CHAPTER 6: CLOSED-LOOP DYNAMICS

6.1 INTRODUCTION

A closed-loop system normally has a controller together with other hardware components, but the key component here is the controller. The closed-loop response also depends on the transfer function of the system and on the nature of the change. Normally the change is divided into two, namely, set point and disturbance. If there is a set point change, the feed back controller acts in such a way as to keep the ultimate response as close as possible to the changing set point. On the other hand, if there is any form of disturbance but the set point remains the same, then the feed back controller tries to eliminate the impact of the disturbance or load changes and keeps the ultimate response at the desired set point. However, the presence of other hardware components could lead to oscillatory behavior and unstable systems. Therefore it is important to design controller systems that will eliminate all the instability.

6.2 CONTROLLER TUNING

Performance of feedback controllers depends on the values of their chosen parameters. If these parameters are properly chosen, they offer the highest flexibility to achieving the desired controlled response and stability. The process of choosing these parameters is known as controller tuning. There are three general approaches that are used in the controller tuning process. These are; Time integral performance criteria, Use of simple criteria such as one quarter decay ratio and Semi-empirical rules, which have been proven in practice. In this section use is to be made of the semi-empirical rules to tune the controller parameters on some of the examples in the exercises. The two main semi-empirical rules used here are those of Cohen and Coon also known as the process reaction curve method derived from open-loop systems. The other is the Ziegler and Nichols method derived mainly from closed-loop systems.

The Cohen-Coon tuning method requires the response of an open-loop system to an input step change. The response generates a process reaction curve, which can adequately be represented by a first order system with dead time. From the generated curve, the static gain, the time constant and the dead time can all be estimated and used in the rules summarized in Table 6.1 to find the controller parameters.

The Ziegler-Nichols is based on frequency response analysis. It requires the generation of two key process parameters from a closed-loop system with a proportional controller. The two parameters are obtained by increasing the gain of the proportional controller until the closed-loop system exhibits sustained oscillations of constant amplitude. The period of these oscillations is defined as the ultimate period (P_u). The controller gain at which these oscillations occur is referred to as the ultimate gain (K_u). It is these two parameters that are used in conjunction with the equations of Table 6.2 to arrive at the tuned parameters for use in the controller.

These two semi-empirical methods will be used to calculate Controller parameters for a PID controller on the Evaporation process. The values obtained will be compared with each other and used to run the processes mentioned in order to draw conclusions on the superiority (if any) of one method over the other.

Table 6.1 Cohen-Coon Formulas.[16]

Controller Type	Controller Gain Kc	Reset time τ_I	Derivative Time τ_D
P	$K_c = \left(\frac{1}{K_p}\right)\left(\frac{\tau_p}{t_d}\right)\left(1+\frac{td}{3\tau_p}\right)$		
PI	$K_c = \left(\frac{1}{K_p}\right)\left(\frac{\tau_p}{t_d}\right)\left(\frac{9}{10}+\frac{td}{12\tau_p}\right)$	$\tau_I = t_d\left(\frac{30+3t_d/\tau_p}{9+20t_d/\tau_p}\right)$	
PID	$K_c = \left(\frac{1}{K_p}\right)\left(\frac{\tau_p}{t_d}\right)\left(\frac{4}{3}+\frac{td}{4\tau_p}\right)$	$\tau_I = t_d\left(\frac{32+6t_d/\tau_p}{13+8t_d/\tau_p}\right)$	$\tau_D = t_d\frac{4}{11+2t_d/\tau_p}$

Let us now revisit Fig. 1.13. Using the same steps described in chapter 5, the open-loop response for the evaporator process could be used to obtain Table 5.5 and the values of this table (for the gain, time constant and the dead time) are plugged into the equations of Table 6.1 to obtain the Cohen-Coon controller parameters. Another way of obtaining the open-loop parameters of Table 5.5 is to run the single closed-loop module in an open-loop mode fashion as discussed in the following sections.

Table 6.2 Ziegler-Nichols Formula [16]

Controller Type	Controller Gain Kc	Reset time τ_I	Derivative Time τ_D
P	$K_c = 0.5K_u$		
PI	$K_c = 0.45K_u$	$\tau_I = \dfrac{P_u}{1.2}$	
PID	$K_c = 0.6K_u$	$\tau_I = \dfrac{P_u}{2}$	$\tau_D = \dfrac{P_u}{8}$

Revisit Fig. 1.13 of chapter one. Using the main menu of this figure, choose the Forced Circulation Evaporator to get Fig. 1.16, and then from this menu choose the second item (Single-loop control Evaporator) to get Fig. 6.1.

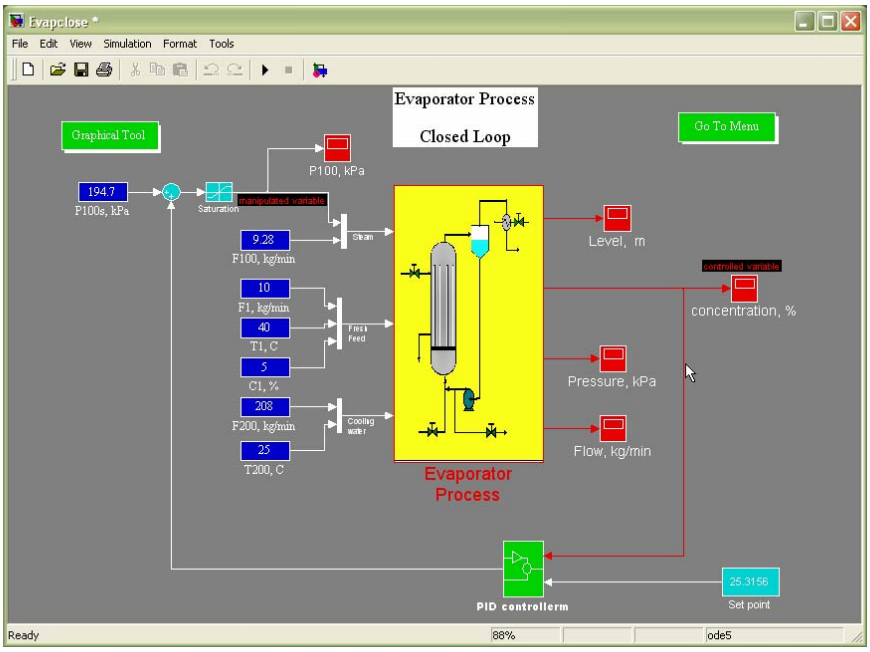

Fig. 6.1 Process flow sheet of closed-loop evaporator process.

This figure represents the closed-loop set up for the evaporator process. Notice the addition of two new color codes different from the previous figures. The light green color code is the designation for the controller, in this case using a PID controller to control the outlet concentration of the evaporator process. The manipulated variable in this case is the feed steam pressure. The light blue color code represents that for the set point. The loop pairing is chosen for demonstration purposes. The user can simply reconfigure the control loop to link any output to any input presented in the module.

6.2.1 Selecting the Coon and Cohen Parameters (CC)

Should there be a need for the open-loop parameters, the reader can simply run the simulation open-loop mode. To do so, double click the PID controller Box (green Box) and enter zero for all controller parameters as shown in Fig. 6.2.

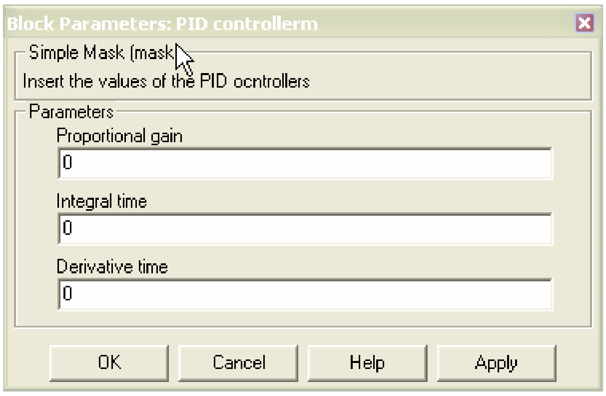

Fig. 6.2 Block Parameter for changing the PID controller settings

Afterward, inset a step change in the desired manipulated variable, say the steam pressure. The step change should be well known value as discussed in chapter 5. Here, the steam pressure was stepped by 1 kPa. Now, run the simulation the usual way and observe the simulation results for the controlled variable which is the product concentration. The plot of the response of the controlled variable is shown in the designated scope box given in Fig. 6.3. From this response calculate the open-loop parameters as discussed in chapter 5. The parameters calculated for this run, i.e. k_p, τ_p and t_d, are given in Table 6.3. Using these values in the Coon and Cohen formula of Table 6.2, the PID controller settings are calculated in listed in table 6.3

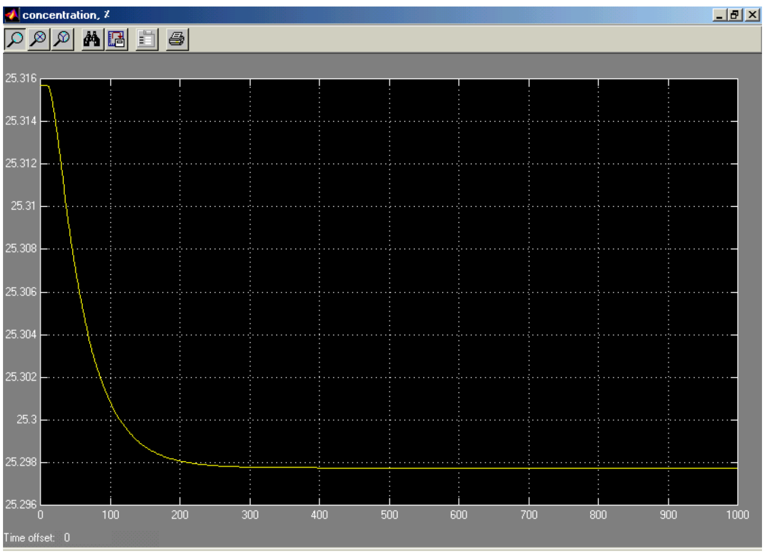

Fig. 6.3 Plot of Concentration with time for a unit step change in P_{100}

6.2.2 Ziegler and Nichols Method (ZN)

To obtain the parameters for the Ziegler-Nichols controller settings it is necessary to make two changes on the closed-loop process. First double click on the set-point icon of Fig. 6.1 to obtain Fig. 6.4. Change the set point value by highlighting the current value and type 26.3156 (set point change of unity).

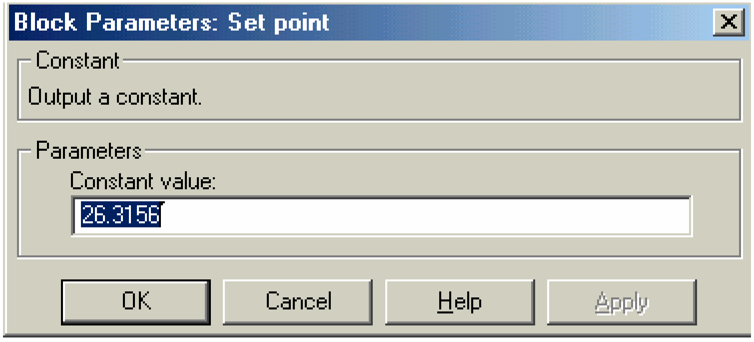

Fig. 6.4 Block Parameter for changing the set point

This way a set point change is introduced. Press the enter button to apply this change to the process. Now double Click the block parameter for the PID controller icon. For the proportional band enter the value –320 by highlighting the current value and typing on it. Then change the settings for the reset time and the derivative time to read zero as shown in Fig. 6.5.

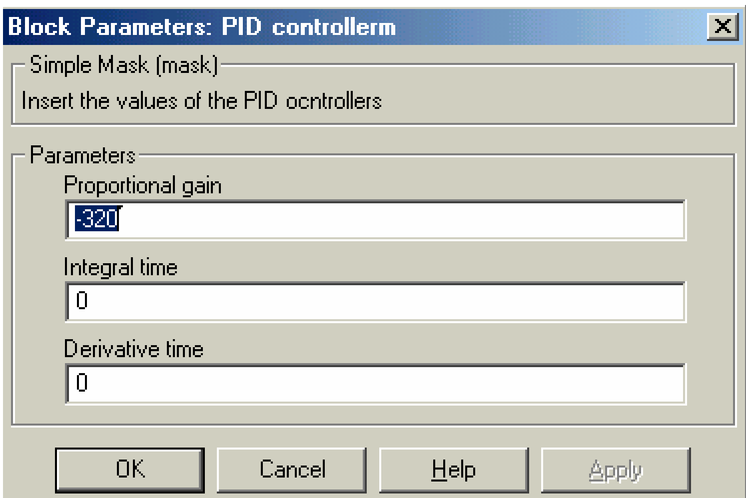

Fig. 6.5 Block Parameter for PID controller

Again, run the simulation the usual way and observe the result shown in Fig. 6.6. It portrays the response of a set-point change in concentration. As the concentration rises to the new set point, the response starts to oscillate, but slowly the oscillation dies away and begins to stabilize like a typical second order system discussed in the previous chapter. Since the oscillation is not a sustained one, it is necessary to make a second guess of the proportional gain. To do this, again double click the light green PID Controller representation to get Fig. 6.5. When you obtain the Block Parameter icon, change the value of the proportional gain from –320 to –350. Press the OK button and rerun the simulation. Observe the response on your screen similar to Fig. 6.7. Notice that this time around the concentration rises to the new set point but with a sustained oscillation of constant amplitude. This occurs only at the proportional band settings of (-350). The value then becomes our K_u. From the figure, the period of the sustained cycling is taken as the average time of two successive crests. To do this, the graph of Fig. 6.7 is expanded using the left top most icon to drag and enclose an expanded region with the help of the mouse to obtain Fig. 6.8. The time interval for a complete cycle was found to 94 seconds. Therefore P_u was assigned the value of 94 seconds. Using the equations of Table 6.2, the values for the controller parameters were then calculated and allocated to the PID block parameter. The calculated controller parameter values for the two methods are shown on Table 6.3.

Table 6.3 Estimated Parameter values for a PID controller

	Cohen-Coon Method	Ziegler-Nichols Method
t_d	10	
τ	61.62	
k_p	-0.018	
k_u	-	-350
P_u	-	94
k_c	-469.15	-206
τ_I	23.06	47
τ_D	3.532	11.75

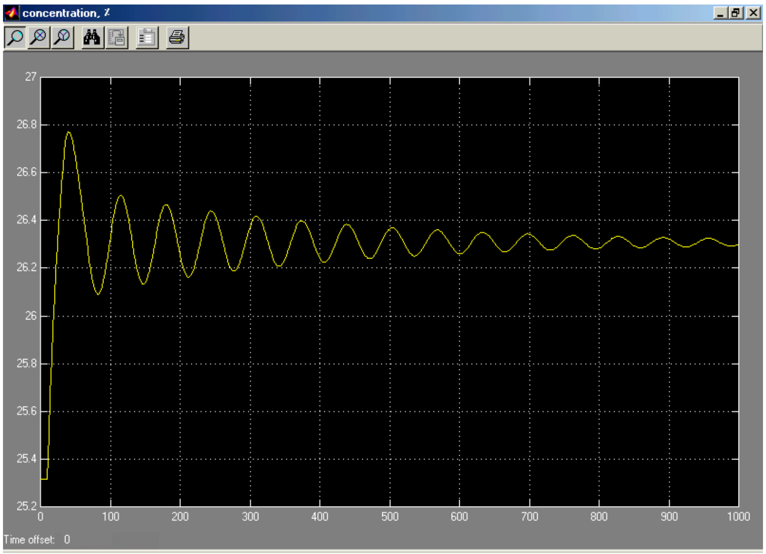

Fig. 6.6 System responses to set point change at gain of –320

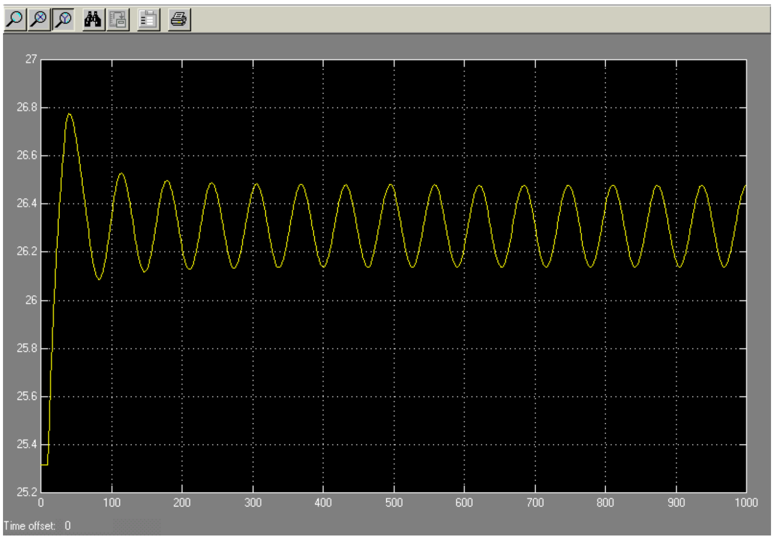

Fig. 6.7 System response to set point change at gain of –350

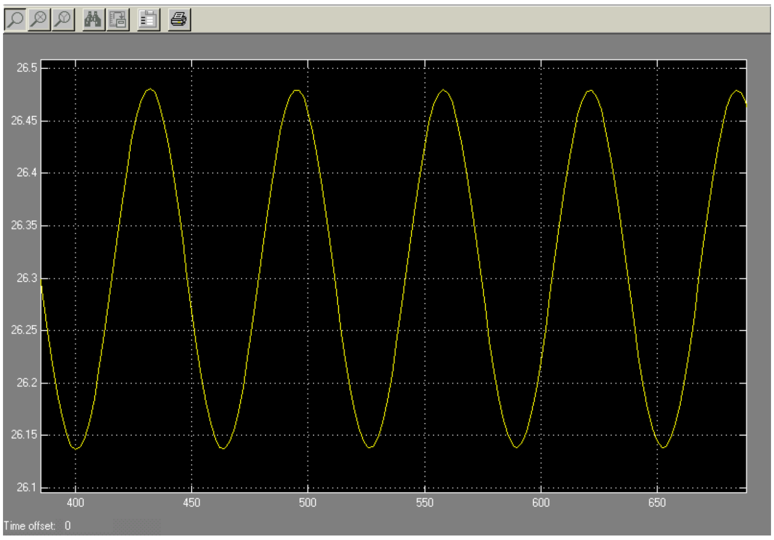

Fig. 6.8 Expanded Closed-loop response of concentration to set-point change

For the sake of rigid response, the controller parameters are re-defined in the software. The gain, k_c, is maintained as is, but the reset time is defined as integral gain $k_I = k_c/\tau_I$ and the derivative time as derivative gain $k_D = k_c\tau_D$. The modified parameters are listed in table 6.4. This issue is also discussed in chapter 1 section 1.4.3. It should be noted that the negative process gain and consequently proportional gain is the result of the increase/decrease behavior of the output-input (concentration-Steam Pressure) pair. The error signal used in the PID controller is based on the negative gain concept, i.e. $e = y^{sp} - y$. Therefore, if one wishes not to use negative values for the PID settings, which is the common practice in industrial application, then the definition of the error signal should be reversed. This modification can be easily handled, but we prefer to overlook it because we are simply dealing with simulations.

Table 6.4 Parameters used for the PID controller

	Cohen-Coon Method	Ziegler-Nichols Method
k_c	-469.15	-206
τ_I	23.06	47
τ_D	3.532	11.75
k_c/τ_I	-4.99	-4.39
k_c/τ_D	-406.2	-2421

6.3 TESTING THE ZN AND CC PID SETTINGS THROUGH SIMULATION

Using the values obtained in Table 6.3, the response of the process to set point changes and disturbances was tested. To do this the parameters to be used are recalculated to satisfy the requirement of the software. The values of these parameters are as given in Table 6.4. If these parameters are used and the response is unsatisfactory (highly oscillatory), the rule of thumb is to divide k_c by two and recalculate the other parameters by this new definition for the software. This is repeated until a satisfactory response is achieved.

For the set point change, double clicking on the set point icon of Fig. 6.1. The set point Block Parameter similar to Fig. 6.4 was obtained. The set point value was stepped from 25.316 to 26.316 by typing the new value. Press the enter button to complete this operation.

Now double click the PID controller icon to get the PID Block Parameter similar to Fig. 6.5. Then using the curser to highlight the parameter spaces enter the values for Proportional gain, Reset time gain and Derivative time gain for the Cohen-Coon settings as given in the last three rows of Table 6.4. Press enter and run the simulation to produce Fig. 6.9. Note in the response shown in Fig. 6.9, the CC proportional gain is divided by two because the original value produced very oscillatory response. Repeat the same steps for the Ziegler-Nichols settings to produce Fig. 6.10.

For the same set point change, Fig. 6.9 shows the product concentration rising to as high as 26.81 %. Then after two decays it settled at a steady state value of 26.316 %, showing no offset at all. The figure gave a rise time of about 60 seconds and a response time of close to 500 seconds. Fig. 6.10 produced almost a similar response. There was an overshoot but no decay, with a similar rise time to that of Fig. 6.9 but a faster response time of about 300 seconds. Not only did both settings produce similar responses but also the final steady state concentration values of 26.316 % for Cohen-Coon settings and 26.315 % for the Ziegler-Nichols settings are in very good agreement.

Judging from the responses depicted in Fig. 6.9 and 6.10, the only conclusion we can draw is that both methods provided excellent guesses for the values of the controller parameters.

In feedback control systems, controllers do not only act to keep responses as close as possible the desired set point changes but they also try to eliminate the impact of load changes from achieving the desired set point changes. Having already looked at how effectively our controller settings can cope with set point change, will an incoming disturbance sway the system from achieving the desired set point?

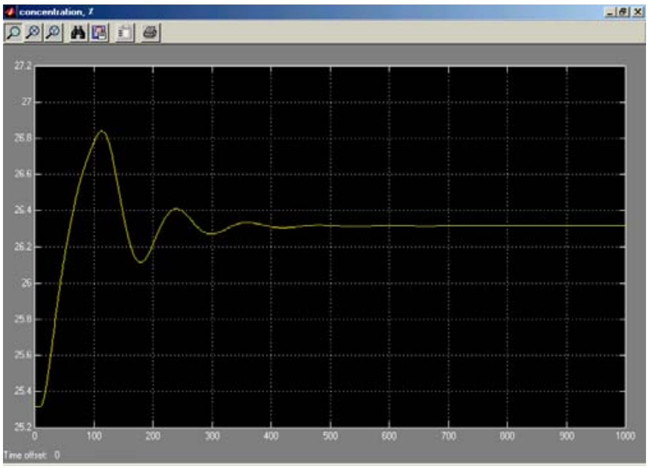

Fig. 6.9 Response of Evaporator Process to set point change using Cohen-Coon settings

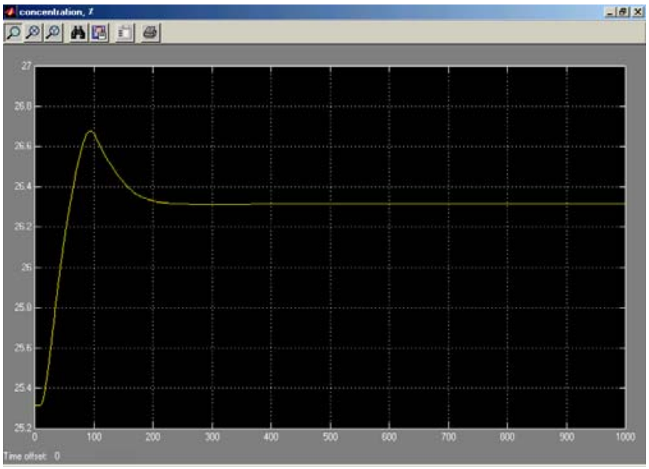

Fig. 6.10 Response of Evaporator Process to set point change using Ziegler-Nichol settings

To find out, the set point is maintained at its original value of 25.316 % and a disturbance introduced. Using Fig. 6.1, any of the input parameters (blue) can act as a disturbance. In this case the feed flow F_1 was chosen as the disturbance parameter. The flow was increased by a step change of 0.1 kg/min. This is done by double clicking on the F_1 icon to obtain a block parameter, from where the change is effected. Fig. 6.11 shows the open-loop response of the concentration to this disturbance. The open-loop response shows the concentration rising from the value of 25.316 % to a new steady state value of 26.36 % without limitation.

Fig. 6.12 and 6.13 show the controlled-responses to a 0.1 kg/min step change in $F_{1,}$ the feed flow rate. Note how in both responses, the concentration rapidly rose to approach the value of the open loop response but was quickly brought back to the set point value of 25.316 %. Just like the set point response, the two graphs of the closed-loop system showed responses different from that of the open-loop response. Note the similarity between the responses of Fig. 6.12 and 6.13. The response controlled by the ZN settings settled faster with a response time of about 250 seconds as against 500 seconds for the CC settings. In both cases, the disturbance swiftly increased the concentration (as shown in the beginning of the two graphs) but the controllers acted immediately to bring back the concentration to the set point value of 25.316 %.

As concluded earlier, the controller setting parameters of both Cohen-Coon and Ziegler-Nichols are equally effective.

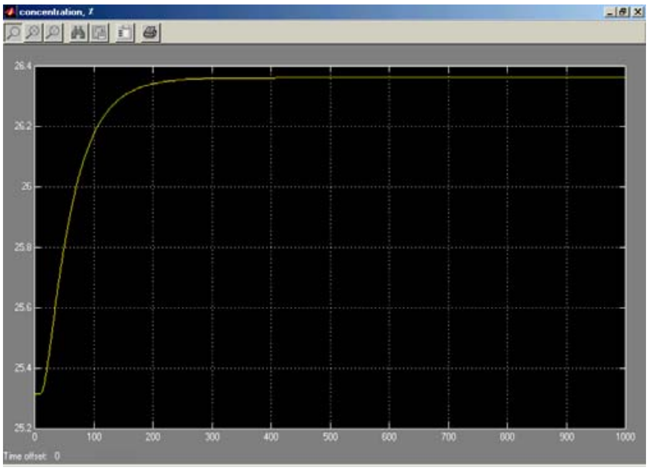

Fig. 6.11 Effect of Feed Flow disturbance on concentration in open-loop system

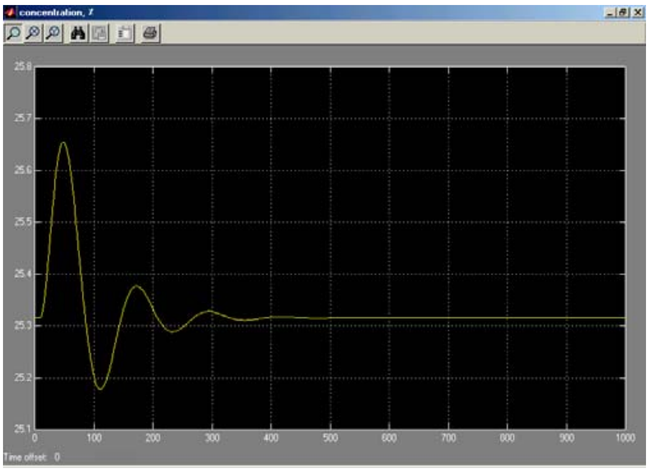

Fig. 6.12 Effect of feed flow disturbance on concentration in closed-loop system with Cohen-Coon settings

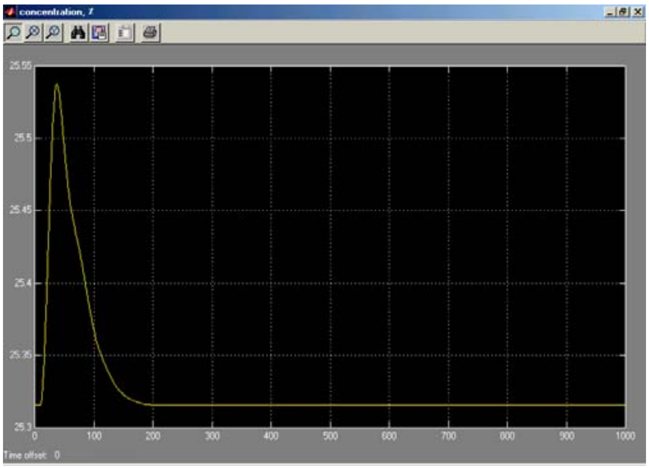

Fig. 6.13 Effect of feed flow disturbance on concentration in closed-loop system with Ziegler-Nichols settings

Remarks:

- The green box labeled "Go to menu" exists in the Simulink modules can be used to switch between the active Simulaink module with the current active sub menu.
- The green box labeled "graphical tool" exists in the Simulink modules can be used to trigger the plotting forum. The usage of the plotting forum is discussed in Appendix A.
- The Saturation block in the Simulink modules is used to limit the input values between upper and lower constraints. The user can change the default values for the constraints by simply clicking the saturation block and insert the new values.