**TEMPERATURE**

**OBJECTIVE**

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

**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.

**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.

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 analyzed 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

Where, = rate of heat flow in Joule/sec.

= temperature difference in °C

= Constant

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

Which is analogous to the V-I relationship of a capacitor, namely . 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

With the initial condition. Now, taking Laplace transform with zero initial condition

………………………………… (1)

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

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:

1. 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 tem,, to be included in the transfer function, where is the time lag in seconds.
2. Unlike the equivalent electrical circuit of Fig. 2, the heal 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.
3. Referring to the closed loop oven control system of Fig. 3, it may be seen that in the steady state the error is given as

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 becomes negative, the heat input is cut off and the oven must cool down slowly.

The temperature T therefore oscillates around the nominal value.

**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.

**ON-OFF or Relay type controllers,**

This is 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 behavior of this controller is shown in Fig. 4. The two positions of the controller are and H is the hysteresis or differential gap.

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.

**Proportional** **controller**

It is simply an amplifier of gain 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, of 20.

**Proportional**-**Integral** (**Pl**) **controller**:

Mathematical equation of such a controller is given by

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, 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 (1) block in the present system is realized with a circuit shown in Fig.8 and has a transfer function

…………………………………. (2)

The integral gain is therefore adjustable in the range 0 to 0.024 (approx.). Due to the tolerance of large capacitances, the value of is approximate.

**Proportional-Integral-Derivative (PID) controller:**

Mathematical equations governing the operation of this controller is as

So that in the Laplace transform domain,

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 realized with the circuit of Fig. 9. This has a transfer function

(approx.)

The derivative gain is therefore adjustable in the range 0 to 20 approximately. Again, the approximation is due to the higher tolerance in the values of large capacitances.

PID controller is one of the most widely used controller because of its simplicity. By adjusting its coefficients and 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.



**FIG.10. OPEN LOOP RESPONSE OF THE OVEN**

**Temperature** **Measurement**

The oven temperature can be sensed by a variety of transducers like thermistor, thermocouple, RTD and 1C 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 ADS90. Further, these sensors are linear and have a good sensitivity, viz.. 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.

**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 15-20 minutes. This would limit the number of runs to about four in a usual laboratory class. The experiments suggested could be completed in about 6-8 hours.

**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.

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 S2). 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 S1 to 'WAIT', S2 to 'SET' and open 'FEEDBACK' terminals.

Connect P output to the driver input and switch ON the unit.

Set P potentiometer to 0.5 which gives.

Adjust reference potentiometer to read 5.0 on the DVM.

This provides an input of 0.5 V to the driver.

Put switch S2 to the 'MEASURE' position and note down the room temperature.

Put switch S1 to the 'RUN' position and note temperature readings every 15 sec. till the temperature becomes almost constant.

Plot temperature-time curve on a graph paper.

Referring to Figure calculate T1 and T2 and hence write the transfer function of the oven including its driver as G(s) = K exp(-sT2)/(1+ sT1), with T in °C.

**ON-OFF Controller**

Keep switch S1 to 'WAIT' position and allow the oven to cool to room temperature. Short 'FEEDBACK' terminals.

Keep switch S2 to the 'SET' position and adjust reference potentiometer to the desired output temperature, say, 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 S2 to 'MEASURE' and S1 to 'RUN' position. Read and record oven temperature every 15/30 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.

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**FIG. 12. RESPONSE WITH P-CONTROLLER**

**Proportional Controller**

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

Starting with a cool oven, keep switch S1 to 'WAIT' position and connect P output to the driver input. Keep R, D and I outputs disconnected. Short 'FEEDBACK' terminals.

Set P potentiometer to the above calculated value of, keeping in mind that the maximum gain is 20. The measurement and interpretation ofand P-control potentiometer setting needs some explanation here. The formula for above is for a unity feedback system and has the dimension of. In the present unit a temperature sensor having sensitivity of is used between oven output and controller input. Thus, the calculated above will need to be divided by 0.01 to obtain the P-control potentiometer setting. Have dimensions of 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.

Keep switch S1 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.



**FIG. 13. RESPONSE WITH PI-CONTROLLER**

**Proportional**-**Integral** **Controller**

Ziegler and Nichols suggested the value of KP and KI for P-I controller as

Starting with a cool oven, keep switch S1 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 respectively, keeping in mind that the maximum value of is 20 and that of is 0.024.

Select and set the desired temperature to say C.

Keep switch S1 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.



**FIG. 14.RESPONSE WITH PID CONTROLLER**

**Proportional**-**Integral**-**Derivative** **Controller**

Ziegler and Nichols suggest the values of KP, KD and KI for this controller as

Starting with a cool oven, keep switch S1 to 'WAIT' position and connect P, D 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 keeping in mind that the maximum values for these are 20, 0.024 and 23.5 respectively.

Select and set the desired temperature, say

Switch S1 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.

**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 the optimum values of 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 a sensitivity of.

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.

**TYPICAL** **RESULTS**

Open - loop measurement: The constant K for oven plus driver is given by

From the graph between temperature and time Fig.11, the final oven temperature for an input of 0.5 volt is 68°C. Hence, K=53.2/0.5=106.4°C/V. With reference to Fig.10. , as measured from the open-loop graph are (Note that these values may differ from unit to unit).

Calculation for: The coefficient settings according to Ziegler and Nichols are different for different types of control. The calculations for them are illustrated below.

With temperature-sensor sensitivity of 10 mV/°C and maximum gain of P-amplifier as 20, actual .Hence P-setting required for proportional control is 70%. The Temperature vs Time plot is shown in Fig.12.

Hence, P-setting required = 63%.

I-setting = (0.0144/0.0244)x100=0.59x100=60%

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

This gives a P-coefficient setting of 84%

I-setting= (0.0238/0.0244)x100 = 0.975x 100 = 98%

D-setting = (10.5/23.5)x100 = 0.447x100 = 45%

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

Results: Fig. 12-15 show the graph of temperature vs. time using P, PI, PID controller with above coefficient settings, for a set temperature of 60.0°C and also the relay 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.

**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 optimize 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 in spite 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.