Decoupling Control of a FCC Unit Using Fuzzy Logic

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Abstract

A control system of a fluidized-bed catalytic cracking unit has been developed in this work where the dynamic and control system based on basic energy balance in the reactor and regenerator systems have been carried out. For the control system, the important input variables were chosen to be the reactor temperature and the regenerator temperature. The manipulated variables are the catalyst recirculation rate, and the regenerator air rate. The transfer function models relating the outputs and inputs were developed using Sundaresan and Krishnaswamy's method. The degree of interaction was determined based on Relative Gain Array (RGA) and should be avoided by implementing a decoupling system. Two Decouplers were designed which should eliminate the interaction effects between the control loops. Tuning of Control Parameters was found by the Internal Model Control (IMC) to find the initial values of Proportional gain (K_c), Integral time (τ_I) and Derivative time (τ_D). PID control was implemented as a control strategy for both reactor and regenerator. Fuzzy logic control system was used as another strategy to compare with conventional control system. For two cases, the Fuzzy logic controller is preferable because it does not require an accurate mathematical model to be built for the process. On the other hand, another control strategy used needs a wide knowledge of the process dynamics and an accurate mathematical model to be built and solved. In addition Fuzzy logic control gives lower value of ISE when compared with optimized PID control.

Keywords: Decoupling Control, FCC unit, Fuzzy Logic system.

سيطرة الغاء التداخل لوحدة التكسير بالعامل المساعد المتميع باستخدام منطقي الضبابي

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الخلاصة

تم تطوير نظام السيطرة لوحدة التكسير بالعامل المساعد المتميع في هذا العمل حيث اعتمد على موازنة الطاقة في كل من المفاعل و المنشط في دراسة السلوك الديناميكي و نظام السيطرة. في نظام السيطرة هذا، اختيرت درجة حرارة المفاعل و درجة حرارة المنشط كمتغيرات مقاسة و اعتبركل من معدل جريان العامل المساعد و معدل جريان الهواء كمتغيرات معالجة. تم ايجاد دوال الانتقال لكل من المتغيرات المقاسة و المتغيرات المعالجة باستخدامSundaresan and Krishnaswamy's method. حددت درجة التداخل بالاعتماد على مصفوفة الكسب النسبي(RGA) مما يتطلب الى نظام Decoupling. تم تصميم نظامين Decouplers لالغاء تاثير التداخل في دوائر السيطرة. تم توصيف مؤشرات السيطرة بطريقة و هي Internal Model Control لايجاد افضل قيم للمعاملات Kc و τ_I و τ_D . تم تطبيق صيغة PID في استراتيجية نظام السيطرة لكل من المفاعل و المنشط و قد تم استخدام نظام السيطرة المنطقي كاستراتيجية اخرى للمقارنة مع نظام السيطرة التقليدي وفي الحالتين نجد ان نظام السيطرة المنطقي هو الافضل حيث انه لا يحتاج الى موديل رياضي دقيق في حين تحتاج استراتيجية السيطرة الاخرى الى معرفة واسعة لديناميكية العمليات والى موديل رياضي واضح. بالاضافة الى ان نظام السيطرة المنطقي اعطى اقل قيمة للخطا في جميع الحالات التي استخدمت في هذه الدراسة

الكلمات المفتاحية: سيطرة الغاء التداخل، وحدة التكسير بالعامل المساعد، نظام المنطقي الضبابي.

Nomenclature

Symbol	Definition	Units
(A)	Fuzzy subset	[–]
D	Decoupler system	[–]
D(s)	Transfer function of disturbance	[–]
$D_1(s)$	Dynamic element (Decoupler) for loop 1	[–]
$D_2(s)$	Dynamic element (Decoupler) for loop 2	[–]
E	Error	[^oC]
$F_a(s)$	Transfer function of air	[kg /sec]
$F_s(s)$	Transfer function of regenerated catalyst	[kg /sec]
$G_c(s)$	Transfer function of controller	[–]
$G_d(s)$	Transfer function of disturbance	[–]
$H_{ij}(s)$	Transfer functions between output and input	[–]
$H_{11}(s)$	Transfer functions between $T_{rea}(s)$ and $F_s(s)$	[–]
$H_{12}(s)$	Transfer functions between $T_{rea}(s)$ and $F_a(s)$	[–]
$H_{21}(s)$	Transfer functions between $T_{reg}(s)$ and $F_s(s)$	[–]
$H_{22}(s)$	Transfer functions between $T_{reg}(s)$ and $F_a(s)$	[–]
K_c	Proportional gain	[psig/^oC]
s	Laplacian variable	[sec^{-1}]
t_d	Time delay	[sec]
U_i	Control action	[–]
U_s	Scalar control unit	[–]
XG	Controller gain in Fuzzy logic control	[–]
y	Output variable	[–]
y_{st}	Desired set point of controlled output	[–]

Greek Symbols

Symbol	Definition	Units
Λ	Relative gain array	[–]
λ_{ij}	Elements of relative gain array	[–]
λ_{11}	Relative gain between T_{rea} and F_s	[–]
λ_{12}	Relative gain between T_{rea} and F_a	[–]
λ_{21}	Relative gain between T_{reg} and F_s	[–]
λ_{22}	Relative gain between T_{reg} and F_a	[–]
τ	Time constant	[sec]
τ_C		
τ_D	Derivative time	[sec]
τ_I	Integral time	[sec]
υ	Universe of discourse	[–]
μ	Membership function	[–]

List of Abbreviations

Symbol	Definition
FCCU	Fluidized Catalytic Cracking Unit
FLC	Fuzzy Logic Control
ISE	Integral of Square of Error
NB	Negative Big
NCB	Negative change of Error Big
NEB	Negative Error Big
NES	Negative Error Small
NS	Negative Small
NUB	Negative control action Big
NUS	Negative control action Small
PB	Positive Big
PEB	Positive Error Big
PES	Positive Error Small
PS	Positive Small
PCB	Positive change of Error Big
PCS	Positive change of Error Small
PUB	Positive control action Big
PUS	Positive control action Small
RGA	Relative Gain Array
ZC	Zero change of error
ZE	Zero Error
ZU	Zero control action

Introduction

Fluid catalytic cracking (FCC) continues to play a key role in an integrated refinery as he primery process. For many refiners. The cat cracker is the key to profitability in that tha successful operation of the unit determines wherter or not the refiner can remain competitive in today’s marcket.(1)

Main Components of Fluid Catalytic Cracking Unit

Reactor

The gasoil feed is preheated and vaporized in an extensive heat exchanger network and a fired furnace. It is then combined with a large stream of hot solid catalyst and some steam at the bottom of a riser. The hydrocarbon vapor and steam provide the motive force to convey the solid and gas phases upward together at high velocity. This type of fluidized bed is called a “transport” reactor (co-current flow of solid and gas phases). The gasoil cracks to form lighter hydrocarbons and coke (mostly carbon), which is deposited on the solid catalyst particles. The very large endothermic heat of reaction of the cracking reactions is provided by the sensible heat of the hot catalyst. The reactor operates at about 1000 ^{o}F (537.78 ^{o}C), and the hot catalyst enters from the regenerator at about 1250 ^{o}F (676.67 ^{o}C). The hot gases leave the top of the reactor through cyclones to reject any catalyst particles and go to the separation section of the plant (fractionator, compressor, absorber, and light-end distillation columns). The solid catalyst, which now contains a significant amount of coke, is steam-stripped to remove most of the residual hydrocarbons (Figure (1)). [(2)]

Regenerator

The second reaction vessel in a catalytic cracker is called the "regenerator." The solid catalyst from the reactor is combined with a compressed air stream from an air blower, and the solid and gas phases flow upward into a bed of fluidized solid catalyst. The early designs used a "bubbling bed" reactor in which the velocity in the bed is slightly above the minimum fluidization velocity. More recent designs use a transport fluidized-bed reactor. A typical air-to-oil weight ratio is 0.54. The oxygen in the air burns the carbon and any residual entrained hydrocarbons off the catalyst, producing carbon monoxide, carbon dioxide, and water. Catalytic coolers are usually installed in the regenerator vessel to provide heat removal capacity when needed for balancing the energy requirements in the unit. These coolers generate steam for use elsewhere in the refinery. The combustion gases flow through cyclones and leave as stack gas. There is incomplete burning of the CO to CO_2 in the dense phase of the catalyst bed in the regenerator. However, in the dilute phase above the bed, this reaction proceeds further. Since the $CO + \frac{1}{2} O_2 \rightarrow CO_2$ reaction is very exothermic, there is an increase in temperature between the catalyst bed and the stack gas. This is called "afterburning." If the stack gas temperature gets too high, there may be thermal damage to the cyclones (Figure (1)).

Heat Balance of a FCC Unit

The heat of combustion of the coke supplies the majority of heat required for the reaction, and it was always realized in the design of crackers that it was important to maintain the correct heat balance between reactor and regenerator. Consequently, early units were built with feed preheaters to supply additional heat to the reactor, if required, and also means of removing heat from the regenerator such as catalyst coolers and water injection.(3)

Heat Balance of the regenerator

Heat of combustion of coke equals to net heat transfer to reactor plus heat required

1. To raise air to regenerator temperature.
2. To raise coke on catalyst from reactor temperature to regenerator temperature.
3. To make up losses by conduction, radiation, etc.
4. To make up heat removed by catalyst coolers, water injection, etc. (3)

With the condition:

- ❖ Spent catalyst entered the regenerator at 500 ^{o}C (737 K).
- ❖ Air entered the regenerator at 500 ^{o}C (737 K).
- ❖ The operating temperature for the regenerator is 720 ^{o}C (993 K).(4)

Heat Balance of the reactor

Net heat transfer from regenerator equals to heat required

5. To heat combined feed to reactor temperature.
6. To supply heat to reaction.
7. To raise stripping stream to reactor temperature.
8. To make up losses by conduction, radiation, etc. (3)

With the condition:

- ❖ Fresh feed entered the reactor at 200 ^{o}C (473 K).
- ❖ Regenerated catalyst entered the reactor at 720 ^{o}C (993 K).
- ❖ Steam entered to the reactor at 250 ^{o}C (523 K).
- ❖ The operating temperature in the reactor is 500 ^{o}C (773 K).(4)

As above, the heat of coke combustion is seen to be equal to the sum of items 1-8. The contribution of each item towards the total will of course vary according to the design and operating condition but a typical distribution would be as follows: (3)

1. Heating feed equals to 50% of heat of combustion of coke.
2. Heat of reaction equals to 20% of heat of combustion of coke.
3. Heating air equals to 20% of heat of combustion of coke.
4. Losses equals to 7% of heat of combustion of coke.
5. Heat stripping steam equals to 3% of heat of combustion of coke.

Unit Control of a Fluidized Catalytic Cracking Unit

A typical control system of Fluidized Catalytic Cracking Unit (FCCU) is shown in Figure (1) where fresh feed and recycle are flow controlled and the reactor temperature is controlled by the regenerator slide valve which regulated the flow of the hot catalyst to the transfer line. Reactor pressure is regulated by control of the gas compressor in the system recovery system and regenerator pressure is controlled by differential pressure instrument between reactor and regenerator acting in the flue-gas outlet line. [3]

Although numerous advanced control concepts have been proposed, the control of most chemical and petroleum processes is still largely based on some form of multi loop feedback. Yet there is a real need for control logic that effectively utilizes the available process measurements and model information characteristic of many processes. The fluidized catalytic cracking (FCC) unit of a petroleum refinery is an example of such a process. More effective control would offer steady-state operation nearer the constraint boundary, as well as reduce disturbance effects.

Any FCC control should maintain a suitable reactor temperature distribution so as to achieve good product characteristics. The regenerator temperature profile should also be bounded so as to prevent abnormal combustion and excessive temperatures. At the same time, energy and material balances must be maintained between the two parts of the unit. The reactor pressure can be maintained by manipulating the fractionator overhead gas compressor speed or the overhead gas recycle rate. The flue gas rate can be manipulated to maintain the regenerator pressure.

The measurements that are available include numerous point temperatures, vessel pressures, catalyst levels, air flow, catalyst rates, flue-gas oxygen composition, and, often, a variety of other on-line and off-line measurements. Common manipulations, in addition to those mentioned above, are air rate, spent catalyst rate, regenerated catalyst rate, regenerator heat removal rate, and feed temperature manipulation. [4,5]

Modeling of a FCC Unit

Catalytic cracking is one of the largest and most intensively used processes in industry. This process is considered as one of the most important developments of chemical engineering of the last century.

There are numerous papers relating to the FCC process. They present various aspects of mathematical modeling and simulation, stability, optimization, and optimal control. As the investigation of the dynamics and control of a system requires a model to work with, this is the subject of many of the FCC papers. Some of these papers present useful approaches but insufficient information to allow to their use. For our purposes it is sufficient to discuss the properties of the most recent models used by investigators as these incorporate most of the previous work. These are the model proposed by Lee and Groves and the model published by McFarlane et al. [6]

The model used by Lee and Groves [7] gives description in the fluid dynamic description of the regenerator. It is simple stirred tank with no dilute phase. Lee and Groves use the three-lump model. McFarlane et al. [8] published their model in the context of the AIChE industrial challenge problem. This model describes an old Exxon Model IV unit which has no independent way to control catalyst flow and is rather obsolete today. Chang S.L. et al. [9] developed a new and modified process to meet more stringent environmental regulations. Short residence time FCC riser reactor is one of the advanced processes that the refining industry is actively pursuing because it can improve the yield selectivity and efficiency of an FCC unit. Raul et al. [10] developed a mathematical model of the gas-solid flow that takes place in FCC risers. On the other hand, Pashne et al. [11] developed an integrated FCC simulator that can be used for studying the performance of the reactor (riser) and the regenerator and also the interactions between them. An integrated dynamic model for the complete description of the fluid catalytic cracking unit (FCCU) was developed by Bollas G.M et al. [12]; the model simulates successfully the riser and the regenerator of FCC and incorporates operating conditions, feed properties and catalyst effects. The simulator can be utilized as a basis for a model based control of

FCC units. Osman A. M. [13] developed a kinetic model to simulate the riser of a residue fluid catalytic cracking unit (RFCC) processing residue from Sudanese crude oil. She used the MATLAB environment to solve and analyze the kinetic model and process variables. Hassan Sh. [14] developed Material and energy balance calculations to design Fluidized catalytic cracking (FCC) unit from Iraqi crude oil. She used the visual basic program in her work.

Control of FCCU

There are many control formulations that concern the description of the control system of a fluidized catalytic cracking unit (FCCU) and how to choose the controlled variables, manipulated variables and disturbance variables. The following are some scientific searches in this field.

Snodgrass [15] developed the three principal Feedback loops that provide the automatic control and these are: (1) control of reactor catalyst level by manipulation of spent catalyst rate, (2) control of a reactor temperature by manipulation of the regenerated catalyst rate*;* and (3) control of flue-gas oxygen composition by manipulation of regenerator air rate. Grosdidier [16] et al. provided simulation results for a representative FCCU regenerator control problem. The problem involves controlling flue gas composition, flue gas temperature, and regenerator bed temperature by manipulating feed oil flow, recycle oil flow and air to the regenerator. McFarlane et al. [8] developed their model as following: controlled variables (cracking temperature and Flue gas oxygen concentration), manipulated variables (lift air compressor speed and flue gas valve opening). chunyang et al. [17] made the formulation of a FCCU control as following: Controlled variables (riser outlet temperature, reactor bed and regenerator differential and reactor bed level), manipulated variables (regenerator catalyst flow rate, flue gas flow rate and spent catalyst flow rate). Moro & Odloak [18] proposed six variables to be controlled: riser temperature, severity, temperature of the dense phase of the regenerator first stage, temperature of the regenerator dense phase of the second stage, the differential valve pressure of the regenerated catalytic and the rotation velocity of the gas compressor. They also proposed the following manipulated variables: feed flow rate to the unit, air flow rate to the regenerator, valve opening of the regenerated catalytic and the feed temperature. The chosen controlled variable here was the temperature of the dense phase of the regenerator first stage, manipulating the air flow rate to the regenerator. Finally, the fluid catalytic cracking (FCC) unit, owing to the tight interaction between the regenerator and the reactor, is dynamically sensitive. It is difficult to accomplish satisfactory control of the FCC operation under frequent disturbances. Since the FCC unit is one of the principal refinery processes for gasoline production, an understanding of its dynamic characteristics is extremely important. It is, therefore, not surprising that a number of investigators have studied the dynamics and control of the FCC. [(19)]

FCC Model Developments

A fluidized catalytic cracking unit (FCCU) is an important process in oil refineries. A simplified process schematic and instrumentation diagram is shown in Figure (1).

The control of the coupled reactor–regenerator is challenging because of the interaction between the two vessels and the "neat" operation in terms of energy. The temperatures in both vessels must be controlled at levels that are just below the metallurgical limits of the equipment materials. A variety of conventional and advanced control structures have been used or proposed for catalytic cracking units. The most authoritative work is presented by Shinnar and coworkers. They discuss both modeling and control structure issues in detail and show that the 2 × 2 control structures provide effective control: Temperature of reactor controlled by F_{cat} and Temperature of regenerator controlled by F_{air}. Other advanced control structures have been studied, including nonlinear control, fuzzy logic control and MPC. A recent review of control studies is given by Uygun and coworkers. In current industrial practice, reactor (or riser) temperature is usually controlled by the flow rate of hot catalyst fed to the reactor from the regenerator. A slide valve in the catalyst transfer line adjusts this flow rate. Since high catalyst-to-oil ratios favor high conversion, the feed preheating temperature can be reduced to increase catalyst flow. A minimum feed temperature is set by requiring that the material be completely vaporized. If the slide valve on the transfer line becomes wide open, reactor temperature can be controlled with feed preheat. The temperature in the regenerator is conventionally controlled by the flow rate of air from the blower.

However, many catalytic cracking units run at maximum airflow as limited by the air blower. In this situation catalyst cooling rates in the regenerator can be used to hold regenerator temperature. However, if air is at a maximum constraint, the amount of coke that can be burned is limited. Therefore, feed flow rate may have to be reduced or feed composition altered (feed lighter gasoil and less heavy material). The catalyst bed level in the reactor is controlled by adjusting a slide valve in the catalyst return line from the reactor to the regenerator. Since the total amount of catalyst in both vessels is essentially constant, the level in the regenerator is not controlled. The thermal capacitance in the system is mostly in the solid catalyst. The catalyst holdup in the regenerator is much larger than in the reactor, so the dynamic response of the reactor is faster than that of the regenerator. Disturbances include changes in the composition of the feed and changes in throughput. Since crude oil is a naturally occurring raw material, its composition changes from source to source. [2]

FCCUs present challenging multivariable control problems. The selection of good inputs (manipulated variables) and outputs (measured variables) is an important issue, as the pairing of chosen controlled and manipulated variables for decentralized control. In this case, the important measured variables are chosen to be the reactor bed temperature /riser outlet temperature (T_{rea}), the regenerator cyclone temperature (T_{reg}). The manipulated variables are the catalyst recirculation rate (F_s) and the regenerator air rate (F_a). [20]

A number of simplified assumptions were made in order to formulate the energy balances in reactor and regenerator which include:

1. Neglecting the conduction, convection and radiation terms.
2. Heat of reaction and Heat of combustion are constant.

Reactor Modeling [14]

Input stream –[Output stream-Heat of reaction] =Rate of Accumulation (1)

Heat of Reg. catalyst + Heat of Feed + Heat of Steam – Heat of Effluent – Heat of Spent Catalyst + Heat of reaction= Rate of Accumulation (2)

$$F_s\, Cp_s\, T_{reg} + F_o\, Cp_o\, T_o + F_{st.}\, H_{st.} - F_p\, Cp_p\, T_{rea} - F_d Cp_d\, T_{rea} + \Delta H_R = (M_p\, Cp_p + M_d\, Cp_d)\,\frac{dT_{rea}}{dt} \quad (3)$$

Where:

Mass of reactor product (M_p): steady state value = 314.76 kg.

Mass of spent catalyst (M_d): steady state value = 2316.86 kg.

Mass flow rate of reactor product (F_p): steady state value = 62.95 kg/sec.

Mass flow rate of spent catalyst (F_d): steady state value = 463.37 kg/sec.

Input (Manipulated Variable):

Regenerated catalyst feed rate (F_s): steady state value = 454.79 kg/sec.

Output (Controlled variable):

Reactor bed temperature (T_{rea}) : steady state value = 503 ^{o}C (776 K).

Regenerator Modeling [14]

Input stream –[Output Stream + Heat of Combustion] = Rate of Accumulation (4)

Heat of Spent catalyst + Heat of Air – Heat of Combustion – Heat of Reg. Catalyst – Heat of Flue gases= Rate of Accumulation (5)

$$F_d\, Cp_d\, T_{rea} + F_a\, Cp_a\, T_a - \Delta H_c - F_s\, Cp_s\, T_{reg} - F_f Cp_f\, T_{reg} = (M_s\, Cp_s + M_f\, Cp_f)\,\frac{dT_{reg}}{dt} \quad (6)$$

Where:

Air temperature (T_a): steady state value = 500 ^{o}C (773 K)

Mass flow rate of regenerated catalyst (F_s): steady state value = 454.79 kg/sec.

Mass of regenerated catalyst (M_s): steady state value = 4547.93 kg.

Mass flow rate of flue gases (F_f): steady state value =75.00 kg/sec.

Mass of flue gases (M_f): steady state value = 750.00 kg.

Input (Manipulated Variable):

Air rate (F_a): steady state value = 66.41 kg/sec.

Output (Controlled variable):

Regenerator cyclone temperature (T_{reg}) : steady state value = 715.5 ^{o}C (988.5 K).

State Space Analysis

In state space analysis we are two types of variables that are involved in the modeling of dynamic system; input variables and output variables, the state space representation for a given system is not unique, except that the number of state variables is the same for any of the different state space representation of the same system. [21]

State space realizations for selected control schemes are given below. Note that the matrices are written as follows:

$A=A_p=A_d$; $B=[B_p\ B_d]$; $C=C_p=C_d$; $D=[D_p\ D_d]$

Where subscript p refers to the plant matrices and subscript d refers to the disturbance matrices. The vertical lines in the B and D matrices indicate the separation point. The linear time invariant model of the system is given by: [22]

$$\dot{X} = Ax + [B_p\ B_d] \begin{bmatrix} u \\ d \end{bmatrix} \quad (7)$$

$$y = Cx + [D_p\ D_d] \begin{bmatrix} u \\ d \end{bmatrix} \quad (8)$$

Where:

u = vector of manipulated variables.

y= vector of output variables.

d = vector of disturbances.

x = vector of system states.

A: is a matrix represents the coefficients of output variables (T_{rea} & T_{reg}).

B: is a matrix represents the coefficients of input variables (F_a & F_s).

C: is an identity matrix.

D: is a matrix represents the coefficients of indirect variables.

The elements of state space A matrix are found by: [23]

$$A_{ij}=\frac{\partial f_i}{\partial x_j} \quad (9)$$

While the elements of B matrix are:

$$B_{ij}=\frac{\partial f_i}{\partial u_j} \quad (10)$$

Fitting of a first order plus time delay model

Sundaresan and Krishnaswamy's Method

The advantage of this method avoids use of the point of inflection construction entirely to estimate the time delay. They proposed that two times, t_1 and t_2, be estimated from a step response curve, corresponding to the 35.3% and 85.3% response times, respectively. The time delay and time constant are then estimated from the following equations: [24]

$$t_d = 1.3t_1 - 0.29t_2 \quad (11)$$

$$\tau = 0.67(t_2 - t_1) \quad (12)$$

These values of t_d and τ approximately minimize the difference between the measured response and the model, based on a correlation for many data sets. By using actual response date, model parameters k, t_d and τ can vary considerably, depending on the operating conditions on the process, the size of the input step change and direction of the change. These variations usually can be attributed to process nonlinearities and unmeasured disturbances. [24]

Control Tuning

Empirical tuning roughly involves doing either an open loop or a closed-loop experiment, and fitting the response to a mode [25]. The controller gains are calculated based on this fitted function and some empirical relations. When empirical tuning relations were used, system dynamic response specifications cannot be dictated. The controller settings are seldom optimal and most often require field tuning after installation to meet more precise dynamic response specifications. Empirical tuning may not be appealing from a theoretical viewpoint, but it gives a quick-and dirty starting point.

Internal model control (IMC) method is used to find the optimal values of controller for PID feedback systems shown in Table (1). [25]

An optimization technique was used to determine the optimum values of the controller parameters (K_C, τ_I and τ_D) to give the minimum integral square of error (ISE). [26]

A suitable performance index is the integral of square of error, which is defined as:

$$ISE=\int_0^t E^2(t)\,dt. \qquad (13)$$

The performance index of Equation (13) is easily adapted for practical measurements because a squaring circuit is readily obtained. Furthermore, the squared error is mathematically convenient for analytical and computational purposes.

As in Equation (13), the ISE means the area under the curve between the squared error and the time. (26)

Decoupling Control System

Interaction of Control Loops

Whenever a single manipulated variable can significantly affect two or more controlled variables, the variables are said to be coupled and there is interaction between loops, this interaction can be troublesome. Some variables are difficult enough to be controlled because of being subjected to upsets from other loops. (27) In the present work, the control system is designed into two loops (Figure (2)).

Loop 1 is designed to control the reactor bed temperature (T_{rea}) and loop 2 is designed to control the regenerator cyclone temperature (T_{reg}). The reactor bed temperature is affected directly by catalyst flow rate (F_s), while the regenerator cyclone temperature (T_{reg}) can be affected by air flow rate (F_a). In Figure (2), the solid line indicates the direct coupling while dashed line indicates indirect interaction.

Relative Gain Array (RGA)

The RGA is a matrix of numbers. The ijth elements in the array are called relative gain (λ_{ij}). It is a ratio of the steady-state gain between the ith controlled variable and the jth manipulated variable when all other manipulated variables are constant. Divided by the steady-state gain between the same two variables where all other controlled variables are constant. (28)

The Relative Gain Array provides exactly such a methodology, whereby we select pairs of input and output variables in order to minimize the amount of interaction among the resulting loops. It was first proposed by Bristol and since 1980s; it was a very popular tool for the selection of control loops. (27)

The relative gain array indicates how the input should be coupled with the output to form loops with the smallest amount of interaction. The object is to control a given process output by manipulating the one input that will have the greatest influence on it. If this can be done, every input will have more influence on the controlled variables than the one, which is manipulated through the controller. [27]

Actually, two different open loop gains can be found for a pair of variables (y_i) and (m_j). The gain (d_{yi}/d_{mj}) with all loops open may differ from that with all the rest of the loops closed. A convenient measure of the relative loop gain is found to be the ratio of the process gain for these two conditions.

To state it a little differently, the relative gain array is defined as the ratio of open loop gain in terms of (m_j), (i.e., with all other m's constant) to the gain in terms of (y_i), (i.e., with all other y's constant), the term (λ_{ij}) will be used to designate the dimensionless change in (y_i) with respect to a change in (m_j).

$$\lambda_{ij} = \frac{(\Delta y_i / \Delta m_j)m}{(\Delta y_i / \Delta m_j)y} \tag{14}$$

It is convenient to arrange a table of those gains in form of a matrix, the relative gain array of interacting process is:

$$\begin{matrix} & F_s & F_a & \\ \Lambda = & \lambda_{11} & \lambda_{12} & T_{rea} \\ & \lambda_{21} & \lambda_{22} & T_{reg} \end{matrix} \tag{15}$$

The matrix has the following characteristics:

The sum of the relative gains in any row or column of the array is equal to one, i.e.

$$\lambda_{11} + \lambda_{12} = 1, \; \lambda_{11} + \lambda_{21} = 1 \tag{16}$$

The controlled variable is coupled with the manipulated variable that has the largest positive number of relative gain.

The FCCU composed of two controlled outputs and two manipulated inputs as shown in Figure (3), the input/output relationships are given by:

$$T_{rea}(s) = H_{11}(s)\,F_s(s) + H_{12}(s)\,F_a(s) \tag{17}$$

$$T_{reg}(s) = H_{21}(s)\, F_s\,(s) + H_{22}(s)\, F_a\,(s) \quad (18)$$

Where $H_{11}(S)$, $H_{12}(S)$, $H_{21}(S)$ and $H_{22}(S)$ are the four transfer functions relating the two outputs (T_{rea} and T_{reg}) to the two inputs (F_s and F_a) (see Figure (3)). Equations (17 & 18) indicate that a change in (F_s or F_a) will affect both controlled outputs. The calculation of the four transfer functions are given in Appendix (A).

The relative gain between the controlled variable (T_{rea}) and the manipulated variable (F_s) will be denoted by (λ_{11}).

$$\lambda_{11} = \frac{\text{open loop gain}}{\text{closed loop gain}} \quad (19)$$

Mathematically, the relative gain can be expressed as:

$$\lambda_{11} = \frac{(\Delta T_{rea} / \Delta Fs)_{F_a}}{(\Delta T_{rea} / \Delta Fs)_{Treg}} = \frac{H_{11}}{\dfrac{H_{11}H_{22} - H_{12}H_{21}}{H_{22}}} \quad (20)$$

$$\lambda_{11} = \frac{1}{1 - \dfrac{H_{12}H_{21}}{H_{11}H_{22}}} \quad (21)$$

In most cases, the steady state relative gain analysis is a sufficient indicator for control loops combination, so the steady state relative gain could be calculated from the following equations:

$$\lambda_{11} = \frac{1}{1 - \dfrac{K_{12}K_{21}}{K_{11}K_{22}}} \quad (22)$$

The open loop static gain is between (T_{rea} and F_a) when (F_s) is kept constant and the other, when (T_{reg}) is constant by the control loop. The values of other relative gains could be calculated from above relative gain (λ_{11}).

Where: $\lambda_{12} = \lambda_{21} = 1 - \lambda_{11}$, $\lambda_{11} + \lambda_{12} = 1$ and $\lambda_{11} + \lambda_{21} = 1$

In other hand, the elements of the RGA can be calculated for a system of any size by using the following equation. [28]

$$\lambda_{ij} = \text{(ijth element of } k_p) \times \text{(ijth element of } [k_p^{-1}]^T) \quad (23)$$

Design of Non-interacting Control Loops

The RGA indicates how the inputs should be coupled with the outputs to form loops with the smaller amount of interaction. But the persisting interaction, although it is the smallest possible, may not be small enough.

The purpose of decouples is to cancel the interaction effect between the two loops and thus render two non-interacting control loops. [27]

To design decouples for a FCCU, Equations (17 & 18) have been used. From Equation (17), in order to keep T_{rea} constant (i.e. T_{rea}=0), Fs should be changed by the following:

$$0 = H_{11}(s)\, F_s\,(s) + H_{12}(s)\, F_a(s)$$

(24)

$$F_s = -\frac{H_{12}(s)}{H_{11}(s)}\, F_a(s)$$

(25)

Equation (25) implies that dynamic element is introduced with a transfer function:

$$D_1(s) = -\frac{H_{12}(s)}{H_{11}(s)}$$

(26)

It uses the value of F_a as input and provides as output the amount by which it should change F_s, in order to cancel the effect of F_a on T_{rea}.

This dynamic element (decoupler) when installed in the control system cancels any effect that loop 2 might have on loop 1, but not vice versa.

To eliminate the interaction from loop 1 and loop 2, the same reasoning as above has been followed and it was found that the transfer function of the second decoupler is given by:

$$D_2(s) = -\frac{H_{21}(s)}{H_{22}(s)} \qquad (27)$$

When the designer is confronted with two interacting loops, it is recommended to use decoupling. The best system design is to reject or to minimize any possible interaction between control loops.

It is possible to apply decoupling in a variety of ways because the process is accessible at both its inputs and outputs, a decoupler could be interposed between the process and controller at either end or in some combinations. [27]

The control loop one-way decoupler and two-way decoupler are shown in Figures (3 & 4).

The block diagram of the process with two Feedback control loops, and two decouplers is given in Figure (5).

From Figure (6), the following two closed loop input-output relationships are developed as:

$$y_1 = \frac{Gc_1[H_{11} - H_{12}H_{21}/H_{22}]}{1 + Gc_1[H_{11} - H_{12}H_{21}/H_{22}]} y_{1,\,sp} \tag{28}$$

$$y_2 = \frac{Gc_2[H_{22} - H_{12}H_{21}/H_{11}]}{1 + Gc_2[H_{22} - H_{12}H_{21}/H_{11}]} y_{2,\,sp} \tag{29}$$

Where $y_{1,\,sp}$ and $y_{2,\,sp}$ are the set point value of y_1 and y_2 respectively Gc_1 and Gc_2 are the controller transfer functions of the first and second loops respectively. The last two equations demonstrate complete decoupling of the two loops.

In present work, y_1 and $y_{1,\,sp}$ correspond to T_{rea} and $T_{rea,sp}$. While y_2 and $y_{2,\,sp}$ correspond to T_{reg} and $T_{reg,\,sp}$ respectively.

Fuzzy Logic Control (FLC)

Fuzzy logic is a super set of traditional logic, according to Zadeh, [29] who invented this concept in 1965s. He said it is the logic of approximate reasoning and it is unlike other branches of artificial intelligence (AI) that use conventional logic. [29] Since then, the theory of mathematics has gained more recognition from many researches in a wide range of scientific fields. Fuzzy mathematics is attractive not only because it is based on the very intuitive idea of Fuzzy sets, but because it is capable of generating many structures that provide today's scientists and engineers with new insights into interesting, significant and often-debated problems in both science and engineering. [30, 31]

The theory of Fuzzy sets has one of its aims, the development of a methodology for the formulation and solution of problems that are too complex or too ill-defined to be analyzed by conventional techniques.

Hence the theory of Fuzzy sets is likely to be recognized as a natural development in the evaluation of scientific thinking. [32]

Today, the Fuzzy logic can be considered as a tool of promise for control. It can AL's sector, which ensures to enhance tomorrow's industrial control system. [29] In this description one should be curious to know all about Fuzzy logic control.

Application of Fuzzy Logic Control System

There are five types of systems where fuzziness is necessary and these systems are:

1. Complex systems and those are difficult to model.
2. Systems controlled by human expertise.
3. Systems with complex and continuous change in inputs and outputs.
4. Systems that use human observation as inputs or as the basis for rules.
5. Systems which are naturally vague, such as those in behavioral and social sciences. [33]

Advantages of Fuzzy Logic Control System

1. It relates output to input without having understood all the variables, permitting the design of a system that may be more accurate and stable than are with a conventional control system.
2. Rapid prototyping is possible because a system designer does not have to know everything about the system before starting.
3. It is cheaper to make than conventional systems because it is easier to design
4. It has increased robustness.
5. It simplifies knowledge acquisition and representation. [34,35]

Design of Fuzzy Logic Controller

The purpose of any plant controller is to relate the state variables to action variables. Now the controller of a physical system need not itself be physical but may be purely logic. Furthermore, where known relationships are vague and qualitative. A Fuzzy logic controller may be constructed to implement the known heuristic. Thus in such a controller the variables are equated to non-Fuzzy universe given the possible range of measurement or action magnitudes. These variables, however, take on linguistic values which are expressed as Fuzzy subset of the universe. The complete procedure of the Fuzzy controller design can be described as following: [37]

1. Choose a suitable scaled universe of discourse (ν) of $-L \leq (E_i, CE_i) \leq L$,

Where: L and –L represent to the positive and negative ends respectively of this universe which is quantized into equally spaced levels in between those two ends. E_i and CE_i represent the error and its rate of change for the same instant (i).

2. Define the non-Fuzzy set intervals (the quantized levels scaled values) for E_i, CE_i and control action (U). Each level has a value (I) lying between ($-XG \leq I \leq XG$) where: XG and –XG represent the controller gain and they are regarded as the values of the universe of discourse limits (L and –L) respectively.
3. The theory of Fuzzy sets deals with a subset (A) of the universe of discourse (ν), where the transition between the full membership (μ=1) and on membership (μ=0), is gradual rather than abrupt.[41] The Fuzzy-sets definitions in control for E, CE and U are used as in Table (2):
4. The Fuzzy decision rules are developed linguistically to do a particular Control task and are implemented as set of Fuzzy conditional statements of the form:

IF E IS PB AND CE IS NB THEN ZERO ACTION

This form can be translated with the help of Fuzzy sets definition into a new statement.

IF PEB IS NCB AND ZU

The derivation of the Fuzzy rules can be obtained directly from the phase-plane of error and its rate of change. The five Fuzzy sets definition generates (25) rules Fuzzy controller. To read these one can obtain the following translation of the first three rules.

IF PEB AND PCB THEN NUB

IF PEB AND PCS THEN NUB

IF PEB AND ZC THEN NUB and so on

It is worthy to know that in any control system:

E_i= (Set values) – (Measured values)$_i$ (30)

CE_i= (Instant error) – (pervious error) (31)

But in certain Fuzzy applications

E_i= (Measured values) $_i$ - (Set values)

(32)

To clear this difference, consider the initial condition state for a system subjected to a unit step change in input.

For Conventional controller.

E (0) =+1 , CE (0) =0 (33)

And according to Table (2), the Fuzzy rule will be:

IF BEB AND ZC THEN NUB

The action will be negative and the output will follow it. To overcome this problem we must use the Equation (33).

E (0) =-1 , CE (0) =0 (34)

And the Fuzzy rule will be:

IF NEB AND ZC THEN PUB

So the action will be positive and the output will follow it. This Fuzzy definition E and CE will be considered in this work.

5. Both Ei and CEi are multiple by the scale factor of the universe of discourse to ensure mapping their values into suitable intervals that belong to each one, also this scale factor helps to simplify handling of the numerical values of all variables.
6. Control algorithm: the following steps shows the algorithm design of a Fuzzy logic controller for SISO (single input – single output) system which is shown in Figure (8).
7. Calculate the scalar control action (U_s), using the center of gravity method on which the selected deterministic output has a vector value that divides the area under a Fuzzy set into two equal halves.[30,31]

$$Us=\frac{\sum_{n=1}^{N} I_n*(weight)_n}{\sum_{n=1}^{N}(weight)_n} \quad (35)$$

Where:

(Weight) represents the elements (membership) of the net control action vector. (I) represents the value on the interval n.

8. An integral procedure (an algebraic sum) is required to obtain the effective control action scalar for each instant (i).

$$Us_{i+1}=U_{Si}+Us_{i-1} \quad (36)$$

9. A scalar factor is used to remove the first scalar factor in order to put the values into real one.

Fuzzy Logic Control Procedure for MIMO System

Figure (9) describes a 2 × 2 Fuzzy controlled process. The Fuzzy control procedure for MIMO (multi input – multi output) system is similar to the one for SISO process. All Fuzzy control functions are defined and calculations are made except that the fuzzy rules will be divided for each controlled variable taking into account the other controlled variables with (ANY membership) which gives a membership ($\mu = 1$) whenever it appears. To clarify the idea, the following Fuzzy rules are examined:

IF E1 IS PEB AND CE1 IS PCS AND E2 IS ANY AND CE2 IS ANY THEN NUB

The same shape of rules will be fulfilled for other controlled variable as shown below

IF E1 IS ANY AND CE1 IS ANY AND E2 IS PEB AND CE2 IS PCS THEN NUB And so on for all rules. From the definition of AND (min), (ANY) membership will have no effect on the control procedure.

Fuzzy Control Tuning:

To modify the Fuzzy controlled response, three parameters are to be taken into account:

1. Gain tuning: This is achieved by varying the gain and fixing other parameters.
2. Interval tuning: This can be done by varying the quantized level (interval) and fixing other parameters.
3. Fine tuning: This can be achieved using more than one digit.

Controller Selection:

To choose the suitable controller, the following points must be taken into account: The controller ability to give a reasonable response, which depends on

- Number of rules.
- Number of interval.
- Interval values.
- Fuzzy sets definition.
- For real-time applications, the computer execution time required for performing the Fuzzy algorithm must be within the sampling period so as to give the appropriate control action.

Results and Discussion

A good starting point in modeling of FCC unit is the good selection of the manipulated and controlled variables in reactor and regenerator. In this work, Dynamic models have been developed to study the influence of manipulated variables on controlled variables of the process.

Analysis of the Dynamic behavior

The behavior of the regenerator dominates both the dynamic and steady state behavior of the system. This is due to the adiabatic nature of the system in which the need to balance coke formation and combustion is the overriding force. The reactor residence times are much shorter compared to the response time of regenerator hence at any instance the reactor can be described by a set of steady state relations that simplify the dynamic analysis. [9]

Results of State Space model

The full description of the state space model is given in Appendix (A), and the results of this model are:

$$A=\begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}=\begin{bmatrix} -0.22 & 0.10 \\ 0.08 & -0.10 \end{bmatrix},$$

$$B=\begin{bmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{bmatrix} = \begin{bmatrix} 0.21 & 0 \\ -0.10 & 0.16 \end{bmatrix}$$

$$C=\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad D=\begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$$

Relative Gain Array (RGA) Calculations

RGA must be calculated to choose the best pairing of the two controlled variables (T_{rea} and T_{reg}) and the two manipulated variables (F_s and F_a

$$RGA=\begin{bmatrix} 0.83 & 0.17 \\ 0.17 & 0.83 \end{bmatrix} \tag{39}$$

So the best coupling are obtained by pairing the reactor bed temperature (T_{rea}) with regenerated catalyst flow rate (F_s), and the regenerator cyclone temperature (T_{reg}) with air flow rate (F_a), since $\lambda_{11}$is positive and greater than 0.5.

Results of control tuning

Control tuning was applied using PID controller mode for the reactor and regenerator. The results of the controller parameters are given in Table (3) while Table (4) refers to control tuning using fuzzy logic control.

Figures (9 & 10) refers to the closed response at interaction case for the reactor and regenerator respectively using PID controller, it is clear that this case is undesirable and sluggish and it required more time to be in stabile while Figures (11 & 12) refers to the closed response at interaction case for reactor and regenerator respectively using Fuzzy logic controller. From these figures, using fuzzy controller is better than PID Feedback under considerations of response time, overshoot, ISE and settling time.

Decoupler Design

The decoupler of loop1 ($D_1(s)$) was designed to eliminate the effect of interaction of loop2 on loop1 using Equation (26) on substitution the values of $H_{11}(s)$ and $H_{12}(s)$ the decoupler shows the following value:

$$D_1(s) = -\frac{\dfrac{1.14e^{-4.1s}}{19.03s+1}}{\dfrac{0.78e^{-0.1s}}{3.71s+1}} = -1.46\left(\frac{3.71s+1}{19.03s+1}\right)e^{-4s} \qquad (40)$$

The value of $D_1(s)$ is coupled with the value of the main regenerated catalyst flow rate (F_s) to get the final value, after each time interval.

) before applying the control techniques. In this work, the results of RGA calculation are shown in Appendix (B). The resulted array is given as:

In the same way, the decoupler of loop2 ($D_2(s)$) was designed to eliminate the effect the loop1 on loop2. After applying the value of $H_{21}(s)$ and H_{22} (s) the value is:

$$D_2(s) = -\left(\frac{-\dfrac{0.37e^{-0.1s}}{3.68s+1}}{\dfrac{2.51e^{-0.1s}}{18.9s+1}}\right) = 0.147\frac{18.9s+1}{3.68s+1} \qquad (41)$$

The decoupler obtained to justify the main value of air flow rate (F_a).

Conclusions

Based on the simulation study and results of control system of a FCCU, the following conclusions can be drawn:

1. An important step in implementing the mathematical model of the FCCU is the selection of the controller parameters. Different methods were used in the computer simulation to optimize the numerical value of controller parameters, the ISE give a good comparison and clearance of the error.
2. Fuzzy logic controller gave a marked improvement over Feedback controller. However the Fuzzy logic controller is preferable since it does not require an accurate mathematical model for the process to be controlled, while Feedback control strategy requires very wide knowledge about the dynamic behavior and an accurate mathematical model of the process.
3. Two-way decouplers are very important in order to eliminate the interaction.

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Table (1): Tuning Relations Based on IMC

Process Model	Controller	K_c		
	PID	$\frac{1}{K_p}\frac{2\tau_p/t_d+1}{2\tau_c/t_d+1}$	τ	2

Table (2): 25-Rule Fuzzy Logic Controller

NCB	*NCS*	*ZC*	*PCS*	*PCB*
PUB	*PUB*	*PUB*	*PUS*	*ZU*
PUB	*PUS*	*PUS*	*ZU*	*NUS*

NEB	*PUB*	*PUS*	*ZU*	*NUS*	*NUB*
NES	*PUS*	*ZU*	*NUS*	*NUS*	*NUB*
ZE	*ZU*	*NUS*	*NUB*	*NUB*	*NUB*
PES					
PEB					

Table (3): Initial Control Parameters of PID Controller

Type	Parameters			ISE
	K_c	τ_I	τ_D	
Reactor	43.3	3.76	0.05	0.3402
Regenerator	64.7	18.95	0.05	0.3347

Table (4): Initial Control Parameters of Fuzzy Controller

Type	Control Gain	ISE
Reactor	0.3	0.3465
Regenerator	0.3	0.3321

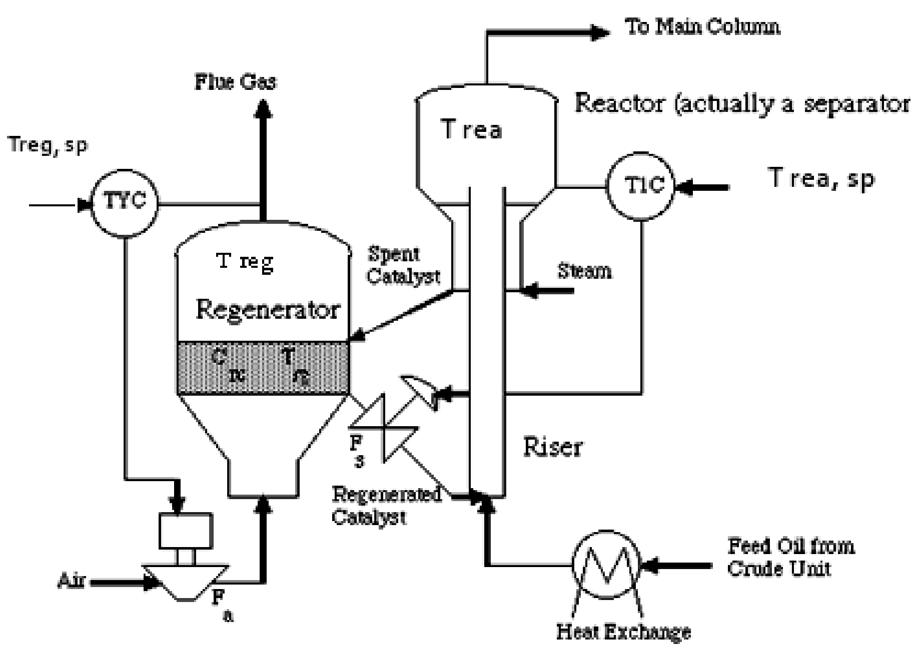

Figure (1): Schematic Diagram of a FCCU. [20]

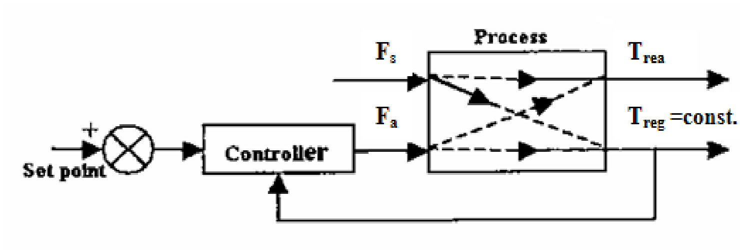

Figure (2): Interaction among controls loops (one loop closed). [27]

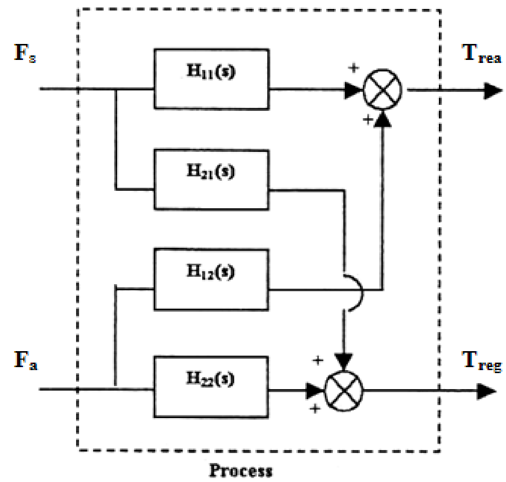

Figure (3): Block diagram of Process with two Controlled output and two Manipulated variables. [27]

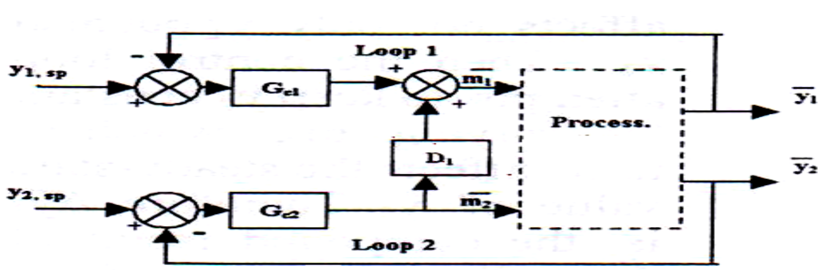

Figure (4): A 2×2 Processes with One Decoupler. [27]

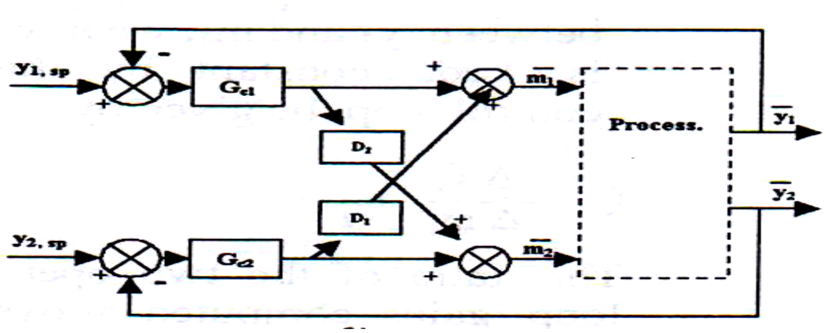

Figure (5): A 2×2 Processes with Two Decouplers. (27)

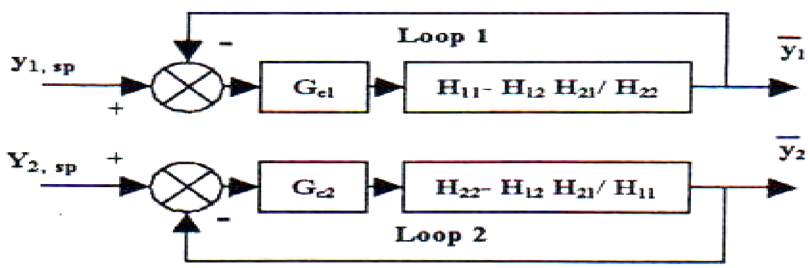

Figure (6): Equivalent Block diagram with Complete Decoupling. (27)

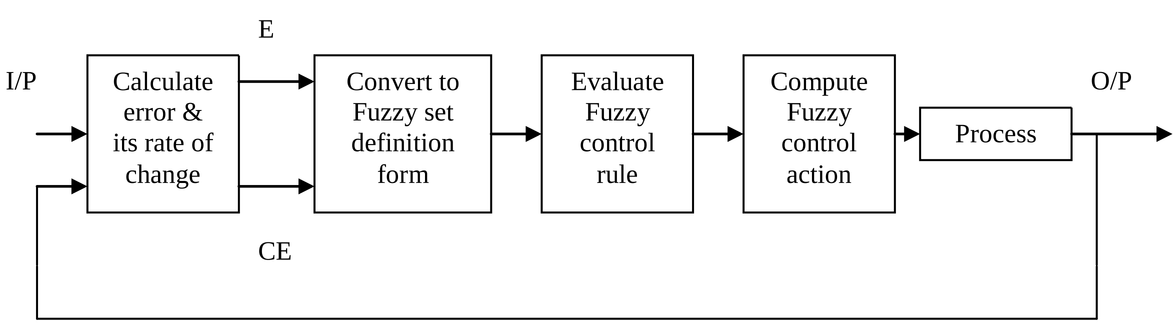

Figure (7): Block diagram of a control system using Fuzzy Logic Control

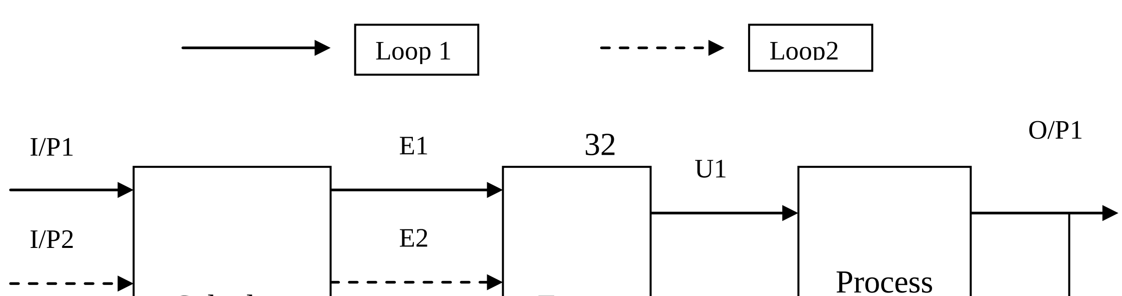

Figure (8): block diagram of fuzzy logic controller for 2×2 process

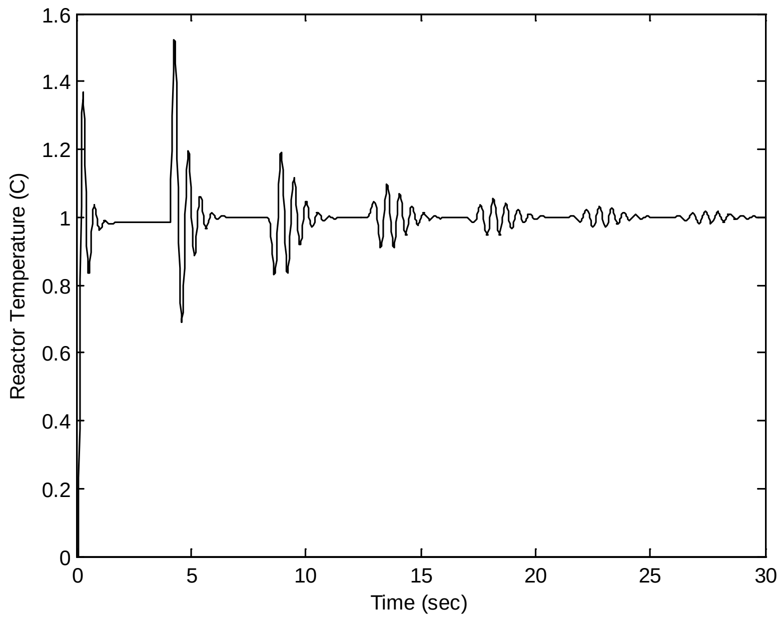

Figure (9): Transient Response of the Reactor with PID controller mode at interaction.

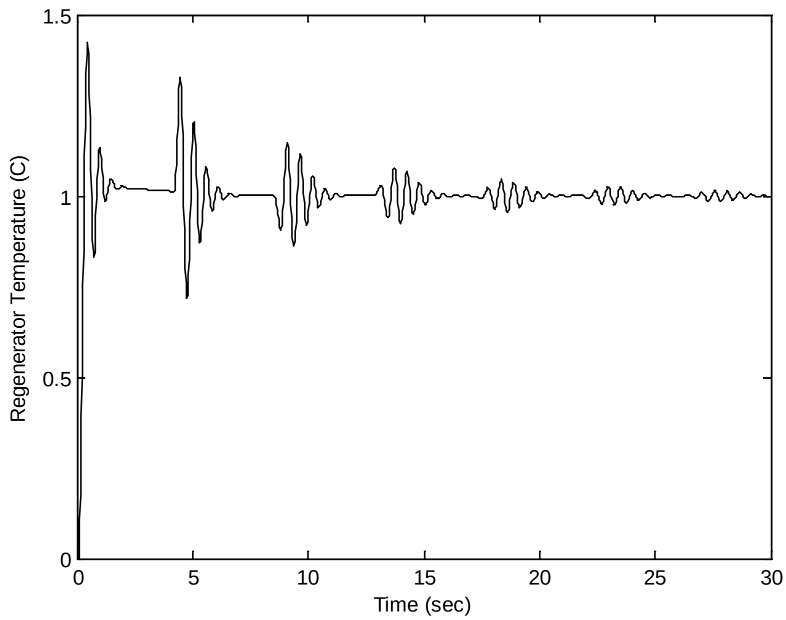

Figure (10): Transient Response of the Regenerator with PID controller mode at interaction.

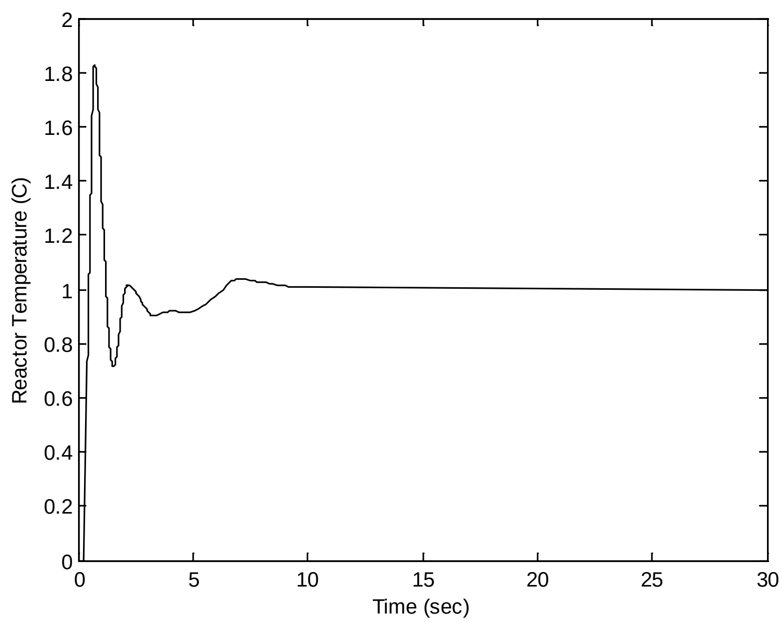

Figure (11): Transient Response of the Reactor with Fuzzy controller mode at interaction.

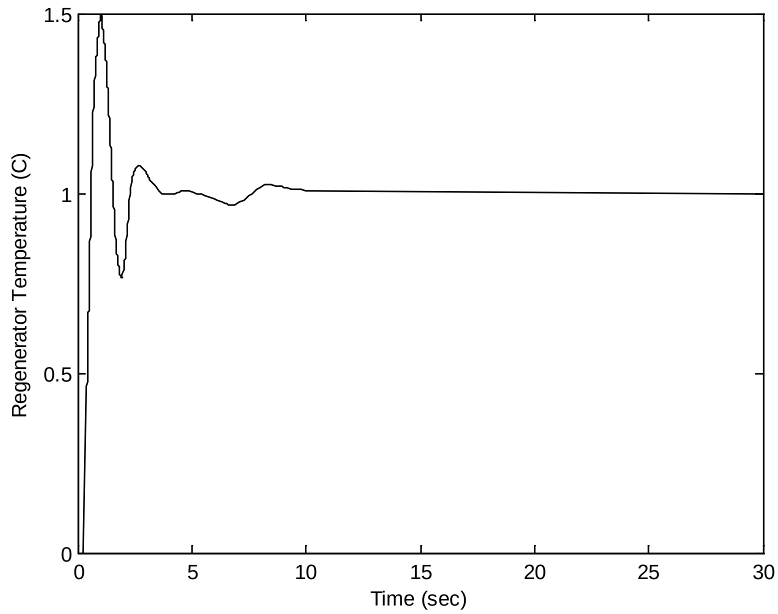

Figure (12): Transient Response of the Regenerator with Fuzzy controller mode at interaction.

Appendix (A): State Space Analysis

The state space model was used in this work to convert the system from non-linear to linear in order to find the transfer functions between the manipulated/disturbance variables and controlled variables.

As in Equations (7) and (8) the state variables in our work are following:

$$X=\begin{bmatrix} Trea - Treas \\ Treg - Tregs \end{bmatrix} \tag{A.1}$$

And the input variables are following:

$$U=\begin{bmatrix} Fs - Fss \\ Fa - Fas \end{bmatrix} \tag{A.2}$$

And the output variables are following:

$$Y=\begin{bmatrix} Trea - Treas \\ Treg - Tregs \end{bmatrix} \tag{A.3}$$

The state space model was applied on Equations (9 & 10) to find the matrix (A & B) as following:

Calculation of matrix (A)

As in Equation (10), the matrix (A) with respect to this work is defined as following:

$$A=\begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \qquad (A.4)$$

Where:

$$A_{11}=\frac{\partial f_1}{\partial T_1}=\frac{-F_pCp_p-F_dCp_d}{M_pCp_p+M_dCp_d} \qquad (A.5)$$

$$A_{12}=\frac{\partial f_1}{\partial T_{cy}}=\frac{F_sCp_s}{M_pCp_p+M_dCp_d} \qquad (A.6)$$

$$A_{21}=\frac{\partial f_2}{\partial T_1}=\frac{F_dCp_d}{M_sCp_s+M_fCp_f} \qquad (A.7)$$

$$A_{22}=\frac{\partial f_2}{\partial T_{cy}}=\frac{-F_sCp_s-F_fCp_f}{M_sCp_s+M_fCp_f} \qquad (A.8)$$

By using the data [14] with applying the above equations the results of matrix (A) is:

A_{11}= -0.22

A_{12}= 0.10

A_{21}= 0.08

A_{22}= -0.10

Equation (B.4) is:

$$\mathbf{A}=\begin{bmatrix} -0.22 & 0.10 \\ 0.08 & -0.10 \end{bmatrix} \qquad (A.9)$$

Calculation of matrix (B)

As in Equation (11), the matrix (B) with respect to this work is defined as following:

$$B=\begin{bmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{bmatrix} \qquad (A.10)$$

Where:

$$B_{11}=\frac{\partial f_1}{\partial F_s}=\frac{Cp_sT_{cy}}{M_pCp_p+M_dCp_d}$$

(A.11)

$$B_{12}=\frac{\partial f_1}{\partial F_a}=\frac{0}{M_pCp_p+M_dCp_d}$$

(A.12)

$$B_{12}=\frac{\partial f_2}{\partial F_s}=\frac{-Cp_sT_{cy}}{M_sCp_s+M_fCp_f} \qquad (A.13)$$

$$B_{12}=\frac{\partial f_2}{\partial F_a}=\frac{Cp_aT_a}{M_sCp_s+M_fCp_f} \quad \text{(A.14)}$$

By using the data [14] with applying the above equations the result of matrix (B) is:

B_{11}= 0.21

B_{12}= 0

B_{21}= -0.10

B_{22}= 0.16

Equation (B.14) is:

$$\mathbf{B}=\begin{bmatrix} 0.21 & 0 \\ -0.10 & 0.16 \end{bmatrix} \quad \text{(A.15)}$$

Appendix (B): Relative Gain Array (RGA)

For the two output variables (T_{rea}, T_{reg}) and two manipulating variables (F_s, F_a), the following two equations can be written in order to calculate the relative gain array:

$$T_{rea}(s) = H_{11}(s)\ F_s\ (s) + H_{12}(s)\ F_a\ (s) \quad \text{(B.1)}$$

$$T_{reg}(s) = H_{21}(s)\ F_s\ (s) + H_{22}(s)\ F_a\ (s) \quad \text{(B.2)}$$

$$H_{11}=\frac{K}{\tau\ s+1}e^{-t_d S} \quad \text{(B.3)}$$

As shown in Figures (B.1) - (B.4), the calculated system parameters (K, τ, and t_d) are shown in Tables (B.1) and (B.2):

Table (B.1): The values of the system parameters for step change in catalyst flow rate (F_s).

Controlled Variable	K ($\frac{°C}{Kg/\sec}$)	τ (sec)	t_d (sec)
T_{rea}	0.78	3.71	0.1
T_{reg}	-0.37	3.68	0.1

Table (B.2): The values of the system parameters for step change in air flow rate (F_a).

Controlled Variable	K ($\frac{°C}{Kg/\sec}$)	τ (sec)	t_d (sec)
T_{rea}	1.14	19.03	4.11
T_{reg}	2.51	18.90	0.1

From the above results, the following input-output relations are obtained:

$$T_{rea}(s) = \frac{0.78e^{-0.1s}}{3.71s+1}F_s(s) + \frac{1.14e^{-4.11s}}{19.03s+1}F_a(s) \quad \text{(B.4)}$$

$$T_{reg}(s) = -\frac{0.37e^{-0.1s}}{3.68s+1}F_s(s) + \frac{2.51e^{-0.1s}}{18.90s+1}F_a(s) \quad \text{(B.5)}$$

To compute the relative gain array:

1. Make a unit step change in $F_s(s)$ (i.e. F_s =1/s) while keeping F_a constant (i.e. F_a=0), then from Equation (B.4)

$$T_{rea}(s) = \frac{0.78e^{-0.1S}}{3.71s+1}\frac{1}{s}$$

Using final value theorem to find resulting new steady state in T_{rea}:

$$T_{reas} = \lim_{s\to 0}\left[sT_{rea}(s)\right] = 0.78$$

$$Therefore: (\Delta T_{rea}/\Delta F_s)_{F_a} = 0.78/1 = 0.78$$

2. Keep T constant under control by varying F_a introduce a unit step change in F_s. Since T_{reg} must be remaining constant (i.e. T_{reg} =0) Equation (B.5) becomes:

$$\frac{0.37e^{-0.1s}}{3.68s+1}F_s(s) = \frac{2.51e^{-0.1s}}{18.90s+1}F_a(s) \quad \text{(B.6)}$$

$$F_a(s) = \frac{\frac{0.37e^{-0.1s}}{3.68s+1}}{\frac{2.51e^{-0.1s}}{18.90s+1}} F_s(s) \tag{B.7}$$

By substituting Equation (B.7) into Equation (B.4)

$$T_{rea}(s) = \frac{0.78e^{-0.1s}}{3.71s+1} F_s(s) + \frac{1.14e^{-4.11s}}{19.03s+1} \frac{\frac{0.37e^{-0.1s}}{3.68s+1}}{\frac{2.51e^{-0.1s}}{18.90s+1}} F_s(s) \tag{B.8}$$

Then the resulting new steady state for T_{rea} is given by

$$T_{reas} = \lim_{s \to 0} \left[sT_{rea}(s) \right] = 0.78 + 1.14 * \frac{0.37}{2.51} = 0.94$$

$$Therefore \ (\Delta T_{rea} / \Delta F_s)_{Treg} = 0.94/1 = 0.94$$

$$\lambda_{11} = \frac{(\Delta T_{rea} / \Delta F_s)_{F_a}}{(\Delta T_{rea} / \Delta F_s)_{T_{cy}}} = \frac{0.78}{0.94} \approx 0.83$$

$$\lambda_{12} = 1 - \lambda_{11} = 1\text{-}0.83 \approx 0.17$$

$\lambda_{21} = \lambda_{12} \approx 0.83$ and $\lambda_{22} = \lambda_{11} \approx 0.17$

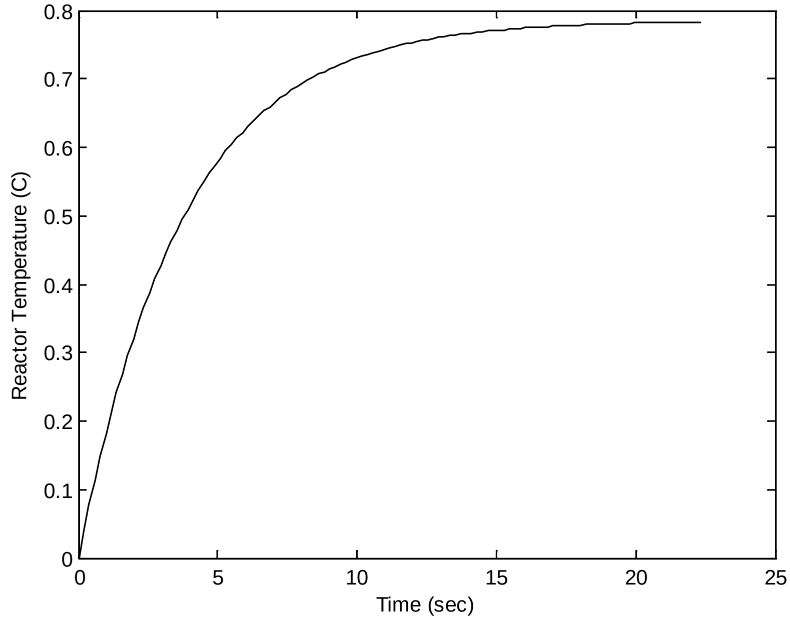

Figure (B.1): Reactor Temperature with respect to Time at Catalyst Flow Rate in dynamic behavior.

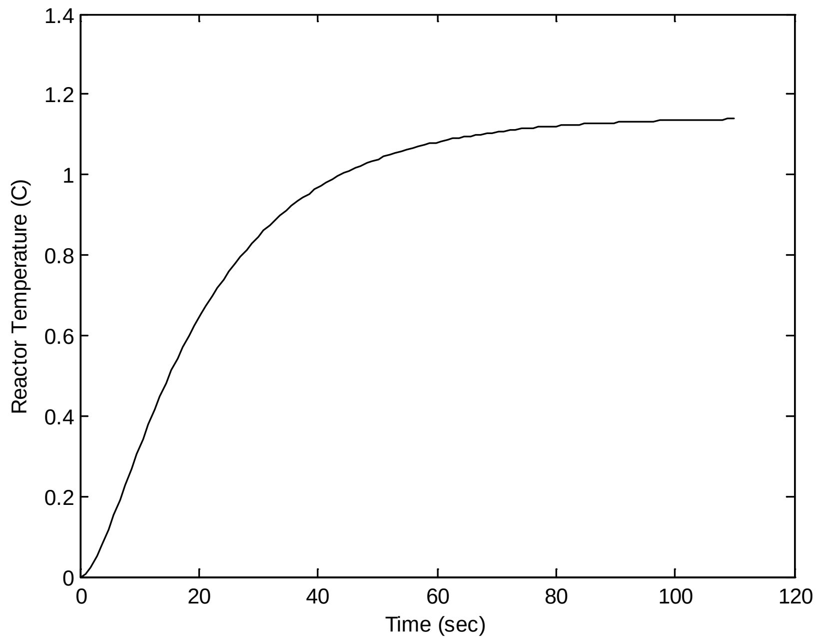

Figure (B.2): Reactor Temperature with respect to time at Air Flow Rate in dynamic behavior.

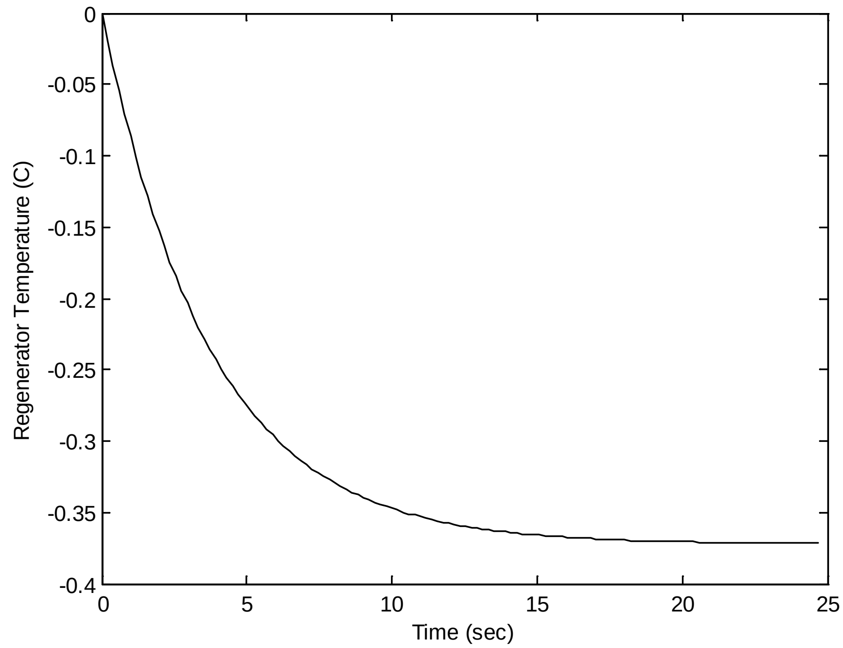

Figure (B.3): Regenerator Temperature with respect to Time at Catalyst Flow Rate in dynamic behavior.

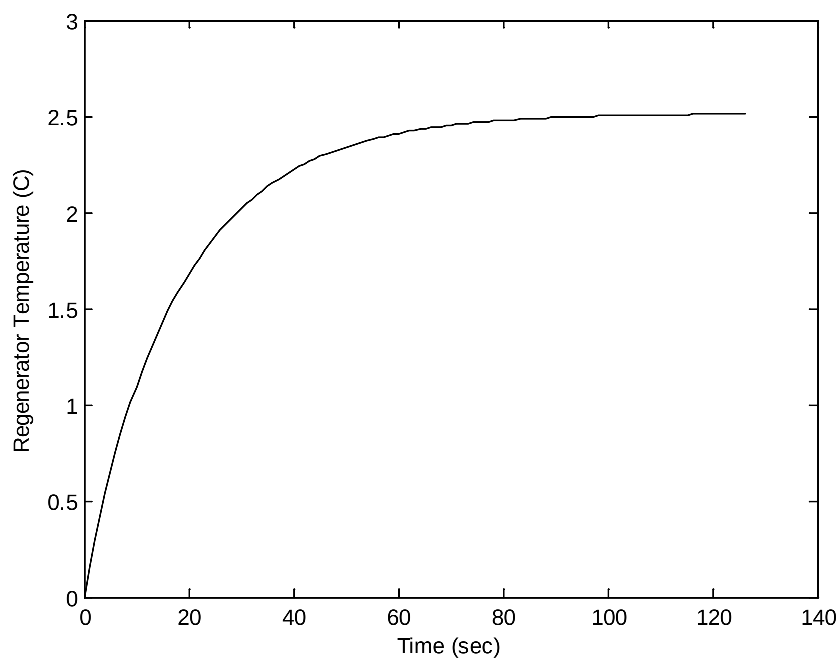

Figure (B.4): Regenerator Temperature with respect to time at Air Flow Rate in dynamic behavior.