



# **Monitoring pH Sensor with Temperature Compensation using MCU 32-bit Equipped with RS-485 Communication Module**

## **Final Project**

**By:  
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**Electronics Manufacturing Engineering Study Program  
Electrical Engineering Department  
Politeknik Negeri Batam  
2025**

## Statement of Authenticity of Final Project

I, the undersigned, certify that the contents of part or all of my Final Project entitled: "Monitoring pH Sensor with Temperature Compensation using MCU 32-bit Equipped with RS-485 Communication Module" is my **own work, completed without the use of materials that are not permitted**, and is **not the work of other parties which I acknowledge as my own work**. All references cited or referred to have been written in full in the bibliography. If it turns out that my statement is not true, I am willing to accept sanctions in accordance with applicable regulations.

Batam, 4 September 2025



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# Approval sheet

The Final Project is structured to fulfill one of the requirements for obtaining a degree  
Bachelor of Associate Engineer (AMd.T.)  
in  
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# **[ Monitoring pH Sensor with Temperature Compensation using MCU 32-bit Equipped with RS-485 Communication Module]**

## **Abstract**

This study discusses the application of an automatic temperature compensation (ATC) system on pH sensors to improve accuracy to 0.01 pH. The analog values (mV) of pH solutions are very low and susceptible to interference and temperature fluctuations, so an independent pH module was developed with a differential sensor, a DC-to-DC isolator module, and an Op-Amp module as a buffer to stabilize the analog signal. The gradient method was used to manage the slope between temperature and pH, and the ATC formula from Hanna Instruments was applied for temperature compensation. Test results show that pH shifts occur every time the solution temperature decreases, and ATC is able to correct pH measurements. However, the target accuracy of 0.01 pH has not been achieved due to differences in calculation results between manual calculations and the microcontroller. The measurement error percentage of the microcontroller is 0.6%, resulting in an accuracy percentage of 99.4%.

Keywords: Automatic Temperature Compensation (ATC), Differential pH sensor, Gradient method, pH measurement.

## Foreword

I express my deepest gratitude to Almighty God for the smooth completion of my industrial internship at PT. FEEN MARINE. With the guidance and direction from Mr. Achmad Hafidz Effendi as my mentor at the company and Mr. Vivin Octowinandi as my academic supervisor, I was able to carry out the internship activities and complete this final project titled "Monitoring pH Sensor with Temperature Compensation using 32-bit MCU Equipped with RS-485 Communication Module" as part of the requirements for the Manufacturing Electronics Engineering program at Politeknik Negeri Batam.

This project aims to develop a pH sensor measurement module with continuous monitoring of each measurement and improvements on the pH sensor module under development. Although the research is still in the development stage, the measurement results obtained so far have been quite satisfactory. I would like to express my deepest thanks to:

1. Mr. Achmad Hafidz Effendi, Manager of Automation and mentor at the company.
2. Ms. Dessy Oktani, ST., MT, lecturer in the Department of Electrical Engineering, who has provided meaningful guidance and support to the author during the internship process at the company.
3. Mr. Vivin Octowinandi, S.Tr.T., M.Sc., as a lecturer in the Electrical Engineering Department and academic advisor, who has provided guidance, input, and full support in the preparation of this report.
4. All employees and staff at PT. DVE Marine Engineering and PT. Feen Marine who have welcomed the author warmly.

In closing, the author sincerely apologizes for any mistakes or shortcomings in this report. Constructive criticism and suggestions for future improvement are highly appreciated. It is hoped that this report will provide valuable benefits to its readers. With that, the author expresses sincere gratitude.

Batam, 08 Agustus 2025



Santo Mykolardo Sidabutar

# Monitoring pH Sensor with Temperature Compensation using MCU 32-bit Equipped with RS-485 Communication Module

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**Keywords:** Automatic Temperature Compensation (ATC), Differential pH sensor, Gradient method, pH measurement.

## I. INTRODUCTION

pH (potential of Hydrogen) is a measure of the degree of acidity or alkalinity of a solution. pH indicates the concentration of hydrogen ions ( $H^+$ ) in a solution and is defined as the negative logarithm of the activity of those hydrogen ions. pH values are used to determine whether a solution is acidic, neutral, or basic. The pH scale ranges from 0 to 14: values below 7 indicate an acidic solution, values above 7 indicate a basic solution, and exactly 7 indicates a neutral solution [1]. A pH meter is an instrument used to measure the concentration of hydrogen ions [ $H^+$ ] in a solution [2].

To measure the acidity or alkalinity (pH) of a liquid, one method that can be used is litmus paper. However, litmus paper is not very effective because it only provides qualitative results and is not very accurate. A more effective and accurate method for determining pH levels is to use a pH sensor. [3]. A pH sensor is an electronic device used to measure the acidity or alkalinity (pH) of a liquid [2].

pH sensors have various measurement methods, one of which is the differential method. In this study, the differential pH measurement method will be used by utilizing a differential pH sensor as a pH measuring device. pH differential is a pH measurement method that uses two

measuring electrodes, two measuring electrodes can be two glass electrodes, or one glass electrode and one specific ion electrode (usually sodium) as well as one metal ground electrode as a reference. pH calculation involves directly subtracting the readings from the two glass electrodes from the ground reference electrode, then comparing the signals to produce a more stable measurement [4], [5].

However, changes in temperature can affect the measurement of the acidity or alkalinity (pH) of a liquid. The relationship between temperature and pH is very close, because an increase in temperature can accelerate the rate of chemical reactions in water, including acid-base reactions. As a result, when the water temperature increases, the pH value of the liquid can also change [6], [7]. Changes in temperature during pH measurement will affect the slope of the pH. At 25°C, each one-unit change in pH (pH slope) represents a change in the glass electrode potential of +/- 59.16 mV from the initial pH point of 7 (0 mV). At 80°C, each one-unit change in pH (pH slope) represents a potential change of +/- 70.1 mV [8], [9]. A study conducted by Wati L, Gumiwang H, and Titisari D titled "Effect of Temperature on a pH Meter Based on Arduino Uno with Internal Calibration." This study presents pH measurement data of samples at non-standard temperatures, specifically at 25°C. From the measurement results table, it can be observed that pH values change with increasing temperature in the samples, indicating the influence of temperature on pH measurement results [7].

Research to test pH using a pH meter has also been conducted extensively, including research conducted by Rahmi H, Zakiyyah U, and Supriyadi K entitled "Arduino-based pH measuring device." [10], Research conducted by Hariyadi, Kamil M, Ananda P entitled "Automatic Water pH Checking System Using Arduino-Based pH Probe Sensor in Drilled Wells" [2], Research conducted by Yoga P, Suar K, Agus M entitled "Design of a PH meter with Arduino-based water PH sensor" [3]. Research conducted by Arief R, Hardianto, and Muliawan A entitled "Design of an Automatic pH Meter Using ATmega16 in an Effort to Improve the Accuracy of pH Readings of Chemical Compounds" [11]. From these studies, the research only measured pH in samples. This study has weaknesses because pH measurements were not compensated for sample temperature at the time of measurement. This can affect the accuracy of

the pH measurement results obtained.

Based on previous studies, the author developed a pH meter that can compensate for changes in pH levels when the temperature of the sample changes. Temperature compensation is crucial because pH values can vary depending on the temperature of the solution. This study discusses the use of differential pH sensors in designing a pH meter system capable of monitoring the pH level of a liquid with temperature compensation [8], achieving measurement accuracy of 0.01 pH. This resolution is essential to ensure that even small changes in the acidity or alkalinity of a solution can be detected accurately. With this feature, pH measurements provide more consistent and accurate results even when temperature changes occur in the sample being measured. The application of this research can be used to measure the pH level of water in a well or to measure the pH level in homes that require a clean supply.

II. METHOD

In the pH sensor monitoring study, the pH sensor module that will be used to monitor pH will use a differential pH sensor. This sensor uses a pH electrode measurement method with an additional reference pH electrode in a pH7 buffer solution, and this differential pH sensor is equipped with a PT 1000 Resistance Temperature Detector (RTD) temperature sensor [12]. The analog output from the sensor will be amplified using an amplifier module design. The module is equipped with ADUM5401 as a galvanic isolator to protect the circuit from electrical noise and interference from the surrounding environment, which will improve the overall operational stability of the module [13]. This study will use two IC OP AMPs, namely IC AD8603 and AD8607, to amplify and buffer the pH and temperature sensor signal data [14], and a low-pass filter (LPF) circuit was added to reduce noise in the output signal, thereby ensuring the accuracy of the output data from the AD8603 and AD8607 operational amplifier IC modules [15]. The analog output signal from the operational amplifier (Op-Amp) IC will be processed by the STM32F103C8T6 microcontroller as the data processing unit [16], equipped with a program-based ATC (Automatic Temperature Compensation) system to compensate for temperature fluctuations during the pH measurement process [8].

A. Design of a pH sensor module

This flowchart is a basic overview of the designed system. Each part of the system block has its own function. By understanding the flowchart, the designed system can be built correctly. The flowchart to be designed is shown in Figure 2.2.

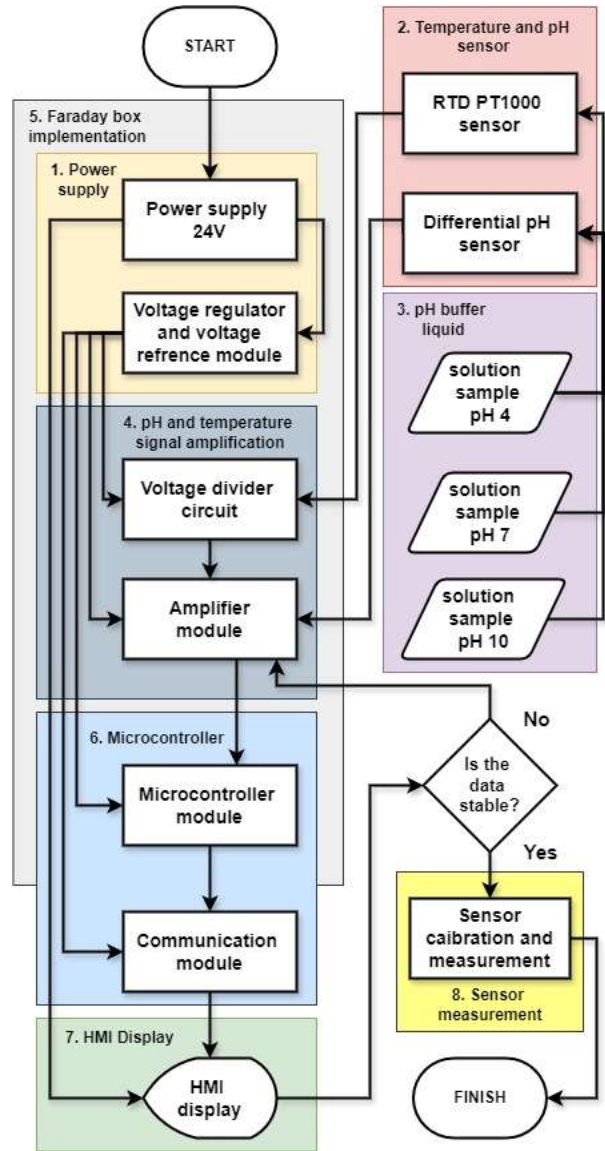


Figure 2. 1 Flowchart temperature and pH sensor system monitoring

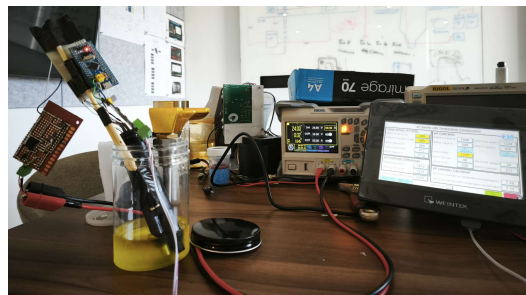


Figure 2. 2 Monitoring pH and temperature

A full explanation of the block diagram above is as follows:

1) Power Supply

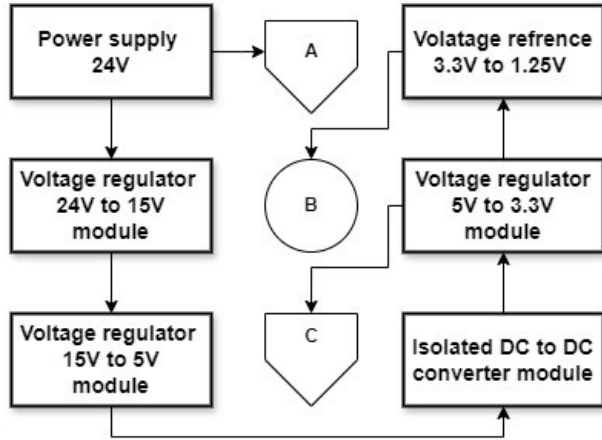


Figure 2.3 Block Diagram of Power Supply

The main power source provides the required voltage for the entire system, which is 24V using a power supply. This voltage is then reduced to 15V using the LM7815 IC regulator module and then the voltage is reduced again to 5V voltage using the LM7805 regulator module [17], after that the 5V voltage will be isolated in order to reduce noise using the ADUM 5401 IC [13]. The 5V voltage that has been isolated is then reduced back to 3.3V using the AMS1117 regulator IC [18] and reduced back to 1.25V using the LM4140 regulator IC [19]. The 24V voltage will be used as a power source for the HMI device. The isolated 3.3V voltage is used as a power source for the amplifier module, microcontroller and RS-485 module and the 1.25V voltage will serve as an offset for the pH comparator module.

2) Temperature and pH Sensor

The working principle of the sensor designed in this study is to use a differential type pH sensor, which applies a measurement method with the main pH electrode and an additional reference electrode placed in a pH 7 buffer solution. This differential pH sensor is also equipped with a PT1000 Resistance Temperature Detector (RTD) type temperature sensor to accurately measure the temperature of the solution [12]. In acidic solutions, the concentration of H<sup>+</sup> ions is high, so the glass electrode of the pH sensor produces a more negative voltage. Conversely, in alkaline solutions, the concentration of H<sup>+</sup> ions is low and the concentration of OH<sup>-</sup> ions is high, so the glass electrode produces a more positive voltage. The way this sensor works is by comparing the voltage measurement results from the pH sensor to the reference value obtained from the pH 7 buffer solution [4], [5].

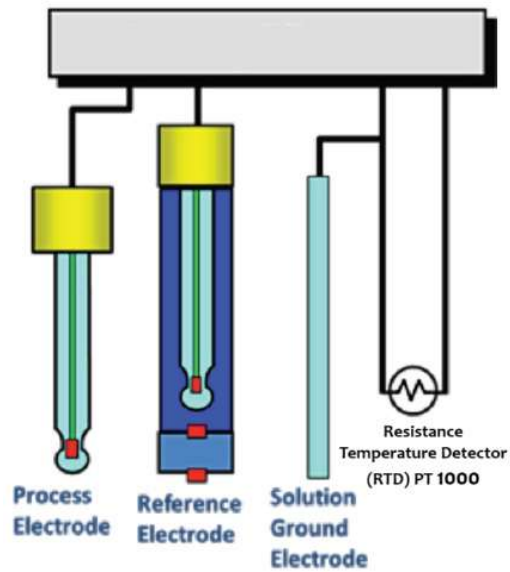


Figure 2.4 Differential pH and RTD PT 1000 sensor

3) pH buffer Liquid

Liquid pH measurements will be carried out using buffer solutions with pH 4 and pH 7.



Figure 2.5 pH 4 and pH 7 Buffer Liquid

These measurements will be carried out at various temperature conditions, with an ideal temperature range between 24°C and 25°C.

4) pH and Temperature Signal Amplification

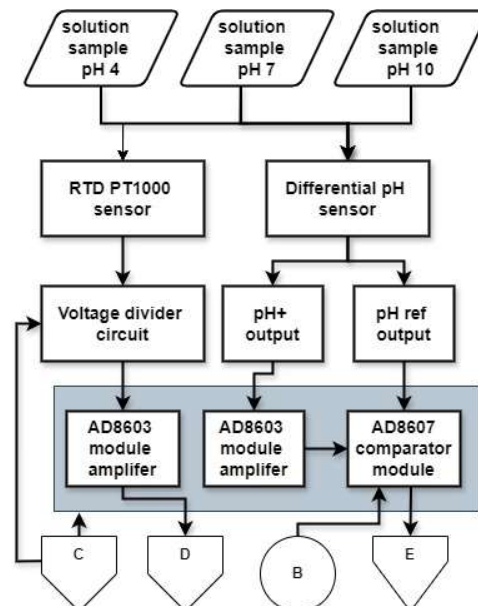


Figure 2.6 Block Diagram of Signal Amplification

In pH measurement, each pH solution has different levels of ions and this difference causes each solution to produce a different voltage. [10]. However, the voltage produced is very small, in millivolts (mV) [20].

TABLE I  
PH SENSOR MEASUREMENT OUTPUT VOLTAGE

pH	mV	Offset (+1.250 mV)
0	+414	+1664
1	+355	+1605
2	+296	+1546
3	+237	+1487
4	+177	+1427
5	+118	+1368
6	+59	+1309
7	0	+1250
8	-59	+1191
9	-118	+1132
10	-177	+1073
11	-237	+1013
12	-296	+954
13	-355	+895
14	-414	+836

Due to the small value of this voltage, a buffer circuit is needed to keep the signal stable and unaffected by interference or loads from the next circuit. The buffer circuit designed using the AD8603 op-amp IC is very suitable for this application because the IC has a very small input bias current, with a maximum value of only 1pA. Thus, this buffer circuit does not overload the sensor so that even very small voltage signals can still be processed. For the buffer circuit in pH measurement can be seen in Figure 2.3.

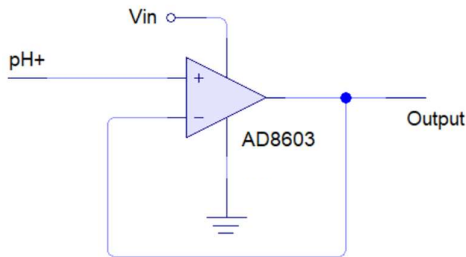


Figure 2. 7 pH Signal Conditioning Circuit

After the voltage from the pH sensor is buffered using the AD8603 op-amp IC, the next step is to compare or process the signal to get the measurement results using the AD8603 op-amp IC. For the comparator circuit can be seen in Figure 2.4

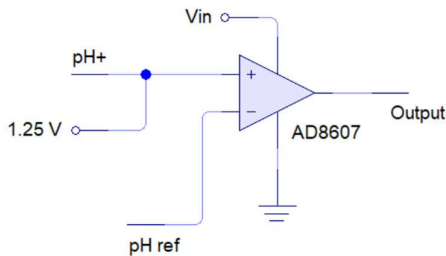


Figure 2. 8 pH Signal Comparator Circuit

An offset voltage of 1.25 V is required so that the pH measurement results in alkaline conditions can be read by the microcontroller. This is because pH measurements in alkaline environments can produce negative voltages, so without an offset, the microcontroller cannot read the value directly. For temperature measurement, the pH sensor used is equipped

with an RTD (Resistance Temperature Detector) PT1000 sensor. PT1000 works based on changes in platinum resistance that occur with changes in temperature. When the temperature rises, the resistance of the sensor also increases [21]. By measuring this resistance, the temperature can be accurately determined. The resistance value of the RTD PT 1000 sensor can be seen in Figure 2.5 [22].

PT1000 CELSIUS TEMPERATURE CHARACTERISTIC

temp. (°C)	resist. (Ω)	temp. (°C)	resist. (Ω)	temp. (°C)	resist. (Ω)	temp. (°C)	resist. (Ω)
-40.0	842.7	1.0	1003.9	41.0	1159.3	81.0	1312.8
-39.0	846.7	2.0	1007.8	42.0	1163.1	82.0	1316.6
-38.0	850.7	3.0	1011.7	43.0	1167.0	83.0	1320.4
-37.0	854.6	4.0	1015.6	44.0	1170.9	84.0	1324.2
-36.0	858.6	5.0	1019.5	45.0	1174.7	85.0	1328.0
-35.0	862.5	6.0	1023.4	46.0	1178.6	86.0	1331.8
-34.0	866.5	7.0	1027.3	47.0	1182.4	87.0	1335.7
-33.0	870.4	8.0	1031.2	48.0	1186.3	88.0	1339.5
-32.0	874.3	9.0	1035.1	49.0	1190.1	89.0	1343.3
-31.0	878.3	10.0	1039.0	50.0	1194.0	90.0	1347.1
-30.0	882.2	11.0	1042.9	51.0	1197.8	91.0	1350.9
-29.0	886.2	12.0	1046.8	52.0	1201.7	92.0	1354.7
-28.0	890.1	13.0	1050.7	53.0	1205.5	93.0	1358.4
-27.0	894.1	14.0	1054.5	54.0	1209.4	94.0	1362.3
-26.0	898.0	15.0	1058.5	55.0	1213.2	95.0	1366.1
-25.0	901.9	16.0	1062.4	56.0	1217.1	96.0	1369.9
-24.0	905.6	17.0	1066.3	57.0	1220.9	97.0	1373.7
-23.0	909.8	18.0	1070.2	58.0	1224.7	98.0	1377.5
-22.0	913.7	19.0	1074.1	59.0	1228.6	99.0	1381.3
-21.0	917.7	20.0	1077.9	60.0	1232.4	100.0	1385.0
-20.0	921.6	21.0	1081.8	61.0	1236.3	101.0	1388.9
-19.0	925.5	22.0	1085.7	62.0	1240.1	102.0	1392.6
-18.0	929.9	23.0	1089.6	63.0	1243.9	103.0	1396.4
-17.0	933.4	24.0	1093.5	64.0	1247.8	104.0	1400.2
-16.0	937.3	25.0	1097.4	65.0	1251.6	105.0	1404.0
-15.0	941.3	26.0	1101.2	66.0	1255.4	106.0	1407.8
-14.0	945.2	27.0	1105.1	67.0	1259.3	107.0	1411.6
-13.0	949.1	28.0	1109.0	68.0	1263.1	108.0	1415.4
-12.0	953.0	29.0	1112.9	69.0	1266.9	109.0	1419.1
-11.0	956.9	30.0	1116.7	70.0	1270.8	110.0	1422.9
-10.0	960.9	31.0	1120.6	71.0	1274.6	111.0	1426.7
-9.0	964.8	32.0	1124.5	72.0	1278.4	112.0	1430.5
-8.0	968.7	33.0	1128.4	73.0	1282.2	113.0	1434.3
-7.0	972.6	34.0	1132.2	74.0	1286.0	114.0	1438.0
-6.0	976.5	35.0	1136.1	75.0	1289.9	115.0	1441.8
-5.0	980.4	36.0	1140.0	76.0	1293.7	116.0	1445.6
-4.0	984.4	37.0	1143.8	77.0	1297.5	117.0	1449.4
-3.0	988.3	38.0	1147.7	78.0	1301.3	118.0	1453.1
-2.0	992.2	39.0	1151.6	79.0	1305.2	119.0	1456.9
-1.0	996.1	40.0	1155.4	80.0	1309.0	120.0	1460.6
0.0	1000.0						

Figure 2. 9 PT1000 Celsius Temperature Characteristics

The temperature signal measurement also needs to be buffered using the AD8603 op-amp IC to maintain signal stability and not be affected by interference or loads from the next circuit. For the buffer circuit on temperature measurement can be seen in Figure 2.6

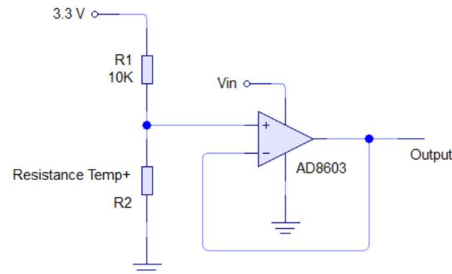


Figure 2. 10 Temperature Signal Conditioning Circuit

Using an input voltage of 3.3V then passes through a voltage divider circuit using a resistor and then enters the V+ input voltage on the AD8603 op-amp IC. The resistor labeled (Temp+) on the schematic is the resistance generated from the RTD PT1000 sensor.

5) Faraday Cage Implementation

A Faraday Cage is an enclosure made from electrically conductive material or a mesh of such material. The cage works by redistributing the electromagnetic energy around its surface, effectively preventing the waves from penetrating the interior. A “Faraday Cage” is an enclosure made of conducting material, which can be solid or mesh (matrix of conductors). It works by creating an “equipotential surface”, distributing electric charge evenly across its exterior, effectively nullifying the electric field within the enclosure. There is no field within the conducting walls, and hence there

is no field inside the hollow or solid objects. The inside space of the conductor is shielded from outside influences. Silver, aluminum and copper are best Faraday cage conducting materials.



Figure 2.11 Implementation of Faraday Cages on pH Sensors

Figure 2.11 shows the implementation of a Faraday cage on the pH sensor module. This implementation uses an iron tube that completely encases the pH module and is connected to a negative voltage (GND) to form a conductive shield. The primary function of this iron tube is to block external electromagnetic interference that could affect the analog signal from the pH sensor. With the Faraday cage in place, electrical noise and electromagnetic interference from the surrounding environment can be significantly minimized. This is crucial because the signal from the pH sensor is highly sensitive and easily disrupted by electromagnetic interference, so the use of a Faraday cage enhances the stability and accuracy of pH readings. Additionally, proper grounding of the iron tube ensures that electromagnetic interference is effectively dissipated into the ground, thereby not affecting the overall measurement system.

6) Microcontrollers

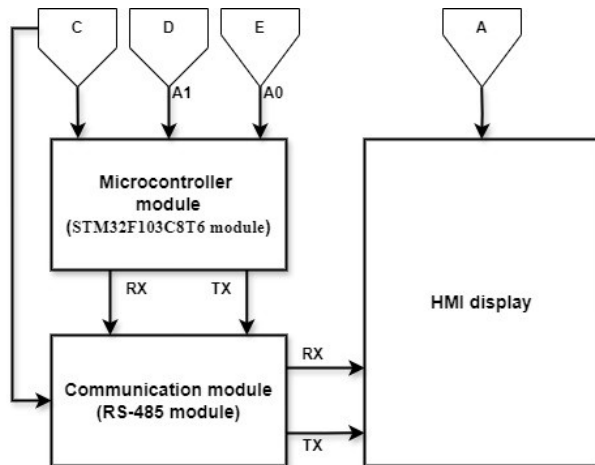


Figure 2.12 Block Diagram of a Microcontroller System with RS-485 Communication Module and HMI Display

In this research, the analog output data from the pH sensor and temperature sensor will be processed using the STM32F103C8T6 microcontroller module.

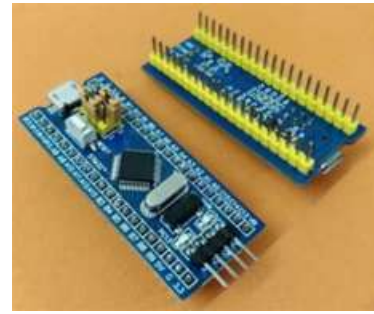


Figure 2.13 STM32F103C8T6 Module

Analog signals from the pH and temperature sensors will be connected to the ADC (Analog-to-Digital Converter) pins on the microcontroller, namely pins A0 and A1. The analog data will then be converted into digital data by the ADC on the STM32F103C8T6. Furthermore, this digital data will be processed using a program that applies the gradient formula to obtain accurate pH and temperature values. After the processing is complete, the measurement data will be sent to the Human Machine Interface (HMI) device using an RS-485 communication module with the Modbus RTU protocol. The use of RS-485 allows stable data communication and longer transmission distances, thus facilitating real-time monitoring and control. In addition, this system can also be developed for integration with other automatic control systems to improve efficiency and accuracy.

This research does not directly discuss microcontroller programming. However, the basic concept of how the pH data will be processed by the microcontroller is still explained as part of the pH measurement system circuit. For processing pH and temperature data, a straight line equation formula is used which utilizes the concept of gradient (slope) [23]. This formula is applied to determine the slope value in the relationship between voltage output (mV) and changes in pH, as well as between voltage output (mV) and changes in temperature. Thus, it can be known how much the voltage change (mV) that occurs due to a change in pH levels by one unit or a change in temperature by 1°C.

a) Process Temperature Data Using the Gradient Formula

The analog data signal from the pH sensor will be processed by the op-amp IC AD8603, but proper circuit adjustment is also taken into account. For Input data ( $V_{in+}$ ) on the AD8603 op-amp IC, a voltage divider resistor with a resistance of 10K  $\Omega$  is given and then in series with the RTD PT1000 from the sensor. The use of 10K  $\Omega$  resistance in the voltage divider circuit to adjust the resistance produced by RTD PT1000.

In Figure 2.5 provides information that RTD PT1000 if measuring liquid at 0°C, the resistance is worth 1K  $\Omega$  and if the measurement is 100°C, the resistance will be 1385  $\Omega$  [22]. Using Ohm's law formula to divide the voltage in a series resistor circuit, to find the input value ( $V_{in+}$ ) at 0°C and 100°C temperature measurements:

$$V_{out} = \frac{R_{Temp} +}{R1 + R_{Temp} +} \times 3.3 V$$

The measurement results at 0°C were finalized as follows:

$$V = 3.3V$$

$$R1 = 10K \Omega$$

$$\text{Temp } 0^\circ\text{C} = R \text{ Temp} + = 1000$$

$$V_{out} = \frac{1000}{10000 + 1000} \times 3.3V = 300mV$$

The measurement results at 100°C were finalized as follows:

$$V = 3.3V$$

$$R1 = 10K \Omega$$

$$\text{Temp } 10^\circ\text{C} = R \text{ Temp} + = 1385 \Omega$$

$$V_{out} = \frac{1385}{10000 + 1385} \times 3.3V = 400mV$$

The analog value obtained at a temperature measurement of 0°C is 300 mV, while at a temperature of 100°C it is 400 mV. To calculate the slope (gradient) value and determine the temperature based on the analog value, the gradient formula of a line through two points, namely (x<sub>1</sub>, y<sub>1</sub>) and (x<sub>2</sub>, y<sub>2</sub>), can be used. In this case, x represents temperature (°C) and y represents analog value (mV). The lowest temperature (0°C) and the highest temperature (100°C) along with their corresponding analog values can be depicted on a cartesian diagram for easier understanding. The slope is important to know how much the voltage increases when there is a 1°C change.

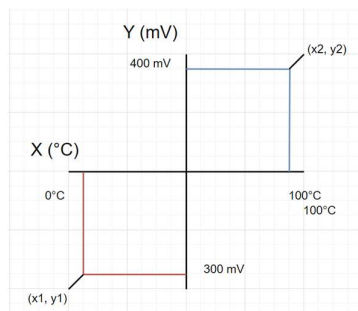


Figure 2. 14 Illustration of cartesian coordinate system diagram using PT1000 sensor data characteristics

Use the gradient formula to calculate the amount of analog voltage (mV) produced by the RTD output when there is a temperature change of 1°C. To find the slope, you can use the formula:

$$\text{slope} = \frac{y_2 - y_1}{x_2 - x_1}$$

Description:

x = the Temperature (°C)

y = the mV value based on temperature

$$\text{slope temperature} = \frac{400 - 300}{100 - 0} = 1 \text{ mV}$$

The analog voltage generated for every 1°C change in temperature is 1 mV

The formula for finding the temperature value:

$$\text{Temperature} = \frac{x - 0^\circ\text{C}}{\text{slope temperature}} = b$$

Description:

x = Temperature sensor measurement mV value

0°C = Temperature mV value

b) Process pH Data Using the Gradient Formula

Slope refers to the calibration slope of a pH meter at several calibration points. The typical slope for a pH meter is around 59.16 mV per pH unit, meaning that for every one-unit increase in pH, the expected voltage change is approximately 59.16 mV. For example, if the voltage at pH 7 is 0 mV, at pH 8 it should be about 59.16 mV, and so on, increasing by roughly 59.16 mV for each additional pH unit Data processing.

In Table 1, there is information about the value of mv pH. To calculate the slope, you can apply the formula for the gradient of a line through two points (x<sub>1</sub>, y<sub>1</sub>) and (x<sub>2</sub>, y<sub>2</sub>):

$$\text{slope} = \frac{\text{pH } 4 - \text{pH } 7}{4 - 7}$$

For example:

Based on the pH table, the initial value of pH 7 is 0 mV, then after being offset, the pH 7 value becomes 1250 mV. While the initial value of pH 4 is 177 mV, then after being offset, the pH 4 value becomes 1427 mV. Using the gradient formula:

$$\text{slope} = \frac{1427 - 1250}{4 - 7} = \frac{177}{3} = 59 \text{ mV}$$

The pH slope value is 59 mV

c) Process pH Data Using Automatic Temperature Compensation System

Table 1 provides data on voltage output (mV) versus pH at a temperature of 25°C. However, pH electrode measurements can be affected by changes in temperature, which can be visualized in the graph in Figure 2.14 [20]. Figure 2.14 shows the relationship between pH values and temperature with probe readings, illustrating how the electrode output voltage shifts as the temperature of the measured solution changes.

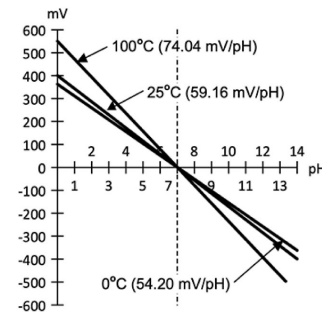


Figure 2. 15 pH Characteristic Curve Against Temperature

Temperature greatly affects the measurement of the output voltage of a pH electrode because the activity of hydrogen ions (H<sup>+</sup>) in the solution changes with temperature. As temperature increases, molecular vibration also increases, leading to increased water ionization and higher H<sup>+</sup> ion concentration, which results in changes in the electrical potential generated by the electrode. Consequently, the electrode's output voltage (mV) is not constant at a specific

pH and shifts depending on the temperature of the sample solution.

Based on the shift in pH value due to temperature changes, a temperature compensation system is required in pH measurements to obtain accurate results. This temperature compensation system, Automatic Temperature Compensation (ATC), functions to correct the effect of temperature on pH readings because pH electrodes are very sensitive to temperature changes. Data processing using the ATC system can use the formula:

$$S(T_{sample}) = S(T_{cal}) * \frac{T(sample) + 273.15}{T(Cal) + 273.15}$$

Description:

S = Slope

T = Temperature °C

Cal = Calibration

For Example:

Calibration was done with pH 4.01 and 7.00 buffers at 24°C. After that, the sample solution was kept cold and the measurement was taken at 10°C and the measurement value was 100 mV, what is the pH level of the sample solution?

Solution:

pH at 24°C = 59.16, find the temperature slope using the formula to compensate for temperature:

$$slope(10^{\circ}C) = slope(24^{\circ}C) * \frac{10 + 273.15}{24 + 273.15}$$

$$slope(10^{\circ}C) = 59,16 * \frac{283.15}{297.15}$$

$$slope(10^{\circ}C) = 56.37$$

The slope at 10°C is: 56. 37 mV. Using the formula for finding the pH value, the pH level in the sample solution is:

$$pH = \frac{100}{56.37} = 1.77$$

$$pH = 7 - 1.77 = 5.23$$

The pH value of the liquid is pH 5.23

However, if you measure pH without using the ATC system, you will get results:

$$pH = \frac{100}{59.16} = 1.69$$

$$pH = 7 - 1.69 = 5.31$$

The pH value of the liquid is pH 5.31

By comparing the two measuring systems with compensated and uncompensated temperature, it shows a difference of 0.08 pH. This is why it is important to measure and correct the temperature precisely.

7) Display Human Face Interface (HMI) pH sensor Module



Figure 2. 16 Display Human Face Interface (HMI)

This Human Machine Interface (HMI) is designed to perform real-time calibration and monitoring of pH and temperature parameters. There are four blocks on the HMI display: temp sensor, electrode, calibration, and calculation.

a) Temp Sensor

The “Temp sensor” block on the HMI display is used to measure the analog value of the temperature sensor and calibrate the sensor. The temperature sensor calibration is calculated from temperatures of 0°C and 100°C.

b) Electrode

The “Electrode” block on the HMI display is used to display the analog value from the pH sensor.

c) Calibration

The “Electrode” block on the HMI display is used to calibrate the pH sensor.

d) Calculation

The “Calculation” block on the HMI display is used to display the pH measurement value. pH measurement with temperature compensation using the Automatic Temperature Compensation (ATC) system, and measurement without temperature compensation.

When measuring temperature and pH, researchers need to consider the stability of the analog output signal from the pH sensor. If the output signal is unstable, researchers will reanalyze the amplifier module. This is because pH data reading and processing greatly affect the performance of the amplifier module. The instability of the analog output produced by the amplifier module can affect the analog value readings on the microcontroller, thereby directly reducing the accuracy of temperature and pH data processing. Therefore, ensuring the stability of the amplifier output signal is an important step in obtaining valid and reliable measurement data.

8) Temperature and pH sensor calibration, measurement and monitoring

Calibration and measurement of the pH sensor will be performed using buffer solutions with pH values of 4 and 7 as reference standards. For measurement and monitoring purposes, pH measurements will continue to use buffer solutions with pH values of 4, 7, and 10 to ensure the stability of the solution's pH during monitoring.



Figure 2. 17 Sample Liquid for pH Measurement

Measurements were taken using cooled buffer solutions to observe changes in pH values due to temperature variations in the liquid.

Next, the pH measurement results will be compared between two systems: one that applies temperature compensation and one without temperature compensation. The purpose of this comparison is to evaluate the effect of temperature compensation on the accuracy of pH readings. Additionally, during each measurement session, data accuracy analysis will be conducted by comparing the measurement results obtained from the microcontroller with direct manual calculations. This approach aims to measure the accuracy of the assembled pH sensor module and to ensure that the system can provide reliable measurement results under various temperature conditions. Therefore, this evaluation is important in optimizing the performance of the pH sensor system for practical applications that require high precision.

### III. RESULT AND DISCUSSION

Before monitoring pH, the pH sensor must first be calibrated using pH 4 and pH 7 buffer solutions to ensure the accuracy of the measurement results. This calibration process is carried out at a standard temperature, so that the sensor can provide consistent and reliable data. Additionally, the sensor is cleaned before and after the calibration process to prevent contamination that could affect pH measurement results. Once calibration is complete and the sensor is in optimal condition, pH monitoring can be conducted on a regular basis as needed. The pH calibration results for the sensor are shown below:

TABLE 2  
SENSOR CALIBRATION DATA WITH PH 4 AND PH 7 BUFFER SOLUTION

pH Buffer Solution	Analog Temp Value (mV)	Temp (°C)	pH	Analog pH Value (mV) with Offset (1.25V)
pH 4 Buffer Solution	324	24 °C	4.00	1432
pH 7 Buffer Solution	324	24 °C	7.00	1251

The analog voltage value measured at pH 4 is 177 mV, while at pH 7 it is 0 mV. However, by providing an analog voltage offset of 1250 mV, the microcontroller can read and manage the resulting pH value better. The analog offset value for pH can be seen in Table 1. From the calibration pH, an analog temperature value of 324 mV was obtained, and pH values of 1432 mV at pH 4 and 1251 mV at pH 7. To measure the pH slope for pH measurement monitoring, it can be described below:

- At pH 4: 1431- 1251 = 180 mV
- At pH 7: 1251-1251 = 1 mV

$$slope = \frac{180 - 1}{4 - 7} = \frac{179}{3} = 59.6$$

For pH measurements at various temperatures, researchers can determine the slope value of the pH electrode based on temperature changes, using the formula below:

$$S(T_{sample}) = S(T_{cal}) * \frac{T(sample) + 273.15}{T(Cal) + 273.15}$$

From the temperature slope measurement, the pH measured was around 59.6 mV, but in the programming system, the slope was listed as around 60 mV. To determine the percentage of error in a measurement, you can use the formula below:

$$\%Error = \frac{Sample Value - accurate value}{accurate value} * 100\%$$

Using the error percentage formula. The slope error percentage based on the formula is 0.67%.

After the calibration process was complete, buffer solutions with pH 4, pH 7, and pH 10 were observed under two conditions: measurement at standard temperature (room temperature) and measurement after the buffer solution was cooled in a refrigerator. The temperature data under both conditions were compared using a thermometer. The monitoring results are shown in the sub-section below:

#### A. Measurement of Buffer Solutions at Standard Temperature

Monitoring buffer solutions using three types of solutions, namely pH 4, pH 7, and pH 10 at standard temperature. Temperature measurements were taken using an RTD PT1000 and a thermometer as a temperature reference. The monitoring results are shown below:

##### 1) Measurement of Temperature and pH in a pH 4 Buffer Solution under Standard Conditions

###### a) Temperature measurement in buffer solution with pH 4

For monitoring temperature measurements, the results can be displayed in the table below:

TABLE 3  
MONITORING THE TEMPERATURE OF A PH 4 BUFFER SOLUTION

Test	Thermometer	RTD Sensor	Temp Diff	Error Temp (%)	Slope based on RTD sensor (mV)
1	21°C	24°C	-3°C	14.3	59.6
2	21°C	23°C	-2°C	14.3	59.39
3	21°C	24°C	-3°C	14.3	59.6
4	21°C	23°C	-2°C	9.5	59.39
5	21°C	23°C	-2°C	9.5	59.39
6	21°C	23°C	-2°C	9.5	59.39
7	21°C	24°C	-3°C	14.3	59.6
8	21°C	23°C	-2°C	9.5	59.39
9	21°C	23°C	-2°C	9.5	59.39
10	21°C	24°C	-3°C	14.3	59.6
Avg	21°C	23.4°C	-2.4°C	11.9	59.47

Based on Table 3, the temperature measurements using a thermometer and a Resistance Temperature Detector (RTD) sensor show consistent differences. The temperature recorded using the thermometer remains around 21°C, while the RTD sensor records temperatures between 23°C and 24°C. The temperature difference between the two devices ranges from 2°C to 3°C, with the percentage difference (error) in temperature measurements between the RTD and thermometer falling within the range of 9.5% to 14.3%, where the values measured by the RTD are always higher. For the pH slope, the slope value based on the RTD sensor measurements in the table was relatively stable, ranging from 59.39 mV at a temperature of 23°C to 59.6 mV at a temperature of 24°C. The average slope value from ten measurements was 59.47 mV. To clarify, the difference in the temperature measurement graph for a pH 4 buffer solution can be seen in the following graph:

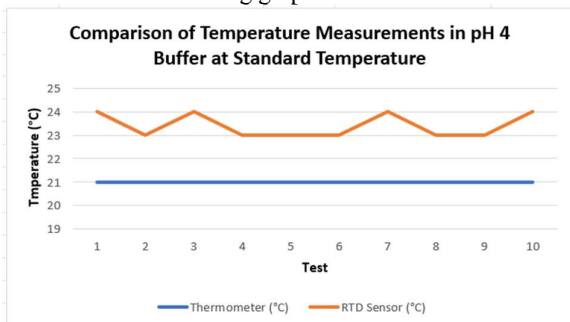


Figure 3. 1 Comparison graph of temperature measurements in pH 4 buffer fluid at standard temperature

b) pH Measurement in Buffer Solutions with pH 4

For monitoring pH measurements, the results can be displayed in the table below:

TABLE 4  
MONITORING OF PH 4 BUFFER SOLUTION

Test	Results of pH measurement			pH Diff
	Analog pH Value (mV)	pH based on the formula	pH based on program	
1	1432	3.96	3.99	-0.03
2	1422	4.13	3.99	0.14
3	1422	4.13	4.1	0.03
4	1418	4.19	4.2	-0.01
5	1437	3.87	3.97	-0.1
6	1427	4.04	4.05	-0.01
7	1432	3.96	3.94	0.02
8	1432	3.96	3.94	0.02
9	1431	3.97	4.15	-0.18
10	1432	3.94	3.96	-0.02
Avg	1428.5	4.01	4.02	-0.01

Based on Table 4, the pH 4 measurement data using the formula and application of the system on the HMI shows that both methods produce very similar pH values, with an average difference of only 0.01. The pH difference between the two methods ranges from 0.01 to 0.18, with most tests showing a very small difference. The average pH from the formula calculation is 4.01, while the average pH from the program is 4.02. The percentage error based on the average measurement ranges from 0.25% to 0.5%. To clarify, the difference in the pH measurement graph for the pH 4 buffer solution can be seen in the following graph:

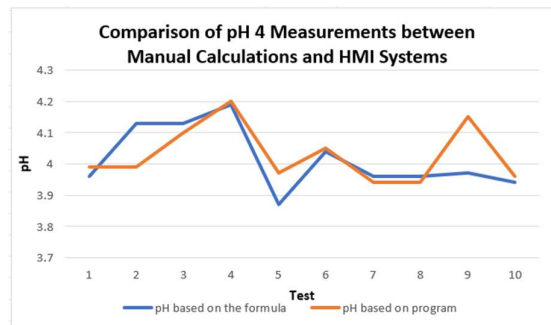


Figure 3. 2 Comparison of pH 4 Measurements between Manual Calculations and HMI Systems

2) Measurement of Temperature and pH in a pH 7 Buffer Solution under Standard Conditions

a) Temperature measurement in buffer solution with pH 7

For monitoring temperature measurements, the results can be displayed in the table below:

TABLE 5  
MONITORING THE TEMPERATURE OF A PH 7 BUFFER SOLUTION

Test	Thermometer	RTD Sensor	Temp Diff	Error Temp (%)	Slope based on RTD sensor (mV)
1	20°C	23°C	-3°C	15	59.39
2	20°C	22°C	-2°C	10	59.19
3	20°C	23°C	-3°C	15	59.39
4	20°C	22°C	-2°C	10	59.19
5	20°C	22°C	-2°C	10	59.19
6	20°C	22°C	-2°C	10	59.19
7	20°C	22°C	-2°C	10	59.19
8	20°C	23°C	-3°C	15	59.39
9	20°C	22°C	-2°C	10	59.19
10	20°C	23°C	-3°C	15	59.39
Avg	20°C	22.4°C	-2.4°C	12	59.27

Based on Table 5, temperature measurements using a thermometer and a Resistance Temperature Detector (RTD) sensor show consistent differences. The temperature recorded using the thermometer remains around 20°C, while the RTD sensor records temperatures between 22°C and 23°C. The temperature difference between the two devices ranges from 2°C to 3°C, with the percentage difference (error) in temperature measurements between the RTD and thermometer falling within the range of 10% to 15%, where the values measured by the RTD are always higher. For pH slope, the slope values based on RTD sensor measurements in the table are relatively stable, ranging from 59.19 mV at 22°C to 59.39 mV at 23°C. The average slope value from ten measurements is 59.27 mV. To clarify, the differences in the temperature measurement graph for the pH 7 buffer solution

can be seen in the following graph:

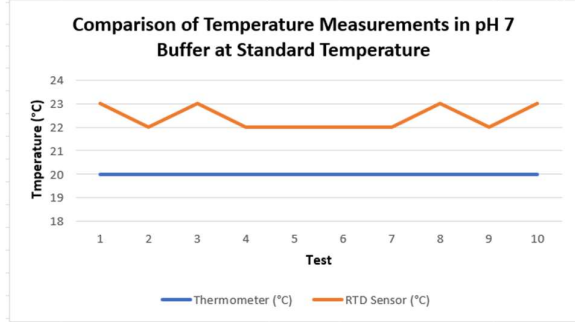


Figure 3.3 Comparison graph of temperature measurements in pH 7 buffer fluid at standard temperature

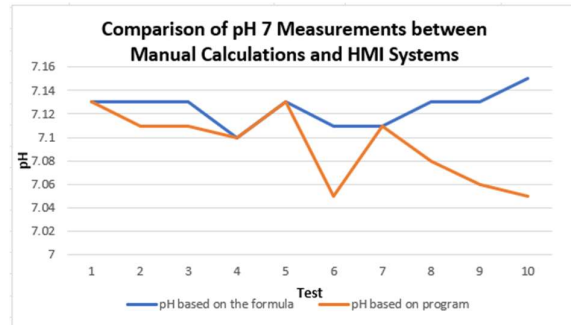


Figure 3.4 Comparison of pH 7 Measurements between Manual Calculations and HMI Systems

3) Measurement of Temperature and pH in a pH 10 Buffer Solution under Standard Conditions

a) Temperature measurement in buffer solution with pH 10

For monitoring temperature measurements, the results can be displayed in the table below:

TABLE 7  
MONITORING THE TEMPERATURE OF A PH 10 BUFFER SOLUTION

Test	Thermometer	RTD Sensor	Temp Diff	Error Temp (%)	Slope based on RTD sensor (mV)
1	23°C	25°C	-2°C	8.69	59.8
2	23°C	25°C	-2°C	8.69	59.8
3	23°C	24°C	-1°C	4.34	59.6
4	23°C	24°C	-1°C	4.34	59.6
5	23°C	24°C	-1°C	4.34	59.6
6	23°C	25°C	-2°C	8.69	59.8
7	23°C	25°C	-2°C	8.69	59.8
8	23°C	24°C	-1°C	4.34	59.6
9	23°C	25°C	-2°C	8.69	59.8
10	23°C	25°C	-2°C	8.69	59.8
Avg	23°C	24.6°C	-1.6°C	6.95	59.72

Based on Table 7, temperature measurements using a thermometer and a Resistance Temperature Detector (RTD) sensor show consistent differences. The temperature recorded using the thermometer remains around 23°C, while the RTD sensor records temperatures between 24°C and 25°C. The temperature difference between the two devices ranges from 1°C to 2°C, with the percentage difference (error) in temperature measurements between the RTD and thermometer ranging from 4.34% to 8.69%, where the values measured by the RTD are always higher. For pH slope, the slope values based on RTD sensor measurements in the table are relatively stable, ranging from 59.6 mV at 24°C to 59.8 mV at 25°C. The average slope value from ten measurements is 59.72 mV. To clarify, the differences in the temperature measurement graph for the pH 10 buffer solution can be seen

b) pH Measurement in Buffer Solutions with pH 7

For monitoring pH measurements, the results can be displayed in the table below:

TABLE 6  
MONITORING OF PH 7 BUFFER SOLUTION

Test	Results of pH measurement			pH Diff
	Analog pH Value (mV)	pH based on the formula	pH based on program	
1	1243	7.13	7.13	0
2	1243	7.13	7.11	0.02
3	1243	7.13	7.11	0.02
4	1245	7.10	7.10	0
5	1243	7.13	7.13	0
6	1244	7.11	7.05	0.06
7	1244	7.11	7.11	0
8	1243	7.13	7.08	0.05
9	1243	7.13	7.06	0.07
10	1442	7.15	7.05	0.1
Avg	1263.3	7.12	7.09	0.03

Based on Table 6, pH 7 measurement data using the formula and the application of the program system on the HMI show that both methods produce very similar pH values, with an average difference of only 0.03. The pH difference between the two methods ranges from 0.02 to 0.1, with most tests showing very small differences. The average pH from the formula calculation is 7.09, while the average pH from the program is 7.12. The percentage error based on the average measurement ranges from 1.28% to 1.71%. To clarify, the differences in the pH measurement graphs for the pH 4 buffersolution can be seen in the following graph:

in the following graph:

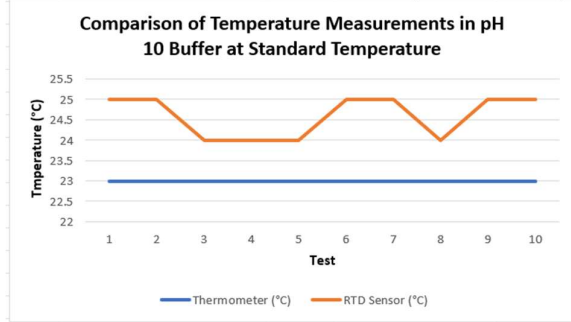


Figure 3. 5 Comparison graph of temperature measurements in pH 10 buffer fluid at standard temperature

b) pH Measurement in Buffer Solutions with pH 10

For monitoring pH measurements, the results can be displayed in the table below:

TABLE 8  
MONITORING OF pH 10 BUFFER SOLUTION

Results of pH measurement				
Test	Analog pH Value (mV)	pH based on the formula	pH based on program	pH Diff
1	1057	10.25	10.11	0.14
2	1063	10.15	10.15	0
3	1058	10.23	10.13	0.1
4	1057	10.25	10.11	0.14
5	1073	9.98	9.96	0.02
6	1073	9.98	9.96	0.02
7	1053	10.12	9.98	0.14
8	1058	10.23	10.13	0.1
9	1055	10.28	10.08	0.2
10	1063	10.15	10.15	0
Avg	1061	10.16	10.07	0.08

Based on Table 8, pH 10 measurement data using the formula and the application of the program system on the HMI show that both methods produce very similar pH values, with an average difference of only 0.08. The pH difference between the two methods ranges from 0.02 to 0.14, with most tests showing very small differences. The average pH from the formula calculation is 10.16, while the average pH from the program is 10.07. The percentage error based on the average measurement ranges from 0.7% to 1.6%. To clarify, the differences in the pH measurement graphs for a pH 10 buffer solution can be seen in the following graph:

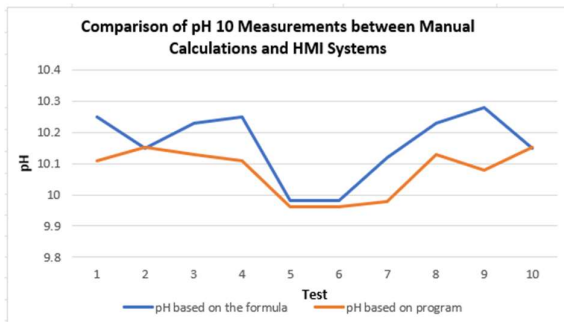


Figure 3. 6 Comparison of pH 7 Measurements between Manual Calculations and HMI Systems

B. Measurement of Buffer Solution after Cooling

Monitoring of buffer solutions using three types of solutions, namely pH 4, pH 7, and pH 10, which have been cooled in a refrigerator. Temperature measurements were

taken using an RTD PT1000 and a thermometer as a temperature reference. The monitoring results are shown below:

1) Measurement Data for Temperature and pH of pH 4 Buffer Solution After Cooling

a) Measurement of temperature in a buffer solution with pH 4 after cooling

For monitoring temperature measurements, the results can be displayed in the table below:

TABLE 9  
MONITORING THE TEMPERATURE OF pH 4 BUFFER SOLUTION AFTER COOLING

Test	Thermometer	RTD Sensor	Temp Diff	Error Temp (%)	Slope based on RTD sensor (mV)
1	12°C	11°C	1°C	8.33	56.99
2	12°C	12°C	0°C	0	57.19
3	12°C	12°C	0°C	0	57.19
4	12°C	12°C	0°C	0	57.19
5	12°C	12°C	0°C	0	57.19
6	12°C	12°C	0°C	0	57.19
7	12°C	13°C	-1°C	8.33	57.39
8	12°C	13°C	-1°C	8.33	57.39
9	12°C	13°C	-1°C	8.33	57.39
10	12°C	13°C	-1°C	8.33	57.39
Avg	12°C	12.3°C	-0.3°C	4.16	57.25

Based on Table 9, the temperature measurement results using a thermometer showed a value of around 12°C, while measurements with a Resistance Temperature Detector (RTD) sensor were in the range of 11°C to 13°C. There is a difference in temperature measurement results between the RTD and the thermometer of approximately 4.16%, where the RTD readings tend to fluctuate in response to changes in the temperature of the liquid. Additionally, the pH slope values from the temperature measurements range from 56.99 mV to 57.39 mV. To clarify, the differences in the temperature measurement graph for the pH 4 buffer solution can be seen in the following graph:

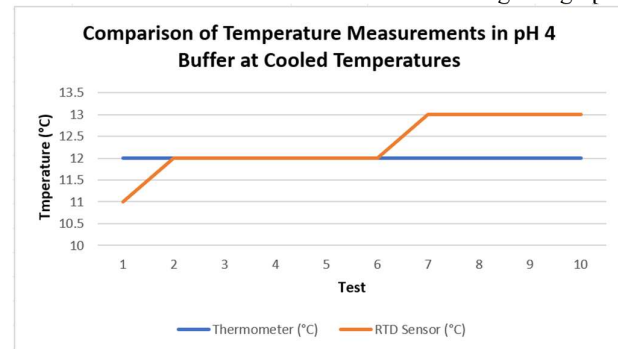


Figure 3. 7 Comparison of Temperature Measurements in pH 4 Buffer at Cooled Temperatures

b) Measurement of pH in a buffer solution with a pH of 4 after cooling

For monitoring pH measurements, the results can be displayed in the table below:

TABLE 10  
pH MONITORING OF COOLED pH 4 BUFFER SOLUTION

Test	RTD Sensor Temp	Results of pH measurement			pH Diff
		Analog pH	pH no temp compensation	pH with temp compensation	
1	11°C	10.11	10.11	10.11	0.00
2	12°C	10.15	10.15	10.15	0.00
3	12°C	10.23	10.23	10.23	0.00
4	12°C	10.25	10.25	10.25	0.00
5	12°C	9.98	9.98	9.98	0.00
6	12°C	9.98	9.98	9.98	0.00
7	13°C	10.12	10.12	10.12	0.00
8	13°C	10.23	10.23	10.23	0.00
9	13°C	10.28	10.28	10.28	0.00
10	13°C	10.15	10.15	10.15	0.00
Avg	12.3°C	10.16	10.07	10.16	0.08

		Value (mV)			
1	11°C	1421	4.10	4.06	0.04
2	12°C	1422	4.07	4.02	0.05
3	12°C	1425	4.02	3.97	0.05
4	12°C	1434	4.04	3.99	0.05
5	12°C	1428	4.12	4.07	0.05
6	12°C	1423	4.12	4.02	0.1
7	13°C	1426	4.09	4.04	0.05
8	13°C	1426	4.10	4.06	0.04
9	13°C	1422	4.07	4.02	0.05
10	13°C	1425	4.14	4.09	0.05
Avg	12.3°C	1425.2	4.08	4.03	0.05

Based on Table 10, for the monitoring of pH in a cooled pH 4 buffer solution, the measurement results showed a shift in pH value, with an average shift of 0.5 pH. pH measurements using the Automatic Temperature Compensation (ATC) system were found to be more accurate compared to those without ATC, with the percent error between measurements with ATC and without ATC recorded at around 1.24%. To clarify, the differences in the pH measurement graph for the pH 4 buffer solution can be seen in the following graph:

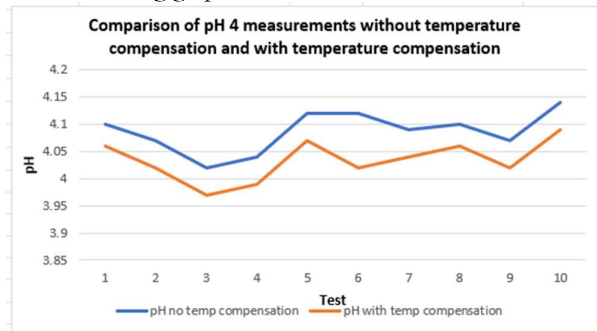


Figure 3. 8 Comparison of pH 4 measurements without temperature compensation and with temperature compensation

c) Analysis of data processing accuracy in microcontrollers at pH 4

The analysis of the accuracy of the ATC system in pH measurements is presented in the table below:

TABLE 11  
ANALYSIS pH MONITORING OF COOLED PH 4 BUFFER SOLUTION

Test	RTD Sensor Temp	Results of pH measurement with temperature compensation			pH Diff
		Analog pH Value (mV)	pH based on the formula	pH based on program	
1	11°C	1421	4.01	4.06	0.05
2	12°C	1422	4.01	4.02	0.01
3	12°C	1425	3.95	3.97	0.02
4	12°C	1434	3.80	3.99	0.19
5	12°C	1428	3.90	4.07	0.17
6	12°C	1423	3.99	4.02	0.03
7	13°C	1426	3.95	4.04	0.09
8	13°C	1426	3.95	4.06	0.11
9	13°C	1422	4.02	4.02	0
10	13°C	1425	4.02	4.09	0.07
Avg	12.3°C	1425.2	3.96	4.03	-0.07

Based on Table 11, the pH values obtained from temperature-compensated analog (mV) pH measurements, both through the program and formulas, showed only a small difference between the two methods. The average pH based on the program was 4.03, while the average calculated using formulas was 3.96, with an average difference (pH Diff) of 0.07. To clarify, the differences in the pH measurement graph

for the pH 4 buffer solution can be seen in the following graph:

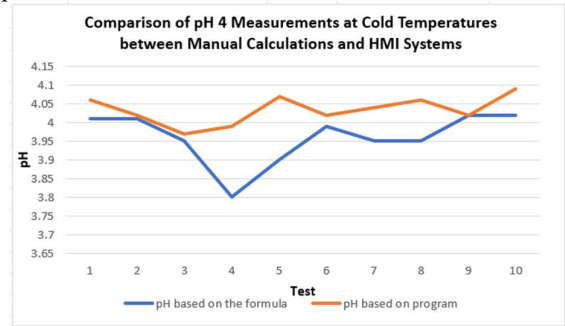


Figure 3. 9 Comparison of pH 4 Measurements at Cold Temperatures between Manual Calculations and HMI Systems

2) Measurement Data for Temperature and pH of pH 7 Buffer Solution After Cooling

a) Measurement of temperature in a buffer solution with pH 7 after cooling

For monitoring temperature measurements, the results can be displayed in the table below:

TABLE 12  
MONITORING THE TEMPERATURE OF PH 7 BUFFER SOLUTION AFTER COOLING

Test	Thermometer	RTD Sensor	Temp Diff	Error Temp (%)	Slope based on RTD sensor (mV)
1	14°C	14°C	0°C	0	57.59
2	14°C	14°C	0°C	0	57.59
3	14°C	14°C	0°C	0	57.59
4	14°C	14°C	0°C	0	57.59
5	14°C	15°C	-1°C	7.14	57.79
6	14°C	14°C	0°C	0	57.59
7	14°C	15°C	-1°C	7.14	57.79
8	14°C	14°C	0°C	0	57.59
9	14°C	15°C	-1°C	7.14	57.79
10	14°C	15°C	-1°C	7.14	57.79
Avg	14°C	14.4°C	0.4°C	2.8	57.67

Based on Table 12, the temperature measurement results using a thermometer showed a value of around 14°C, while measurements with a Resistance Temperature Detector (RTD) sensor were in the range of 14°C to 15°C. There is a difference in temperature measurement results between the RTD and the thermometer of approximately 2.8%, where the RTD readings tend to fluctuate in response to changes in fluid temperature. Additionally, the pH slope values from the temperature measurements range from 57.59 mV to 57.79 mV. To clarify, the differences in the temperature measurement graph for a pH 7 buffer solution can be seen in the following graph:

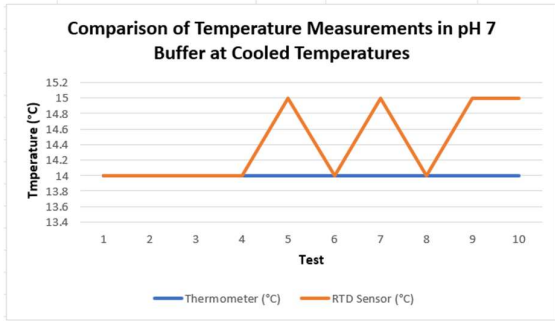


Figure 3. 10 Comparison of Temperature Measurements in pH 7 Buffer at Cooled Temperatures

b) *Measurement of pH in a buffer solution with a pH of 7 after cooling*

For monitoring pH measurements, the results can be displayed in the table below:

TABLE 13  
PH MONITORING OF COOLED PH 7 BUFFER SOLUTION

Test	RTD Sensor Temp	Results of pH measurement			pH Diff
		Analog pH Value (mV)	pH no temp compensation	pH with temp compensation	
1	14°C	1253	6.99	6.99	0
2	14°C	1254	6.97	6.97	0
3	14°C	1251	6.97	6.97	0
4	14°C	1253	6.99	6.99	0
5	15°C	1253	6.99	6.99	0
6	14°C	1252	6.97	6.97	0
7	15°C	1252	7.00	7.00	0
8	14°C	1253	6.97	6.97	0
9	15°C	1250	6.99	6.99	0
10	15°C	1252	7.00	7.00	0
Avg	14.4°C	1252.3	6.98	6.98	0

Based on Table 13, the measurement results show that the pH values obtained from both methods were the same in each test, with no significant shift in pH. However, in some experiments, the pH change still showed instability, with the pH value shifting from 6.97 to 7.00. The percentage error of the pH measurement based on the pH 7 buffer solution compared to the measurements made by the researchers ranged from 0.42%.

c) *Analysis of data processing accuracy in microcontrollers at pH 7*

The analysis of the accuracy of the ATC system in pH measurements is presented in the table below.

TABLE 14  
ANALYSIS PH MONITORING OF COOLED PH 7 BUFFER SOLUTION

Test	RTD Sensor Temp	Results of pH measurement with temperature compensation			pH Diff
		Analog pH Value (mV)	pH based on the formula	pH based on program	
1	14°C	1253	6.96	6.99	-0.03
2	14°C	1254	6.94	6.97	-0.03
3	14°C	1251	7.00	6.97	0.03
4	14°C	1253	6.96	6.99	-0.03
5	15°C	1253	6.96	6.99	-0.03
6	14°C	1252	6.98	6.97	0.01
7	15°C	1252	6.98	7.00	-0.02

8	14°C	1253	6.96	6.97	-0.01
9	15°C	1250	7.00	6.99	0.01
10	15°C	1252	6.98	7.00	-0.02
Avg	14.4°C	1252.3	6.97	6.98	-0.01

Based on Table 14, the pH values obtained from analog measurements (mV) and corrected for temperature, both by program and formula, show little difference between the two methods. The average pH based on the formula is 6.97, while that based on the program is 6.98, with an average difference (pH Diff) of 0.02. To clarify, the difference in the pH measurement graph of the pH 7 buffer solution can be seen in the following graph:

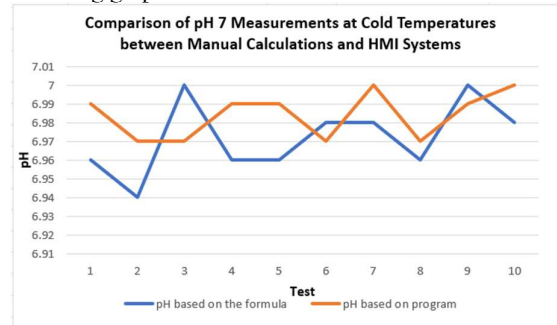


Figure 3. 11 Comparison of pH 7 Measurements at Cold Temperatures between Manual Calculations and HMI Systems

3) *Measurement Data for Temperature and pH of pH 7 Buffer Solution After Cooling*

a) *Measurement of temperature in a buffer solution with pH 10 after cooling*

For monitoring temperature measurements, the results can be displayed in the table below:

TABLE 15  
MONITORING THE TEMPERATURE OF PH 10 BUFFER SOLUTION AFTER COOLING

Test	Thermometer	RTD Sensor	Temp Diff	Error Temp (%)	Slope based on RTD sensor (mV)
1	16°C	17°C	-1°C	6.25	58.19
2	16°C	15°C	1°C	6.25	57.79
3	16°C	17°C	-1°C	6.25	58.19
4	16°C	16°C	0°C	0	57.99
5	16°C	16°C	0°C	0	57.99
6	16°C	17°C	-1°C	6.25	58.19
7	16°C	17°C	-1°C	6.25	58.19
8	16°C	15°C	1°C	6.25	57.79
9	16°C	15°C	1°C	6.25	57.79
10	16°C	16°C	0°C	0	57.99
Avg	16°C	16.1°C	-0.1°C	4.3	57.85

Based on Table 15, temperature measurements using a thermometer showed a value of around 16°C, while measurements using a Resistance Temperature Detector (RTD) sensor were in the range of 15°C to 17°C. There is a difference in temperature measurement results between the RTD and the thermometer of approximately 4.3%, where the RTD readings tend to fluctuate in response to changes in fluid temperature. Additionally, the pH slope values from temperature measurements range from 57.79 mV to 58.19 mV. For clarification, the differences in the temperature



Measurements on standard pH solutions	4	4.01	4.02	1.7
	7	7.12	7.09	0.2
	10	10.16	10.07	0.4
Measurement of cooled pH solutions	4	3.96	4.03	0.1
	7	6.97	6.98	0.4
	10	10.10	10.05	0.8
Average				0.6

Based on the data in Table 18, the average measurement error percentage is 0.6%, resulting in an average measurement accuracy percentage of 99.4%. This percentage indicates that the system can be used to measure pH levels with temperature compensation if temperature changes occur during the monitoring process. However, measurement accuracy up to 0.01 pH has not yet been fully achieved.

#### IV. CONCLUSION

Based on the results of monitoring and analysis of pH buffer solution measurements at standard temperature and after the cooling process, it can be concluded that the application of an automatic temperature compensation (ATC) system can improve the accuracy of pH measurements, especially when temperature changes occur. However, accuracy up to 0.01 pH has not yet been fully achieved. This is evidenced by a comparison between manual calculations and measurements using a microcontroller, where the microcontroller system still produces slightly different and less accurate values compared to manual calculations, with an average accuracy percentage of 99.4% and an average error percentage of 0.6%.

Measurement errors in microcontrollers can occur due to noise in the amplifier module. Noise greatly affects pH measurements. Fluctuations in analog pH measurements affect the optimization of microcontroller readings and data processing, which can influence pH data measurements in a solution. Recommendations for further research include optimizing analog pH signal measurements, particularly in differential pH sensors. Optimizing the amplifier module, such as reducing noise and improving the quality of the analog pH signal output, will significantly impact the accuracy of microcontroller readings. Such optimization can be achieved by applying an appropriate low-pass filter to reduce noise.

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