, remarkable expandability, minimal pressure loss, a broad range of flow measurement capabilities, and a long service life. The gradual replacement of traditional mechanical water meters with intelligent ultrasonic water meters has been observed [2]. The implementation of the intelligent ultrasonic water meter will have a significant impact on the precise management of water supply, identification of leaks, and localization of pipeline networks. The development of intelligent water meters also encounters a significant challenge. In order to ensure the accuracy of water meter measurements, a rigorous flow calibration process must be conducted on the water meter prior to its distribution for sale and use. Prolonged exposure to water, especially hard water, can lead to fouling near the water meter sensor. Furthermore, chemical elements and various ions in the water can cause corrosion to the sensors in the water meter, resulting in a decrease in the accuracy of the water meter, which may exceed the specified range. Therefore, it is essential to conduct regular checks and recalibrations [3]. The water meter is a device used to quantify the volumetric flow rate of liquid passing through a pipe by applying a specific pressure over a defined cross-sectional area within a given time period. Therefore, it is necessary to develop a test device that can simulate the flow of liquid in a dynamic state indirectly. The flow calibration facility(FCF) is a real flow simulation facility designed to assess the measurement accuracy of the meter being tested. Its primary objective is to ensure that the meter accurately reproduces and transmits flow values within its specified flow range. Calibration methods are categorized into three primary

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types [4]: the volumetric method [5], the dynamic weighing method [6], and the master meter method [7]. The application of the volumetric method of FCF has a more stable flow rate and higher reliability. But the detection cycle is long and energy consumption is notably high. Especially, these drawbacks become more apparent when utilized for testing water meters with larger diameters. The dynamic weighing method has gained widespread usage in flow calibration studies due to its high reliability when the density of liquids changes with ambient temperature. The master meter method is a method to assess the precision of water meter by using turbine flowmeter [8], electromagnetic flowmeter [9], ultrasonic flowmeter [10] and other flowmeters as a standard measuring instrument and the inspected water meter in the same time interval in a continuous comparison, which can greatly improve the calibration efficiency. The volumetric method was frequently utilized by early metrology organizations for the purpose of flow calibration. In current flow calibration research, the dynamic weighing method has become widely utilized due to its enhanced reliability. With the advancement of measurement technology and industrial automation, the utilization of flowmeters in flow calibration devices has become increasingly prevalent. This is primarily due to their compact size, enhanced accuracy, and improved operational efficiency.

In recent decades, a lot of works have been done to certify water meter flow. Reference [11] measures cold drinking water with good repeatability through a combination of instruments. The test equipment at the RISE National Volumetric Laboratory in Sweden [12], [13] is one of the best in the world for hot and cold water, and it meets the requirements for dynamic testing of domestic water meter flows. The Germany PTB Laboratory Institute of Physics and Technology [14], [15], [16] has designed a water flow facility with a flow range of 0.1-2100 m^3/h. The calibration caliber ranges from DN80 to DN400, and the extended uncertainty of measurement is better than 0.02%. Most of factors that affect the uncertainty of the facility, such as the commutator and the impact of water flow in the weighing vessel and temperature, have been addressed with corresponding measures. However, the system complexity of the facility remains high and expensive. The NMIJ Institute in Japan has constructed a high Reynolds number water flow meter calibration facility [17], [18]. This facility has a maximum flow rate of 1200 m^3/h and utilizes the weighing method with high reliability and an extended uncertainty of 0.077%. Reference [7] calibrated a water flow meter using the master meter method, achieving a measurement uncertainty of as low as 0.20%. Reference [19] performed field test of a thermal energy meter using an ultrasonic clamp-on flow meter. The results showed significant uncertainties in the measurement of flow, with values ranging from 1.3% to 1.9% at flow velocities of 1.0 m/s and 0.3 m/s, respectively. Reference [20] reduced the absolute error of flow measurement to less than 2.5% by employing a combination of a Koch flowmeter and an online flow conditioner for gas-liquid two-phase flow metering. Additionally, they utilized a neural network algorithm to further enhance the accuracy of the measurements.

Currently, the majority of papers are calibrated using the same method, and after comparison, it has been observed that the calibration system with high accuracy is both complex and expensive, whereas the simpler equipment tends to have higher errors and uncertainties. The calibration facility described in this paper is designed to measure a wide flow range of 0.2-630 m^3/h. Due to the large flow range, it is challenging to achieve rapid and stable calibration using a single method. Therefore, this paper proposes a comprehensive design of a flow calibration facility that combines the standard meter method and the dynamic weighing method. The combination of these two methods allows the facility to achieve optimal performance. A flow correction algorithm, utilizing linear interpolation [21], was developed and implemented to calibrate the error of the water meter subsequent to the flow test. Finally, through the analysis of the calibration data and uncertainty [22], it is demonstrated that the flow calibration system(FCS) designed in this article exhibits excellent stability and accuracy. Moreover, this analysis also serves to validate the rationality of the calibration algorithm designed in this study. This feature enables the facility to achieve a high level of accuracy while maintaining a lower level of complexity.

The subsequent sections of this article are presented in an organized manner below. Section II describes the work associated with the design of the FCF. Section III provides an analysis of the functions and algorithms employed by automated control systems. The test will be elucidated in Section IV. Finally, Section V provides a comprehensive summary of the paper and presents potential directions for future research.

II. FLOW CALIBRATION FACILITY AND AUTOMATION DESIGN

A. FLOW CALIBRATION FACILITY DESIGN IDEAS

The objective of the flow detection facility designed in this study is to detect ultrasonic water meters with sizes ranging from DN 100 to 300, corresponding to a typical flow rate of 100-1000 m^3/h. DN is an abbreviation for Nominal Diameter, and its unit is in millimeters (mm). Each meter caliber comprises six range ratios(dimensionless). They are 100, 160, 250, 400, 500 and 800. Taking the range ratio of 500 as an illustrative example, the test flow points are shown in TABLE 1.

The maximum flow rate of this facility is limited to 630 m^3/h, therefore, the flow test of 1000 m^3/h only assesses the flow point of 630 m^3/h. In summary, this article designs the calibration facility to measure the flow range of 0.2-630 m^3/h. Due to the large range of flow, a single flow calibration facility is insufficient to achieve optimal performance. It is necessary to design a distinct flow calibration facility for the large and small caliber water meters.

TABLE 1. Test flow rate with range ratio of 500.

DN(mm)	Typical flow(m^3/h)	transition flow(m^3/h)	minimum flow(m^3/h)
100	100	0.32	0.2
125	160	0.5	0.31
150	250	0.8	0.5
200	400	1.26	0.78
250	630	2	1.25
300	1000	3.2	1.87

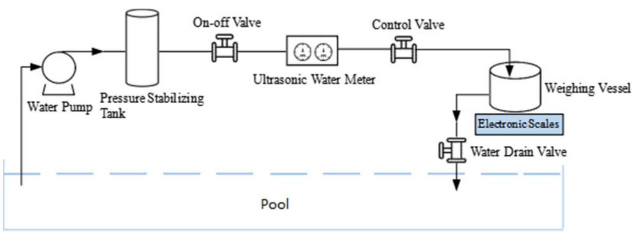


FIGURE 1. Structure of flow calibration facility based on dynamic weighing method.

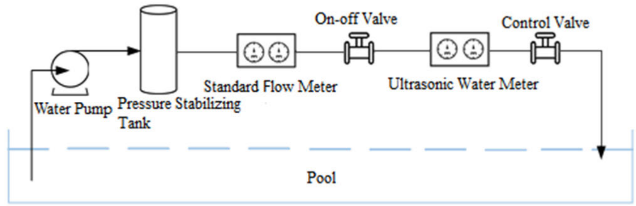


FIGURE 2. Structure of flow calibration facility based on master meter method.

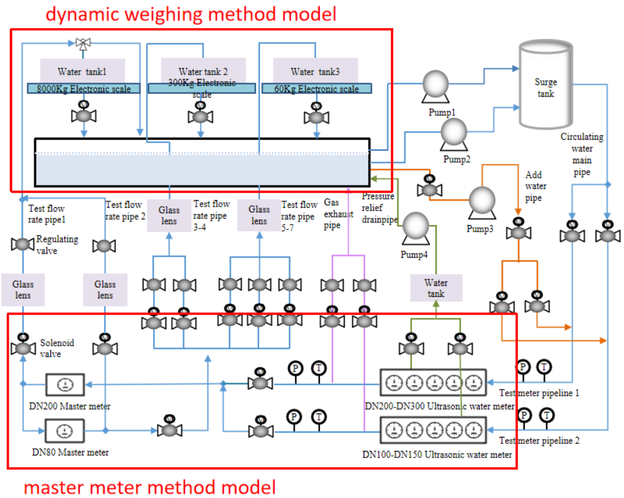


FIGURE 3. Structure diagram of flow verification facility.

According to the principle of transitivity, the master meter method has high calibration efficiency, simple structure, small volume and wide flow range of the detection test facility. It has positive significance for the calibration of large-caliber water meters. The weighing method has high accuracy and good repeatability. At the same time, the weighing method can also be used to calibrate the flow rate of the standard meter used in the facility. In this way, the accuracy of the facility can be guaranteed. Therefore, this paper combines the two methods to design the FCF to achieve the best performance.

B. STRUCTURAL DESIGN OF FCF

The dynamic weighing method relies on measuring the mass of water that enters a standardized weighing vessel within a specified time period. The volume of water flow is then determined through temperature compensation calculations. Subsequently, under conditions of equal time, the measurement error of the inspected meter is determined by comparing it with the cumulative flow rate of the meter being inspected. The primary instruments used in the dynamic weighing method include a water pump, pressure stabilizing tank, on-off valve, ultrasonic water meter, control valve, weighing vessel, electronic scale, and pool. The schematic representation of the flow calibration facility, which utilizes the dynamic mass method, is depicted in Fig. 1.

When using the standard meter method for water meter calibration, the pivotal component of the calibration facility is the standard flow meter, and its selection holds utmost significance. The precision of the standard flow meter is linked to the precision of the meter being evaluated. Therefore, it is crucial to select a standard flow meter that exhibits superior performance. The cost of electromagnetic flow meters may be higher. however, their exceptional accuracy, reliable repeatability, absence of moving components, negligible pressure loss, wide range ratio, and extended lifespan make them the preferred choice as standard meters. The electromagnetic flow meters chosen for this study have a caliber of DN80 and DN200, and they are capable of measuring a flow range of 4-630 m^3/h.

The FCF based on the standard meter method incorporates the principle of flow continuity [23], with the standard flow meter as the main standard. Firstly, the standard flow meter and the tested meter are concurrently connected in series within the flow calibration facility. Then proceed with the direct comparison of the value [24], which will get the measurement error of the meter under inspection. The primary instruments used in the dynamic weighing method include a water pump, pressure stabilizing tank, standard flow meter, on-off valve, ultrasonic water meter, control valve, and pool. The schematic representation of the flow calibration facility based on the master meter method is shown in Fig. 2.

Therefore, this article presents a novel approach that combines the dynamic mass method with the standard meter method and incorporates remodeling of the original facility, after the modification of the structure of the standard calibration facility structure shown in Fig. 3.

The modified calibration facility mainly includes: pools, pumps, pressure stabilizing tanks, flow control valves, solenoid valves, pneumatic ball valves, electronic scales, standard flow meters, the water meters to be tested, clamping cylinders, temperature sensors, pressure transmitters and other related parts. They are controlled entirely through an automated flow detection operating system.

From Fig. 3, it is evident that the FCF designed in this study is primarily comprised of several components, including the main water flow pipeline, water adding pipeline, pressure relief drainage pipe, gas exhaust pipeline, test meter pipeline, and test flow rate pipeline. The primary water flow pipeline is connected to the surge tank, which in turn connects to two pumps. The activation of specific pumps is determined by the magnitude of the detected flow rate, ensuring an appropriate power supply. The pipeline of the inspected meter aligns with the main water pipeline in a sequential manner. The meter being inspected utilizes a pipeline configuration consisting of two horizontally parallel rows, allowing for compatibility with inspection meters of various calibers. The upper pipeline is a fixed DN200 pipeline that has the potential to be replaced with a DN250 or DN300 water meter. The lower pipeline is a fixed DN150 pipeline that has the potential to be substituted with a DN100 or DN125 water meter. Then, the parallel master meter group is used to converge the parallel inspection water meter group. It can reduce the floor space requirements and usage costs, while simultaneously enhancing the flow stability within the facility. Finally, the flow rate point is regulated to the desired level by manipulating the solenoid valve and regulating valve in the flow point pipelines. This allows for the recycling of water back into either the pool or electronic scale.

The pipelines of the flow rate point are interconnected in a parallel configuration to facilitate the detection of various flow points. When the flow range is 4-630 m^3/h, it is detected through the utilization of the standard meter method. If the flow rate falls within the range of 100.1 m^3/h to 630 m^3/h, a DN200 caliber standard flow meter is utilized. If the flow rate falls within the range of 4-100 m^3/h, a DN80 caliber standard flow meter is utilized. The flow meter with a caliber of DN200 corresponds to flow point pipe 1, while the flow meter with a caliber of DN80 corresponds to flow point pipe 2. When the measured flow range falls within the range of 0.2-3.99 m^3/h, it is detected using the dynamic mass method. This corresponds to the flow point pipeline 3-4 and the right flow point pipeline 5-7, which are specifically designed for testing small flow ranges.

After completing the flow calibration procedure, the water within the pipeline is discharged via the pressure relief drainage pipeline. The traditional facility discharges the tested liquid by installing a drain valve at the end of the pipeline and relying on the internal pressure. In this study, the drainage efficiency is improved by increasing the exhaust pipe and the pressure relief drainage pipeline. These modifications result in a reduction of both exhaust and drainage time, and greatly increasing the flow verification efficiency.

C. AUTOMATIC CONTROL SCHEME

The FCS is mainly composed of PLC, a flow detection bench, and control system. The flow calibration automatic control scheme is depicted in Fig. 4.

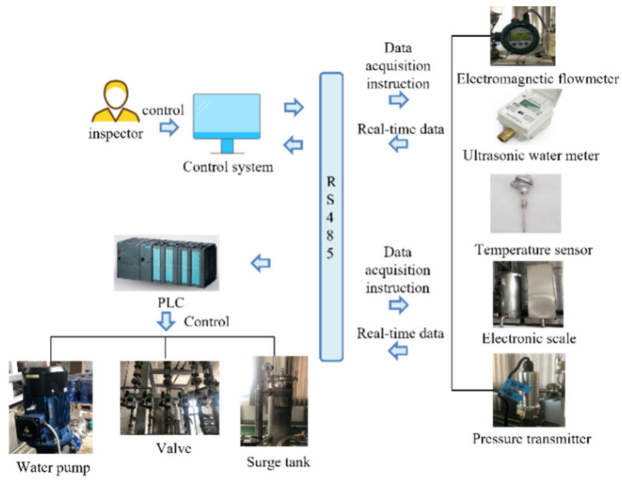


FIGURE 4. Automated control diagram.

As the host, the control system establishes communication with a diverse range of devices, including ultrasonic water meters, standard flow meters, electronic scales, temperature sensors, pressure transmitters, and other devices. The communication process can be outlined as follows:

(1) The ultrasonic water meter uses a magnetic infrared reading head to convert the infrared signal into an RS485 signal, enabling the regular retrieval of parameter information from the ultrasonic water meter and its subsequent transmission to the control system. After the packet is parsed on the server side, the data is subsequently processed within the control system.

(2) In the process of flow calibration, the control system collects the real-time pulse signal from the standard flow meter via the RS485 serial port. And calculates the standard flow rate according to the collected pulse, test time and standard flow meter error.

(3) The temperature sensor has a measurement range of 0-100 °C and outputs a current signal of 4 to 20 mA. The pressure transmitter has a measurement range spanning from 0 MPa to 4 MPa, while concurrently generating a current signal ranging from 4 mA to 20 mA. Hence, the utilization of the Modbus protocol enables the temperature sensor and pressure sensor to transmit the recorded temperature and pressure values to the control system via the RS485 serial port.

(4) During the testing process of the dynamic weighing method, the electronic scale continuously outputs real-time serial port data through RS485 in the form of a 4-20 mA analog current signal. This allows the control system to automatically acquire the start and end data, convert them, and record the weighing value. Simultaneously, real-time detection of the ambient temperature is conducted, the liquid density is calculated, and the weighing value of the electronic scale is corrected to obtain precise measurements of the liquid quality in the weighing container.

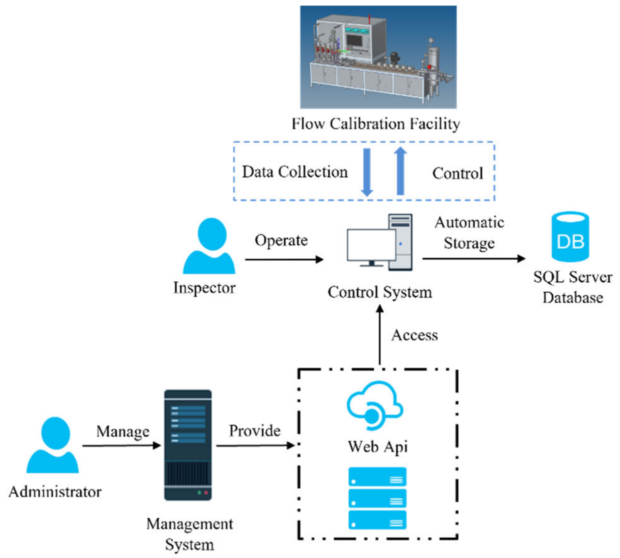


FIGURE 5. Overall framework of FCS.

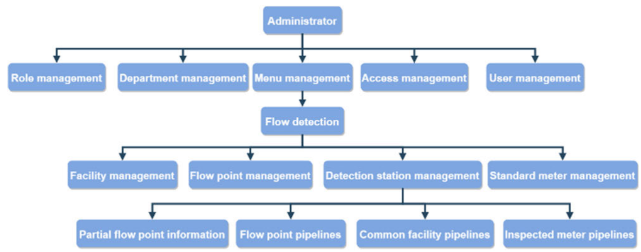


FIGURE 6. Use case diagram of flow calibration management system.

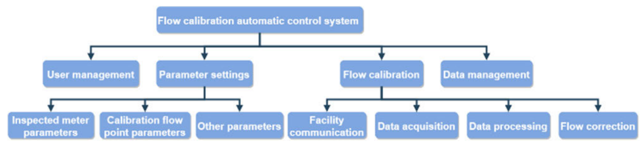


FIGURE 7. Flow calibration control system block diagram.

(5) The control system establishes communication with the PLC via the RS485 serial port. Through this connection, the control system is able to issue commands to control various actuators, including clamping cylinders, valves, pumps, pressure stabilizer tanks and other equipment. The calibration facility utilizes an on/off valve comprising a pneumatic ball valve and a solenoid valve. The solenoid valve is operated by a 24 V voltage signal and provides feedback through a 0 or 24 V voltage signal to indicate its operational status.

III. DESIGN OF FCS AND ALGORITHM

A. OVERALL SYSTEM ARCHITECTURE ANALYSIS AND DESIGN

This article divides the FCS into two modules based on its main functions: web management and flow calibration control. It combines these two modules for design and development. The overall framework is shown in Fig. 5.

According to Fig. 5, the FCS is specifically described as follows:

(1) The web management system is based on the B/S structure and is primarily responsible for the unified management of flow calibration facility, pipelines, equipment, testing flow points, standard meter errors, and other information. Administrators can operate by logging into the web page.

(2) The control system is primarily responsible for achieving flow calibration in real flow simulation work. It communicates with detection devices, standard flow meters, pumps, electronic scales, control valves, pressure transmitters, temperature sensors, and other equipment to complete the flow calibration process. This ensures that the error in the water meter display value meets the requirements of national calibration regulations.

The control system is connected to the web management system through the application programming interface (API) provided by the server side. Based on the caliber, common flow rate, and range ratio of the current ultrasonic water meter and the existing testing platform, the management system automatically connects the information of the testing bench pipeline, equipment, flow points, and other details to the control system through an API. This eliminates the need for operators to configure numerous testing tables, pipelines, and flow point information, simplifying the flow detection operation steps and enhancing flow detection efficiency.

1) ANALYSIS OF MANAGEMENT SYSTEM FUNCTIONAL MODULES

The flow calibration management system is a platform for managing information related to users, detection stations, facilities, flow points, pipelines, and standard meter errors in FCF. The use case diagram is shown in Fig. 6.

The flow calibration management menu includes submenus such as detection station management, facility management, flow point management, and standard meter management. The detection platform consists of electromagnetic flow meters, water pumps, electronic scales, temperature sensors, pressure transmitters, and other equipment and pipelines. According to the design of the FCS structure in Fig 3, the pipelines in the detection platform are divided into the tested meter pipeline, flow point pipeline, and common equipment pipeline. This division facilitates the control and data processing of the automation control system. And bind some of the flow points in the submenu to the detection platform, simplifying the process of configuring the range and specific information of flow points for a particular detection platform.

2) ANALYSIS OF CONTROL SYSTEM FUNCTIONAL MODULES

The flow calibration control system is primarily a fully automated system controlled by the computer during FCF operation. The block diagram of the system is shown in Fig. 7.

As the central component of automatic flow calibration, the system seamlessly integrates data acquisition, data processing and analysis, and data management modules to enable intelligent equipment management, automatic control of the calibration process, and data science statistics. This integration eliminates the need for extensive manual involvement and mitigates the risk of low efficiency and low reliability in the calibration process. It mainly includes the following modules:

(1) User management: The system includes a permission management module that assigns different levels of permissions to different user roles. Only administrators and personnel with flow calibration permissions are allowed to log in to the flow calibration control system.

(2) Parameter settings: When the flow calibration main interface is first loaded, it will automatically select and initialize the current detection platform, electronic scale, standard flow meter, and other parameters. Automatically retrieve the calibration flow point parameters from the server, based on the caliber and commonly used flow rate of the currently tested ultrasonic water meter. The parameters of the ultrasonic water meter can also be set through the optical port. This includes settings such as baud rate, stop bit, check bit, water meter protocol, acquisition frequency, unit, whether there is a pressure module, display of empty tube alarm, allowance of pulse output, pulse equivalent, pulse time, and other parameters.

(3) Facility communication: data communication between the facility and the control system is established through the serial port. Therefore, it is essential to initialize the serial port configuration in the flow verification control system. This involves setting the serial port parameters, such as baud rate, check digit, data bit, stop bit, etc., in order to facilitate communication with ultrasonic water meters, standard flow meters, electronic scales, pumps, valves and other facilities.

(4) Data acquisition: The control system automatically collects data from ultrasonic water meters, temperature sensors, pressure sensors, scales, standard flow meters and other devices using different communication protocols. After the flow calibration process begins, the control system continuously collects real-time data from the equipment mentioned above through the data communication serial port. This data includes the current liquid temperature, pipeline pressure, instantaneous flow rate, cumulative volume flow rate, electronic scale reading and other relevant information. The FCS interface displays the standard flow parameters and standard weight parameters of the standard measuring facility. It can also achieve automatic control of the inverter, pump, valve and other equipment based on the operator's commands. This allows for flow switching and flow regulation during the flow calibration process.

(5) Data processing: The automatic processing of data acquisition is adopted. After the program completes the data acquisition process, the system calculates and outputs the measurement error of the inspected meter. This calculation is based on the current ambient temperature, density, as well as the data from the standard measuring facility and the inspected meter. The collected flow data, flow quality and calibration time data are processed and analyzed to calculate the standard value, error value, and other relevant data.

(6) Flow correction: After calibrating all test flow points, the flow correction process can be initiated. The new flow coefficient can then be calculated based on the magnitude of the error and stored in the memory chip of the water meter being tested. After completing the flow correction, the process of verifying the test flow point can be restarted to collect and process the errors of the meter under test. This allows for the calculation and evaluation of the error in its indication value.

(7) Data management: Record all data for each calibration of the tested ultrasonic water meters, including real-time data for each facility in the flow verification process, current environmental parameters, information about the current standard used by the system and the results of each flow calibration. This will ensure data preservation and enable data management and other related functions.

B. OVERALL SYSTEM ARCHITECTURE ANALYSIS AND DESIGN

1) AUTOMATIC CONTROL ALGORITHM DESIGN

The principle of the dynamic weighing method is as follows:

The system reads and records the initial value V_0 of the inspected meter and the initial value M_0 of the electronic scale. During the water meter calibration process, the cumulative flow rate of the water meter is recorded in real time. When the water volume reaches the preset value V_1 for current calibration, the system automatically closes the corresponding on-off valves. At this time, the volume V_i of the inspected meter is obtained, as shown in (1):

$$V_i = V_1 - V_0 \tag{1}$$

In (1), V_0 is the initial value of the inspected table; V_1 is the preset water volume; V_i represents the volume of water measured by the water meter, they are all in units of m^3.

After the water flow becomes stationary and stable, the actual mass M of the water in the standard weighing container is read, and the temperature of the current testing environment is obtained using the temperature acquisition module. The standard volume V_s is obtained using the formula for density and temperature.

The standard volume formula is:

$$V_s = \frac{M - M_0}{\rho}(1 + \varepsilon) \tag{2}$$

In (2), V_s is the standard volume, the unit is m^3; M_0 is the initial weight of the electronic scale before the start of the calibration, the unit is kg; M is the end weight of the electronic scale after the end of the calibration, the unit is kg; ε is the air buoyancy correction factor(dimensionless).

The expression for the air buoyancy correction factor ε is:

$$\varepsilon = \rho_A \left(\frac{1}{\rho_W} - \frac{1}{\rho_P}\right) \tag{3}$$

In (3), ρ_A is the air density; ρ_W is the density of the liquid in the weighing container; ρ_P is the density of the weight material. They are all in units of $\mathrm{kg/m^3}$.

The liquid density uses the density-temperature equation given by International Association for the Properties of Water and Steam [25]:

$$\rho_W = c_0\left(\frac{1 + c_1 t_n + c_2 t_n^2 + c_3 t_n^3}{1 + c_4 t_n + c_5 t_n^2}\right) \tag{4}$$

In (4), t_n is the standardized water temperature, $t_n = \frac{t}{100}$, where t is water temperature, the unit is °C; ρ_W is the the density of pure water at temperature t, the unit is $\mathrm{kg/m^3}$. The values of the constant terms in the formula are: $c_0 = 999.84382$, $c_1 = 1.4639386$, $c_2 = -0.015505$, $c_3 = -0.0309777$, $c_4 = 1.4572099$, $c_5 = 0.0648931$, they are all in units of $\mathrm{kg/m^3}$.

Finally, the error of the inspected meter can be calculated:

$$\mathrm{E} = \frac{V_i - V_s}{V_s} \times 100\% \tag{5}$$

The dynamic weighing method has high verification accuracy, excellent repeatability, and a wide range for flow calibration. Today's electronic scales generally offer higher accuracy and are particularly precise when measuring smaller quantities of liquid. Therefore, the dynamic weighing method is preferred when dealing with low flow rates.

The principle of the master meter method is as follows: Turn on the pump and adjust the flow rate to the specified value. After stabilizing the flow rate, count the signal pulses from the standard meter. Measure the number of pulses from the standard flow meter within a specific time interval to determine the cumulative flow rate of the standard meter:

$$V_c = N_s \times K_s \tag{6}$$

In (6), V_c is the cumulative flow rate of the standard meter, the unit is $\mathrm{m^3}$; N_s is the cumulative output pulse of the standard meter in a certain time interval, It represents the volume of water here; K_s is the pulse coefficient of the standard meter(dimensionless).

In order to ensure that the standard meter is measured at the same time interval as the inspected meter, the standard cumulative flow rate is calculated as:

$$V_s = \frac{V_c}{S_c} \times S_i \tag{7}$$

In (7), V_s is the standard cumulative flow rate; S_c is the standard meter detection time; S_i is the test time of the inspected meter, the unit is h.

The measurement error formula of the inspected meter is the same as (5).

The principle of the standard meter method allows for real-time comparison between the ultrasonic water meter being inspected and the standard flow value. This method is particularly advantageous when verifying large-diameter water meters, as its benefits become more pronounced. In the process of flow calibration, the standard table method is chosen for large flow due to its simple structure, efficient measurement, wide range ratio and compact size.

FIGURE 8. Flow chart of overall control algorithm.

The control algorithm flow of the system is shown in Fig. 8.

The process of flow calibration point testing is comprised of two methods: the master meter method flow point testing and the dynamic weighing method flow point testing. Due to the broad measurement range and significant flow disparity exhibited by ultrasonic water meters of a specific caliber, it is necessary to employ various calibration methods for different flow points. Therefore, when calibrating a specific flow point, it is essential to replace the flow rate point. Firstly, it is imperative to ascertain the water pump that corresponds to the specific flow point under examination. When the flow rate point reaches a value of 4 or higher, it is recommended to utilize a large water pump and employ the standard meter method for calibration. When the flow point is below 4, it is recommended to utilize a small water pump, deactivate any other water pumps, and proceed to open both the front and rear valves of the meter pipeline being tested. The dynamic weighing method should be employed for calibration purposes. When the flow meter is used for an extended period, the system will autonomously assess the need for testing the flow meter. If the test results indicate satisfactory performance, the flow meter can continue to be used. However, if the test results are unsatisfactory, the system will prompt the replacement of the water meter.

TABLE 2. Standard corrected flow point table.

caliber	point 1	point 2	point 3	…	point 13	point 14	point 15
DN100	0.12	0.16	0.24	…	35.00	60.00	100.00
DN125	0.20	0.30	0.40	…	60.00	100.00	200.00
DN150	0.30	0.40	0.60	…	95.00	150.00	300.00
DN200	0.50	0.70	1.00	…	120.00	250.00	800.00
DN250	0.80	1.10	1.60	…	200.00	400.00	1200.00
DN300	1.20	1.60	2.40	…	350.00	600.00	1400.00

2) FLOW CORRECTION ALGORITHM DESIGN

After the completion of the real flow simulation, the reading displayed by the meter being inspected will exhibit a certain degree of deviation from the true value. Given the significance of precise water meter measurements, it is imperative to conduct flow correction calibration. Flow correction is categorized into two types: forward flow correction and reverse flow correction. This division ensures that the error results of the inspected meter align with the accuracy level specified in the metrological calibration regulations JJG162-2009 [26].

In order to optimize the calibration process, the test flow point will be limited to a specific range rather than covering the entire flow range. According to the varying range ratios of the instrument, the selection of test flow points differs. For instance, when the range ratio is below 100, there are 4 test flow points. Similarly, when the range ratio is below 400, there are 5 test flow points, and when the range ratio is below 800, there are 6 test flow points. Therefore, it is imperative to perform calibration on the instrument at a specific reference point. In this study, a linear interpolation technique is employed to calculate correction parameters by considering the instrumentation error between two consecutive typical flow points. If the quantity of test flow points does not adhere to the aforementioned condition, an alert will be issued indicating that the number of flow points is not in compliance, resulting in a failure in flow correction.

The test flow points are categorized into various flow ranges according to the instrument's different calibers. Therefore, it is necessary to address all the flow points that require correction for the ultrasonic water meter of DN100-DN300 are divided into 15 standard flow points. As shown in TABLE 2, the units for each correction point are m^3/h.

First of all, it is imperative to retrieve the measurement points and associated errors of the water meter under examination from the database. As shown in TABLE 3, the aforementioned data represents the discrepancy in display values for a DN100 ultrasonic water meter at various test flow points.

TABLE 3. Indication error of DN100 ultrasonic water meter under different test flow points.

Flow rate point(m^3/h)	Real flow rate(m^3/h)	Water meter display value(m^3/h)	Water meter display value error(%)
100	100.08	99.801	-0.279
7	7.2	7.1909	-0.126
1.6	1.61	1.6056	-0.274
0.64	0.64	0.6333	-1.052
0.4	0.42	0.4197	-0.77
0.24	0.25	0.2483	-0.68

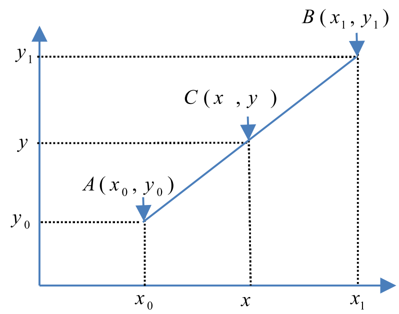


FIGURE 9. Schematic diagram of linear interpolation method.

As can be seen from TABLE 3, the flow calibration test point reveals that the actual flow rate does not fully meet the required measurement flow rate. Therefore, it is imperative to calculate the display values error of the 15 standard points based on the actual measurement points.

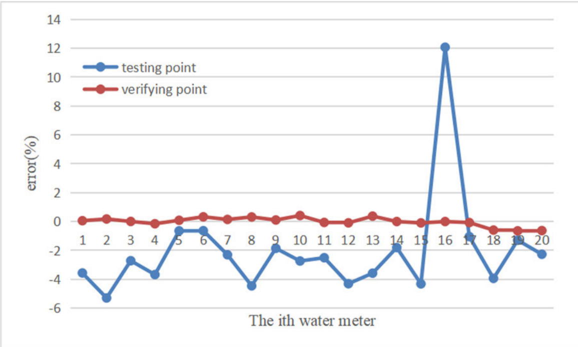
In order to rectify the display value error of 15 flow points in the water meter, this study employs the linear interpolation method to perform linear correction on the window type. The correction parameters are obtained through the calibration of several representative flow points. The schematic diagram illustrating the principle of linear interpolation is depicted in Fig. 9. The calculation of the slope involves determining the horizontal and vertical coordinates of points A and B, which subsequently allows for the determination of the value of point C.

The error correction equation is shown in (8):

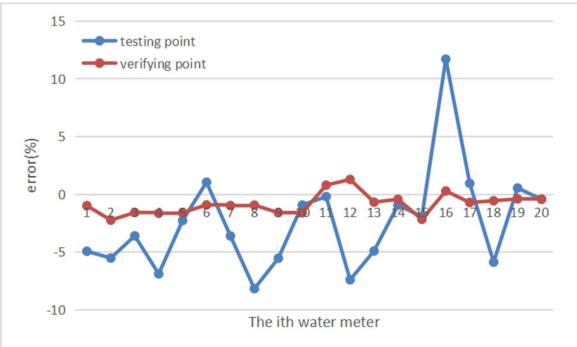
$$\mathrm{error_s}[i] = \frac{\mathrm{error_t}[j+1] - \mathrm{error_t}[j]}{\mathrm{flow_t}[j+1] - \mathrm{flow}[j]} \times (\mathrm{flow_s}[i] - \mathrm{flow_t}[j]) + \mathrm{error_t}[j] \quad (8)$$

As shown in (8), $\mathrm{error_s}$ represents the Standard flow rate error; $\mathrm{error_t}$ represents the flow rate error of the water meter being tested; $\mathrm{flow_t}$ represents the test flow rate of the water meter being tested; $\mathrm{flow_s}$ represents standard flow rate.

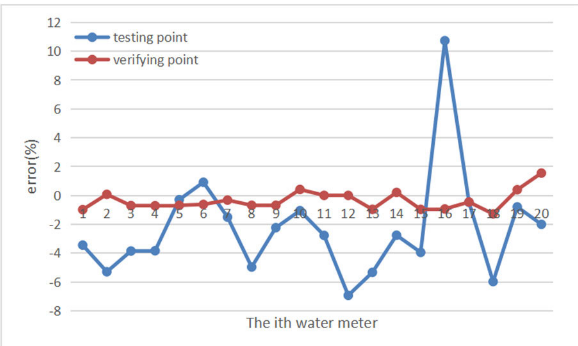
According to the aforementioned algorithm, the errors of 15 standard rates are computed, and the correction parameters that can be detected by the water meter are determined. Finally, the calibration process is concluded by transmitting the correction parameters to the ultrasonic water meter via the serial port. This allows for the simultaneous calibration of multiple water meters.



(a) Testing and verifying flow error of 160 m^3/h.



(b) Testing and verifying flow error of 0.51 m^3/h.



(c) Testing and verifying flow error of 0.32 m^3/h.

FIGURE 10. Testing and verifying flow error of DN100 water meter at different flow points.

IV. TEST RESULTS AND ANALYSIS

A. ERROR ANALYSIS

In this study, a total of 20 ultrasonic water meters with a caliber of DN125 and a flow rate ratio of 500 were chosen to examine the discrepancy in indication error between the test rate and the verified rate following flow correction at various flow rates. Under the condition of a flow rate of 160 m^3/h, the error between the test rate and the verification rate of these 20 water meters is shown in Fig. 10(a). The flow rate condition of 0.51 m^3/h is shown in Fig. 10(b). And under the conditions of 0.32 m^3/h, is shown in Fig. 10(c).

Fig. 10 clearly illustrates that the measured value without flow correction exhibits a significant error, with the sixteenth water meter showing an error of approximately 10%. After undergoing the flow correction treatment, the ultrasonic water meter undergoes a subsequent inspection to validate the accuracy of the flow rate. The experimental findings indicate that the indication error of the inspected water meter at the "high area" flow point falls within the acceptable range of ±2%. In the "low zone" flow point, the water meter being inspected should have an indication error that does not exceed ±3%.

TABLE 4. Repeatability of master meter method flow calibration.

Times	Error (%)	Times	Error (%)
1	1.61	11	1.58
2	1.70	12	1.56
3	1.65	13	1.57
4	1.66	14	1.62
5	1.65	15	1.54
6	1.55	16	1.63
7	1.62	17	1.67
8	1.58	18	1.65
9	1.66	19	1.56
10	1.69	20	1.69

TABLE 5. Repeatability of dynamic weighing method flow calibration.

Times	Error (%)	Times	Error (%)
1	1.15	11	1.19
2	1.22	12	1.20
3	1.18	13	1.14
4	1.21	14	1.22
5	1.15	15	1.17
6	1.19	16	1.20
7	1.25	17	1.12
8	1.23	18	1.14
9	1.17	19	1.16
10	1.26	20	1.18

B. REPEATABILITY TESTING

In the analysis of errors in water meter measurements, the accuracy of the indication error is influenced by various factors, including fluctuations in the water level of the standard, variations in temperature and pressure, among others. These factors can result in deviations from the expected indication value. The aforementioned factors contribute to the uncertainty associated with the error of the water meter. Among the various uncertainties, the most significant influencing factor is repetition [27], [28].

Repeatability pertains to the capacity to provide an approximate value for the measurement standard when measuring the same quantity under identical measurement conditions. Repeatability suggests that the variability of the random effect surpasses the obtained measurement outcomes. The repeatability should be rigorously examined in order to ensure its reliability. The calculation of repetitiveness is determined by the (9):

$$s = \sqrt{\frac{\sum_{k=1}^{n} (q_k - \bar{q})^2}{n-1}} \tag{9}$$

As shown in (9), n is the number of repeated observations, $\bar{q}$ is the arithmetic mean value of n observations, q_k is the kth observation result.

1) REPEATABILITY OF MASTER METER METHOD FLOW CALIBRATION

To evaluate the accuracy of the water flow standard facility, this paper conducted 20 repetitive measurements on DN100 ultrasonic water meters using the master meter method, with the results presented in TABLE 4.

In the present study, the repeatability of the weighing method employed by the facility was determined to be S = 0.049%, which meets the requirements.

2) REPEATABILITY OF MASTER METER METHOD FLOW CALIBRATION

Twenty repetitive measurements of a DN100 ultrasonic water meter were taken using the weighing method to verify the accuracy of the water flow standard facility. TABLE 5 presents the recorded measurements.

In this experiment, the repeatability of the weighing method employed by the facility is determined to be S = 0.038%, which satisfies the specified criteria.

V. CONCLUSION

The system designed in this article solves the problem that different calibration facilities cannot be well reused in the same system and the calibration steps are cumbersome. This paper presents the design of the system's overall architecture and proposes enhancements to the original flow calibration device, aiming to achieve full automation of the entire system. Finally, the experimental data presented in this paper provides evidence that the FCF ultrasonic water meter, developed herein, exhibits a high level of measurement accuracy following flow correction. The overall error can be maintained at a level of 3%, and the repeatability is less than 0.05%. These values are sufficient to fulfill the requirements of flow meter verification and experimental research. The computer control system possesses several notable characteristics, including a high level of reliability, a high degree of automation, and simple operation. These features contribute to significantly enhancing the efficiency of flow calibration. The calibration process is fully automated, eliminating the need for human intervention. As a result, the calibration time is significantly reduced. The implementation of this system significantly decreases the duration of manual inspection from several hours to approximately 15 minutes. The flow correction coefficient is automatically calculated and relevant information is also generated automatically, thereby minimizing the occurrence of human errors. The system exhibits several advantageous features, including high efficiency, low cost, energy conservation, safety and reliability, convenient operation, and easy maintenance. The development of this technology addresses the requirements of water meter manufacturers who seek batch automatic calibration for their products, thereby significantly enhancing labor productivity.

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