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Graduate Attribute 4

Investigations, Experiments and Data Analysis

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Abstract- This report investigates the performance and optimisation of a temperature control system using manual and PID control methods. Experiments were conducted to evaluate the system's heating and cooling behaviour under various conditions, with data collected and analysed using the HMI data logging feature. The study compared the efficiency of manual control, manual PID tuning using the Ziegler-Nichols method, and PID autotuning. Results indicate that the autotuned PID controller provided more consistent temperature regulation with minimal oscillations. Recommendations for system improvement include increasing sample size and testing across multiple setpoints to enhance the accuracy and reliability of the control system.

Assignment Declaration

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Nomenclature

CSV	Comma Separated Value
I/O	Input/Output
PID	Proportional Integral Derivative
PLC	Programmable Logic Controller
RTD	Resistance Temperature Detector
PV	Process Variable
SP	Set Point
ZN	Ziegler-Nichols

1.0 Plans and Conducts Investigations and Experiments

The following section describes the experimental approach to analysing a temperature measurement system. The experimental test plan below is carefully laid out with the primary objective of giving the reader insight into the system at hand and how the data readings collected were statistically analysed to understand the system more deeply.

1.1 Parameter Design Plan

The temperature control system used in this data analysis included two fans, a heat sink and a PT100 Resistance Temperature Detector (RTD). The various other components can be seen in Figure 1 below. The temperature of the system is increased by heating the heat sink and decreased by turning on the cooling fans on either side of the heat sink.

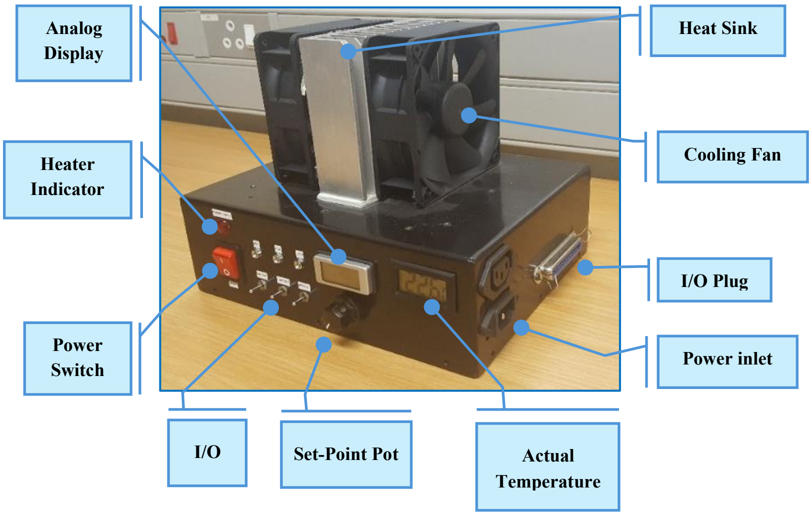


Figure 1: Temperature Control Test System

1.1.1 Variables

Variables are units that influence the outcome of the experiment. Unlike dependent variables, independent variables can be changed independently of other variables. There may also be extraneous variables which cannot be controlled during the measuring process but could affect the readings.

Table 1: Temperature measurement system variables

Dependent Variables	Independent Variables	Extraneous Variables
Heat Sink Temperature	Fan Speed	Ambient Temperature
	Setpoint Temperature	Humidity
	Time	Interference
		Noise
		Heat Sink Material

The cause and effect diagram below shows the independent and extraneous variables and their influence on the heat sink temperature (dependent Variable).

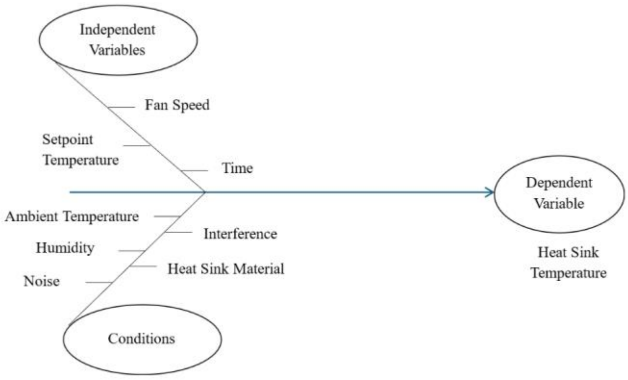


Figure 2: Cause and effect relationship of temperature control system

1.1.2 Parameters

The temperature control system incorporates various digital and analog inputs and outputs, outlined in Figure 3, to manage and monitor the system effectively.

TEMPERATURE STATION I/O	
DIGITAL INPUTS	SWITCH 1
	SWITCH 2
	SWITCH 3
DIGITAL OUTPUTS	LED 1
	LED 2
	LED 3
	HEATER RELAY
ANALOG INPUTS	SETPOINT POTENTIOMETER
	TEMP SENSOR FEEDBACK
ANALOG OUTPUTS	LCD DISPLAY
	FAN SPEED CONTROL

Figure 3: Inputs and outputs of the temperature station

1.2 System and Tolerance Design Plan

This system and tolerance design plan outlines the equipment, technique, and test procedure used to collect readings and ensure the reliability of the data collected.

1.2.1 Measurement Technique

Methods to accurately measure and record temperature data during the experiments were taken, minimising errors and uncertainties. The following steps were taken to achieve reliable data readings throughout this experiment:

1. Device Configuration:
    - The first step to ensuring the system can operate is to configure the device (PLC), connecting the program to the controller. Furthermore, compiling and downloading the program to the device is essential to start the HMI simulation.
2. Data Acquisition:
    - Set an appropriate sampling rate, ensuring sufficient time to capture temperature changes.
3. Temperature Control:

- Use the heat sink and cooling fans to maintain stable temperature conditions. Ensure that the cooling fans operate at specified speeds to achieve the desired temperature control.

4. Setpoint Adjustment:
    - Use the potentiometer to set and adjust the desired temperature set point (SP) accurately. Confirm the setpoint settings by checking the SP on the HMI.
5. Data Logging:
    - Use the HMI's data logging feature to record temperature readings throughout the experiment. Ensure that the HMI is correctly configured to log data at the specified intervals and store it in a format suitable for analysis.
6. Export Data:
    - After obtaining the comma-separated value (CSV) files from the PLC's IP address, export the logged data to Excel for further analysis and visualisation.

1.2.2 Equipment

The following equipment on the temperature measurement station was used to obtain readings during the experiment:

1. Temperature System Control Box
2. Heat Sink
3. Cooling Fans
4. PT100 Resistance Temperature Detector
5. Potentiometer

1.2.3 Software Scaling

The requirement was to record readings using the HMI data logging feature and analyse the readings in Excel. The PLC program for the temperature control system had already been developed using the software and hardware described below.

Programming Software:

- SIEMENS TIA Portal: A tool for programming and configuration of Siemens PLCs.
- SIEMENS TIA Portal HMI Simulation: A tool for testing HMIs with a simulation.

Programming Hardware:

- SIEMENS S7-1200 CPU: Programmable logic controller.

1.3 Data Reduction Design Plan

1.3.1 Sensor Calibration

Sensor calibration is essential to ensure the accuracy and reliability of temperature measurements. The calibration process involves comparing the sensor readings against a known temperature standard and making necessary adjustments to eliminate any offset. This process helps in maintaining the precision of the measurements and ensures the sensor operates within its specified accuracy range.

If the sensor reading deviates from the known standard, the sensor's calibration settings require adjustments to correct the offset. The comparison of the sensor to known standards can be repeated at different temperature points for more accurate calibration.

1.4 PID Control Implementation and Tuning

The schematic diagram of the temperature control system in Figure 4 illustrates the use of the RTD sensor, the A/D converter, the PID controller, and the actuators (heating element and fan). The closed-loop control system illustrates the primary objective of the temperature station to maintain a set point temperature by receiving feedback from the PT100. During PID mode, the controller controls the system by switching on and off the heater and fans to maintain the temperature selected by the user.

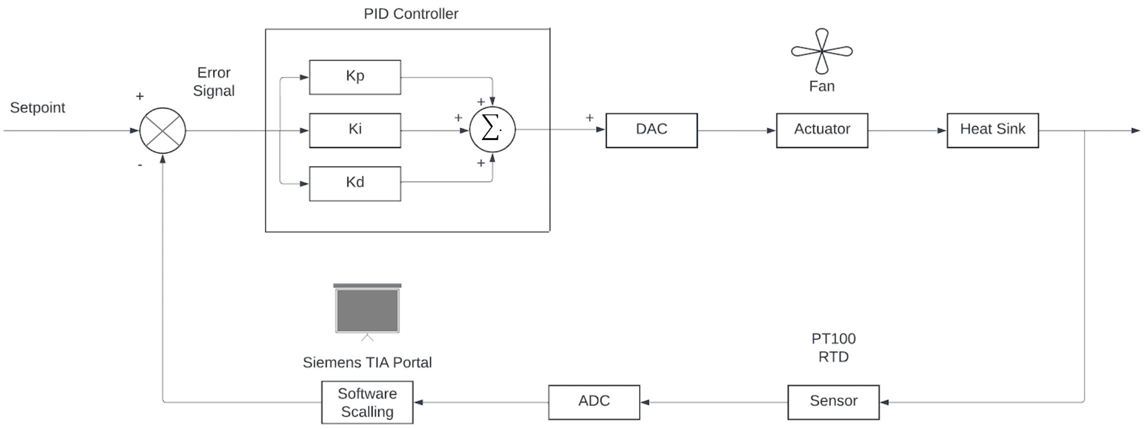


Figure 4: Temperature station closed-loop control system

The components of the closed-loop feedback control system in Figure 4 include:

1. Setpoint: The desired temperature set by the user.
2. Error Calculation: The difference between the setpoint and the measured temperature.
3. PID Controller: Adjusts the control outputs (heater and fan) based on the error.
4. DAC (Digital-to-Analog Converter): Converts the digital input from the user to an analog signal that the actuators can read.
5. Actuators: The heat sink and fan heat or cool the system, depending on the error.
6. Sensor: A device (PT100 in this case) that measures the output temperature of the system.
7. ADC (Analog-to-Digital Converter): Converts the analog signal from the sensor to a digital signal to display the current temperature of the system on an LCD.

The controller maintains the set point temperature using a DAC by turning the fans and heat sink ON and OFF. The PID, PI, or P controller receives feedback from the PT100 RTD, indicating the output temperature using an ADC. If the temperature is below or above the set point, the controller switches ON and OFF the fan and heat sink, maintaining the desired temperature.

1.5 Planning Flow Chart

The flow chart in Figure 5, outlines the systematic approach taken to conduct experiments for the temperature control system. This experimental plan was intended to evaluate the heating and cooling performance of the system, adjust PID control parameters, and analyse the data to ensure accurate temperature regulation.

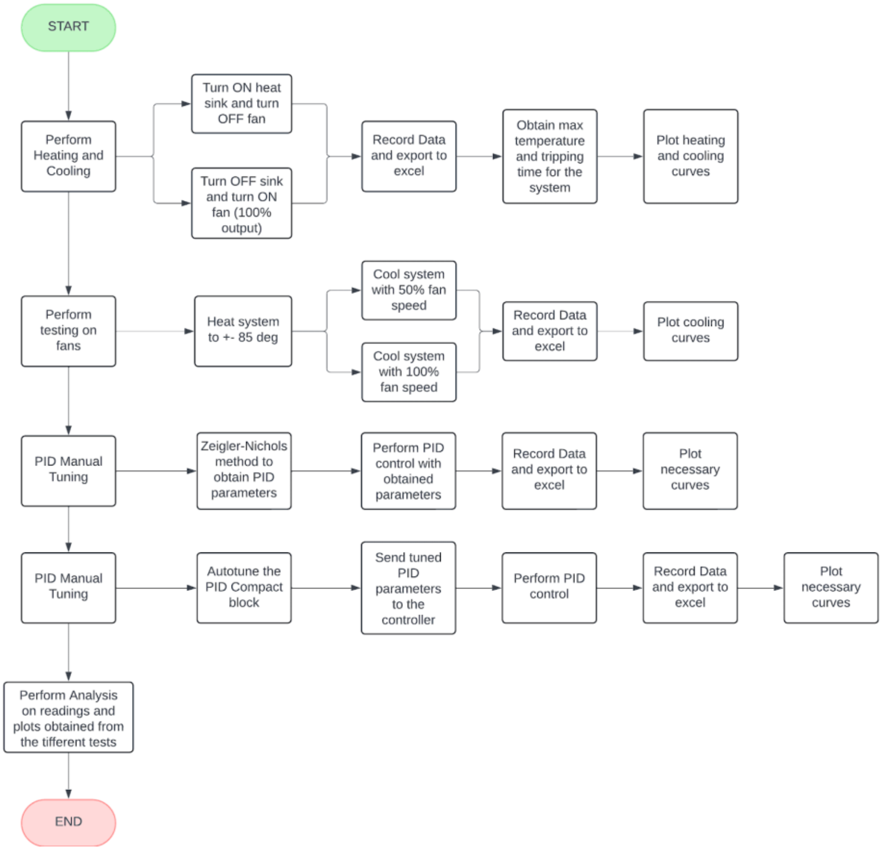


Figure 5: Experimental plan flow chart

The procedure included manual and automated control modes, data recording, and analysis, with the ultimate goal of achieving stable and accurate temperature control.

1.6 Process Control Tuning

The primary objective of this investigation was to implement a controller to maintain a desired (setpoint) temperature chosen by the operator. Experiments were conducted to test various control methods, analyse their readings and discuss the results. Tuning the controller is crucial to ensure regulation of the output temperature. The two methodologies under investigation were manual and automatic tuning of PID parameters, both of which were performed using TIA Portal simulation software.

1.6.1 Manual Control Mode

In the manual control mode, the heating and cooling curves of the system were obtained using the Human-Machine Interface (HMI). This mode allowed for direct control over the system components without automatic regulation.

To test the heating conditions of the system, the following procedure was followed:

1. The system was initially cooled till $35°C$.
2. The fans were turned off.
3. The heat sink was turned on to start heating the system.
4. A sample size of 300 readings was used to ensure sufficient data was collected to observe the system reaching its maximum temperature threshold.
5. Once the heating test was complete, the fans were switched on and set to 100% to observe the system cooling.

To compare the cooling conditions at different fan speeds, the following procedure was followed:

1. The system was heated to approximately $85°C$.
2. The heat sink was turned off.
3. The fan speed was set to 50% and a sample size of 100 was recorded to observe the cooling curve.
4. The system was heated again to approximately $85°C$.
5. The heat sink was turned off.
6. The fan speed was set to 100% and a sample size of 100 readings was recorded to capture the cooling curve at double the fan speed.

The system's performance under manual control was examined by plotting the heating and cooling curves. This provided insights into the system's thermal dynamics and helped identify the conditions under which the system operates most efficiently.

1.6.2 PID Manual Control Mode

The primary objective of this mode was to manually tune the PID controller to maintain a setpoint temperature. The Ziegler-Nichols (ZN) method was used which involved determining the ultimate gain (K_u) and the oscillation period (T_u) of the system, which is then used to calculate the PID gains.

The procedure followed for ZN tuning:

1. The setpoint temperature was set to $75°C$.
2. The proportional gain (K_P) was initially set to 0.
3. The integral gain (K_i) and the derivative gain (K_d) were set to 0.
4. K_P was increased by 1 until the system achieved stable and consistent oscillations.
5. The value of K_P that resulted in these oscillations was identified as the ultimate gain K_u.
6. The period of the oscillations T_u was measured.
7. The ultimate gain and the oscillation period were used to calculate the PID parameters based on the type of controller (P, PI, or PID) using the formulas provided in Table 2.

Table 2: PID ultimate gain calculations

Controller	K_P	K_I	K_D
P	$0.5K_u$		
PI	$0.45K_u$	$0.83T_u$	
PID	$0.6K_u$	$0.5T_u$	$0.125T_u$

1.6.3 PID Autotune Control Mode

In the PID autotune control mode, the system automatically tunes the PID parameters to achieve the best performance. The following procedure outlines the steps taken to record and implement the autotune mode:

1. The fans were manually turned on to cool the system to a temperature below $30°C$.
2. Using the slider on the HMI, the setpoint temperature was adjusted to $75°C$.
3. Under program blocks in TIA Portal, the cyclic interrupt was opened and the PID compact block was located.
4. The controller type (Temperature) was selected in the configuration window and the commissioning window was opened.
5. On the HMI, the fan was turned off once the temperature was below $30°C$.
6. Manual mode was turned off, and ON-OFF control and PID autotune mode were turned on.
7. In the commissioning window, the sample time was started, as well as the tuning process.
8. The autotuning algorithm adjusted the PID parameters to minimise the error and achieve a stable response.
9. Once the PID tuning was complete, the tuned parameters were transferred to the controller.
10. The live plot on the HMI indicated the output temperature of the system using the tuned PID parameters, showing how the system responded to the new parameters.

2.0 Conducts a Literature Search and Critically Evaluates Material

The design stage uncertainty of the PT100 RTD and TH100 was performed to ensure accurate temperature measurements. Furthermore, a repeatability test was conducted to understand the reasons for fluctuations in test results under the same conditions.

2.1 Design Stage Uncertainty Analysis

The PT100 Resistance Temperature Detector (RTD) operates using a principle based on the correlation between a metal and temperature. These devices are one of the most popular in the industrial industry due to their reliability and wide operating range, as depicted in Table 3 (Wieber et al., 2024). The sensor measures the desired variable, which in this case is temperature, while the transducer converts this into an electrical signal. The design stage uncertainty of the PT100 RTD was performed.

Table 3: PT100 Temperature sensor specifications

Sensor Specifications	
Range	$-100\ to\ 250\ °C$
Resistance	$100\ \Omega\ \ (0°C)$
Accuracy	$\pm\ 0.1°C$
Resolution	$14 - bit\ ADC$

Table 4: TH100 Transducer specifications

Transducer Specifications	
Range	$4 -\ 20\ mA$
Resistance	$100\ \Omega$
Accuracy	$\pm 0.05\%\ FS$
Resolution	$14 - bit\ ADC$

The above tables were derived from technical datasheets found in Appendix A. These values prove significant in determining the design stage uncertainty for the system. The accuracy of the transducer was assumed to be $\pm$0.05% full-scale (FS). Throughout the calculations below, the variables related to the PT100 are represented with a subscript PT and variables for the TH100 are represented with a subscript TH.

Design stage uncertainty

$$u_d = \sqrt{(u_d)_{PT}^2 + (u_d)_{TH}^2}$$

Where,

$$(u_d)_{PT} = \sqrt{u_o^2 + u_c^2}$$

$$(u_d)_{TH} = \sqrt{u_o^2 + u_c^2}$$

Sensor:

$$Resolution = \frac{1}{2^{bits}} Range = \frac{250\,°C - (-100\,°C)}{2^{14}} = 0.0214°C = u_o$$

$$Accuracy = \pm 0.1°C = u_c$$

$$(u_d)_{PT} = \sqrt{(0.0214)^2 + (0.1)^2} = 0.1022°C$$

Transducer:

$$Resolution = \frac{1}{2^{bits}} Range = \frac{20mA - 4mA}{2^{14}} = 0.0009766mA = u_o$$

$$Accuracy = \pm 0.05\% \text{ x } (20mA - 4mA) = 0.008mA = u_c$$

$$(u_d)_{TH} = \sqrt{(0.0009766)^2 + (0.008)^2} = 0.00806mA$$

Converting mA to $°C$:

$$\frac{350°C}{16mA} = 21.875°C/mA$$

$$(u_d)_{TH} = 0.00806mA \text{ x } 21.875°C/mA = 0.176°C$$

Therefore, the total design stage uncertainty

$$u_d = \sqrt{(0.1022)^2 + (0.176)^2} = 0.204°C$$

The total design stage uncertainty of the temperature measurement system is approximately $\pm 0.204°C$. This uncertainty considers the PT100 RTD sensor and the transducer, ensuring a good understanding of the system's measurement accuracy. This level of uncertainty should be factored into the analysis of experimental results to account for potential measurement errors.

2.3 Repeatability of Sensor/Actuator at an Operating Point

The waveform in Figure 6 illustrates the repetitive strategy taken to record data sufficient to perform repeatability analysis on the heating and cooling of the temperature system at a set point temperature of $75°C$.

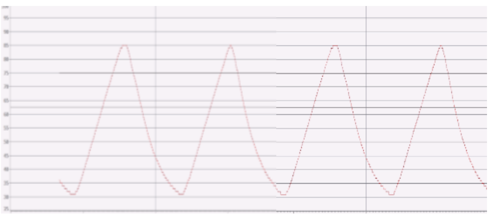


Figure 6: Repeatability test waveform

The results of the testing procedure outlined in the figure above, yield the heating and cooling curves shown in Figure 7 and Figure 8.

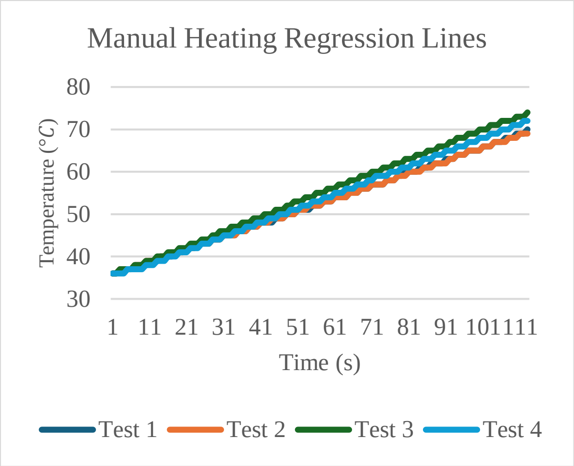


Figure 7: Four heating tests regression lines

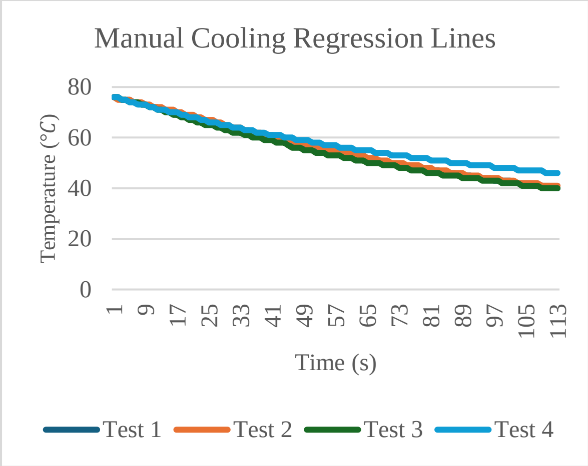


Figure 8: Four cooling tests regression lines

The Analysis ToolPak on Excel was used to generate the following for each of the four heating and cooling tests:

Table 5: Heating tests data analysis

Heat Test 1		*Heat Test 2*		*Heat Test 3*		*Heat Test 4*	
Mean	52.47788	Mean	52.45133	Mean	54.83186	Mean	53.38938
Standard Error	0.92847	Standard Error	0.918794	Standard Error	1.055276	Standard Error	1.021222
Median	52	Median	52	Median	55	Median	53
Mode	37	Mode	37	Mode	37	Mode	37
Standard Deviation	9.869775	Standard Deviation	9.766919	Standard Deviation	11.21773	Standard Deviation	10.85574
Sample Variance	97.41245	Sample Variance	95.3927	Sample Variance	125.8375	Sample Variance	117.847
Kurtosis	-1.20457	Kurtosis	-1.20511	Kurtosis	-1.2145	Kurtosis	-1.22443
Skewness	0.033358	Skewness	0.021879	Skewness	-0.00882	Skewness	0.019717
Range	34	Range	33	Range	38	Range	36
Minimum	36	Minimum	36	Minimum	36	Minimum	36
Maximum	70	Maximum	69	Maximum	74	Maximum	72
Sum	5930	Sum	5927	Sum	6196	Sum	6033
Count	113	Count	113	Count	113	Count	113
Confidence Level(95.0%)	1.839645	Confidence Level(95.0%)	1.820473	Confidence Level(95.0%)	2.090893	Confidence Level(95.0%)	2.02342

Table 6: Heating tests data analysis

Cool Test 1		*Cool Test 1*		*Cool Test 1*		*Cool Test 1*	
Mean	55.53982	Mean	56.19469	Mean	54.72566	Mean	58.17699
Standard Error	1.006775	Standard Error	1.009504	Standard Error	1.013908	Standard Error	0.823105
Median	54	Median	55	Median	53	Median	57
Mode	44	Mode	42	Mode	45	Mode	47
Standard Deviation	10.70217	Standard Deviation	10.73118	Standard Deviation	10.77799	Standard Deviation	8.749725
Sample Variance	114.5363	Sample Variance	115.1582	Sample Variance	116.1651	Sample Variance	76.55768
Kurtosis	-1.12139	Kurtosis	-1.20584	Kurtosis	-1.05253	Kurtosis	-1.01099
Skewness	0.33483	Skewness	0.26951	Skewness	0.408748	Skewness	0.414438
Range	36	Range	35	Range	36	Range	30
Minimum	40	Minimum	41	Minimum	40	Minimum	46
Maximum	76	Maximum	76	Maximum	76	Maximum	76
Sum	6276	Sum	6350	Sum	6184	Sum	6574
Count	113	Count	113	Count	113	Count	113
Confidence Level(95.0%)	1.994796	Confidence Level(95.0%)	2.000203	Confidence Level(95.0%)	2.008929	Confidence Level(95.0%)	1.630877

It can be noted that there are slight discrepancies in the mean and standard deviations for each of the four tests for heating and cooling. This can be due to several reasons, namely:

1. Systematic Variations:
    - Slight variations in initial conditions, such as the exact starting temperature or the ambient temperature, could lead to differences in the mean values recorded across tests.

2. Sensor Calibration:
    - Variations in sensor calibration might cause slight discrepancies in temperature readings. Not calibrating the sensor between tests could result in different mean values.
3. External Influences:
    - External factors such as airflow, humidity, or power variations in the heating element and fans could affect the test results, causing variations in the mean temperature.
4. Equipment Accuracy:
    - Differences in the accuracy and precision of the equipment used for each test could result in variability in the recorded data, affecting the standard deviation.
5. Noise:
    - The noise due to electrical interference, fluctuations in the power supply, or inherent noise in the sensor readings could lead to higher standard deviations.

3.0 Selects and uses appropriate equipment or software (Excel)

The use of appropriate equipment and software is critical in obtaining accurate data and performing effective analysis in process control experiments. The following details how Excel was used to enhance the investigation, experimentation, and data analysis of the temperature measurement system.

1. Data Logging and Collection:
    - Temperature readings were recorded using the HMI data logging feature and then imported into Excel for detailed analysis.
2. Statistical Analysis:
    - Using the Analysis ToolPak in Excel, statistical measures such as mean, standard deviation, and confidence intervals were produced for all tests. This helped in understanding the repeatability and reliability of the system.
3. Visualization:
    - Graphs and plots illustrating the regression lines for the various tests were created in Excel to visually represent the data. Some plots were plotted on the same axes to compare the regression lines, assisting in the comparison of different control methods and system responses.

4.0 Performs Necessary Analyses

The temperature measurement system incorporates a Human Machine Interface (HMI), shown in Figure 9, to offer control to the user. A data-logging feature is included, allowing the user to input a sample size and record their readings.

4.1 HMI Modes of operation

1. **Manual Control Mode** - Manual control over the heater, fan and fan speed.
2. **ON-OFF Control Mode** – Specify a set point temperature, upper-temperature band (heater turns off) and lower temperature band (heater turns on).
3. **PID Manual Control Mode** – This mode allows the user to tune the controller using methods such as Ziegler-Nichols. Have to specify an operating temperature in the ON-OFF control mode by determining the optimal operating temperature range of the system through experimentation.
4. **PID Auto-Tune Mode** – A special tuning feature that automatically tunes the PID.

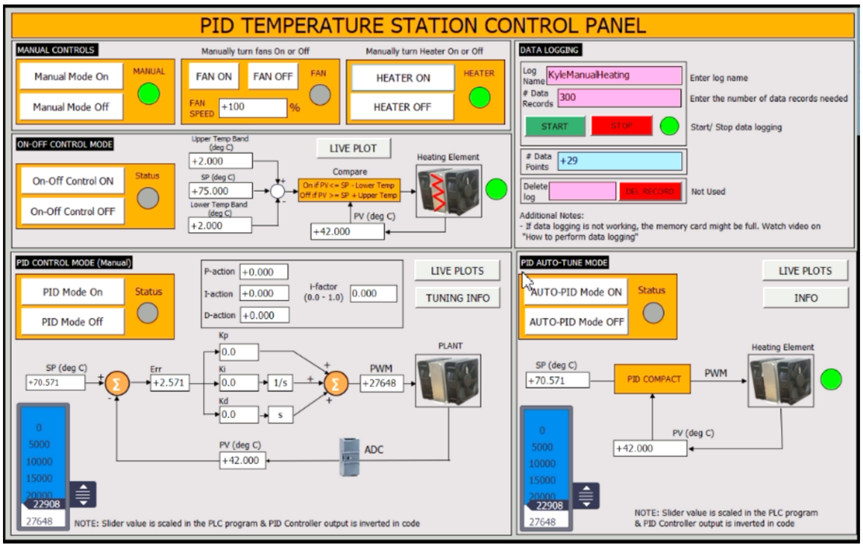


Figure 9: Human Machine Interface

Figure 9 illustrates the four modes of operation that the HMI incorporates and additional features that can be used when interacting with the temperature system. These features include:

1. Set Point Temperature:
   - Users can input the desired set point (SP) temperature for the system to maintain. This value is essential for both the ON-OFF and PID control modes.
2. Upper and Lower Temperature Bands:
   - These bands define the range around the set point within which the system will operate. The heater turns off when the temperature reaches the upper band and turns on when it reaches the lower band.
3. Temperature Adjustment Slider:
   - A slider enables easy adjustments to the set point temperature.
4. Heater and Fan Indicators:

- Visual indicators show the current status of the heater and fan (ON or OFF). These indicators help users visually monitor the system's operation.

5. Data Logging Feature:
   - The HMI includes a data logging function, essential for recording and analysing temperature data over time, where users can input the sample size for their recording.
6. Control Buttons:
   - Various buttons are provided for starting, stopping, and resetting the control processes.
7. Live Plot and Tuning Information:
   - The HMI displays real-time plots of the temperature data and control signals.

5.0 Results: Data Recording

This section provides numerous graphs, figures and tables from the results obtained during the experimental stage. The performance characteristics of the temperature measurement system will be outlined in detail with explanations of assumptions and observations.

5.1 Manual Control Mode

The heating and cooling curves of the system were obtained using the manual control mode on the HMI.

5.1.1 Heating and Cooling Curves

The curves in Figure 10 show the heating and cooling characteristics of the temperature system. By turning the heater ON and the fans OFF, the tripping time for the station was determined.

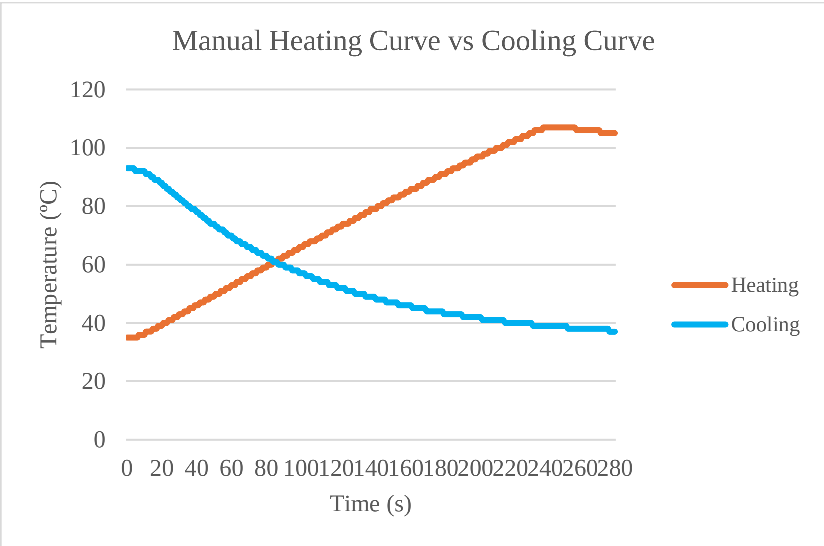


Figure 10: Manual heating and cooling curve

Data Analysis (Heating)	
Mean	76.33214286
Standard Error	1.404194719
Median	78.5
Mode	106
Standard Deviation	23.49667182
Sample Variance	552.0935868
Kurtosis	-1.28207362
Skewness	-0.228746817
Range	72
Minimum	35
Maximum	107
Sum	21373
Count	280
Confidence Level (95.0%)	2.764161695

Data Analysis (Cooling)	
Mean	53.93333333
Standard Error	0.97514637
Median	47
Mode	38
Standard Deviation	16.89003057
Sample Variance	285.2731327
Kurtosis	-0.329774222
Skewness	0.950342041
Range	56
Minimum	37
Maximum	93
Sum	16180
Count	300
Confidence Level(95.0%)	1.919019472

Figure 10 shows the starting temperature of $\pm 35°C$ before the system was heated and a starting temperature of $\pm 95°C$before cooling the system. Observations included an increase in temperature until it reached its maximum and tripped. The temperature then started to decrease slowly without the fans being on. Turning the fans on at 100% showed that the system's ability to cool down slightly faster than it can heat up. The characteristics of the station in Table 7 were found as a result of these tests.

Table 7: Maximum threshold temperature and tripping time of the temperature station

Maximum Threshold Temperature	$107°C$
Tripping Time	$250s$

The results in Table 7 give a good understanding of the system characteristics and what the optimal temperature range for the system was. This leads to testing the fan performance to understand how the system is cooled.

5.1.2 Fan Performance

Two different fan speeds (50% and 100%) were tested to cool the system with their results yielding the curves in Figure 11. The cooling curves in were plotted on the same axes to compare the difference in the rate of change in temperature.

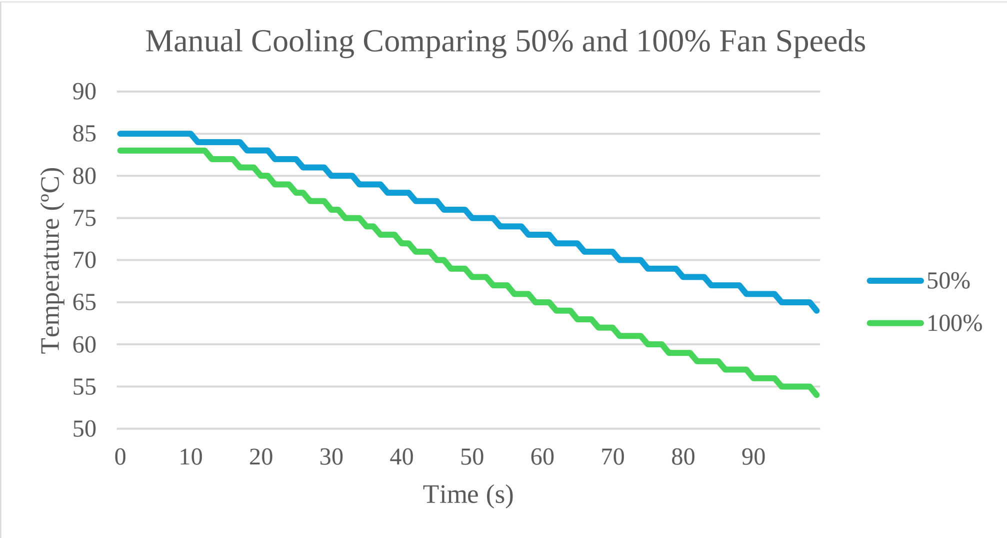


Figure 11: Cooling curves for 50% and 100% fan speeds

Data Analysis (50% fan speed)	
Mean	75.49
Standard Error	0.667952548
Median	75.5
Mode	85
Standard Deviation	6.679525478
Sample Variance	44.61606061
Kurtosis	-1.340225113
Skewness	-0.04045678
Range	21
Minimum	64
Maximum	85
Sum	7549
Count	100
Confidence Level(95.0%)	1.325362768

Data Analysis (100% fan speed)	
Mean	69.2
Standard Error	0.961060021
Median	68.5
Mode	83
Standard Deviation	9.610600208
Sample Variance	92.36363636
Kurtosis	-1.390928551
Skewness	0.069236872
Range	29
Minimum	54
Maximum	83
Sum	6920
Count	100
Confidence Level(95.0%)	1.906951585

The regression lines in Figure 11 show the cooling of the system from about $85°C$ down till two different temperatures due to the different fan speeds. From the data analysis it was noted that the system reached a much lower temperature in the same amount of time when cooled with 100% fan speed as opposed to 50%.

5.2 PID Manual Control Mode

Applying the ZN tuning technique by increasing the value of K_P with K_I and K_D equal to zero, constant oscillations of the waveform were achieved. The test was done for a set point of 75℃ and the initial gain was set at 0 and increased in increments of 1. The peaks and troughs of the waveform in Figure 12 are consistently spaced and have a uniform amplitude, hence a regular oscillating signal.

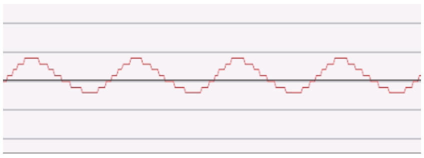


Figure 12: Waveform oscillations at a gain

A value of $K_P = 15$ achieved these constant oscillations, hence the ultimate gain $K_u = 15$ and the period between the oscillations was $T_u = 67s$. Substituting these values into their respective parameters in Table 2 yields the values for K_P, K_I and K_D in Table 6.

Table 8: Manual PID control parameter values

Variable	Value
K_P	9
K_I	33.5
K_D	8.375

The tabulated values were loaded to the PID controller using the HMI, as indicated in the manual PID control mode in Figure 13 below. Furthermore, to run manual PID control mode, ON-OFF control mode needs to be enabled. The reason for this is to set the desired (set point) temperature and its upper and lower bands.

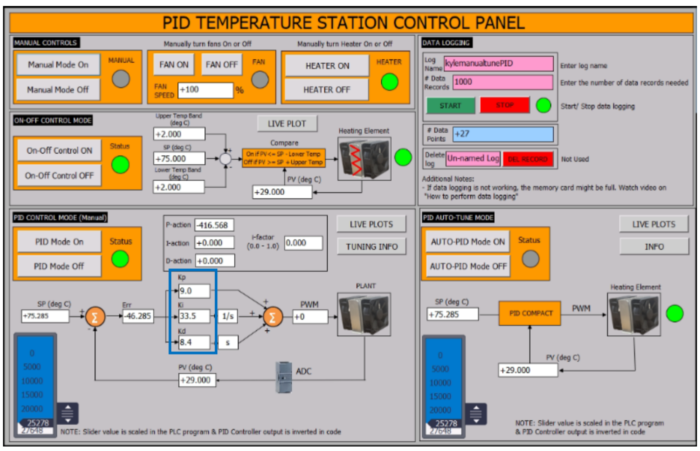


Figure 13: HMI during manual PID mode

Enabling these two modes allows the tuned PID controller to turn the fans and heater ON and OFF, keeping the output temperature within the upper and lower temperature bands specified in the ON-OFF control mode block in Figure 13. The output waveform for the manually tuned PID controller is shown in Figure 14.

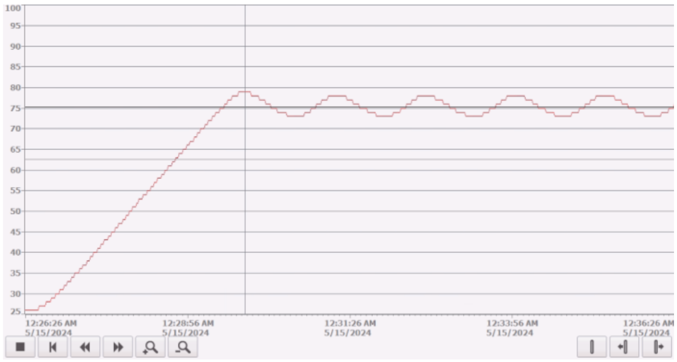
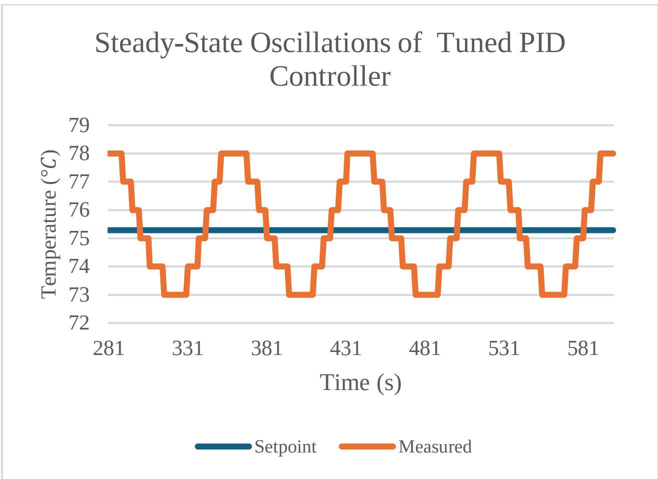


Figure 14: Manually tuned PID controller achieving steady state

A sample size of 320 entries recorded during the PID controller's steady state is illustrated in Figure 15. The 320 temperature readings between 282 and 608 seconds were included in the data analysis to closely examine the waveform oscillations around the setpoint temperature. The tabulated results from the data analysis in Excel can be seen below.



Temperature Data Analysis	
Mean	75.478125
Standard Error	0.10237419
Median	75
Mode	78
Standard Deviation	1.831325192
Sample Variance	3.353751959
Kurtosis	-1.43122572
Skewness	0.070602257
Range	5
Minimum	73
Maximum	78
Sum	24153
Count	320
Confidence Level(95.0%)	0.201413888

Error Data Analysis	
Mean	0.195880027
Standard Error	0.102280401
Median	-0.2853699
Mode	2.71463
Standard Deviation	1.82964743
Sample Variance	3.347609718
Kurtosis	-1.42718807
Skewness	0.067247429
Range	5
Minimum	-2.28537
Maximum	2.71463
Sum	62.6816086
Count	320
Confidence Level(95.0%)	0.201229364

Figure 15: Steady-state oscillations of manual tuned PID controller

5.3 PID Autotune Control Mode

During the PID autotune control mode, the ON-OFF control mode was enabled and a setpoint of 75°C was entered. The upper and lower temperature bands were set to $2°C$ as seen in the figure of the HMI below.

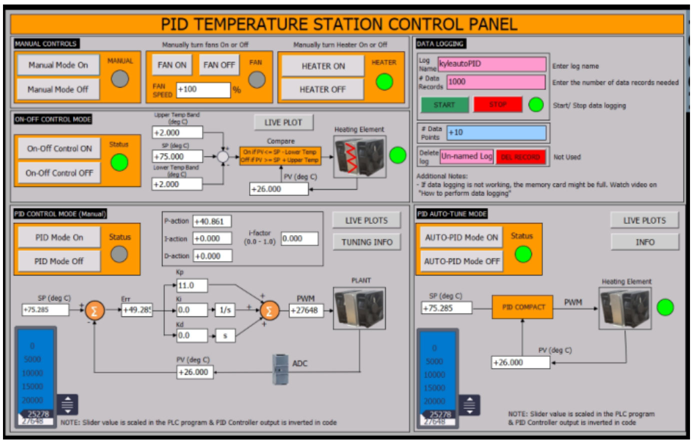


Figure 16: HMI during PID autotune mode

The PID compact block shown in Figure 17 was located in the cyclic interrupt program block and was used to perform autotuning. The PID compact block enables the controller to receive real-time process variable (PV) inputs and adjust the control output to maintain the setpoint temperature.

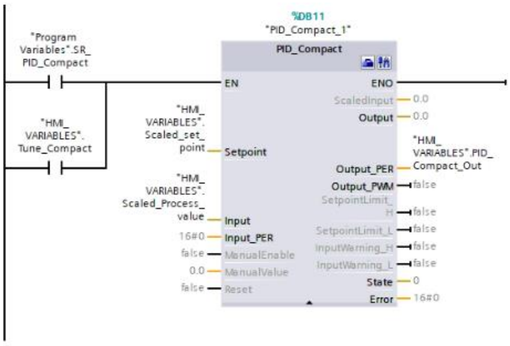


Figure 17: PID Compact block

From this PID compact block, the commissioning window was opened to perform autotuning, as seen in Figure 18.

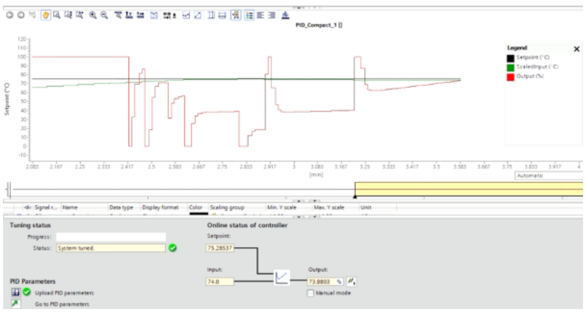


Figure 18: Commissioning window for PID compact block

The tuned PID gains in Figure 19 were transferred to the PID controller and it began to function with the tuned parameters, yielding the output waveform shown in Figure 20.

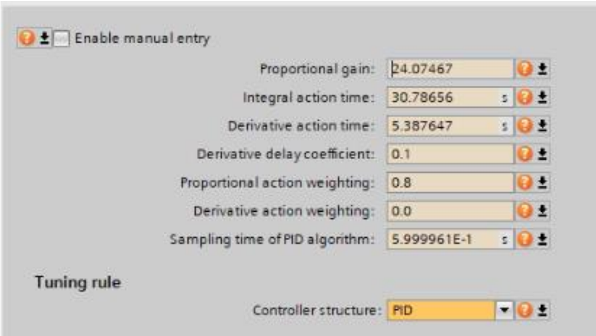


Figure 19: Tuned PID gains

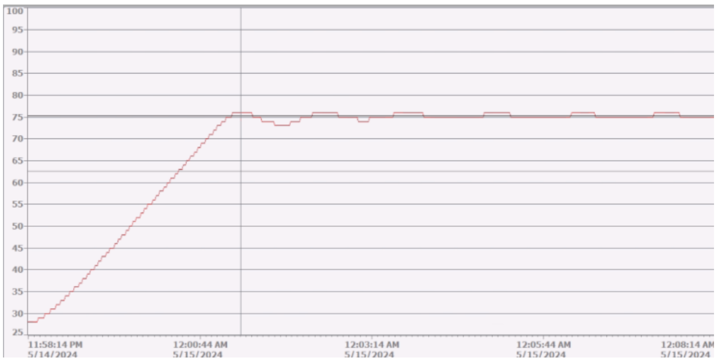
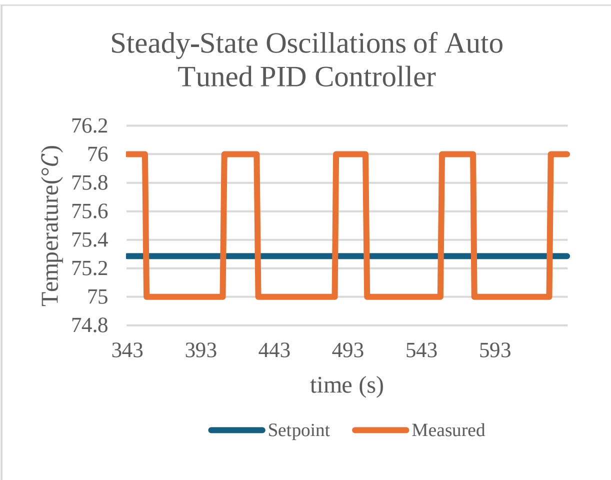


Figure 20: Autotuned PID controller achieving steady state

Temperature readings between 343 and 642 (sample size of 300) seconds were included in this analysis to examine the oscillations of the waveform. The steady-state performance of the autotuned PID controller was evaluated based on the recorded temperature data.



Temperature Data Analysis	
Mean	75.30333333
Standard Error	0.02658502
Median	75
Mode	75
Standard Deviation	0.460466053
Sample Variance	0.212028986
Kurtosis	-1.269008118
Skewness	0.85993995
Range	1
Minimum	75
Maximum	76
Sum	22591
Count	300
Confidence Level(95.0%)	0.052317449

Error Data Analysis	
Mean	0.007288437
Standard Error	0.026691765
Median	0.2853699
Mode	0.2853699
Standard Deviation	0.46231494
Sample Variance	0.213735104
Kurtosis	-1.080448553
Skewness	-0.877752807
Range	1.4292602
Minimum	-0.7146301
Maximum	0.7146301
Sum	2.1865312
Count	300
Confidence Level(95.0%)	0.052527517

Figure 21: Steady-state Oscillations of Auto-Tuned PID Controller

6.0 Analyses, Interprets and Derives Information from Data

This section discusses the results from data recordings and the Excel plots obtained. The goal is to interpret the data, evaluate the performance of the control methods, and derive conclusions from the results in the previous section.

6.1 Manual Control

The manual control mode results indicate how the system behaves without any automatic control mechanisms. The heating and cooling curves obtained through this mode provide an understanding of the system's natural response to temperature changes.

The system reached a maximum threshold temperature of $107°C$ in 250 seconds. This indicates the system's capacity to heat up when manually controlled. The tripping time shows how quickly the system can reach its maximum temperature, which is important for understanding the system's limits.

Cooling tests with fan speeds of 50% and 100% showed that the system cooled down significantly faster at 100% fan speed. This comparison highlights the importance of fan speed in controlling the cooling rate of the system, providing insights into how the cooling mechanism can be adjusted.

6.2 PID Control

The PID manual control mode was implemented using the Ziegler-Nichols tuning method. The primary objective was to achieve a stable and regular oscillation of the temperature around the setpoint. The manually tuned PID controller demonstrated the ability to regulate the temperature around the setpoint but had noticeable oscillations and a higher standard deviation when compared to the autotune mode. This indicates that while manual tuning can achieve control, it may not be as precise or stable as automatic tuning.

6.3 PID Autotune Control

The autotuned PID controller effectively maintained the setpoint temperature with minimal oscillations and deviations. The analysis of steady-state oscillations indicated a high level of accuracy and stability in maintaining the desired temperature, demonstrating the effectiveness of the autotuning process.

The PID autotune mode efficiently adjusted the controller parameters to ensure optimal performance, maintaining the setpoint temperature with precision and reliability. The autotune process determined the best PID parameters, which were then transferred to the controller. The system maintained a mean temperature of $75.303°C$ with a standard deviation of $0.460°C$ and a range of $1°C$. The autotune PID controller showed better performance with minimal oscillations and variations from the setpoint.

6.4 Comparison of PID Control Methods

The table below shows the comparison between the manual PID control and the autotune PID control modes.

Table 9: Comparison of Manual and Autotune PID control mode

Parameter	Manual PID Control	Autotune PID Control
Mean Temperature (°C)	75.478	75.303
Standard Deviation (°C)	1.831	0.460
Range (°C)	5	1
Confidence Level (95.0%) (°C)	± 0.201	± 0.052
Oscillation Consistency	Moderate	High
Ease of Tuning	Requires manual adjustment and monitoring	Automatic and efficient

The comparison between the two modes shows a major difference in their performance and ease of use. Both methods maintained the temperature close to the set point ($75°C$). The mean temperatures were very similar, with the manual PID control at $75.478°C$ and the autotune PID control at $75.303°C$.

The autotune PID control system maintained stable oscillations around the setpoint, while manual PID control had more visible oscillations. The autotune control revealed a much lower standard deviation compared to the manual PID control. This indicates that the autotune PID control provided more consistent temperature regulation with fewer fluctuations.

The range of temperature fluctuations was significantly narrower in the autotune control (1°C) compared to the Manual PID Control (5°C). A narrower range indicates more accurate control and better stability.

The confidence interval for the mean temperature was much smaller for the autotune PID control compared to the manual PID control. A smaller confidence interval indicates more precise control.

7.0 Draws Conclusions Based on Evidence

The manual PID control mode tuned using the Ziegler-Nichols method, achieved acceptable control but showed larger oscillations around the setpoint. The mean temperature was close to the setpoint, but the standard deviation and range indicated larger fluctuations.

In contrast, the autotune PID control mode provided a more stable and consistent temperature control with minimal oscillations. The autotuned parameters resulted in a lower standard deviation and a smaller range, demonstrating better control performance. The autotune method proved to be efficient and reliable, offering precise temperature control with less manual involvement. The automatic tuning process adjusted the PID parameters effectively, resulting in improved system stability and accuracy in maintaining the setpoint temperature.

The analysis and comparison of manual and autotune PID control methods highlight the advantages of using autotune for precise and reliable temperature control. The autotune method outperforms manual tuning in terms of stability, precision, and ease of use. This makes it the preferred method for achieving precise and reliable temperature regulation in automated systems. The conclusions drawn from this study provide valuable insights for optimising control systems in various industrial applications.

8.0 Suggestions

Collecting more data points can improve the accuracy of the analysis and provide better insights into system performance. A larger dataset reduces the impact of outliers and random errors, leading to more reliable results.

Testing the system at multiple setpoints can help understand the control performance over a wider range of operating conditions. This helps in identifying any limitations or weaknesses in the control strategy that may only be visible under certain conditions. Covering a broader range of setpoints ensures that the control system is robust and reliable in various situations.

While the autotuned PID controller provides a good starting point, further enhancement can be achieved through fine-tuning. This process involves making small adjustments to the PID gains to improve the controller's accuracy. Fine-tuning can be done in the commissioning window right after autotuning. This can make the controller more precise and reactive to changes in the setpoint or disturbances.

References

Data Acquisition | Test and Measurement Solutions. (2024). What is a PID Controller? [online] Available at: https://dewesoft.com/blog/what-is-pid-controller [Accessed 20 May 2024].

Muhammad, Kishore Bingi, Arun, P. and Ibrahim, R. (2024). Design and Development of Complex-Order PI-PD Controllers: Case Studies on Pressure and Flow Process Control. Applied system innovation, [online] 7(3), pp.33–33. doi:https://doi.org/10.3390/asi7030033.

Wieber, C., Mads Rosenhøj Jeppesen, Finster, K., Claus Melvad and Šantl-Temkiv, T. (2024). Micro-PINGUIN: microtiter-plate-based instrument for ice nucleation detection in gallium with an infrared camera. Atmospheric measurement techniques, [online] 17(9), pp.2707–2719. doi:https://doi.org/10.5194/amt-17-2707-2024.

Appendix

Appendix A: PT100 RTD Specifications

Electric system

Temperature Probe 8060 — Temperature Controller 8071/2D, IP67 enclosure — Electric G Valve

The electric valve system incorporates the use of an electrically actuated three-way control valve with an electronic controller (type 8071D). The 8071D controller can be either panel or wall mounted. The system is completed with the temperature sensor type 8060.

The electric G Valve system is simple to install with standard four core cable, and provides more accurate measurement and control than typical pneumatically operated systems.

Specification

Temperature range	-100°C to 250°C	-150°F to 482°F
Accuracy	IEC 751 : 1983	(BS EN60751 : 1996) Class B
RTD	3 wire platinum	(100 Ohm element)
Connection head	Heavy duty aluminum	IP67
Conduit thread	M20, PG 13.5″ or 16″, 1/2″ NPT	
Thermal well	Stainless steel	
Installation thread	1/2″ BPS. Tr, 1/2″ NPT	
Terminations	Threaded	
Cable entry (3 core)	4 to 7 mm diameter	2 to 6 gauge
Heat transfer compound	Silicon