CAHAPTER 5: OPEN-LOOP DYNAMIC ANALYSIS

5.1 INTRODUCTION

Of the seven systems that were defined in chapter 2, some follow the response of first order systems, others follow that of second order systems and yet others follow those of higher order systems. In this chapter we will practice the responses of some of these systems to input manipulations or disturbances. The response of an output parameter to changes in an input parameter with time is referred to as system dynamics. Normally the input parameter must behave in a certain defined fashion like step, ramp or sinusoidal.

As discussed in the previous chapter, dynamic analysis can be performed on an open-loop model as well as on a closed-loop model. For systems that mimic first order dynamics, system parameters like gain, time constant and dead time can be computed. These parameters are typical to system response to a step change in the input

Here, it is intended to perform the computations of these parameters using the PCLAB software described in chapter one. This will provide a hands-on application and will enable the reader to calculate the parameters that characterize the system.

5.2 FIRST-ORDER SYSTEM'S DYNAMIC ANALYSIS

In order to run the software, recall how you were instructed to lunch PCLAB in chapter one. Follow the same steps till you arrive at Fig. 1.13. Using the main menu of this figure, choose the Forced Circulation Evaporator to get Fig. 1.16, and then from this menu choose the first item on the menu to get Fig. 5.1.

Fig. 5.1 shows the open-loop configuration of an evaporator process. The blue colors to the left indicate input parameters. There are seven of them as defined in the chapter on modeling. These include temperature, flow rates, pressure and the concentrations defining the process. The red-colored items to the right represent the output parameters that are important to process performance. These four parameters represent the level, pressure, flow and concentration for the evaporator. The yellow portion in the middle, represent the process itself. Observe the green icons on the top left, one of which can take you back to the menu and the other to the interactive graphic tool. The coloration code is typical for all the case studies available in the software.

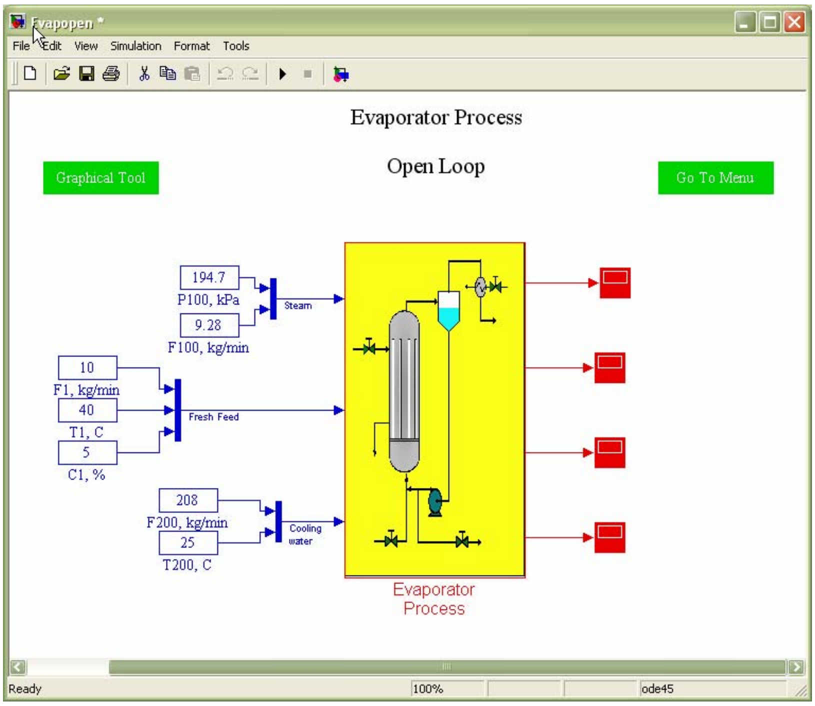

Fig. 5.1 Open Loop Evaporator Process menu

Double clicking on any of the input boxes, will give you access the seven inputs described earlier. For instance, if you need to make a change on the feed flow rate to the evaporator, double click on the third input box, designated by F_1. A Block Parameter window will appear, as shown in Fig. 5.2.

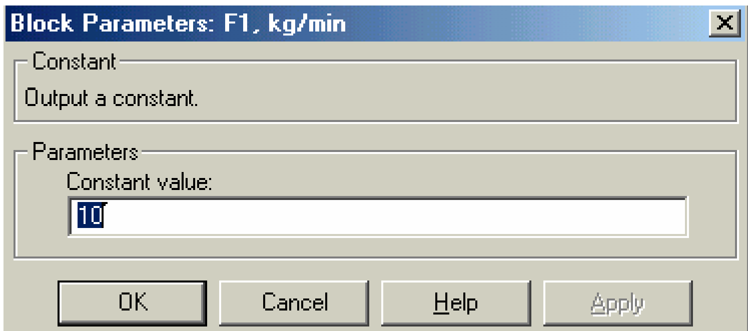

Fig. 5.2 Block Parameter window for feed flow input

Note that the current flow rate is 10 kg/min. To change this number simply use the mouse to highlight the number 10 by right clicking the mouse, hold and drag slightly to the right until the number 10 is fully highlighted, then release the mouse. Now type in the number 11 and press the OK button. This way, a 10% step increase in the inlet flow is attributed to F_1.

After effecting this change, press on the run icon or press simulation and then start. Note that in this case the 300 seconds allotted may not be enough, so click on Simulation then Parameters to get Fig. 4.3. Using the parameter menu option (see Appendix A.3), the stop time of this run should be changed from 300 seconds to 400 seconds. This will enable you to capture enough time for steady state operation. Use the same procedure as in changing the value of the Block Parameter window, change the run time from 300 to 400 seconds.

Now run the simulation by pressing on the start button in the simulation menu. After the 400 seconds has elapsed, the run will be complete. Click on the first output icon for level to view Fig. 5.4. The input has changed step-wise from 10 to 11 kg/min. The output response of the tank to this change is seen to rise steadily to attain a new steady state value. Observe the dead time represented by the flat portion of Fig. 5.4. In this region, the liquid height in the tank does not change with time. In order to read the numerical value of the time during which the system stayed flat, choose the first icon on the top left. Click this icon to allow you enlarge the scale and read the corresponding value on the x-axis as shown in Fig. 5.5. The enlarged portion shows the output response beginning after 10 seconds.

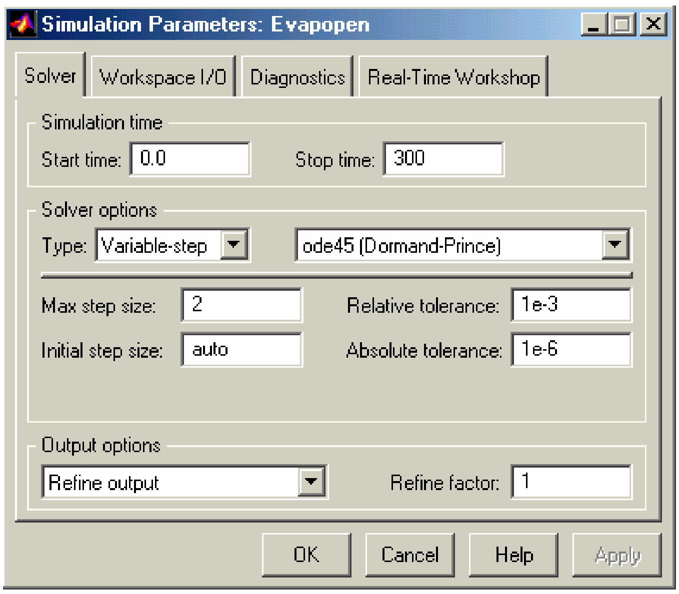

Fig. 5.3 Simulation Parameter window for stop time change

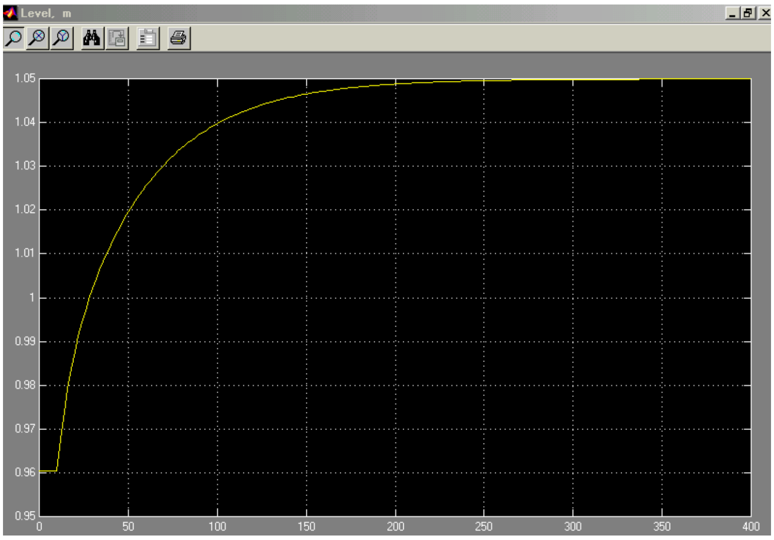

Fig. 5.4 Output showing the height of tank versus time

The region or period is known as the dead time during which the system does not respond to any input change or disturbance. One can then use the plot of Fig. 5.4 to calculate the process gain and the time constant as per (3.2) and (3.3).

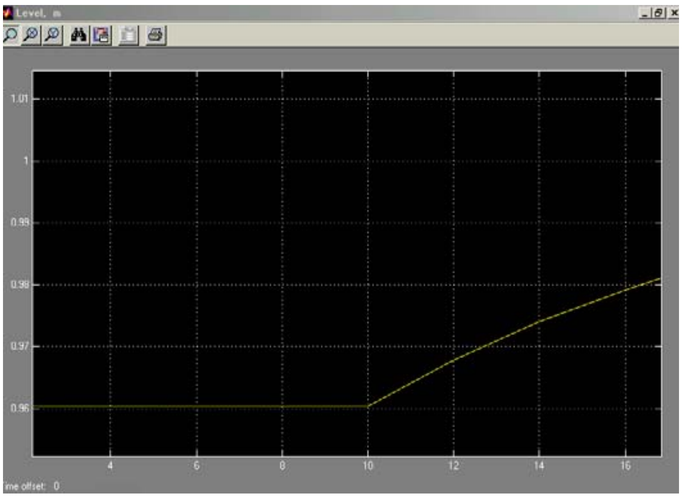

Fig. 5.5 Part of Output showing the height of tank versus time

The gain is defined as the change in output over the change in the input. This ratio is given by (5.1) for the liquid level

$$\frac{L_{ss} - L_0}{F_2 - F_0} \tag{5.1}$$

Where L_0, is the initial level of the tank and L_{ss} the final tank level. F_0 is the initial flow and F_2 the final flow.

$$\frac{1.05-0.961}{11-10}$$

This gives a value of 0.089 m-min/kg as the steady state gain. This value of the gain tells us that the for a ten percent change in the input flow rate the liquid level in the storage tank of the evaporator process will change by about 9 percent. Or for a unit step change in the input the tank level will increase by 0.089m.

Similarly, the time constant, τ_p, of the process can also be calculated from the graph. Refer to Fig. 3.1 to refresh your memory on some of these calculations. To do this calculation, the change in the output from the initial steady state to the final steady state value is calculated through (5.2) below.

$$\Delta L = L_{ss} - L_0 \tag{5.2}$$

ΔL, is calculated as (1.05-0.961) to get 0.089m. Now apply (5.3) to get the level of the tank at one time constant.

$$L_{\lambda P} = L_0 + 0.632 * \Delta L = 1.017248 \tag{5.3}$$

Double click on the first red output icon to revisit Fig. 5.4. Then use the icon with binoculars to auto-scale your plot. Now use the three zoom options to the top left of your plot to vary the y-axis until you read the height of 1.017m. Note the corresponding reading on the x-axis as 46.5 seconds. This gives you the value of λ_p for the process.

Now look at the output concentration icon by double clicking on it. Enlarge the graph to obtain Fig. 5.6. Notice how the concentration response falls rapidly to a new level of concentration as against the rise in the level of the tank. Using the same methodology, the gain for the concentration icon was calculated as –7.03 %-min/kg. This means for a unit step change in the input flow, the concentration falls seven percentage points. From this it is clear that process gains can be negative. The time constant was calculated as 17.05 seconds. The concentration response is therefore seen to be 2.7 times faster than the level response.

Table 5.1 was generated for all the four output parameters that were calculated using the procedure above. The graphs of the outputs were plotted separately and the values of K_p, , τ_p and t_d were all calculated from the graphs based on 10% change in the input flow.

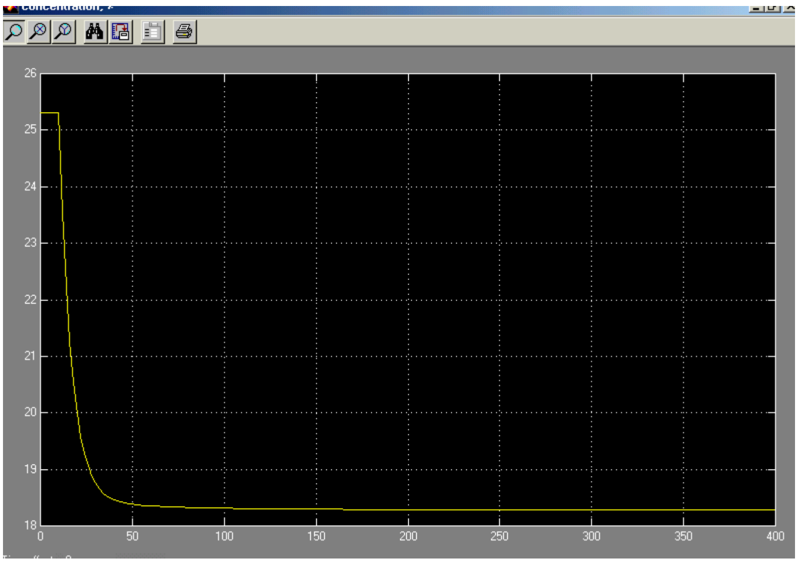

Fig. 5.6 Output showing the change in concentration with time

Table 5.1 Calculated values of the characteristic parameters for positive step change

	K_p	τ_p	t_d
Level	0.089	46.5	10
Concentration	-7.03	17.05	10
Pressure	-0.4472	46.2	10
Flow	0.033	37.5	0

If K_p is large the system becomes very sensitive and a small change in the input forcing function will result in a very large response. The output concentration has the largest gain and therefore a small change in the input flow will result in a big change in the concentration. On the other hand, The outlet flow has the smallest gain of 0.033, so if large changes are made in the input flow, the outlet flow will not be unduly disturbed. It is possible for the gain parameter to be negative. If it is negative, then the next steady state value will be lower than the initial steady state and the curve will be seen to fall to the new value as in the cases of pressure and concentration. However, if the gain is positive, then the response curve rises and settles at a higher new value.

The time constant, is a measure of how fast a particular parameter responds to an input forcing function. The concentration parameter has the smallest time constant and therefore it is the most sensitive to changes in the inlet flow. The pressure and the flow both respond within the same magnitude of time.

All the parameters show the same value for the dead time except the outlet flow. This is the time it takes before the parameters start or begin to respond to the forcing function. Probably, this dead time is inherent in the system.

The analysis can also be done by storing the raw data to a workspace which could be used in other software like EXCEL or the MATLAB itself. To achieve this, double click the output icon whose data you wish to store before starting the run. For instance, if you wish to store the data of the level in the tank, then double click the first output icon of Fig. 5.1. Doing so will open for you the window similar to Fig. 5.4 but without any plots. Then click on the sixth icon on the top left (Properties). Next, click on the Data History icon to get Fig. 5.7.

Now, mark the box of ‘Save data to workspace’ and give it a variable name. Choose “Matrix” for Format box. Click on ‘Apply’ or ‘OK’ to continue. Make your run or simulation as described earlier and continue. The stored data can be viewed on MATLAB command window by typing the variable name at the prompt option of

MATLAB. The data will be stored in MATLAB workspace as a matrix under the chosen variable name. the data can be saved for further analysis or plotting.

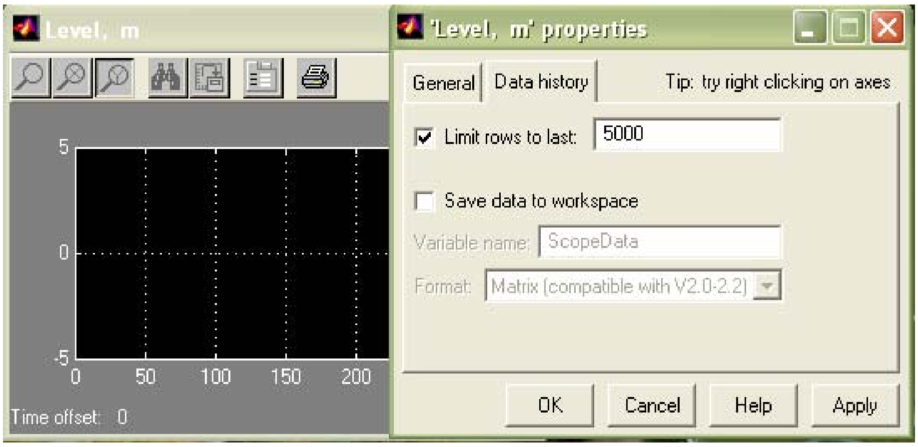

Fig. 5.7 Level Properties window for saving data to a workspace

5.2.1 Nonlinearity Analysis

Approximating the process dynamics by a first order system is based on that assumption that the physical process responds linearly to input variation. However, this is not true for most chemical processes except at a very narrow operating region. Therefore, it is necessary to use small process perturbation in order to obtain faithful process parameters, i.e. static gain and time constant. However, the input perturbation should be large enough to create reasonable signal to noise ratio. In this sense, the appropriate procedure for identifying the process parameters is a trial-and-error. This will be explained in the next paragraphs.

Now, let us see what happens when the step change is –10%. This is done the same way by invoking the Block Parameter of F_1 and changing the flow rate from 10 to 9 kg/min. Fig. 5.8 is the graph for the response of the tank to the input forcing function. From the graph, there is an immediate inverse response before the curve picks up to respond normally. Similar to the previous paragraph, the parameters of this run are captured and listed in Table 5.2

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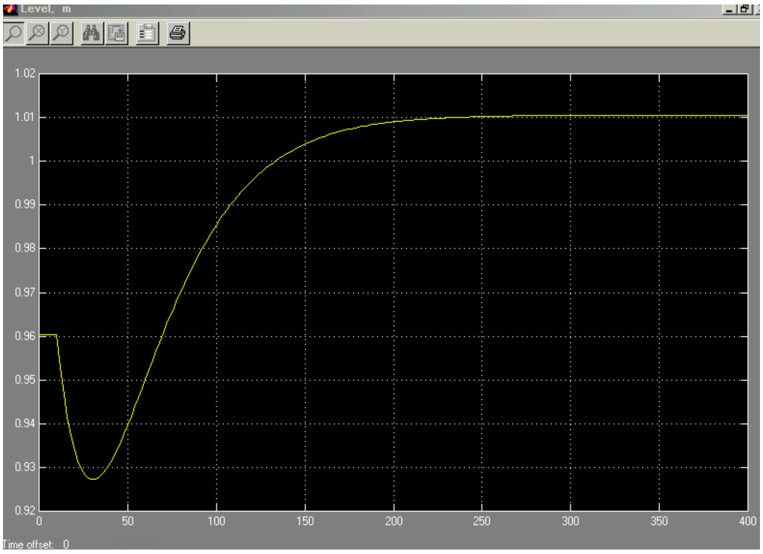

Fig. 5.8 Output showing the height of tank versus time

Table 5.2 Calculated values of the characteristic parameters for negative step change

	K_p	τ_p	t_d
Level	-0.05	111.2	10
Concentration	-20.1	28.8	10
Pressure	0.26	116	10
Flow	-0.0235	118	0

Table 5.2 still shows the concentration output parameter to be the most sensitive with a time constant of 28.8 seconds. The gain is seen to be very high reaching 20.1 % for a step change of –10 %. The gain and the time constant parameters in Table 5.3 are different from those in Table 5.2 and 5.1 for an input step change of 10% and –10%. It should be noted that the dead time was not affected by the step change because it is intrinsic property of the process. Moreover, the dead time incorporated by ad hoc method.

For linear systems, the process parameters must have the same absolute magnitude for the same magnitude of step change. Therefore the systems dynamics for 10% step change do not exhibit linearity in that region. Since linearity is the basis of these calculations, further tests need to be carried out to establish the existence of linearity. One can also check the process linear behavior through testing the plant for step changes of specific proportional magnitudes. In this case, the calculated process parameters should have the same proportional magnitudes. Otherwise the process is said to behave nonlinearly.

Table 5.3 Comparison of the values of the characteristic parameters

	K_p	τ_p	t_d
+10% step change	0.089	46.5	10
-10% Step Change	-0.05	111.2	10

In order to establish this linearity, the step changes were reduced by ten orders of magnitude. Instead of an increment of 1 kg/min on the flow rate, an increment of 0.1 kg/min was made. The module is simulated and the corresponding process parameters were estimated as shown in Table 5.4. The step change was then doubled to an increment of 0.2 kg/min. using the same procedure outlined above, Table 5.4 was produced. In this region an approximation of linearity can be assumed because the values of the gains are close to each other at 0.058 and 0.06 m-min/kg respectively, while the time constants are also close to 30 seconds.

Table 5.4 Calculated values of the characteristic parameters for 1% step change.

	Step Change 0.1 kg/min	Step Change 0.2 kg/min
L_0	0.9604	0.9604
L_{ss}	0.9662	0.9729
ΔL	0.0058	0.0125
$0.632\Delta L$	0.00367	0.0079
$L_0 + 0.632\Delta L$	0.9641	0.9683
L_τ	0.9641	0.9683
τ	27.6	30
K_p	0.058	0.06

5.3 SECOND ORDER SYSTEM DYNAMICS

Let us now look at the open-loop response of second order systems. These systems are known to have differential equations of the form given in (3.3). The Laplace transform of this differential equation yields a second order transfer function given by the equation below.

$$\frac{y(s)}{u(s)} = G(s) = \frac{Kp}{\tau^2 s^2 + 2\zeta\tau_p s + 1} \qquad (5.4)$$

Where:

y(s) is the system output

u(s) is the input forcing function

K_p is the system gain

τ_p is the natural period of the system

ζ is the damping coefficient

Second order systems occur in nature. Such systems are said to be inherently second order. They can be derived from a multi-capacity system, such as two first order systems in series through which material or energy flow. Many closed-loop systems also exhibit second order behavior.

In this chapter, the dynamic behavior of these systems is to be studied based on step changes in the input forcing function. When there is an input forcing function, the response of these systems follows that of the transfer (5.4). The key parameter of this equation is the damping factor. Depending on the value of the damping factor, the system can be overdamped, critically damped or underdamped.

Fig. 3.2 shows a typical output response of an under-damped second order system to a step change in the input. From the data generated by simulating the system, its characteristic parameters can be calculated as shown in the Figure.

In this case, the Polyethylene Reactor example is to be used to make the necessary parametric calculations. To do this, revisit Fig. 1.13 and choose the Polyethylene example on the menu by clicking on it to get Fig. 5.9. The figure shows the Polyethylene Process Menu. Choose the second item on the menu (Polyethylene (stable)) by simply clicking on it. This leads to the process flow sheet of the polyethylene process as shown in Fig. 5.10. Remember, the coloration code discussed earlier still applies.

Double click on the input parameter of the recycle flow rate F_g, to obtain the Block Parameter icon. Then increase this recycle flow from 8500 to 9020 moles/s. After this is done, close the Block parameter icon for the recycle and double click that for hydrogen flow, F_H to obtain Fig. 5.11. Once this is displayed on your screen use the keyboard to enter 2.2 moles/s instead of the 1.16. Press the enter button for the system to accept this entry. Now, run the simulation as the same way it was done in the first part of the chapter. When the run button is pressed, PCLAB will run your simulation based on the values of the new parameters that were entered.

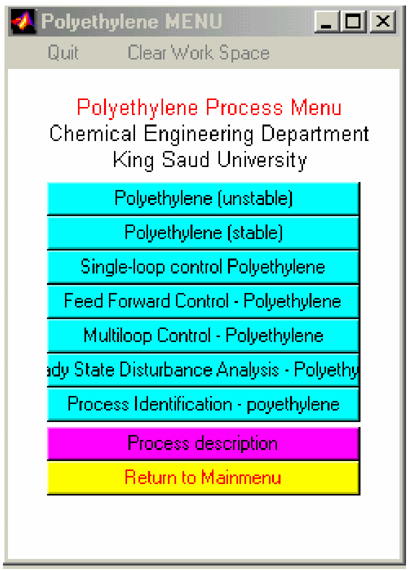

Fig. 5.9 Polyethylene Process Menu

After the run is complete, double click on the last red icon to the right of your screen, the temperature T, to get Fig. 5.12. The graph shows the plot of output bed temperature versus time for a typical second order system. The nature of the graph resembles that of Fig. 3.2. Applying the definitions used in the Figure, A is found by subtracting the steady state height (T) from the maximum reading of 122.65 ^{o}C as shown in Table 5.5. B is similarly calculated as the ultimate value of the response. Then the ratio of A/B gave the overshoot. The period is also calculated by taking the time elapsed between two consecutive crests. Using the equations and the appropriate figures of Chapter 3, Table 5.6 was generated. The overshoot is the ratio of the maximum amount by which the response exceeded its ultimate value to the ultimate value of the response. It is related to the damping factor through the equation shown in the Table. It increases with decreasing ζ and as ζ approaches 1, the overshoot takes the value of zero and the system response is described as being critically damped.

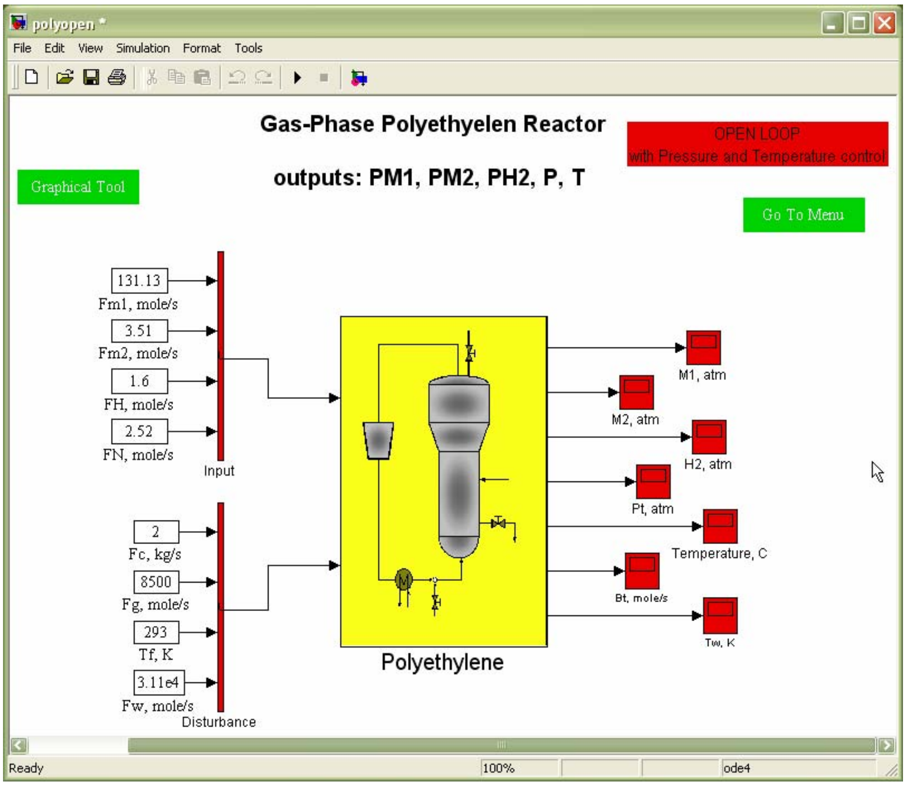

Fig. 5.10 Process Flow Diagram of the Polyethylene system

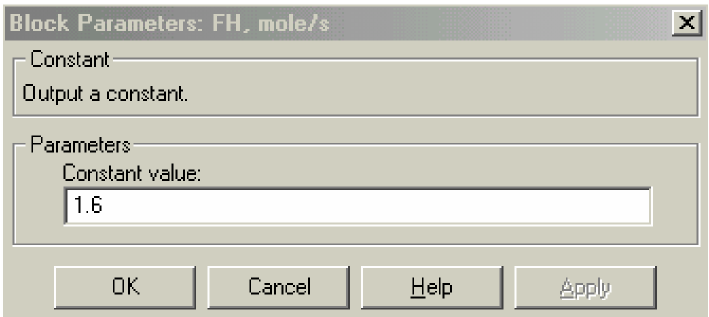

Fig. 5.11 Block Parameter for hydrogen flow, FH moles/s

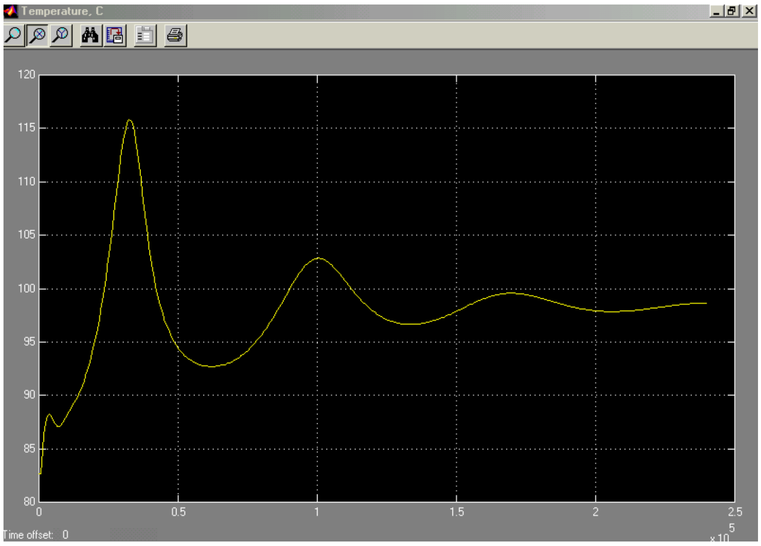

Fig. 5.12 Simulation Results of the Open Loop Polyethylene Reactor.

The system seems to have a very large time constant of 11515 seconds. The static gain of 26.5 seems to be equally large. This shows that the system has very large capacitance. Good design engineers are able to reduce these parameters so that the system can have quick response.

Other parameters that can be calculated from the graph are the rise time and the response time. Since the system took a response time of 2.29×10^5 seconds to reach its ultimate value with equally large value of the rise time (found to be 22,200 seconds), then the system is expected to have large capacitance. The system seems to have a very large time constant of 11515 seconds. The static gain of 26.5 seems to be equally large. This shows that the system has very large capacitance. Good design engineers are able to reduce these parameters so that the system can have quick response.

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Remarks:

- The green box labeled “Go to menu” shown in the Simulink Module can be used to switch between the active Simulaink module with the current active sub menu.

- The green box labeled "graphical tool" shown in the Simulink Module can be used to trigger the plotting forum. The usage of the plotting forum is discussed in Appendix A.

Table 5.5 Calculated characteristic parameters for the Polyethylene Process

Parameter	Equation	Value from Graph
A	122.65-99.9	22.75
B	99.9	99.9
OVERSHOOT	A/B	0.2277
DECAY RATIO	(OVERSHOOT)^2	.0519
T_2	$8.76*10^4$	87600
T_1	$1.52*10^4$	15200
T	T_2-T_1	72400
T_n	$\frac{T\psi}{2\pi}$	11515
ζ	$\exp(\frac{-2\pi\varsigma}{\psi})$	0.03621
τ	$\frac{T\psi}{2\pi}$	11515
K_p	$\frac{x_{ss}}{\Delta u}$	26.5