Optimal Control of Reactor Concentration and Temperature in Sulfuric Acid Production Process

Mohammed Dermo

A Thesis Submitted to the Department of Electrical Power and Control Engineering School of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirement for the Degree of Master of science in Electrical Control Engineering

Office of Graduate Studies

Adama Science and Technology University

March 2024

Adama, Ethiopia

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Declaration

I hereby declare that this Master Thesis entitled "**Optimal Control of Reactor Concentration and Temperature in Sulfuric Acid Production Process**" is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

Mohammed Dermo	____________________	______________
Name of the student	Signature	Date

Recommendation of Advisor

I, the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled "**Optimal Control of Reactor Concentration and Temperature in Sulfuric Acid Production Process**" prepared under my guidance by Mohammed Dermo submitted in partial fulfillment of the requirements for the degree of Mater's of Science in Electrical Control Engineering Therefore, I recommend the submission of revised version of the thesis to the department following the applicable procedures.

Dr.Cs Reddy	____________________	________________
Advisor	Signature	Date

Approval Page of M.Sc.Thesis

Thesis I, the advisor of the thesis entitled "**Optimal Control of Reactor Concentration and Temperature in Sulfuric Acid Production Process**" and developed by Mohammed Dermo, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

______________________	______________________	______________
Major Advisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis by Mohammed Dermo have read and evaluated the thesis entitled "Optimal Control of Reactor Concentration and Temperature in Sulfuric Acid Production Process" and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Electrical Control Engineering.

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Primarily, I want to express my gratitude and honor to my All-Powerful God, who has given me the strength, forbearance, potential, and discernment necessary to finish my master's thesis. I would like to express my gratitude to **Dr.Cs Reddy**, my research advisor, whose knowledge and encouragement have been crucial in forming this study. Throughout this process, their advice and observations have been really helpful.

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a_p specific surface area of the packing $(\mathrm{m}^2/\mathrm{m}^3)$

A_v Specific area $(\mathrm{m}^2/\mathrm{m}^3)$

c_{in} Concentration of component i $(\mathrm{kmol/m}^3)$

c_p Specific heat capacity (J/kg·K)

D Diameter (m)

D_i Diffusion coefficient (component i)

D_z axial dispersion coefficient $(\mathrm{m}^2/\mathrm{s})$

f_f friction factor

H_A Henry constant for component A

H_w Total heat transfer coefficient (W/m2·K)

$k_{G/L}$ partial mass transfer coefficient (gas or liquid phase)

L length of the operating unit

N_i molar flux of component i

p pressure (Pa)

p partial pressure component i (Pa)

r reaction rate (kmol/kg.cat)

R Rydberg constant (8.3145 J/mol·K)

R_e Reynolds number

t time (s)

T temperature (K)

T_c temperature coolant (K)

u velocity $(\mathrm{m/s})$

α individual heat transfer coefficient $(\mathrm{W/m2 \cdot K})$

λ thermal conductivity $(\mathrm{W/m \cdot K})$

ΔH_r enthalpy of reaction $(\mathrm{J/mol})$

ε void fraction

ρ_b density of the bulk (bed) catalyst $(\mathrm{kg/m3})$

ρ_f density of the fluid $(\mathrm{kg/m3})$

μ *dynamic viscosity* $(Pa \cdot s)$

ABSTRACT

The current laws are making rules stricter to lessen the impact of the chemical industry on the environment. In this study, it is defined at how a sulfuric acid plant operates through modeling, simulating, and optimizing its processes. The model, which was used, covers various parts like reactors, heat exchangers, mixers, and absorption columns. However, it was mainly focusing on the reactor part for this document. Some parameters were adjusted based on actual plant data, while others were estimated using standard methods. The results from this modeling match up well with in real plants modelling. Additionally, the controller was proposed using a Fuzzy logic system specifically designed for sulfuric acid plants. This system involves identifying inputs, outputs, and setting membership functions for different conditions from regular operations to emergencies in a sulfuric acid plant. In addition, after the fuzzy is designed the PI controller is added as fuzzy-PI controller for getting better optimality in the whole process in the reactor. This document mainly possesses modelling and control of concentration and temperature inside the reactor. Both parameters are tasted in both side of the reactor, which is inlet and outlet part. The fuzzy-PI controller is used for optimizing the concentration and creating stability in temperature inside the reactor.in addition to the controller the servo and regulator techniques are applied to the system for better performance. The whole simulation is tasted in MATLAB Simulink. After the simulation, the validation of the controller is analyzed and the regulated fuzzy-PI controller have better performance that PI controller and servo based fuzzy-PI controller. This all validation and performance are checked by showing the dynamic performance parameter described in chapter 5 in table 5.1. from this figure error in PI controller from temperature is 1.127% and in fuzzy PI controller the error is 0.24 and the overshoot is reduced from 0.168% to 0.0254% in PI and fuzzy PI controller respectively. Settling time in concentration was reduced from 6.539 to 1.248 in PI and fuzzy PI controller. From this it is concluded that fuzzy PI controller have better performance than PI controller for this system.

Keywords:- *Fuzzy controller, PI controller, Fuzzy-PI controller, Temperature, Sulfuric acid MATLAB/SIMULINK.*

CHAPTER ONE

INTRODUCTION

1.1 Background

Consumption of sulfuric acid, the world's most manufactured industrial chemical, is frequently used as a gauge for industrialization levels. Annual production of sulfuric acid surpasses that of any other chemical. (Davenport, 2005) (Consulting, 2006). Currently, global production surpasses 160 million tons, with the United States and Asia leading as the primary consumers. The majority of sulfuric acid facilities are aging and encounter the added task of optimizing energy output while reducing their environmental footprint. Sulfuric acid stands as the most extensively manufactured chemical solely within the United States, about 40 million tons per year. It has a wide range of applications and plays an important role in the manufacture of almost all industrial products. About 65% of the H_2SO_4 produced is used to make agricultural fertilizers. Sulfuric acid is also a particularly corrosive and dangerous acid that causes extreme environmental and health damage if not produced, used and regulated correctly. Sulfuric acid finds diverse uses, such as in the manufacturing of phosphate fertilizers, dyes, alcohols, plastics, rubber, ether, adhesives, film, explosives, medications, paints, food packaging, wood treatments, cleansers, pharmaceuticals, petroleum derivatives, and in pulp and paper production. A standard lead acid battery is one of the few consumer products that actually contains H_2SO_4. Sulfuric acid is also widely used as a solvent for ores and as a catalyst in oil refining and polymer production. Certainly, it is worth noting that agricultural fertilizers constitute the primary application of sulfuric acid, representing as much as 65% of its usage. The most common process of manufacturing phosphate fertilizers consists of two steps:

1. Production of phosphoric acid and gypsum, by reacting phosphate rock with H_2SO_4

$$Ca_2\left(PO_4\right)_2\left(s\right)+3H_2SO_4\left(lq\right)+6H_2O\left(lq\right)\rightarrow H_3PO_4\left(lq\right)+3CaSO_4.2H_20\left(s\right) \quad (1.1)$$

2. Reaction of phosphoric acid with ammonia to make ammonium phosphates

$$2H_2PO_4\left(s\right)+3NH_2\rightarrow NH_4H_2PO_4+(NH_4)_2HPO_4 \quad (1.2)$$

The distribution of sulfuric acid plants in the industrialized world is as follows: 35% in Asia, 24% in North America, 7% in South and Central America, 10% in Western Europe, 10% in Eastern Europe, 11% in Africa, and 3% in Oceania and Australia . The majority of sulfuric acid facilities are situated in close proximity to the sites where the acid is utilized in the production processes, such as Close to phosphate fertilizer factories, nickel ore mining sites, and oil refineries, sulfuric acid plants are typically located due to the cost-effectiveness of transporting elemental sulfur compared to sulfuric acid. Note also that the fluctuation in the price of sulfuric acid is due to a slight imbalance between the demand and supply of the acid and the difficulty of storing large quantities of the acid. The recent large price increase is due to China's growing demand for fertilizers, hence sulfuric acid.

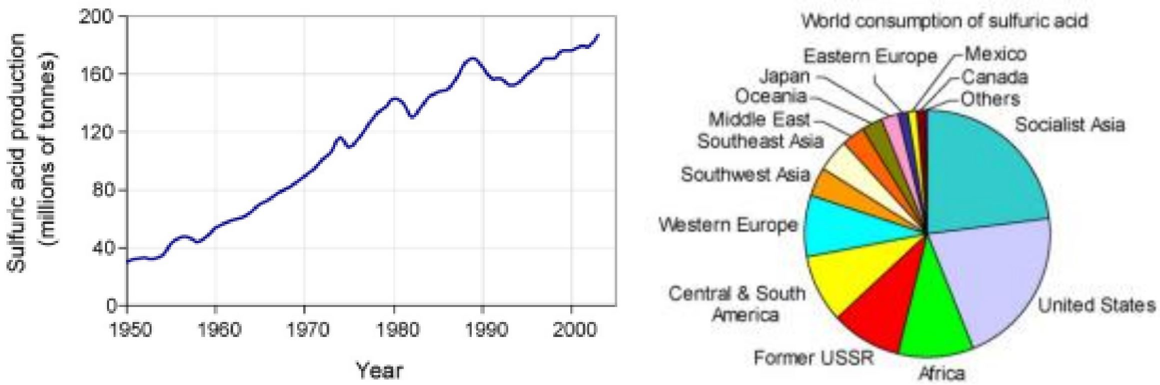

Figure 1. 1.*Sulfuric acid production (left) and consumption (right) in the world*

The advantages of model-based optimization and control applications in industrial enterprises can be highlighted by some recent contributions. As an illustration, model-based control techniques have been implemented for regulating temperature in an industrial batch reactor and overseeing product quality during batch crystallization processes . Reports on model-based fluid control. A confined expansion batch reactor under conditions of recipe uncertainty. Dynamic modeling was mainly used to comprehensively compare control strategies for bulkhead columns (van, 2010). The dynamics and control of a new process for fatty acid esterification by dual reactive distillation is discussed by . The discussion revolves around the dynamics and regulation of a novel process for fatty acid esterification, employing double reactive distillation (C D. A., 2008).

Among other standard simulation environments used in the chemical industry, MATLAB/Simulink using fuzzy logic has a proven record of accomplishment of being successfully applied in major research areas.

1.1.1 Sulfuric Acid Production

Production of sulfuric acid is a necessary step in the smelting process to reduce the amount of sulfur dioxide emitted into the atmosphere. This method of reducing emissions has proven to be effective in ensuring that smelters meet SO_2 emission targets. Sulfuric acid is an end byproduct with a wide range of uses, including fertilizers, ore leaching, oil refining, pigment production, steel pickling, and the production of explosives, detergents, plastics, and human fibers. This is an additional economic advantage for sulfide ore processing plants. The feed for the acid plant is a combination of exhaust gases from different units of the smelter. Meat ovens produce very strong SO_2 emissions, while roasters (matte finish), MK copper reactors and Pierce-Smith converters produce low SO_2 emissions. Sulfuric acid is produced from exhaust gases containing SO_2 by catalytic reacting SO_2 and oxygen (SO_2) to form sulfur trioxide (SO_3) gas in the catalyst. In absorption towers, SO_3 gas reacts with liquid water (H_2O) 98.5 wt% H_2SO_4, 1.5 wt% H_2O, resulting in the formation of enriched sulfuric acid. The oxidation reaction of the catalyst determines the amount of SO_2 captured in the exhaust gas and the amount that is thus prevented from being released into the atmosphere. Therefore, the amount of SO_2 oxidized and removed from the flue gas determines the overall performance of the acid plant.

The raw material of sulfuric acid is sulfur dioxide (SO_2) gas. It is acquired through the combustion of elemental sulfur with air, the smelting and fumigation of metal sulfide minerals, and the decomposition of contaminated (spent) sulfuric acid catalysts. The following table 1.1 describes the three feed gases of a sulfuric acid plant. This indicates that the SO_2 feed to the acid plant is always mixed with other gases. The gases may also contain small amounts of CO_2 or SO_3. The information is taken from the industry tables in Chapters 3 to 9.

Table 1. 1.Compositions of acid plant feed gases entering SO2 oxidation *'converters', 2005*

	Sulfur burning furnace	Sulfide mineral smelter and roaster	Spent acid decomposition furnace
Gas		*Volume%*	
SO_2	11	10	9
O_2	10	11	11
N_2	79	79	76

Essentially, sulfuric acid is made from these gases by catalytically reacting their SO_2 and O_2 to form SO_3 gas, and the product SO_3 (g) reacts with H_2O (lq) 98.5 wt% H_2SO_4, 1.5 wt% H_2O in sulfuric acid. Industrially, both processes are carried out quickly and continuously, figure. 1.2.

1.1.2 Sulfuric Acid Plant

Picture. 1.2. This is a diagram of a sulfuric acid plant burning sulfur . The main components are the catalyst $SO_2 + 1/2O_2 \rightarrow SO_3$ 'converter' (tall, rear), two H_2SO_4 production towers ('absorption') located in the middle and a large molten sulfur tank located in the front. The combustion air filter and air-drying tower ("drying") are on the right. The sulfur incinerator is hidden. Catalysts are usually 12 meters in diameter.

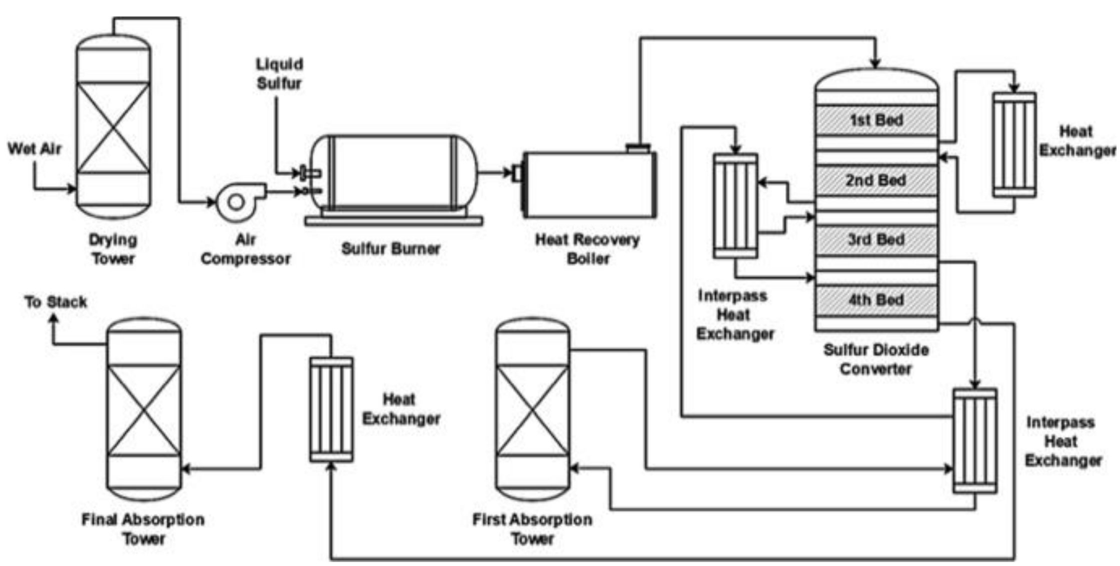

Figure 1. 2.Schematic of sulfuric burning acid Diagram

1.1.3 Fuzzy Logic Controller

In most areas of the chemical industry, chemical reaction processes are non-linear in nature. In addition, it is difficult to model. In the chemical industry, processes are usually complex, slow, and non-linear; it is not always possible to control them with classic. The biggest disadvantage of fuzzy control is the lack of analytical design technique, i.e. Parameterize of membership functions. A basic knowledge of pure physics and chemistry combined with advanced technology is required to develop a system of instrumentation to control chemical processes. Traditional and advanced controllers (e.g., PID and MRAC, respectively) require the most accurate modeling; in addition, simulation also has shortcomings in virtual implementation and testing. The behavior of fuzzy controllers is non-linear, making them useful tools for the chemical industry (B, June, 2005). The application of Fuzzy Set Theory in many control applications made it possible to create intelligent control in these areas. A relationship between inputs and outputs must be developed using a fuzzy controller (Osofisan, May, 2007). Sulfuric acid production is also one of the non-linear and exothermic. Here, two parameters, concentration and temperature, play an important role and show non-linear behavior in sulfuric acid production. To ensure accurate and safe operation, both plants and processes must have a very good mathematical model. It is difficult to obtain good control and accuracy due to lower reliability of the mathematical model or errors in the model. So instead of a traditional or advanced controller that depends entirely on a mathematical model, a fuzzy logic control strategy is chosen as an alternative. This control system evaluates certainty within uncertainty and parameter usage range to continuously control the entire process despite fluctuation . Fuzzy management offers effective solutions for nonlinear and partially unknown processes, mainly because it can combine information from different sources . A fuzzy database comprises if/then rules that are physically interpretable, offering insight into the process. Therefore, the process industry needs more reliable, accurate, durable, efficient and flexible control systems for the operation of the process plant.

1.2 Statement of the Problem

During the past two decades, a literature review has shown that research on sulfuric acid production has discovered interesting topics that require reliable (dynamic) modeling, such as: Numerical simulation of a batch-flow reverse reactor for SO_2 oxidation . Modeling of hot and cold start-ups . Modeling of hot and cold starts , Modeling the oxidation of sulfur dioxide in a fed bed reactor and modeling sulfur dioxide oxidation in a fixed bed reactor with intermittent flow reversal . , optimization studies of H2SO4 production . Optimization of an adiabatic multilayer catalytic reactor for SO_2 oxidation . As mentioned in the above paragraph, the studies focused either only on the sulfur dioxide oxidation reactor or exclusively on SO3 absorption. On the other hand, this research introduces a comprehensive dynamic model of an industrial sulfuric acid plant utilized in the fertilizer industry, along with the outcomes of plant simulation and optimization. Due to its powerful features, fuzzy logic was chosen for all optimization simulation tasks. The complete plant model proved effective for dynamic simulations, assessing the plant's non-steady-state performance, detecting variations in product quality, and minimizing the overall emission of sulfur oxides into the atmosphere.

1.3 Objectives of the Research

1.3.1 General Objective

The general objective of this research is designing of optimal control of reactor concentration and temperature in sulfuric acid process plant

1.3.2 Specific Objective

The specific objectives of the thesis are:

- To study the mathematical model of the sulfuric acid process plant for control design
- To design optimal controller Simulink based using fuzzy logic controller for the modeled sulfuric acid plant.
- Optimizing sulfuric acid process plant model using fuzzy PI controller
- To simulate and analyze the controller in MATLAB (SIMULINK)

1.4 Significance of the Thesis

Chemical control of plants is important because it also covers small plants that vary from water control to chemical composition control. Most chemical processes are non-linear and non-stationary. In addition, the process dynamics of these processes are not known due to some unknown disturbances. Fuzzy logic control is therefore best suited for processes where process dynamics are complex. Traditional and advanced controllers (e.g., PID and MRAC, respectively) require the most accurate modeling; in addition, simulation also has shortcomings in virtual implementation and testing. However, fuzzy controllers have a non-linear behavior that makes them a useful tool for the chemical industry. In addition, fuzzy logic plays an important role in factory optimization. The goal of the first optimization was to maximize the amount of energy produced. Increasing energy production corresponds to maximizing the amount of sulfur dioxide converted into products. In addition, another optimization goal sought to minimize the total amount of SO_2 emitted to the atmosphere.

1.5 Scope of the Research

This thesis is divided into different parts as follows; the first part describes the introductory part of the research work, which clearly explains the background of the thesis, problem solving, the purpose of the thesis, i.e. it talks about the general and specific purpose of the thesis. Sulfuric acid plant and fuzzy logic-based plant, the third part mentions the methodology process description and mathematical modeling of sulfuric acid plant with contact process, the fourth part explains the optimal control design of sulfuric acid process plant, fuzzy logic. Controller for factory optimization. The fifth part contains simulation, result analysis works with MATLAB/Simulink, and the last part of this thesis mentions the conclusion and recommendation.

1.4 Limitation

The thesis will be limited to simulation of the system using MATLAB Simulink by showing how the different components of the system interact with each other. This is because implementation of the real system is difficult because of the component are not available in our country and along with it the additional time and cost incurred in making the actual implementation.

CHAPTER TWO

LITRATURE REVIEW

In the sulfuric acid production industry, most scientists and engineers focus on interesting topics that require reliable (dynamic) modeling and optimization. Over the past two decades, a literature review has shown that research on sulfuric acid production has uncovered interesting topics that require reliable (dynamic) modeling, such as: Numerical simulation of a batch flow reverse reactor for SO_2 oxidation. Modeling of hot and cold starts modeling of sulfur dioxide oxidation in a bed reactor, modeling of sulfur dioxide oxidation in a fixed bed reactor with discontinuous flow direction . The purpose of this work is a contribution related to the investigation of the controllability of the hot point temperature of an industrial SO_2 transformer. The reactor under study operates adiabatically without flow change and is used for the highly exothermic oxidation of SO 2 to produce sulfur dioxide (SO_3). Sulfuric anhydride is still used for the synthesis of sulfuric acid (H_2SO_4). A cascade or series of catalytic fixed beds must be used to achieve high SO2 conversion rates. Therefore, an industrial reactor usually consists of four catalytic fixed beds. The purpose of controlling such reactors is to prevent the formation of hot spots in the catalyst layers. Achieving this involves employing a control loop for each catalyst layer to maintain the maximum catalyst temperature at a predetermined and constant value. The purpose of the control is to prevent the formation of a hot spot within the catalyst bed and then to prevent catalyst deactivation or sintering (P, 1984). Mathematically speaking, this reactor type falls within the realm of distributed parameter systems.

Controlling such processes with conventional and fixed controller parameter methods can be a problem mostly in those cases where the operating point changes or the reactor dynamics are affected by various changes in the inlet flow parameters. This difficulty should be overcome by using some recent control strategies such as adaptive control, predictive control, etc. Managing an adiabatic catalytic fixed bed presents significant challenges in comparison to a cooled catalytic fixed bed due to the absence of numerous control variables. In this study, the volumetric flow rate of the inlet gas is used as a manipulated variable in the control of such a reactor. To do this, a dynamic model of the process (adiabatic catalytic bed) is integrated using data related to its nominal operating point, then a generalized predictive algorithm (GPC) is applied to it with offline recursive least-squares detection. Model.

Optimization Studies in H_2SO_4 Production this study reveals the findings from dynamic simulation and optimization conducted on an established sulfuric acid plant. Operational problems can occur when the process is interrupted due to a change in production rate or catalyst deactivation, where the non-linear response of the plant causes continuous oscillations. Since the plant is operating at almost full capacity, only a small increase in energy production can be achieved. However, ≈40percentage or more by optimizing operating parameters can significantly reduce SO_2 emissions.

Simulation and control automation of the sulfuric acid production process utilizing fuzzy logic (Rana, 2012). In this work, a fuzzy logic system was designed, which is particularly suitable for a sulfuric acid plant. System planning begins with the identification of inputs and outputs and the selection of the member function of each room, from normal operation to emergency use of the sulfur plant. Full automation and control of the sulfuric acid production process was implemented, showing consistent results. The plant model is not mentioned in this article.

Temperature modeling and control of a sulfuric acid plant in an industrial smelter . In this study, acid plant temperature control is a multi-input, multi-output control problem that can be controlled by a PI controller. The Bristol Relative Leverage Table and Single Value Analysis are used to determine the most effective pair of variables. The temperature control input of the mutual control system is investigated. Simulations of large perturbations such as feed gas flow rate and SO_2 concentration are performed using two alternative controller pairs. The results of the simulations are reviewed and the merits of each pair of controllers are discussed.

Optimization of an adiabatic multi-layer catalytic reactor for SO_2 oxidation (Nodehi, 2007).The simulation and optimization of a multilayer adiabatic reactor for the catalytic oxidation of SO_2 is presented after a developed software using a heterogeneous plug flow model. A method employing orthogonal collocation (OC) with as many as eight collocation points was applied to solve the nonlinear two-point boundary value differential equation governing the catalyst particles. It was demonstrated that the system could be effectively characterized using the two-collocation-point OC technique. Due to the non-linear behavior of the efficiency factor along the layers, the optimal distribution of the catalyst between the layers and the corresponding inlet temperatures were determined by two methods, including: (1) using the internal value or (2) the actual value. Value reaction rate in optimization criteria. . The results showed that in the second case, the minimum amount of catalyst can be reached at lower temperatures, the required amount of catalyst is always smaller, and the number of layers is greater or equal to the first case.

In this work temperature and concentration of reactor is controlled using a fuzzy-controller by considering Sulfuric acid production process.

CHAPTER THREE

METHODOLOGY

3.1. Introduction

This chapter deals with the data collection, designing process of reaction process, mathematical modeling for concentration, designing and modeling of temperature, and modelling and designing of fuzzy-PI controller.

3.2. Methodologies

To achieve the overall goals and specific objectives of this study, various methods and techniques were employed, as depicted in Figure 3.1. The initial step involved reviewing relevant literature and conducting a comprehensive analysis. Subsequently, the necessary data for the research was collected and examined. The overall methodology encompassed several distinct tasks that were executed to successfully fulfill the requirements of this thesis.

Literature review: This thesis is based on previous studies by researchers in the field on the chosen topic. An extensive literature review was conducted to collect relevant and relevant information, including various sources such as books, articles, papers, journals, published materials, and online resources, with a special focus on reactor concentration and temperature control.

Analysis: Collected data are analyzed using established theoretical formulas to control, model and design the feasibility of temperature and concentration in reactor systems. This process involves a thorough examination of the data, application of proven formulas, and the use of modeling techniques to assess the viability and effectiveness of temperature and concentration.

Modeling and designing: the overall model and designs of the proposed fuzzy logic PI controller have been simulated using MATLAB/Simulink software depending on the data analysis to get the best optimizing solution.

Finally, documentation: the final work is showing the overall works of the thesis starting to ending including, MATLAB simulation results, conclusion, recommendation, and future work that have been made based on the research finding and the simulation studies.

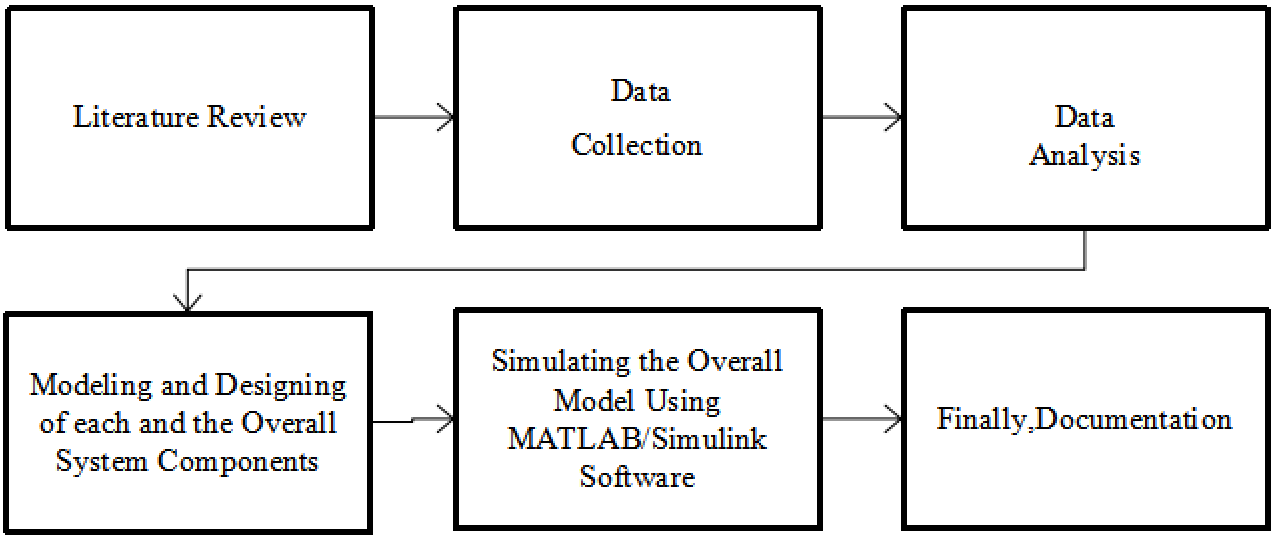

Figure 3. 1.Block diagram of overall methodologies

3.3. Materials

For the system design and editing thesis documentation, the following computer software's are used.

- Microsoft office 2019,
- Math Type 6.0 equation,
- MATLAB/2019a, and

Microsoft Office are used to edit the thesis documentation. Math Type 6.0 is used to write mathematical equations in Microsoft Office Word and Power Point presentations. MATLAB is used to simulate the system design

3.4 Process Description

Two primary methods are employed in sulfuric acid production: the lead chamber process and the contemporary contact process . The main steps in the contact process are the combustion of sulfur (S) in air to sulfur dioxide (SO_2), the conversion of SO_2 to sulfur trioxide (SO_3) in the absence of oxygen (O_2), and the absorption of SO_3 into water. (H_2O).) or with dilute sulfuric acid solution (H_2SO_4) to form a concentrated acid solution (>96%).

$$S(g)+O_2(g)\rightarrow SO_2(g) \tag{3.1}$$

$$So_2(g) + \frac{1}{2}O_2(g) \rightarrow SO_3(g) \tag{3.2}$$

$$SO_3(g) + H_2O(lq) \rightarrow H_2SO_4(lq) \tag{3.3}$$

Where ΔH_R in the three equation is $\Delta H_R = -300\ kJ/mol$ $\Delta H_R = -100\ kJ/mol$ and $\Delta H_R = -132\ kJ/mol$ respectively

A simplified flow diagram of an industrial sulfuric acid production process consists of a sulfur burner, a multi-pass converter, heat exchangers and dampers, as shown in Figure 3.1. The main compressor draws filtered outside air through an efficient drying tower to remove moisture. Dry compressed air passes through a stubborn-lined furnace where molten sulfur is burned to produce sulfur dioxide (SO_2). The high-temperature SO_2 fuel gas is subsequently cooled to the appropriate temperature within the boiler to facilitate its conversion to SO_3 during the conversion phase. A multilayer catalytic adiabatic reactor is used because the oxidation reaction of SO_3 is limited by chemical equilibrium. Note that O_2 will not oxidize SO_2 to SO_3 without a catalyst, so this is a must. The catalyst used here is vanadium oxide (V_2O_5) mixed with alkali metal sulfate . This mixture is applied to small beads of silica and is liquid at high temperature in the . Recently, other catalysts have been reported .

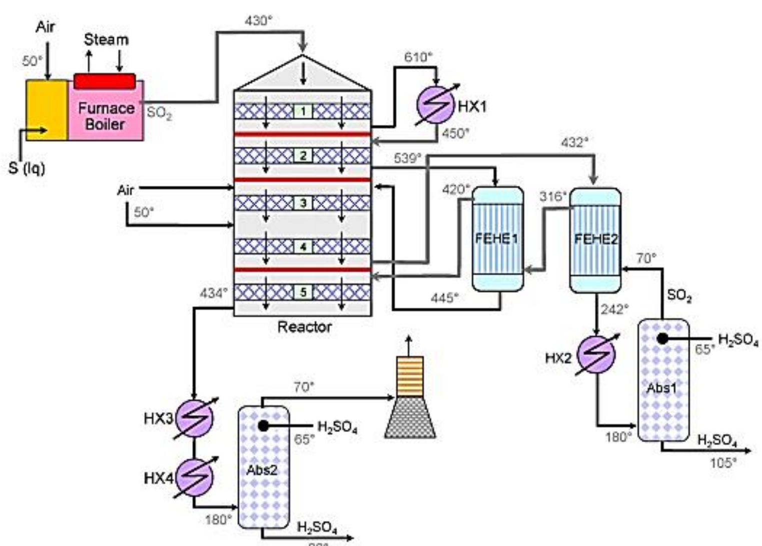

Figure 3. 2. Simplified flow sheet of the sulfuric acid production plant (Bunimovich, 1995).

The complete procedure aims to transform over 99.7% of sulfur dioxide into sulfuric acid. Multiple conversion stages, fresh air, and interstage cooling are necessary due to the reversible and exothermic nature of the reaction (Froment, 1979). O_2 conversion is further improved and tail gas emissions are reduced using the SO_3 medium (Abs1). This adsorption step occurs after the fourth catalyst layer and changes the gas composition, thus shifting the equilibrium curve to higher conversions, as shown in the figure. 3.1 and explained below.

SO3 absorption ends in the second absorber (Abs2). Two feed-exhaust heat exchangers (FEHE) are used for heat integration. It should be noted that the operation of an industrial reactor follows a maximum reaction curve.

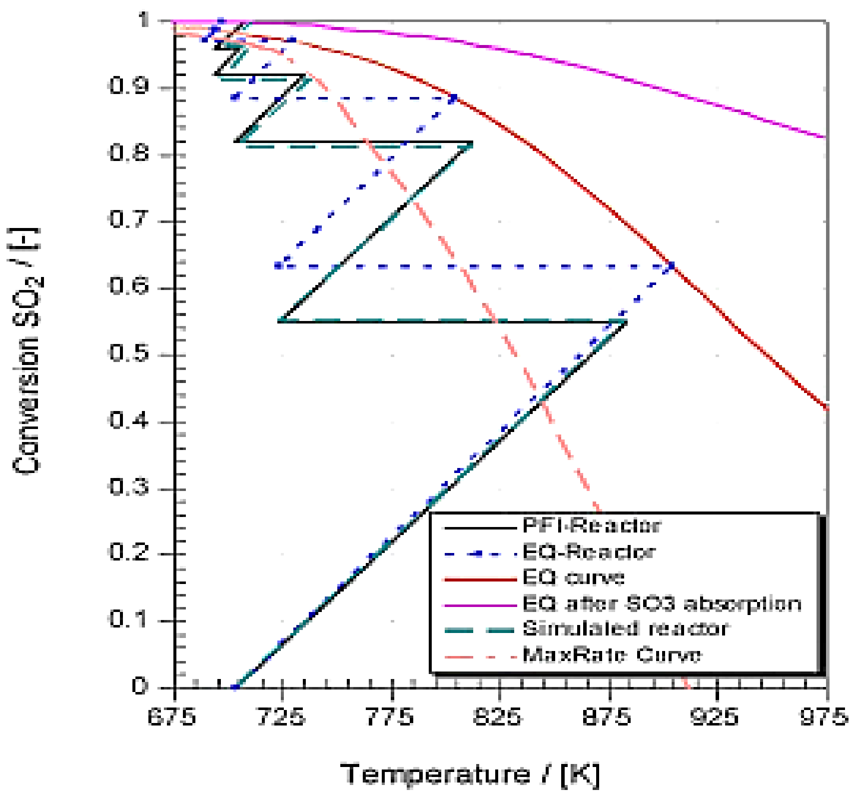

Figure 3. 3.Temperature-conversion diagrams.

While in operation, adjustments can be made to the airflow rates entering the sulfur burner and channels 3 and 4 of the converter. Furthermore, it is feasible to vary the exchanged energy levels in the intake-use water heat exchangers FEHE1 and FEHE2 by diverting a portion of the cold flow (output from the absorption stage by Abs1).

3.5 Dynamic model

According to this paradigm, the model of a sulfuric acid production plant shown in Figure 3.1 is constructed by defining the sulfur burner, catalyst bed, heat exchanger, feed-to-ejection heat exchanger (FEHE) and absorption column models by specifying the appropriate no. of each type of unit and connecting them according to the flowchart topology. To achieve inter-unit coupling, each model is written such that the molar flow rate, molar composition, pressure and temperature of its outlet streams are calculated in the model. These variables are then equated to the variables associated with the downstream unit, where the values are used to calculate the variables needed to solve the model. Diagrams illustrating the units and symbols utilized for modeling are presented in Figures 3.3 to 3.7.

The subsequent section provides the principal differential and algebraic equations utilized in the Models for each operational unit.

Sulfur burner

Mass balance:

$$F_{i,out} = F_{i,in} + \mathrm{v}_i \cdot \xi, \quad \xi = F_{Sulfur,in} \tag{3.4}$$

1) Catalytic reactor bed (pseudo-homogeneous, axial dispersion model, adiabatic operation)

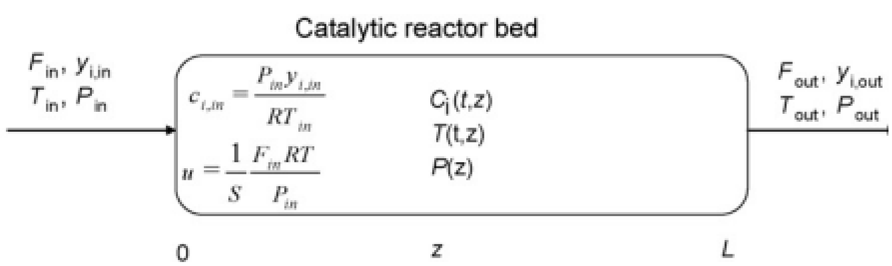

Figure 3.4 Models used to describe the sulfuric acid plant for catalytic reactor bed

Mass balance:

$$\frac{dc_i}{dt} = -u\frac{dc_i}{dz} + \rho_b . v_i . r + D_z \frac{d^2 c_i}{dt^2} \tag{3.5}$$

Energy balance:

$$(\varepsilon \cdot p_f \cdot c_{p,f} + p_b \cdot c_{p,cat}) \cdot \frac{dT}{dt} = -\rho_f \cdot c_{p,f} \cdot u \frac{dT}{dz} + \rho_b \cdot r(-\Delta H_r) + k_z \frac{d^2T}{dz^2} \qquad (3.6)$$

Pressure drop:

$$\frac{dp}{dz} = -f_f \cdot \rho_f \cdot \frac{u^2}{D_p} \qquad (3.7)$$

With the boundary conditions:

$$at\ \mathrm{z} = 0:\ \mathrm{D}_z \frac{dc}{dz} = u \cdot (c_{in} - c);$$

$$\mathrm{k}_z \frac{dT}{dz} = \rho_f \cdot c_{p,f} \cdot u \cdot (T_{in} - T) \qquad (3.8)$$

at z = L :

$$\frac{dc}{dz} = 0; \quad \frac{dT}{dz} = 0; \quad \frac{dp}{dz} = 0 \qquad (3.9)$$

A kinetic model is the same to the one proposed by Fremont and Bischoff (Froment, 1979) was used:

$$r = \frac{k_1 \cdot po_2 \cdot pso_2 \cdot (1 - (Pso_3 / K_p \cdot Pso_2 \cdot Po_2^{1/2}))}{22.414 \cdot (1 + K_2 \cdot Pso_2 + K_3 \cdot Pso_3)^2} [kmol / (kg.cat.s)] \qquad (3.10)$$

The parameters of the kinetic model were fine-tuned to ensure that the projected behavior aligns with the actual plant data. (see Figure. 3.1). In this work, the following values were used:

$$K_p = \exp(\frac{-10.68 + 11300}{T}) \ [1/\mathrm{atm}^{1/2}] \qquad (3.11)$$

$$k_1 = 2.1125 \times 10^5 \cdot \exp(\frac{-3599.78}{T}) \ [\mathrm{kmol/(kg.cat.atm^2.s)}] \qquad (3.12)$$

$$K_2 = 14.641 \quad [\mathrm{atm}^{-1}] \qquad (3.13)$$

$$K_3 = 6.5775 \quad [\mathrm{atm}^{-1}] \qquad (3.14)$$

2) Heat exchangers (constant temperature on the shell side, T_c)

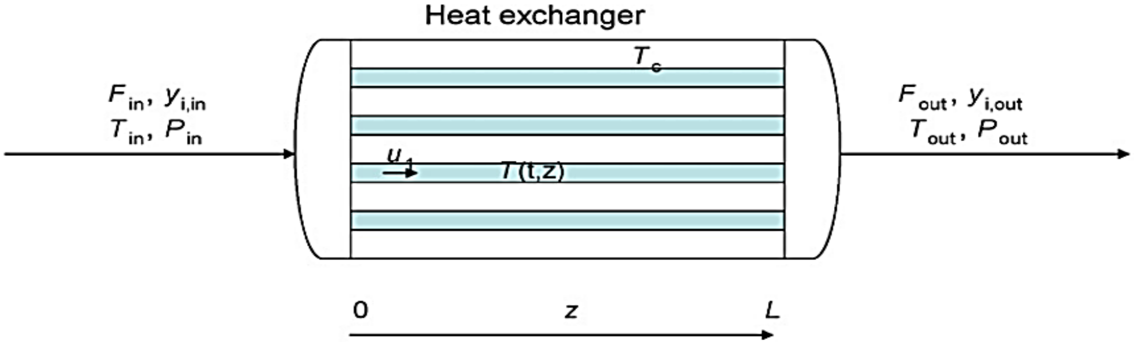

Figure 3.5 Models used to describe the sulfuric acid plant for Heat exchanger

Energy balance:

$$\rho_f \cdot c_{p,f} \frac{dT}{dt} = -\rho_f \cdot c_{p,f} \cdot u \cdot \frac{dT}{dz} - \frac{4}{D} \cdot H_w \cdot (T - T_c) \tag{3.15}$$

3) Feed-effluent heat exchangers:

Energy balance (tube side):

$$\frac{dT_1}{dt} = -u_1 \frac{dT_1}{dz} - \frac{4}{D} \cdot \frac{H_w}{\rho_2 \cdot C_{p,1}} \cdot (T_1 - T_2) \tag{3.16}$$

Energy balance (shell side):

$$\frac{dT_2}{dt} = -u_2 \frac{dT_2}{dz} + A_v \cdot \frac{H_w}{\rho_1 \cdot C_{p,2}} (T_1 - T_2) \tag{3.17}$$

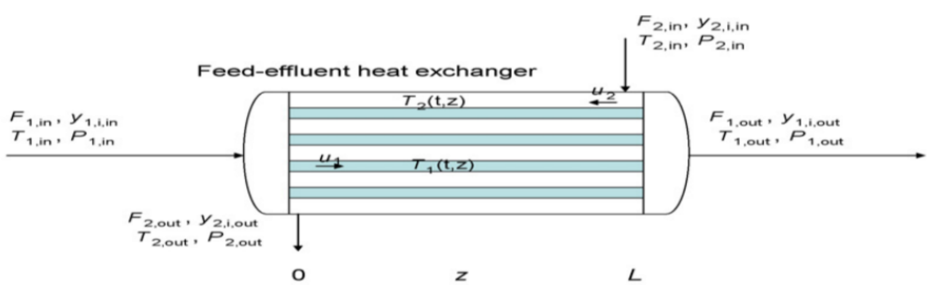

Figure 3.6. Models used to describe the sulfuric acid plant for feed-effluent heat exchanger

4) Absorbers

The absorption model assumes one-dimensional mass and heat transport normal to the interface, thermodynamic equilibrium at the interface, and instantaneous reaction. Component A is SO_3 in gas phase, while B is H_2O in liquid phase.

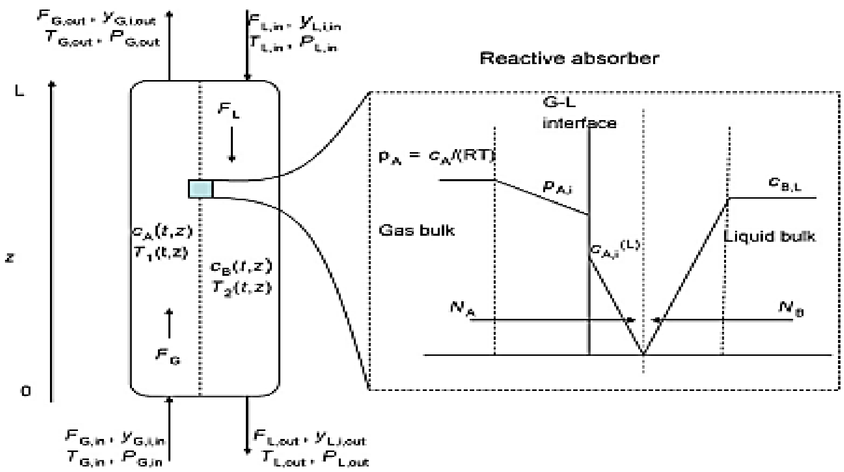

Figure 3.7 Models used to describe the sulfuric acid plant for Reactive absorber

Mass balance gas (A):

$$\varepsilon_G \cdot \frac{dc_A}{dt} = \frac{4}{\pi D^2} \frac{d}{dz}(F_G \cdot C_A) - N_A \cdot A_v \tag{3.18}$$

Mass balance liquid (B):

$$\varepsilon_L \cdot \frac{dc_B}{dt} = -\frac{4}{\pi D^2} \frac{d}{dz}(F_L \cdot C_B) - N_B \cdot A_v \tag{3.19}$$

Molar flux of components:

$$N_A \cdot (\frac{1}{k_L} + \frac{1}{k_G \cdot H_A}) = \frac{P_A}{H_A} + \frac{D_B}{D_A} \cdot C_{B,L} \text{ and } N_B = N_A \tag{3.20}$$

Energy balance (gas):

$$\varepsilon_G \cdot \frac{dT_1}{dt} = -\frac{4}{\pi D^2} \cdot F_G \frac{dT_1}{dz} - \frac{H_w \cdot A_v}{\rho_G \cdot C_{p,G}} (T_1 - T_2) \tag{3.21}$$

Energy balance (liquid):

$$\varepsilon_L \cdot \frac{dT_1}{dt} = \frac{4}{\pi D^2} \cdot F_L \frac{dT_1}{dz} + \frac{H_w \cdot A_v}{\rho_G \cdot C_{p,L}} (T_1 - T_2) + \frac{N_w \cdot A_v}{\rho_L \cdot C_{p,L}} (-\Delta H_R) \tag{3.22}$$

Pressure drop:

$$\frac{dP}{dz} = -f_f \cdot \rho_f \cdot \frac{u^2}{D_p} \tag{3.23}$$

CHAPTER FOUR

CONTROLLER DESIGN

4.1 Fuzzy Logic control

Fuzzy Logic Control (FLC) techniques typically divide a complex system into several subsystems, relying on expert system knowledge. At the same time, a set of simple and straightforward management laws are used to imitate the human control strategy in each local area of operation. Then, a global control law is formed by combining all local control functions through fuzzy membership functions, or weight functions. Visually, the analysis and synthesis use human experience qualitative linguistic variables "IF-THEN" conditional statements with simple models instead of one complex mathematical model.

Fuzzy logic can be seen as an extension of a multi-valued logical system. In a two-valued logical system, a statement is either true or false. In a multi-valued logical system, a statement can be true or false, or it can have an intermediate truth value, which can be an element of infinite truth-value set In fuzzy logic, truth values can vary according to a fuzzy subset A fuzzy logic controller is designed to handle situations where an available data source is imprecise, subjectively interpreted, or uncertain. The main forms of fuzzy controller are fuzzification, database, rule base, inferential strategy and defuzzyification. Figure 4.1 depicts the block diagram of the Fuzzy controller (Ahmed, 2007). Fusion is the process of converting input variable values (sensor signal values) into linguistic variable values or membership functions of fuzzy logic sets (fuzzy values). A fuzzy logic rule base divides a control problem into a series of IF X AND Y THEN Z rules that define a desired system output response given certain system input conditions . The quantity and intricacy of the rules are contingent upon the count of input parameters to be managed and the number of fuzzy variables linked with each parameter. Develop fuzzy logic membership functions to delineate the significance (values) of the input/output terms utilized in the rules. Fuzzification entails converting a typed linguistic variable value (fuzzy variable value) into a precise value (real value).

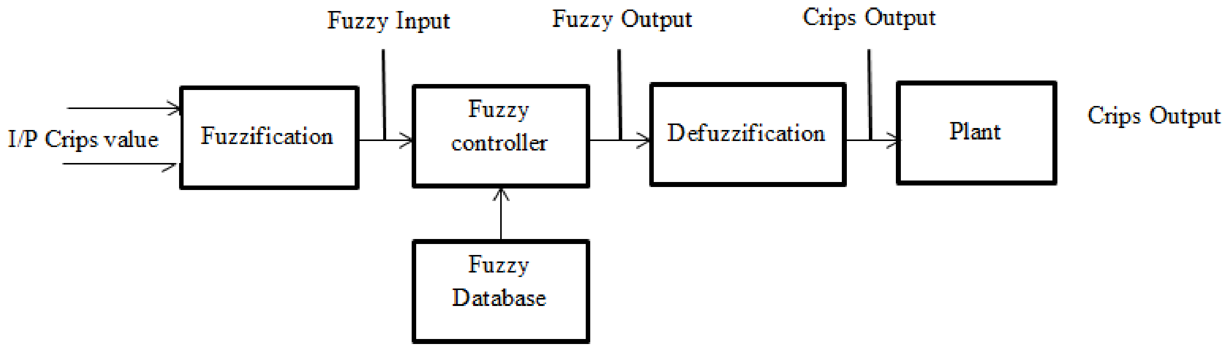

Figure 4. 1.Basic block diagram of Fuzzy logic control structure

In this study, Mamdani type FLC is proposed to control the effluent pH value in the neutralization In this study, a Mamdani-type FLC is proposed to control the pH value of wastewater in the neutralization process. The structure of the proposed FLC is shown in Figure 4.2. In the proposed FLC, error (e = csp - c) with error ratio (de/dt) and error (e) =Tsp-T with error ratio (de/dt) are used as inputs. The change in the manipulated variable (Δu = uk – uk-1) is chosen as the output. Nine MFs (Negative Very Big, NVB; Negative Big, NB; Negative Medium, NM; Negative Small, NS; Zero, Z; Positive Small, PS; Positive Medium, PM; Positive Big, PB; Positive Extra Very Big, PVB) error , seven MFs (NB, NM, NS, Z, PS, PM, PB) for error level and seven MFs (NB, NM, NS, Z, PS, PM, PB) for change in the manipulated variable. Structure of FLC. Triangular membership functions are used for inputs and outputs and are tuned to their best values through simulations. The graphical representations of the membership functions of the inputs are shown in Figures 5.3 and 5.4, and the graphical representations of the output are shown in Figure 5.5.

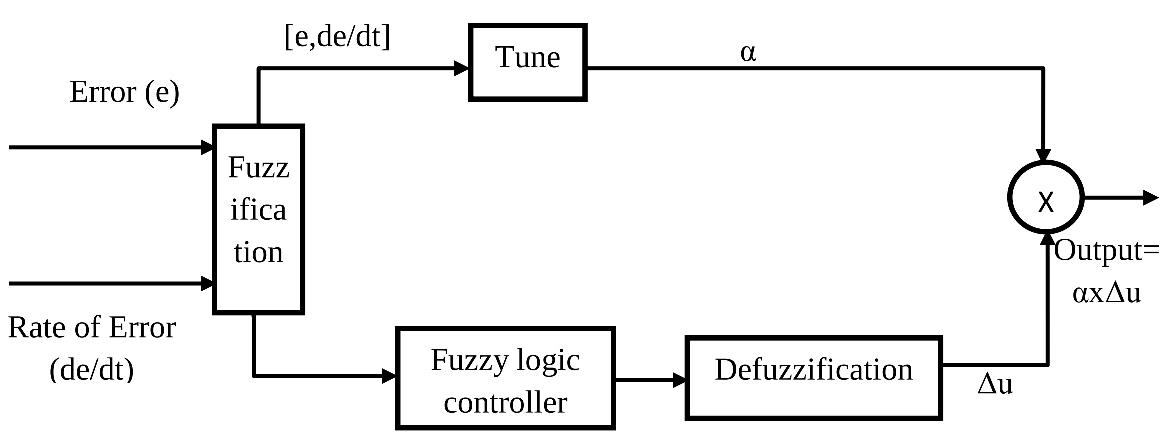

Figure 4. 2. block diagram of the proposed fuzzy logic structure

4.2 PI control

Proportional integral (PI) control merges proportional and integral control functions into a single controller. It operates as a feedback control circuit that computes an error signal by comparing the system outputs. Figure 4.7 shows the PI control circuit.(Ogata, n.d.).

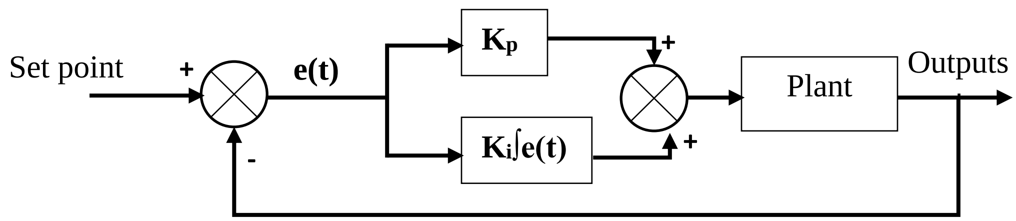

Figure 4. 3.PI Control Loop

Figure 4.3 shows the PI control circuit. An error signal is given to the PI controller of this image. The controller contains the sum of proportional and integral gain. Inclusion of an integrator in the circuit ensures that the typical input error diminishes to zero during steady-state conditions. The time domain equation for the controller is derived as follows:

$$u_c(t) = K_{pc}\left[e(t) + \frac{1}{T_{ic}}\int e(t)dt\right] \quad (4.1)$$

Where u_c is controller input signal, K_{pc} is the proportional gain, T_{ic} is the integral gain, and K_{ic}= K_{pc}/T_{ic} is the integral gain, and e(t) is the error signal.

4.4 Fuzzy PI Control Based Reactor Control

The controller used in this system combines both fuzzy controllers and PI controllers. Fuzzy logic controllers enable fast and accurate adjustment of PI controller parameters, with PI parameters (Kp and Ti) adapting to process changes caused by external disturbances. As a result, the PI parameter equation indicated by Equation 4.2 can be expressed as:

$$K_p(t) = K_p(t) + \Delta K_p$$
$$T_i(t) = T_i(t) + \Delta T_i \quad (4.2$$

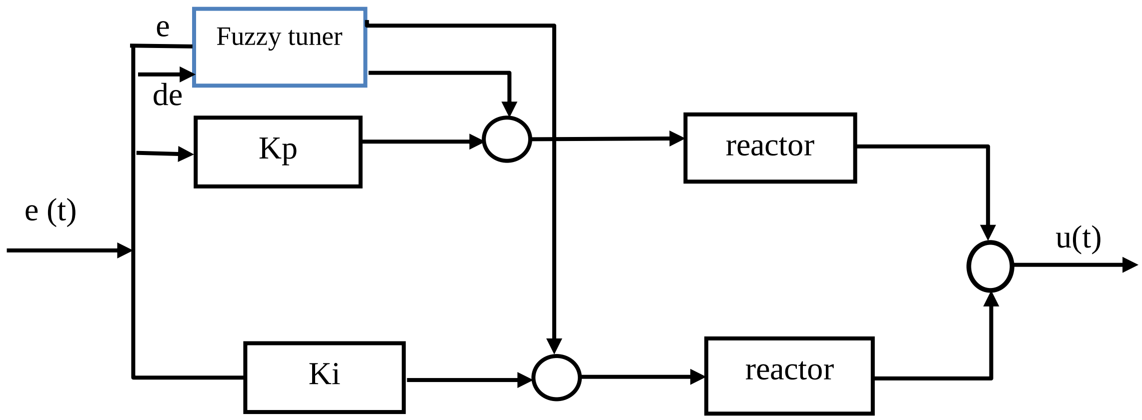

Figure 4. 4. Block diagram of fuzzy PI control structure

The fuzzy tuner produces two outputs namely temperature and SO_2 concentration for the trial error fuzzy controller.

The proposed MPPT controller based on Fuzzy Logic Controller (FLC) includes four main components: input/output membership functions (MFs), fuzzy inference engine, fuzzy. Controller rules and fuzzy wire. The blurring inference process uses the Mandan method, while blurring uses the centrefold to determine the FLC output, which indicates the change in temperature and SO_2 concentration.

As described above, the blurring controller takes two inputs: the temperature error and the SO_2-concentration the concentration error is the difference between the desired concentration output and the actual SO_2 concentration. The change in error indicates how fast the concentration error is changing. The output of the turbidity controller is a temperature variable used to control the temperature of the reactor. These two parameters can be calculated using the following equation (Islam, 2006).

$$E(k) = c(k) - c(k-1)$$
$$E(k) = T(k) - T(k-1) \tag{4.1}$$

The change in error is given by,

$$\Delta E(k) = E(k) - E(k-1) \tag{4.2}$$

The output of the fuzzy controller is the temperature and concentration,

$$(k) = T(k-1) - dT$$
$$(k) = c(k-1) - cT \tag{4.3}$$

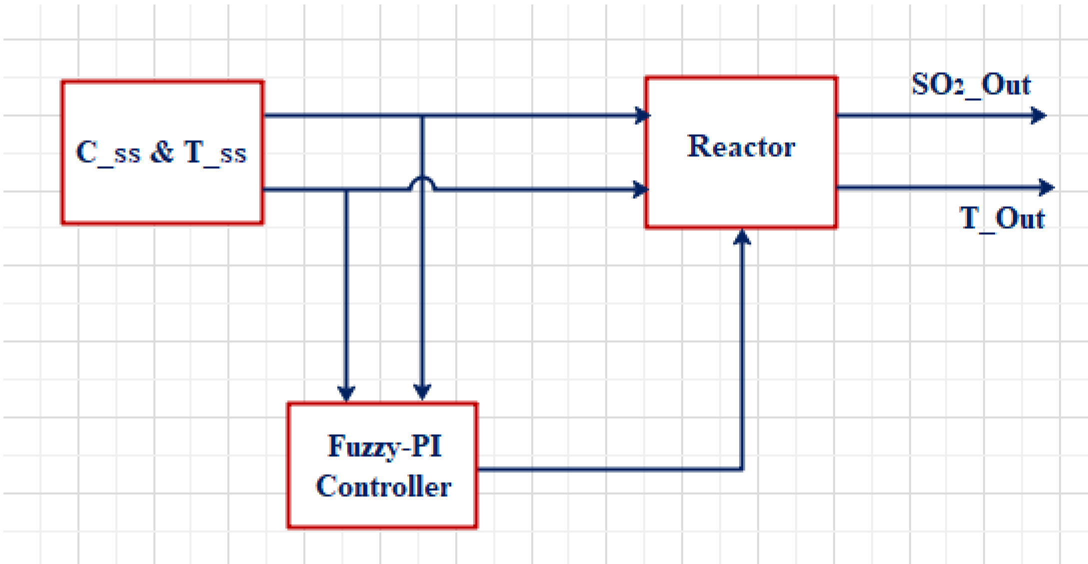

Figure 4. 5. Fuzzy-PI control structure

The fuzzy controller (FLC) takes two input variables at sampling time k: concentration variation (Δcso2) and temperature variation (ΔT). The output variable is the sulfur dioxide concentration and temperature in the reactor. The values of Δcso2 and ΔT can be calculated by the following equations: (Islam, 2006),

$$\Delta c = G_c \left(c(k) - c(k-1) \right) \tag{4.4}$$

$$\Delta T = G_T \left(T(k) - T(k-1) \right) \tag{4.5}$$

And the crisp value of the output variable Δ Δc_{so2} (k) and ΔT (k) is computed by;

$$c(k) = c(k-1) + G_c \Delta c(k) \tag{4.6}$$

$$T(k) = T(k-1) + G_T \Delta T(k) \tag{4.7}$$

The scaling factors Gc and GT are used to normalize the values of Δc(k), ΔT(k) in the fuzzy controller (FLC). These scaling factors are critical to optimizing FLC performance and can be determined by trial and error, tailored for a specific application. The normalized output signal c(k) and T(k) are then sent to the system. Input variables Δc and ΔT Nine MFs (Negative Extra Large, NVB; Negative Large, NB; Negative Medium, NM; Negative Small, NS; Zero, Z; Positive Small, PS; Positive Medium, PM; Positive Large, PB; Positive very large, PVB) for error, seven MFs (NB, NM, NS, Z, PS, PM, PB) for error level, and seven MFs (NB, NM, NS, Z, PS, PM, PB) for manipulated variable for changes in the FLC structure defined (santos, 1996). Triangular membership functions are used for both inputs, outputs, and are tuned to their best valuesthrough simulation. The algorithm is inspired by Perturbation and Observation (PandO), and Figure 3.9 illustrates the membership function and rule base, respectively. Inputs and outputs. The fuzzy rule database is divided into nine regions based on the characteristics of the P-V curve of the solar cell. Detailed analyzes and discussions of these areas are provided below.

Region 1: When both concentration and temperature decrease concurrently, the reactor's operational position shifts towards the inlet side. Analyzing these concentration and temperature variations enables the identification of decreased production.

Region 2: If the concentration capacity of the reactor remains constant, but the outlet temperature decreases, then the operating point is assumed to be of high concentration. In this case, the output of the algorithm is set to ZE to avoid conflicts.

Region 3: If the inputs remain constant and both concentration and temperature increase, the operating point is at the reactor exit. Increases in yield can be determined by analyzing changes in concentration and temperature. However, if the output command is too large, it can cause the operating point to shift from the output side of the reactor to the supply side, resulting in uneven outputs and fluctuations. Therefore, the output step size should not be too large.

Region 4: In this zone, the temperature remains constant while the concentration decreases. Without altering the inputs, the system cannot ascertain the position of the operating point within the reactor. Consequently, the output in this area is designated as ZE to prevent conflicts, even amidst input alterations.

Region 5: If both concentration and temperature stabilize without further changes, this indicates that the system has successfully monitored and achieved high reactor capacity. The output remains unchanged and the output is set to ZE.

Region 6: In this region, the output S02 concentration increases while the output voltage remains constant. As in region 4, the system cannot determine the location of the operating point relative to the reactor power without changing the input. Therefore, to avoid conflicts, the output of this range is set to ZE.

Region 7: If the inputs remain constant, the SO_2 concentration capacity decreases, and the temperature capacity increases, the operating point is located on the outlet side of the reactor. The power is adjusted according to changes in concentration and temperature.

Region 8: In this region, the SO_2 concentration remains constant while the exhaust temperature rises. Assuming that the input remains constant, the reactor capacity is considered to be reached and the output is set to ZE. Even if the input is changed, the range cannot determine whether it has increased or decreased, which avoids conflicts by setting the output to ZE.

Region 9: If both reactor power concentration and temperature rise simultaneously at the same inlet, this means that the operating point is on the inlet side of the reactor. The reduction in output can be determined by analyzing changes in concentration and temperature. However, if the output command is too large, it can cause the operating point to shift from the input side to the output side of the reactor. In this case, both the concentration and the temperature would have to increase and the power would have to be increased to keep up with the reactor capacity. This conflicts with the need to reduce production according to the fuzzy rule database. Major power changes should be avoided to avoid system fluctuations.

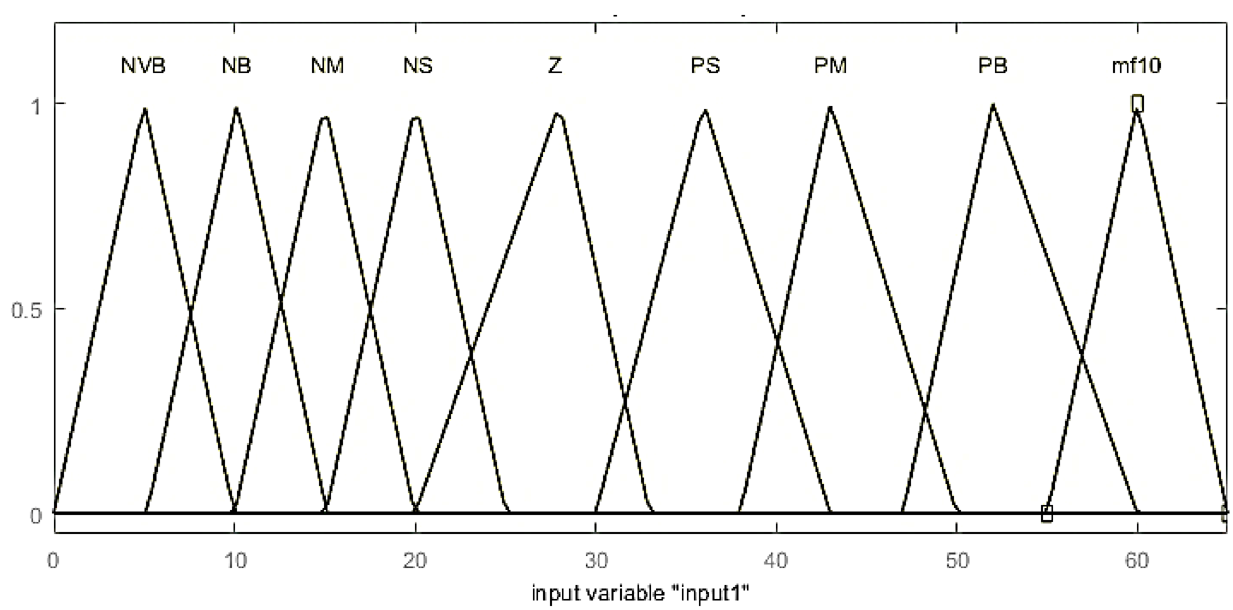

Figure 4. 6.Membership Functions for Error

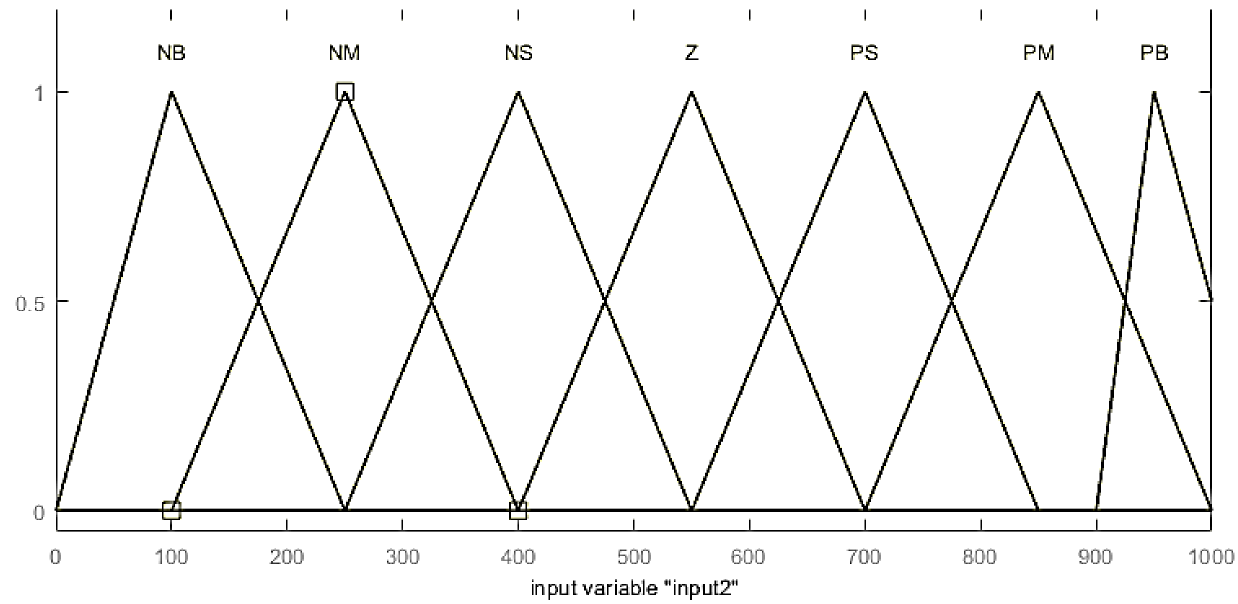

Figure 4. 7.Membership Functions for Rate–of–Error

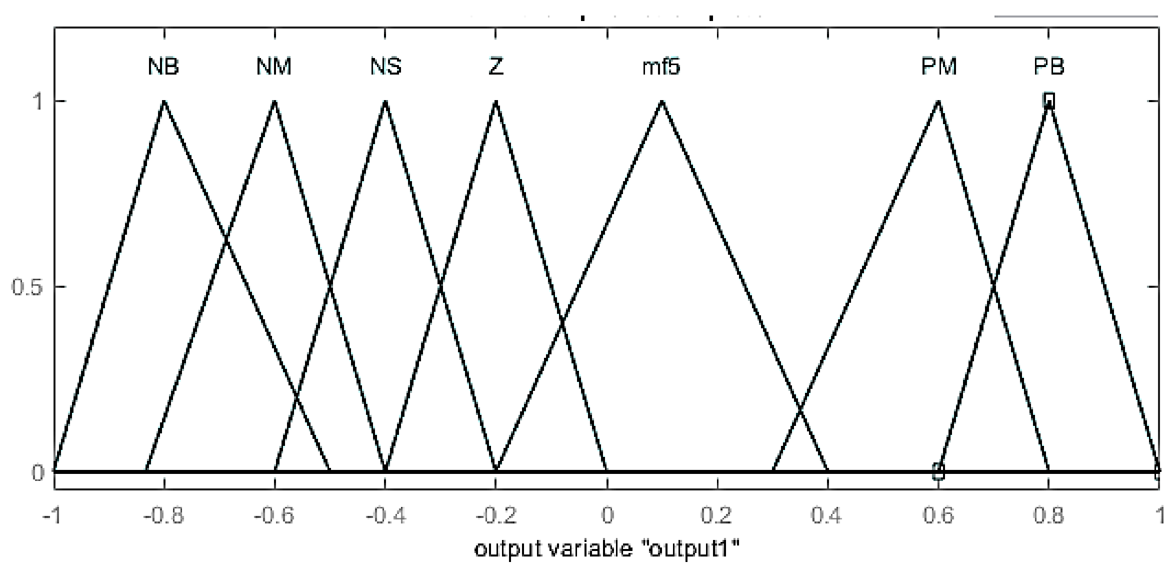

Figure 4. 8.Membership Functions for output Variables

Table 4.1 Rule base for the proposed fuzzy logic control

		Rate of error de/dt						
		NB	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
error	**NVB**	NB	NB	NB	NB	NB	NB	NB
	NB	NB	NB	NB	NM	NM	NS	Z
	NM	NB	NB	NM	NM	NS	Z	PS
	NS	NB	NM	NM	NS	Z	PS	PM
	Z	NM	NM	NS	Z	PS	PM	PM
	PS	NM	NS	Z	PS	PM	PM	PB
	PM	NS	Z	PS	PM	PM	PB	PB
	PB	Z	PS	PB	PM	PB	PB	PB
	PVB	PB	PB	PB	PB	PB	PB	PB

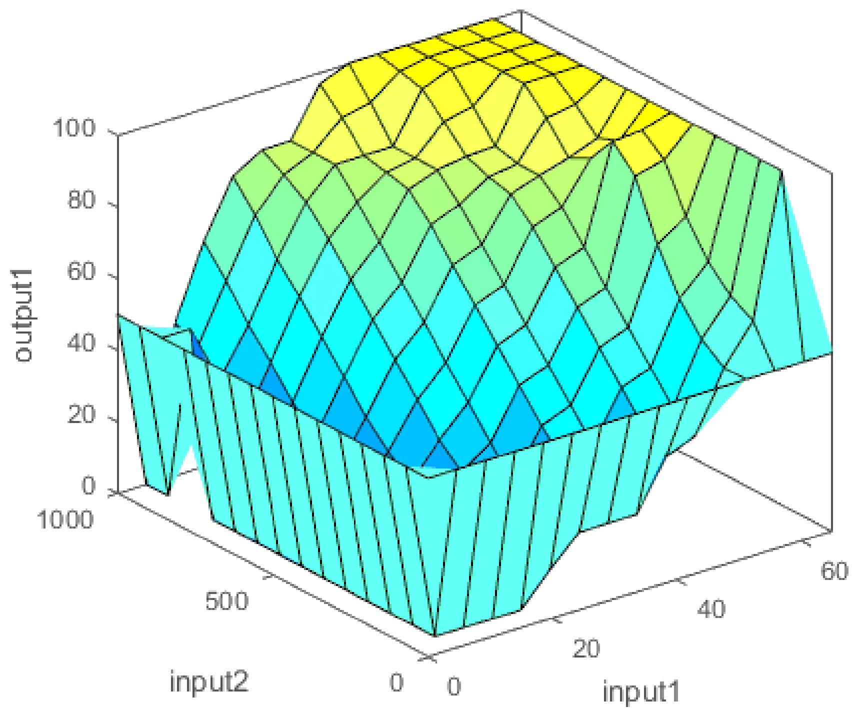

Figure 4. 9.3D surface view of the control rules

Figure 4. 10.Rule views of the control algorithm

The process of concentration and temperature involves regulating the concentration and temperature output of the reactor. The concentration and temperature is converted to their stable condition in the reactor. The output of the fuzzy controller is then applied to the temperature and concentration of the reactor and is scaled to a range of [-1, 1]. By adjusting the amount of concentration and temperature, the aim is to achieve the stable concentration and temperature from the reactor system.

CHAPTER FIVE

RESULT AND DISCUSSION

5.1. Introduction

In this chapter, the result and analysis of the proposed Reactor concentration and temperature control using Fuzzy-PI controller. The system design includes a reactor temperature and concentration modelling of SO_2, fuzzy-PI controller design and modelling. All this process is done and clarified starting from the introduction part.

A comparison analysis of the proposed system in the open and controlled system, which is applied in the reactor system, is done for checking the performance of different PI and fuzzy-PI controller. The initial value of Kp and Ki is 100 and 10 respectively. However, these values will vary according to fuzzy tunnel.

5.2 Open Loop Simulation Result

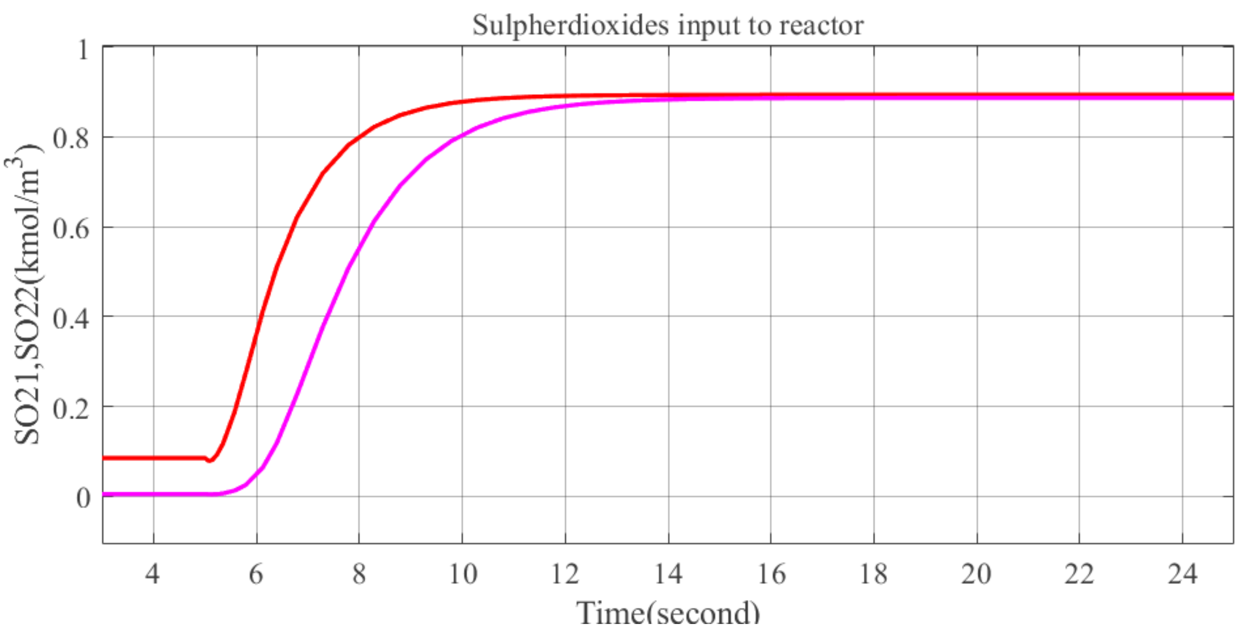

Figure 5. 1. Open loop output for sulfurdioxide concentration (kmol/m^3)

Figure 5.1 and figure 5.2 are the concentration and temperature output of the reactor without applying a controller. From this figures it is understood that the stable point takes more time and the rise time is high. In addition, the inlet and outlet concentration have much difference in the reactor. The temperature settling time also high and the temperature value is high at the start of the simulation.SO21 and SO22 are the left and right-side output of the reactor that is the inlet and outlet of the reactor.

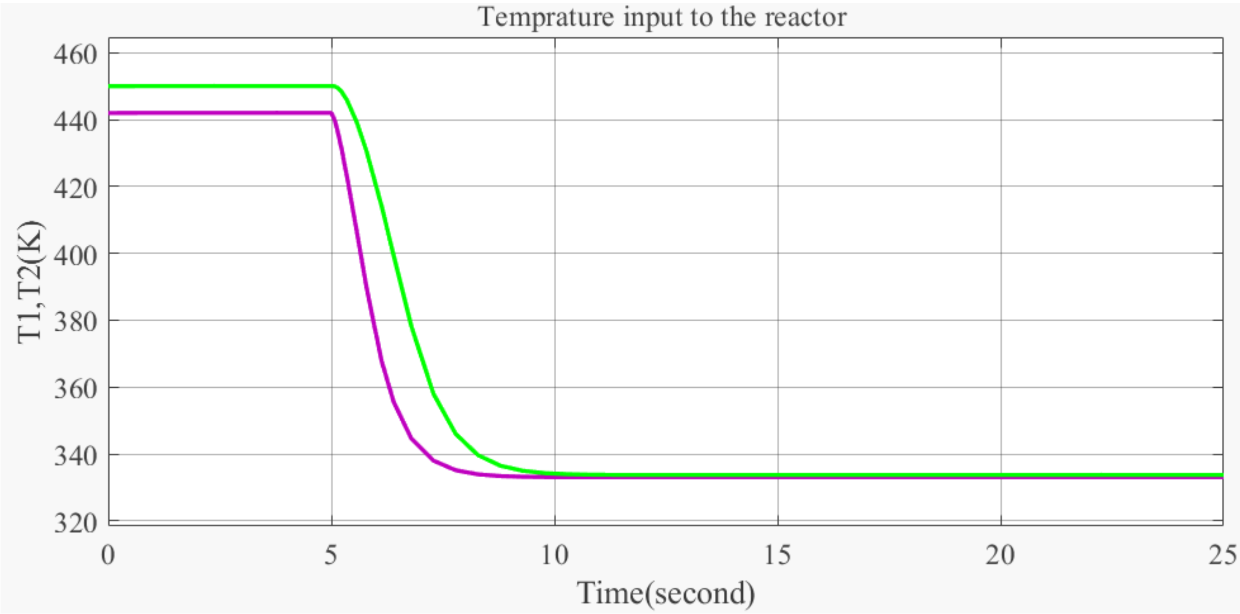

Figure 5. 2. Reactor temperature output

5.3 PI controller output

5.3.1 PI Control Using Servo Technique

Servo technique describes in PI control uses a constant specific heat capacity and temperature which is an input to the reactor. The system is tasked with tracking a reference trajectory for the desired concentration and temperature profiles, the fuzzy-PI controller exhibited commendable performance. It effectively tracked the set points, mitigating deviations and ensuring that the reactor operated within the desired ranges. This capability is crucial in applications where maintaining precise process parameters is paramount to achieving desired product quality or reaction kinetics.

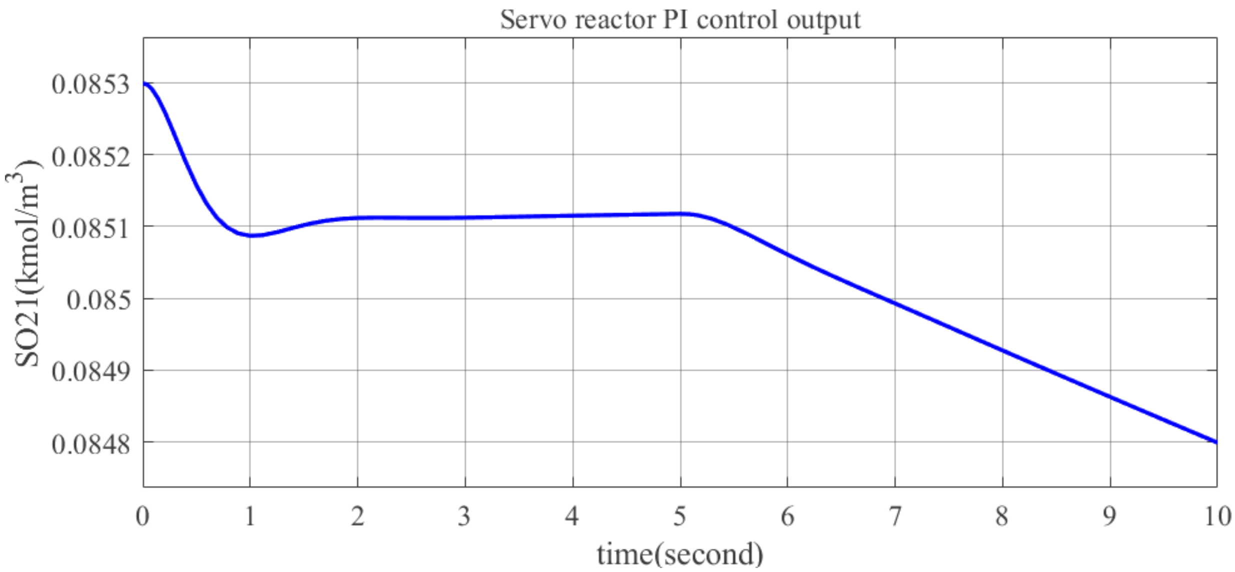

Figure 5. 3. Concentration output of SO_2 in the left side of reactor

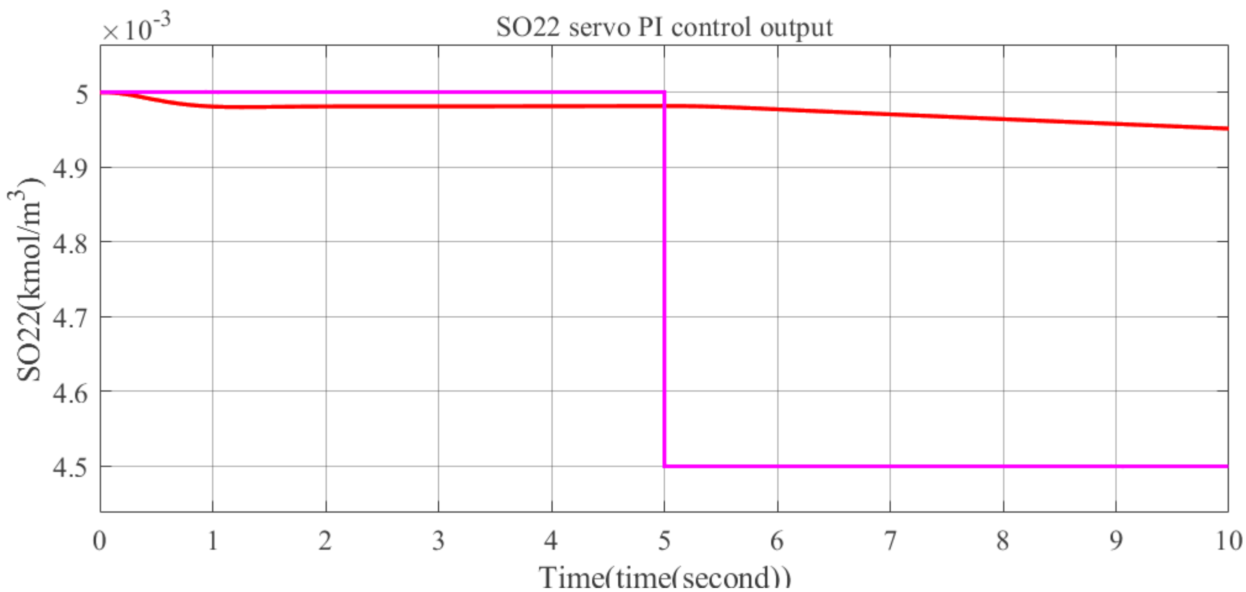

Figure 5. 4. Concentration output of SO_2 in the right of reactor

Figure 5.3 and 5.4 is the concentration of SO_2 in the left side and right side of the reactor respectively.in the left side of the reactor the concentration is reduced at the start and have stable region in some time the if falls.it have good settling time than that of without controller. Figure 5.4 is right side concentration of the reactor.it have better performance than that of the left side concentration. Both are simulated in servo PI control technique. The servo runs in constant specific latent heat capacity and temperature.

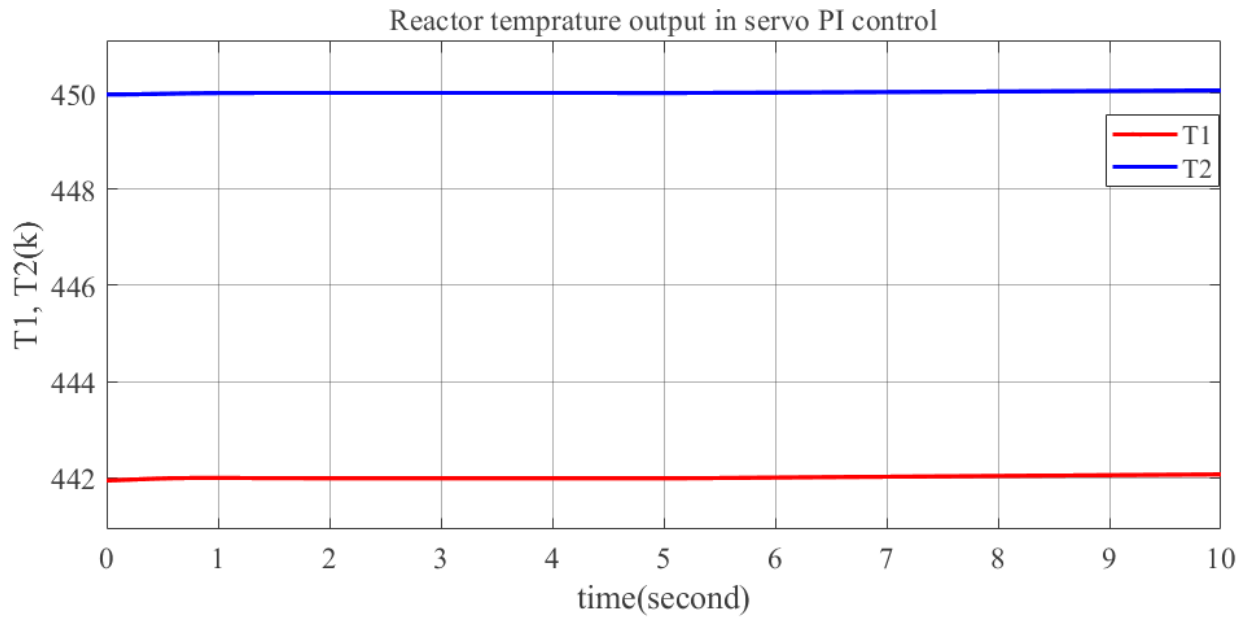

Figure 5. 5. Temperature output of reactor in servo PI control

The temperature has only small difference in the two side of the reactor when applying servo PI control. The difference is the value in kelvin and have the same settling and rise time. Enen if they have the same result both high temperatures.

5.3.2 PI Control Using Regulator Technique

The regulator conditions, where the controller is responsible for maintaining the concentration and temperature at set points despite disturbances or changes in operating conditions, the fuzzy-PI controller displayed its robustness. It promptly responded to disturbances, swiftly adjusting control actions to restore the system to the desired operating points. This resilience is essential for ensuring operational stability and reliability in industrial processes where disturbances are commonplace.

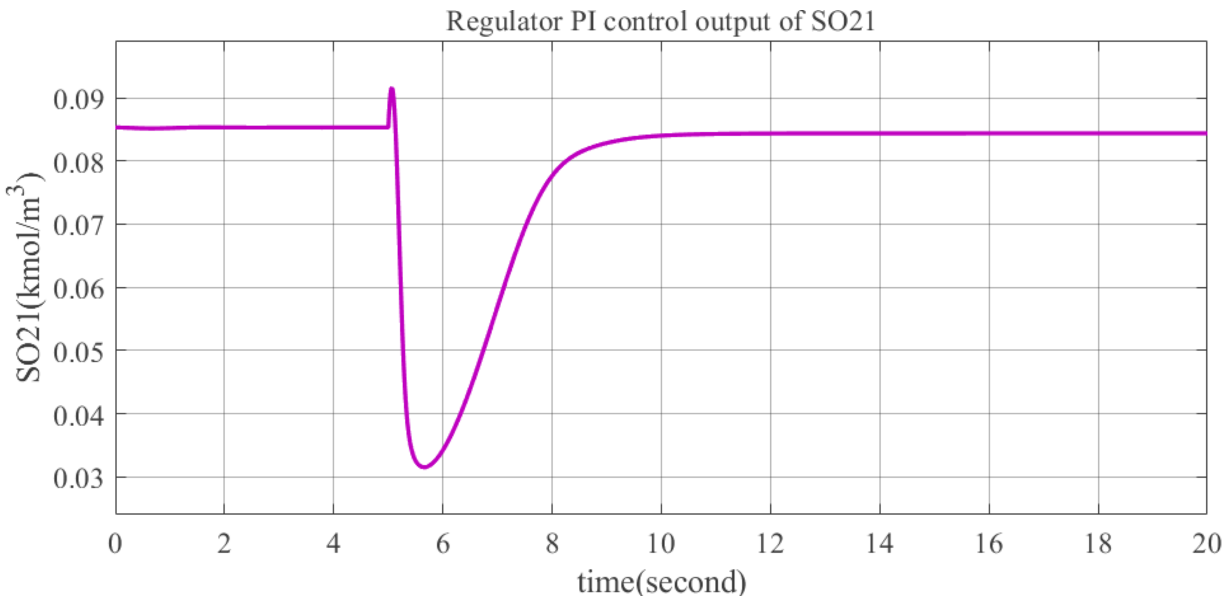

Figure 5. 6. Concentration output of SO_2 in the left side of reactor in regulator method

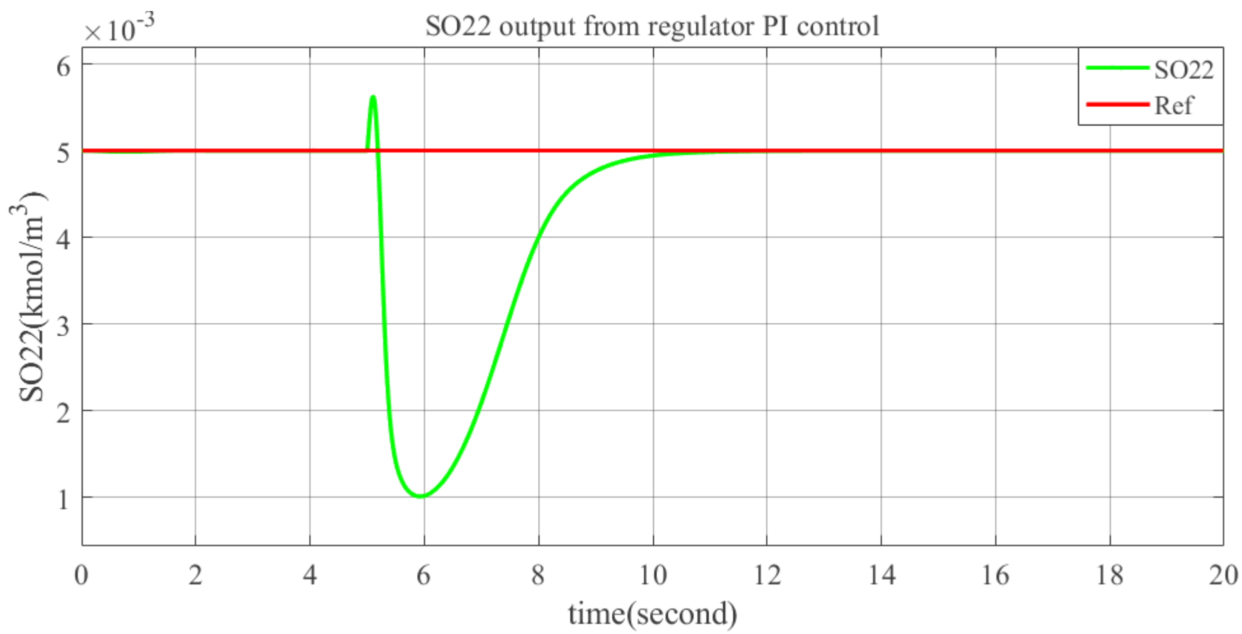

Figure 5. 7. Concentration output of SO_2 in the right side of reactor in regulator method

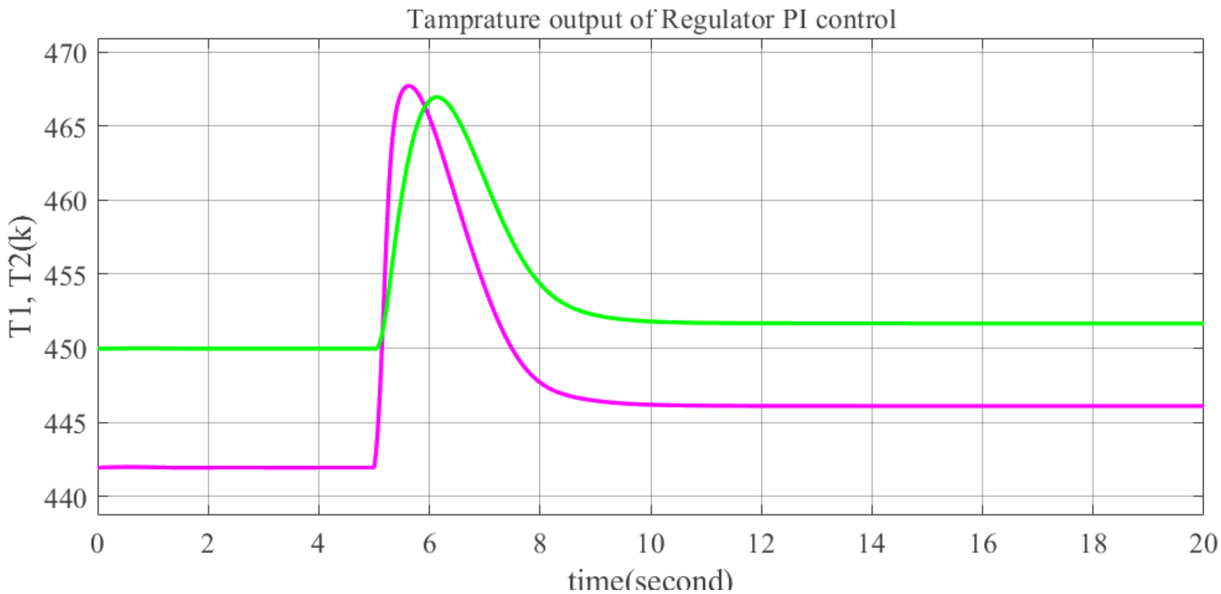

Figure 5. 8. Temperature output of reactor using regulator

Figure 5.6 and 5.7 are the concentration of SO_2 in the left and right side of the reactor after applying PI controller. The concentration is higher in the left side of the reactor and low in the right side. Both figure 5.6 and 5.7 have similar dynamic performance parameters.as compared with the servo PI control technique, the regulator has better performance in the concentration and temperature. Figure 5.8 is the temperature output in both side of the reactor. In this case, the temperature has better performance except the value, which is high. Moreover, the temperature rise exponentially in some time from 5 to 7 sec.

5.4 Fuzzy-PI controller output

5.4.1 Fuzzy-PI Control Using Servo Technique

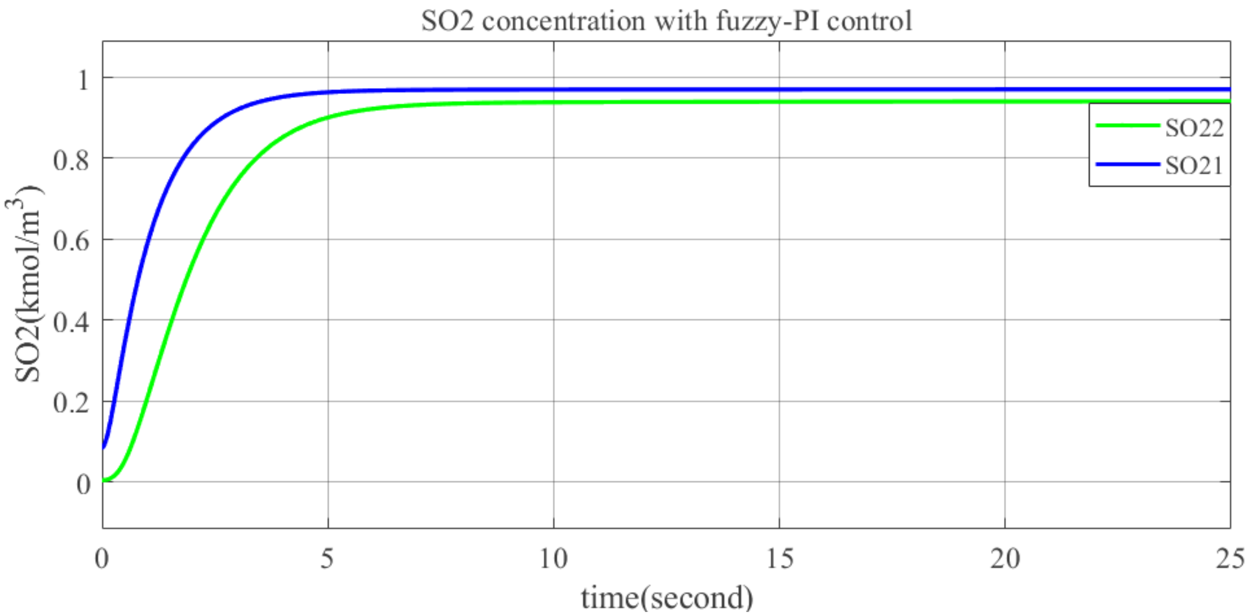

Figure 5. 9.concentration output of SO2 in the left and right of reactor in servo based fuzz-PI

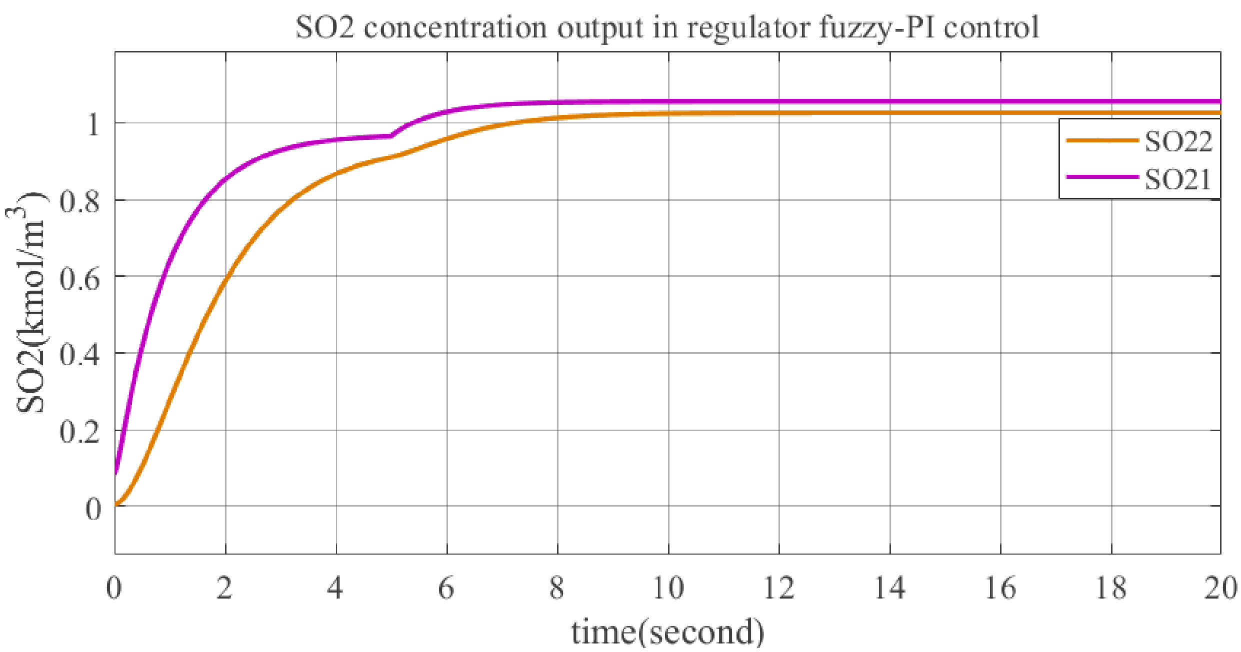

Figure 5.10-

Figure 5. 10. Concentration output of SO_2 in the left and right of reactor in regulated fuzzy-PI

Figure 5.9 and 5.10 describes the concentration of SO_2 in the left and right side of the reactor. The first figure 5.9 is the concentration using servo input fuzzy-PI control technique.as shown in this figure the signal has very good stable signal as compared with servo PI control. In addition, the value of concentration increases with the application of fuzzy-PI controller. This shows that fuzzy-PI controller is effective.

The next figure 5.10 is the concentration output of SO_2 in the left and right side of the reactor with regulated fuzzy-PI controller.at the first run time of the simulation there is very small undershoot in the left side concentration. But the value of the concentration is higher than the other concentration.

From this, it is clear that the regulated fuzzy-PI controller is more effective than that of the above control methods.

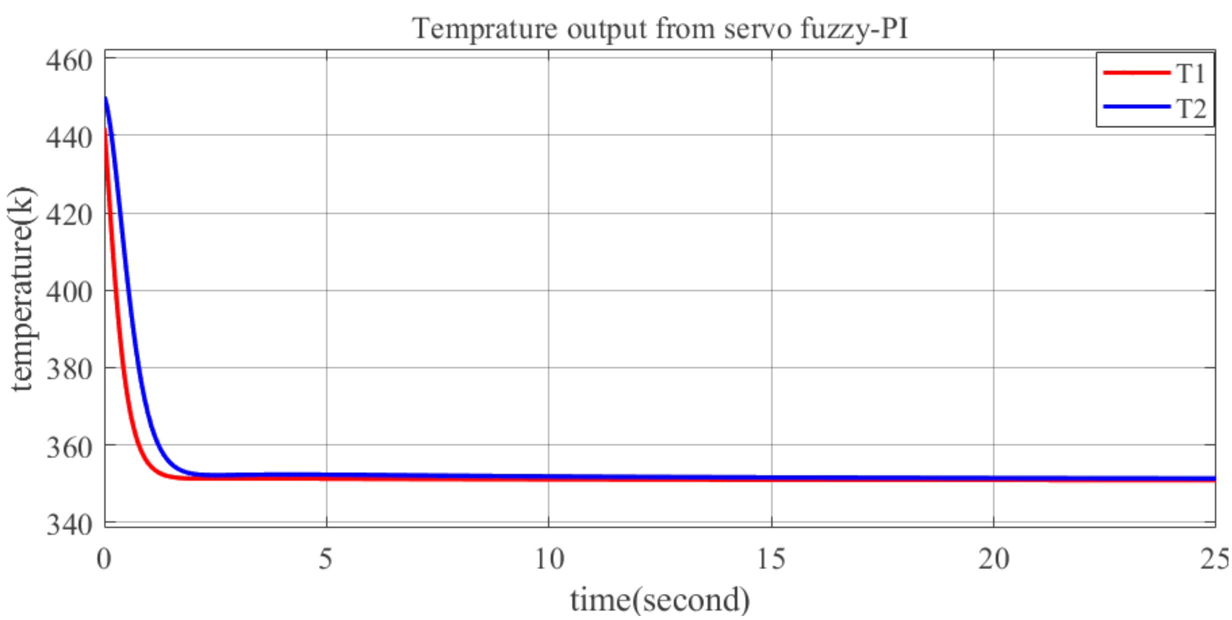

Figure 5. 11.Temperature output left and right of reactor in servo based fuzzy-PI control

Figure 5.11 and 5.12 describes the temperature output in the left and right side of the reactor. The first shows the temperature output-using servo based fuzzy-PI control. The temperature result has better performance and the two temperatures have an approaching value. In addition, the two temperatures have almost had the same dynamic performance parameters.in fuzzy-PI controller the temperature output is reduced in standard form in the reactor.

The next figure 5.12 is the temperature output from regulated fuzzy-PI controller in the reactor control. From this figure, the temperature at the start almost has the same output. Compared to figure 5.11 the regulator is more important in control application.

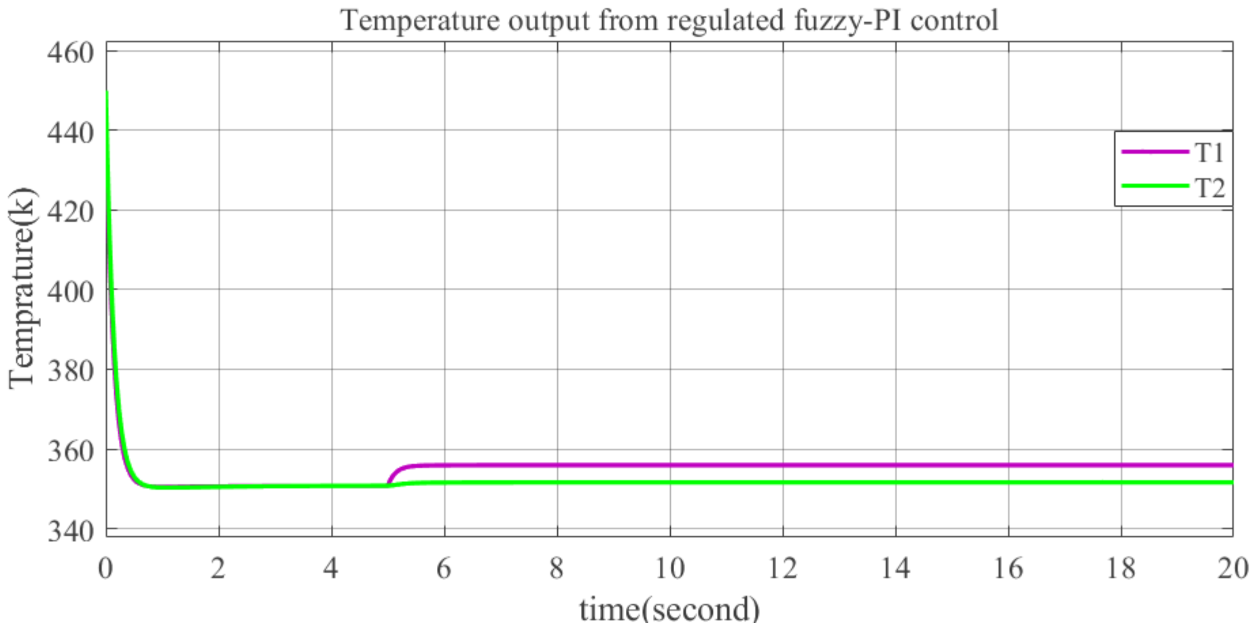

Figure 5. 12.Temperature output left and right of reactor in regulator based fuzzy-PI control

In general, the regulated fuzzy-PI control is more effective that other control described in the above figures. Regulator with a controller is also more important in reaction system control. The effectiveness of the different controlling mechanism in concentration and temperature are analyzed using the following tables.

Table 5. 1.Dynamic performance of the different controller output

Performance	**Open loop**		**PI controller**		**Fuzzy-PI controller**	
parameters	concentration	Temperature	concentration	Temperature	concentration	Temperature
Error (%)	1.589	1.365	1.208	1.127	0.364	0.24
Settling time(sec)	8.512	8.04	6.539	5.421	1.248	0.847
Overshoot (%)	0.689	0.548	0.216	0.168	0.0451	0.0254
Rise time	2.054	1.652	1.173	1.065	0.82	0.241

The table 5.1 described above is the compression of different controlling mechanism in the reactor with concentration and temperature parameter. From this compression the fuzzy-PI controller has more efficiency in controlling the reactor by removing the unnecessary noise and by removing error detected in the reactor. The controller balances the temperature and concentration of SO2 in the reactor left and right side.

CONCLUSION AND RECOMENDATIONS

Conclusion

In this study, it was successfully implemented a fuzzy-PI controller to regulate the concentration and temperature of a reactor under both servo and regulator conditions. The utilization of fuzzy logic combined with proportional-integral control has demonstrated its efficacy in achieving precise and robust control over these critical process variables.

The implementation of the fuzzy-PI controller has enabled us to navigate the complexities inherent in reactor control systems, where nonlinearities, uncertainties, and disturbances are prevalent. By incorporating fuzzy logic, the controller possesses the ability to handle imprecise and vague input information, thereby enhancing its adaptability to various operating conditions.

Under servo conditions, where the system is tasked with tracking a reference trajectory for the desired concentration and temperature profiles, the fuzzy-PI controller exhibited commendable performance. It effectively tracked the set points, mitigating deviations and ensuring that the reactor operated within the desired ranges. This capability is crucial in applications where maintaining precise process parameters is paramount to achieving desired product quality or reaction kinetics.

Similarly, in regulator conditions, where the controller is responsible for maintaining the concentration and temperature at set points despite disturbances or changes in operating conditions, the fuzzy-PI controller highlighted its robustness. It promptly responded to disturbances, swiftly adjusting control actions to restore the system to the desired operating points. This resilience is essential for ensuring operational stability and reliability in industrial processes where disturbances are commonplace.

The versatility of the fuzzy-PI controller in handling both servo and regulator tasks underscore its potential for widespread adoption across various industrial sectors. Its ability to provide accurate and adaptive control makes it a valuable tool for optimizing process performance, reducing energy consumption, and enhancing product quality.

The effectiveness of fuzzy PI controller is also analyzed using dynamic performance parameters. For example, the overshoot of concentration in open loop system is 0.689%, in PI controller 0.216 and in fuzzy PI controller 0.0451%. similarly in temperature these same parameters are 0.548%, 0.168% and 0.0254% respectively. Likewise, the other performance parameters are compared on table 5.1. from this it can be concluded that the performance parameter has better performance in fuzzy PI in regulator condition.

Furthermore, the successful implementation of the fuzzy-PI controller in this study opens avenues for further research and development. Future work could explore advanced control strategies, such as adaptive fuzzy control or fuzzy model predictive control, to further enhance the performance of reactor systems.

In the system the fuzzy and PI controller are applied insolently and the result of then are compared to check their effectiveness in controlling the whole system.

In general, the application of the fuzzy-PI controller has proven to be a promising approach for controlling the concentration and temperature of reactors in both servo and regulator conditions. Its ability to provide robust, adaptive, and precise control signifies its potential to revolutionize process control in various industrial applications, contributing to improved efficiency, reliability, and product quality.

RECOMMENDATION FOR FUTURE WORK

Future researcher can focus on refining and enhancing the fuzzy logic strategies employed in the fuzzy-PI controller. Exploring advanced fuzzy logic techniques, such as adaptive or hybrid fuzzy control, could improve the controller's adaptability and performance in handling complex and dynamic reactor systems.

Future researcher in this area can develop methodologies for real-time implementation of the fuzzy-PI controller in industrial-scale reactor systems. Explore hardware-in-the-loop (HIL) simulation techniques to validate controller performance under realistic operating conditions. Additionally, investigate methods for online tuning and optimization of fuzzy-PI controller parameters to adapt to varying process conditions and enhance controller robustness and efficiency.

Investigate techniques for detecting and mitigating faults, such as sensor failures, actuator faults, or process disturbances, using fuzzy logic-based fault detection algorithms. By incorporating fault-tolerant control strategies, the controller can maintain process stability and performance even in the presence of abnormalities or uncertainties.

In addition, future researcher can conduct experimental validation of the fuzzy-PI controller in practical reactor systems to assess its performance under real-world operating conditions. Collaborate with industrial partners to implement the controller in pilot-scale or commercial-scale reactor processes and evaluate its effectiveness in improving process efficiency, product quality, and energy consumption. Gather feedback from industry stakeholders to identify areas for further refinement and optimization of the controller design.

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APPENDIX

A.Mathlab program for S function

```
function [sys,x0,str,ts,simStateCompliance] = sfunction(t,x,u,flag)
switch flag,
  % Initialization %
  case 0,
    [sys,x0,str,ts,simStateCompliance]=mdlInitializeSizes;
  % Derivatives %
  case 1,
    sys=mdlDerivatives(t,x,u);
  case 2,
    sys=mdlUpdate(t,x,u);
  case 3,
    sys=mdlOutputs(t,x,u);
  case 4,
    sys=mdlGetTimeOfNextVarHit(t,x,u);
  case 9,
    sys=mdlTerminate(t,x,u);
  otherwise
    DAStudio.error('Simulink:blocks:unhandledFlag', num2str(flag));
end
function [sys,x0,str,ts,simStateCompliance]=mdlInitializeSizes
sizes = simsizes;
sizes.NumContStates  = 4;
sizes.NumDiscStates  = 0;
sizes.NumOutputs     = 4;
sizes.NumInputs      = 4;
sizes.DirFeedthrough = 0;
sizes.NumSampleTimes = 1;   % at least one sample time is needed
```

```
sys = simsizes(sizes);

%
% initialize the initial conditions
%
x0  = [0.085299 441.94 0.005 449.97];
str = [];
ts  = [0 0];
simStateCompliance = 'UnknownSimState';
function sys=mdlDerivatives(t,x,u)
sys = eqs(x,u);
function sys=mdlUpdate(t,x,u)
sys = [];
function sys=mdlOutputs(t,x,u)
sys = x;
function sys=mdlGetTimeOfNextVarHit(t,x,u)
sampleTime = 1;    %  Example, set the next hit to be one
function sys=mdlTerminate(t,x,u)
sys = [];
% end mdlTerminat
function dxdt = eqs(x,u)
% Arranging the system of equations.
% state variables:
C1 = x(1);
T1 = x(2);
C2 = x(3);
T2 = x(4);
% inpute variables:
q = u(1);
Cf = u(2);
```

```
Tf = u(3);
qc = u(4);
% Constants:
v = 100;
rho = 1000;
hA = 1.67*10^5;
E_R = 10000;
cp = 0.239;
k0 = 7.2*10^10;
Tcf = 350;
dH = 4.78*10^4;
% Four differential equations:
dC1 = (q/v)*(Cf-C1) - k0*C1*exp(-E_R/T1);
dT1 = (q/v)*(Tf - T1) + (k0*dH*C1/(rho*cp))*exp(-E_R/T1) + (qc/v)*(1-exp(-
hA/(rho*cp*qc)))*(Tcf - T1);
dC2 = (q/v)*(C1-C2) - k0*C2*exp(-E_R/T2);
dT2 = (q/v)*(T1-T2) + (k0*dH*C2/(rho*cp))*exp(-E_R/T2) + (qc/v)*(1-exp(-
hA/(rho*cp*qc)))*(T1-T2+(exp(-hA/(rho*cp*qc)))*(Tcf-T1));
% Packing the system of equation to insert it into the s-function solver:
dxdt = [dC1 dT1 dC2 dT2]
function F = StStFun(y)
% Calculation of steady-state values of state variales.
% Unpacking the initial values:
C1_ss = y(1);
T1_ss = y(2);
T2_ss = y(3);
qc = y(4);
% Constant values:
C2_ss = 0.005;
q = 100;
v = 100;
```

```
rho = 1000;
Cf = 1;
hA = 1.67*10^5;
E_R = 10000;
Tf = 350;
cp = 0.239;
k0 = 7.2*10^10;
Tcf = 350;
dH = 4.78*10^4;
% Differential equations of the system at steady-state condition:
F(1) = (q/v)*(Cf-C1_ss) - k0*C1_ss*exp(-E_R/T1_ss);
F(2) = (q/v)*(Tf - T1_ss) + (k0*dH*C1_ss/(rho*cp))*exp(-E_R/T1_ss) + (qc/v)*(1-exp(-
hA/(rho*cp*qc)))*(Tcf - T1_ss);
F(3) = (q/v)*(C1_ss - C2_ss) - k0*C2_ss*exp(-E_R/T2_ss);
F(4) = (q/v)*(T1_ss - T2_ss) + (k0*dH*C2_ss/(rho*cp))*exp(-E_R/T2_ss) + (qc/v)*(1-exp(-
hA/(rho*cp*qc)))*(T1_ss-T2_ss+(exp(-hA/(rho*cp*qc)))*(Tcf-T1_ss));
clc
% Setting up the initial conditions for iteration.
% Other values which are not so out of range will end up
% with the same results below:
C1_ss_init = 0.5;
T1_ss_init = 400;
T2_ss_init = 450;
qc_init = 100;

% Packing up the initial conditions:
y0 = [C1_ss_init, T1_ss_init, T2_ss_init, qc_init];
% Using fsolve to find the answers of 4-equations and 4-unknowns system.
% Open the StStFun.m file beforehand.
fun = @StStFun;
y = fsolve(fun,y0);
```

```
% Printing the results:
C1_ss = y(1);
T1_ss = y(2);
T2_ss = y(3);
qc = y(4);
formatspec = '\nCA1_ss: %f   mol/lit \nT1_ss: %f  K \nT2_ss: %f  K \nqc_ss: %f   lit/min \n';
fprintf(formatspec, C1_ss, T1_ss, T2_ss, qc)
```

B. Simulink Model

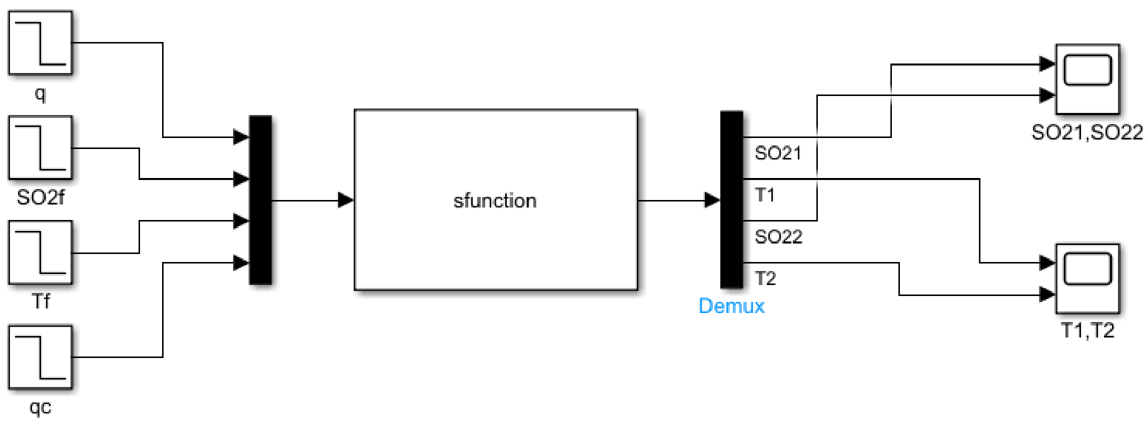

Figure B. 1. Open loop Simulink model

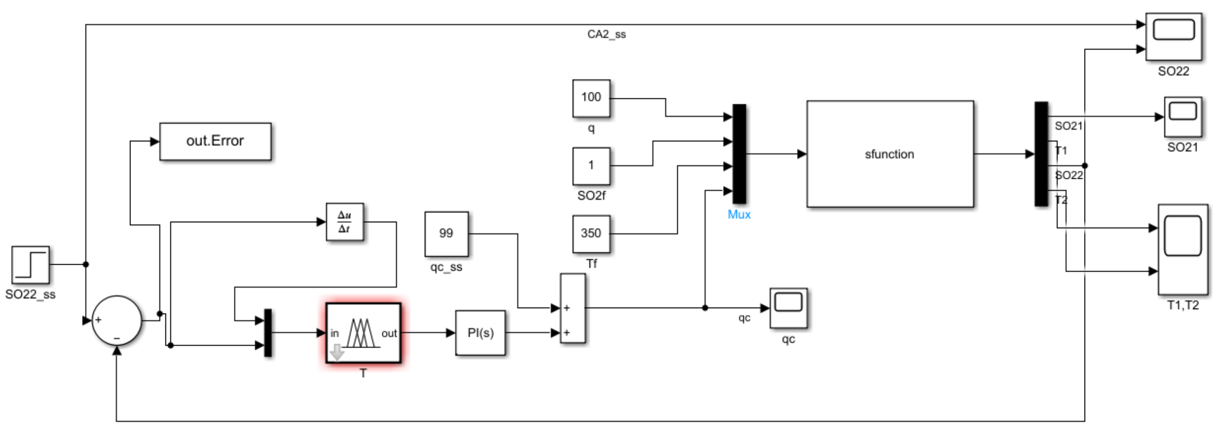

Figure B. 2.simulink model of Fuzzy-PI reactor control with servo system

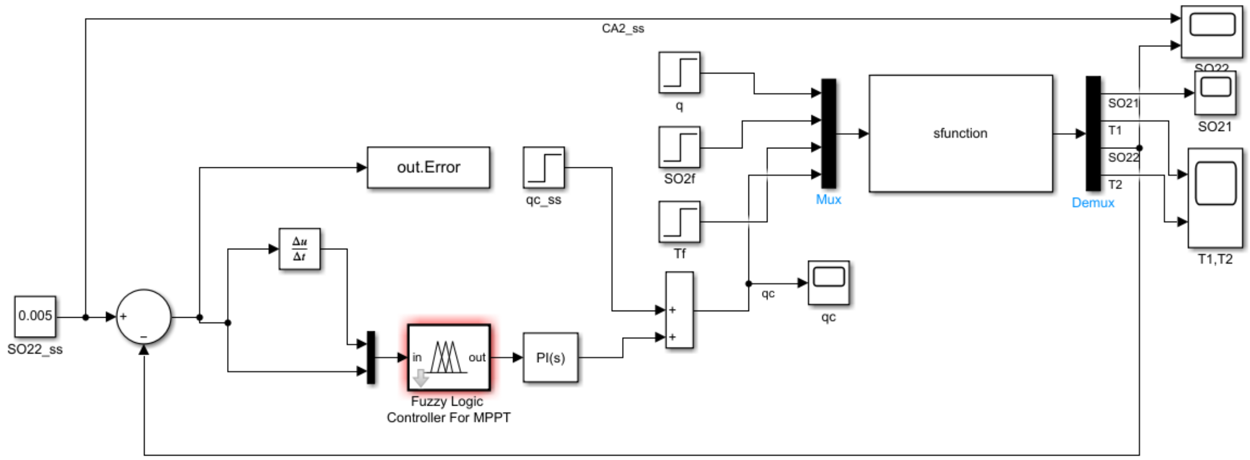

Figure B. 3.Simulink model of Fuzzy-PI reactor control with regulator system