CHAPTER 3

CLOSED LOOP SIMULATION WITH CONVENTIONAL CONTROL SCHEMES

3.1 GENERAL

The control of the exit air temperature of AHS is an important aspect in a drying process. The control objective is to regulate the temperature of the exit air by varying the voltage input to the heater with the help of a thyristor controller. Thus, in the present work, the controlled variable is the exit air temperature, $T_0$, and the manipulated variable is the voltage input to the heater. The controller to be designed has to maintain $T_0$ at the desired set value by adjusting the heater input. In the subsequent sections, the closed loop simulation with PI, PID and MPC schemes are presented.

3.2 CLOSED LOOP SIMULATION WITH PI SCHEME

3.2.1 PI controller design

The PI controller is designed based on the process parameters determined from the dynamic response of AHS obtained through open loop experimental studies using reaction curve method. Accordingly, the process parameters obtained are as follows: The process gain, $K_p = 0.2 \, ^\circ C \, v^{-1}$, dead time, $\theta = 16$ sec.
and the time constant $\tau = 225$ sec. The PI controller is represented in the velocity form of discrete algorithm (Appendix 7) given by equation (3.1).

$$\Delta U_k = K_c \left[1 - T/T_R\right] e_k - K_c e_{k-1}$$  \hspace{1cm} (3.1)

The PI controller parameters obtained from Ziegler Nichol’s tuning (Harriott 1972) are presented in Table 3.1.

Table 3.1 PI Controller Parameters (Ziegler Nichols’s Tuning Rule)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_c$</td>
<td>$50.67 \degree C \ v^{-1}$</td>
</tr>
<tr>
<td>$T_R$</td>
<td>52.35 sec</td>
</tr>
</tbody>
</table>

3.2.2 Simulation Studies

After designing the PI controller, the actual exit air temperature of AHS is determined using the equation (3.2). The determination of the constants of the equation (3.2) are presented in the Appendix 8.

$$c(t) = 0.9955 \times c(t-1) + 0.0009 \times u(t-17)$$  \hspace{1cm} (3.2)

The performance of the PI controller for set-point change in the exit air temperature is studied and displayed in Figure 3.1(a). The corresponding changes in the manipulated heater voltage are presented in Figure 3.1(b). The PI controller shows negligible overshoot (0.2%). The rise time is high (95 sec) and there is no offset. A 2% white noise is introduced in the measurement level and
Figure 3.1(a) Closed loop response of AHS with PI controller for set-point change in exit-air temperature.
Figure 3.1(b) Changes in the manipulated heater input for the PI scheme (Fig. 3.1(a))
the closed loop behaviour was observed and presented in Figure 3.2 (a). The corresponding changes in the manipulated heater voltage are presented in Figure 3.2(b). The values along the y-axis represent the deviations from the operating point.

3.3 CLOSED LOOP SIMULATION WITH PID SCHEME

3.1 PID Controller design

A PID controller scheme is designed using the process parameters determined from the dynamic response of AHS by reaction curve method. The parameters (Table 3.2) of the PID controller are obtained using Ziegler Nichol’s tuning rule. The PID controller is represented in the velocity form of discrete algorithm (Appendix 7) given by equation (3.3).

\[
\Delta U_k = K_c \left[ 1 + \frac{T}{T_r} + \frac{T_d}{T} \right] e_k - K_c \left[ 1 + 2 \frac{T_d}{T} \right] e_{k-1} + K_c (T_d/T) e_{k-2}
\]  (3.3)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_c$</td>
<td>67.56 °C v$^{-1}$</td>
</tr>
<tr>
<td>$T_r$</td>
<td>31.41 sec</td>
</tr>
<tr>
<td>$T_d$</td>
<td>7.85 sec</td>
</tr>
</tbody>
</table>
Figure 3.2(a) Closed loop response of AHS with PI controller for set-point change in exit-air temperature (under 2% measurement noise).
Figure 3.2(b) Changes in manipulated heater input for the PI controller (Fig. 3.2(a)).
3.3.2 Simulation studies

After designing the PID controller, the actual exit air temperature of AHS is determined using the equation (3.2). The performance of PID controller for set-point change in the exit air temperature is studied and displayed in Figure 3.3 (a). The corresponding changes in the manipulated heater voltage are presented in Figure 3.3 (b). The controlled output shows 15% overshoot in the exit air temperature. At the same time, there is decrease in the rise time (70sec) due to derivative action. A white noise of 2% is introduced in the measurement level and the closed loop behaviour, thus obtained, is presented in Figure 3.4 (a). The corresponding changes in the heater voltage are presented in Figure 3.4 (b).

The performance of both PI and PID controllers under unmeasured disturbance is not satisfactory. To alleviate this drawback, an MPC scheme is designed for the temperature regulation of AHS.

3.4 CLOSED LOOP SIMULATION WITH MPC SCHEME

3.4.1 Development of control law

The Dynamic Matrix Control (DMC) scheme is a design technique emanating from MPC strategy. The DMC algorithm minimises an objective function to find out the future moves of the manipulated variable (Luyben 1990). The number of prediction horizons, NP are chosen such that the dynamic response of AHS, shown in Figure 2.2, reaches 90 to 95% of its final value. The number of control horizons, NC are chosen as 50% of NP value. If there are changes in the input over NC steps, the output for the next NP steps would be given as in equation (3.4).
Figure 3.3(a) Closed loop response of AHS with PID controller for set-point change in exit air temperature.
Figure 3.3(b) Changes in the manipulated heater input for the PID controller (Fig. 3.3(a)).
Figure 3.4(a) Closed loop response of AHS with PID controller for set-point change in exit air temperature (under 2% measurement noise).
Figure 3.4(b) Changes in the manipulated heater input for the PID controller (Fig. 3.4(a)).
\[
\begin{bmatrix}
y_1 \\
y_2 \\
y_3 \\
\vdots \\
y_{NP}
\end{bmatrix} =
\begin{bmatrix}
b_1 & 0 & \ldots & 0 \\
b_2 & 0 & \ldots & 0 \\
b_3 & 0 & \ldots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
b_{NP} & b_{NP-1} & \ldots & b_{NP+1-NC}
\end{bmatrix}
\begin{bmatrix}
\Delta u_1 \\
\Delta u_2 \\
\Delta u_3 \\
\vdots \\
\Delta u_{NC}
\end{bmatrix}
\]

(3.4)

\[Y = B \times \Delta U\]  

(3.5)

where \(Y\) is a column matrix with dimension \(NP \times 1\) and \(B\) is a matrix with dimension \(NP \times NC\). The matrix \(\Delta U\) is also a column matrix with dimension \(NC \times 1\). Now, a new \(NP \times NC\) matrix \(A\), is defined and set equal to matrix \(B\), above such that the elements \(a_{ij}\) of the matrix \(A\) are related to the elements of \(B\) through the relation \(a_{ij} = b_{i+j-1}\).

Thus we have,

\[y_i = \sum a_{ii} \Delta u_i\]  

(3.6)

In other words,

\[y_i = \sum b_{i+j-1} \Delta u_i\]  

(3.7)

where, \(b_{ii}, i = 1\) to \(NP\), are the step response coefficients.

The above equation gives how \(\Delta u_i\) affects the \(i^{th}\) output \(y_i\), using step response coefficients, \(b_{i+j-1}\). If there have been \(NP\) changes in the manipulated variable during the previous \(NP\) steps and if no other changes were made, the output would have changed in the future state because of the "old" changes in the input. If these old changes in the input are \((\Delta u_i)^{old}\), then the response to these old changes is called open loop response, \(y_{old}\). At the current sampling instance \((0^{th}\) state), the actual output of the process, \(y_0\) can be measured. The difference
between the $y_{o \text{mea}}$ and predicted value at the current sampling instant is added to the predicted value at the $i^{th}$ sampling period to get a better prediction of the open loop response. Knowing the values of NP, NC, $b_i$ and the detuning factor, $f$, the values of $(\Delta u_i)^{\text{new}}$ can be found. The closed loop response $y_{c,i,j}$ can be written as the sum of the open loop response $y_{o,i,j}$ and the effect of the future changes in the manipulated variables $(\Delta u_i)^{\text{new}}$.

DMC algorithm has the following steps: (Luben 1990)

1. Calculate

$$Y_{o,i,j} = y_{o \text{mea}} + \sum [b_{i+j-1} - b_{i-1}] (\Delta u_i)^{\text{old}}$$

(3.8)

2. Calculate NC values of future changes in the manipulated variable

$$(\Delta u_i)^{\text{new}} = [A^TA + f^2I] A^T. [Y]$$

(3.9)

where $A$ is NP by NC matrix with coefficients $a_{il}$

3. Implement the first change $(\Delta u_1)^{\text{new}}$

4. At the next sampling period, measure the controlled variable to get a new value of $Y_{\text{mea}}$ and repeat the above steps.

The closed loop response is given by

$$Y_{c,i,j} = Y_{o,i,j} + \sum a_{il} (\Delta u_i)^{\text{new}}$$

(3.10)

The block diagram representation of closed loop control of AHS using MPC scheme is shown in Figure 3.5. The plant is represented by the first order with dead time model. From the real time open loop studies, the step response coefficients are determined. These coefficients are used to formulate the linear
Figure 3.5 Block diagram representation of closed loop control of AHS using MPC scheme.
convolution model. This model is used in parallel to the plant to predict the future open loop response. Then the open loop response is predicted using equation (3.8). The change in the final control element is derived using equation (3.9). The detuning factor, \( f \), prevents large changes in the manipulated variables. With an increase in the value of \( f \), the system becomes less underdamped and more robust. The closed loop response is obtained from equation (3.10). The controller parameters of DMC scheme are presented in Table 3.3.

### Table 3.3 Controller Parameters of MPC Scheme

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>NP</td>
<td>50</td>
</tr>
<tr>
<td>NC</td>
<td>25</td>
</tr>
<tr>
<td>( f )</td>
<td>0.5</td>
</tr>
</tbody>
</table>

#### 3.4.2 Simulation Studies

After synthesising the control law, the performance of DMC scheme for set-point tracking is studied and presented in Figure 3.6 (a). The corresponding changes in the manipulated heater voltage are presented in Figure 3.6 (b). The closed loop behaviour of the DMC strategy in the presence of 2% measurement noise is shown in the Figure 3.7 (a). The changes in the manipulated heater voltage are shown in Figure 3.7 (b). Under normal conditions, DMC scheme shows higher overshoot with small rise time. There is a steady state error of 5% in the exit air temperature. However, under the presence of measurement noise,
Figure 3.6 (a) Closed loop response of AHS with MPC scheme for set-point change in exit-air temperature.
Figure 3.6(b) Changes in the manipulated heater input for the MPC scheme (Fig. 3.6(a)).
Figure 3.7 (a) Closed loop response of AHS with MPC scheme for set-point change in exit-air temperature (under 2% measurement noise)
Figure 3.7 (b) Changes in the manipulated heater input for the MPC scheme (Fig. 3.7(a)).
the controller settles down quickly. There are no oscillations in the controlled output. This would increase the actuator’s life.

3.5 COMPARISON OF PERFORMANCES OF PI, PID AND MPC SCHEMES

After implementing all the three controllers, their closed loop behaviour are compared. The comparison of time-domain specifications of the three controllers are presented in Table 3.4. The three controllers are evaluated using error integral criteria. The Table 3.5 presents the comparison of the performance indices of the three control schemes.

Table 3.4 Comparison Of Time Domain Specifications (PI, PID and MPC Schemes)

<table>
<thead>
<tr>
<th>Controller</th>
<th>%Overshoot</th>
<th>Rise time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI</td>
<td>0.2</td>
<td>95</td>
</tr>
<tr>
<td>PID</td>
<td>15</td>
<td>70</td>
</tr>
<tr>
<td>MPC</td>
<td>44</td>
<td>40</td>
</tr>
</tbody>
</table>

Table 3.5 Comparison of Performance Indices (PI, PID and MPC Schemes)

<table>
<thead>
<tr>
<th>Controller</th>
<th>ISE</th>
<th>ITAE</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI</td>
<td>44.02</td>
<td>3069.74</td>
</tr>
<tr>
<td>PID</td>
<td>35.10</td>
<td>2431.69</td>
</tr>
<tr>
<td>MPC</td>
<td>34.13</td>
<td>2976.91</td>
</tr>
</tbody>
</table>
3.5 SUMMARY

The conventional control schemes namely, PI, PID and MPC schemes are implemented on the AHS by simulation. The PI and PID controllers are represented in velocity form and tuned using Ziegler Nichol's tuning rule. The design procedure of both the schemes are simple but their performance under unmeasured disturbance is not satisfactory. The MPC scheme namely DMC is implemented using time-domain step-response model. It performs satisfactorily under the presence of measurement noise. However, the computational effort increases with increase in NP and NC values. Also, without an *a priori* model, it is difficult to develop the MPC scheme. In the subsequent chapter, the implementation of ANN based MPC scheme is discussed where the time-domain step-response model is replaced by an ANN model.