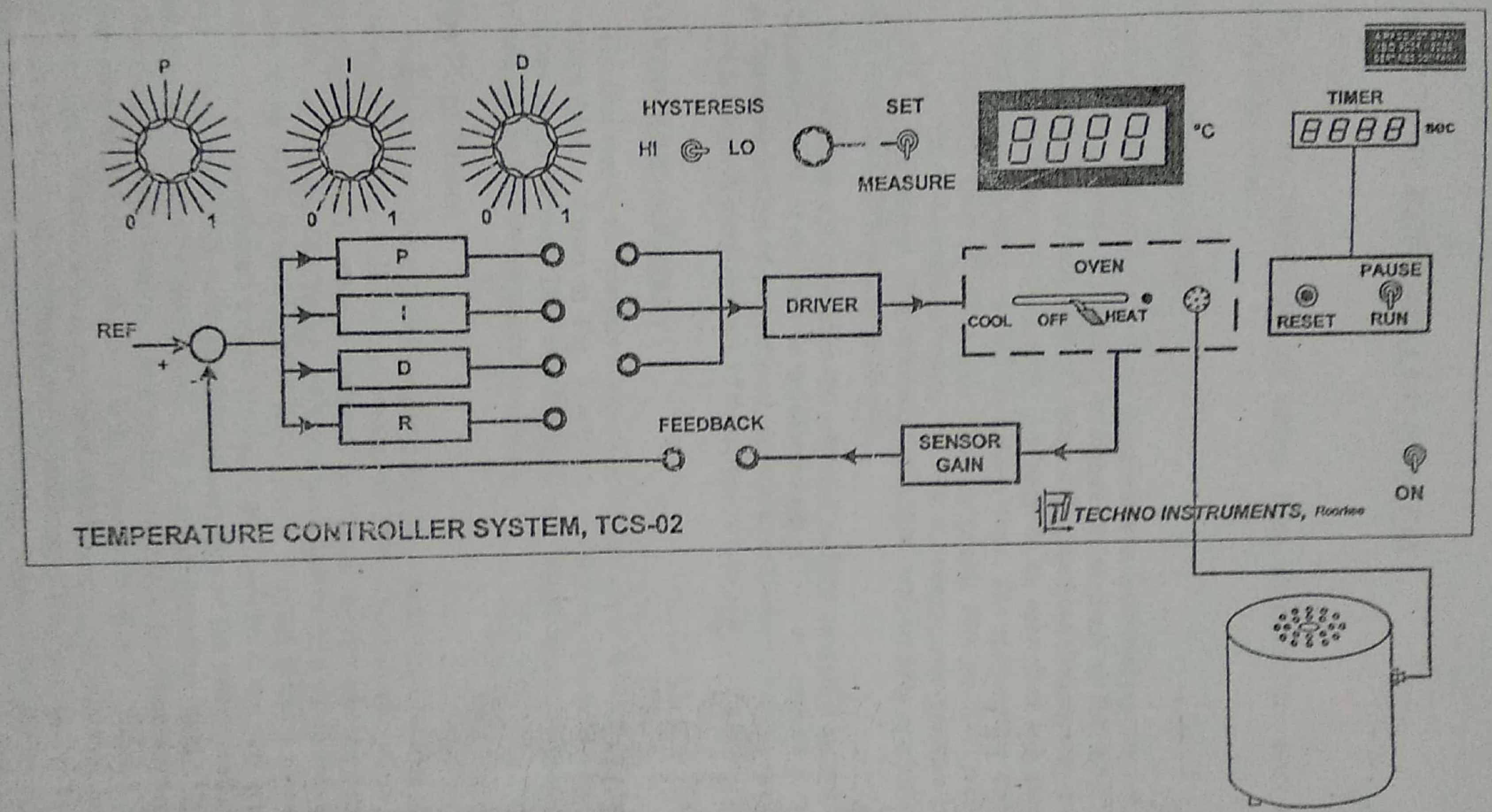
CONTROL ENGINEERING LABORATORY, NSIT

Experiment No. - 2

User's Manual

TEMPERATURE CONTROLLER SYSTEM

(Model: TCS-02)



Panel Drawing Temperature Controller System, Model TCS-02

TEMPERATURE CONTROLLER SYSTEM

TCS-02

1. OBJECTIVE

To study the performance of various types of controllers used to control the temperature of an oven.

2. SYSTEM DESCRIPTION

Temperature control is one of the most common industrial control systems that are in operation. This equipment is designed to expose the students to the intricacies of such a system in the 'friendly' environment of a laboratory, free from disturbances and uncertainties of plant prevalent in an actual process. The 'plant' to be controlled is a specially designed oven having a short heating as well as cooling time. The temperature time data may be obtained manually, thus avoiding expensive equipment like an X-Y recorder or a pen recorder. A solid state temperature sensor converts the absolute temperature information to a proportional electric signal. The reference and actual temperatures are indicated in degree Celsius on a switch selectable digital display.

The controller unit compares the reference and the measured signals to generate the error. Controller options available to the user consist of ON-OFF or relay with two hysteresis settings and combination of proportional, derivative and integral blocks having independent coefficient settings. A block diagram of the complete system is shown in Fig. 1.

3. BACKGROUND SUMMARY

The first step in the analysis of any control system is to derive its mathematical model. The various blocks shown in Fig. 1 are now studied in detail and their mathematical descriptions are developed. This would help in understanding the working of the complete system and also to implement control strategies.

3.1 The Plant (Oven)

Plant to be controlled is an electric oven, the temperature of which must adjust itself in accordance with the reference or command. This is a thermal system which basically involves transfer of heat from one section to another. In the present case we are interested in the transfer of heat from the heater coil to the oven and the leakage of heat from the oven to the atmosphere. Such systems may be conveniently analysed in terms of thermal resistance and capacitance as explained below. However, this analysis is not very accurate, since the transfer of heat essentially takes place from every part of the oven - thermal resistance and capacitance are obviously distributed. The lumped parameter model described here is therefore only an approximation. For a precise analysis, a distributed parameter model must be used. Another difficulty associated with temperature control systems is that whereas the temperature rise is produced by energy input, which is controllable, the temperature fall is due to heat loss which is uncontrollable and unpredictable. This implies that the oven will have different time constants while heating and cooling. Again, these will depend on the ambient temperature and the set point chosen. Such a system is therefore rather difficult to control.

There are three modes of heat transfer viz. conduction, convection and radiation. Heat transfer through radiation maybe neglected in the present case since the temperatures involved are quite small. For conductive and convective heat transfer

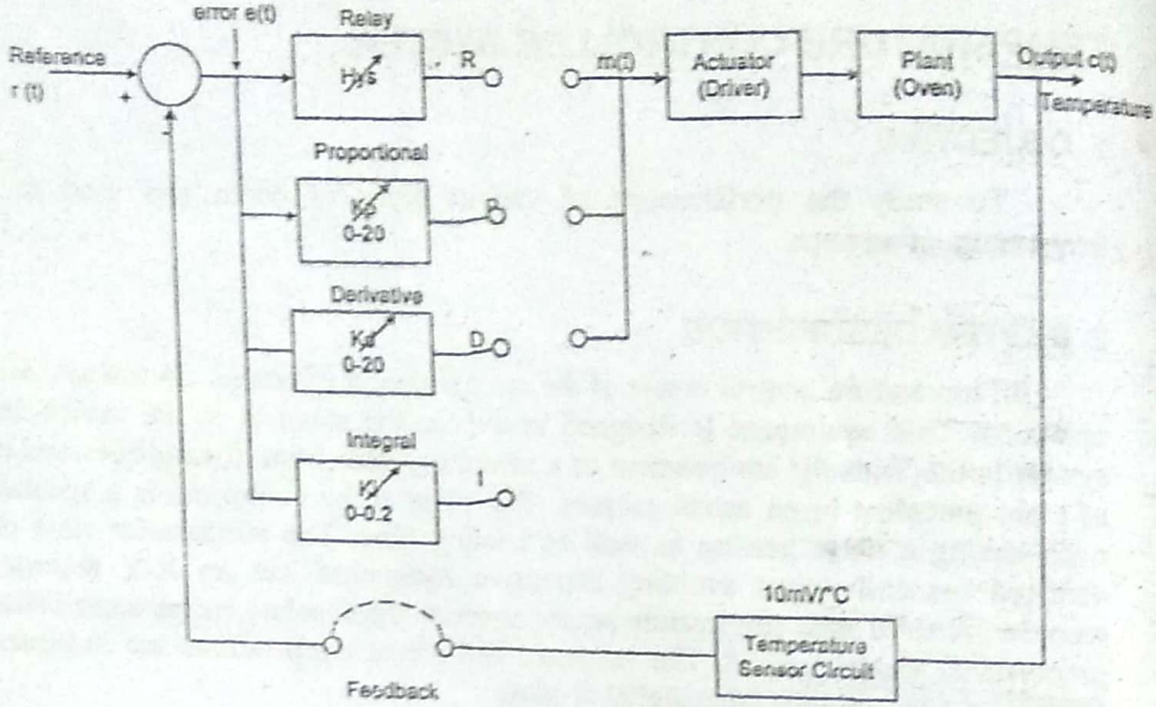


Fig.1. Block Diagram of the Temperature

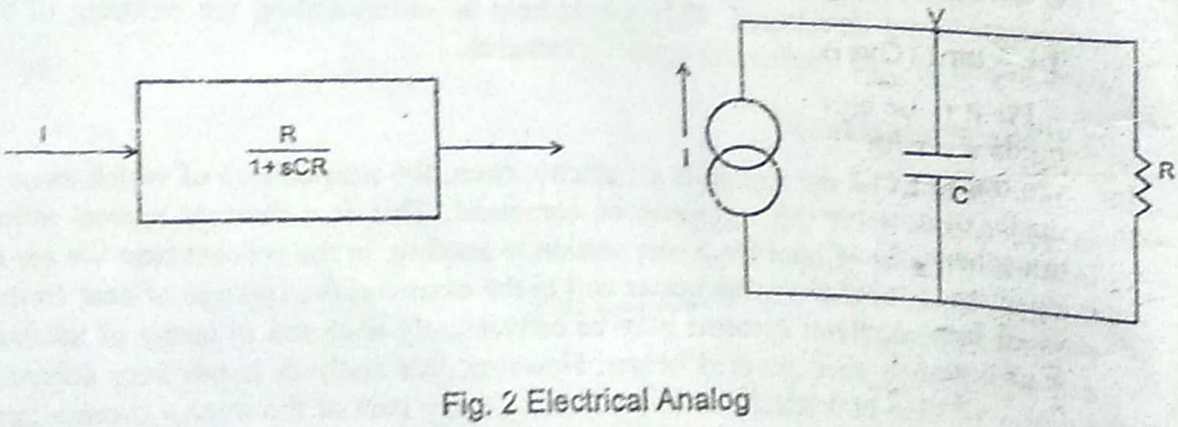


Fig. 2 Electrical Analog

$$\Theta = \alpha\Delta T$$

where, Θ = rate of heat flow in Joule/sec.

ΔT = temperature difference in °C

α = Constant

t = time in seconds

Under assumptions of linearity, the thermal resistance is defined as, R = Temperature-difference/rate of heat flow = $\Delta T/\Theta = 1/\alpha$. This is analogous to electrical resistance defined by I = V/R. In a similar manner thermal capacitance of the mass is defined by

$$\Theta = C d(\Delta T)/dt$$

which is analogous to the V-I relationship of a capacitor, namely I = C dV/dt. In the case of heat,

C = Rate of heat flow/Rate of temperature change

The equation of an oven may now be written by combining the above two equations, implying that a part of the heat input is used in increasing the temperature of the oven and the rest goes out as loss. Thus

$$\Theta = C\, dT/dt + (1/R)\times T,$$

with the initial condition $T(t=0) = T_{amb}$. Now, taking Laplace transform with zero initial condition

$$\frac{T(s)}{\Theta(s)} = \frac{R}{1+sCR} \qquad (1)$$

An analogous electrical network and block diagram may be drawn as in Fig.2 defined by the equation

$$I = C\, dV/dt + V/R$$

Eq.(1) is an extremely simplified representation of the thermal system under consideration and it gives rise to a transfer function of the first order and type zero. Such a system should be easily controlled in the closed loop. Difficulties are however faced in the system due to the following reasons:

(a) The temperature rise in response to the heat input is not instantaneous. A certain amount of time is needed to transfer the heat by convection and conduction inside the oven. This requires a delay or transportation lag term, $\exp(-sT_l)$, to be included in the transfer function, where T_l is the time lag in seconds.

(b) Unlike the equivalent electrical circuit of Fig. 2, the heat input in the thermal system cannot have a negative sign. This means that although the rate of temperature rise would depend on the heat input, the rate of temperature fall would depend on thermal resistance R. The conventional analysis methods then become inapplicable.

(c) Referring to the closed loop oven control system of Fig. 3, it may be seen that in the steady state the error e_{ss} is given as

$$e_{ss} = \lim_{t\to\infty} (T_{ref} - T) = T_{ref}/(1+AR)$$

In this system, A cannot be increased excessively in an attempt to reduce error, since a large gain is likely to lead to instability due to transportation lag. Also, every time $(T_{ref} - T)$ becomes negative, the heat input is cut off and the oven must cool down slowly. The temperature T therefore oscillates around the nominal value.

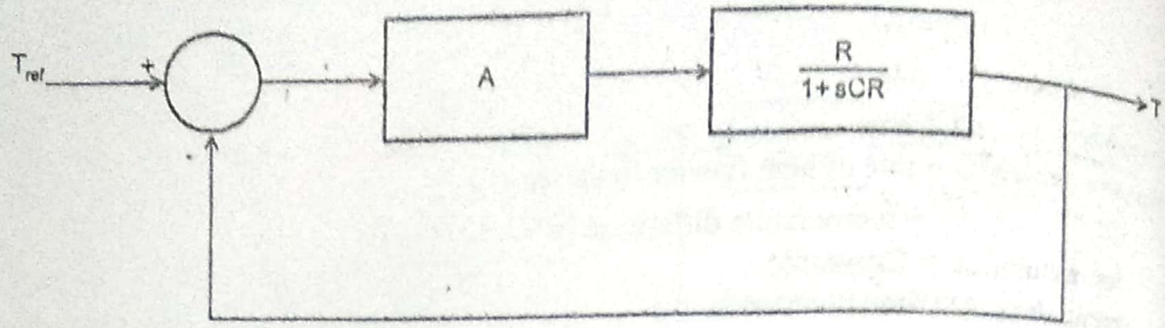


Fig. 3 Closed Loop Temperature Control System

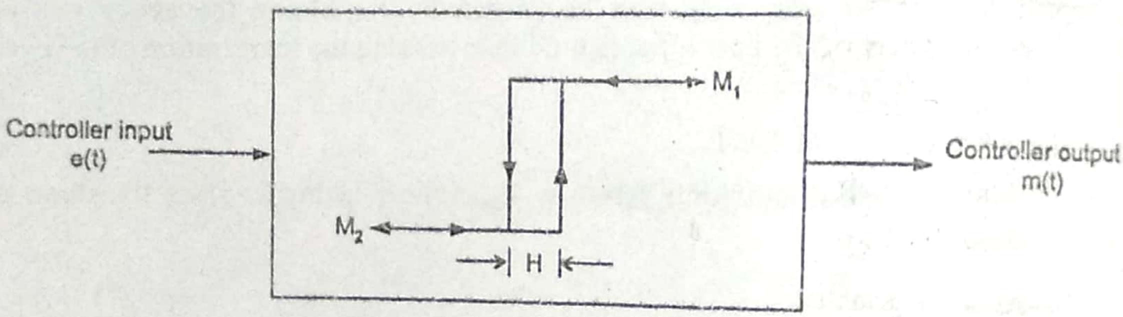


Fig. 4 ON-OFF Controller

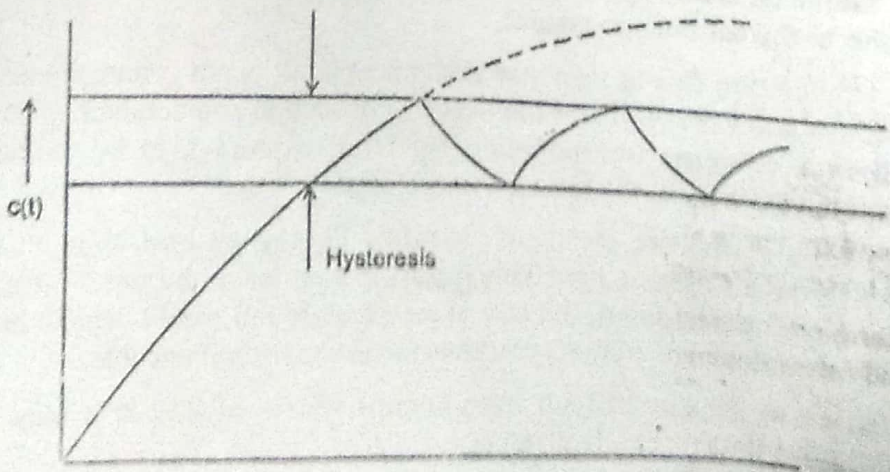


Fig. 5 Response of ON-OFF Control System

3.2 Controller

Basic control actions commonly used in temperature control systems are

- ON-OFF or relay
- Proportional
- Proportional-Integral
- Proportional-Integral-Derivative

These are described below in some detail.

(a) ***ON-OFF or Relay type controllers***, also referred to as two position controllers, consist of a simple and inexpensive switch/relay and are, therefore, used very commonly in both industrial and domestic control systems. Typical applications include air-conditioner and refrigerators, ovens, heaters with thermostat. Solenoid operated two position valves are commonly used in hydraulic and pneumatic systems. The basic input-output behaviour of this controller is shown in Fig. 4. The two positions of the controller are M_1 and M_2, and H is the hysteresis or differential gap.

The hysteresis is necessary, as it enables the controller output to remain at its present value till the input or error has increased a little beyond zero. Hysteresis helps in avoiding too frequent switching of the controller, although a large value results in greater errors. The response of a system with ON-OFF controller is shown in Fig. 5. Describing function technique is a standard method for the analysis of non-linear systems, for instance, one with an ON-OFF controller.

(b) ***Proportional controller*** is simply an amplifier of gain K_p which amplifies the error signal and passes it to the actuator. The noise, drift and bias currents of this amplifier set the lower limit of the input signal which may be handled reliably and therefore decide the minimum possible value of the error between the input signal and output. Also the saturation characteristics of this amplifier sets the linear and non-linear regions of its operation. A typical proportional controller may have an input-output characteristics as in Fig. 6. Such controller gives non-zero steady state error to step input for a type-0 system as indicated earlier. The proportional (P) block in the system consists of a variable gain amplifier having a maximum value, $K_{p\,max.}$ of 20.

(c) ***Proportional-Integral (PI) controller***: Mathematical equation of such a controller is given by

$$m(t) = K_p e(t) + K_I \int_0^t e(t)\,dt = K_p e(t) + 1/T_I \int_0^t e(t)\,dt$$

and a block diagram representation is shown in Fig. 7. It may be easily seen that this controller introduces a pole at the origin, i.e. increases the system type number by unity. The steady state error of the system is therefore reduced or eliminated. Qualitatively, any small error signal e(t), present in the system, would get continuously integrated and generate actuator signal m(t) forcing the plant output to exactly correspond to the reference input so that the error is zero. In practical systems, the error may not be exactly zero due to imperfections in an electronic integrator caused by bias current needed, noise and drift present and leakage of the integrator capacitor.

The integral (I) block in the present system is realised with a circuit shown in Fig.8 and has a transfer function

$$G_I(s) = 1/(28s) = K_I/s \qquad (2)$$

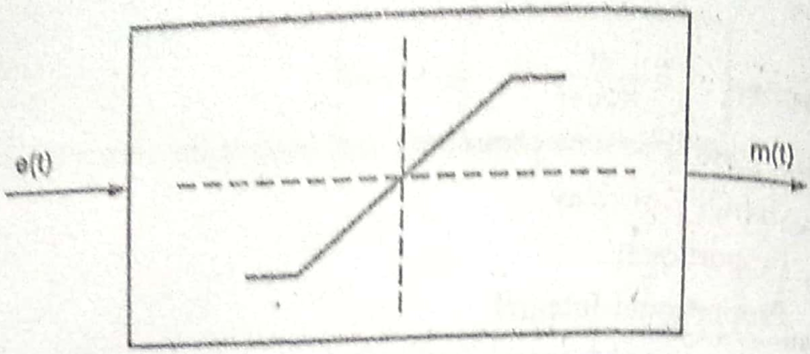


Fig. 6 Proportional Controller with Saturation

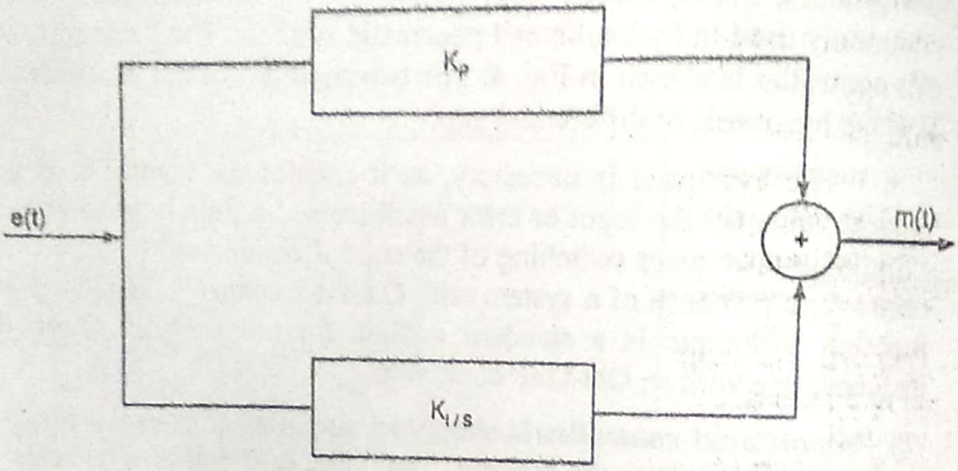


Fig. 7 P-I Controller

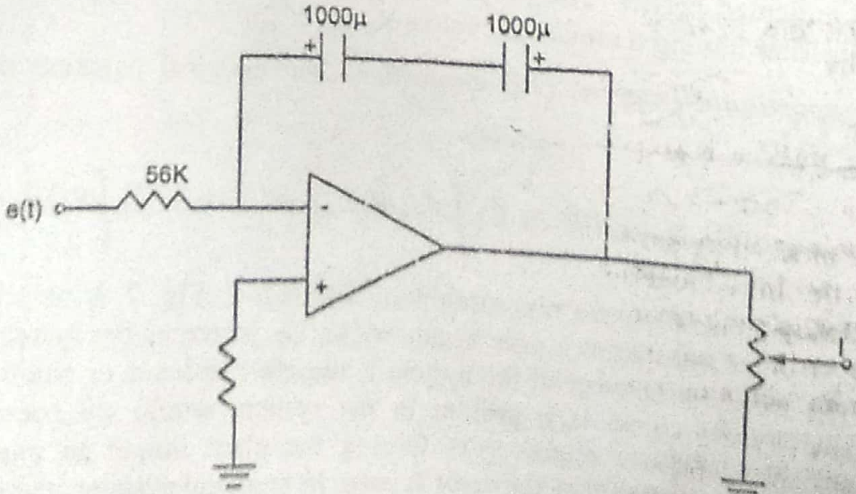


Fig.8 Circuit for Integrator

The integral gain is therefore adjustable in the range 0 to 0.036 (approx.). Due to the tolerance of large capacitance's, the value of K_I is approximate.

(d) ***Proportional-Integral-Derivative (PID) controller:*** Mathematical equations governing the operation of this controller is as

$$m(t) = K_P e(t) + K_I \int_0^t e(t)\,dt + K_D de(t)/dt$$

$$= K_P e(t) + 1/T_I \int_0^t e(t)\,dt + T_D de(t)/dt$$

so that in the Laplace transform domain,

$$M(s)/E(s) = (K_p + T_D s + 1/T_I s)$$

A simple analysis would show that the derivative block essentially increases the damping ratio of the system and therefore improves the dynamic performance by reducing overshoot. The PID controller therefore helps in reducing the steady state error with an improvement in the transient response.

The derivative (D) block in this system is realised with the circuit of Fig. 9. This has a transfer function

$$G_D(s) = 19.97\ s\ \text{(approx.)} \qquad (3)$$

The derivative gain is therefore adjustable in the range 0 to 20 approximately. Again, the approximation is justified due to the higher tolerance in the values of large electrolytic capacitance's.

PID controller is one of the most widely used controller because of its simplicity. By adjusting its coefficients K_P, K_D (or T_D) and K_I (or T_I) the controller can be used with a variety of systems. The process of setting the controller coefficients to suit a given plant is known as tuning. There are many methods of 'tuning' a PID controller. In the present experiment, the method of Ziegler-Nichol has been introduced which is suitable for the oven control system, although better methods are available and may be attempted.

3.3 Temperature Measurement

The oven temperature can be sensed by a variety of transducers like thermistor, thermocouple, RTD and IC temperature sensors. In the present setup, the maximum oven temperature is around 90°C which is well within the operating range of IC temperature sensor like AD590. Further, these sensors are linear and have a good sensitivity, viz. 1μA/K. Associated electronic circuits convert this output to 10mV/°C which may be easily measured by a DVM. The time constant of the sensor has however been neglected in the analysis since it is insignificant compared with the oven time constant.

4. EXPERIMENTAL WORK

A variety of experiments may be conducted with the help of this unit. The principal advantage of the unit is that all power sources and metering are built-in and one needs only a watch to be able to note down the temperature readings at precise time instants. After each run the oven has to be cooled to nearly the room temperature, which may take about 20-25 minutes with forced cooling provided. This would limit the number of runs to about four in an usual laboratory class. The experiments suggested could be completed in about 6-8 hours.

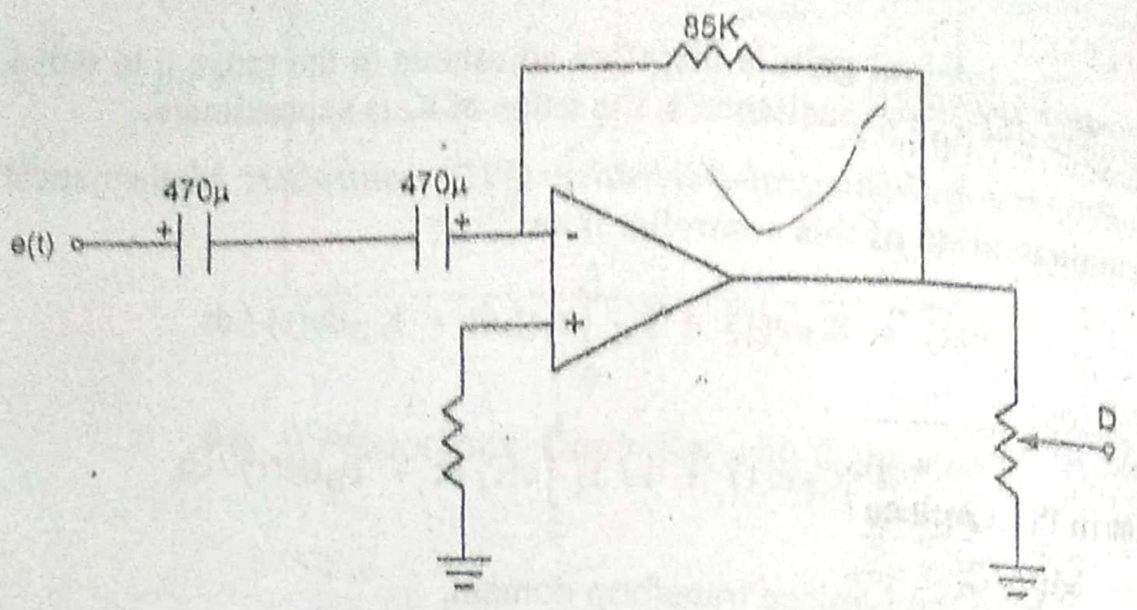


Fig. 9 Circuit for Differentiator

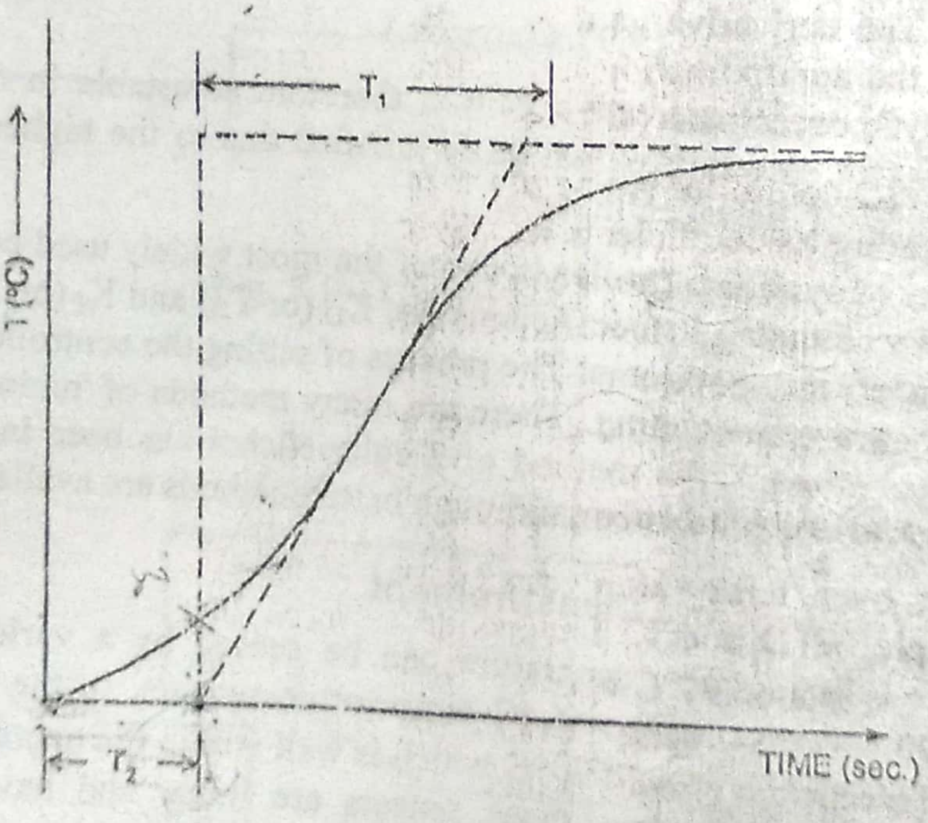


Fig. 10 Open Loop Response of the Oven

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4.1 Identification of Oven Parameters

Plant identification is the first step before an attempt can be made to control it. In the present case, the oven equations are obtained experimentally from its step response as outlined below. The procedure is as per Ziegler-Nichol reaction curve method.

In the open-loop testing, the oven is driven through the P-amplifier set to a gain of 10. The input to this amplifier is adjusted through reference potentiometer (the one next to switch S_2). This input can be seen on digital display, so that when you set 5.0°C, the input to Proportional amplifier is 50 mV (@ 10mV/°C) and its output (which acts as input to driver circuit) is 0.5V (50mVx10).

- Keep switch S_1 to 'WAIT', S_2 to 'SET' and open 'FEEDBACK' terminals. (refer panel drawing)
- Connect P output to the driver input and switch ON the unit.
- Set P potentiometer to 0.5 which gives $K_p=10$. Adjust reference potentiometer to read 5.0 on the DVM. This provides an input of 0.5 V to the driver.
- Put switch S_2 to the 'MEASURE' position and note down the room temperature.
- Put switch S_1 to the 'RUN' position and note temperature readings every 10 sec.. till the temperature becomes almost constant. Use the timer on the panel to monitor time.
- Plot temperature-time curve on a graph paper. Referring to Fig. 10, calculate T_1 and T_2 and hence write the transfer function of the oven including its driver as

  $G(s) = K\exp(-sT_2)/(1+sT_1)$, with T in °C.

4.2 ON-OFF Controller

- Keep switch S_1 to 'WAIT" position and allow the oven to cool to room temperature. Short 'FEEDBACK' terminals.
- Keep switch S_2 to the 'SET' position and adjust reference potentiometer to the desired output temperature, say 60.0°C, by seeing on the digital display.
- Connect R output to the driver input. Outputs of P, D and I must be disconnected from driver input. Select 'HI' or 'LO' value of hysteresis. (First keep the hysteresis switch to 'LO').
- Switch S_2 to 'MEASURE' and S_1 to 'RUN' position. Read and record oven temperature every 10 sec., for about 20 minutes.
- Plot a graph between temperature and time and observe the oscillations (Fig. 15) in the steady state. Note down the magnitude of oscillations.
- Repeat above steps with the 'HI' setting for hysteresis and observe the rise time, steady-state error and percent overshoot.

4.3 Proportional Controller

Ziegler and Nichols suggest the value of K_P for P-Controller as

$$K_P = \left(\frac{1}{K}\right) \times \left(\frac{T_1}{T_2}\right)$$

- Starting with a cool oven, keep switch S_1 to 'WAIT" position and connect P to the driver input. Keep R, D and I outputs disconnected. Short 'FEED terminals.

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- Set P potentiometer to the above calculated value of K_p, keeping in mind that the maximum gain is 20. The measurement and interpretation of K_p and P-control potentiometer setting needs some explanation here. The formula for K_p above is for an unity feedback system and has the dimension of Volts/°C. In the present unit a temperature sensor having sensitivity of 10mV/°C (0.01V/°C) is used between oven output and controller input. Thus, the K_p calculated above will need to be divided by 0.01 to obtain the P-control potentiometer setting. K_D and K_I have dimensions of sec. and sec^{-1} respectively hence do not require any further consideration. These values may be set directly on the respective potentiometers.
- Select and set the desired temperature to say 60.0°C.
- Keep switch S_1 to 'RUN' position and record temperature readings as before.
- Plot the observations on a linear graph paper and observe the rise time, steady-state error and percent overshoot.

4.4 Proportional-Integral Controller

Ziegler and Nichols suggested the value of K_P and K_I for P-I controller as

$$K_P = \left(\frac{0.9}{K}\right) \times \frac{T_1}{T_2} \;;\; T_I = \frac{1}{K_I} = 3.3\,T_2, \text{ giving } K_I = \frac{1}{3.3T_2}$$

- Starting with a cool oven, keep switch S_1 to 'WAIT', connect P and I outputs to driver input and disconnect R and D outputs. Short feedback terminals.
- Set P and I potentiometers to the above values of K_P, and K_I respectively, keeping in mind that the maximum value of K_P is 20 and that of K_I is 0.036.
- Select and set the desired temperature to say 60.0°C.
- Keep switch S_1 to 'RUN' position and record temperature readings as before.
- Plot the response on a graph paper and observe the steady state error and percent overshoot.

4.5 Proportional-Integral-Derivative Controller

Ziegler and Nichols suggest the values of K_P, K_D and K_I for this controller as

$$K_P = \left(\frac{1.2}{K}\right) \times \frac{T_1}{T_2} \;;\; T_I = \frac{1}{K_I} = 2T_2, \text{ giving } K_I = \frac{1}{2T_2}$$

$$K_D = T_D = 0.5T_2$$

- Starting with a cool oven, keep switch S_1 to 'WAIT' position and connect P and I outputs to driver input. Keep R output disconnected. Short feedback terminals.
- Set P, I and D potentiometers according to the above calculated values of K_P, and K_D keeping in mind that the maximum values for these are 20, 0.036 and 23.5 respectively.
- Select and set the desired temperature, say 60.0°C.
- Switch S_1 to 'RUN', and record temperature-time readings.
- Plot the response on a linear graph paper and observe the rise time, steady state error and percent overshoot.(See Fig. 14)
- Compare the results of the various controller options.

Fig. 11 Open Loop Response of the Oven

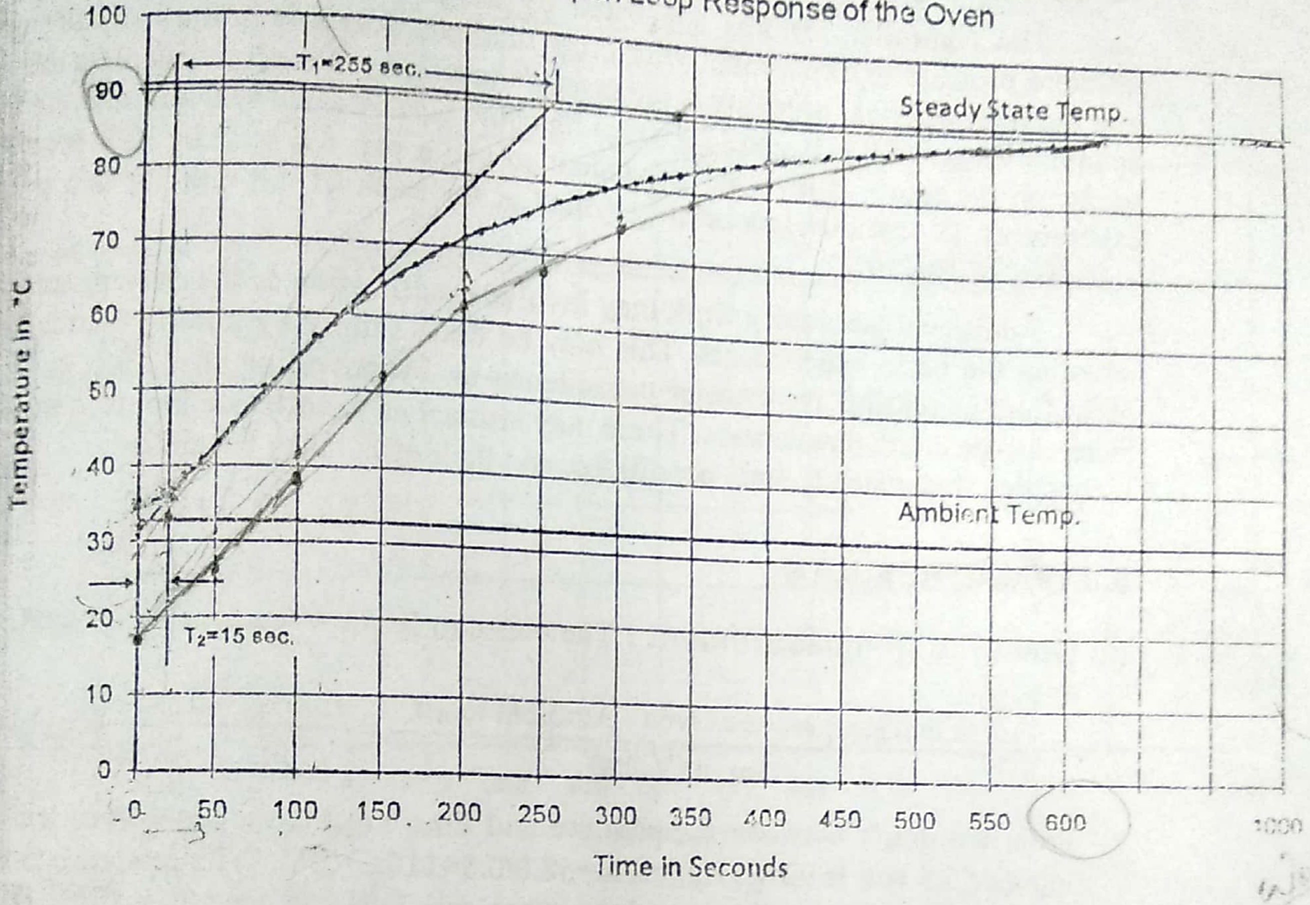
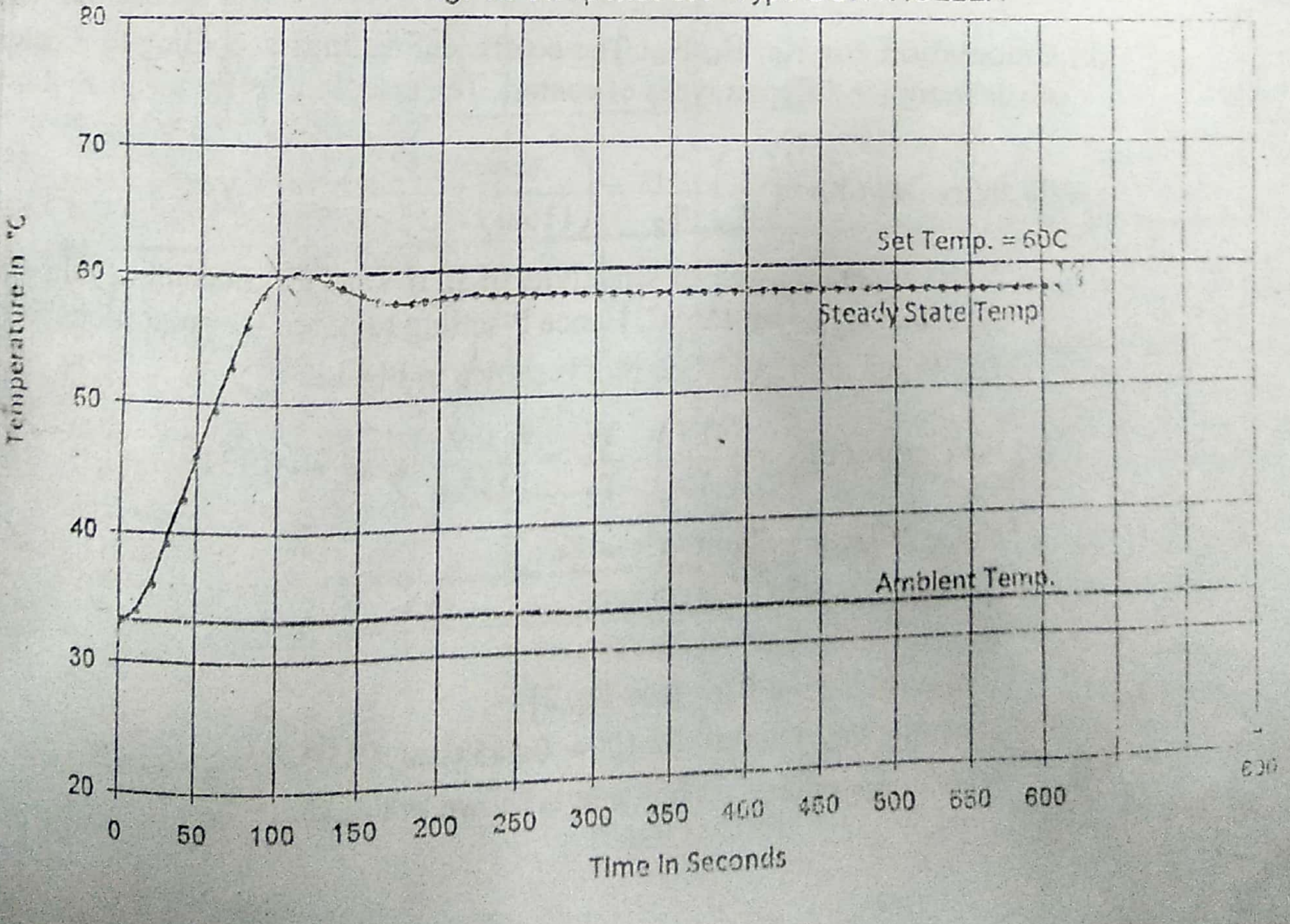


Fig. 12 Response of P-Type CONTROLLER



4.6 Further Experimentation

The controller settings suggested by Ziegler and Nichols are not optimum. It is therefore possible to experiment with other methods available in the literature or to attempt trial and error settings. Students at the master's level may attempt to calculate theoretically optimum values of K_P, K_D and K_I based on some performance criterion and then verify the results on the setup. It may be convenient to use a pen recorder or X-Y recorder for such experiments. A terminal has been provided at the back of the unit for this purpose with sensitivity of 10mV/°C.

Additional laboratory work may involve modification of the oven parameters and then repeating the basic experiments. This may be done simply by putting thermal load into the oven, thus increasing its thermal capacitance or by providing insulation to the oven thus increasing its thermal resistance. These may also act as disturbance inputs to the oven while it is operating under steady-state conditions, and their effect may be studied.

5. TYPICAL RESULTS

(a) Open - loop measurement : The constant K for oven plus driver controller is given by

$$K = \frac{\text{Final temperature Oven - Ambient temp.}}{\text{Input (Volts)}} = \frac{92.0 - 34.0}{0.5} = \frac{58.0}{0.5} = 116.0$$

From the graph between temperature and time Fig.11, the final oven temperature for input of 0.5 volt is 92°C. Hence, K=58.0/0.5=116.0°C/V. With reference to Fig.10, T_1 & T_2, as measured from the open-loop graph are: $T_1 = 255$ sec.; $T_2 = 15$sec. (Note that these values may differ from unit to unit).

(b) Calculation for K_P, K_I, K_D: The coefficient settings according to Ziegler and Nichols are different for different types of control. The calculations for them are illustrated below

(i) ***P Control*** : $K_P = \left(\frac{1}{K}\right) \cdot \frac{T_1}{T_2} = \left(\frac{1}{116.0}\right) x \frac{255}{15} = 0.1466$ V/°C

With temperature-sensor sensitivity of 10 mV/°C and maximum gain of P-amplifier 20, actual $K_{p\ max.}$=0.1V/°C. Hence P-setting required for proportional control is 73%. The Temperature vs Time plot is shown in Fig.12.

(ii) ***P-I Control*** : $K_P = \left(\frac{0.9}{K}\right) \cdot \frac{T_1}{T_2} = \left(\frac{0.9}{116.0}\right) x \frac{255}{15} = 0.1319$

hence, P-setting required = 66%.

$T_I = 3.3T_2 = 3.3x15 = 49.5$ sec;

$K_I = 1/T_I = 1/49.5 = 0.020$/sec.

$K_{I\ max.} = 1/28 = 0.036$, {see Eq. 2}

I-setting = (0.020/0.036)x100 = 0.555x100 = 55.5% ≈56%

The Temperature vs Time plot is shown in Fig.13.

Fig. 13 Response with PI-type CONTROLLER

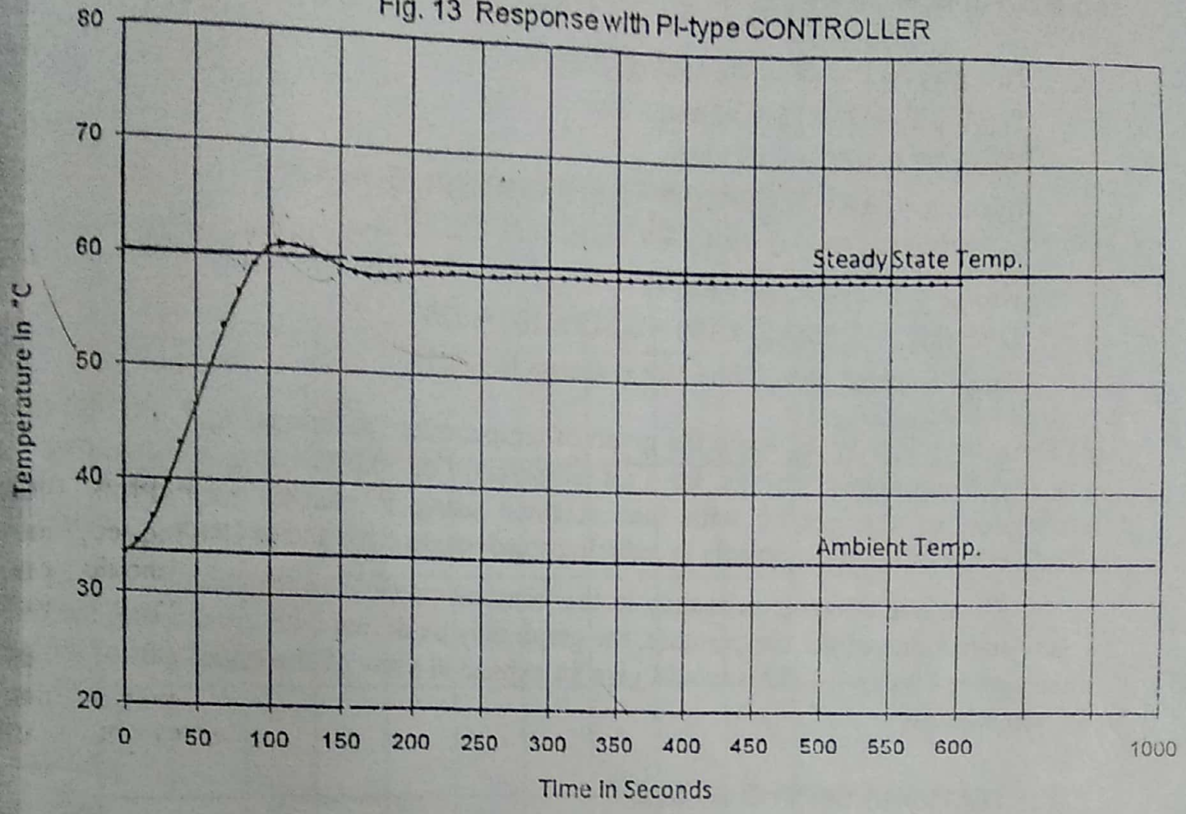
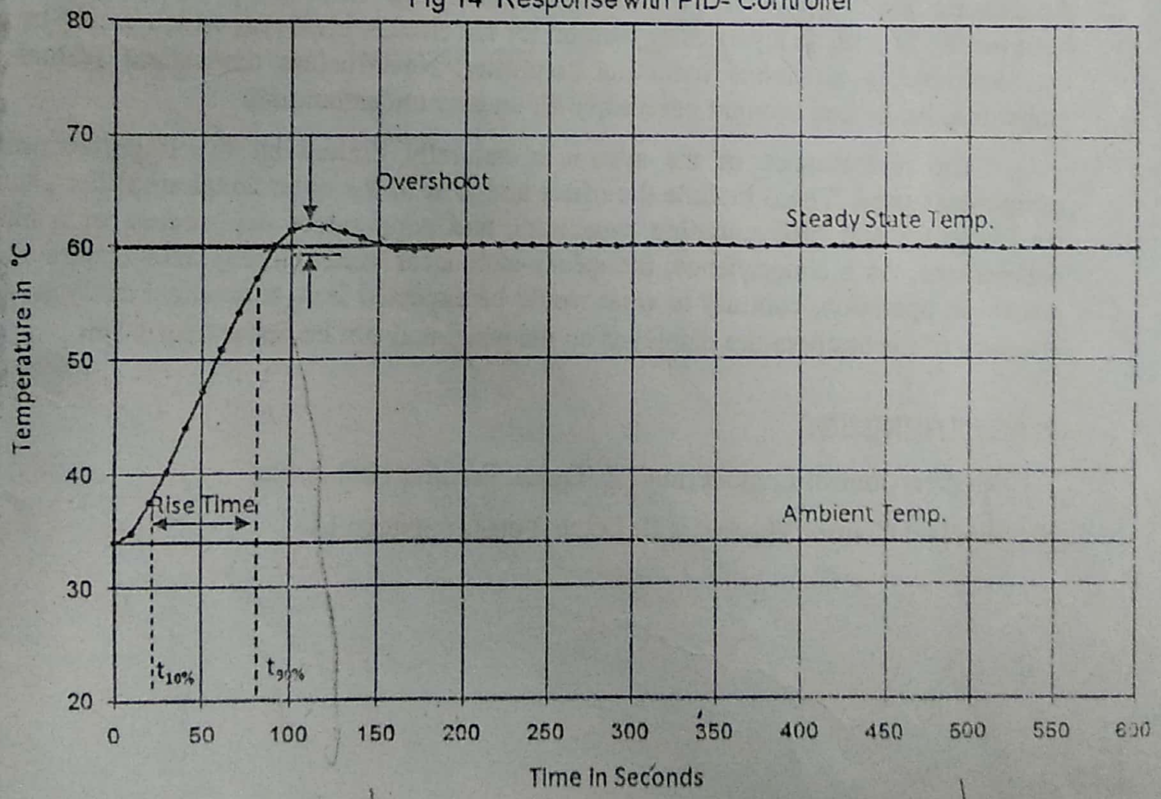


Fig 14 Response with PID- Controller



(iii) *P-I-D Control* : $K_P = \left(\frac{1.2}{K}\right) \cdot \frac{T_1}{T_2} = \left(\frac{1.2}{116.0}\right) \times \frac{255}{15} = = 0.1758$

This gives a P-coefficient setting of 88%

$T_I = 2.0\ T_2 = 2.0 \times 15 = 30$ sec;

$K_I = 1/12 = 1/30 = 0.033$ sec

I-setting = $(0.033/0.036) \times 100 = 0.916 \times 100 = 91.6\% \approx 92\%$

$K_D = T_D = 0.5\ T_2 = 0.5 \times 15 = 7.5$ sec.

$K_{D\,max.} = 23.5$ sec., {see Eq. 3}

D-setting = $(7.5/23.5) \times 100 = 0.319 \times 100 = 32\%$

The Temperature vs Time plot is shown in Fig.14.

(c) Results : Fig. 12-15 show the graph of temperature vs. time using P, PI, PID controllers with above coefficient settings, for a set temperature of 60.0°C and also the realy control. A comparison of the graphs with that obtained using P control only should reveal the effectiveness of I and D controls in reducing steady-state error and percentage overshoot.

Since our intereset in mainly in the transient part of the resposes as well as the final steady state value of the temperature, the graph may be drawn with break along the time axis as shown in Fig. 11-14. This would give an expanded view of the initial part of the responses for better clarity.

6. LIMITATIONS OF THE SYSTEM

It must be appreciated that this is a purely experimental model designed for studying the different control strategies available for controlling temperature. No effort has therefore been made to optimise a particular method for the circuits involved, which would be possible and desirable in an actual industrial controller. Nevertheless the salient features of the techniques have been brought out clearly for an easy understanding.

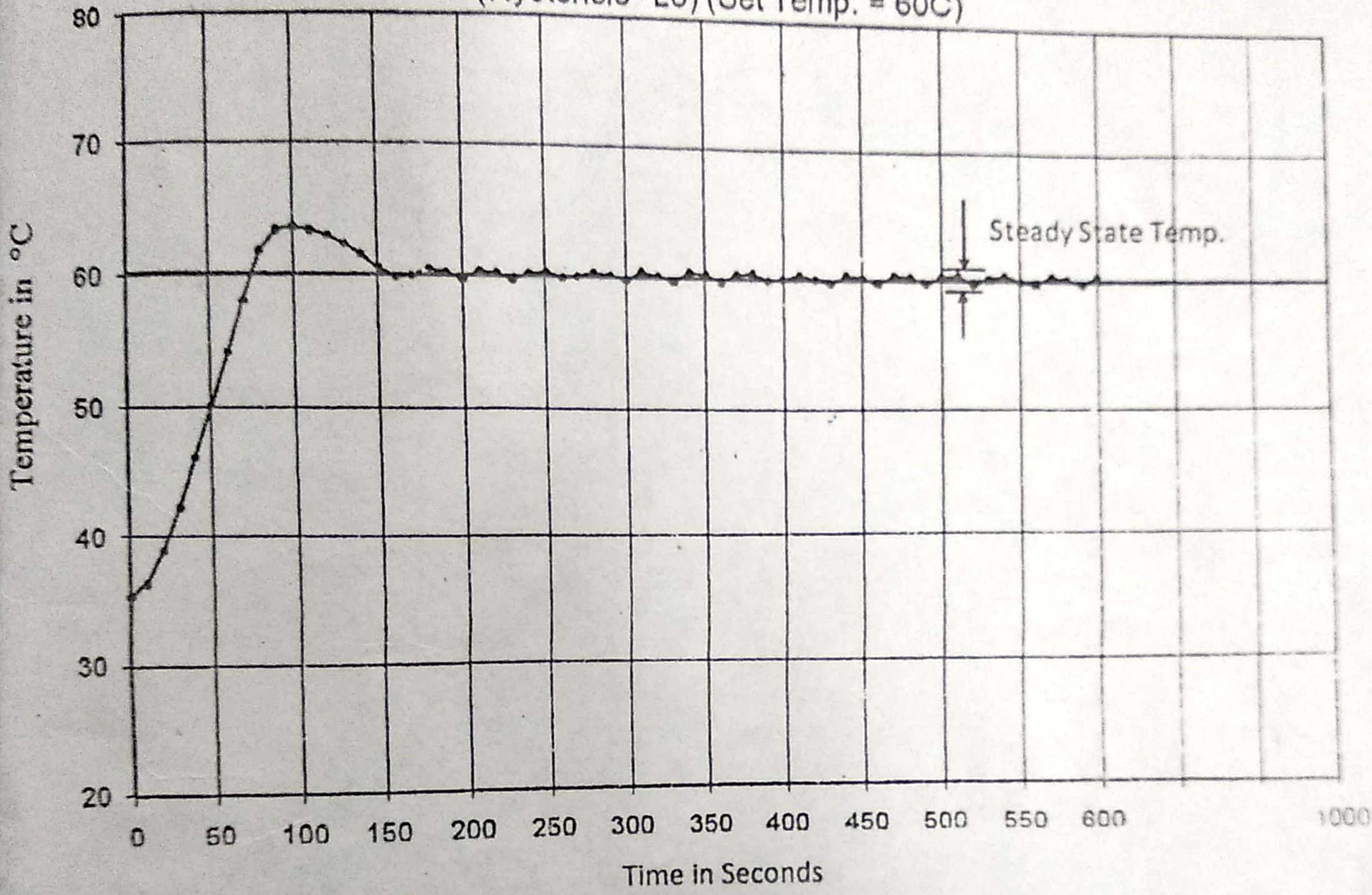
The performance of the system is naturally limited by the imperfections of the components used. These include the offset and drift in the operational amplifiers, leakage of the integrator and differentiating capacitors, and temperature dependence of a number of components. As a consequence, the steady-state error is not exactly zero inspite of Integral control in operation, contrary to what would be expected from theoretical analysis. Also, the accuracy of the temperature displayed on the panel may not be better than ± 5%.

7. REFERENCES

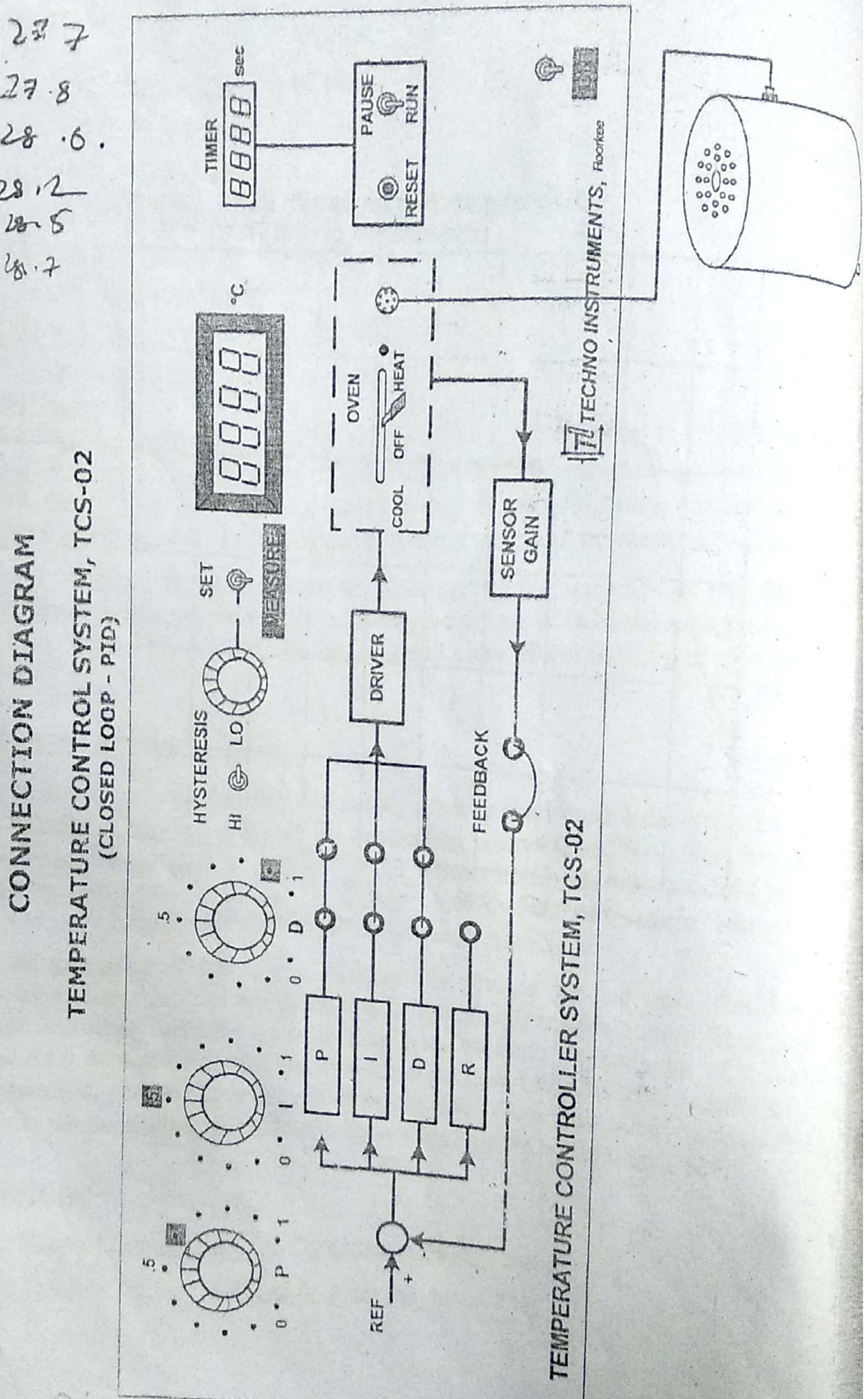
[1] 'Modern Control Engineering', K. Ogata, Prentice Hall India.

[2] 'Applied Control Theory', J.R. Leigh, Peter Pergamon Ltd.

Fig 15 Response with Relay -Controller
(Hysterisis - Lo) (Set Temp. = 60C)



room temp : 25.8
10s → 26.4
10s → 26.9
10s/- 27.3
10/s - 27.7
27.8
28.6.
28.2
28.5
28.7



0.5 → 29.1