Instrumentation and Process Control
Series 3531

Process Control

Temperature

Courseware Sample
86010-F0

INSTRUMENTATION AND PROCESS CONTROL
SERIES 3531

PROCESS CONTROL

Temperature

Courseware Sample

by
the staff
of
Lab-Volt Ltd.

Printed in Canada
April 2011

Foreword

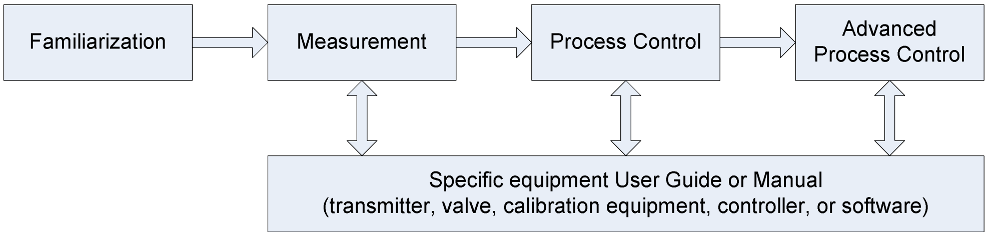
Automated process control offers so many advantages over manual control that the majority of today's industrial processes use it at least to some extent. Breweries, wastewater treatment plants, mining facilities, the automotive industry, and just about every other industry sector use it.

Maintaining process variables such as pressure, flow, level, temperature, and pH within a desired operating range is of the utmost importance when manufacturing products with a predictable composition and quality.

The Instrumentation and Process Control Training System, series 353X, is a state-of-the-art system that faithfully reproduces an industrial environment in which students can develop their skills in the installation and operation of equipment used in the process control field. The use of modern, industrial-grade equipment is instrumental in teaching the theoretical and hands-on knowledge that is required to work in the process control industry.

The modularity of the system allows the instructor to select the equipment required to meet the objectives of a specific course. Two versatile, mobile workstations, on which all of the equipment is installed, form the basis of the system. Several optional components used in pressure, flow, level, temperature, and pH control loops are available, as well as various valves, calibration equipment, controllers, and software.

Standard Learning Path



We hope that your learning experience with the Instrumentation and Process Control Training System will be the first step toward a successful career in the process control industry.

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Sample Exercise

Extracted from

Student Manual

Exercise 2-1

Tuning and Control of a Temperature Loop

EXERCISE OBJECTIVE When you have completed this exercise, you will be familiar with three different methods for tuning your controller and you will have gained experience using at least one of them on a temperature process.

DISCUSSION OUTLINE The Discussion of this exercise covers the following points:

- Recapitulation of relevant control schemes
- Tuning with the trial-and-error method
- Tuning with the ultimate-cycle method
- Limits of the ultimate-cycle method
- The open-loop Ziegler-Nichols method

DISCUSSION

This exercise introduces three control schemes and puts them to use in a temperature process loop. This allows a comparative analysis of the different schemes in terms of efficiency, simplicity, and applicability to various situations. An intuitive method to tune controllers is also presented.

Recapitulation of relevant control schemes

A controller in proportional mode (P mode) outputs a signal ($m(t)$ – manipulated variable) which is proportional to the difference between the target value (SP: set point) and the actual value of the variable ($c(t)$ – controlled variable). This simple scheme works well but typically causes an offset. The only parameter to tune is the controller gain K_c (or the proportional band ($PB\% = 100\%/K_c$) if your controller uses this parameter instead).

A controller in proportional/integral mode (PI mode) works in a fashion similar to a controller in P mode, but also integrates the error over time to reduce the residual error to zero. The integral action tends to respond slowly to a change in error for large values of the integral time T_i and increases the risks of overshoot and instability for small values of T_i.Thus, the two parameters which require tuning for this control method are K_c (or $PB\%$) and T_i (or the integral gain, defined as $G_i = 1/T_i$).

A controller in proportional, integral, and derivative mode (PID mode) incorporates the three control actions into a single polyvalent and powerful control scheme. The addition of derivative action to the PI mode covered in the previous exercise results in the capacity to attenuate overshoots to some extent, but adds the risk of instability if the process is noisy.

Tuning a controller in PID mode requires careful adjustment of the proportional gain (K_c), the integral time (T_i), and the derivative time (T_d) to properly address the control requirements of the process. In some circumstances, the controller output must not be zero when the error is null. In these cases, a bias (b), also known as **manual reset**, must be set.

The on-off control mode is the simplest control scheme available. It involves either a 0% or a 100% output signal from the controller based on the sign of the measured error. The option to add a dead band is available with most controllers to reduce the oscillation frequency and prevent premature wear of the final control element. There are no parameters to specify for this mode beyond a set point and dead band parameters. Note that it is possible to simulate an on-off mode with a controller in P mode for a large value of K_c (or a very small $PB\%$).

Tuning with the trial-and-error method

The **trial-and-error method** of controller tuning is a procedure for adjusting the P, I, and D parameters until the controller is able to rapidly correct its output in response to a step change in the error. This correction is to be performed without excessive overshooting of the controlled variable.

This method is widely used because it does not require the characteristics of the process to be known, and it is not necessary to bring the process into a sustained oscillation. Another important aspect of this method is that it is instrumental in developing an intuition for the effects of each of the tuning parameters.

However, the trial-and-error method can be daunting to perform for inexperienced technicians because a change in tuning constant tends to affect the action of all three controller terms. For example, increasing the integral action increases the overshooting, which in turn, increases the rate of change of the error and then increases the derivative action. A structured approach and experience help in obtaining a good tuning relatively quickly without resorting to involved calculations.

A good trial-and-error method is to follow a geometrical progression in the search for optimal parameters. For example, multiplying or dividing one of the tuning parameters by two at each iteration can help you converge quickly toward an optimal value of the parameter.

A procedure for the trial-and-error method

The trial-and-error method is performed using the following procedure (also refer to Figure 2-25 and Figure 2-26 for PI control):

1. Set the controller in the mode you want to use: P, PI, PD, or PID. Follow the instructions to adjust every parameter relevant to the mode you are using. Note that, if your controller allows doing so, you can use the PID mode to perform any of the modes by simply setting the parameters to appropriate values (e.g. $T_d = 0$ for PI mode).

Adjusting the P action

2. With the controller in manual mode, turn off the integral and derivative actions of the controller by setting T_i and T_d respectively to the largest possible value and 0.

The controller gain K_c is related to the proportional band: $PB\% = 100\%/K_c$.

If your controller uses the proportional band, start with a value of $PB\% = 100\%$, and replace instructions to increase K_c by a factor of two by instructions to decrease $PB\%$ by a factor of two.

3. Set the controller gain K_c to an arbitrary, but small, value, such as 1.

4. Place the controller in the automatic (closed-loop) mode.

5. Make a step change in the set point and observe the response of the controlled variable. The set point change should be typical of the expected use of the system.

   Since the controller gain is low, the controlled variable will take a relatively long time to stabilize (i.e., the response is likely to be overdamped).

6. Increase K_c by a factor of 2 and make another step change in the set point to see the effect on the response of the controlled variable.

   The objective is to find the value of K_c at which the response becomes underdamped and oscillatory. This is the ultimate controller gain. Keep increasing K_c by factors of 2, performing a set point change after each new attempt, until you observe the oscillatory response.

   Once the ultimate controller gain is reached, revert back to the previous value of K_c by decreasing the controller gain by a factor of 2. The P action is now set well enough to add another control action if required.

Adjusting the I action

7. Start bringing in integral action by setting the integral time T_i at an arbitrarily high value. Decrease T_i by factors of 2, making a set point change after each setting.

   Do so until you reach a value of T_i, at which the response of the controlled variable becomes underdamped and oscillatory. At this point, revert back to the previous value of T_i by increasing T_i to twice its value.

   The I action is now set and you can now proceed to the adjustment of the D action, if required.

Adjusting the D action

8. Start bringing in derivative action by setting the derivative time at an arbitrarily low value. Increase T_d by factors of 2, making a set point change after each setting.

   Do so until you reach the value of T_d that gives the fastest response without amplifying the overshooting or creating oscillation.

   The D action is now set.

Fine-tuning of the parameters

9. Fine-tune the controller until the requirements regarding the response time and overshooting of the controlled variable are satisfied.

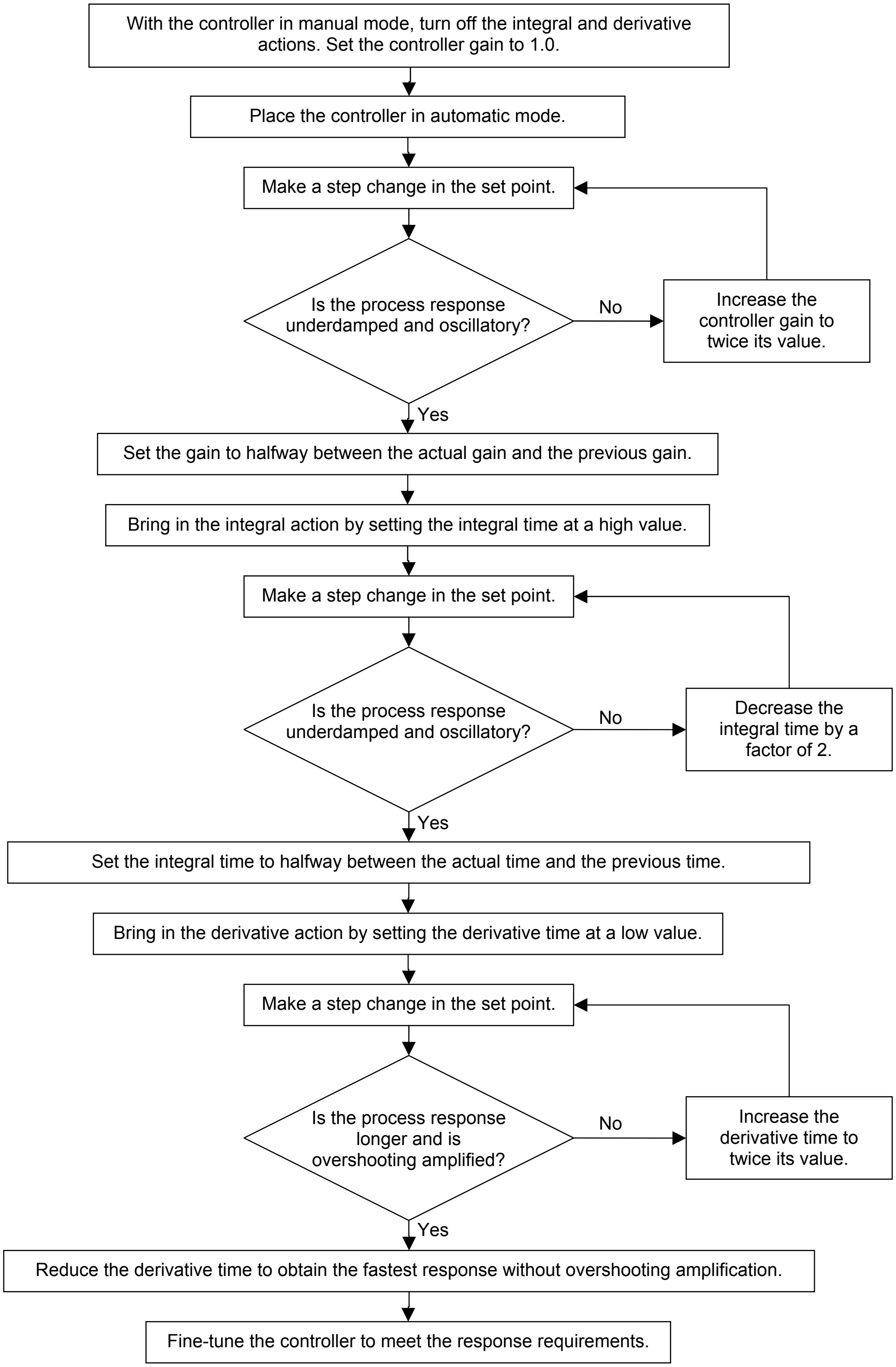


Figure 2-25. Trial-and-error tuning method.

A complementary approach to trial-and-error tuning

Another, more visual approach is to use Figure 2-26 to assist you in tuning your controller. The figure presents responses of a PI process to a step change for different combinations of parameters. A good tuning is shown in the center of the figure for 'optimal' K_c and T_i parameters. The tuning in the center is not necessarily the most appropriate for the process you want to control; but the response shown is a good target for a rough first tuning.

The figure also shows responses for detuned parameters (both above and below the 'optimal' K_c and T_i). Comparing the response you obtain for your system with the detuned responses in the figure tells you in which direction to change K_c, T_i, or both to converge towards the center case. Changing the parameters by a factor of two at every step until you get very close to the optimal value is a good method to converge rapidly.

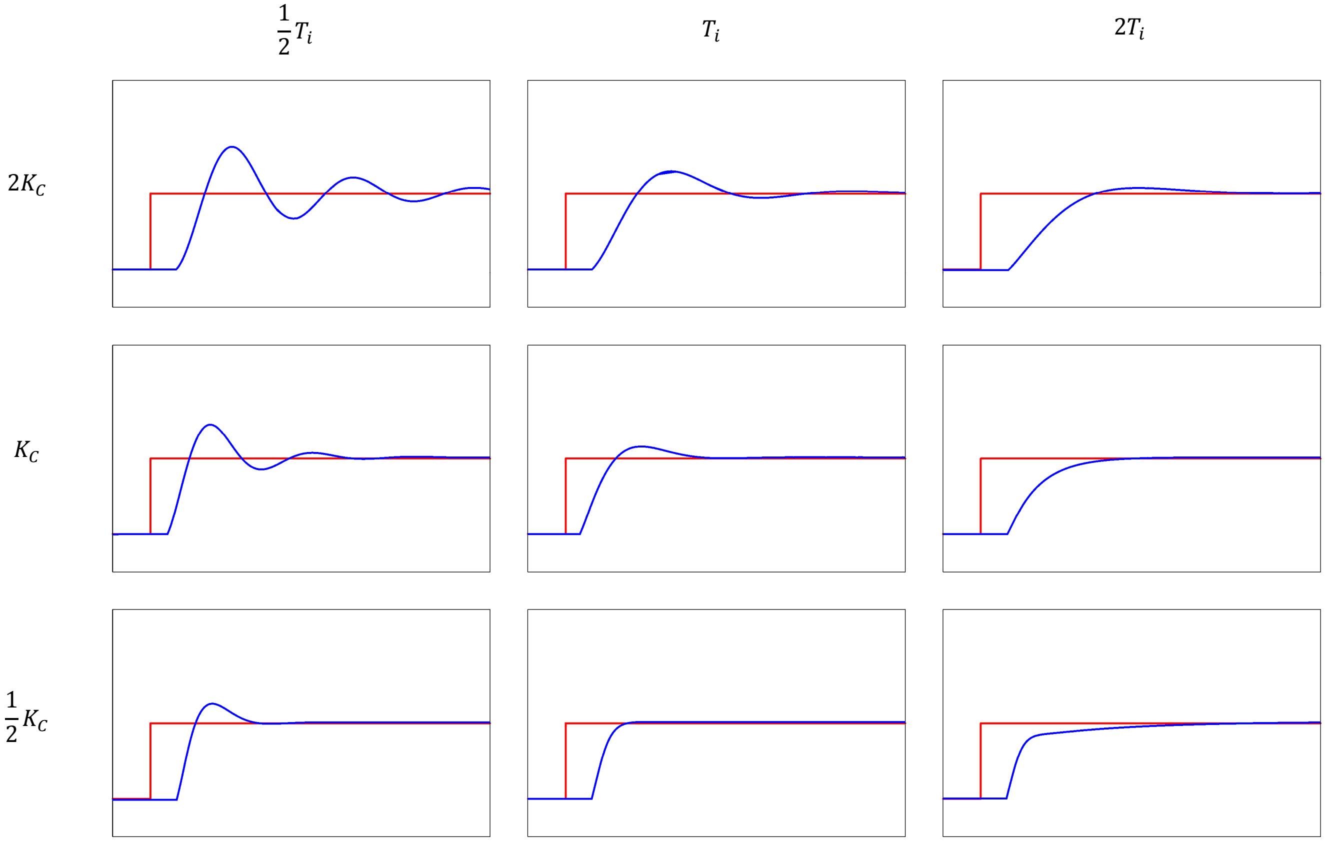


Figure 2-26. PID tuning chart.

If required, derivative action can then be added to the control scheme by following step 8 of the trial-and-error method. Then, fine-tune the parameters to optimize the control and to meet the specific requirements of your process.

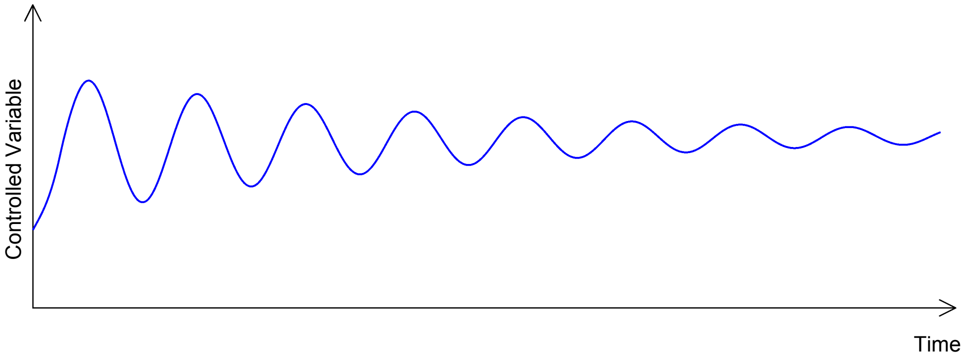
Tuning with the ultimate-cycle method

The ultimate-cycle tuning method is one of the first heuristic methods suggested by Ziegler and Nichols for tuning PID controllers (the method is consequently sometimes called the closed-loop Ziegler-Nichols method). The ultimate-cycle tuning method is designed to produce quarter-amplitude decay in the controlled variable after a given step change in the set point. This method enables the operator to calculate the P, I, and D tuning constants required for P, PI, PD, or PID control of a process using two parameters of the process: the ultimate gain (K_u) and the ultimate period (T_u).

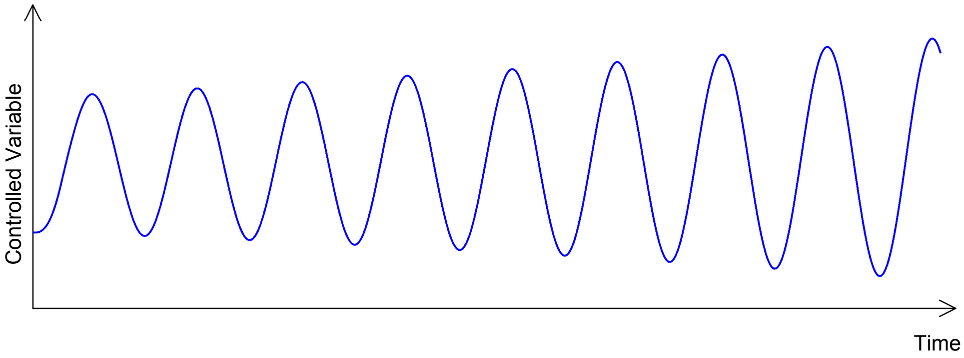
The ultimate gain K_u is the largest value of K_c in P-only control mode such that the process is still stable (albeit marginally), i.e., the system is in a continuous, sustained oscillation. The **ultimate period** T_u is the period of the response when the gain is set to the ultimate gain.

The ultimate proportional band PB_u can be used instead of K_u. It is then defined as the smallest value of PB for which the process is stable.

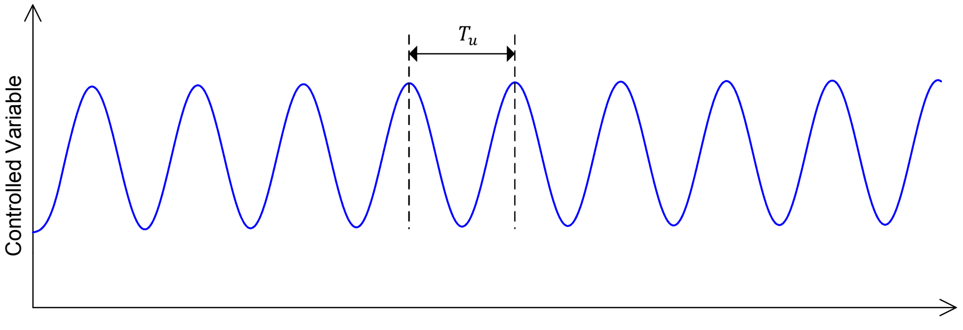
$$PB\% = \frac{100\%}{K_c}$$



(a) Decreasing oscillation.



(b) Increasing oscillation.



(c) Sustained oscillation.

Figure 2-27. Types of oscillations and determination of the ultimate period.

The ultimate-cycle tuning method follows this procedure:

1. With the controller in manual mode, turn off the integral and derivative actions so as to use only P mode.

2. Set the proportional gain K_c at an arbitrary, but somewhat small, value, such as 1.

3. Place the controller in automatic (closed-loop) mode.

4. If the process starts to oscillate by itself, go to step 7. Otherwise, create a step change in the set point. The set point change should be typical of the expected use of the system.

5. If the process does not oscillate, increase the gain by a factor of 2.

6. Repeat steps 4 and 5 until the response becomes oscillatory.

7. Determine whether the oscillation is sustained—i.e., if it continues at the same amplitude without increasing or decreasing as in Figure 2-27c. If not, make small changes in the proportional gain until a sustained oscillation is achieved.

   Note: *It is often necessary to wait for the completion of several oscillations before it can be determined if the oscillation is sustained.*

   The proportional gain, at which the sustained oscillation begins without causing saturation of the controller output, is the ultimate proportional gain, K_u. Note this value. Then note the period of the oscillation of the process, as shown in Figure 2-27c. This is the ultimate period, T_u.

8. Using the ultimate proportional gain and ultimate period, calculate the tuning constants of the controller as follows:

Table 2-2. Control parameters for the ultimate-cycle tuning method.

Mode	Controller Gain K_c	Integral Time T_i	Derivative Time T_d
P	$K_c = 0.5K_u$ $(PB = 2PB_u)$	-	-
PI	$K_c = 0.45K_u$ $(PB = 2.2PB_u)$	$T_i = T_u/1.2$	-
PD	$K_c = 0.6K_u$ $(PB = 1.65PB_u)$	-	$T_d = T_u/8$
PID	$K_c = 0.6K_u$ $(PB = 1.65PB_u)$	$T_i = T_u/2.0$	$T_d = T_u/8$

Once the tuning constants of the controller are adjusted to the calculated values and the controller is returned in the automatic (closed-loop) mode, changes in the set point should produce a quarter-amplitude decay response. Optimization of the controller settings may require further fine-tuning.

Quarter-amplitude decay ratio

John G. Ziegler and Nathaniel B. Nichols, who were pioneers in control engineering, established a criterion to determine if a controller is appropriately tuned. This criterion is the **quarter-amplitude decay** ratio. It states that, for two successive oscillations, the amplitude of the second oscillation should be one fourth of the amplitude of the first oscillation.

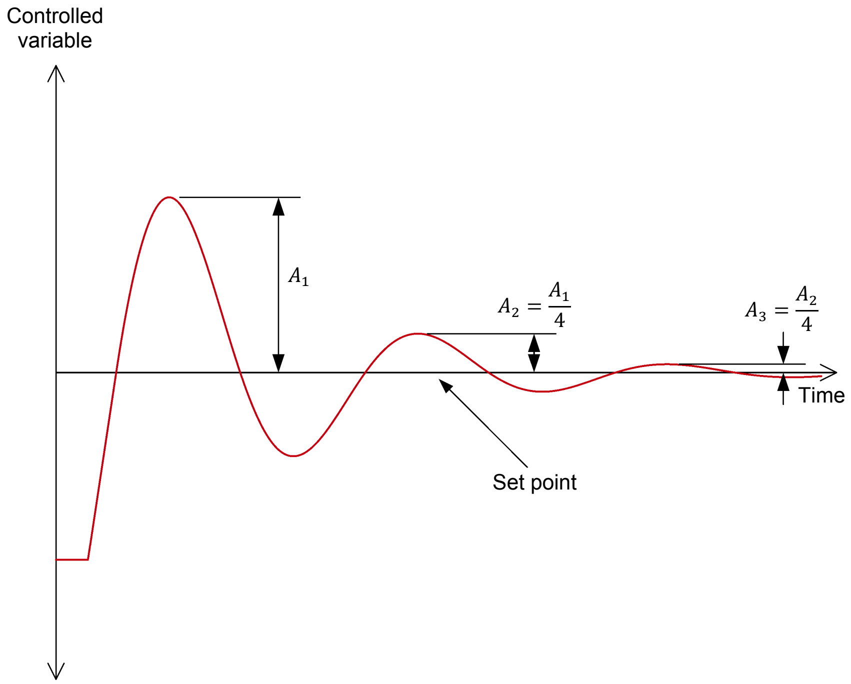


Figure 2-28. Quarter-amplitude decay ratio.

Presence of a quarter-amplitude decay ratio in a response is a rough approximation for the optimal tuning of PID controllers. A controller is generally considered to be reasonably tuned when it satisfies this criterion; but fine-tuning may be required to adapt the controller response to a specific process control application.

The quarter-amplitude decay response is a compromise between an underdamped and an overdamped response. The process response is **overdamped** when the controlled variable slowly returns to the set point after the step change without overshooting it. The response is **underdamped** when the controlled variable quickly returns to the set point with one or more overshoots before stabilizing. An underdamped response often means that the controller reacts too aggressively to correct the error, thereby overdoing it.

Limits of the ultimate-cycle method

It is important to note that the formulas given above apply only for non-interacting ideal controllers. Other formulas must be used for series or non-interacting parallel controllers. Refer to the section entitled *Structure of controllers* on page 50 for details.

It is also important to stress that using the ultimate-cycle tuning method may be out of the question in processes where bringing the system into continuous oscillation could be dangerous or might cause damage. Instead, another method of tuning, such as the trial-and-error method or the open-loop step response method, should be used. The open-loop step response method is also known as the open-loop Ziegler-Nichols method.

The open-loop Ziegler-Nichols method

This method of controller tuning was developed in 1942 by John G. Ziegler and Nathaniel B. Nichols. It enables the operator to calculate the P, I, and D tuning constants required for P, PI, or PID control of a process based on the open-loop response of the process to a step change in the set point.

The open-loop step response method is performed according to the following procedure:

1. With the controller in open-loop mode, create a step change in controller output. The resulting change in controlled variable should be typical of the expected use of the system. Note that you can use a calibrator instead of the controller to create a step change.

2. Based on the response curve of the controlled variable, determine the process gain K_p, the dead time t_d, and the time constant τ of the process. Refer to Ex. 1-1 for a discussion about process parameters.

   Calculate the value of the parameter κ

$$\kappa = \left|\frac{\tau}{\mathrm{t_d K_p}}\right|$$

3. Using the process characteristics found in step 2, calculate the tuning constants of the controller as follows:

Table 2-3. Control parameters for the open-loop Ziegler-Nichols tuning method.

Mode	Proportional Gain K_c	Integral Time T_i	Derivative Time T_d
P	$K_c = \kappa$	-	-
PI	$K_c = 0.9\,\kappa$	$T_i = 3.33\,t_d$	-
PID	$K_c = 1.2\,\kappa$	$T_i = 2\,t_d$	$T_d = 0.5\,t_d$

Once the tuning constants of the controller are adjusted to the calculated values and the controller is returned to the closed-loop mode, a typical change in the set point should produce the desired quarter-amplitude decay response. The controller should also be able to correct for load changes rapidly, without excessive overshooting or oscillation of the controlled variable. Note, however, that small readjustments of the P, I, and D tuning constants may be required to obtain the optimum controller setting.

It is important to note that the formulas given above apply only to non-interacting, ideal controllers. Other formulas must be used for series or non-interacting parallel controllers. Refer to the section titled *Structure of controllers* on page 50 for details.

An advantage of the open-loop step response method is that the process needs to be disturbed only once to obtain the required process characteristics. On the other hand, the determination of precise process parameters requires a few calculations and, often, some adjustments.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Setup and connections
- Tuning the controller
- Controlling a temperature process

PROCEDURE

Setup and connections

Although a specific tuning method is proposed in this exercise, feel free to try and compare the results of other tuning methods.

1. Verify that the emergency push button is wired so as to be able to cut the power in case of emergency. The *Familiarization with the Training System* manual covers the security issues related to the use of electricity with the system as well as the wiring of the emergency push button.

2. Make sure the 3531 system is properly set up to use the Heating/Cooling unit. The system should also be in its basic setup configuration.

3. Connect the equipment according to the piping and instrumentation diagram (P&ID) shown in Figure 2-29, and use Figure 2-30 to position the equipment correctly on the frame of the training system. To set up your system for this exercise, start with the basic setup presented in the *Familiarization with the Training System* manual and add the equipment listed in Table 2-4. Drives 3 and 4 and pumps 3 and 4 must be connected to the setup as explained in the *Familiarization with the Training System* manual even though they are not shown explicitly in Figure 2-29.

Note how a T-shaped connector is used to split the flow of water from HV2B between the heat exchanger and the three-way control valve. This setup allows stopping the flow of cold water in the heat exchanger using the control valve.

Table 2-4. Material to add to the basic setup for this exercise.

Name	Model	Identification
Brazed plate heat exchanger	46905	
J-type thermocouple	46916	TE1B
Platinum RTD	46917	TE1A
Temperature transmitter	46940	TIT
Paperless recorder	46972	
Controller	----	TIC

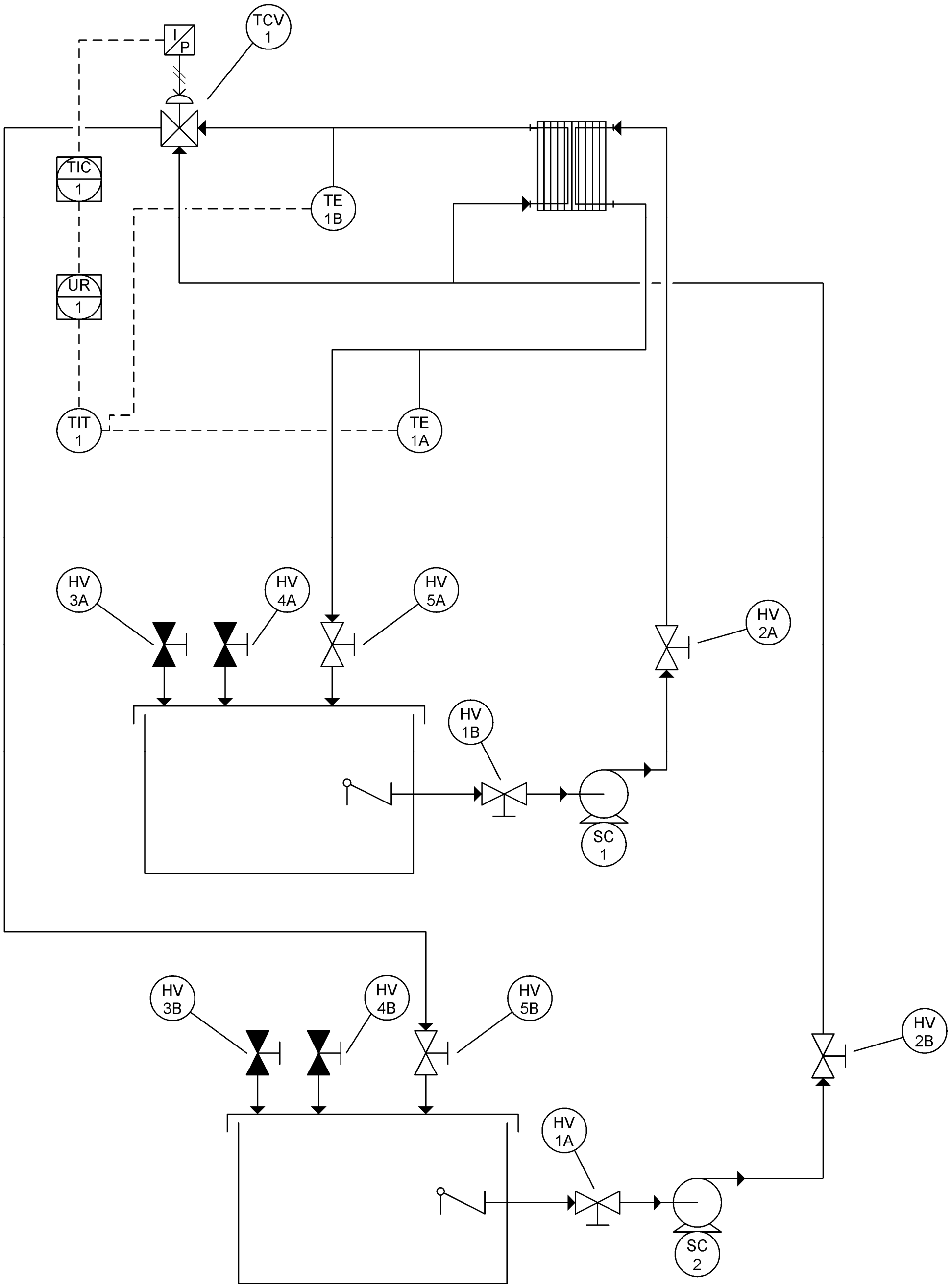


Figure 2-29. P&ID – Heat exchanger control.

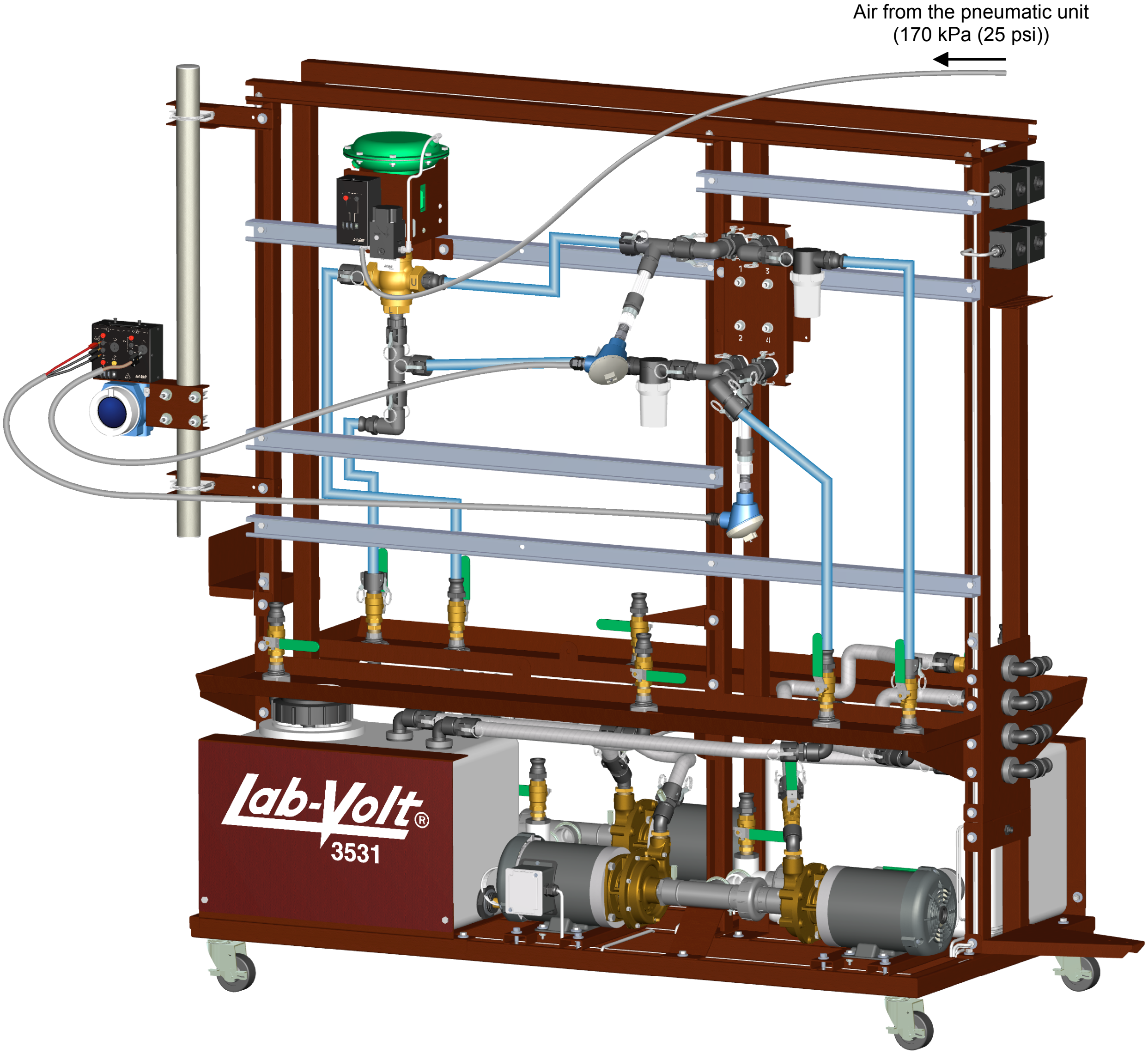


Figure 2-30. Setup – Heat exchanger control.

4. Connect the pneumatic unit to a dry-air source with an output pressure of at least 700 kPa (100 psi).

5. Connect the I/P converter of the three-way control valve to the pneumatic unit. Use the low-pressure port to do so.

6. Do not power up the instrumentation workstation yet. Do not turn on the electrical panel or the heating/cooling unit before your instructor has validated your setup—that is not before step 11.

7. To perform control of your process, you must connect the output of your controller to the control valve and the temperature transmitter to the input of the controller. You must include the recorder in your connection. On channel 1 of the recorder, plot the signal from the controller output and on channel 2, plot the signal from the transmitter output. Be sure to use the analog input of your controller to connect the temperature transmitter. Refer to the manual of your controller for details on how to connect it to other devices.

8. Figure 2-31 shows how to connect the paperless recorder to your system to plot the control signal from the controller on channel 1 and the controller input on channel 2.

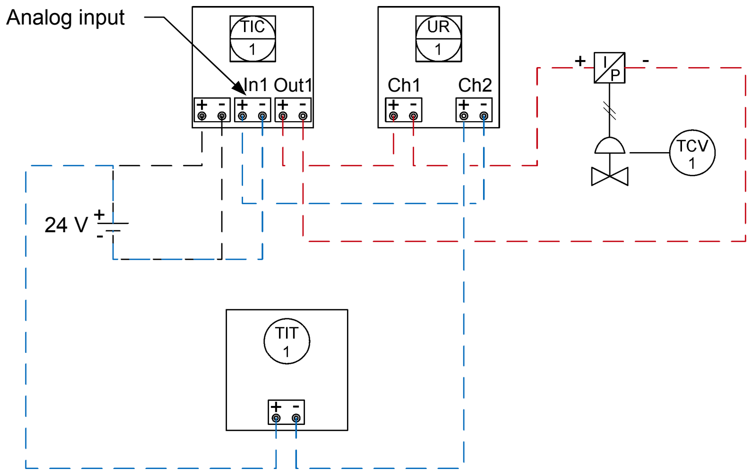


Figure 2-31. Connecting the equipment to the recorder.

9. Before proceeding further, complete the following checklist to make sure you have set up the system properly. The points on this checklist are crucial elements for the proper completion of this exercise. This checklist is not exhaustive, so be sure to follow the instructions in the *Familiarization with the Training System* manual as well.

- Every piece of equipment used is secured to the station with the appropriate bolt-and-nut mechanism.
- The heat exchanger is properly installed on the station.
- The hand valves are in the positions shown in the P&ID:

  Open valves: HV1A, HV1B, HV2A, HV2B, HV5A, and HV5B.
  Closed valves: HV3A, HV3B, HV4A, and HV4B.
- The hand valves under the drip trays are in the positions specified in the *Familiarization with the Training System* manual:

  Open valves: HV1A, HV1B, HV8A, and HV8B.
  Closed valves: HV6A, HV6B, and HV7.
- The L port of the three-way control valve is fully open.
- The pneumatic connections are correct.

- The controller is properly connected to the temperature transmitter.
- The controller is properly connected to the three-way control valve.
- The paperless recorder is connected correctly to plot the calibrator signal on channel 1 and the temperature transmitter output on channel 2.

10. Ask your instructor to check and approve your setup.

11. Power up the electrical unit. This starts all electrical devices as well as the pneumatic devices.

Adjust the pressure at the low-pressure port so 170 kPa (25 psi) is sent to the I/P converter of the control valve.

12. Start the drives 3 and 4 (pumps P3 and P4). These pumps make the water of the two tanks flow in the heating/cooling unit. Ensure the process fluid from each tank is circulating correctly, then power up the heating/cooling unit. Make sure valve HV7 is closed. Continue with the next steps while the water in each tank is respectively heating and cooling toward their temperature set points.

13. Test your system for leaks. Use drives 1 and 2 to make pumps P1 and P2 run at low speed to produce a small flow rate. Progressively increase the frequency output of drives 1 and 2 up to 30 Hz. Repair any leaks.

Let drives 1 and 2 run at 30 Hz.

14. The temperature in the two tanks should be stable and at their respective set points by now. If this is not the case, identify the problem or wait until the temperatures of the tanks stabilize.

15. Test the three-way control valve with your controller in manual mode and make sure it is fully open on L for a 4 mA signal and fully open on U for a 20 mA signal.

16. Configure the paperless recorder so it displays and records the control signal to the three-way control valve on channel 1 and the process temperature on channel 2.

The sampling rate of the paperless recorder should be set to 1 s. To do so, go in the Main Menu ► Setup ► Application ► Signal Group ► Group X (where X is the number of your active group, typically set to 1) ► Save Cycle ► 1 s.

17. Use the temperature transmitter to display the temperature measured by the RTD (TE1A) and to send the related 4-20 mA signal to your controller and trend recorder. The RTD should be installed at the output of the heat exchanger, where the cooled water exits.

18. With the controller in manual mode, set the controller output to 100% to maximize the amount of cold water that circulates in the heat exchanger. Wait for the temperature to stabilize and record the transmitter output (the temperature) in percentage below.

TE1A output (100% controller output): _______________%

19. Unplug the RTD from the temperature transmitter. After a few seconds, the transmitter should display the temperature measured by the thermocouple and it should send the associated 4-20 ma signal to the trend recorder. Record the temperature of the cold water output for a 100% controller output in percentage below:

Cold water temperature (100% controller output): _______________

20. Plug the RTD back in place and be sure the paperless recorder displays the warm water flow temperature.

21. Set the controller output to 0% to stop the cold water flow in the heat exchanger. Wait for the temperature to stabilize, and record the transmitter output (the temperature) in percentage below.

TE1A output (0% controller output): _______________%

22. Again, unplug the RTD from the temperature transmitter. After a few seconds, the transmitter should display the temperature measured by the thermocouple. Record the temperature of the cold water output for a 0% controller output in percentage below:

Cold water temperature (0% controller output): _______________

23. Plug the RTD back in place and be sure the paperless recorder displays the warm water flow temperature.

Tuning the controller

24. The temperature process can be controlled using various control schemes (on-off, P, PI, PD, and PID). However, you are more likely to obtain good results using a controller set to the PI mode. Set your controller to this mode and adjust the parameters using the open-loop Ziegler-Nichols method.

Use the process characteristics obtained in the previous exercise for your calculations and note the parameters entered in the controller:

K_c = ______________

T_i = ______________

25. Switch the controller to the automatic mode and have it maintain a set point of 70%.

26. Test your settings extensively by creating step changes in the controller set point (e.g., from 70% to 60%).

27. Does the open-loop Ziegler-Nichols method gives good results without further tuning of the controller parameters?

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28. If the control is not satisfactory, fine-tune the controller parameters manually using Figure 2-26 to find the best PI parameters. If you had to change the controller parameters, note the new parameters below:

K_c = ______________

T_i = ______________

Controlling a temperature process

29. Once the controller is properly tuned, erase the internal memory of the paperless recorder. Wait a few seconds after the recorder is done rebooting, then perform a set point step change from 70% to 60%.

30. Wait for the value of the process variable to stabilize.

31. Once the system is at steady state, transfer the data from the paperless recorder to a computer or save it on a USB key. Follow the procedure in the *Familiarization with* the *Training System* manual to do so.

32. Stop the system.

33. Plot the process data using a spreadsheet software.

34. Stop drives 1 and 2, and let the water drain out of the hoses.

35. Turn off the heating/cooling unit, then stop drives 3 and 4. Turn off the pneumatic unit and the electrical unit. Turn off your calibrator if one was used.

36. Store the equipment adequately, clean up your workspace, and leave the station ready for the next team.

CONCLUSION

This experiment presented the control of a temperature process loop. You became acquainted with the widely used open-loop Ziegler-Nichols tuning method.

REVIEW QUESTIONS

1. What is the advantage of adding integral action to a proportional control scheme?

2. Why is on-off control not efficient in the experiment presented above?

3. Why does the trial-and-error method proceed with a factor of two change at every iteration?

4. What happens if you increase the K_c parameter in a PI control scheme?

5. Which process characteristic determines both the integral time and the derivative time when using the open-loop Ziegler-Nichols tuning method?

Sample

Extracted from

Instructor Guide

Exercise 2-1 Tuning and Control of a Temperature Loop

ANSWERS TO PROCEDURE STEP QUESTIONS

18. TE1A output (100% controller output): 55% (about 26°C (79°F)).

19. Cold water temperature (100% controller output): Approximately 58% (about 27°C (80.5°F)).

21. TE1A output (0% controller output): Approximately 78% (about 33°C (91°F)).

22. TE1B output - Cold water temperature (0% controller output) = Approximately 55% (about 27°C (80°F)).

24. The Ziegler-Nichols method suggests the following relationships to obtain the parameters in PI mode:

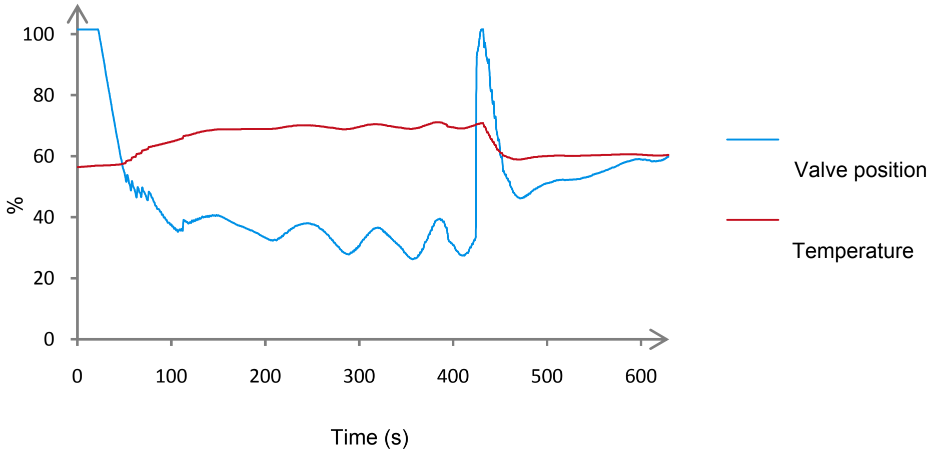
$$K_c = 0.9\,\kappa \qquad T_i = 3.33\,t_d \qquad \kappa = \left|\frac{\tau}{t_d K_p}\right|$$

Using the process characteristics obtained in the previous exercise ($K_p = -0.575$, $\tau = 34$ s, and $t_d = 13\ s$), we can calculate the parameters. Note that the results obtained are indicative only and are likely to differ.

$$K_c = 4.089 \qquad T_i = 43.3 \text{ s}$$

27. In our case, the results were acceptable. The precision and care invested in the measurement of process characteristics have a large impact. A fine-tuning remains almost always advantageous.

33. The graph obtained as the process underwent a 70-60% step change (past the 400 s mark) is provided below. Your results may vary.



Process data for the temperature process.

ANSWERS TO REVIEW QUESTIONS

1. A well tuned integral action eliminates the offset typical of P-only control.

2. On-off control works well for slow-changing processes with large capacitance. In the experiment at hand, the temperature varies too quickly to be controlled by a two-state scheme.

3. This method (geometrical progression) typically converges toward the solution faster than a fixed increment method (arithmetic progression).

4. The response will have a larger amplitude of oscillation and will take more time to stabilize.

5. t_d, the dead time of the process

Bibliography

Benson, Harris. *University Physics*, New York, John Wiley & Sons, 1996, ISBN 0-471-00689-0

Bird, R. Byron, W. E. Stewart, and E. N. Lightfoot. *Transport Phenomena*, New York: John Wiley & Sons, 1996, ISBN 0-471-07392-X.

Çengel, Y. A., and M. A. Boles. *Thermodynamics: An Engineering Approach*, 4th edition, McGraw-Hill College, 2001, ISBN 0-072-38332-1.

Chau, P. C. *Process Control: A First Course with MATLAB*, Cambridge University Press, 2002, ISBN 0-521-00255-9.

Coughanowr, D. R. *Process Systems Analysis and Control*, Second Edition, New York: McGraw-Hill Inc., 1991, ISBN 0-07-013212-7.

Fahrenheit, D. G. Fahrenheit's Letters to Leibniz and Boerhaave, Amsterdam: Radopi, 1983, ISBN 90-6203-586-8.

Feynman, R. P., R. B. Leighton, and M. Sands. *Feynman Lectures on Physics*, Addison Wesley Longman, 1963, ISBN 0-201-02010-6-H.

Halpern, A. *Schaum's Outline of Beginning Physics I: Mechanics and Heat*, McGraw-Hill, 1995, ISBN 0-070-25653-5.

Haynes, W. M. *CRC Handbook of Chemistry and Physics*, 91th edition, CRC Press, 2010, ISBN 1-439-82077-5.

Incropera, F. P., and D. P. DeWitt. *Fundamentals of Heat and Mass Transfer*, 4th edition, John Wiley and Sons, 1996, ISBN 0-471-30460-3.

Lipták, B. G. *Instrument Engineers' Handbook: Process Control*, Third Edition, Pennsylvania: Chilton Book Company, 1995, ISBN 0-8019-8542-1.

Lipták, B. G. *Instrument Engineers' Handbook: Process Measurement and Analysis*, Third Edition, Pennsylvania: Chilton Book Company, 1995, ISBN 0-8019-8197-2.

Luyben, M. L., and W. L. Luyben. *Essentials of Process Control,* McGraw-Hill Inc., 1997, ISBN 0-07-039172-6.

Luyben, W. L. *Process Modeling, Simulation and Control for Chemical Engineers*, Second Edition, New York: McGraw-Hill Inc., 1990, ISBN 0-07-100793-8.

McMillan, G. K., and R. A. Cameron. *Advanced pH Measurement and Control*, Third Edition, NC: ISA, 2005, ISBN 0-07-100793-8.

McMillan, G. K. *Good Tuning: A Pocket Guide*, ISA - The Instrumentation, Systems, and Automation Society, 2000, ISBN 1-55617-726-7.

McMillan, G. K. *Process/Industrial Instruments and Controls Handbook*, Fifth Edition, New York: McGraw-Hill Inc., 1999, ISBN 0-07-012582-1.

Bibliography

Perry, R. H., and D. Green. *Perry's Chemical Engineers' Handbook*, Sixth Edition, New York: McGraw-Hill Inc., 1984, ISBN 0-07-049479-7.

Pitts, D., and L. E. Sissom. *Schaum's Outline of Heat Transfer*, 2nd edition, McGraw-Hill, 1998, ISBN 0-070-50207-2.

Raman, R. *Chemical Process Computation*, New-York: Elsevier applied science ltd, 1985, ISBN 0-85334-341-1.

Shah, R. K., and D.P. Sekulić. *Fundamentals of Heat Exchanger Design*, New York: John Wiley & Sons, Inc., 2003, ISBN 0-471-32171-0.

Ranade, V. V. *Computational Flow Modeling for Chemical Reactor Engineering*, California: Academic Press, 2002, ISBN 0-12-576960-1.

Shinskey, G. F. *Process Control Systems*, Third Edition, New York: McGraw-Hill Inc., 1988.

Smith, Carlos A. *Automated Continuous Process Control*, New York: John Wiley & Sons, Inc., 2002, ISBN 0-471-21578-3.

Soares, C. *Process Engineering Equipment Handbook*, McGraw-Hill Inc., 2002. ISBN 0-07-059614-X.

The International System of Units (SI), 8th edition.

Weast, R. C. *CRC Handbook of Chemistry and Physics*, 1st Student Edition, Florida: CRC Press, 1988, ISBN 0-4893-0740-6.