MODELLING AND CONTROL FOR COMPOSITION OF NON-ISOTHERMAL CONTINUOUS STIRRED TANK REACTOR (CSTR) USING FUZZY LOGIC

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Modelling and control for composition of non-isothermal Continuous Stirred Tank Reactor (CSTR) using fuzzy logic

by

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Dissertation submitted in partial fulfilment of
the requirements for the
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CERTIFICATION OF APPROVAL

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Approved by,

____

(Nasser Mohammed Ramli)

UNIVERSITI TEKNOLOGI PETRONAS

BANDAR SERI ISKANDAR, PERAK

September 2015

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

RAIHAN FIKRI BIN ROSLAN

ABSTRACT

As a matter of fact, several of chemical or petrochemical industries still using the old technology of conventional control; one of it is PID controller. This is due to the limitation budget of the companies provided. But it stills had a lot of weaknesses that need to be concerned, which it's the accuracy and it's precision. Due to that reason, the researchers had found the initiative to solve this situation by creating the Artificial Intelligence (AI), one of it is the Fuzzy Logic. For this research paper, it will introduces the concept of Fuzzy Logic approach towards the control system of non –isothermal continuous stirred tank reactor (CSTR). This simulation study had been made by using the MATLAB SIMULINK, and there will be a comparison with PID controller in order to justify the effectiveness of the modern technology concept in the control system. The result had shown that the fuzzy logic approach can gives the most favorable result in term of its accuracy and robustness. It is clear that this modern approach is better compared with the conventional PID controller.

ACKNOWLEDGEMENT

It is my proud privilege to release the feelings of my gratitude to several people who helped me directly or indirectly to conduct this Final Year Project with the topic "Modelling and control for composition of non-isothermal CSTR by using fuzzy logic".

I would like to express my heart full in debt and owe a deep sense of gratitude to my supervisor, Mr. Nasser Mohammed Ramli, for sincerely gives guidance, encouragements and giving me opportunity throughout this project. He is the only person that willingly spends his time to teach and help to solve my problems about the process control. Beside, every word and advice he shared to me had become the source of inspiration and motivation for me to strive a successful project that can give benefits to the others.

My thanks and highly indebted to our FYP I and II Coordinators for arranging various tutorial and seminars for the final year students, in order to develop our understanding and knowledge to do a proper research. Besides, it is a great pleasure to them for providing us sufficient time to ensure that we will be able to complete the final year project within the exact timeframe.

Not to forget, I would like to thank to all the lecturers in Chemical Engineering Department for their continuous support and guidance throughout this semester. In addition, I would like to thank to my colleagues for providing help, support and give cooperation to ensure the success of this project.

Last but not least, many thanks go to my parents, Mr. Roslan Kamarudin and Madam Siti Norbaya Brahan for giving me strength to survive during internship for almost 7 month.

The experiences and study has indeed helped me to explore more knowledgeable and faced a lot of hardships. It will sure help me in my future

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CHAPTER 1

INTRODUCTION

1.1 Background

In the industrial society, people are searching on how to produce high amount production without using a lot of money (spending this money to cover the loss of production and any errors in the system). Due to that reasons, the topic of controlling of the reactor is very important subject to the engineers and the researchers. This is because it is a key to create a successful plant for the companies. Continuous stirred tank reactor (CSTR) is the most popular or typical chemical reactor compared to the others. Besides, this reactor exposed with a complicated nonlinear dynamic characteristic. Anyway, this will help the researchers to introduce the opportunity for a diverse range of process dynamic. However, if lacking in understanding the operation of CSTR may make difficult to develop a suitable control strategy. Besides, in order to achieve an effective control system of CSTR required an accurate mathematical model.

In any cases, to develop mathematical model is a must in order to control the reactor. The model need to be controlled in order to use the designing control law. In order to achieve an excellent controller required a very accurate and precise control system. In deriving the mathematical model, the designer follows two models, the researcher must follows based on data from the suitable principles or equations and the experimental data from the investigation. In any cases, to develop mathematical model is a must in order to control the reactor.

However, it is not easy to develop the mathematical model specially to study the complicated system. This is because it very complex and consume a lot of time as it requires several expectations. This problems had led the researchers to investigate and study by exploiting the Artificial Intelligence (AI), one of it is the fuzzy logic tools in modelling complex system.

1.2 Problem Statement

Until now, several of chemical/petrochemical refineries are still running the old conventional controller (PID controller) in the plant control system. The management overlooked some of the qualities of their products but only focusing on the budget as the matter of facts that the PID controller had some weaknesses, specially its precision and accuracy. However, the development of the system has insist the rising demands for consistency and stability for the quality that need to be take care on and also the other possible considerations.

Next, the modelling for composition of non-isothermal CSTR is taken out in the complex model equation which is very complicated and time consumed. Basically, all of this equations are based on the components of mass balance and energy balance principle. Several assumptions had been made; such as, the constant volume with no control and etc. All of these assumptions were based on the literature review and discussion with the supervisor.

Thus, this simulation project had been prepared, to see whether this modern control approach to the plant control is expected to do better in term of its precision and stability even easy to handle (does not require accurate mathematical model).

1.3 Objectives and Scope Study

The primary aim of this task is to find out the effect of CSTR based on the varieties of the composition of the substance. For further study, the following objectives below are set:

- To develop a simulation model for continuous stirred tank reactor (CSTR) model by using fuzzy logic (MATLAB SIMULINK) specifically in finding its concentration inside the reactor
- To analyze and justify the effectiveness the modern control, fuzzy logic in continuous stirred tank reactor (CSTR) by comparing with the conventional control, PID controller

In order to achieve the main targets of this project, the simulation models is using the S-function blocks in Simulink in MATLAB based on the parameters given. Next is to develop the control system for non-isothermal CSTR by applying PID Controller and fuzzy logic controller using MATLAB. Lastly, is to compare the concentration response curve of fuzzy logic control system with the PID controller, to justify its effectiveness.

CHAPTER 2

LITERATURE REVIEW AND THEORIES

2.1 Continuous Stirred Tank Reactor (CSTR)

Mostly in chemical or petrochemical plant refineries, the selection of tank reactor plays the important rules in the chemical process in order to gain high quality products. In this chemical reaction, there are 2 types of energy which are exothermic reaction and endothermic reaction, therefore the unit operation engineers require to identify whether the energy need to added or removed to the reactor to archive and maintained a constant temperature level.

To design the chemical reactor requires the understanding of the chemical engineering. The chemical engineers design reactor to maximize the net present value for the given reaction. It is also requires high efficiency towards the desire output product, highest yield of product while requiring small amount of money, CAPEX and OPEX.

As for this project, a chemical reactor, continuous stirred tank reactor (CSTR) is considered. This is because of the dynamic behavior of CSTR had been studied extensively and it is well known to exhibit strong parametric sensitivity. Besides, the CSTR model has become one of the standard test applications for theoretical results in the area of the nonlinear control. (Amir Mehdi Yazdani, Mohammad Ahmadi Movahed and Somaiyeh Mahmoudzadeh, 2013)

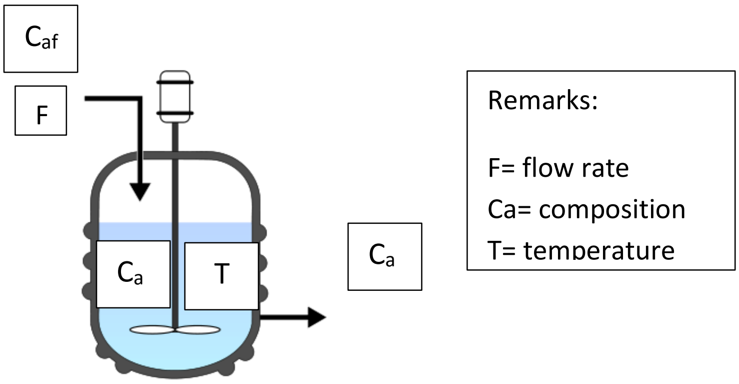

FIGURE 2.1 Non-isothermal CSTR

A model of CSTR is required for the process control system. The mathematical model equations are obtained by the components mass balance and energy balance principle in the reactor:

Mass Balance:

(Accumulation of component MASS) = (component MASS) $_{in}$ - (component MASS) $_{out}$ + (Generation of component MASS) (1)

Energy Balance:

(Accumulation U+ PE + KE) = (H + PE + KE) $_{in}$ - (H+ PE + KE) $_{out}$ + Q – W_s (2)

The mathematical model of non-isothermal CSTR is

$$\frac{dCa}{dt} = \left(\frac{F}{V}\right) \times (Caf - Ca) - k0.exp\left[-\frac{Ea}{R.(T+460)}\right].Ca \quad (3)$$

$$\frac{dT}{dt} = \left(\frac{F}{V}\right) \times (Tf - T) - \frac{\Delta H}{\rho.Cp}\left[k0.exp\left[-\frac{Ea}{R.(T+460)}\right].Ca\right] - \left(\frac{U.A}{\rho.Cp.V}\right).(T - Tj) \quad (4)$$

2.2 Fuzzy Logic Control

Fuzzy logic control is a methodology bridging artificial intelligence and traditional control theory. This generally referred as logical system and complex control problems which is an extension of multivalued logic (Suja Malar and Thyagarajan, 2009). This methodology is usually applied in the only cases when accuracy is not of high necessity or important. Wide spread of the fuzzy control and high its effectiveness of its application in a great extend is determined by formalization opportunities of necessary behavior of a controller as a flexible (fuzzy) representation. This representation usually formulated in the form of logical (fuzzy) rules under linguistic variable of a type “If A then B”. Basically, the fuzzy logic is all about the relative importance of precision.

This shows that this control can provides a practicable way to understand and manually influence the mapping behavior. In other meaning, is that the fuzzy logic can use simplify methodology to describe the system of interest rather than analytical equations in which easy to the user to understand and applied. The advantage, such as robustness and speed, the fuzzy logic is one of the best solutions for this process modelling and control system. (Suja Malar and Thyagarajan, 2009)

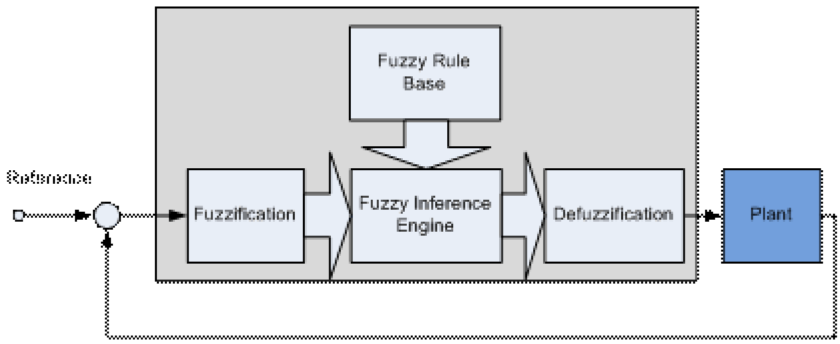

FIGURE 2.2 Fuzzy logic

CHAPTER 3

METHODOLOGY AND PROJECT WORK

3.1 Project Methodology

Overall, this main project is only using computer simulation hence all the analysis will be focusing on the result that obtained from the MATLAB simulation work. The outcome will be analyzed and proper validation will be made.

3.1.1 Research from the literature

For the first phase of this project is by selecting the related articles/ journals/literatures from the reliable sources. This project mainly focus on fuzzy logical system by using the Simulink, which may related to Imperialist Competitive Algorithm (ICA), Artificial Intelligence Techniques, Takagi-Sugeno-Kang type (T-S-K) fuzzy logic and etc.

3.1.2 MATLAB Simulation

Modelling of non-isothermal CSTR system is done by using MATLAB Software to generate two outputs, which are the temperature and composition. However, for this project only focusing on composition (concentration) of the content inside.

3.1.3 Documentation and Report

All the outcomes obtained will be analyzed and documented. A brief explanation and comparison with other research paper will be made, for getting a proper conclusion for this project.

3.2. Project Process Flow

Below is the process flow diagram for this final year project, to make sure the objectives of the study can be achieved.

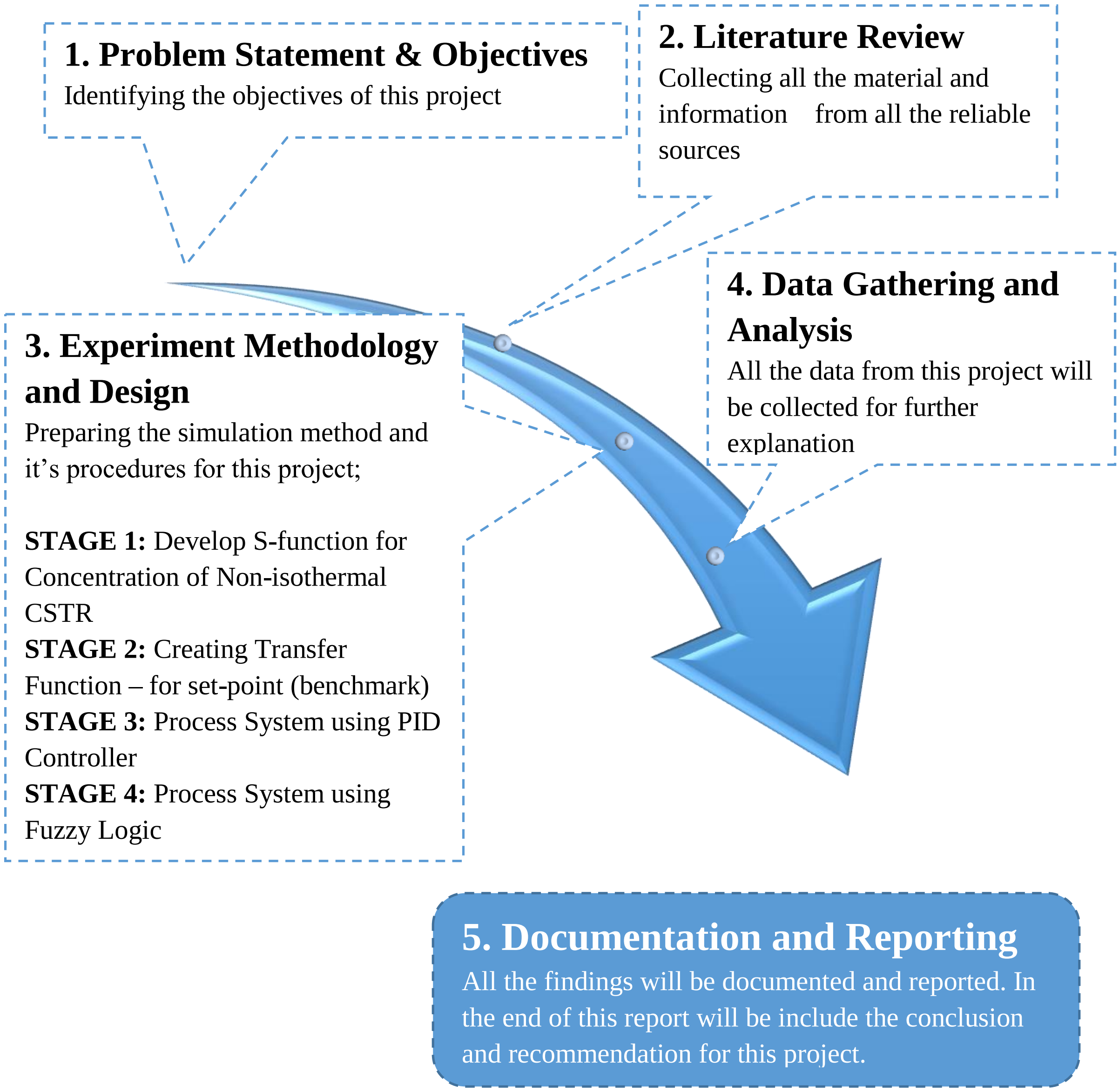

FIGURE 3.1 Project Process Flow

3.3 Gantt Chart and Key Milestones

TABLE 3.1 Gantt chart and Key Milestones

NO	DETAILS	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Selection on Project Title	■	■												
2	Preliminary Research Work and Literature Review		■	■	■	■									
3	Submission of extended proposal (first draft)						■	■							
4	Submission of extended proposal (final draft)							★							
5	Preparation for Proposal Defense								■	■					
6	Proposal Defense								★	★					
7	Simulation Work										■	■	■		
8	Detailed Literature Review											■	■		
9	Preparation of Interim Report												■		
10	Submission of the draft of Interim Report													★	
11	Submission of Interim Report Final														★

■ **Gantt chart**

★ **Key Milestone**

3.4 Project Methodology

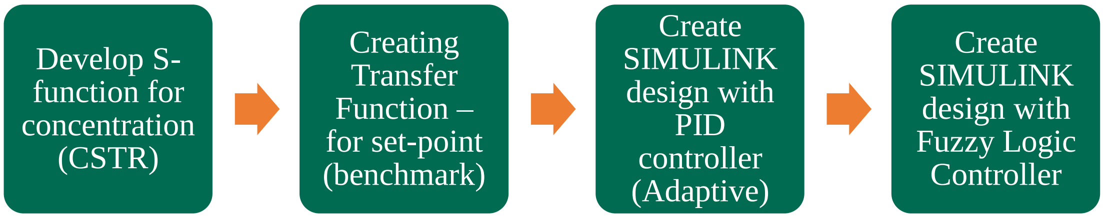

FIGURE 3.2 Summary of project methodology

3.4.1 STAGE 1: Develop S-function for Concentration of Non-isothermal CSTR

The simulation model in MATLAB Simulink will be build based on these predefined parameters and operating conditions:

TABLE 3.2 Project Operating Variable

Operating Variables	Notation	Units	Value
Concentration of reactant A in the exit stream	**Ca**	lbmol/ft^3	-
Temperature	**T**	oF	-
Activation energy of reactant A	**Ea**	BTU/Ibmol	32400
Frequency factor	**K0**	hr^{-1}	15e12
Universal gas constant	**R**	BTU/Ibmol-oF	1.987
Volume	**V**	ft^3	750
Volumetric feed flow rate	**F**	ft^3/hr	3000
Concentration of reactant A in the feed stream	**Ca$_f$**	lbmol/ft^3	0.132
Feed temperature	**T$_f$**	oF	60
Cross sectional area of the reactor	**A**	ft^2	1221

The data from Table 3.2., supposed to model the non-isothermal CSTR from equation (3) and (4);

From the figure 2.1, we can see that the Concentration, Ca and Temperature, T will the output of this reaction. However, it should aware that our concern is to control the concentration of this reactor to achieve at certain set point.

This will be the mathematical coding for m-file: (APPENDICES A)

```
function  dx = reactor(t,x,Tj)
%
% model for reactor
%
 Ca = x(1) ; % lbmol/ft^3
 T = x(2) ; % oF
 Ea = 32400 ; % BTU/lbmol
 k0 = 15e12 ; % hr^-1
 dH = -45000 ; % BTU/lbmol
 U = 75 ; % BTU/hr-ft^2-oF
 rhocp = 53.25 ; % BTU/ft^3
 R = 1.987 ; % BTU/lbmol-oF
 V = 750 ; % ft^3
 F = 3000 ; % ft^3/hr
 Caf = 0.132 ; % lbmol/ft^3
 Tf = 60 ; % oF
 A = 1221 ; % ft^2

 ra = k0*exp(-Ea/(R*(T+460)))*Ca;
 dT = (F/V)*(Tf-T)-(dH)/(rhocp)*ra...
 -(U*A)/(rhocp*V)*(T-Tj);
 dCa = (F/V)*(Caf-Ca)-ra;

 dx =[dCa;dT];
end
```

Next, this will be the mathematical coding, that will be sync with S-function block design.

```
function [sys,x0,str,ts]=...
 reactor_sfcn(t,x,u,flag,Cinit,Tinit)

switch flag
 case 0 % initialize
 str=[] ;
 ts = [0 0] ;
 s = simsizes ;
 s.NumContStates = 2 ;
 s.NumDiscStates = 0 ;
 s.NumOutputs = 2 ;
 s.NumInputs = 1 ;
 s.DirFeedthrough = 0 ;
 s.NumSampleTimes = 1 ;
 sys = simsizes(s) ;
 x0 = [Cinit, Tinit] ;
 case 1 % derivatives
 Tj = u ;
 sys = reactor(t,x,Tj) ;
 case 3 % output
 sys = x;
 case {2 4 9} % 2:discrete
 % 4:calcTimeHit
 % 9:termination
 sys =[];
 otherwise
 error([' unhandled flag =',num2str(flag)]) ;
end
```

The S-function Simulink design for concentration of non-isothermal CSTR;

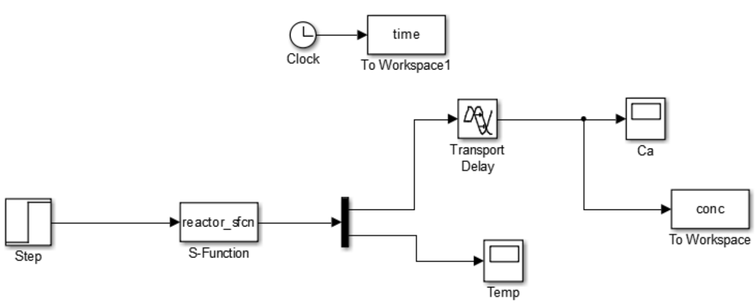

FIGURE 3.3 Simulink design for set-point (benchmark)

3.4.2 STAGE 2: Creating Transfer Function – for set-point (benchmark)

The result of the mathematical model, which is the graph of benchmark of this project that will be shown in Figure 4.1. The transfer function is calculated as;

$$Transfer\ function\ (TF) = \frac{Unstable\ process\ gain, Kp}{Process\ time\ constant, \tau_c\ (s)+1}\ e^{-Time\ delay, \tau_d(S)} \quad (5)$$

where;

$$Unstable\ process\ gain, Kp = \frac{\Delta PV\ (\ Process\ Variable)}{\Delta MV\ (Step\ size)} \quad (6)$$

To get the process time constant, τ_c

$$x\ = 0.632(\Delta PV) \quad (7)$$

*the value of x will lead to the process time constant, τ_c in the graph;

These parameters are obtained from the benchmark graph; based on (5), (6), (7)

TABLE 3.3 The parameters in the transfer function

Unstable process gain, Kp	Process Time Constant, τ_c	Time Delay, τ_d
0.1287	0.2	3

So; the transfer function for this project is:

$$Transfer\ function\ (TF) = \frac{0.1287}{0.2s+1}\ e^{-3S} \qquad (8)$$

3.4.3 STAGE 3: Create SIMULINK design with PID controller (Adaptive)

As for this project, selected PID Control strategy application for this reactor, which is the adaptive control with respect to the set point and disturbance.

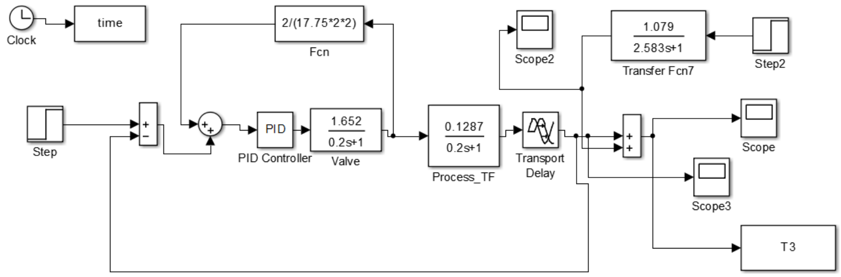

FIGURE 3.4. Simulink design with Adaptive PID controller

3.4.4 STAGE 4: Create SIMULINK design with Fuzzy Logic Controller

This project basically to design the PID controller with a simple modification of fuzzy logic based on IF-THEN rules into the control system. Besides it does not have analytic formula to use for control specification and stability analysis. The fuzzy PID controller are the accepted extensions for the conventional control system, which prevent the errors and increase of its precision, with just a simple analytical formulas as their final result of the design.

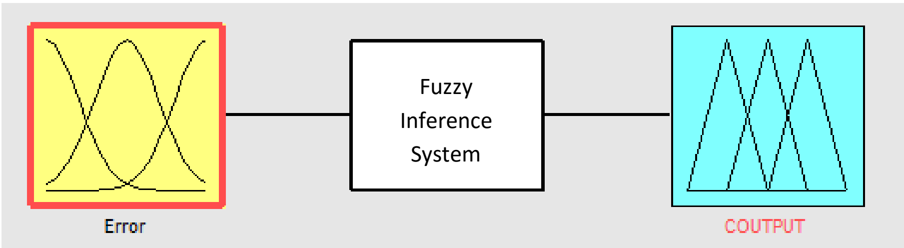

FIGURE 3.5 The concept of mamdani based fuzzy inference system

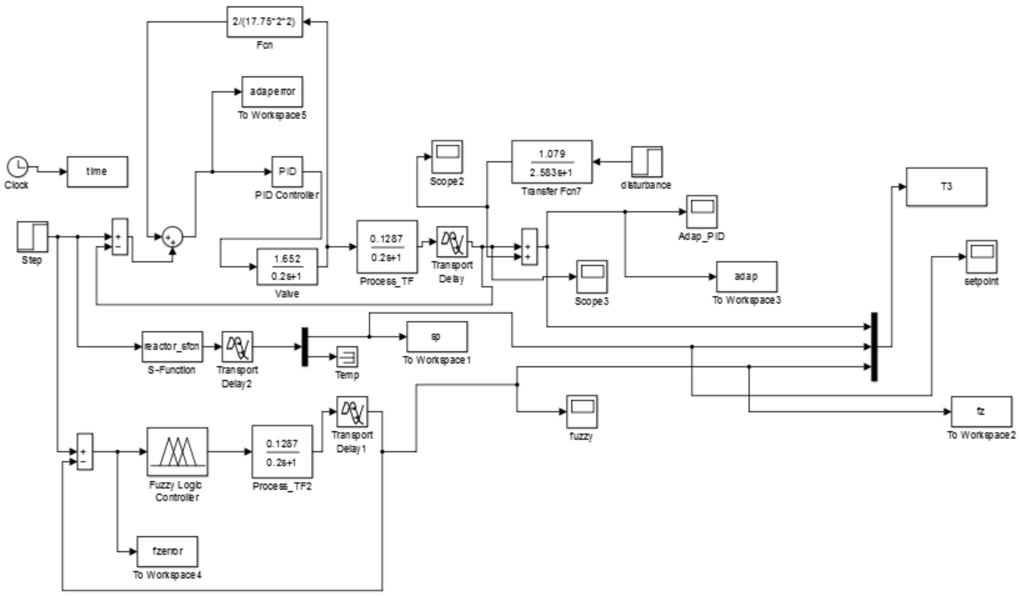

FIGURE 3.6 Proposed Simulink design of Fuzzy logic and Adaptive PID controller

Figure 3.5 shows the concept of fuzzy inference system that had developed for this project. Figure 3.6 shows the overall Simulink design of this project, based on the transfer function of this project (keeps the general design of PID controller as shown figure 3.4)

TABLE 3.4 The linguistic variable for fuzzy set rules

VARIABLE	**NH**	**NL**	**ZERO**	**PL**	**PH**
ERROR (Error)	Negative High	Negative Low	Zero	Positive Low	Positive High
COUTPUT (Controller Output)	Negative High	Negative Low	Zero	Positive Low	Positive High

The fuzzy set rules (base) had been described as below:

1. IF “Error is very NH” THEN “Controller Output is very PH”

2. IF “Error is very NL” THEN “Controller Output is very PL”

3. IF “Error is very ZERO” THEN “Controller Output is very ZERO”

4. IF “Error is very PL” THEN “Controller Output is very NL”

4. IF “Error is very PH” THEN “Controller Output is very NH”

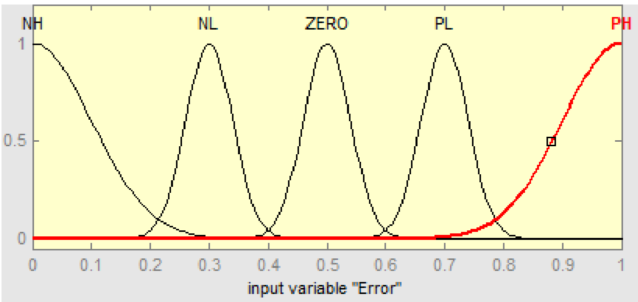

FIGURE 3.7 Inputs membership function

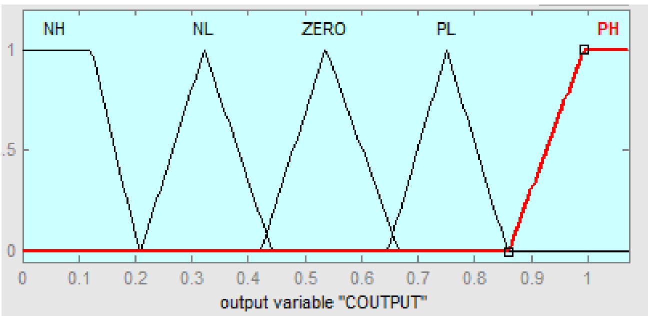

FIGURE 3.8 Outputs membership function

Figure 3.7 and 3.8 shows the inputs, e (t) and output, u (t) of membership function of mamdani based fuzzy inference system

CHAPTER 4

RESULT AND DISCUSSION

4.1 Result – Benchmark Non-Isothermal CSTR Concentration

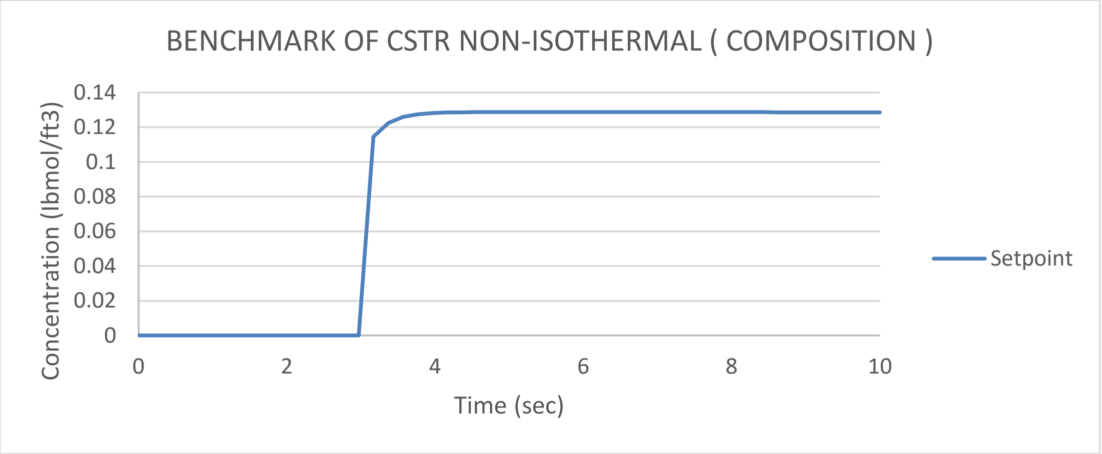

FIGURE 4.1 Result Benchmark of non-isothermal CSTR Concentration

TABLE 4.1 Result Data of benchmark of non-isothermal CSTR Concentration with respective time

TIME	COMPOSITION	TIME	COMPOSITION	TIME	COMPOSITION
0	0	3.3707	0.1225	6.2	0.1287
0.1707	0	3.5707	0.126	6.4	0.1287
0.3707	0	3.7707	0.1275	6.6	0.1287
0.5707	0	3.9707	0.1282	6.8	0.1287
0.7707	0	4.1707	0.1285	7	0.1287
0.9707	0	4.3707	0.1286	7.2	0.1287
1.1707	0	4.5707	0.1287	7.4	0.1287
1.3707	0	4.7707	0.1287	7.6	0.1287
1.5707	0	4.9707	0.1287	7.8	0.1287
1.7707	0	5	0.1287	8	0.1287
1.9707	0	5	0.1287	8.2	0.1287
2.1707	0	5	0.1287	8.4	0.1287
2.3707	0	5.2	0.1287	8.6	0.1286
2.5707	0	5.4	0.1287	8.8	0.1286
2.7707	0	5.6	0.1287	9	0.1286
2.9707	0	5.8	0.1287	9.2	0.1286
3.1707	0.1145	6	0.1287	9.4	0.1286

4.2 Result – Non-Isothermal CSTR for Concentration by using Adaptive PID Controller

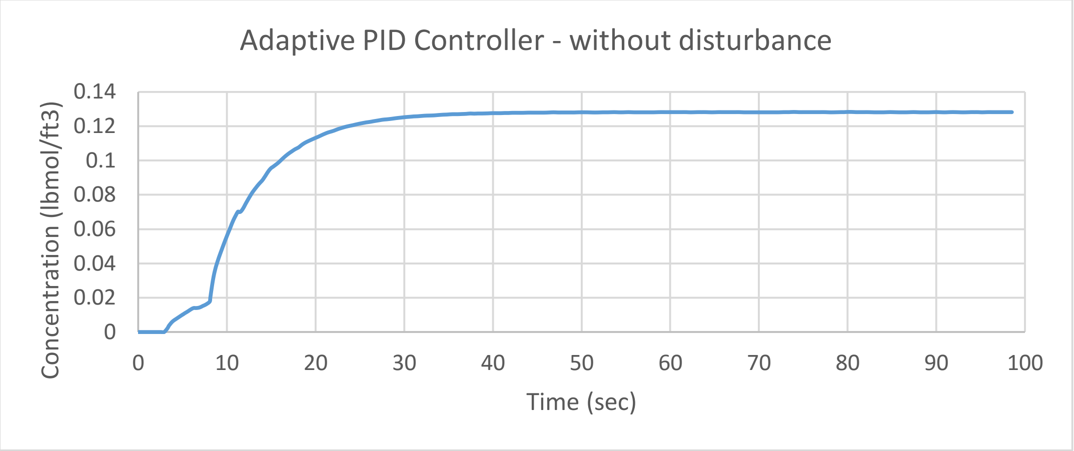

FIGURE 4.2 Result Adaptive PID Controller without disturbance

From the FIGURE 4.2, is the result of Adaptive PID controller without any disturbance. The concentration is most almost reach to the set-point, 0.1287. It just a small amount of steady state error, 0.31%.

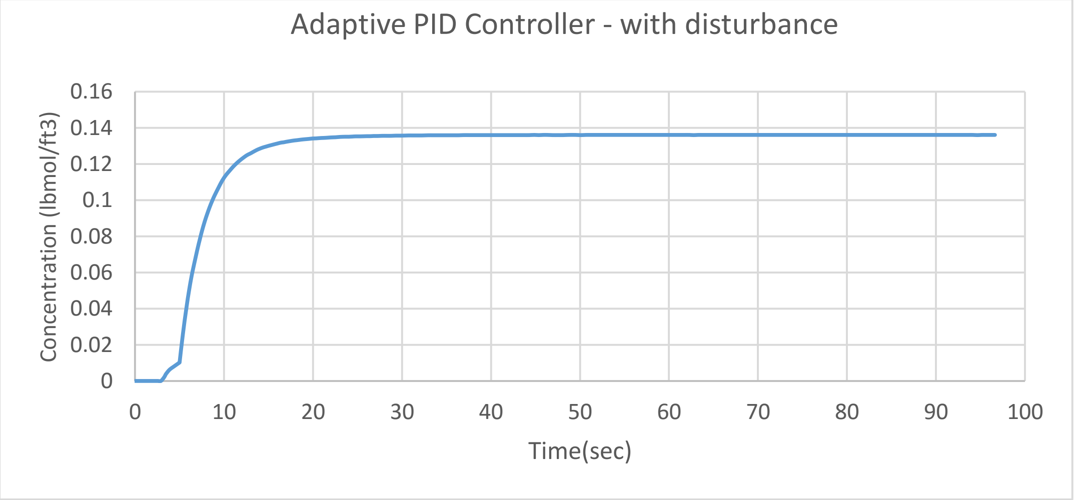

FIGURE 4.3 Result Adaptive PID Controller with disturbance

Meanwhile, this FIGURE 4.3 is the result of Adaptive PID controller with disturbance. The concentration response of the system generates 5.8% of steady state of error.

4.3 Result – Non-Isothermal CSTR for Concentration by using Fuzzy Logic Controller with different source

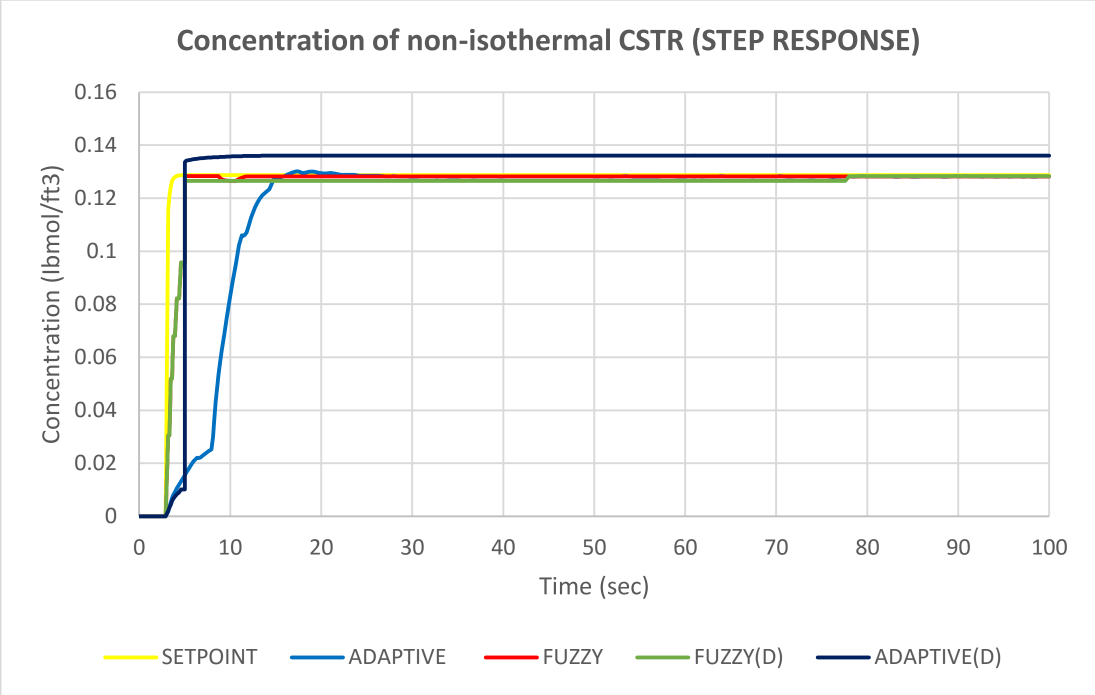

FIGURE 4.4 Graph of concentration of CSTR (step response)

TABLE 4.2 Summary result of controller tuning for concentration in CSTR

DETAILS	FUZZY LOGIC	ADAPTIVE	FUZZY LOGIC DISTURBANCE	ADAPTIVE DISTURBANCE
Rise Time	1.07E-05	0.0453	6.20E-06	0.0237
Settling Time	0.1282	0.1282	0.1265	0.1361
Peak Time	0.1282	0.1282	0.1265	0.1361
IAE	2.45	8.73	4.12	11.32

As we can see from the figure and the result, it had shown us that, by using the fuzzy logic controller, generates small of Integral Absolute Error, IAE (area under graph), 2.45 compared with the Adaptive controller in which generate 8.73. But if creating the control system with disturbance, the fuzzy logic will generates, 4.12 and Adaptive PID controller generates, 11.32. A huge effect from the Adaptive controller almost 5% decreasing. In meantime, fuzzy logic's settling time is very quick compared to the others.

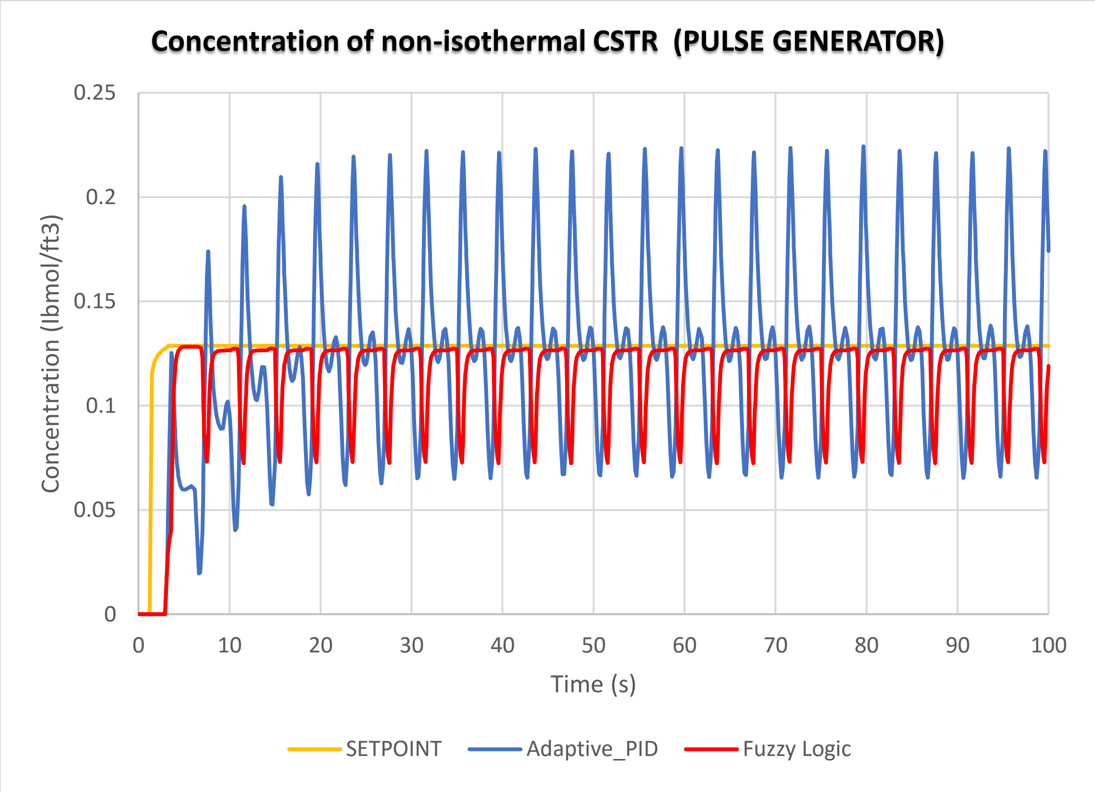

FIGURE 4.5 Graph of concentration of CSTR (Pulse generator)

TABLE 4.3 Summary result of controller tuning for concentration in CSTR (Pulse generator)

DETAILS	FUZZY LOGIC	ADAPTIVE_PID
Rise Time	1.02E-05	0.03
Settling Time	0.1265	0.125
Peak Time	0.119	0.1742
IAE	11.38	12.36

For the pulse generator shown in Figure 4.5, the error gain from the fuzzy logic is smaller than adaptive PID controller (IAE fuzzy = 11.38 and IAE adaptive PID = 12.36). Besides, the PID controller fluctuates more compared to the fuzzy logic.

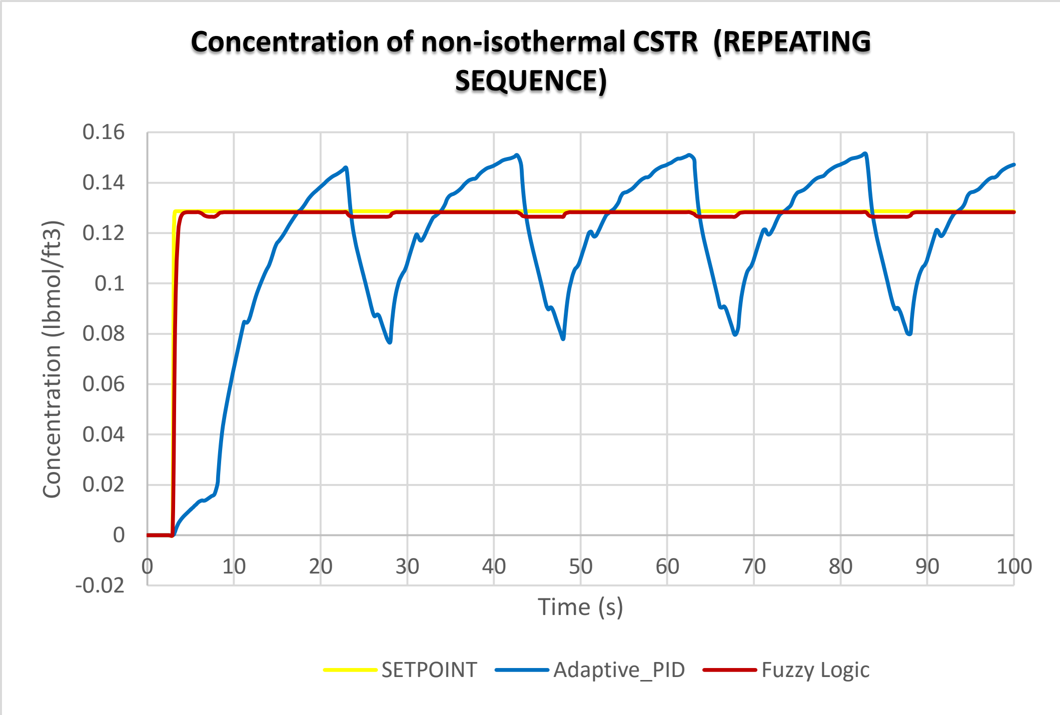

FIGURE 4.6 Graph of concentration of CSTR (Repeating Sequence)

TABLE 4.4 Summary result of controller tuning for concentration in CSTR (Repeating Sequence)

DETAILS	FUZZY LOGIC	ADAPTIVE_PID
Rise Time	1.02E-07	0.0431
Settling Time	0.1283	0.1427
Peak Time	0.1283	0.1742
IAE	4.47	13.91

As for repeating sequence shown in Figure 4.6, the error gain from the fuzzy logic is 4.47 meanwhile adaptive PID controller is 13.91. It shows that PID controller still produce a lot error compared to the fuzzy logic controller. More oscillation produced from the PID controller from 0.08 to 0.15 Ibmol/ft3. However, as for fuzzy logic less fluctuation been produced even its value is quite close to the set point.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

As for the conclusion, we could find that the fuzzy logic can gives the most favorable result. This is because the IAE is very small, the settling time settle quickly and less oscillation. The target of the concentration is 0.1287 lbmol/ft3 with time delay of 3 second.

So based on the result, the fuzzy logic concept has proven to us that it can be an effective solution to a complex control problem. Thus it is an alternative to the use of another controller. Yet, the author believes that it can brings more benefits in the development of industrial process control system.

Usually, the fuzzy logic concept is still not a perfect in process control. It is just an improvement to old conventional controller. So, there is a several recommendations can be made;

1. By studying and review back the fuzzy logic concept’s weakness.
2. Develop new concept in which does not require a complex equation model and do the comparison with the fuzzy logic
3. All the data must be based on the experimentation to ensure that there is no slight error that can be made.

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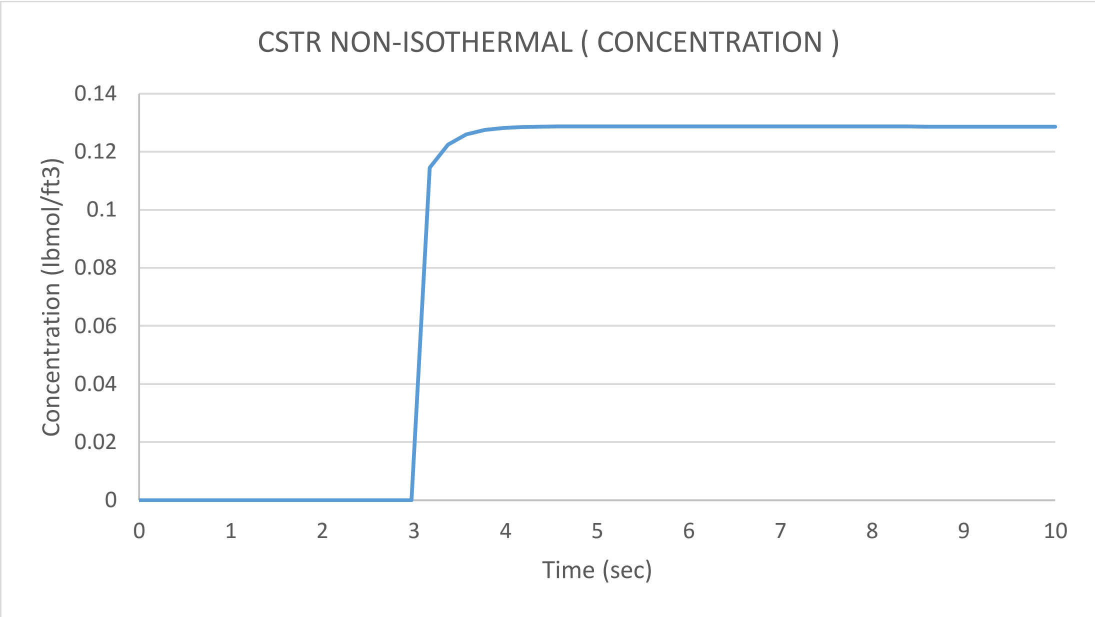
APPENDICES

APPENDICES A

To calculate the transfer function, based on the values given from the graph:



Process variable; PV = 0.1287

Manipulated variable, MV = 1 (step size, final value-initial value) from simulation

Time delay, τd= 3 sec

The unstable process gain, Kp = $Kp = \frac{PV}{MV} = \frac{0.1287}{1}$

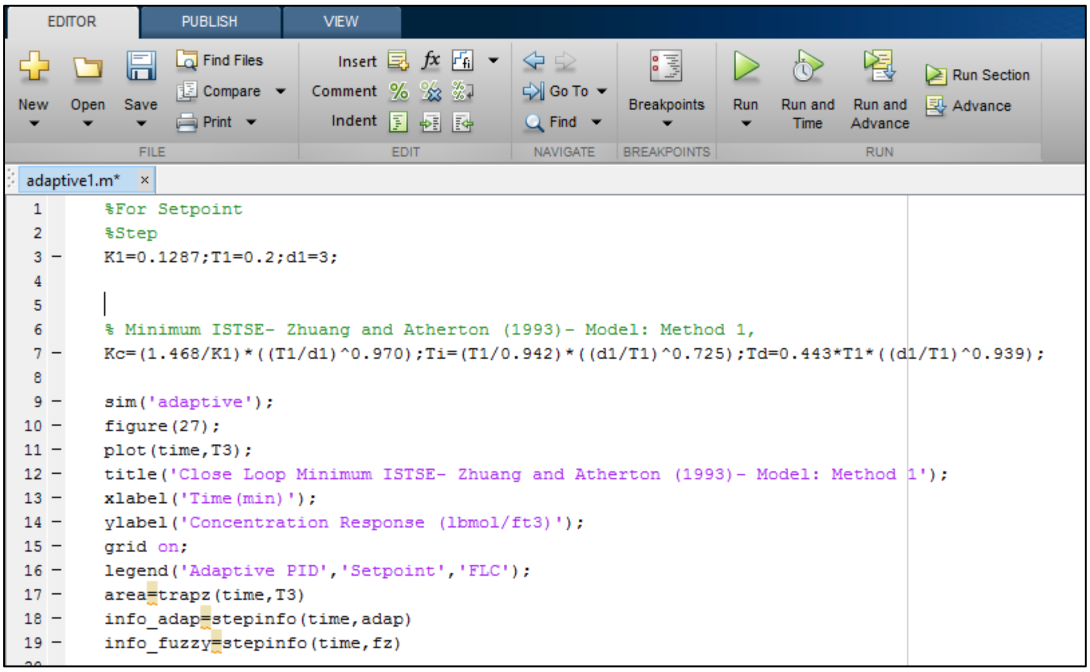
Process time constant, τc

$$x = 0.632(PV) = 0.632(0.1287) = 0.08134{\sim}0.08$$

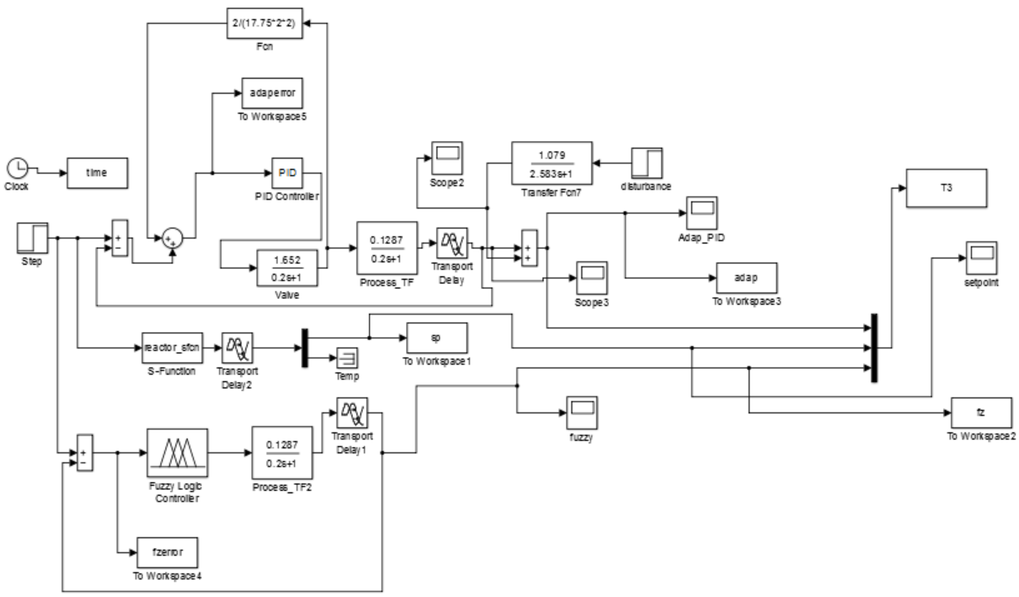
Then, find the time that reach to the concentration 0.08, so the τc = 3.2-3.0 =0.2 sec, minus with the time delay, 3 sec,

So, for the transfer function; Transfer Function (TF) = $\frac{Kp}{\tau c\ s+1}\ e^{-\tau dt}$

Substitute, the value inside the transfer function, TF = $\frac{0.1287}{0.2\,s+1}\;e^{-3t}$



Mathematical Coding in m.files



Overall Simulink design with Fuzzy Logic controller

APPENDICES B

B.1 ADAPTIVE PID CONTROLLER (WITHOUT DISTURBANCE)

Data of the Adaptive PID Controller without disturbance

TIME	CONC	TIME	CONC	TIME	CONC	TIME	CONC	TIME	CONC
0	0	1.4743	0	5	0.0102	5	0.0102	94.3149	0.1282
0.0002	0	1.9274	0	5	0.0102	5	0.0102	94.752	0.1282
0.0012	0	2.5385	0	5	0.0102	5	0.0102	95.1787	0.1281
0.0062	0	2.9056	0	5	0.0102	5	0.0102	95.7497	0.1282
0.0314	0	3.2727	0.0021	5	0.0102	5	0.0102	96.3207	0.1282
0.117	0	3.4141	0.0034	5	0.0102	5	0.0102	97.0816	0.1282
0.2028	0	3.5555	0.0044	5	0.0102	5	0.0102	97.5349	0.1282
0.3143	0	3.786	0.0058	5	0.0102	5	0.0102	97.9882	0.1282
0.4525	0	3.9887	0.0067	5	0.0102	5	0.0102	98.5308	0.1282
0.6237	0	4.215	0.0075	5	0.0102	5	0.0102	99.0258	0.1282
0.8398	0	4.4505	0.0083	5	0.0102	5	0.0102	99.6031	0.1282
1.1263	0	4.6784	0.0091	5	0.0102	5	0.0102	100	0.1283

B.2 ADAPTIVE PID CONTROLLER (WITH DISTURBANCE)

Data of the Adaptive PID Controller with disturbance

TIME	CONC	TIME	CONC	TIME	CONC	TIME	CONC	TIME	CONC
0	0	1.9274	0	5	0.0102	8.3843	0.0962	94.1351	0.1361
0.0002	0	2.5385	0	5.3751	0.026	8.6729	0.0997	94.6601	0.136
0.0012	0	2.9056	0	5.7501	0.0398	8.9548	0.1028	95.1258	0.1361
0.0062	0	3.2727	0.0021	6.0719	0.0502	9.4145	0.1073	95.5241	0.1361
0.0314	0	3.4141	0.0034	6.3196	0.0572	9.6661	0.1097	96.0356	0.1361
0.117	0	3.5555	0.0044	6.4812	0.0611	9.9177	0.1118	96.6337	0.1361
0.2028	0	3.786	0.0058	6.6428	0.0648	10.1537	0.1135	97.1032	0.1361
0.3143	0	3.9887	0.0067	6.8661	0.0698	10.3626	0.1148	97.5727	0.1361
0.4525	0	4.215	0.0075	7.0701	0.0742	10.6074	0.1162	98.0331	0.1361
0.6237	0	4.4505	0.0083	7.2583	0.078	11.0164	0.1185	98.4641	0.1361
0.8398	0	4.6784	0.0091	7.4897	0.0825	11.3662	0.1202	98.8851	0.1361
1.1263	0	5	0.0102	7.8181	0.0881	11.7054	0.1217	99.4417	0.1361

B.3 FUZZY LOGIC CONTROLLER (WITHOUT DISTURBANCE

Data of the Fuzzy logic Controller without disturbance

TIME	CONC	TIME	CONC	TIME	CONC	TIME	CONC	TIME	CONC
0	0	1.9107	0	5	0.1283	5	0.1283	94.2595	0.1271
0.0002	0	2.5156	0	5	0.1283	5	0.1283	94.7235	0.1271
0.0012	0	2.8931	0	5	0.1283	5	0.1283	95.1876	0.1271
0.0062	0	3.1905	0.0785	5	0.1283	5	0.1283	95.6711	0.1271
0.0314	0	3.3257	0.1026	5	0.1283	5	0.1283	96.1592	0.1271
0.1124	0	3.461	0.1152	5	0.1283	5	0.1283	96.5796	0.1271
0.1965	0	3.6194	0.1225	5	0.1283	5	0.1283	97.1281	0.1271
0.3074	0	3.7683	0.1252	5	0.1283	5	0.1283	97.7011	0.1271
0.445	0	3.9135	0.1268	5	0.1283	5	0.1283	98.1047	0.1271
0.6159	0	4.145	0.1279	5	0.1283	5	0.1283	98.5083	0.1271
0.8319	0	4.3765	0.1281	5	0.1283	5	0.1283	98.9653	0.1271
1.1162	0	4.5899	0.1283	5	0.1283	5	0.1283	100	0.1271

B.4 FUZZY LOGIC CONTROLLER (WITH DISTURBANCE)

Data of the Fuzzy Logic Controller with disturbance

TIME	CONC	TIME	CONC	TIME	CONC	TIME	CONC	TIME	CONC
0	0	1.9107	0	5	0.1283	5	0.1283	94.2595	0.1283
0.0002	0	2.5156	0	5	0.1283	5	0.1283	94.7235	0.1283
0.0012	0	2.8931	0	5	0.1283	5	0.1283	95.1876	0.1283
0.0062	0	3.1905	0.0943	5	0.1283	5	0.1283	95.6711	0.1283
0.0314	0	3.3257	0.1113	5	0.1283	5	0.1283	96.1592	0.1283
0.1124	0	3.461	0.1196	5	0.1283	5	0.1283	96.5796	0.1283
0.1965	0	3.6194	0.1255	5	0.1283	5	0.1283	97.1281	0.1283
0.3074	0	3.7683	0.1272	5	0.1283	5	0.1283	97.7011	0.1283
0.445	0	3.9135	0.128	5	0.1283	5	0.1283	98.1047	0.1283
0.6159	0	4.145	0.1282	5	0.1283	5	0.1283	98.5083	0.1283
0.8319	0	4.3765	0.1283	5	0.1283	5	0.1283	98.9653	0.1283
1.1162	0	4.5899	0.1283	5	0.1283	5	0.1283	100	0.1283