**PART IB EXPERIMENTAL ENGINEERING**

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|---|---|---|
| SUBJECT: | INFORMATION ENGINEERING | EXPERIMENT I2 (SHORT) |
| LOCATION: | EIETL, INGLIS BUILDING | |

**PROCESS CONTROL**

# Objectives

1. To Introduce feedback control systems – the ideas, the components, and some of the terminology.
2. To give experience of making measurements and adjustments on very slow dynamic processes.
3. To demonstrate that feedback systems can become unstable, especially if the measurements are delayed.
4. To demonstrate that increasing the gain in a feedback loop improves the quality of control (up to a point).
5. To demonstrate that 'Integral Control' is effective at eliminating steady-state errors completely.
6. To give some experience of control systems design (parameter tuning).

# Introduction

In this experiment we investigate the temperature control of a shower heater. This has several features common in the control of many industrial processes, such as: slow dynamics, delayed measurements, limited range and power of control action.

The mechanical and electrical design of the heater is already complete; but you can change the *control law*, namely the rule for applying power to the heater, as a function of the measured water temperature.

The experiment involves

- Becoming familiar with the equipment provided, particularly the integrator,

- Observing the behavior of the heater with different flow rates, but without any control , and
- Implementation of feedback control.

# The Equipment

Fig.1 shows the experiment set-up. Water flows through a shower heater via a flow-meter, and out through some tubing. A thermistor is located in the tubing, 2.5 meters downstream from the heater. This is the point at which we imagine the shower head to be located. A second thermistor is located at the heater inlet, to allow the inlet temperature to be monitored, but this is not used in the experiment. On entering the laboratory you should turn the water tap (at the sink) fully on, and adjust the flow rate to 1500 cm$^3$/min.

Fig. 2 shows the layout of the control panel. **All the sockets are for monitoring only: the necessary connections are already in place**.

At the top left is a box labelled **Inlet temperature**. The toggle switch should be set to '0 V'; this ensures that the inlet temperature signal has no effect on the operation of the control system – the signal $\theta_c(t)$ should be fixed at $0V$.

Fig. 3 shows a *block diagram* of the control system. This shows that if the **Outlet temperature** differs from the **Demanded temperature** then a **Temperature error** signal is formed which is used to drive the heater in such a way as to reduce the error. This is negative feedback.

By reference to Fig. 3, identify the role of the various parts of the control panel. Note the following points:

- The panels labelled **Proportional control** and **Integral control** together implement the 'control law'
- The panel labelled **Demanded temperature** includes a 3-position switch, which allows step changes of $\pm 1$ volt to be superimposed on whatever voltage has been set up by the 10-turn potentiometer.
- The voltmeter at the top right has a range of 0 to 10 volts (or -10 to 0 if you reverse the polarity using the +/- switch) and is not connected to anything. (The 0 - 3 V scale should be ignored). You can use it to monitor signals at any socket on the panel by means of the flying leads. The 0 V terminal should be connected to the appropriate terminal on the chart recorder.
- The signal which can be monitored at the box labelled **Heater power** is a voltage in the range 0 to 10 volts. This controls the mark/space ratio of the heater. The neon light in the panel is illuminated when the heater is on.

# Familiarization with Equipment

Put the switch in the lower left corner of the control panel to the FEEDBACK OFF position – note from Fig. 3 that the effect of this is to open the feedback loop. Using the voltmeter, check the **Temperature error** signal is now the same as the **Demanded temperature** signal $\theta_d(t)$, and adjust this to be 1 volt.

The **Proportional control** panel is simply a variable-gain amplifier. If its gain is $K_P$ and its input signal is $e(t)$, then its output is $K_P e(t)$. Using the voltmeter, verify that gains between 0 to 10 (approximately) can be obtained.

The panel labelled **Integral control** contains an integrator, namely a circuit like that shown in Fig.4. If its input is $e(t)$ then its output is $K_i \int_0^t e(\tau)d\tau$, with the 'gain' $K_i$ being set by the potentiometer. When this integrator is not required its output should be clamped to 0 volts by means of the toggle switch. (If you just turn $K_i$ down to zero, you cannot be sure what the integrator output is – the capacitor may hold an unknown charge, or the charge may vary.) In practice, the output of the integrator is $K_i \int_0^t [e(\tau) + v_0]d\tau$, where $v_0$ is an offset voltage due to the imperfections in the electronic components, which causes the output to change even if $e(t) = 0$. The potentiometer labelled **Integrator offset** allows $v_0$ to be 'backed-off' to zero (approximately). Since the integrator output can exceed the range of the voltmeter, a $\div 2$ monitor socket is provided for this signal.

Connect the integrator output to one channel of the chart recorder. Set the recorder speed to 0.5 mm/sec. Set the **Temperature error** signal $e(t)$ to 0 Volts as follows: Adjust the potentiometer in the **Demanded temperature** panel to give +1V; then put the switch to the -1V position. In this way 0 V can be set up accurately. Now adjust the **Integrator offset** until the integrator output remains constant, in order to 'back off' the effect of imperfect components in the integrator. Leave this unchanged for the remainder of the experiment. Remember to set the switch at the integrator output correctly before doing this!

Now set $e(t)$ to 1V(which you can do by returning the **Demanded Temperature** switch to its central position) and record the output of the integrator with various settings of the potentiometer. This will allow you to calibrate the potentiometer in terms of $K_i$: since $e(t) = 1$, the integrator output is $K_i t$.

(NB: The potentiometer setting is 0.2 when the 'window' shows '2' and the dial is set to 0, so that the potentiometer setting cannot exceed 1.000).

| e(t) = 1V | Potentiometer setting | Slope of output | $K_i$ |
|---|---|---|---|
| | 0.2 | ........ (V/sec) | ........ ($\text{sec}^{-1}$) |
| | 0.4 | ........ (V/sec) | ........ ($\text{sec}^{-1}$) |
| | 0.8 | ........ (V/sec) | ........ ($\text{sec}^{-1}$) |

(When the integrator output reaches its maximum value – its *saturation level* – or exceeds the range of the recorder, it can be reset to zero by means of the toggle switch)

What is the greatest value of $K_i$ which can be set up?........($\text{sec}^{-1}$)

What is the integrator's saturation level? $V_{sat} =$ ........$(V)$

More information on integrator circuits and offset voltages can be found in Ahmed and Spreadbury (1984),pp. 131 and 148.

# Behaviour of the Uncontrolled Heater

Switch the integrator off. Ensure that you still have FEEDBACK OFF selected. Set $K_p$ to 1.

Assume that an **Outlet temperature** signal of 5 V represents a comfortable shower temperature. By adjusting the **Demanded temperature** potentiometer, measure the **Heater power** signal required to give an **Outlet temperature** signal of 5 V, with flow rates of 1500 and 3000 $\text{cm}^3$/min.

Flow rate = 1500 $\text{cm}^3$/min, Outlet temp. signal = 5 V:

Heat power signal = ............(V).   Call this $V_{1500}$

Flow rate = 3000 V, Outlet temp. signal = 5 V:

Heater power signal = ............(V )      Call this $V_{3000}$

Starting with a flow rate of 3000 cm$^3$/min, a **Heater power** signal of $V_{3000}$ volts, and an **Outlet temperature** signal of 5 volts, change the flow rate to 1500 cm$^3$/min.Observe the behavior of the **Outlet temperature**. When this has settled, change the **Heater power** signal to $V_{1500}$ volts, and again observe the **Outlet temperature**. Obtain a chart recording of both transient behaviors. Observe and record corresponding transients when the flow is increased from 1500 cm$^3$/min to 3000 cm$^3$/min. Verify that the outlet temperature measurement is delayed; it does not begin to change until some time after the flow rate has been changed. Estimate this delay:

Flow rate change: 3000 $\rightarrow$ 1500, Delay = ........(sec).

Flow rate change: 1500 $\rightarrow$ 3000, Delay = ........(sec).

Note that the delay is smaller with the higher flow rate. Why?

# Proportional Control

Now switch FEEDBACK ON and set **Demanded temperature** signal to 5 volts.

(Leave the flow rate at 3000 cm$^3$/min.) Ensure that the integrator is off, and set $K_p = 1$. Let the **Outlet temperature** settle to its new value, and note that this is lower than the **Demanded temperature**.

We now have a feedback control system working, and shall see that its behaviour depends very much on the value of the proportional gain $K_p$. For low gain values the response is overdamped and slow. As the gain is increased the response speed improves, but the response can become underdamped. If the gain is increased still further the control system can become unstable, which typically results in large oscillations of the **Outlet temperature**.

A feature of proportional control is that there is always some error between the demanded and achieved temperature, even in the steady state when all signals have settled down (see the Appendix). Investigate how this steady-state error is affected by changes in $K_p$ and the flow rate, and enter your results in the following table. (Measure the **Temperature error** using the voltmeter).

| | Flow rate = 3000 | Flow rate = 1500 |
|---|---|---|
| $K_p = 1$ | ........(V) | ........(V) |
| $K_p = 2$ | ........(V) | ........(V) |
| $K_p = 3$ | ........(V) | ........(V) |

(If instability occurs, enter'X' for the corresponding condition)

**Table of steady state errors**

Note that the steady-state error decreases as $K_p$ is increased (until instability occurs) and decreases as the flow rate is decreased. Is this reasonable? (See Appendix).

# Proportional and Integral Control

Steady-state errors can be eliminated by using integral as well as proportional control (see Appendix). Set $K_p = 0.5$ and $K_i = 0.05$. (Using the calibration of the 'Integral Control' potentiometer from the previous page.)

Switch the integrator on, and verify that the **Temperature error** settles to zero. (If it does not, check that you have set $K_i$ correctly. If you are sure that you have, you may have to re-adjust the **Integrator Offset**, but check this with a demonstrator first.)

The major purpose of feedback is to reduce the effects of unpredictable changes, and the most significant change which affects shower is flow rate variation. With the **Demanded temperature** set to 5 V, can you adjust $K_p$ and $K_i$ so that the **Outlet temperature** signal remains between 4.1 volts and 5.9 volts when the flow rate changes suddenly from 3000 $cm^3$/min to 1500 $cm^3$/min or vice versa? Record your results in the table below, and spend a little time trying to find the best combination of gains. Note that this is not easy to do by trial and error – that's why we need control theory. Note also that it is easier to meet the specification for one of the changes that for the other one. Can you explain why?

| $K_p$ | $K_i$ | $3000 \rightarrow 1500$ | | $1500 \rightarrow 3000$ | |
|---|---|---|---|---|---|
| | | Min. Temp. | Max Temp. | Min. Temp. | Max Temp. |
| 0.5 | 0.05 | | | | |
| 0.5 | 0.10 | | | | |
| 0.5 | 0.20 | | | | |
| 1.0 | 0.05 | | | | |
| 1.0 | 0.10 | | | | |
| 1.0 | 0.20 | | | | |
| ... | 0.05 | | | | |
| ... | 0.10 | | | | |
| ... | 0.20 | | | | |
| ... | ... | | | | |
| ... | ... | | | | |
| ... | ... | | | | |

What is the best combination of gains you found?

$$K_p = \text{.........} \quad K_i = \text{.........}(\text{sec}^{-1})$$

# References

Ahmed,H and Spreadbury,P.J.,(1984), **Analogue and Digital Electronics for Engineers**, (CPU), NT. 396.

# Appendix – Steady state errors

Consider fig.3. Suppose that the 'control law' is proportional, namely that $u(t) = K_p e(t)$, where $K_p$ is a constant gain. If the outlet temperature is to be higher than the inlet temperature then $u(t)$ must be non-zero (on average, at least). But this is possible only if $e(t)$ is non-zero, on average. But $e(t)$ is just the error between the demanded and the achieved temperature, so this error must be non-zero, on average, with proportional control.

If $K_p$ increases then a given level of $u(t)$ is achieved with a lower level of $e(t)$, so it is reasonable to expect that the average value of $e(t)$ should decrease.

Now suppose that we have integral control (more accurately 'proportional and integral' control), namely that

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau$$

We can now have a non-zero value of $u(t)$ even if $e(t) = 0$. In fact, if the feedback system is stable, so that it eventually settles to a steady state with all signals at constant values then, since $u(t)$ and $e(t)$ are constant, we must have $e(t) = 0$. Thus with integral control the only possible steady state error is zero. (However, it is possible for the control system to be unstable, in which case no steady state error exist.)

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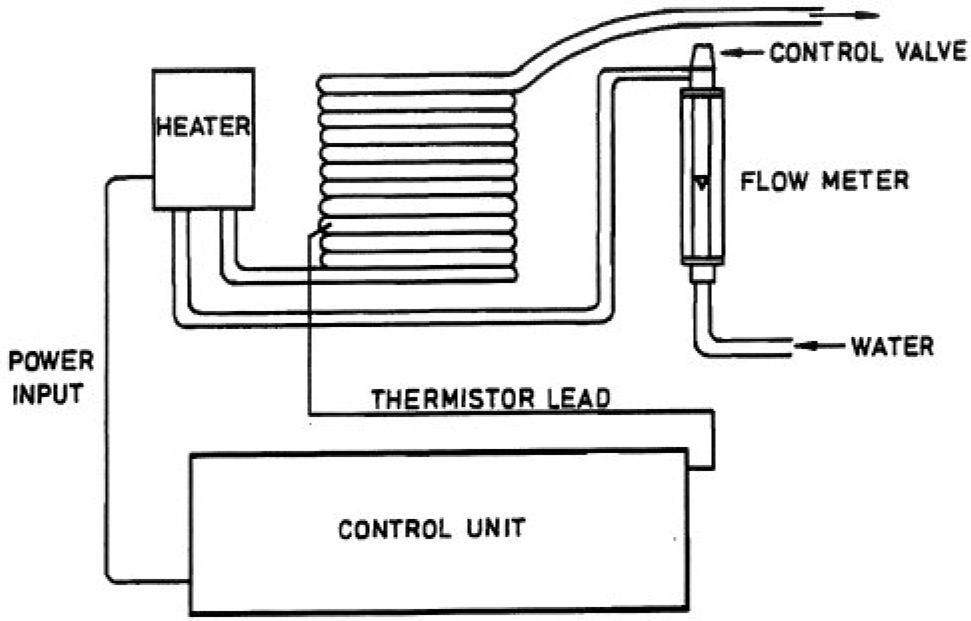


Fig.1 Water Heating System

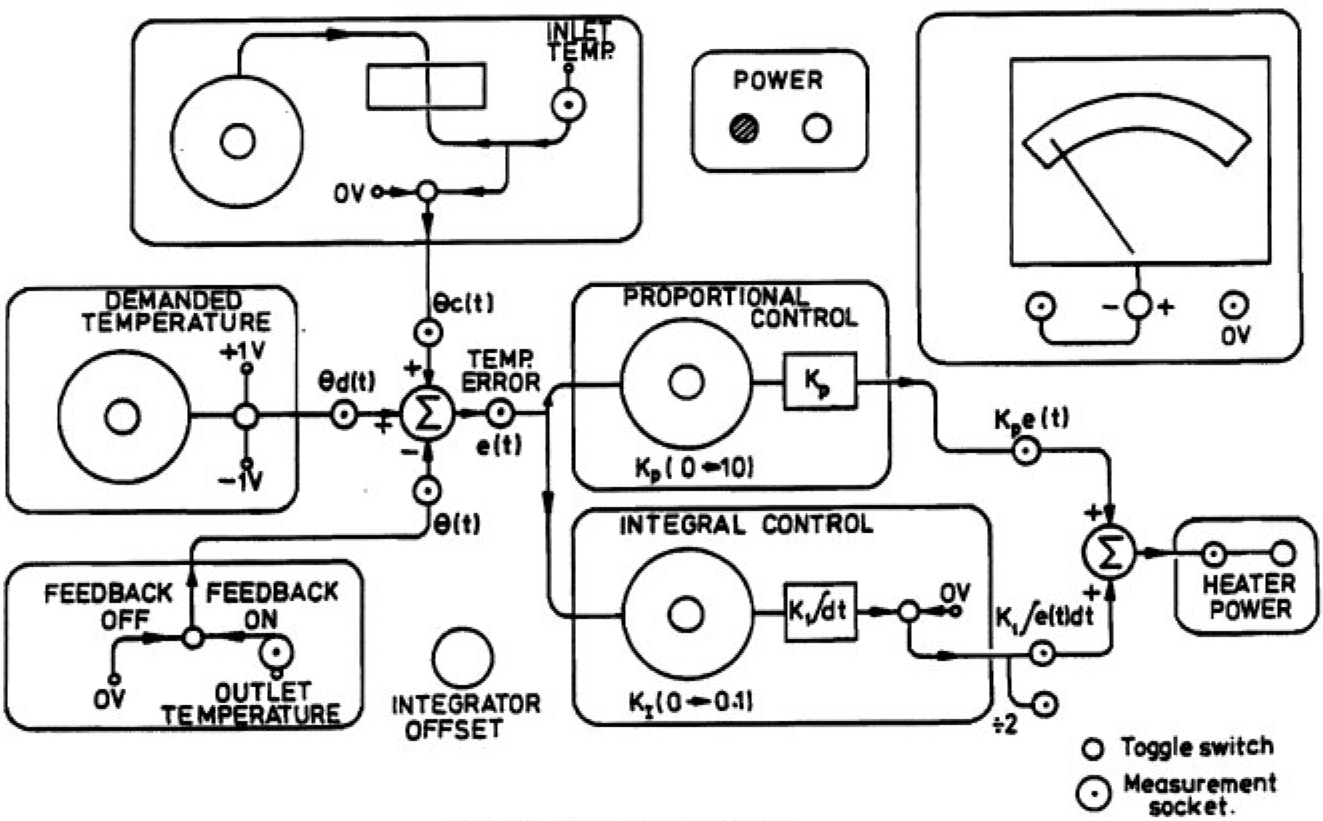


Fig 2. Control Panel

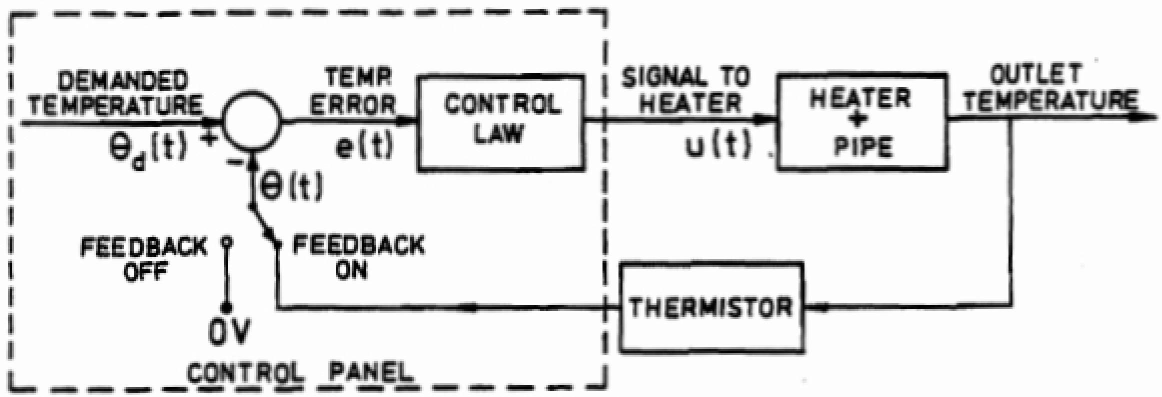


Fig 3 Block Diagram

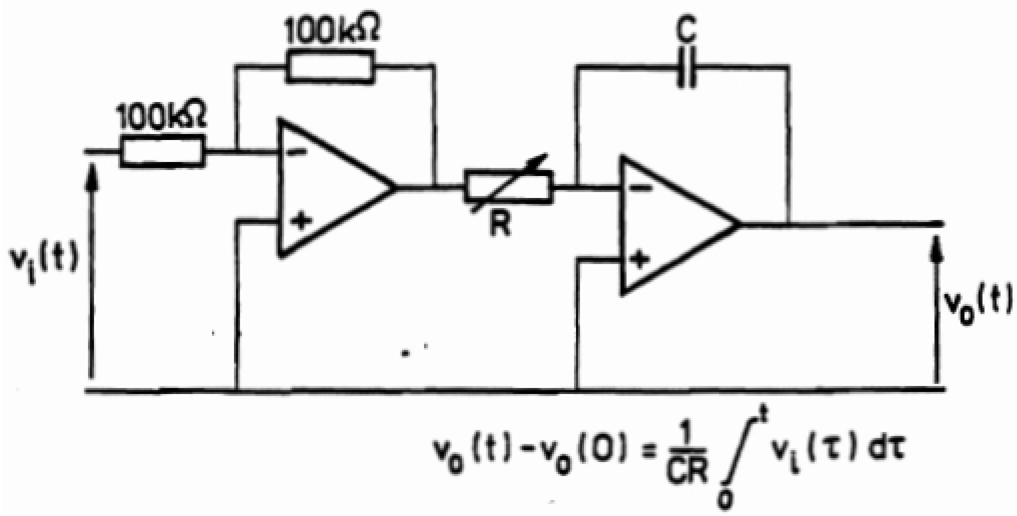


Fig. 4 Integrator Circuit