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Design of testbed system based on infinite cycle algorithm for liquid flowmeter calibration

Sıvı akışölçer kalibrasyonu için sonsuz çevrim algoritmasına dayalı test sistemi tasarımı

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Abstract

In this study, a small-volume, low-cost and high-accuracy microcontroller-based testbed system based on infinite cycle algorithm is designed for the desired time calibration of liquid flowmeters. The fundamental principle of this system is based on weighing the amount of liquid without interrupting the liquid flow. The hardware of the system consists of mechanical and electronic modules including microcontroller, TFT display, load cell, thermocouple, tank, pump, etc. An algorithm for the designed infinite cycle calibration system is developed and microcontroller software is coded in C++. The weight data of the liquid obtained with the load cells are processed in the microcontroller depending on time. As a result, the designed microcontroller-based system contributes to users and researchers by enabling the automatic testing and analysis of liquid flowmeters.

Keywords: Testbed system, microcontroller, infinite cycle algorithm, calibration

Öz

Bu çalışmada, sıvı akışölçerlerin istenen sürede kalibrasyonu için sonsuz çevrim algoritmasına dayalı küçük hacimli, düşük maliyetli ve yüksek doğruluklu mikrodenetleyici tabanlı bir test sistemi tasarlanmıştır. Bu sistemin temel prensibi, sıvı akışını kesmeden sıvı miktarını tartmaya dayanmaktadır. Sistem donanımı mikrodenetleyici, TFT ekran, yük hücresi, termokupl, tank, pompa vb. mekanik ve elektronik modüllerden oluşmaktadır. Tasarlanan sonsuz çevrim kalibrasyon sistemi için bir algoritma geliştirilmiş ve mikrodenetleyici yazılımı C++ dilinde kodlanmıştır. Yük hücreleri ile elde edilen sıvının ağırlık verileri ise zamana bağlı olarak mikrodenetleyicide işlenmektedir. Sonuç olarak bu çalışmada tasarlanan mikrodenetleyici tabanlı sistem, sıvı akışölçerlerin test ve analizlerinin otomatik olarak yapılmasında kullanıcılara ve araştırmacılara katkı sağlamaktadır.

Anahtar kelimeler: Test sistemi, mikrodenetleyici, sonsuz çevrim algoritması, kalibrasyon

1 Introduction

The flow measurement is performed on liquids, gases, and solids in industrial and medical fields [1, 2]. Especially, flow measurement is becoming increasingly important for the liquid sector in industrial fields such as oil and fuel. Flowmeters are widely used in flow measurement. There are different types of flowmeters: positive displacement, differential pressure, electromagnetic, vortex, turbine and ultrasonic [3-5], with numerous global manufacturers [6]. Each flowmeter has its own working principle, advantages, disadvantages and the choice of the flowmeter for the flow measurement depends on some factors such as pipe diameter, liquid type and temperature. Accurate measurement of the total mass or volume of liquid passed in the pipe is very important because a measurement error can result in serious financial losses for either the buyer or seller [7]. Also, inaccurate flow measurement can lead to equipment damage. Thus, many studies have been conducted on flow measurement to improve the measurement quality [8-14].

Flow calibration is the foundational process of verifying and adjusting a flowmeter's accuracy. In order to analyze the measurement quality of the flowmeter, the calibration of the flowmeter should be done precisely. Besides that calibration of flowmeters may deteriorate due to various factors that occur over time, such as damage, breakage, corrosion, and contamination. Therefore, flowmeters must be calibrated regularly.

A flowmeter calibration is done in two methods: i) weighing the quantity of liquid; and ii) measuring the volume of the liquid with the volume tank. The weighing method presents a good calibration performance [15]. This method is widely used in flowmeter calibration laboratories today for liquid flow measurements [16]. The weighing method gives an accurate measurement of flow rate provided that i) achieving the necessary accuracy of the timer; ii) making the necessary corrections for the effects of atmospheric buoyancy; iii) keeping the time of deflection of the diverter small [17].

To date, many techniques have been developed to improve the uncertainty in the calibration of flowmeters. Shimada et al. [18] developed a new system with double diverting wings to reduce the diverter timing error; Vásquez et al. [19] presented a procedure to generate capacity tables for a gravimetric measurement standard; Tawackolian et al. [20] were interested in the calibration of the ultrasonic flowmeter for hot water; Souza et al. [21] described a method to calibrate a cryogenic turbine-based volumetric flow meter using sub-cooled liquid nitrogen; Chun et al. [22] calibrated flow meters using master meter method with less time and costs; Liu et al. [23] designed a pipeline flowmeter calibration system based on PLC control to solve the problems of error and data storage and calculation; Yu et al. [24] proposed an error correction method based on

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low-frequency suppression for in-situ calibration of permanent magnet sodium flowmeter without the bluff body; Mills [25] analyzed the effect of temperatures, pressures and viscosities on the calibration of Coriolis flowmeters. Zhai et al. [26] designed a calibration system that fully automated the calibration process, eliminating the need for human intervention. This approach minimized the risk of human errors and significantly improved labor efficiency. Compared to manual calibration, the designed flow calibration system enabled high-precision automated calibration of ultrasonic water meters, greatly enhancing both detection efficiency and accuracy.

As mentioned above, the main challenges in the calibration process include temporal error, the effect of atmospheric buoyancy and the the diverter's deflection time. Moreover, the calibration system requires a large tank to minimize temporal errors. As the tank capacity increases, the testing time of the liquid flow rate increases, which in turn improves the accuracy of the calibration results. While some meters can be easily calibrated in the field, flowmeters are an exception. Calibrating flowmeters is significantly more complex than other measuring instruments, such as temperature sensors. This increased complexity makes self-calibration more expensive [27]. Therefore, the cost of the calibration system is a crucial factor. In this study, a small-volume, low-cost and high-accuracy microcontroller-based testbed system based on an infinite cycle algorithm is designed for the desired time calibration of the liquid flowmeters. Thus, within certain velocity limits and without the need for a very large tank, the system aims to maintain continuous liquid flow by circulating it and to enhance accuracy by minimizing temporal errors. Additionally, since a diverter is not used in the designed system, the associated error is eliminated. Finally, errors are further minimized by considering the effects of factors influencing the weighing results.

2 Flowmeter calibration by weighing method

In flow measurement, flowmeter error is the deviation of the measurement indicated by the flowmeter under test from the actual or reference value, expressed in Equation (1) [28].

$$Error\ (\%) = \frac{|V_i - V_a|}{V_a} 100 \tag{1}$$

where V_i is the value obtained by the flowmeter under test and V_a is the actual value. To reduce the error, the flowmeter is calibrated by comparing the value indicated by the flowmeter according to the actual value of the liquid.

A flowmeter can be calibrated using weighing and volumetric methods. The weighing method has a good performance [15].

2.1 Weighing method

The weighing method used to calibrate the flowmeter is based on weighing the quantity of liquid. In this method, one of the measurands is the mass flow rate (q_m), which can be calculated using Equation (2) [29].

$$q_m = \frac{M}{t} \tag{2}$$

where M is the actual mass, and t is the calibration time between the start and end of the liquid flow. The units of the qm, M and t are kg/s, kg and s, respectively. Another measurand is the volumetric flow rate (q_v) calculated by Equation (3) [29].

$$q_v = \frac{q_m}{\rho_l} \tag{3}$$

where p_l is the density of the liquid. The units of the q_v and p_l are m^3/s and kg/m^3, respectively. After obtaining the flow rate, the actual liquid flow velocity can be determined using flow rate and pipe diameter. Thus, comparing the actual liquid flow velocity with the liquid flow velocity obtained by the flowmeter under test, the flowmeter is calibrated.

2.2 Factors affecting the weighing result

The commercially available flowmeters are generally calibrated using water [21]. In this study, water is collected into the tank and the mass indicated by the scale (W) is measured by weighing. The factors of gravitational acceleration and buoyancy should be taken into account to obtain M shown in Equation (2).

2.2.1 Gravity acceleration ratio

The mass value indicated by the scale depends on the local value of the acceleration of gravity. Thus, taking into account the gravitational acceleration means a high precision scale. Equation (4) defines the gravity acceleration ratio (R_g) [19].

$$R_g = \frac{g}{g_{ref}} \tag{4}$$

where g and g_{ref} are the gravitational accelerations where the scale is used and manufactured, respectively. If the value of g is less than the value of g_{ref}, the M is greater than the W.

2.2.2 Buoyancy factor

Another factor that affects the value of M is the buoyancy factor [19, 30]. After weighing the mass, the obtained mass value has to be corrected for the effect of air buoyancy. The air buoyancy causes a lower value of the actual mass due to the buoyancy rising force acting upward on the object to be measured. The buoyancy factor (E) is calculated by Equation (5) [19]:

$$E = \left(1 - \frac{p_{air}}{p_l}\right) \tag{5}$$

where p_{air} is the density of the air. After calculating the gravitational acceleration and buoyancy factors, the relationship between the M and the W can be defined in Equation (6) [18, 19].

$$W = M.E.R_g \tag{6}$$

After obtaining the M, q_m can be calculated using Equation (2) and Equation (3) is used to calculate the q_v. As shown in Equation (3) and Equation (5), the liquid density is one of the quantities which impact the uncertainties in the measurement process of calibration [28, 29]. As mentioned above we use water for the designed calibration system. Water's density varies with temperature. Tanaka et al. [31] proposed Equation (7) to compute the density of water, valid in the measurement range 0-40 °C.

$$p_w = a_5 \cdot \left[1 - \frac{(T_w + a_1)^2 \cdot (T_w + a_2)}{a_3 \cdot (T_w + a_4)}\right] \tag{7}$$

where p_w is the density of the water calculated based on temperature and Tw (°C) is the water temperature. The polynomial parameters in Equation (7) are

a_1 = -3.983035 °C

a_2 = 301.797 °C

a_3 = 522528.9 °C^2

a_4 = 69.34881°C

a_5 = 999.974950 kg/m^3.

Thus, we use p_w, obtained by Equation (7), instead of p_l shown in Equation (3) and Equation (5) to calculate the E and the q_v. After calculating the q_v, we calculate the water flow velocity (V_w) shown in Equation (8) because in the industry, besides the amount of liquid transferred by circular-type pipes, its velocity is also used.

$$V_w = \frac{q_v}{\left(\pi \cdot \frac{D^2}{4}\right)} \quad (8)$$

In this expression, D denotes the pipe diameter. Thus, V_w can be used as a reference value along with the flow rate to calibrate the flowmeter under test.

3 Experimental setup

The infinite cycle calibration system is based on the principle that the flow continues uninterrupted through the flowmeter to be calibrated during the process. The block diagram of the infinite cycle calibration system developed according to this principle is shown in Figure 1. In the calibration system, the weighing method is used to determine the amount of water, flow velocity and flow rate. The mass of the water in the weighing tank obtained with the load cells is processed in the microcontroller depending on time and the necessary calculations for calibration are made. During the calibration process, the circulation pump works continuously, ensuring that the water flow continues uninterrupted through the flowmeter to be calibrated. Other pumps are used for filling and discharging the weighing tank. For this reason, the parameters of the amount of water used during the test, circulation speed, weighing precision and filling-discharging times are important.

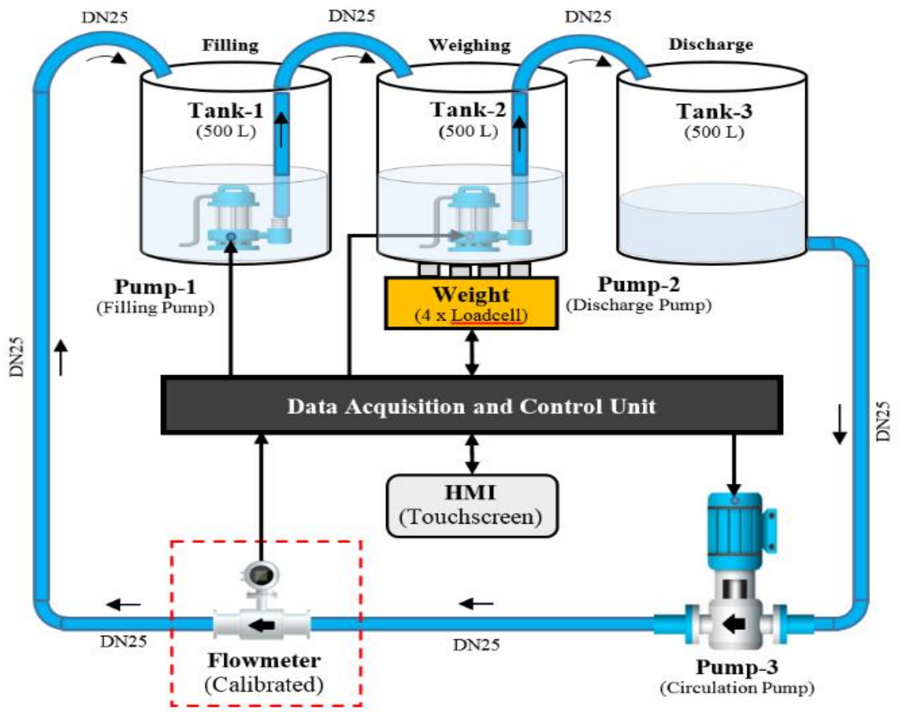


Figure 1. Infinite cycle calibration system basic principle.

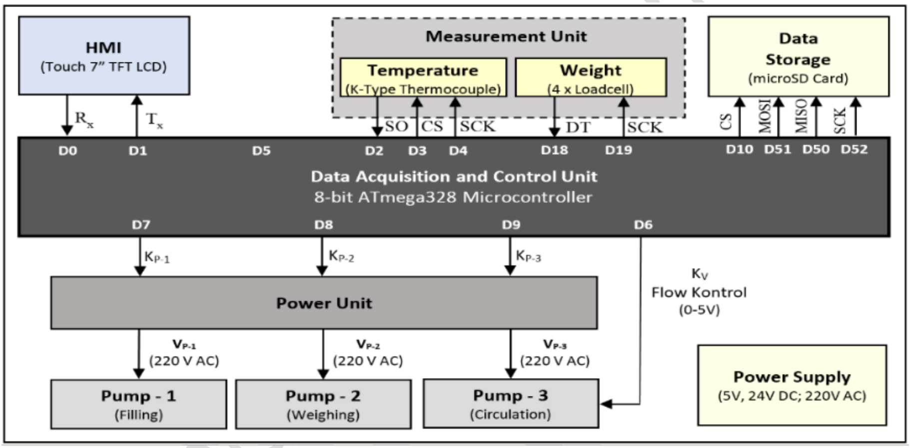
The general view and block diagram of the designed embedded infinite cycle calibration system are shown in Figure 2. The system consists of hardware (mechanical and electronic) and software (microcontroller and TFT display). The general characteristics of the designed system are given in Table 1.

While the mechanical design consists of water tanks and pipe connections, the electronic design consists of electronic components such as microcontroller, sensors, and load cells used for data acquisition and control. In the designed system, three tanks with the dimensions of 70 cm × 70 cm × 110 cm and a capacity of approximately 500 L are used for filling, weighing and discharging. A circulation pump is used to maintain the circulation of water in an infinite cycle, and two submersible pumps are used for filling and discharging the weighing tank. Figure 3 shows the inside of the control panel. This panel is used for the data acquisition and control, where the measurement, control and user interface units are located. In this panel, in terms of the existing mechanical components used in the design for water cycling and weighing, an 8-bit ATmega328 microcontroller with sufficient speed for the required program cycle time for data acquisition and control is used. A Thin-Film-Transistor Liquid Crystal Display (TFT LCD) touch screen, which communicates via a serial port, is used as Human-Machine Interface (HMI). In order to measure the water weight, 4 lama type load cells, each 250 kg in parallel connection, are used. Load cells use the Inter-Integrated Circuit (I^{2}C) protocol for communications. The water temperature required to calculate the water density is measured with a K-type thermocouple using the microcontroller. The test data obtained during the calibration are stored on the micro SDCard, which communicates with the microcontroller via the serial peripheral interface (SPI).

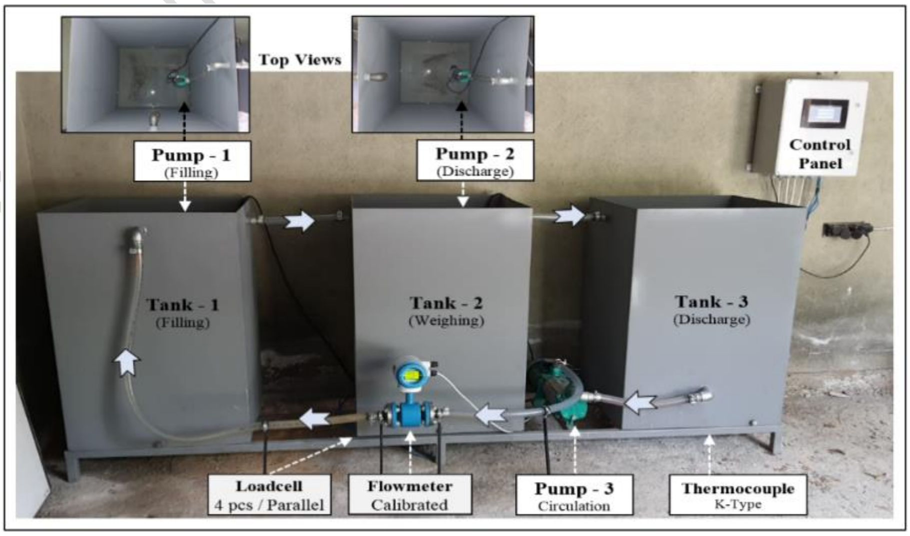
An algorithm for the designed infinite cycle calibration system is developed and coded in C++ using embedded software. Figure 4 shows the flowchart for the operation of the microcontroller software algorithm.

With the start of the system; besides the t, the data sample interval (ts) for the measurement and calculations, the circulation pump speed (Vcp), which determines the water flow velocity in the system, and the pre-weighing limit mass (M_{lim}) required for weighing is read from the microcontroller EEPROM. After this process, the calibration data is reset to prepare the system for the test. Then, the filling pump (pump - I) and discharge pump (pump - II) are operated, and the filling tank (tank-1) and weighing tank (tank-2) are completely emptied. After the tanks are emptied, the circulation pump (pump - III) is started. During the calibration process, the circulation pump works continuously, ensuring that the water flow continues without interruption over the flowmeter to be calibrated. With the operation of the circulation pump, water flow is provided in the system and the discharge pump is turned off and the weighing tank is filled. Upon reaching the M_{lim} value, firstly the filling pump is turned off and the water inlet to the weighing tank is cut off, and then full tank weighing (W_{full}) is performed by waiting for the weighing value to stabilize. After the Tw measurement, the discharge pump is turned on and the weighing tank is emptied and the empty tank weighing (W_{empty}) is performed. After the weighing processes are completed, the data that W, M, q_v, V_w and total actual water mass (M_{sum}) are recorded and reported on the screen. At the end of the calibration time, the circulation pump is turned off and the residual water remaining in the system is weighed. At the end of the calibration process, the filling and discharge pumps are also turned off, and the circulation process is terminated and the data obtained for the calibration test is given in a report. TFT screenshots of the setting and calibration processes for the designed system are shown in Figure 5.

On the settings screen the parameters that calibration time, data sample interval, circulation pump speed and pre-weighing limit are adjusted. On the calibration screen, starting, monitoring and ending the test are performed. As shown in Figure 5, the calibration screen displays the calibration and passing time, instantaneously changing temperature and mass data, cycle number, mass, flow velocity and flow rate parameters obtained at the end of the process.



(a) Block diagram



(b) General view

Figure 2. Designed infinite cycle calibration system.

Table 1. General characteristics of the designed system

Characteristic	Feature
Application Area	Water flowmeter calibration
Method	Weighing of water based on the principle of infinite cycle
Measurements	Water mass (kg) : ±0.1% accuracy in the range of 0-450 kg Water temperature (°C) : ±0.5 °C accuracy in the range of 0-35 °C
Calibration Time	Optional Adjustable
Maximum Flow Velocity	1.5 m/s (Infinite cycle)
Cyclic Water Capacity	400 kg
User Interface	7-inch TFT Touchscreen
Supply	220 V AC 50 Hz

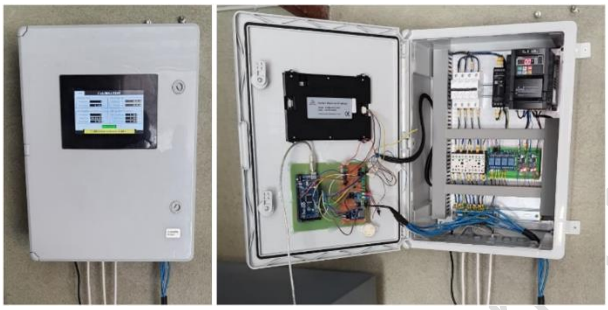


Figure 3. Data acquisition and control panel.

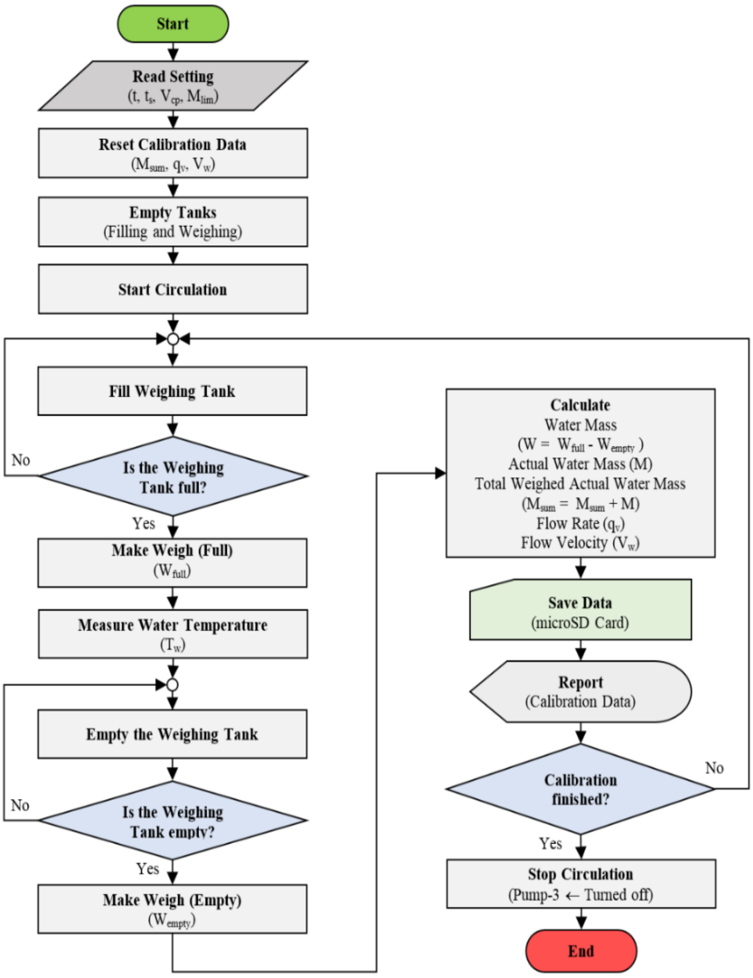
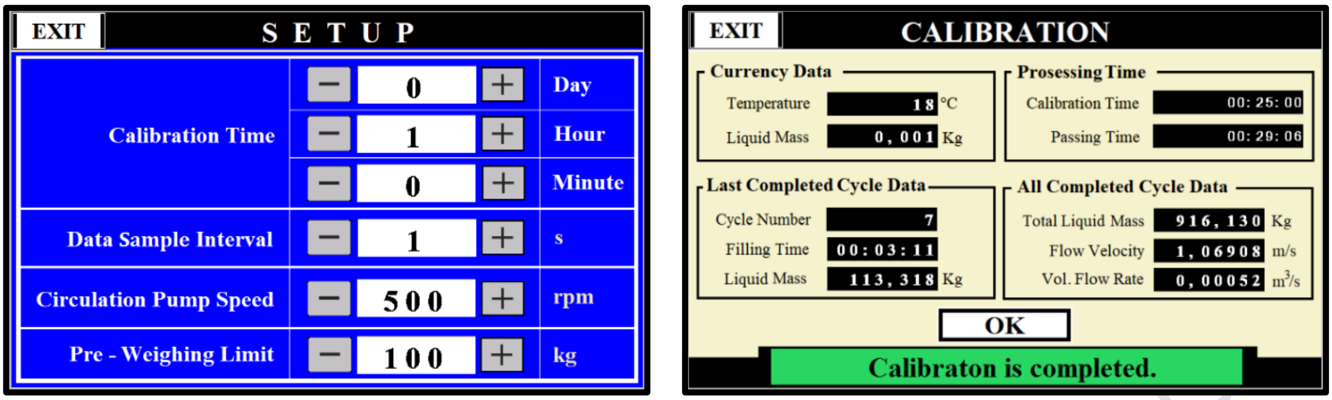


Figure 4. Flowchart for the microcontroller software algorithm.



(a) Setting screen (a) Calibration screen

Figure 5. TFT LCD HMI sample screenshots.

4 Results and discussion

In the developed system, water weighing and temperature measurements are made to obtain the M, V_w, q_v. The averaging method, in which the measurement result is determined by taking the arithmetic average of 100 consecutive measurements, is used. To determine the weighing error of the system, the known weights (between 0 ~ 450 kg) and the results of the system are compared using Equation (1). As shown in Figure 6, weight measurement is performed with a maximum error of ±0.1% in the range of 0 ~ 450 kg.

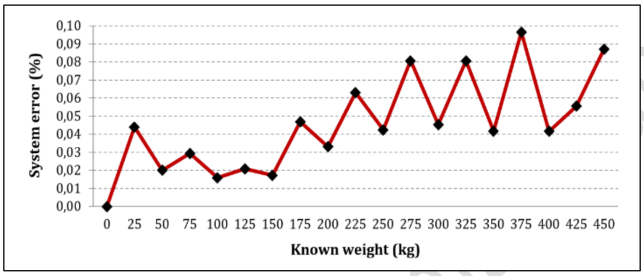


Figure 6. System error due to weight measurement.

In order to determine the temperature measurement error, the temperature values measured by the designed system and the temperature values measured by the Fluke 287 digital multimeter that has ±1% accuracy in the range of -200 °C ~ 1350 °C are compared [32]. As shown in Figure 7, it is observed that the maximum measuring error is ±0.5 °C in the range of 0 °C ~ 50 °C.

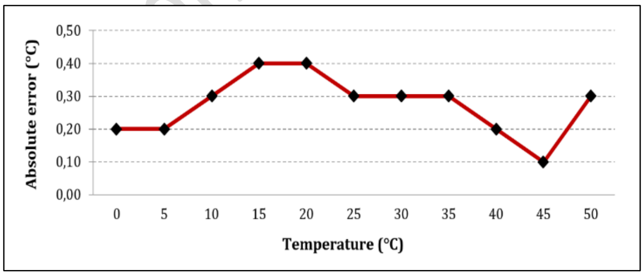


Figure 7. Absolute error depends on the temperature.

In order to weigh the amount of water in the system, filling and discharging the water into the weighing tank should be done quickly. It is observed that the filling and discharging flow rate of the weighing tank is approximately 2.09 kg/s (with a maximum error of ±0.01 kg/s).

Table 2 shows the values of V_w and q_v depending on the capacity of the circulation pump. The capacity of the circulation pump is changed by adjusting its frequency (f). As the value of f increases, the pumping power increases. The circulation pump can operate at a maximum frequency of 30 Hz depending on the power of the driver. As shown in Table 2, the maximum V_w and q_v of the system are approximately 3.7 m/s and 0.0018 m³/s, respectively.

In this study, the performance of the infinite cycle calibration test in the system depending on the water circulation is also examined. The infinite cycle depends on the V_w as well as the M_{lim} value. Table 3 shows the infinite cycle capacity of the system for different V_w and M_{lim} values with 400 kg of water in the cycle.

While an infinite cycle is not provided at very high velocities, it is observed that an infinite cycle is provided for approximately 1.5 m/s. In addition, as the M_{lim} is increased, the temporal resolution decreases because the time difference between the two cycles increases. Increased temporal resolution means better analysis of results, as test data is obtained more frequently. For these reasons, at the maximum V_w = 1.53002933 m/s allowed for an infinite cycle in the designed system, M_{lim} = 100 kg is chosen for the highest value of the temporal resolution.

Finally, the designed calibration system is compared with a commercial flowmeter. As seen in Table 4, the difference between the results obtained from the designed calibration system and the commercial flowmeter for approximately 2 m³ of water at different f values is very small.

5 Conclusion

In this study, a microcontroller-based testbed system is designed to determine the flow velocity, flow rate and amount of water for the calibration of the liquid flowmeter in an infinite cycle or in the desired time. The designed system allows the use of smaller tank volumes with the infinite cycle method. Thus, both the system cost and the amount of water used are reduced. In addition, by increasing the calibration time as desired depending on the user, the temporal error is minimized, the error caused by the diverter is eliminated because the diverter is not used, and the effect of the factors affecting the weighing result is also analyzed, and it is aimed to perform calibration processes with high accuracy. The test processes carried out within the scope of the study show that high-accuracy results are obtained.

Depending on the power of the circulation pump and the drive system, the maximum flow velocity of the system is determined as approximately 3.7 m/s. This velocity can be increased by using a more powerful circulation pump and driver in the system. As a result of the tests carried out, it is observed that the calibration process of flowmeters can be done reliably at the maximum V_w = 1.53 m/s and M_{lim} = 100 kg for an infinite cycle in the designed system using 400 kg water. The obtained infinite cycle maximum flow velocity and the amount of water entering the cycle can be increased by using larger tanks.

In order to weigh the amount of water in the system, filling and discharging the water into the weighing tank should be done quickly. It is observed that the filling and discharging flow rate of the weighing tank is approximately 2.09 kg/s (with a maximum error of ± 0.01 kg/s). On the other hand, a weighing time of approximately 10 s is needed to stably (accurately) weigh the water in the weighing tank using load cells. In order to make at least one cycle by providing circulation in the designed system, the circulation water flow rate should not be greater than the filling-discharging flow rate of the weighing tank and this difference should be at the limit to compensate for the weighing time. Thus, it is possible to increase the number of cycles in the system and provide an infinite cycle by using pumps with higher flow rates for filling and discharging the weighing tank. As a result, the designed microcontroller-based system contributes to the users and researchers in the testing and analysis of liquid flowmeters automatically and can be further developed in the future.

Table 2. Frequency-dependent flow rate and velocity

f (Hz)	q_v (m^3/s)	V_w (m/s)
5	0.000215430	0.438757639
10	0.000556930	1.134277832
15	0.000885083	1.802613589
20	0.001184543	2.412511152
25	0.001491815	3.038318875
30	0.001806705	3.679644015

Table 3. Infinite cycle capacity for different V_w and M_{lim} values

q_v (m^3/s)	V_w (m/s)	n_c - Number of Cycles						
		M_{lim} 50 kg	M_{lim} 100 kg	M_{lim} 150 kg	M_{lim} 200 kg	M_{lim} 250 kg	M_{lim} 300 kg	M_{lim} 350 kg
0.00025035	0.51000978	inf.	inf.	inf.	inf.	inf.	inf.	inf.
0.00050070	1.02001955	inf.	inf.	inf.	inf.	inf.	inf.	inf.
0.00075105	1.53002933	458	inf.	inf.	inf.	inf.	inf.	inf.
0.00100140	2.04003910	20	20	19	19	18	16	12
0.00125175	2.55004888	11	7	5	4	3	2	1
0.00150210	3.06005865	7	5	3	2	2	1	1
0.00175245	3.57006843	6	3	2	2	1	1	1

Table 4. Comparison of the designed system with the commercial flowmeter

f (Hz)	Designed System (m^3)	Commercial Flowmeter (m^3)	Absolute Difference (m^3)
5	2.071560	2.067073	0.004487
10	2.032500	2.030459	0.002041
15	2.062440	2.064652	0.002212

6 Acknowledgements

7 Author contribution statement

In the present work, Author 1 performed design, software and analyses; Author 2 performed literature review and evaluated the results. Authors conceived the presented idea, discussed the results and contributed to the final manuscript.

8 Ethics committee approval and conflict of interest statement

There is no need to obtain permission from the ethics committee for the article prepared.

There is no conflict of interest with any person/institution in the article prepared.

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