Process Control

Process Control
Air, Pressure, and Flow

Courseware Sample

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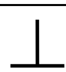
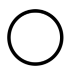
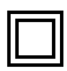
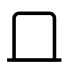
Safety and Common Symbols

The following safety and common symbols may be used in this manual and on the equipment:

Symbol	Description
⚠ DANGER	**DANGER** indicates a hazard with a high level of risk which, if not avoided, will result in death or serious injury.
⚠ WARNING	**WARNING** indicates a hazard with a medium level of risk which, if not avoided, could result in death or serious injury.
⚠ CAUTION	**CAUTION** indicates a hazard with a low level of risk which, if not avoided, could result in minor or moderate injury.
CAUTION	**CAUTION** used without the *Caution, risk of danger* sign ⚠, indicates a hazard with a potentially hazardous situation which, if not avoided, may result in property damage.
	Caution, risk of electric shock
	Caution, hot surface
	Caution, risk of danger
	Caution, lifting hazard
	Caution, hand entanglement hazard
	Notice, non-ionizing radiation
	Direct current
	Alternating current
	Both direct and alternating current
	Three-phase alternating current
	Earth (ground) terminal

Safety and Common Symbols

Symbol	Description
	Protective conductor terminal
	Frame or chassis terminal
	Equipotentiality
	On (supply)
	Off (supply)
	Equipment protected throughout by double insulation or reinforced insulation
	In position of a bi-stable push control
	Out position of a bi-stable push control

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Preface

Automated process control offers so many advantages over manual control that the majority of today's industrial processes use it to some extent. Breweries, wastewater treatment plants, mining facilities, and the automotive industry are just a few industries that benefit from automated process control systems.

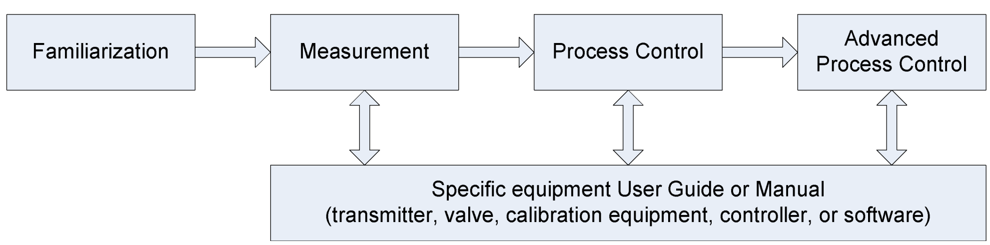
Maintaining process variables such as pressure, flow, level, temperature, and pH within a desired operating range is of the utmost importance when manufacturing products with a predictable composition and quality.

The Instrumentation and Process Control Training System, series 353X, is a state-of-the-art system that faithfully reproduces an industrial environment. Throughout this course, students develop 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 theoretical and hands-on knowledge required to work in the process control industry.

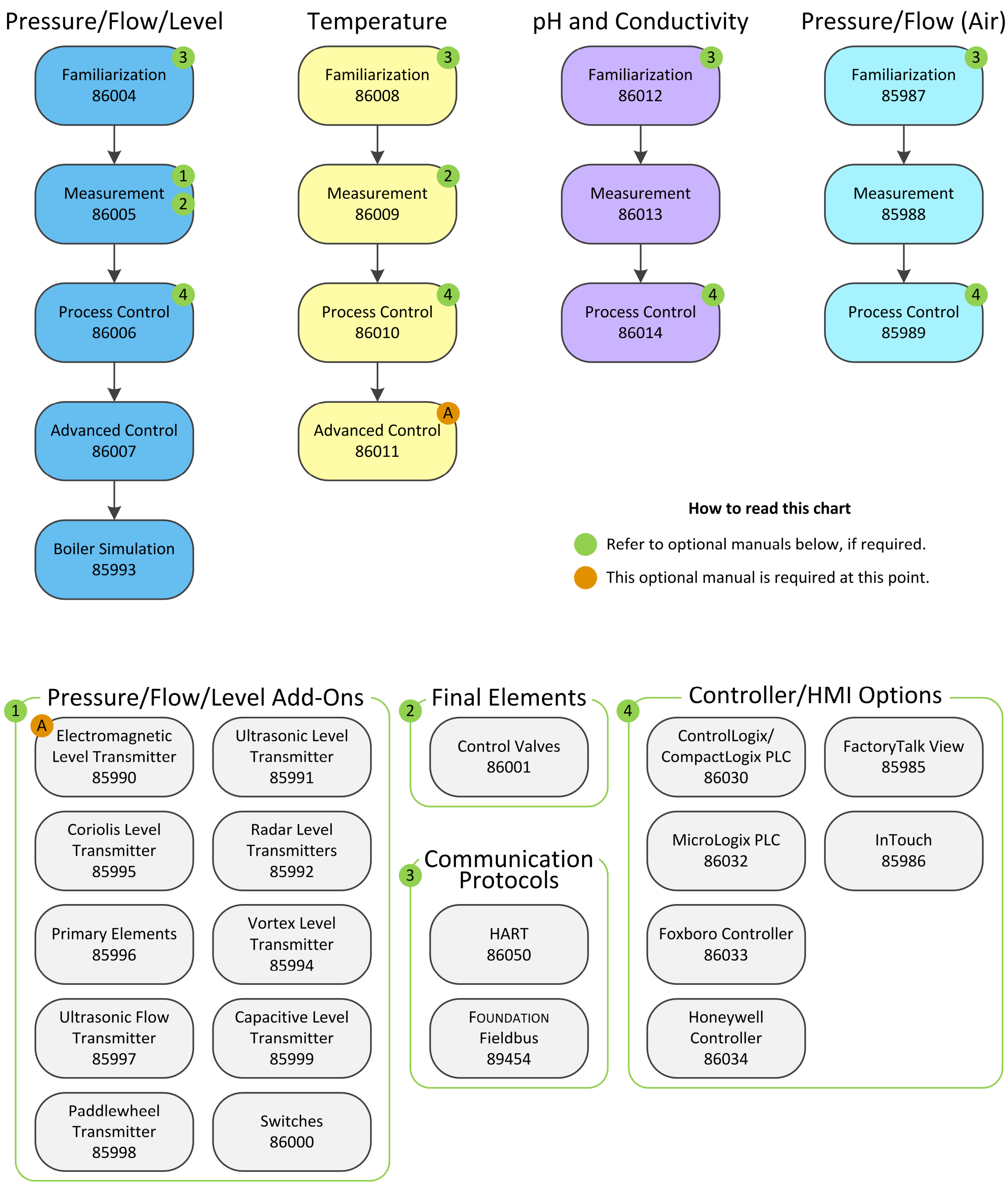
The modularity of the system allows the instructor to select the equipment required to meet the objectives of a specific course. Two mobile workstations, on which all of the equipment is installed, form the basis of the system. Several optional components used in pressure, flow, level, temperature, and pH control loops are available, as well as various valves, calibration equipment, and software. These add-ons can replace basic components having the same functionality, depending on the context. During control exercises, a variety of controllers can be used interchangeably depending on the instructor's preference.

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.

Standard Learning Path



Manuals of the 353X Series



Preface

We invite readers of this manual to send us their tips, feedback and suggestions for improving the book.

Please send these to did@de.festo.com.

The authors and Festo Didactic look forward to your comments.

To the Instructor

You will find in this Instructor Guide all the elements included in the Student Manual together with the answers to all questions, results of measurements, graphs, explanations, suggestions, and, in some cases, instructions to help you guide the students through their learning process. All the information that applies to you is placed between markers and appears in red.

Accuracy of measurements

The numerical results of the hands-on exercises may differ from one student to another. For this reason, the results and answers given in this manual should be considered as a guide. Students who correctly performed the exercises should expect to demonstrate the principles involved and make observations and measurements similar to those given as answers.

Equipment installation

In order for students to be able to perform the exercises in the Student Manual, the Process Control Training Equipment – Air Pressure and Flow must have been properly installed, according to the instructions given in the user guide Familiarization with the Instrumentation and Process Control System – Air Pressure and Flow, part number 85987-E.

Sample Exercise
Extracted from
the Student Manual
and the Instructor Guide

Tuning and Control of a Pressure Loop

EXERCISE OBJECTIVE

Familiarize yourself with the use and manual tuning of PI control scheme applied to pressure loops.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Recapitulation of relevant control schemes
- The open-loop Ziegler-Nichols method
- Tuning with the ultimate-cycle method
  Ultimate-cycle method example. Quarter-amplitude decay ratio.
- Limits of the ultimate-cycle method

DISCUSSION

This exercise introduces three control schemes and puts them to use in a pressure 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.

Some controllers use the proportional band ($PB\% = 100\%/K_c$) instead of the controller gain.

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. Two parameters are required for this control method: K_c (or $PB\%$) and T_i.

Some controllers use the integral gain, defined as $G_i = 1/T_i$ instead of the integral time.

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 $PB\%$).

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.

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

Remember that the process gain is $K_p = \frac{\Delta output}{\Delta input} = \frac{\%\, change\ in\ process\ variable}{\%step\ change}$.

3. Using the process characteristics found in step **Erreur ! Source du renvoi introuvable.**, calculate the tuning constants of the controller as follows:

Table 2-2. 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 entitled *Structure of controllers* on page 59 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.

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 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.

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

The ultimate gain K_u is the smallest 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.

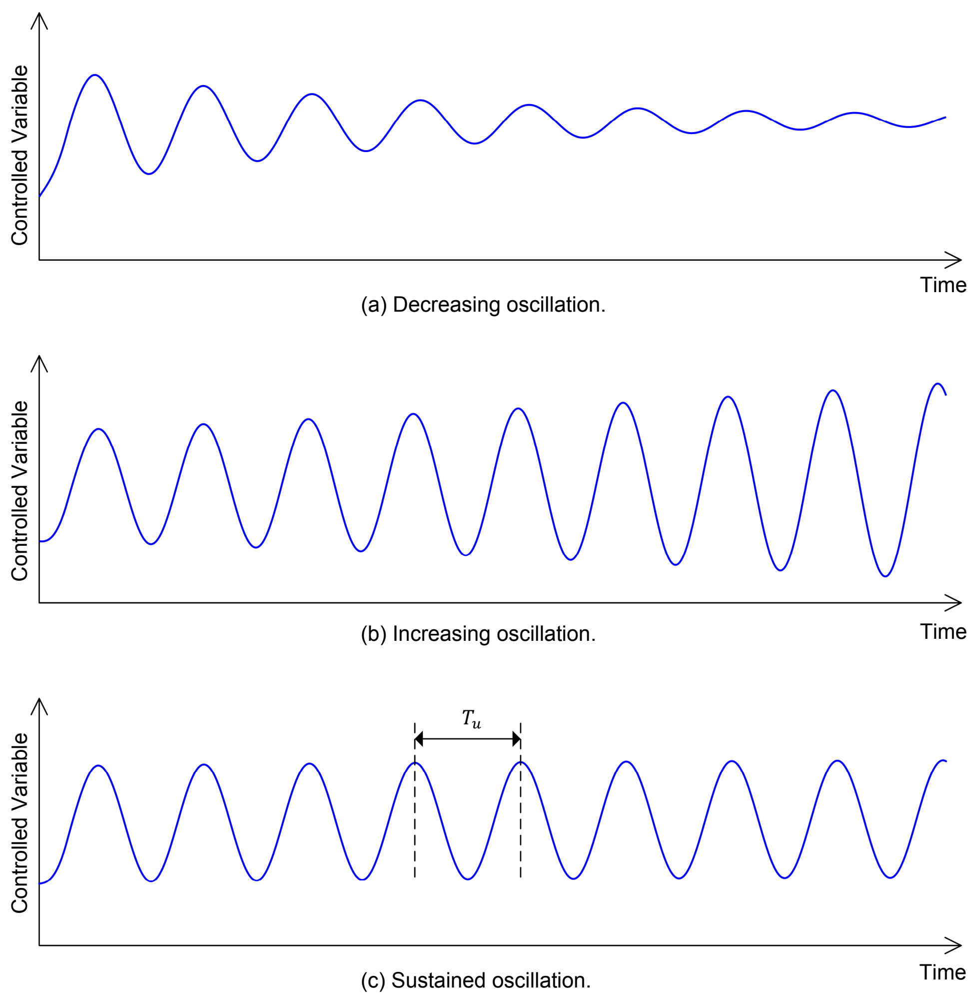


Figure 2-25. Types of oscillations and determination of the ultimate period.

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 2-25c. If not, make small changes in the proportional gain until a sustained oscillation is achieved. The oscillations can be sustained for a gain in a given range. Your goal is to find the minimum gain for which the oscillation is sustained.

   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 2-25c. 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 2-3. 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.

Ultimate-cycle method example

Table 2-5 gives an example of the sequence of adjustments required to fine the ultimate gain for a given process.

Table 2-4. Example of an ultimate-cycle method.

Step	Gain	Type of oscillation
1	1	Decreasing
2	2	Decreasing
3	4	Decreasing
4	8	Decreasing
5	16	Decreasing
6	32	Sustained
7	24	Sustained
8	20	Sustained
9	18	Decreasing
10	19	Sustained
11	18.5	Sustained

In the example above, it took 11 steps to obtain the ultimate gain, K_u=18.5. The oscillation where sustained for a gain value of 32, but this gain was not the minimum gain producing sustained oscillation. Hence for the next step, the gain was set to a value halfway between the actual gain and the last gain producing decreasing oscillations (i.e., 16). This is repeated until decreasing oscillations are obtained again at step 9. The gain was then tampered with some more until sufficient precision on the gain was obtained.

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.

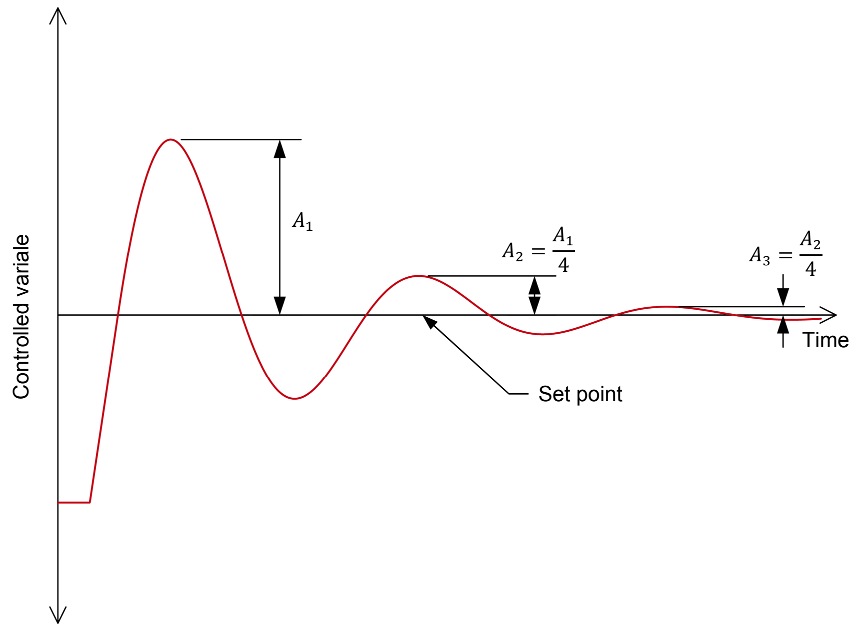


Figure 2-26. Quarter-amplitude decay ratio.

The quarter-amplitude decay 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 59 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.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Set up and connections
- Adjusting the differential-pressure transmitter
- Pressure control
- Ultimate period tuning

PROCEDURE

Set up and connections

⚠ CAUTION

Wear safety glasses and ear plugs at all times. Compressed air entering the body through skin or body cavities can cause serious health issues.

1. Position and secure all the basic air pressure/flow equipment as shown in Figure 1-26.

2. Use plastic tubing to connect the equipment as shown in the piping and instrumentation diagram (P&ID) of Figure 2-27. The control valve I/P converter is connected to the controller and to the pneumatic unit 0-200 kPa (0-30 psi) air outlet.

3. Table 2-5 lists the equipment that is required for this exercise.

Table 2-5. Devices required for this exercise.

Name	Model	Tag number
Emergency push-button	5926-A	
Large tank	46906	
Muffler assembly	46907	
Differential-pressure transmitter (**high**-pressure range)	46920	PDIT 1
Pneumatic control valve	46953	PCV 1
Electrical unit	46970-B	
Pneumatic unit	46971-A	
Paperless recorder	46972	
Accessories	46993	
Controller	----	PIC

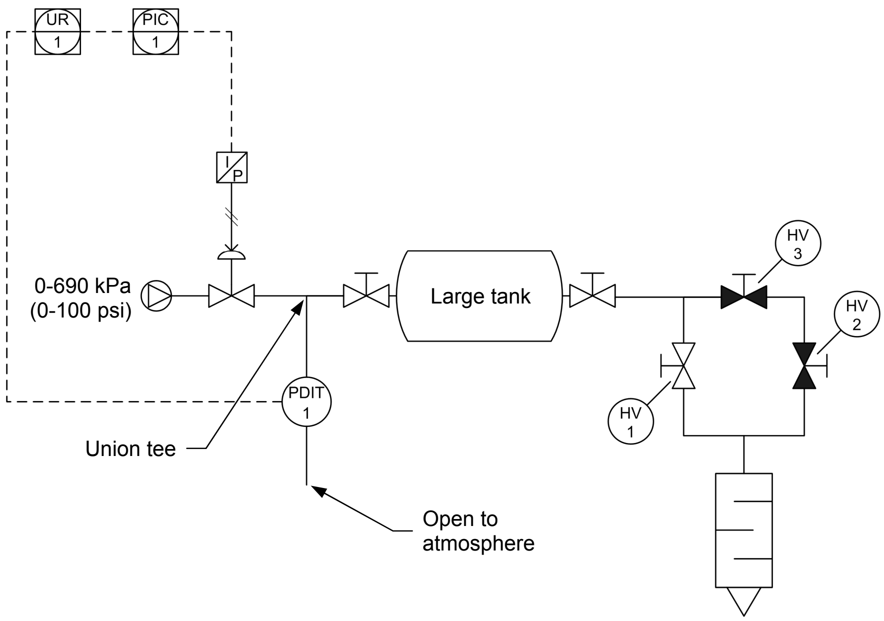


Figure 2-27. Pressure control loop.

CAUTION

Verify every tubing connection on your setup before putting the system under pressure. This is very important to ensure that all connections are secure and that no air escapes.

4. Connect the control valve to the pneumatic unit.

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

6. Wire the emergency push-button so that you can cut power in case of an emergency.

7. Connect the controller to the control valve and to the differential-pressure transmitter. You must also include the recorder in your connections. On channel 1 of the recorder, plot the output signal from the controller and on channel 2, plot the signal from the transmitter. Be sure to use the analog input of your controller to connect the differential-pressure transmitter.

8. Figure 2-28 shows how to connect the different devices together.

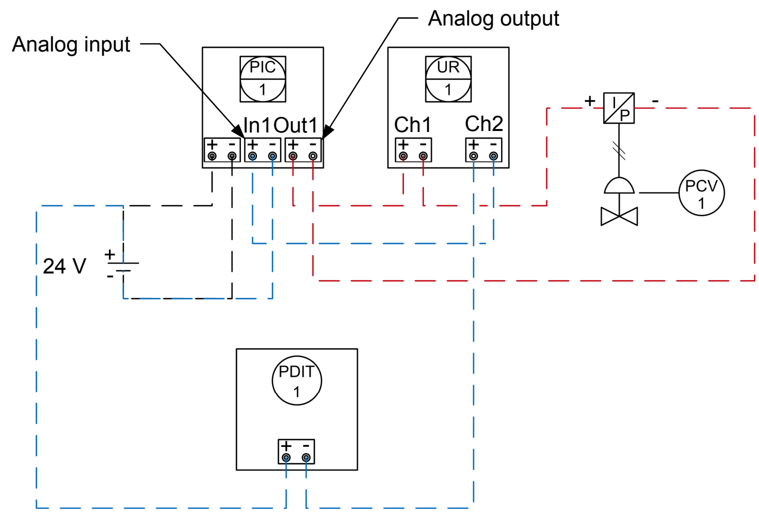


Figure 2-28. Connecting the equipment to the recorder.

9. Do not power up the instrumentation workstation before your instructor has validated your setup.

10. 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. Be sure to follow the instructions in the *Familiarization with the Training System* manual as well.

- ☐ All equipment is correctly fastened to the workstation.
- ☐ The air supply activation valve of the pneumatic unit is closed.
- ☐ The two pressure adjustment knobs of the pneumatic unit are set to minimum pressure.
- ☐ The pneumatic connections are made correctly.
- ☐ All tubing is free of water.

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

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

13. Adjust the zero of the differential-pressure transmitter.

14. Configure the differential-pressure transmitter so that it provides pressure readings in the desired units. Set transmitter parameters so that it sends a 4 mA signal if the pressure is 0 kPa (0 psi) and a 20 mA signal if the pressure is 550 kPa (80 psi).

15. Using the pressure adjustment knob, set the 0-200 kPa (0-30 psi) output connected to the I/P converter of the control valve to 200 kPa (30 psi).

CAUTION

Do not exceed the maximum recommended pressure for the I/P converter.

16. Set the 0-690 kPa (0-100 psi) output connected to the inlet of the control valve to 0 kPa (0 psi).

17. Open the air supply activation valve of the pneumatic unit.

18. In manual mode, set the output of the controller to 100%. The control valve should be fully open. If it is not, revise the electrical and pneumatic connections and make sure the calibration of the I/P converter is appropriate.

19. Test your system for leaks. To do so, lift and gradually turn the 0-690 kPa (0-100 psi) pressure adjustment knobs to increase the output pressure up to 200 kPa (30 psi).

20. Set the output of the controller to 0% to close the control valve, close the air supply, and depressurize the system. Arrange any faulty connections.

Adjusting the differential-pressure transmitter

21. Make sure the control valve is closed, pressurize the system, and open the air supply.

22. Set the 0-690 kPa (0-100 psi) output connected to the inlet of the control valve to 550 kPa (80 psi).

23. Adjust the zero of the differential-pressure transmitter. The circuit is open to atmosphere (through the muffler), therefore the transmitter should read 0 kPa (0 psi) when the control valve is closed.

CAUTION

Be sure to use the differential-pressure transmitter, Model 46920. This differential-pressure transmitter has a high-pressure range.

24. Close the valve at the inlet of the large tank to direct all pressure to the differential-pressure transmitter.

25. In manual mode, set the output of the controller to 100%. This fully opens the control valve. On the differential-pressure transmitter, the pressure reading should be approximately 550 kPa (80 psi). If the pressure reading is correct, proceed with step 26. If not, set the controller output to 0% to close the control valve. Slowly open the valve at the inlet of the large tank to purge pressurized air from the tubing and use the 0-690 kPa (0-100 psi) pressure adjustment knob to readjust the pressure. Repeat steps 24 and 25.

26. If the paperless recorder is correctly configured, channel 1 of the recorder should indicate that the controller output is 100%.

27. Set the output of the controller to 0% and slowly open the valve at the inlet of the large tank to purge pressurized air from the tubing.

28. Make sure the valves positions (open or closed) are as shown in Figure 2-27 (except for the control valve, which should be closed).

Pressure control

29. Use the data from Table 1-3 to calculate the control parameters for a PI control mode and fill Table 2-6.

Table 2-6. PI control parameters for the open-loop Ziegler-Nichols tuning method.

Method	Proportional Gain K_c	Integral Time T_i
Graphical		
2%–63.2%		
28.3%–63.2%		

Using the values from the data analysis table of the previous exercise, the following control parameters can be computed. The values in the table below are provided as a guideline. The control parameters for your setup may vary due to various factors.

PI control parameters for the open-loop Ziegler-Nichols tuning method.

Method	Proportional Gain K_c	Integral Time T_i
Graphical	22.3	0.05 min (2.7 s)
2%–63.2%	10.4	0.08 min (5.0 s)
28.3%–63.2%	9.0	0.1 min (5.7 s)

30. Do these three methods give the same results?

No these three methods use different calculations for the time constant τ and dead time t_d, hence the PI parameters are likely to be different.

31. Program the controller to operate in PI mode. Tune the controller using the proportional gain and integral time from the 28.3%–63.2% method row of Table 2-6 and set the controller set point to 0%.

32. Once the controller is properly configured, place it in the automatic mode. Change the controller set point to 5%.

33. On the paperless recorder, watch the controller struggle to maintain the pressure at the desired set point. If the controller is not properly tuned using the values from Table 2-6, fine tune it by changing the proportional gain and integral time until proper control is obtained.

34. If the controller required fine tuning, record the controller parameter after fine tuning in Table 2-7.

Table 2-7. Tuned controller parameters.

Proportional Gain K_c	Integral Time T_i

The results are presented below.

Tuned controller parameters.

Proportional Gain K_c	Integral Time T_i
8.3	0.1 min

35. Using the paperless recorder, record the response to a step change in the set point from 5% to 10%. Wait for the value of the process variable to stabilize.

For each set point (5%, 10%, 15%, 20%, and 25), note the date and time on the paperless recorder. You will need this information to retrieve your data from the recorder data file.

36. Record the response to a step change in the set point from 10% to 15%. Wait for the value of the process variable to stabilize.

37. Record the response to a step change in the set point from 15% to 20%. Wait for the value of the process variable to stabilize.

38. Record the response to a step change in the set point from 20% to 25%. Wait for the value of the process variable to stabilize.

39. Place the controller in manual mode and set its output to 0% to close the control valve. Wait for the pressure to drop to zero.

40. Follow the procedure in the *Familiarization with the Training System* manual to transfer the data from the paperless recorder to a computer.

Ultimate period tuning

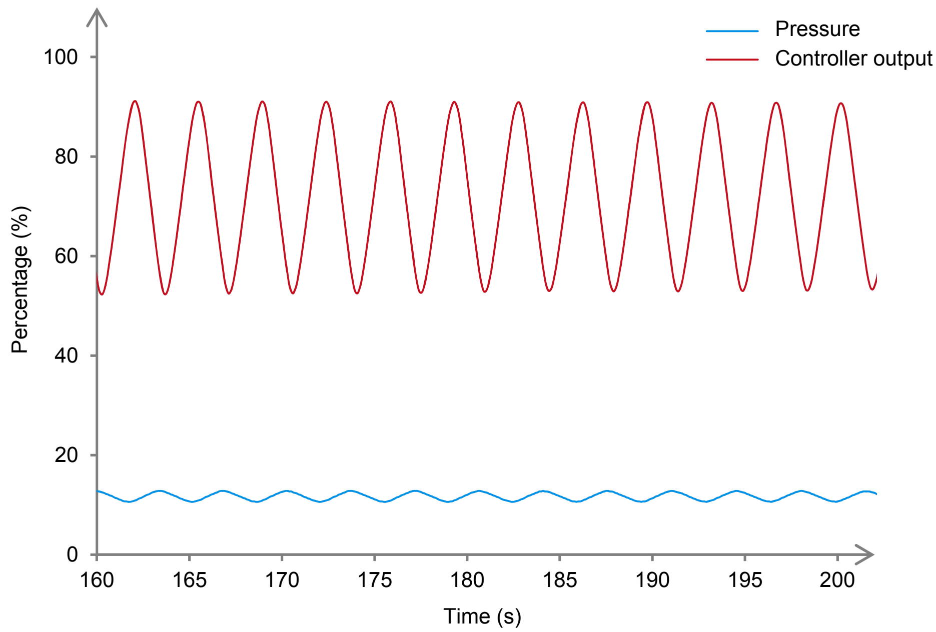
41. Apply the ultimate-cycle method to determine the ultimate gain and period. Record them in Table 2-8. The step change in the set point should be from 10% to 20%.

It might be helpful and more precise to transfer the data to a computer in order to determine T_U using spreadsheet software.

Table 2-8. Ultimate-cycle method.

Ultimate gain K_u	Ultimate period T_u

The results are presented below.



Determining the ultimate gain and period.

Ultimate-cycle method.

Ultimate gain K_u	Ultimate period T_u
18.5	3.5 s

42. Calculate the K_c and T_i parameters for your process and record the results in Table 2-9.

Table 2-9. PI control parameters calculated using the ultimate-cycle tuning method.

Mode	Controller Gain K_c	Integral Time T_i
PI		

Always make sure the units you use are in agreement with those of the controller. For instance, some controllers use units of minutes instead of seconds. Convert your results as required and develop the habit of checking for unit consistency whenever troubleshooting for unexpected behaviors.

The results are presented below.

PI control parameters calculated using the ultimate-cycle tuning method.

Mode	Controller Gain K_c	Integral Time T_i
PI	8.3	0.05 min

43. Program the controller to operate in PI mode. Tune the controller using the proportional gain and integral time from the ultimate-cycle method (Table 2-9) and set the controller set point to 5%.

44. Repeat steps 32 to 39.

45. Close the air supply and depressurize the system.

46. Use the main switch to cut the power to the Instrumentation and Process Control Training System.

Conclusion

In this exercise, you learned four different tuning methods. You used two of these methods to configure the controller for PI control.

Review Questions

1. Explain why on-off control cannot be used for the experiment presented above.

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

2. What are the required parameters for the ultimate-cycle method?

The two parameters involved in the ultimate-cycle method are: the ultimate gain (K_u) and the ultimate period (T_u).

3. How do you find the value of those parameters?

The ultimate proportional gain K_u is the proportional gain (K_c) at which the sustained oscillation initially starts in P mode. The ultimate period T_u is the period of oscillation of the process when K_c is set to K_u in P mode.

4. What does ‘sustained oscillation’ mean?

An oscillation that continues at the same amplitude, without increasing or decreasing.

5. When would it be unsuitable to tune a process via the ultimate-cycle method?

The method is unsuitable in processes where bringing the system into continuous oscillation could be dangerous or might cause damage.

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