CHE322S

Process Design and Control Project

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Contributions

For the analysis and redesigning of all the controllers, it was a team effort in which everyone contributed. Below are the respective parts of the report that individuals were responsible for.

Randy Doradat -1.0 Introduction, 4.0 Feedback Quality Controls

Ishmam Chandan - 3.0 Feedforward Quality Controls, editing

Yonatan Markus 2.0 Basic Controls 5.0 Conclusion

1.0 Introduction

This report deals with the analysis and designing of various controllers that pertain to a distillation column process. See future section for respective P&IDs of the system. The process begins with a 1 kmol/s feed of butane and propane at a composition of 60% and 40%, respectively. The process based around the distillation column aims to separate the two species and produce a distillate of 98% propane and a bottoms of 99% butane. The bottoms is generally controlled by the reboiler duty and the distillate is normally controlled by the reflux, although there are interactions between all the variables. In this report, the controllers are analyzed and designed for disturbances in the feed flowrate and fed composition. The overall goal of the project was to design a system with various controllers that would be able to maintain the desired products despite disturbances to the feed.

2.0 Basic Controls

In this section the basic controls are examined for three controllers: FC, LC11, and LC12. FC controls the flow entering the system by controlling the valve V1. FC is a reverse action controller because an increase in flow requires the closing of the valve to return to the setpoint. LC12 controls the level in the reflux condenser by adjusting the valve V12, which controls the distillate flowrate out of the system. LC11 controls the level in the sump by adjusting valve V11, which controls the bottoms flowrate out of the system. Both LC11 and LC12 are direct action, since an increase in sump level would require in opening of V11 to return to the setpoint.

A P&ID for the basic tuning is shown in Figure 1.

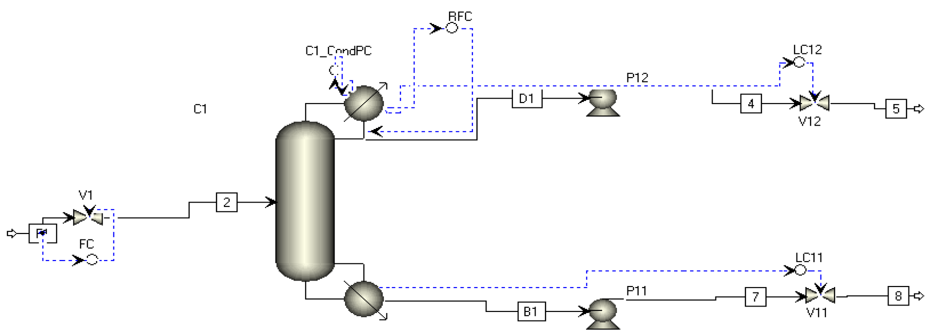
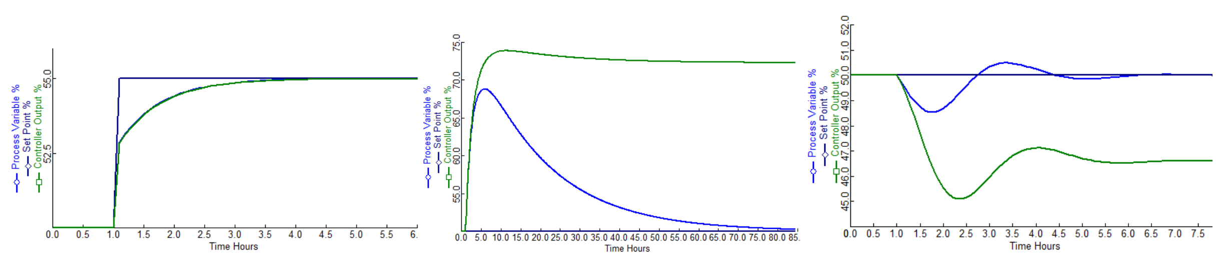
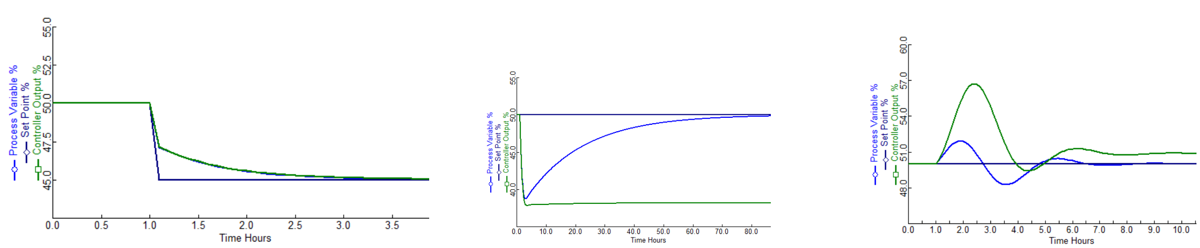


Figure 1: *P&ID for Basic Control*



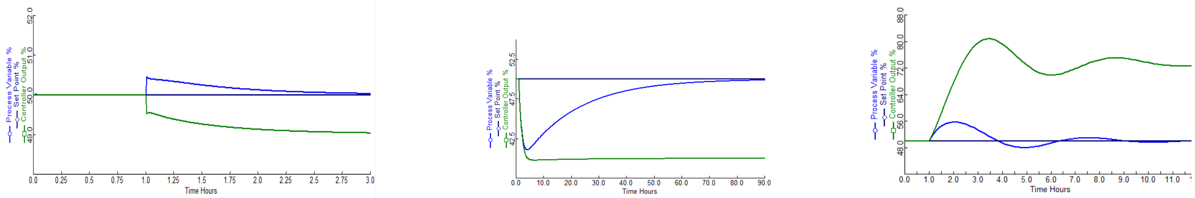
(a) FC *(b) LC11* *(c) LC12*

Figure 2 a-c: *Flow Setpoint Increase Step Test Responses*



(a) FC *(b) LC11* *(c) LC12*

Figure 3 a-c: *Flow Setpoint Decrease Step Test Responses*



(a) FC (b) LC11 c) LC12

Figure 4 a-c: *Feed Composition Change Step Test Responses*

Performing step tests on the system using default controller parameters demonstrates the need for controller tuning. The responses under default conditions are slower than an expectation of the optimized design. The FC controller takes two to three hours to return to setpoint for a 5% increase and decrease in flowrate setpoint, respectively (Test 1 and Test 2), and 2 hours to return to setpoint for a change in feed composition from 60-40% to 50-50% (Test 3). LC11, controlling the level in the sump, takes the longest time to return to setpoint. It takes about 80-90 hours to return to setpoint for the step tests specified above. LC12 is faster, taking 6-12 hours to return to setpoint for the step tests. All responses to the step test can be found in Figures 2-4 above.

To design the controllers FC, LC11 and LC12, open loop step tests were first performed to determine the process responses to the controllers. FC was set as a first order process transfer function because of the shape of the curve in Figure 5b - It shows a first-order response to the controller output. LC11 and LC12 process transfer functions were set as integrators because of the ever decreasing responses to the open-loop step tests (Figure 6b). Table 1 shows the process parameters determined from MATLAB's System Identification (SysID) app.

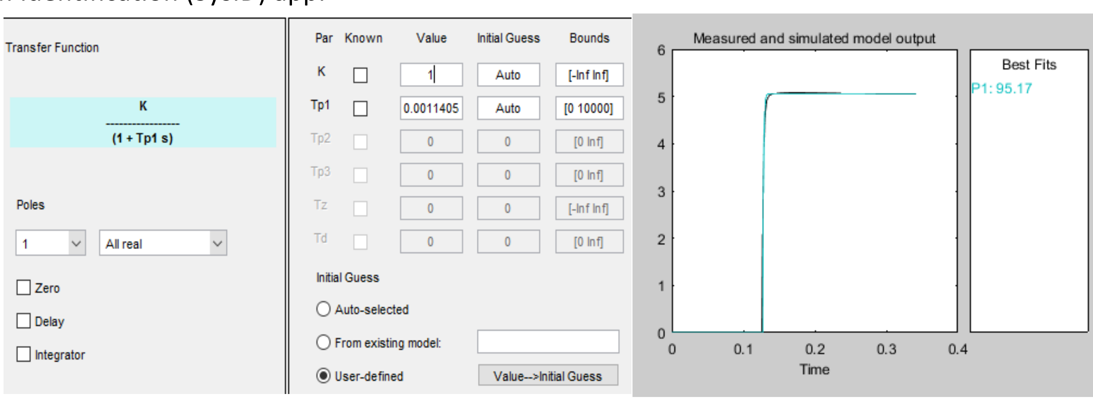


Figure 5 a-b: *Process Model and Model Fit for FC*

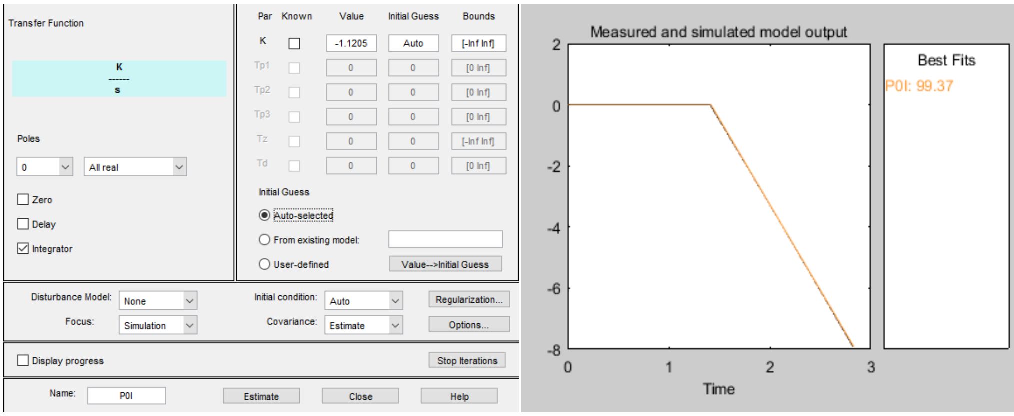


Figure 6 a-b: Process Model and Model Fit for LC11

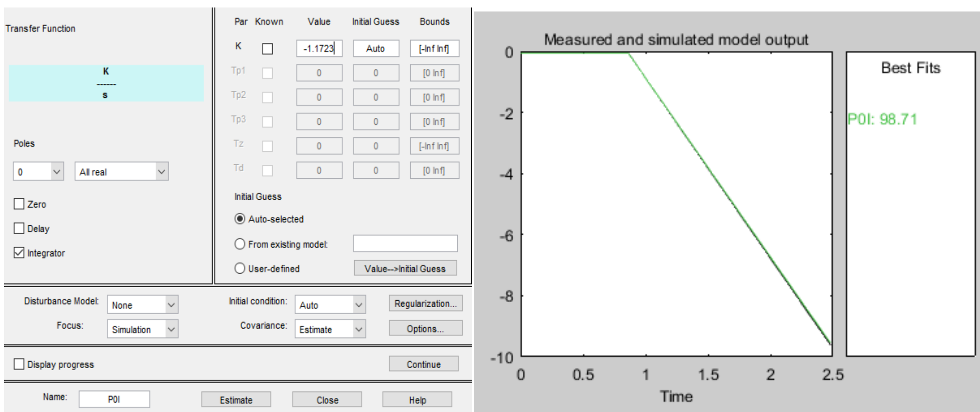


Figure 7 a-b: Process Model and Model Fit for LC12

Table 1: Controller Process Transfer Functions

	FC	LC11	LC12
Type	First-order	Integrator	Integrator
Gain	1 %/%	-1.12 %/%	-1.17 %/%
Time Constant	0.00114 h = 4.11 s	--	--
Transfer Function	$1/(4.11s + 1)$	$-1.12/s$	$-1.17/s$

After determining the process transfer functions, these transfer functions were placed into MATLAB's Control System Designer (CSD) app. All controller transfer functions can be found in Table 2. A PI controller was employed for FC, LC11 and LC12, with the form G = kc*(tau_i*s+1)/tau_i*s. For the FC, the closed-loop poles were changed until the r-y step response was about 15 minutes (900 seconds), as can be seen in Figures 10a, 11a, 12a. The tau_i was set to equal tau_p in order to ensure a first order response for FC.

The same process was undertaken for LC11 and LC12. For example, the Root Locus diagram and step response can be seen for LC12 in Figure 9. It can be seen that this response does not have an offset and does not oscillate.

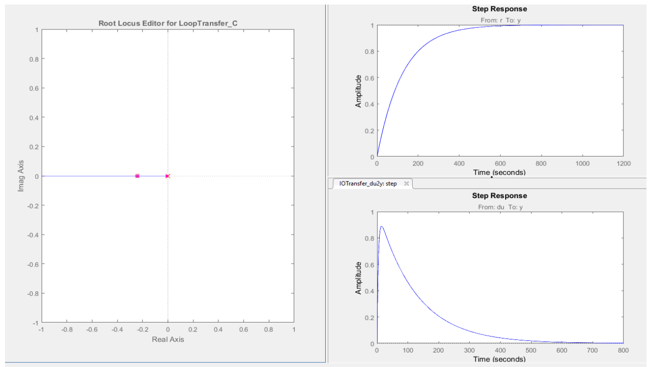


Figure 8: *Locus Plot for FC*

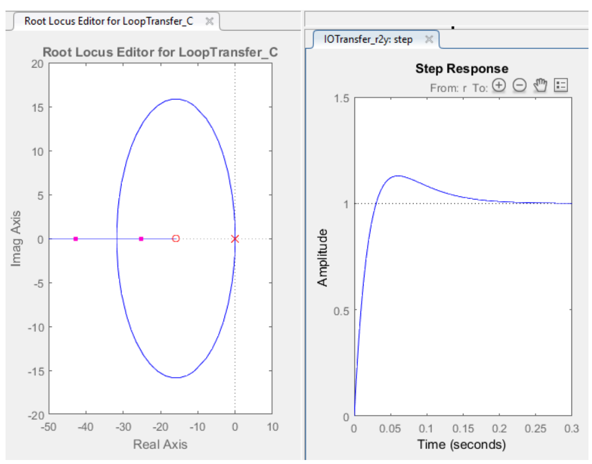
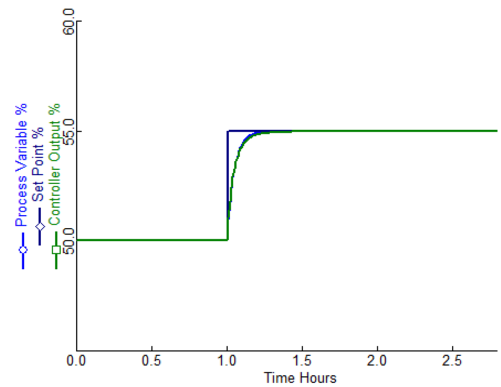


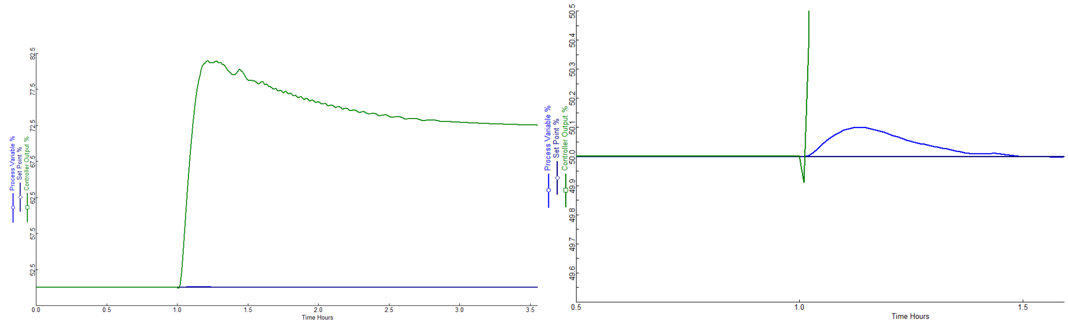
Figure 9: *Locus Plot for LC12*

Table 2: *Controller Transfer Functions*

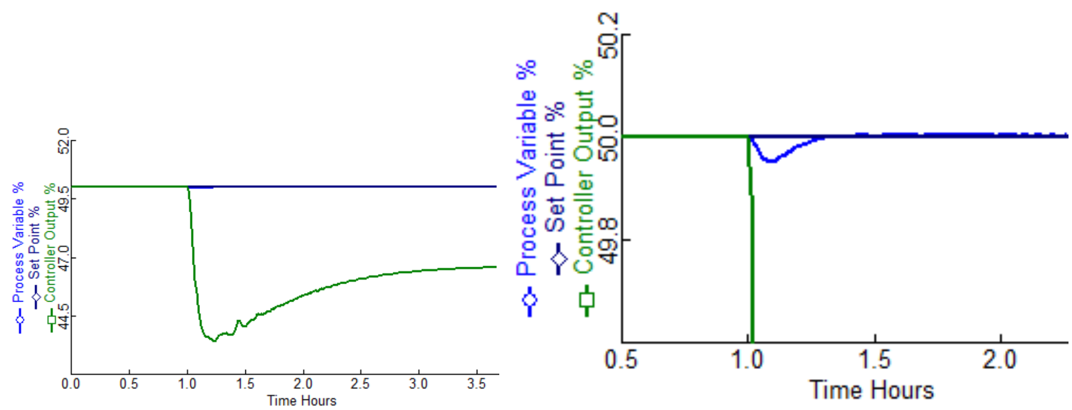
	FC	LC11	LC12
Type	PI	PI	PI
Gain	0.0247 %/%	163.63 %/%	57.58 %/%
Tau_i	4.11 s	0.12 hr	0.063 hr
Transfer Function	0.0247 x (4.11s+1)/4.11s	163.63 x (0.12s+1)/0.12s	57.58 x (0.063s+1)/0.063s



(a) FC

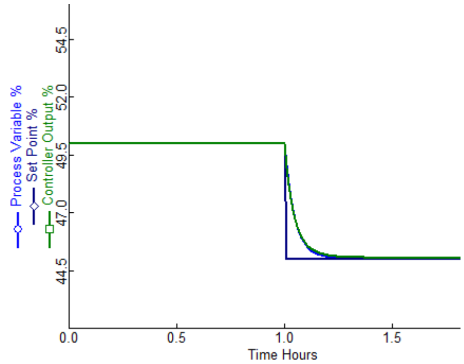


(b) LC11

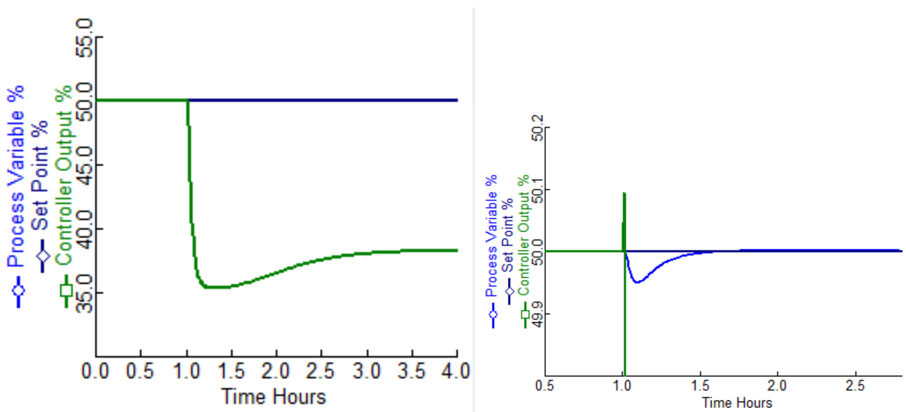


(c) LC12

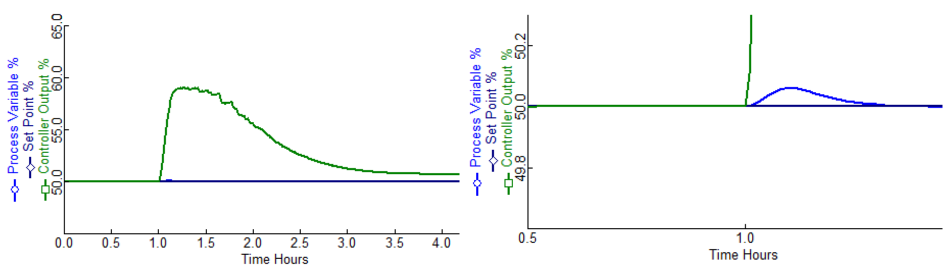
Figure 10: *Response to Test 1*



(a)

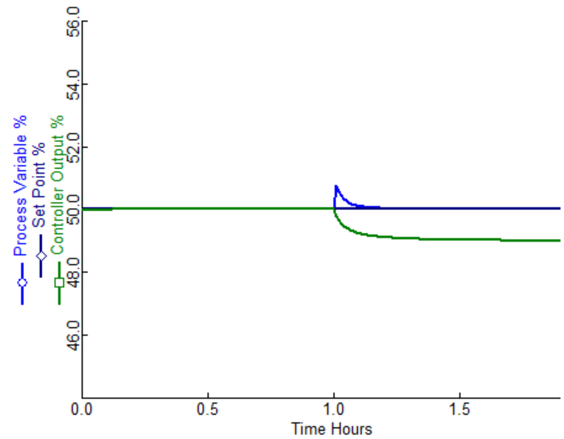


(b) LC11

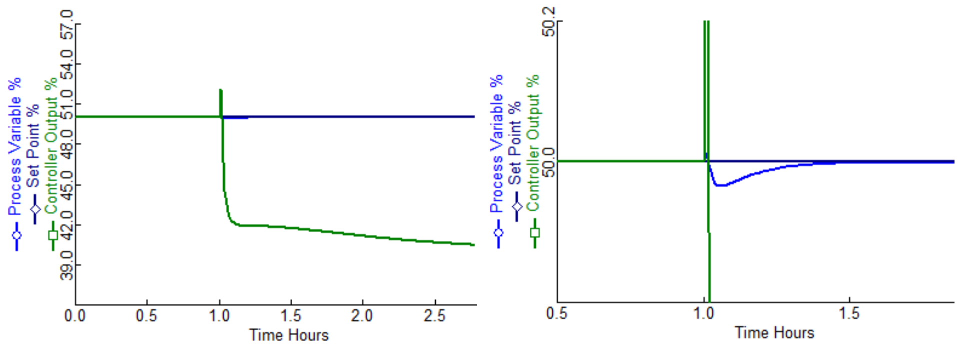


(c) LC12

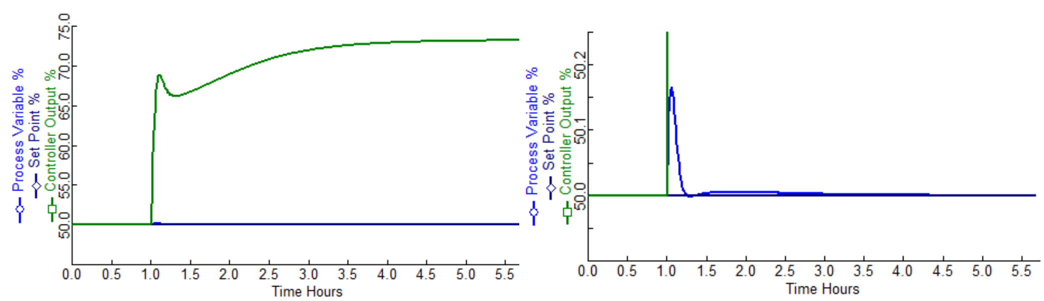
Figure 11: *Response to Test 2*



(a) FC



(b) LC11



(c) LC12

Figure 12: *Response to Test 3*

Figures 10, 11, 12 show the improvement in control when the basic controllers are tuned. FC returns to setpoint within 15 minutes for all three step tests. LC11 and LC12 do not oscillate, and they return to setpoint within 30 minutes for all step tests.

3.0 Feedforward Quality Controls

In this section, a feedforward controller was designed to create offset free performance by measuring the FC setpoint and changing RFC setpoint when a disturbance is detected. The controller was designed as a gain only feedforward controller.

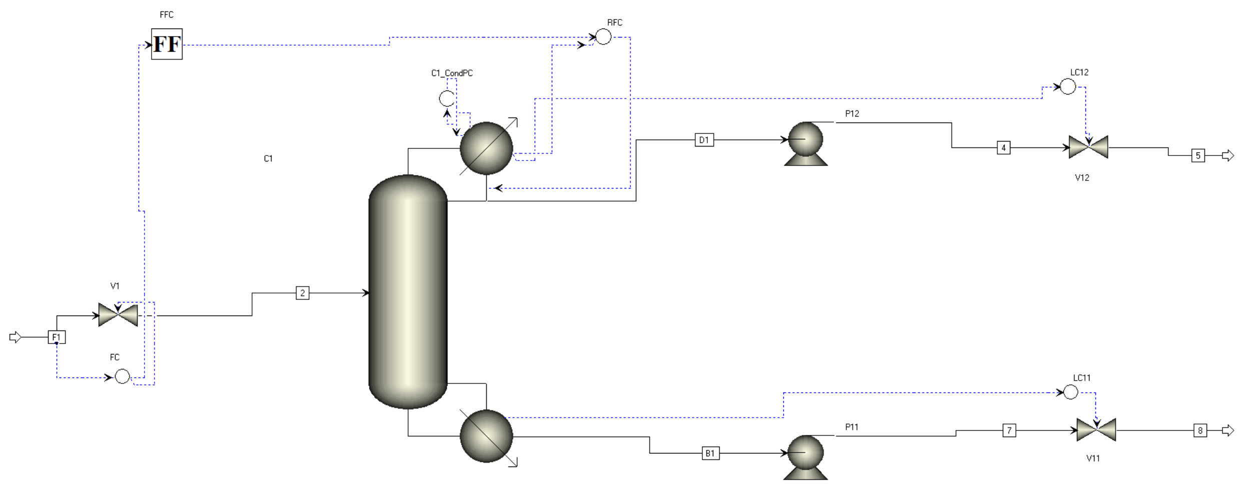
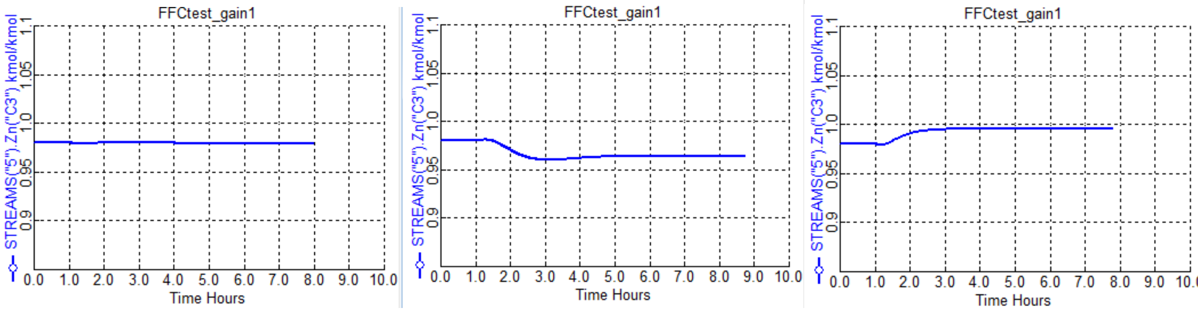


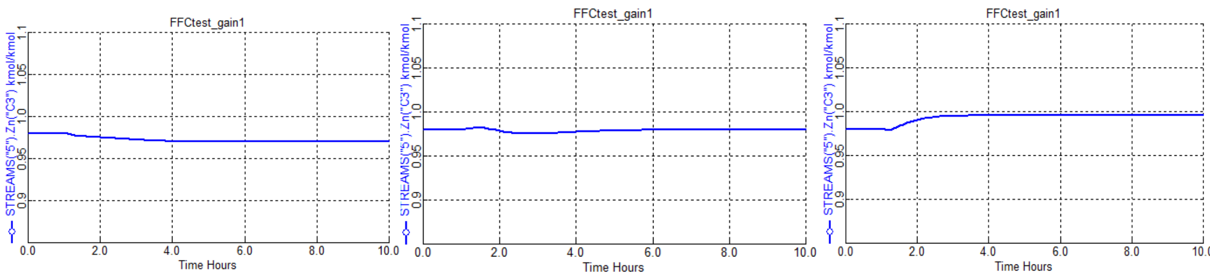
Figure 13: *P&ID for Feedforward*

The gain of the feedforward system was obtained by viewing the impact of the responses for various gain values. It was observed that different step changes required different gains for offset free performance (see Appendix 3 to see the C3 composition response to Tests 1-3 with various gains). For the increase in feed flowrate setpoint test, the gain is -0.4 (C3 distillate fraction goes from 0.979998 to 0.979135, figure 14a), whereas for the decrease in feed flowrate setpoint test the gain is -0.5 (C3 distillate fraction from 0.979998 to 0.979499, figure 15b). The changes of C3 distillate fraction from these tests essentially returns to its initial value, off by 0.000863 (for feed flow increase) and 0.000499 (for feed flow decrease), which is approximately 0 in both cases indicating offset-free performance. For the test involving an increase of feed composition, there were no possible gains that could provide offset free performance. This is because the feedforward controller only measures FC setpoint (flowrate), it is unable to detect an increase of feed composition so the setpoint remains constant for test 3. Therefore, the response for test 3 is unaffected by any gains since no disturbance is detected by the feedforward control.



(a) Flow increase (b) Flow decrease (c) Feed composition change

Figure 14 a-c: *Response of C3 distillate mol fraction with gain = -0.4 (G_FF = K_FF = -0.4)*



(a) Flow increase (b) Flow decrease (c) Feed composition change

Figure 15 a-c: *Response of C3 distillate mol fraction with gain = -0.5 (G_FF = K_FF = -0.5)*

The feedforward controller delivers poor control in this case since different disturbances require different gains and only one disturbance variable is being measured (feed flowrate). So if the system experiences a disturbance unrelated to the measured variable, the feedforward controller will not control the change because no disturbance will be detected.

4.0 Feedback Quality Controls

In this section, two feedback controllers, BCC and DCC are examined. BCC's goal is to maintain the composition of the bottoms by measuring an impurity while manipulating the reboiler heat duty. DCC's goal is to maintain the composition of the distillate by measuring an impurity and manipulating the reflux.

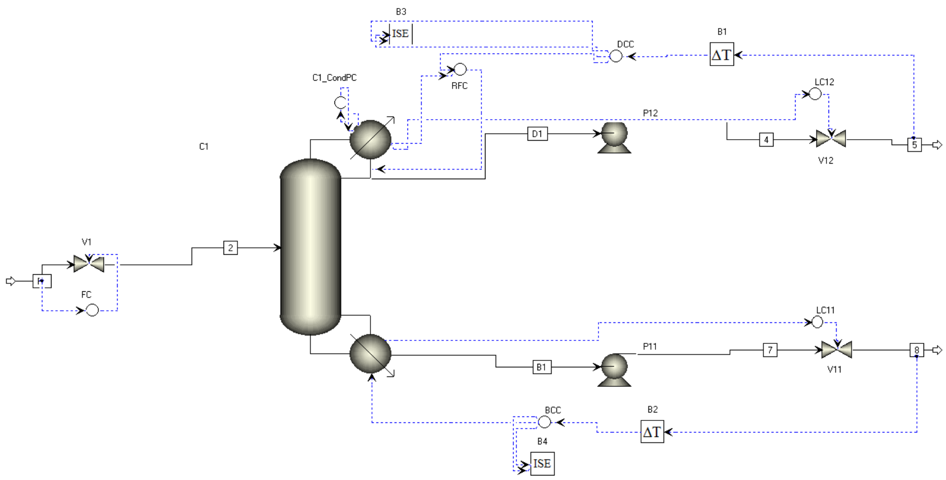


Figure 16: *P&ID for feedback quality control*

Methodology:

The first step to designing these controls was determining whether the system was controllable. This was done by gathering the 4 gains (k11, k12, k21 and k22) and placing them into a matrix, then checking if the matrix was invertible. These gains were obtained by running open loop tests. For this, both controllers (DCC and BCC) were set in manual. All step sizes for these open loop tests were ±0.1% of the OP. All gain values used were the average of two values. For example, two step tests were performed on DCC's OP, +0.1% and -0.1%. From there, the gains were taken directly from the plot for DCC and the average value is k11. The plot for BCC was also examined at this time and the average of the gains for the two steps (+0.1% and -0.1%) was assumed to be k12. To obtain k21 and k22, the same process was performed but the step changes were performed on the OP of BCC. k22 was the gain from the plot for BCC and k21 was the gain from the plot for DCC. These gains were then placed into a matrix and the matrix was found to be invertible indicating the system in controllable (see Appendix 4A).

To determine the pairings that should be used for the design in this section, the relative gains were calculated for one set of pairings. The pairing selected was controlling the C4 impurity in the distillate by manipulating reflux and controlling the C3 impurity in the bottoms using the heat duty of the reboiler.

The relative gains (λ11 and λ22) for this pairing were determined to be positive (see appendix 4B) indicating this pairing was okay to proceed with. If the relative gain was negative, that would imply that the gains changed polarity depending on whether a controller was in manual or automatic and we want to design under conditions where the the gain's polarity remain constant, whether loops are in automatic or manual.

DCC and BCC were initially designed assuming there was no interaction of the reflux on the bottoms composition and no interaction of the reboiler duty on the distillate composition. The initial step in actually designing the DCC and BCC was getting the process transfer functions, G11 and G22 respectively. Going back to the aforementioned open loop tests, the data for those plots were imported into MATLAB's system identification application and then fitted. The fit used for G11 and G22 were first order with time delay transfer functions which provided over a 90% fit in each case (See appendix 4C). These transfer functions can be found in appendix 4C.

Next, the Control System designer application in MATLAB was used. The process for designing BCC is essentially the same as DCC. First, the process transfer function was entered into matlab as "G" and the starting controller transfer function ("C") was $\frac{tau,i*s+1}{tau,i*s}$ with tau, i = tau, p. This tau condition essentially creates a first order response as setting the taus equal to each other lowers the degree of the closed-loop transfer function by 1. This controller transfer function is that of a PI controller which was chosen for BCC and DCC. A first-order response was not required for these designs but the quickest and most stable responses were found to occur when this condition was set. Once the CDS app was opened with the default controller transfer function, some of the closed loop poles may have been on the right side of the plane (see appendix 4D). If at anytime any of the closed-loop poles had a positive value on the real axis, the response would be unstable so the closed loop poles were then shifted left until they had a negative value on the real axis.. The tuning of the controllers (DCC and BCC) entailed moving the red zero (controller transfer function zero) and the closed loop poles around. They were moved around until the fastest response was obtained while being non-oscillatory, stable and having little overshoot if any (see appendix 4D). When a desired response was achieved, the integral time or tau, i and Kc(controller gain) were extracted from the CSD app within the compensator window (see appendix 4D). After the DCC parameters were determined from the CSD, they were entered into ASPEN Dynamics and DCC was switched into automatic, keeping the other controller in manual to observe the results. The same process mentioned was performed for BCC. After the BCC parameters were determined from the CSD, they were entered into ASPEN Dynamics and BCC was switched into automatic, keeping the other controller in manual to observe the results. They were individually tested for each of the three step tests. Then, both controllers were switched into automatic with the redesigned parameters and the three step tests performed.

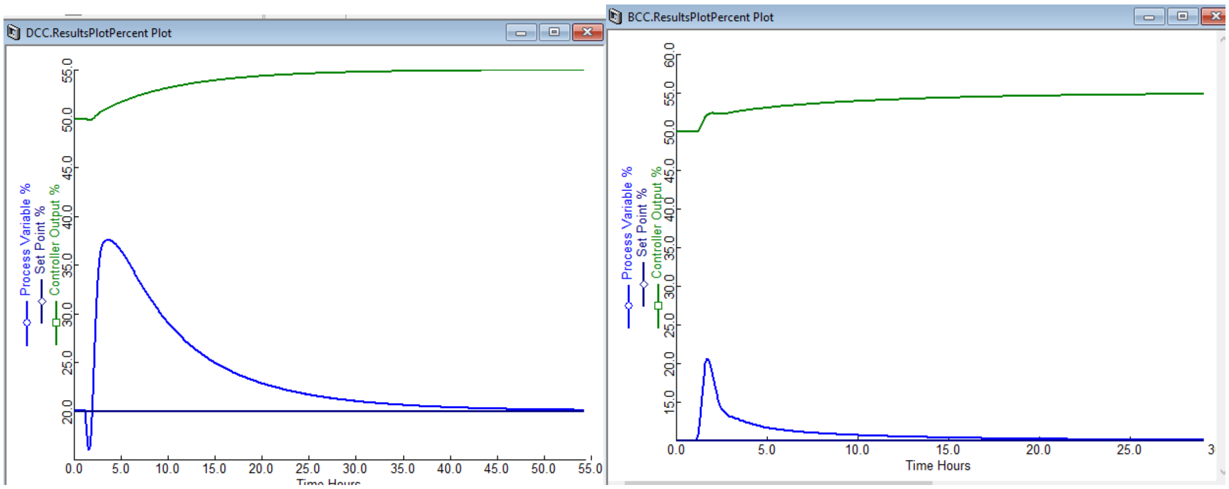
Results for redesigned controllers:

Table 3: *Parameters for designed controllers*

Controller	Action	Gain (% process variable/% valve opening)	Integral Time (hr)
DCC	Direct	0.032084	1.2
BCC	Direct	0.147618	0.8

Below are the results for DCC and BCC for each of the 3 requested tests.

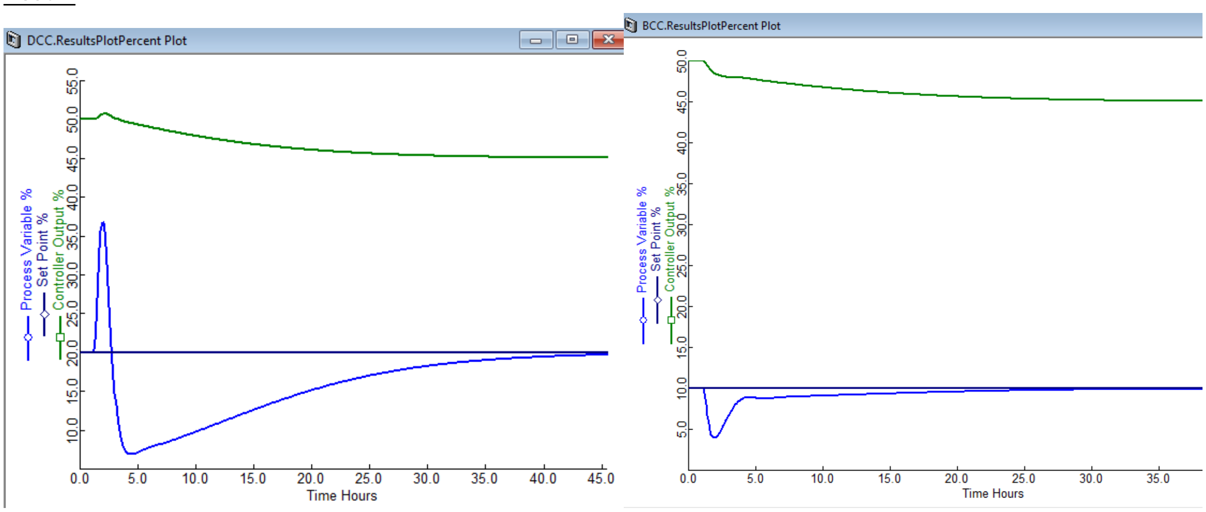
Test 1



(a) DCC Response (b) BCC Response

Figure 17 a-b: *Response to Test 1*

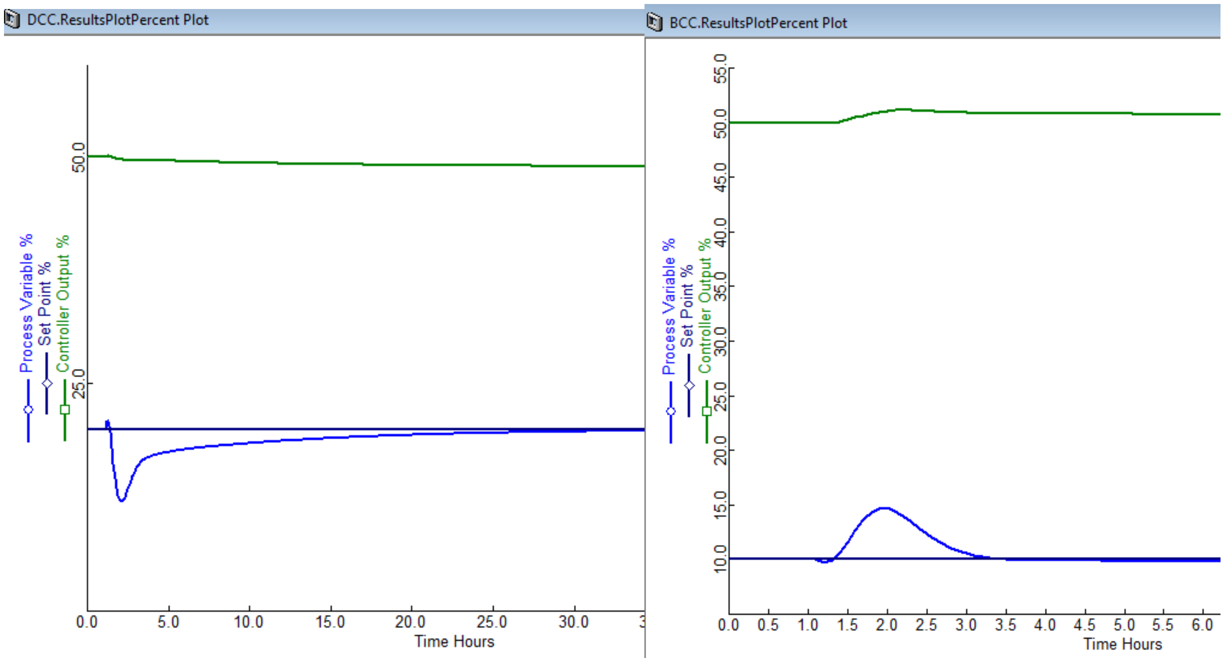
Test 2



(a) DCC Response (b) BCC Response

Figure 18 a-b: *Response to Test 2*

Test 3



(a) DCC Response *(b)* BCC Response

Figure 19 a-b: *Response to Test 3*

Table 4: *Integrated Square error for each controller for all tests*

Test #	ISE for DCC (kmol/kmol*kmol/kmol)	ISE for BCC (kmol/kmol*kmol/kmol)
1	0.00193882	9.87888e-005
2	0.00182972	5.82935e-005
3	1.2402e-004	1.56789e-005

Table 5: *Time to steady-state and max offset at anytime*

Test #	DCC		BCC	
	Time to Steady-state (hrs)	Max offset at anytime (%PV)	Time to Steady-state	Max offset at anytime (%PV)
1	45	18	12	11
2	40	16	15	6
3	25	7.5	2.5	5

In all three tests, DCC and BCC produce non-oscillatory and offset-free performance. Ideally, instead of just using PI control, a derivative control could be implemented to minimize overshoot. DCC shows much slower performance than BCC for all the tests. BCC responds about 3-4 times faster for feed flowrate changes and about 10 times faster for the feed composition change. BCC also exhibits better performance in terms of the maximum offset at anytime indicating tighter control. Overall, the combined system of DCC and BCC produces offset-free performance that is non-oscillatory but may lead to considerably off-spec products for a few hours. Feedback quality control works well as it directly measures what if flowing out of the system downstream and essentially corrects for all disturbances to the system without actually measuring them individually.

5.0 Conclusion

Starting with only basic controls and adding feedback quality controls creates the strongest control of the process. To further optimize the system, more step steps should be performed, and the RFC should be tuned. As well, PID controllers can be used for BCC and DCC to improve performance.

Feedforward has been shown to be unreliable as a control strategy because different controllers need to be designed to optimize performance for a specific step test; this is not how controllers work. As well, feedforward alone cannot be used for distillate and bottoms purity, because it monitors feed flowrate, not composition. Another feedforward controller could be added to monitor feed composition, and then control reflux or boiler duty, although this would have a large delay compared to BCC and DCC. Therefore, the final design with feedback control provides the quickest and best control.

6.0 Appendices

APPENDIX 1

Valve time constants and time-delay deadtimes

V1

	Value	Description	Units	Spec
Dynamics	1st order	Actuator dynamics		
Tau1	5.0	First order time constant	s	Fixed
StrokeTimeDown	2.0	Time for full scale down strok	s	Fixed
StrokeTimeUp	2.0	Time for full scale up stroke	s	Fixed
DBand	0.0	Dead band (%)	%	Fixed

V11

	Value	Description	Units	Spec
Dynamics	1st order	Actuator dynamics		
Tau1	5.0	First order time constant	s	Fixed
StrokeTimeDown	2.0	Time for full scale down strok	s	Fixed
StrokeTimeUp	2.0	Time for full scale up stroke	s	Fixed
DBand	0.0	Dead band (%)	%	Fixed

V12

	Value	Description	Units	Spec
Dynamics	1st order	Actuator dynamics		
Tau1	5.0	First order time constant	s	Fixed
StrokeTimeDown	2.0	Time for full scale down strok	s	Fixed
StrokeTimeUp	2.0	Time for full scale up stroke	s	Fixed
DBand	0.0	Dead band (%)	%	Fixed

DCC

B1.AllVariables Table

	Value	Spec
ComponentList	Type1	
DeadTime	5.0	Fixed
Input_	0.0200024	Free
Output_	0.0200024	Free
TimeScaler	3600.0	
UserNotes		

BCC

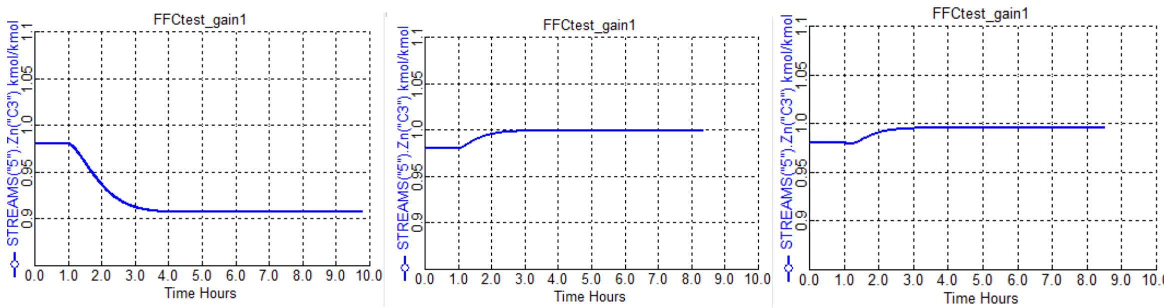
B2.AllVariables Table

	Value	Spec
ComponentList	Type1	
DeadTime	5.0	Fixed
Input_	0.0100009	Free
Output_	0.0100009	Free
TimeScaler	3600.0	
UserNotes		

APPENDIX 2: Basic Control

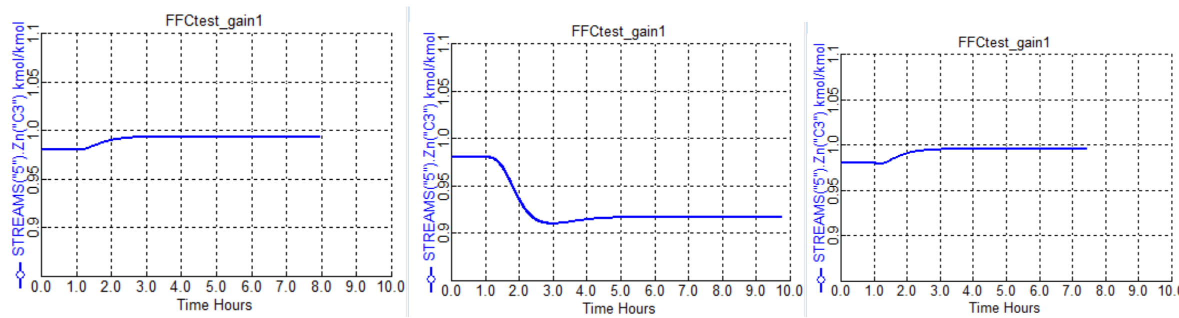
APPENDIX 3: Feedforward Control

Responses to various gain values



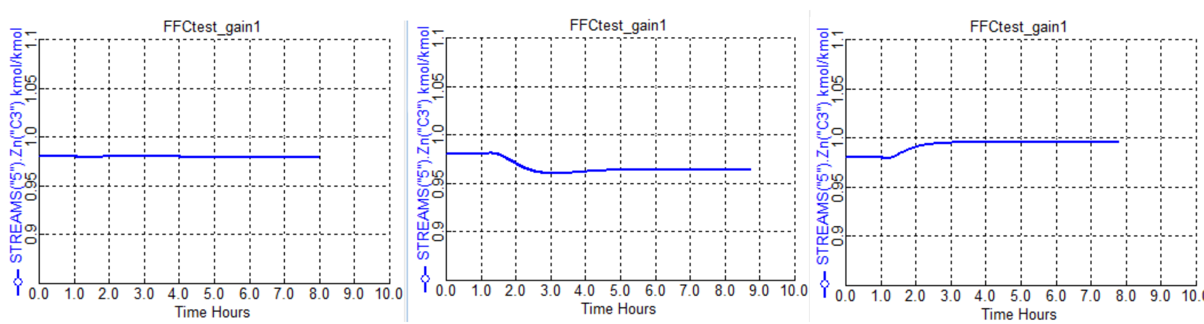
(a) Flow increase *(b) Flow decrease* *(c) Feed composition change*

Figure A3-1 a-c: *Response of C3 distillate mol fraction with gain = -1*



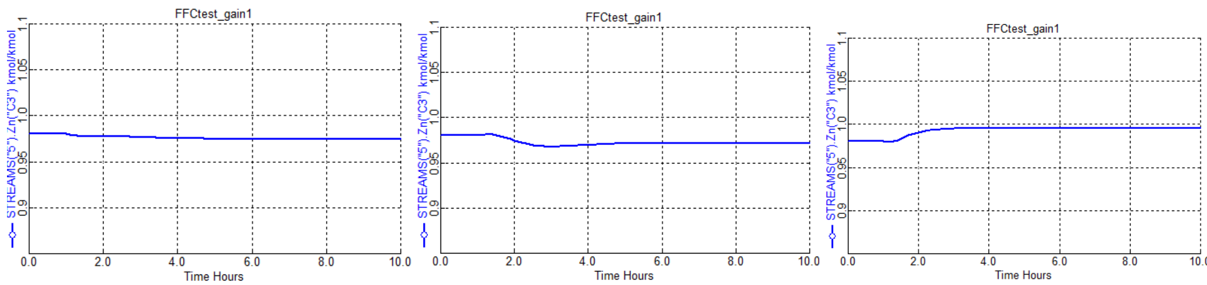
(a) Flow increase *(b) Flow decrease* *(c) Feed composition change*

Figure A3-2 a-c: *Response of C3 distillate mol fraction with gain = -0.1*



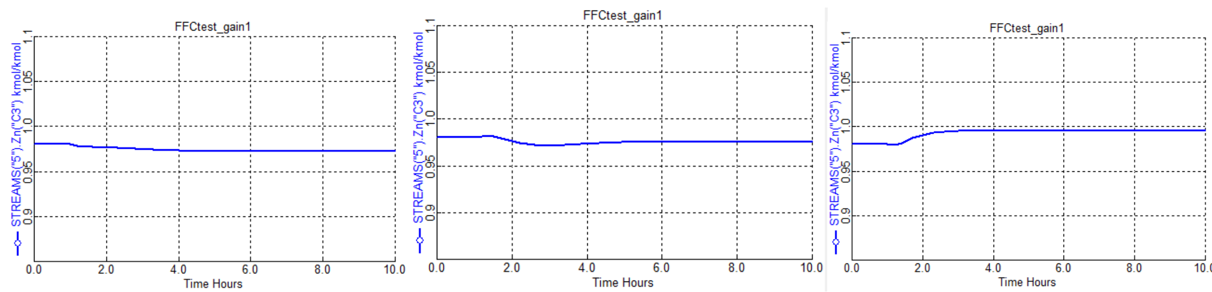
(a) Flow increase *(b) Flow decrease* *(c) Feed composition change*

Figure A3-3 a-c: *Response of C3 distillate mol fraction with gain = -0.4*



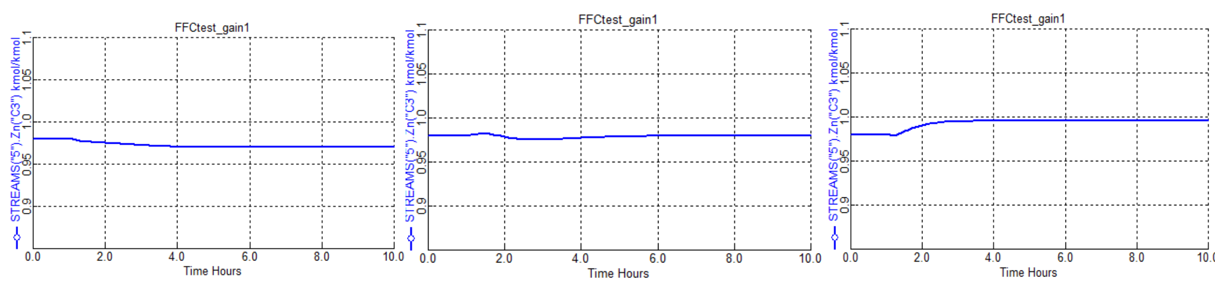
(a) Flow increase *(b) Flow decrease* *(c) Feed composition change*

Figure A3-4 a-c: *Response of C3 distillate mol fraction with gain = -0.45*



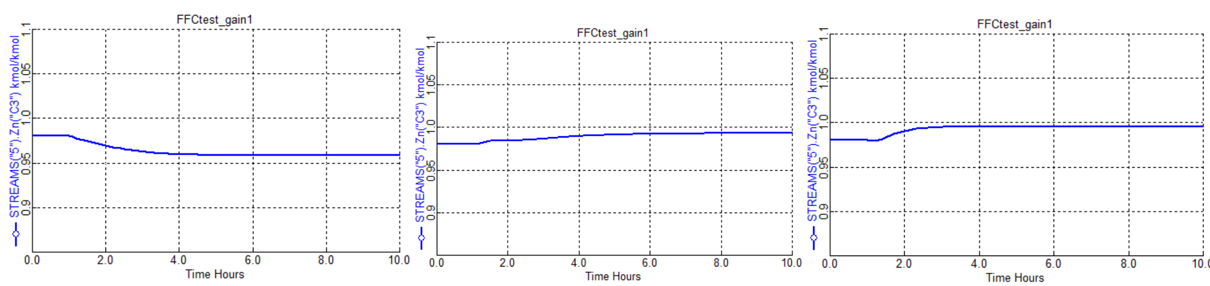
(a) Flow increase *(b) Flow decrease* *(c) Feed composition change*

Figure A3-5 a-c: *Response of C3 distillate mol fraction with gain = -0.475*



(a) Flow increase *(b) Flow decrease* *(c) Feed composition change*

Figure A3-6 a-c: *Response of C3 distillate mol fraction with gain = -0.5*



(a) Flow increase *(b) Flow decrease* *(c) Feed composition change*

Figure A3-7 a-c: *Response of C3 distillate mol fraction with gain = -0.6*

APPENDIX 4: Feedback Quality Controls

4A

K11=-26.2671

K22 -10.7079

K12=5.6364

K21=37.6175

$$\begin{array}{|c|c|}\hline k11 & K12 \\ \hline k21 & K22 \\ \hline \end{array} = \begin{array}{|c|c|}\hline -26.2671 & 5.6364 \\ \hline 37.6175 & -10.7079 \\ \hline \end{array}$$

The matrix above was found to be invertible.

4B

Relative Gain:

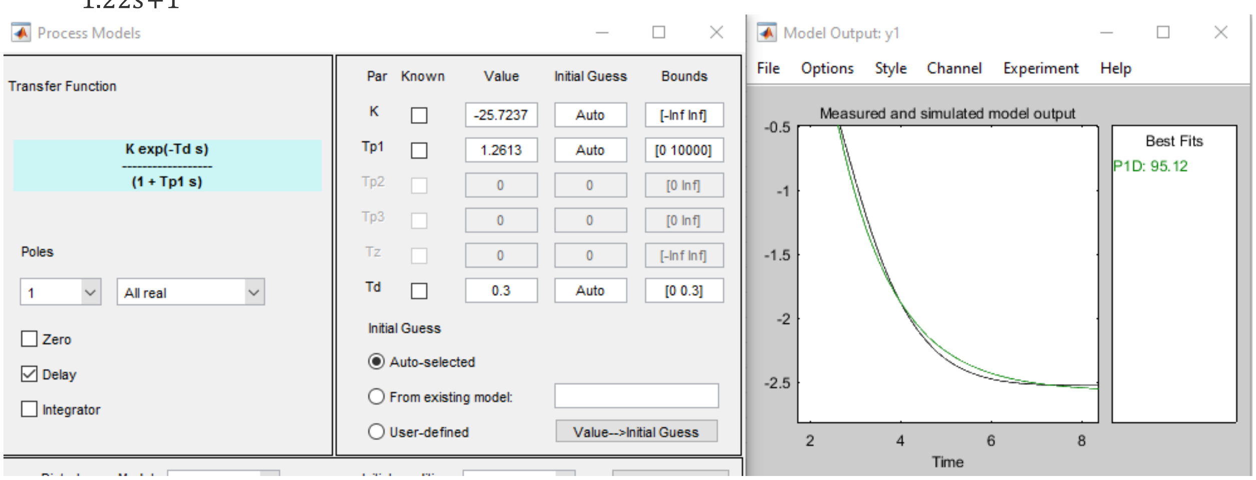
λ11 and λ22

λ22=λ11=1/[1-k21*k12/(k11*k22)]=1/[1-37.6175*5.6364/(-26.2671*-10.7079)]=4.06

4C

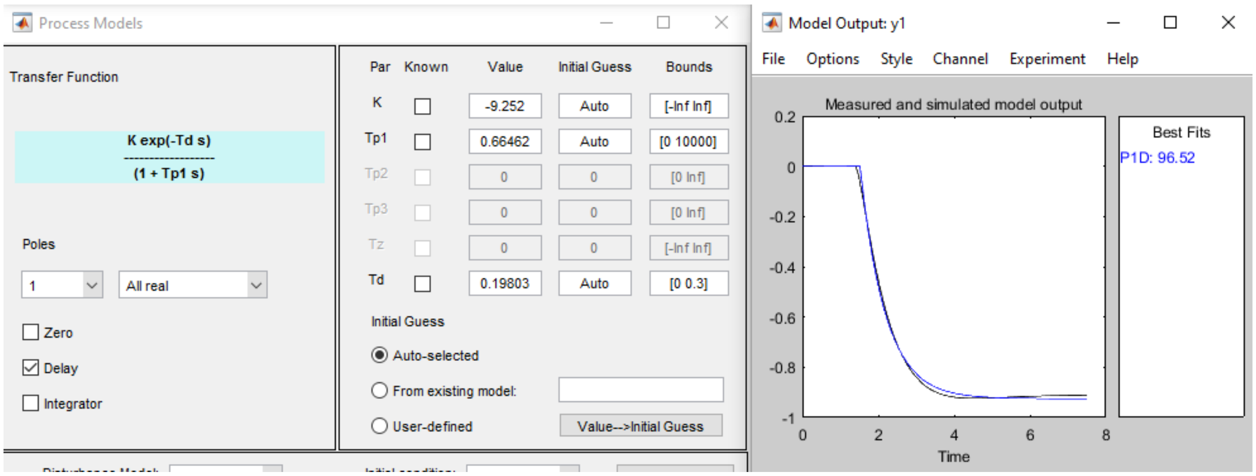
Please note the difference between the process function parameters and what is used in G11 and G12 is due to the fact that G11 and G12's parameters were based on averages from two step tests whereas included below are the results from only one step test.

G11 $=\frac{-26.27}{1.22s+1}$ X exp(-0.35s)



Process model fit for DCC

$$G22 = \frac{-10.71}{0.80s+1} \text{ X } \exp(-0.19s)$$



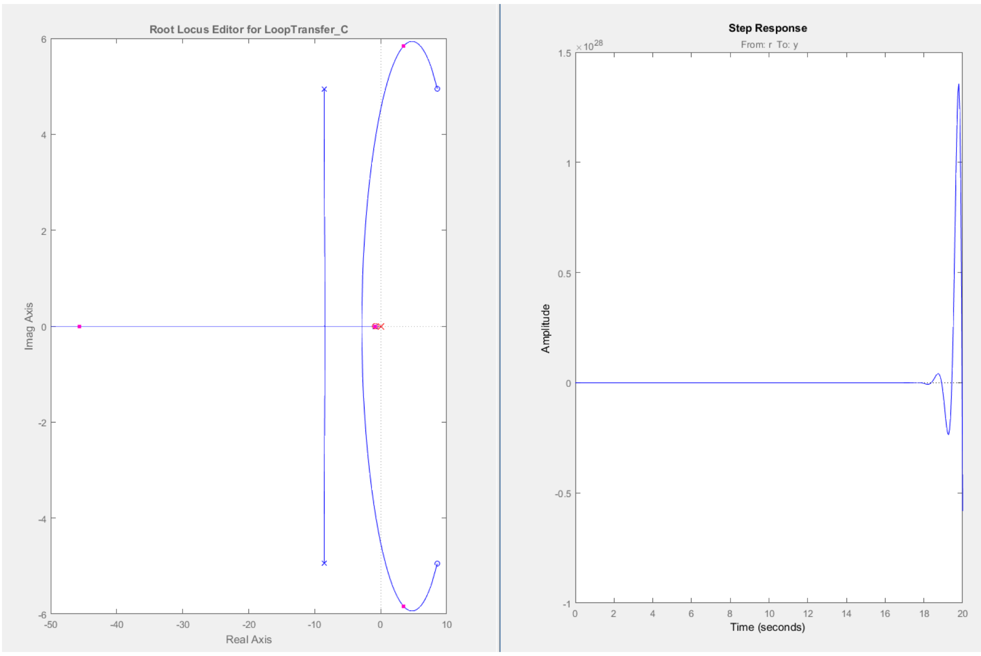
Process model fit for BCC

4D

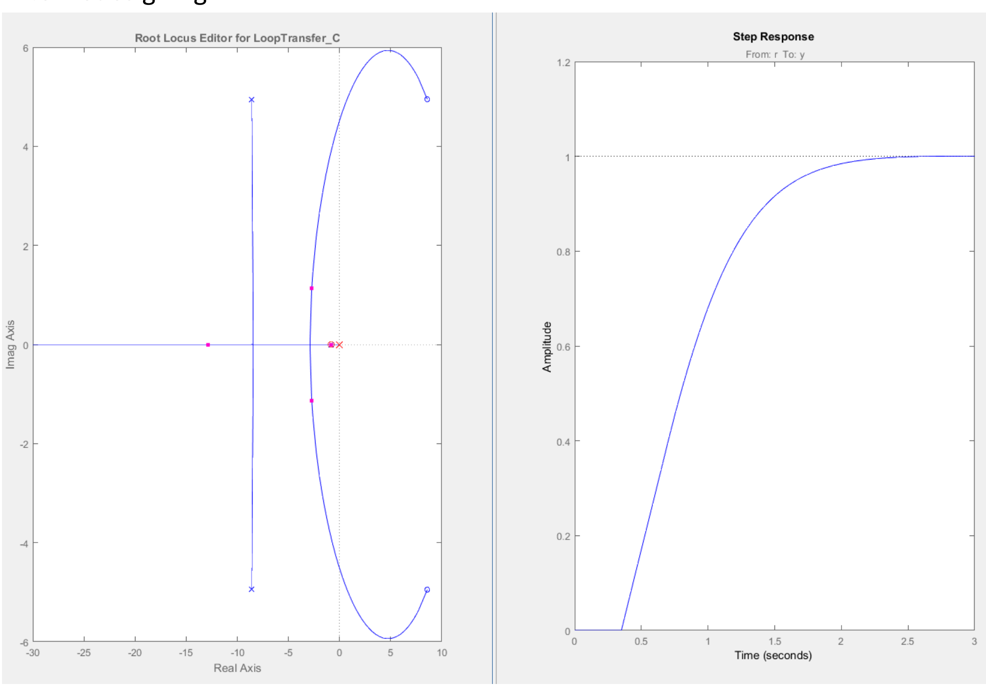
For DCC redesign, transfer functions were entered into MATLAB as shown below.

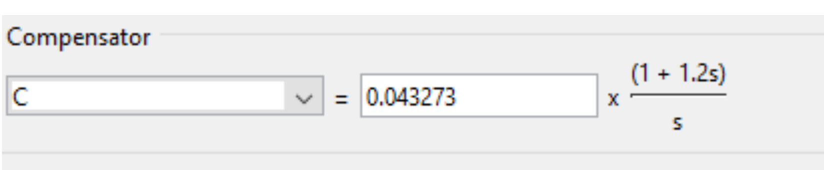
```
G =

                    26.27
  exp(-0.35*s) * -----------
                 1.218 s + 1

C =

  1.218 s + 1
  -----------
    1.218 s
```

Before redesigning:



After redesigning





Tau,i =1.2   kc/tau,i=0.043273, therefore, kc=0.043273*1.2=0.052