# 9 DIRECT HEATING BATCH OPERATION TEMPERATURE CONTROL EXERCISES

## 9.1 Exercise 5.1: Manual control of Heater

**Objective:**

To control the temperature in a process vessel manually by controlling power to a heating element.

**Overview:**

The temperature within the process vessel is monitored using a thermocouple type sensor. By manually switching the power to a heating element on or off, the temperature within the vessel is regulated to maintain the required set point.

**Equipment Required:**

PCT40 bench with small process vessel containing a heating coil.

**Equipment set up:**

Ensure that the apparatus has been set up according to the assembly sheet (see also Appendix A in this manual). The lid with heating coil should be in position on the small process vessel, with the coil surrounding the heating element. The apparatus should be connected to a suitable PC with the PCT40 software installed, using the grey USB cable supplied.

Switch on mains power to the console and run the PCT40 software.

Select 'Configure' from the Sample menu, and set sampling to Automatic at intervals of 30 seconds, with duration as Continuous.

Fill the small process vessel with water:
Using a length of tubing with a quick release fitting at both ends, connect the PSV to one of the fittings on the side of the small process vessel. Ensure that the other fitting on the side of the process vessel is not connected.

Close the drain valve on the process vessel.

In the software, set the PSV to 100% and watch as the small process vessel fills with water.

Wait until the coil inside the vessel is fully covered with water and the level has reached the level sensor mounted in the lid, then set the PSV to 0%.

Disconnect the tube from the small process vessel, and then disconnect the other end from the PSV.

Take a length of tube with a quick release fitting at one end and a Guest push fitting at the other. Connect one end to the PSV and the other end to the coil inside the small process vessel (via the push fitting mounted on the lid).

Take a second length of tube with a quick-release fitting at one end and a drain valve at the other. Connect this end to the other side of the coil, and direct the opposite end of the tube to a suitable drain. Open the drain valve at the end of the tube.

Check that the drain valve on the end of the plinth is open and that it is connected to a suitable drain.

**Procedure:**

**SAFETY NOTE:** During this exercise the apparatus may reach temperatures hot enough to cause burns or scalds. Do not touch the process vessel during the exercise, or remove the coil or sensors from within the vessel. Allow the apparatus to cool before draining the water or disconnecting any of the tubes from the process vessel.

Check that the temperature reading T1 is a sensible value (usually between 5 and 30 degrees Celsius depending on mains water temperature).

A target temperature for the fluid in the vessel is required. 40 degrees centigrade is suggested. (If the mains water temperature is very high- approaching or exceeding 30 °C- then 50 °C may instead be used as the target Set Point temperature)

The heating element is switched on and off manually using the switch on the software screen. Switch on the heater, and observe the temperature T1. Check that this rises as the heater operates.

Heating Characteristics in Batch Operation

The temperature in the vessel may be manually controlled by switching the power to the heating element off and on. When using manual control, consideration should be given to the following:

Time lag between applying a control action and observing a response.

Differences in the rate of heating and cooling.

Take notes on these and other factors that affect the control actions required to reach and then obtain a constant temperature within the process vessel.

Select the  icon to begin data logging.

Manually control the temperature in the tank for a period of five minutes.

Select the  icon to finish data logging.

Create a new results sheet by selecting the  icon.

Disturbances

Within the software it is possible to introduce disturbances in the temperature inside the process vessel by passing cold water through the coil inside the vessel:

Select the  icon to begin data logging.

In the software, send cold water through the coil within the process vessel by setting the PSV to 50%.

Control the heater to maintain the temperature in the vessel.

Increase the PSV setting to 100%.

Continue to control the temperature at the chosen Set Point value.

Set the PSV back to 0%, and continue to control the temperature within the vessel.

Select the  icon to finish data logging.

Create a new results sheet by selecting the  icon.

**Results:**

For easy identification or results, it is suggested that each results sheet is renamed with a descriptive title (e.g. 'Disturbances', etc.). The entire workbook should be saved with a suitable filename for future reference (e.g. PCT40 Exercise 3.1).

Each set of data should be plotted on a graph of temperature T1 against time.

Write up your experiment, commenting on the heating and cooling characteristics of batch operation and the actions required for manual control of the process. Give reasons for any time delay between applying a control action and observing a response. Explain the difference in heating and cooling rates. Give examples of industrial control situations in which a disturbance of the kind investigated might occur.

## 9.2 Exercise 5.2: Proportional temperature input with on/off control

**Objective:**

To control the temperature in a process vessel using an on/off controller connected to a temperature sensor, by controlling power to a heating element.

**Overview:**

The temperature within the process vessel is monitored using a thermocouple type sensor. The output is sent to an On/Off controller that switches a heating element on or off to maintain the required set point temperature within the vessel.

**Equipment Required:**

PCT40 bench with small process vessel containing a heating coil.

**Equipment set up:**

Ensure that the apparatus has been set up according to the assembly sheet (see also Appendix A in this manual). The lid with heating coil should be in position on the small process vessel, with the coil surrounding the heating element. The apparatus should be connected to a suitable PC with the PCT40 software installed, using the USB cable supplied.

Switch on mains power to the console and run the PCT40 software.

Select 'Configure' from the Sample menu, and set sampling to Automatic at intervals of 30 seconds, with duration as Continuous.

Fill the small process vessel with water:
Using a length of tubing with a quick release fitting at both ends, connect the PSV to one of the fittings on the side of the small process vessel. Ensure that the other fitting on the side of the process vessel is not connected.

Close the drain valve on the process vessel.

In the software, set the PSV to 100% and watch as the small process vessel fills with water.

Wait until the coil inside the vessel is fully covered with water, then set the PSV to 0%.

Disconnect the tube from the small process vessel, and then disconnect the other end from the PSV.

Take a length of tube with a quick release fitting at one end and a Guest push fitting at the other. Connect one end to the PSV and the other end to the coil inside the small process vessel (via the push fitting mounted on the lid).

Take a second length of tube with a quick-release fitting at one end and a drain valve at the other. Connect this end to the other side of the coil, and direct the opposite end of the tube to a suitable drain. Open the drain valve at the end of the tube.

Check that the drain valve on the end of the plinth is open and that it is connected to a suitable drain.

**Procedure:**

**SAFETY NOTE:** During this exercise the apparatus may reach temperatures hot enough to cause burns or scalds. Do not touch the process vessel during the exercise, or remove the coil or sensors from within the vessel. Allow the apparatus to cool before draining the water or disconnecting any of the tubes from the process vessel.

Setting the On/Off Controller:
In the PCT40 software, click on the Control box.

Set the Proportional Band (P) to 0%, the Integral Time (I) to 0s and the Derivative Time (D) to 0s. The controller is now set as a simple On/Off controller with fixed hysteresis of 0.5% of full scale.

Type in the Set Point value at which the on/off controller will operate. A recommended starting value is 30 degrees Celsius. A higher Set Point temperature will be required if the mains water inlet supply temperature is close to 30 °C: a value of at least 10 degrees higher than the inlet supply is recommended.

Apply the settings and close the controller window.

From the Sample menu at the top of the screen, select Configure… and set data logging to automatic at intervals of thirty (30) seconds. Check that the reading L1 is varying with the rising water levels.

Check that the temperature reading T1 is a sensible value (usually between 5 and 30 degrees Celsius depending on mains water temperature).

Select the  icon to begin data logging.

Note the behaviour of the heating element as the temperature approaches the temperature set point. It is possible to observe heated water rising from the heating element when the power is on. The heater also responds audibly when power is switched on or off. Additionally, the switch for the heater is displayed on the mimic diagram screen within the software, allowing observation of the heater action.

The change in temperature may be most easily observed using the graph screen in the software. If the graph does not appear automatically when the graph screen is selected, select ‘T1’ for the Y axis and ‘Time’ for the x-axis, then plot the graph. New points will be added as they are logged.

Continue logging for 30 minutes. Select the  icon to finish data logging.

Disturbances

Within the software it is possible to introduce disturbances in the temperature inside the process vessel by passing cold water through the coil inside the vessel:

Create a new results sheet by selecting the icon in the tool bar of the software.

Select the icon to begin data logging.

Log for two minutes (with the software taking readings every 10 seconds), then set the PSV to 50%.

Log for 15 minutes, then set the PSV to 100%.

Continue logging for 15 minutes, then set the PSV to 0%.

Log for a final 15 minutes, then select the icon to finish data logging.

Temperature Set Point

Investigate the effect of changing the temperature at which the on/off heater switch operates:

In the software, alter the temperature set point to 50 °C.

Select the icon to begin data logging.

Log for 15 minutes, and then select the icon to finish data logging.

Select the icon to create a new results sheet.

Repeat the procedure, altering the set point and logging the change in temperature until the oscillations reach stable values. Suggested values for the temperature set point value are 60, 70 and 80 °C. Remember to create a new results sheet for each set of data.

**Results:**

For easy identification or results, it is suggested that each results sheet is renamed with a descriptive title (e.g. 'Flowrate', 'Volume', etc.). The entire workbook should be saved with a suitable filename for future reference (e.g. PCT40 Exercise 5.2).

Each set of data should be plotted on a graph of temperature T1 against time.

Make a comparison of each variation in the experimental conditions against the graph of the initial set of results, noting the difference in response.

Give examples of industrial control situations in which each type of variation in starting conditions might occur. For each example, consider the suitability of an on/off controller for that particular application.

## 9.3 Exercise 5.3: Proportional temperature input with time proportional control of heater

**Objective:**

To control the temperature in the process vessel using a time-proportional controller connected to a temperature sensor, with a heating element raising the temperature of the fluid within the vessel.

**Overview:**

The control system in this exercise consists of a pressure sensor with an output proportional to the temperature detected by the sensor. The output is sent to a time proportional controller which controls the power supply to the heating element. The time proportioning controller turns the output on and off at intervals. This ratio of time "on" to time "off" may be set manually, or may be set automatically by the controller which then varies the ratio according to the difference between the current control variable and the required Set Point value.

**Equipment Required:**

PCT40 bench with small process vessel containing a heating coil.

**Equipment set up:**

Ensure that the apparatus has been set up according to the assembly sheet (see also Appendix A in this manual). The lid with heating coil should be in position on the small process vessel, with the coil surrounding the heating element. The apparatus should be connected to a suitable PC with the PCT40 software installed, via the grey USB cable supplied.

Run the PCT40 software.

Select 'Configure' from the Sample menu, and set sampling to Automatic at intervals of 30 seconds, with duration as Continuous.

Fill the small process vessel with water:

Using a length of tubing with a quick release fitting at both ends, connect the PSV to one of the fittings on the side of the small process vessel. Ensure that the other fitting on the side of the process vessel is not connected.

Close the drain valve on the process vessel.

In the software, set the PSV to 100% and watch as the small process vessel fills with water.

Wait until the coil inside the vessel is fully covered with water, then set the PSV to 0%.

Disconnect the tube from the small process vessel then disconnect the other end from the PSV.

Take a length of tube with a quick release fitting at one end and a Guest push fitting at the other. Connect one end to the PSV and the other end to the coil inside the small process vessel (via the push fitting mounted on the lid).

Take a second length of tube with a quick-release fitting at one end and a drain valve at the other. Connect this end to the other side of the coil, and direct the opposite end of the tube to a suitable drain. Open the drain valve at the end of the tube.

Check that the drain valve on the end of the plinth is open and that it is connected to a suitable drain.

**Procedure:**

**SAFETY NOTE:** During this exercise the apparatus may reach temperatures hot enough to cause burns or scalds. Do not touch the process vessel during the exercise, or remove the coil or sensors from within the vessel. Allow the apparatus to cool before draining the water or disconnecting any of the tubes from the process vessel.

Fixed (manually set) ratio
In the PCT40 software, select the PID control box.

Set P, I and D to 0.

In Manual Control set the percentage time during which the heater will be on. 50% is suggested as a starting value

At the bottom left, set the Cycle Time to 10s- this is the time over which the control percentage will be applied (i.e. for a percentage of 50% and a cycle time of 10s, the heater will be switched on for 5s and switched off for 5s).

Select the Manual Control radio button and click on 'Apply'. The heater should begin to operate intermittently as the time proportional controller sends signals to control it.

Check that there is a new data sheet for data logging.

Select the GO icon to begin data logging, and observe the temperature in the process vessel, T1. When the temperature has risen by more than 20 °C, select the STOP icon to finish data logging.

Adjust the control percentage according to the change in temperature. If the change was rapid, reduce the time 'On' by 25 to 30%. If it was gradual, reduce the value by 10 or 15%.

Continue to monitor the temperature and adjust the percentage value until the temperature maintains a constant level.

Create a new results sheet by selecting the icon in the tool bar of the software.

Select the GO icon to begin data logging, and log the temperature for a few minutes. Select the STOP icon to finish data logging.

Make a note of the settings used.

Open the Control window and set Mode of Operation to Off. Apply and close the window.

On the software screen, set the PSV to 100% to allow cold water to flow through the coil in the vessel, cooling the process fluid.

Observe the temperature T1. When the temperature has dropped to around 20 – 30 °C, set the PSV back to 0%.

Create a new results sheet by selecting the icon in the tool bar of the software.

Controller-controlled time proportioning

In the PCT40 software, select the Control box.

Type in the Set Point value at which the on/off controller will operate. A recommended starting value is 40 °C for level.

Set P to 100%.

Leave I and D set to 0.

The Manual Control setting may be ignored.

Leave the Cycle Time at 10s.

Select the Automatic Control radio button and click on 'Apply'. The valve should begin to operate intermittently as the time proportional controller sends signals to control it.

Select the icon to begin data logging, and observe the temperature T1. Note the behaviour of the heater as the temperature approaches the Set Point. When the oscillations around the Set Point have settled, select the icon to finish data logging.

Disturbances

Within the software it is possible to introduce disturbances in the temperature inside the process vessel by passing cold water through the coil inside the vessel:

Create a new results sheet by selecting the icon in the tool bar of the software.

Select the icon to begin data logging.

Log for two minutes (with the software taking readings every 30 seconds), then set the PSV to 50%.

Continue logging for 15 minutes, then set the PSV to 100%.

Continue logging for a further 15 minutes, then set the PSV to 0%.

Log for a final 15 minutes, then select the icon to finish data logging.

Temperature Set Point

Investigate the effect of changing the temperature at which the on/off heater switch operates:

Create a new results sheet by selecting the icon.

In the software, alter the temperature set point to 50 °C.

Select the icon to begin data logging.

Log the temperature for 15 minutes, then select the icon to finish data logging.

Repeat the procedure, altering the set point and recording the change in temperature over time. Suggested values for the temperature set point value are 75 and 90 °C, but more values may be attempted if laboratory time allows. Remember to create a new results sheet for each set of data.

Return the temperature set point to its original value.

**Results:**

For easy identification or results, it is suggested that each results sheet is renamed with a descriptive title (e.g. 'Disturbance', 'Set Point', etc.). The entire workbook should be saved with a suitable filename for future reference (e.g. PCT40 Exercise 5.3).

Each set of data should be plotted on a graph of temperature T1 against time.

Make a comparison of each variation in the experimental conditions against the graph of the initial set of results, noting the difference in response. Compare the results obtained using time proportioning against those using a simple on/off controller (as in exercise 5.2).

For each variation investigated in the experiment, give an example of a comparable industrial control situation. For each example, consider the suitability of time proportional control for that particular application.

## 9.4 Exercise 5.4: Proportional temperature input with PID control of heater

**Objective:**

To control the temperature in the process vessel with PID control of a heating element, using a temperature sensor to monitor the temperature.

**Overview:**

As for time proportional control, the temperature sensor sends a signal to the controller that varies with the temperature of the sensor. The controller sends a signal to the heater that is proportional to the signal from the sensor. The heater power may only be on or off, so the controller varies the time for which power is supplied to the heater.

PID control adds two extra control parameters, Integral and Derivative, which may already have been investigated in the Level Control exercises:

With proportional control action, the controller produces a signal that is proportional to the error (the difference between the monitored variable and the set point value). This creates an offset between setpoint value and actual value (the controller only supplies an output when there is an error, so there is no controller output when the value is not at the set point). It also generates an overshoot (the system will oscillate above and below the setpoint value at the start of the control period until stability is attained).

With integral control action, the controller gives an output that is proportional to the time integral of the error. Integral control action can potentially be used alone to control a process, but is normally used in conjunction with proportional action. When used with proportional action it can eliminate offset. It can also cause higher maximum deviation and a longer response time than with proportional action alone.

With derivative control action, the controller gives an output that is proportional to the derivative of the rate of change of the error. The output is related only to the rate of change, not to the magnitude of the error. Derivative control action cannot be used alone, but must be combined with another action such as proportional control action. When used with proportional action, derivative control can eliminate excessive oscillation. It cannot eliminate offset errors inherent in proportional action

Proportional, integral and derivative control actions may be combined to eliminate offset, reduce maximum deviation and minimise the frequency of oscillation. Finding the optimum values of P, I and D for a particular process is often referred to as *tuning* or *optimisation*.

**Equipment Required:**

PCT40 bench with small process vessel containing a heating coil.

**Equipment set up:**

Ensure that the apparatus has been set up according to the assembly sheet (see also Appendix A in this manual). The lid with heating coil should be in position on the small

process vessel, with the coil surrounding the heating element. The apparatus should be connected to a suitable PC with the PCT40 software installed, using the grey USB cable supplied.

Switch on mains power to the apparatus and run the PCT software.

Fill the small process vessel with water:
Using a length of tubing with a quick release fitting at both ends, connect the PSV to one of the fittings on the side of the small process vessel. Ensure that the other fitting on the side of the process vessel is not connected.

Close the drain valve on the process vessel.

In the software, set the PSV to 100% and watch as the small process vessel fills with water.

Wait until the coil inside the vessel is fully covered with water, then set the PSV to 0%.

Disconnect the tube from the small process vessel, then disconnect the other end from the PSV.

Take a length of tube with a quick release fitting at one end and a Guest push fitting at the other. Connect one end to the PSV and the other end to the coil inside the small process vessel (via the push fitting mounted on the lid).

Take a second length of tube with a quick-release fitting at one end and a drain valve at the other. Connect this end to the other side of the coil, and direct the opposite end of the tube to a suitable drain. Open the drain valve at the end of the tube.

Check that the drain valve on the end of the plinth is open and that it is connected to a suitable drain.

**Procedure:**

**SAFETY NOTE:** During this exercise the apparatus may reach temperatures hot enough to cause burns or scalds. Do not touch the process vessel during the exercise, or remove the coil or sensors from within the vessel. Allow the apparatus to cool before draining the water or disconnecting any of the tubes from the process vessel.

Select ‘Configure’ from the Sample menu, and set sampling to Automatic at intervals of 30 seconds, with duration as Continuous.

In the PCT40 software, enter a set point value for the temperature of 30 degrees centigrade. If the local water temperature is close to 30 °C then a higher value may be selected. At least 10 °C higher than the mains water temperature is recommended.

Set the PID values for the controller in the appropriate boxes in the software. Suggested starting values are Proportional Band (P) of 100%, Integral Time Constant (I) of 0s and Differential Time Constant (D) of 0s.

Set the software to log at intervals of 10 seconds.

Select the icon to begin data logging.

Log the temperature within the vessel for 10 minutes, then select the icon to stop logging.

Disturbances

Within the software it is possible to introduce disturbances in the temperature inside the process vessel by passing cold water through the coil inside the vessel:

Create a new results sheet by selecting the icon in the tool bar of the software.

Select the icon to begin data logging.

Log for two minutes (with the software taking readings every 10 seconds), then set the PSV to 50%.

Continue logging for 10 minutes, then set the PSV to 100%.

Continue logging for a further 10 minutes, then set the PSV to 0%.

Log for a final 10 minutes, then select the icon to finish data logging.

Temperature Set Point

Investigate the effect of changing the set point temperature:

Create a new results sheet by selecting the icon.

In the software, alter the temperature set point to 40 °C (or 10 degrees higher than the initial set point if a value other than 30 degrees was used).

Select the icon to begin data logging.

Log the temperature for 10 minutes, and then select the icon to finish data logging.

Repeat the procedure, altering the set point and recording the change in temperature over time. Suggested values for the temperature set point value are 50 and 60 °C, but more values may be attempted if laboratory time allows. Remember to create a new results sheet for each set of data. Note that the heater circuit includes a safety cut-out that will shut off power to the heater if the vessel temperature exceeds approximately 80 °C. It is recommended that Set Point values are be kept well below this value.

Once the temperature set point has been investigated, return the temperature set point to its original value.

PID Settings and optimisation

To begin tuning it is necessary to set initial values which can be modified to improve the control results obtained. Follow this simple procedure to find start point values from which to begin optimisation:

Begin with the process vessel set up as described at the start of this laboratory sheet. If the apparatus has been used recently before this section of the exercise it will be necessary to cool the water in the process vessel before beginning this section. This may be speeded up by passing cold water through the heating/cooling coil by setting the PSV to 100%, as for investigating disturbances. Return the PSV setting to 0% after cooling the water to 30 °C or less.

Create a new results sheet by selecting the icon in the tool bar of the software.

Set the software to provide On/Off control (set P to 0%).

Set the temperature set point to 40 °C (this allows room for overshoot during the initial tuning process).

Select the icon to begin data logging.

Wait as the temperature rises to the set point and overshoots. Continue logging as the controller switches off the heater and the water cools. Continue logging until the controller switches on the heater and the temperature begins to rise once more, then select the icon to finish data logging. The cooling process will take some time, as the water cools slowly. DO NOT increase the cooling rate by passing cold water through the coil.

Plot a graph of time against water temperature.

From the graph, determine the peak to peak variation, y, between the highest value of the overshoot and the lowest value of the undershoot.

Calculate the time between these two values, t.

From the values y and t, starting values may be found for P, I and D as follows

P = y / 3
I = t
D = t / 6

Set these values in the software.

Change the temperature set point to 0 °C, and cool the water in the vessel to 30 °C or less. At this point it is possible to use cold water in the heating coil to accelerate the cooling process.

Create a new results sheet by selecting the icon in the tool bar of the software.

Return the temperature set point to 40 °C

Select the  icon to begin data logging.

Log the temperature as it rises and then settles around the set point value. Logging should continue until any oscillations have settled- 15 minutes is suggested.

Select the  icon to finish data logging.

From these new results, plot a graph of temperature T1 against time and observe the shape of the graph.

If the figure for Proportional Band obtained by this method is very small (less than 5%), and the Integral Time very large (more than 30s) then the method chosen for finding approximate tuning values may not be suitable and the best value for Proportional Band may be greater than 100%.

Change the temperature set point to 0 °C, and cool the water in the vessel to 30 °C or less. At this point it is possible to temporarily increase the flow rate through the vessel to accelerate the cooling process. Return the flow rate to its previous value before continuing with the exercise.

Set the Proportional Band to 200%, the Integral Time to 60s and the Derivative Time to 0s.

Create a new results sheet by selecting the  icon in the tool bar of the software.

Return the temperature set point to 40 °C

Select the  icon to begin data logging.

Log the temperature as it rises and then settles around the set point value. Logging should continue until any oscillations have settled- 15 minutes is suggested.

Select the  icon to finish data logging.

Plot a graph of temperature T1 against time and compare the shape of the graph to that obtained using the values obtained from the On/Off control graph.

If a Proportional Band of greater than 100% gives less oscillation and overshoot than the previous settings, leave the PID values as they are.

Proportional control sets the band within which the controller will vary time the heater spends on and off. Outside this band the heater will be always on or always off. If a slow response is observed, or large oscillations occur in temperature, after changing the value of P then reduce the value. Investigate the results of the changed value by plotting a graph of the temperature as it rises from a low value and comparing this to the initial results.

Return the value of P to the basic value obtained from the initial measurements.

Integral control can be adjusted to reduce offset in the temperature. If a significant offset is observed after changing the value of I, reduce the value. Investigate the results of any change by plotting a graph of the temperature as it rises from a low value and comparing this to the initial results.

Return the value of I to the basic value obtained from the initial measurements.

Derivative control can be adjusted to reduce excessive oscillation. If oscillations are extreme after changing the value of D, reduce the value. Investigate the results of the changed value by plotting a graph of the temperature as it rises from a low value and comparing this to the initial results.

From the graphs obtained, select values of P, I and D that give the best results. Perform a final test run, logging the temperature over time as it rises from a low value. Compare this to the initial graph.

**Results:**

For easy identification or results, it is suggested that each results sheet is renamed with a descriptive title (e.g. 'Set Point', etc.). The entire workbook should be saved with a suitable filename for future reference (e.g. PCT40 Exercise 5.4).

Each set of data not already graphed as part of the procedure should be plotted on a graph of temperature T1 against time.

Make a comparison of each variation in the experimental conditions against the graph of the initial set of results, noting the difference in response. Comment on the results obtained by varying the values of P, I and D, and on the ease of optimisation of the process. If the level control exercises have already been performed, compare the ease of optimisation for temperature control with the optimisations for PID level control. Compare the results obtained using PID temperature control against those using a simple on/off controller (as in exercise 5.2) and time proportioning control (exercise 5.3). Discuss the suitability of PID control for regulating process temperature.

# 10 DIRECT HEATING CONTINUOUS OPERATION TEMPERATURE CONTROL EXERCISES

## 10.1 Exercise 6.1: Manual control of heater power

**Objective:**

To control the temperature in a process vessel manually by controlling power to a heating element.

**Overview:**

The temperature within the process vessel is monitored using a thermocouple type sensor. A low, continuous flow of water is passed through the vessel. By manually switching the power to a heating element on or off, the temperature within the vessel is regulated to maintain the required set point.

**Equipment Required:**

PCT40 bench with small process vessel containing a heating coil.

**Equipment set up:**

Ensure that the apparatus has been set up according to the assembly sheet (see also Appendix A in this manual). The lid with heating coil should be in position on the small process vessel, with the coil surrounding the heating element. The apparatus should be connected to a suitable PC with the PCT40 software installed, using the grey USB cable supplied.

Fill the small process vessel with water:
Using a length of tubing with a quick release fitting at both ends, connect the PSV to the upper fitting on the side of the small process vessel. Ensure that the lower fitting on the side of the process vessel is not connected.

Close the drain valve on the process vessel.

In the software, set the PSV to 100% and watch as the small process vessel fills with water.

Wait until the coil inside the vessel is fully covered with water, then set the PSV to 0%.

Check that the drain valve on the end of the plinth is open and that it is connected to a suitable drain.

Select a second length of tubing with a self-sealing fitting on one end and an open end at the other, and direct the open end to a suitable drain. Connect the quick-release fitting to the lower connection on the side of the small process vessel. Water will drain from the free end. Half close the drain valve on the end of the tube.

In the software, increase the PSV value using the arrow keys until the water level in the process vessel is stable and covers the coil. Adjust the drain valve so that the water level in the vessel remains constant and covers the coil at a PSV setting of approximately 50%. The apparatus should not be left unattended, to ensure the process vessel does not overflow or run dry.

**Procedure:**

**SAFETY NOTE:** During this exercise, the apparatus may reach temperatures hot enough to cause burns or scalds. Do not touch the process vessel during the exercise, or remove the coil or sensors from within the vessel. Allow the apparatus to cool before draining the water or disconnecting any of the tubes from the process vessel.

Check that the temperature reading T1 is a sensible value (usually between 5 and 30 degrees Celsius depending on mains water temperature).

Select 'Configure' from the Sample menu, and set sampling to Automatic at intervals of 30 seconds, with duration as Continuous.

The heating element is switched on and off manually using the switch on the software screen. Switch on the heater, and observe the temperature T1. Check that this rises as the heater operates. Switch off the heater again.

Heating Characteristics in Continuous Operation

The temperature in the vessel may be manually controlled by switching the power to the heating element off and on. By switching the heater on and off using the switch on the software screen raise the temperature of the water in the vessel to 30 °C and maintain this temperature by powering the heater off and on. Note the control actions required to maintain a constant temperature within the water flowing through the vessel. Record any differences between the time required for the water to rise and fall in temperature. Note any time lag between applying a control action and observing its effect.

(Note: if the mains water temperature is very high- approaching or exceeding 30 °C- then 40 °C may be used as a Set Point value instead).

Select the  icon to begin data logging.

Maintain the temperature in the vessel, using manual control, for five minutes.

Select the  icon to finish data logging.

Create a new results sheet by selecting the  icon.

Disturbances

Within the software it is possible to introduce disturbances in the temperature inside the process vessel by changing the flowrate of water through the vessel:

Select the  icon to begin data logging.

In the software, increase the PSV setting by 20%. Open the drain valve at the base of the process vessel enough to balance the flow in and out of the vessel, so that the fluid level in the vessel remains constant.

Note the control action required to maintain the temperature within the vessel at the new flow rate.

Increase the PSV setting by a further 20%, and open the drain valve more to maintain the fluid level within the vessel.

Continue to control the temperature, noting the action required.

Set the PSV back to its original setting, close the drain valve, and continue to control the temperature within the vessel.

Select the  icon to finish data logging.

Create a new results sheet by selecting the  icon.

**Results:**

For easy identification or results, it is suggested that each results sheet is renamed with a descriptive title (e.g. 'Disturbances', etc.). The entire workbook should be saved with a suitable filename for future reference (e.g. PCT40 Exercise 6.1).

Each set of data should be plotted on a graph of temperature T1 against time.

Write up your experiment, commenting on the heating and cooling characteristics of continuous operation and the actions required for manual control of the heating process. Give reasons for any time delay between applying a control action and observing a response. Explain any difference between heating and cooling rate. Give examples of industrial control situations in which a step change in flow rate might occur.

## 10.2 Exercise 6.2: Thermostat control of heater power

**Objective:**

To control the temperature in a process vessel using a thermostat to control a heating element.

**Overview:**

The required Set Point temperature within the process vessel is set on a simple thermostat-type controller. The temperature within the process vessel is monitored by the probe of the thermostat. The thermostat then switches a heating element on or off to maintain the required set point temperature within the vessel.

**Equipment Required:**

PCT40 bench with small process vessel containing a heating coil.

**Equipment set up:**

Ensure that the apparatus has been set up according to the assembly sheet (see also Appendix A in this manual). The lid with heating coil should be in position on the small process vessel, with the coil surrounding the heating element. The apparatus should be connected to a suitable PC with the PCT40 software installed, using the grey USB cable supplied.

Switch on mains power to the apparatus and run the PCT40 software.

Fill the small process vessel with water:

Using a length of tubing with a quick release fitting at both ends, connect the PSV to the upper fitting on the side of the small process vessel. Ensure that the lower fitting on the side of the process vessel is not connected.

Close the drain valve on the process vessel.

In the software, set the PSV to 100% and watch as the small process vessel fills with water.

Wait until the coil inside the vessel is fully covered with water, then set the PSV to 0%.

Check that the drain valve on the end of the plinth is open and that it is connected to a suitable drain.

Select a second length of tubing with a self-sealing fitting on one end and an open end at the other, and direct the open end to a suitable drain. Connect the quick-release fitting to the lower connection on the side of the small process vessel. Water will drain from the free end. Half close the drain valve on the end of the tube.

In the software, increase the PSV value using the arrow keys until the water level in the process vessel is stable and covers the coil. Adjust the drain valve so that the water level in

the vessel remains constant and covers the coil at a PSV setting of approximately 50%. The apparatus should not be left unattended, to ensure the process vessel does not overflow or run dry.

**Procedure:**

**SAFETY NOTE:** During this exercise the apparatus may reach temperatures hot enough to cause burns or scalds. Do not touch the process vessel during the exercise, or remove the coil or sensors from within the vessel. Allow the apparatus to cool before draining the water or disconnecting any of the tubes from the process vessel.

Set the temperature at which the thermostat will operate. The Set Point is set by rotating the dial on top of the thermostat mounted in the lid of the small process vessel. The dial is turned until the arrow on the dial points at the required Set Point. A recommended starting value is 30 degrees Celsius. If the local mains water temperature is close to 30 °C then a higher value may be used: at least 10 °C greater than the mains supply is recommended.

Check that the temperature reading T1 is a sensible value (usually between 5 and 30 degrees Celsius depending on mains water temperature).

Set data logging to automatic at intervals of 30 seconds with continuous duration.

Select the  icon to begin data logging.

Note the behaviour of the heating element as the temperature approaches the set point. It is possible to observe heated water rising from the heating element when the power is on. The heater also responds audibly when power is switched on or off. Additionally, the switch for the heater is displayed on the mimic diagram screen within the software, allowing observation of the heater action.

The change in temperature may be most easily observed using the graph screen in the software. If the graph does not appear automatically when the graph screen is selected, select ‘T1’ for the Y axis and ‘Time’ for the x-axis, then plot the graph. New points will be added as they are logged.

Continue logging for 10 minutes. Select the  icon to finish data logging.

<u>Disturbances</u>

Within the software it is possible to introduce disturbances in the temperature inside the process vessel by changing the flowrate of water through the vessel:

In the software, select the  icon to create a new results sheet.

Select the  icon to begin data logging.

In the software, increase the PSV setting by 20%. Open the drain valve at the base of the process vessel enough to balance the flow in and out of the vessel, so that the fluid level in the vessel remains constant.

Log the temperature for 10 minutes.

Increase the PSV setting by a further 20%, and open the drain valve more to maintain the fluid level within the vessel.

Continue to log the temperature for another 10 minutes, and then select the icon to finish data logging.

Set the PSV back to its original setting and close the drain valve.

Temperature Set Point

Investigate the effect of changing the temperature at which the on/off heater switch operates:

Select the icon to create a new results sheet.

On top of the thermostat, alter the temperature set point to 40 °C (or to 10 °C higher than the initial set point value if an initial value of 30 °C was not used).

Select the icon to begin data logging.

Log the temperature for 10 minutes, and then select the icon to finish data logging.

Select the icon to create a new results sheet.

Repeat the procedure, altering the set point and logging the change in temperature until the oscillations reach stable values. Suggested values for the temperature set point value are 50, 60 and 70 °C. Remember to create a new results sheet for each set of data. Note that there is a power cut-out built in to the heating circuit as a safety feature, which operates if the temperature of the water in the vessel exceeds approximately 80°C. Set Point values should therefore be chosen that are significantly lower than 80°C.

**Results:**

For easy identification or results, it is suggested that each results sheet is renamed with a descriptive title (e.g. 'Flow Rate', 'Set Point', etc.). The entire workbook should be saved with a suitable filename for future reference (e.g. PCT40 Exercise 6.2).

Each set of data should be plotted on a graph of temperature T1 against time.

Make a comparison of each variation in the experimental conditions against the graph of the initial set of results, noting the difference in response.

Give examples of industrial control situations for which a simple on/off controller would be suitable.

## 10.3 Exercise 6.3: Temperature input with on/off control of heater power

**Objective:**

To control the temperature in a process vessel using an on/off controller connected to a temperature sensor, by controlling power to a heating element.

**Overview:**

The temperature within the process vessel is monitored using a thermocouple type sensor. The output is sent to an On/Off controller that switches a heating element on or off to maintain the required set point temperature within the vessel.

**Equipment Required:**

PCT40 bench with small process vessel containing a heating coil.

**Equipment set up:**

Ensure that the apparatus has been set up according to the assembly sheet (see also Appendix A in this manual). The lid with heating coil should be in position on the small process vessel, with the coil surrounding the heating element. The apparatus should be connected to a suitable PC with the PCT40 software installed, using the grey USB cable supplied.

Switch on mains power to the apparatus and run the PCT40 software.

Fill the small process vessel with water:
Using a length of tubing with a quick release fitting at both ends, connect the PSV to the upper fitting on the side of the small process vessel. Ensure that the lower fitting on the side of the process vessel is not connected.

Close the drain valve on the process vessel.

In the software, set the PSV to 100% and watch as the small process vessel fills with water.

Wait until the coil inside the vessel is fully covered with water, then set the PSV to 0%.

Check that the drain valve on the end of the plinth is open and that it is connected to a suitable drain.

Select a second length of tubing with a self-sealing fitting on one end and an open end at the other, and direct the open end to a suitable drain. Connect the quick-release fitting to the lower connection on the side of the small process vessel. Water will drain from the free end. Half close the drain valve on the end of the tube.

In the software, increase the PSV value using the arrow keys until the water level in the process vessel is stable and covers the coil. Adjust the drain valve so that the water level in the vessel remains constant and covers the coil at a PSV setting of approximately 50%.

The apparatus should not be left unattended, to ensure the process vessel does not overflow or run dry.

**Procedure:**

**SAFETY NOTE:** During this exercise the apparatus may reach temperatures hot enough to cause burns or scalds. Do not touch the process vessel during the exercise, or remove the coil or sensors from within the vessel. Allow the apparatus to cool before draining the water or disconnecting any of the tubes from the process vessel.

Setting the On/Off Controller:
In the PCT40 software, click on the Control box.

Set the Proportional Band (P) to 0%, the Integral Time (I) to 0s and the Derivative Time (D) to 0s. The controller is now set as a simple On/Off controller with fixed hysteresis of 0.5% of full scale.

Set the temperature at which the on/off controller will operate. A recommended starting value is 30 degrees Celsius. Check that the temperature reading T1 is a sensible value (usually between 5 and 30 degrees Celsius depending on mains water temperature). A higher Set Point temperature will be required if the mains water inlet supply temperature is close to 30 °C: a value of at least 10 degrees higher than the inlet supply is recommended.

Apply the settings and close the controller window.

From the Sample menu at the top of the screen, select Configure… and set data logging to automatic at intervals of thirty seconds.

Select the  icon to begin data logging.

Note the behaviour of the heating element as the temperature approaches the set point. It is possible to observe heated water rising from the heating element when the power is on. The heater also responds audibly when power is switched on or off. Additionally, the switch for the heater is displayed on the mimic diagram screen within the software, allowing observation of the heater action.

The change in temperature may be most easily observed using the graph screen in the software. If the graph does not appear automatically when the graph screen is selected, select ‘T1’ for the Y axis and ‘Time’ for the x-axis, then plot the graph. New points will be added as they are logged.

Continue logging for 10 minutes. Select the  icon to finish data logging.

Disturbances
Within the software it is possible to introduce disturbances in the temperature inside the process vessel by changing the flowrate of water through the vessel:
In the software, select the  icon to create a new results sheet.

Select the  icon to begin data logging.

In the software, increase the PSV setting by 20%. Open the drain valve at the base of the process vessel enough to balance the flow in and out of the vessel, so that the fluid level in the vessel remains constant.

Log the temperature for 10 minutes.

Increase the PSV setting by a further 20%, and open the drain valve more to maintain the fluid level within the vessel.

Continue to log the temperature for another 10 minutes, and then select the icon to finish data logging.

Set the PSV back to its original setting and close the drain valve.

Temperature Set Point

Investigate the effect of changing the temperature at which the on/off heater switch operates:

Select the icon to create a new results sheet.

In the software, alter the temperature set point to 40 °C.

Select the icon to begin data logging.

Log the temperature for 10 minutes, and then select the icon to finish data logging.

Select the icon to create a new results sheet.

Repeat the procedure, altering the set point and logging the change in temperature until the oscillations reach stable values. Suggested values for the temperature set point value are 50, 60 and 70 °C. Remember to create a new results sheet for each set of data. Note that the heater circuit includes a safety cut-out that will shut off power to the heater if the temperature of the process vessel reaches approximately 80 °C. Set point values should therefore be kept below this temperature.

**Results:**

For easy identification or results, it is suggested that each results sheet is renamed with a descriptive title (e.g. 'Flow Rate', 'Set Point', etc.). The entire workbook should be saved with a suitable filename for future reference (e.g. PCT40 Exercise 6.3).

Each set of data should be plotted on a graph of temperature T1 against time.

Make a comparison of each variation in the experimental conditions against the graph of the initial set of results, noting the difference in response.

Give examples of industrial control situations for which a simple on/off controller would be suitable.

## 10.4 Exercise 6.4: Temperature input with time proportional control of heater power

**Objective:**

To control the temperature in the process vessel using a time-proportional controller connected to a temperature sensor, with a heating element raising the temperature of the fluid within the vessel.

**Overview:**

The control system in this exercise consists of a temperature sensor with an output proportional to the temperature detected by the sensor. The output is sent to a time proportional controller which switches the power supply to the heating element on or off. The time proportioning controller turns the output on and off at intervals. This ratio of time "on" to time "off" may be set manually, or may be set automatically by the controller which then varies the ratio according to the difference between the current control variable and the required Set Point value.

**Equipment Required:**

PCT40 bench with small process vessel containing a heating coil.

**Equipment set up:**

Ensure that the apparatus has been set up according to the assembly sheet (see also Appendix A in this manual). The lid with heating coil should be in position on the small process vessel, with the coil surrounding the heating element. The PC should be connected to a suitable PC on which the PCT40 software has been installed using the grey USB cable supplied.

Switch on mains power to the apparatus and run the PCT40 software.

Fill the small process vessel with water:
Using a length of tubing with a quick release fitting at both ends, connect the PSV to the upper fitting on the side of the small process vessel. Ensure that the lower fitting on the side of the process vessel is not connected.

Close the drain valve on the process vessel.

In the software, set the PSV to 100% and watch as the small process vessel fills with water.

Wait until the coil inside the vessel is fully covered with water, then set the PSV to 0%.

Check that the drain valve on the end of the plinth is open and that it is connected to a suitable drain.

Select a second length of tubing with a self-sealing fitting on one end and an open end at the other, and direct the open end to a suitable drain. Connect the quick-release fitting to

the lower connection on the side of the small process vessel. Water will drain from the free end. Half close the drain valve on the end of the tube.

In the software, increase the PSV value using the arrow keys until the water level in the process vessel is stable and covers the coil. Adjust the drain valve so that the water level in the vessel remains constant and covers the coil at a PSV setting of approximately 50%. The apparatus should not be left unattended, to ensure the process vessel does not overflow or run dry.

**Procedure:**

**SAFETY NOTE:** During this exercise the apparatus may reach temperatures hot enough to cause burns or scalds. Do not touch the process vessel during the exercise, or remove the coil or sensors from within the vessel. Allow the apparatus to cool before draining the water or disconnecting any of the tubes from the process vessel.

Run the PCT40 software. Select 'Configure' from the Sample menu and set sampling to Automatic with sample intervals of 30 seconds and a duration of Continuous.

Fixed (manually set) ratio
In the PCT40 software, select the PID control box.

Set P, I and D to 0.

In Manual Control set the percentage time during which the heater will be on. 50% is suggested as a starting value

At the bottom left, set the Cycle Time to 10s- this is the time over which the control percentage will be applied (i.e. for a percentage of 50% and a cycle time of 10s, the heater will be switched on for 5s and switched off for 5s).

Select the Manual Control radio button and click on 'Apply'. The heater should begin to operate intermittently as the time proportional controller sends signals to control it.

Check that there is a new data sheet for data logging.

Select the  icon to begin data logging, and observe the temperature in the vessel, T1. When the temperature has changed by more than 20 °C, select the  icon to finish data logging.

Adjust the control percentage according to the change in temperature. If the change was rapid, reduce the setting by 25 to 30%. If it was gradual, reduce the value by 10 or 15%.

Continue to monitor the temperature and adjust the percentage value until the temperature maintains a constant level.

Create a new results sheet by selecting the  icon in the tool bar of the software.

Select the  icon to begin data logging, and log the temperature T1 for a few minutes. Select the  icon to finish data logging.

Make a note of the settings used.

Open the controller window and set Mode of Operation to Off.

Set the PSV to 100%, allowing cold water to flow through the coil in the small process vessel. When the temperature T1 has reduced to around 20 – 30 °C, set the PSV back to 0%.

Create a new results sheet by selecting the icon in the tool bar of the software.

Controller-controlled time proportioning
In the PCT40 software, select the PID control box.

Set the Set Point to 30 °C (If the mains water temperature is close to 30 °C then a higher Set Point should be chosen, e.g. 40 °C).

Set P to 100%.

Leave I and D set to 0.

The Manual Control setting may be ignored.

Leave the Cycle Time at 10s.

Select the Automatic Control radio button and click on 'Apply'. The valve should begin to operate intermittently as the time proportional controller sends signals to control it.

Select the icon to begin data logging, and observe the temperature in the process vessel. Note the behaviour of the heater as the temperature approaches the Set Point. When the oscillations around the Set Point have settled, select the icon to finish data logging.

Disturbances
Within the software it is possible to introduce disturbances in the temperature inside the process vessel by changing the flowrate of water through the vessel:

In the software, select the icon to create a new results sheet.

Select the icon to begin data logging.

In the software, increase the PSV setting by 20%. Open the drain valve at the base of the process vessel enough to balance the flow in and out of the vessel, so that the fluid level in the vessel remains constant.

Log the temperature for 10 minutes.

Increase the PSV setting by a further 20%, and open the drain valve more to maintain the fluid level within the vessel.

Continue to log the temperature for another 10 minutes, and then select the icon to finish data logging.

Set the PSV back to its original setting and close the drain valve.

Temperature Set Point

Investigate the effect of changing the temperature at which the on/off heater switch operates:

Create a new results sheet by selecting the icon.

In the software, alter the temperature set point to 40 °C (or ten degrees higher than the original set point temperature if a value other than 30 °C was selected).

Select the icon to begin data logging.

Log the temperature for 10 minutes, then select the icon to finish data logging.

Repeat the procedure, altering the set point and recording the change in temperature over time. Suggested values for the temperature set point value are 50 and 60 °C, but more values may be attempted if laboratory time allows. Remember to create a new results sheet for each set of data. Note that there is a safety cutout in the heater circuit that will switch off the heater if the temperature in the vessel exceeds approximately 80 °C. Set Point values should therefore be kept well below this temperature.

Return the temperature set point to its original value.

Cycle Time

Create a new results sheet by selecting the icon in the tool bar of the software.

In the software, set the cycle time to 5s.

Select the icon to begin data logging.

Log the temperature in the vessel for 10 minutes, and then select the icon to finish data logging.

Alter the cycle time again, to 20s.

Select the icon to begin data logging.

Log the temperature in the vessel for 15 minutes, and then select the icon to finish data logging.

Reset the cycle time to 10s.

**Results:**

For easy identification or results, it is suggested that each results sheet is renamed with a descriptive title (e.g. ‘Flow rate’, ‘Set Point’, etc.). The entire workbook should be saved with a suitable filename for future reference (e.g. PCT40 Exercise 6.4).

Each set of data should be plotted on a graph of temperature T1 against time.

Make a comparison of each variation in the experimental conditions against the graph of the initial set of results, noting the difference in response. Compare the results obtained using time proportional control against those using a simple on/off controller (as in exercise 6.1).

Suggest industrial applications in which step-changes in flow rate might be experienced. Discuss the suitability of time-proportional control for those applications.

## 10.5 Exercise 6.5: Proportional temperature input with PID control of heater power

**Objective:**

To control the temperature in the process vessel with PID control of a heating element, using a temperature sensor to monitor the temperature.

**Overview:**

As for time proportional control, the temperature sensor sends a signal to the controller that varies with the temperature of the sensor. The controller sends a signal to the heater that is proportional to the signal from the sensor. The heater power may only be on or off, so the controller varies the time for which power is supplied to the heater.

PID control adds two extra control parameters, Integral and Derivative, which may already have been investigated in the Level Control exercises:

With proportional control action, the controller produces a signal that is proportional to the error (the difference between the monitored variable and the set point value). This creates an offset between setpoint value and actual value (the controller only supplies an output when there is an error, so there is no controller output when the value is not at the set point). It also generates an overshoot (the system will oscillate above and below the setpoint value at the start of the control period until stability is attained).

With integral control action, the controller gives an output that is proportional to the time integral of the error. Integral control action can potentially be used alone to control a process, but is normally used in conjunction with proportional action. When used with proportional action it can eliminate offset. It can also cause higher maximum deviation and a longer response time than with proportional action alone.

With derivative control action, the controller gives an output that is proportional to the derivative of the rate of change of the error. The output is related only to the rate of change, not to the magnitude of the error. Derivative control action cannot be used alone, but must be combined with another action such as proportional control action. When used with proportional action, derivative control can eliminate excessive oscillation. It cannot eliminate offset errors inherent in proportional action

Proportional, integral and derivative control actions may be combined to eliminate offset, reduce maximum deviation and minimise the frequency of oscillation. Finding the optimum values of P, I and D for a particular process is often referred to as *tuning* or *optimisation*.

**Equipment Required:**

PCT40 bench with small process vessel containing a heating coil.

**Equipment set up:**

Ensure that the apparatus has been set up according to the assembly sheet (see also Appendix A in this manual). The lid with heating coil should be in position on the small

process vessel, with the coil surrounding the heating element. The apparatus should be connected to a suitable PC which has the PCT40 software installed, using the grey USB cable supplied.

Fill the small process vessel with water:
Using a length of tubing with a quick release fitting at both ends, connect the PSV to the upper fitting on the side of the small process vessel. Ensure that the lower fitting on the side of the process vessel is not connected.

Close the drain valve on the process vessel.

In the software, set the PSV to 100% and watch as the small process vessel fills with water.

Wait until the coil inside the vessel is fully covered with water, then set the PSV to 0%.

Check that the drain valve on the end of the plinth is open and that it is connected to a suitable drain.

Select a second length of tubing with a self-sealing fitting on one end and an open end at the other, and direct the open end to a suitable drain. Connect the quick-release fitting to the lower connection on the side of the small process vessel. Water will drain from the free end. Half close the drain valve on the end of the tube.

In the software, increase the PSV value using the arrow keys until the water level in the process vessel is stable and covers the coil. Adjust the drain valve so that the water level in the vessel remains constant and covers the coil at a PSV setting of approximately 50%. The apparatus should not be left unattended, to ensure the process vessel does not overflow or run dry.

**Procedure:**

**SAFETY NOTE:** During this exercise the apparatus may reach temperatures hot enough to cause burns or scalds. Do not touch the process vessel during the exercise, or remove the coil or sensors from within the vessel. Allow the apparatus to cool before draining the water or disconnecting any of the tubes from the process vessel.

Run the PCT40 software.

In the PCT40 software, enter a set point value for the temperature of 30 degrees centigrade. If the temperature of the local mains water supply is close to 30 °C then a higher set point value may be chosen, such as 40 °C.

Set the PID values for the controller in the appropriate boxes in the software. Suggested starting values are Proportional Band (P) of 100%, Integral Time Constant (I) of 0s and Differential Time Constant (D) of 0s.

Select ‘Configure...’ from the Sample menu. Set the software to Automatic logging, with a sample interval of 10 seconds and Continuous duration.

Select the icon to begin data logging.

Log the temperature within the vessel for 10 minutes, then select the icon to stop logging.

Disturbances

Within the software it is possible to introduce disturbances in the temperature inside the process vessel by changing the flowrate of water through the vessel:

In the software, select the icon to create a new results sheet.

Select the icon to begin data logging.

In the software, increase the PSV setting by 20%. Open the drain valve at the base of the process vessel enough to balance the flow in and out of the vessel, so that the fluid level in the vessel remains constant.

Log the temperature for 10 minutes.

Increase the PSV setting by a further 20%, and open the drain valve more to maintain the fluid level within the vessel.

Continue to log the temperature for another 10 minutes, and then select the icon to finish data logging.

Set the PSV back to its original setting and close the drain valve.

Temperature Set Point

Investigate the effect of changing the set point temperature:

Create a new results sheet by selecting the icon.

In the software, alter the temperature set point to 40 °C. If the initial Set Point was not 30 °C then a value 10 °C higher than the initial value should be used instead.

Select the icon to begin data logging.

Log the temperature for 10 minutes, and then select the icon to finish data logging.

Repeat the procedure, altering the set point and recording the change in temperature over time. Suggested values for the temperature set point value are 50 and 60 °C, but more values may be attempted if laboratory time allows. Remember to create a new results sheet for each set of data. Note that the heater circuit includes a safety cut-out that will shut off power to the heater if the temperature in the process vessel exceeds approximately 80 °C. For this reason set point values should be kept well below this temperature.

Return the temperature set point to its original value.

PID Settings and optimisation

To begin tuning it is necessary to set initial values, which can be modified to improve the control results obtained. Follow this simple procedure to find start point values from which to begin optimisation:

Begin with the process vessel set up as described at the start of this laboratory sheet. If the apparatus has been used recently before this section of the exercise, it will be necessary to cool the water in the process vessel before beginning this section. This may be speeded up by increasing the flow rate through the vessel. Fully open the drain valve in the base of the vessel, and increase the PSV setting to maintain the fluid level. Close the drain and return the PSV to its previous setting after cooling the water to 30 °C or less.

Create a new results sheet by selecting the icon in the tool bar of the software.

Set the software to provide On/Off control (set P to 0%).

Set the temperature set point to 40 °C (this allows room for overshoot during the initial tuning process).

Select the icon to begin data logging.

Wait as the temperature rises to the set point and overshoots. Continue logging as the controller switches off the heater and the water cools. Continue logging until the controller switches on the heater and the temperature begins to rise once more, then select the icon to finish data logging. This process will take some time, as the water cools slowly.

Plot a graph of time against water temperature.

From the graph, determine the peak to peak variation, y, between the highest value of the overshoot and the lowest value of the undershoot.

Calculate the time between these two values, t.

From the values y and t, starting values may be found for P, I and D as follows

P = y / 3
I = t
D = t / 6

Set these values in the software.

Change the temperature set point to 0 °C, and cool the water in the vessel to 30 °C or less. At this point it is possible to temporarily increase the flow rate through the vessel to accelerate the cooling process. Return the flow rate to its previous value before continuing with the exercise.

Create a new results sheet by selecting the icon in the tool bar of the software.

Return the temperature set point to 40 °C

Select the  icon to begin data logging.

Log the temperature as it rises and then settles around the set point value. Logging should continue until any oscillations have settled- 10 minutes is suggested.

Select the  icon to finish data logging.

From these new results, plot a graph of Temperature T1 against time and observe the shape of the graph.

If the figure for Proportional Band obtained by this method is very small (less than 5%), and the Integral Time very large (more than 30s) then the method chosen for finding approximate tuning values may not be suitable and the best value for Proportional Band may be greater than 100%.

Change the temperature set point to 0 °C, and cool the water in the vessel to 30 °C or less. At this point it is possible to temporarily increase the flow rate through the vessel to accelerate the cooling process. Return the flow rate to its previous value before continuing with the exercise.

Set the Proportional Band to 200%, the Integral Time to 60s and the Derivative Time to 0s.

Create a new results sheet by selecting the  icon in the tool bar of the software.

Return the temperature set point to 40 °C

Select the  icon to begin data logging.

Log the temperature as it rises and then settles around the set point value. Logging should continue until any oscillations have settled- 10 minutes is suggested.

Select the  icon to finish data logging.

Plot a graph of temperature T1 against time and compare the shape of the graph to that obtained using the values obtained from the On/Off control graph.

If a Proportional Band of greater than 100% gives less oscillation and overshoot than the previous settings, leave the PID values as they are.

Proportional control sets the band within which the controller will vary time the heater spends on and off. Outside this band the heater will be always on or always off. If a slow response is observed, or large oscillations occur in temperature, reduce the value of P. Investigate the results of the changed value by plotting a graph of the temperature as it rises from a low value and comparing this to the initial results.

Return the value of P to the basic value obtained from the initial measurements.

Integral control can be adjusted to reduce offset in the temperature. If a significant offset is observed, reduce the value of I. Investigate the results of any change by plotting a graph of the temperature as it rises from a low value and comparing this to the initial results.

Return the value of I to the basic value obtained from the initial measurements.

Derivative control can be adjusted to reduce excessive oscillation. If oscillations are extreme, reduce the value of D. Investigate the results of the changed value by plotting a graph of the temperature as it rises from a low value and comparing this to the initial results.

From the graphs obtained, select values of P, I and D that give the best results. Perform a final test run, logging the temperature over time as it rises from a low value. Compare this to the initial graph.

**Results:**

For easy identification or results, it is suggested that each results sheet is renamed with a descriptive title (e.g. 'Flow Rate', 'Integral Setting', etc.). The entire workbook should be saved with a suitable filename for future reference (e.g. PCT40 Exercise 6.5).

Each set of data not already graphed as part of the procedure should be plotted on a graph of temperature T1 against time.

Make a comparison of each variation in the experimental conditions against the graph of the initial set of results, noting the difference in response. Comment on the results obtained by varying the values of P, I and D, and on the ease of optimisation of the process. If the level control exercises have already been performed, compare the ease of optimisation for temperature control with the optimisations for PID level control. Compare the results obtained using PID temperature control against those using a simple on/off controller (as in exercise 6.1) and time proportioning control (exercise 6.4). Discuss the suitability of PID control for regulating process temperature.