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# FUZZY LOGIC CONTROL OF CONTINUOUS STIRRED TANK FERMENTER

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***Abstract:*** In recent years, the world facing the energy crisis as well as waste management as the biggest problem. This problem can be solved by anaerobic digestion where the waste is converted into biogas. The increase in global warming in addition to rapid depletion of coal and oil have promoted to do research on alternative fuels. Consequently, the use of renewable energy supports to reduce pollution. The temperature along with the concentration of waste must be maintained at a particular threshold level to acquire the high yield of biomass. Hence, there is need to control of these parameters. The primary intention of the undertaking is to develop a controlling system to manage the fermenter temperature as well as the biomass concentration within the tolerance limit. By using the mathematical modeling equations, the continuous stirred tank fermenter is designed in MATLAB/Simulink.
The proportional, proportional and integral, proportional plus integral plus differential and fuzzy logic controlling system techniques are used to control the biomass concentration as well as the temperature of the bioreactor by manipulating the feed dilution rate and the jacket dilution rate respectively. This experiment also carried out without using any controlling strategies. The performance results without as well as with controllers are validated using accuracy, efficiency along with stability of the fermenter. Simulation results depict the Fuzzy controller presents superior performance compared to all other controllers.

***Keywords:*** **Waste management, Global warming, Anaerobic digestion, Continuous stirred tank fermenter, Fuzzy controller, P, PI and PID controller, MATLAB/Simulink.**

## I. INTRODUCTION

### 1.1 Overview

India's rapid economic growth has resulted in a sustainable increase in the waste generation. The waste can be used as a source of energy in which waste is converted into biomass using fermenter the waste will be decomposed under anaerobic condition to produce methane gas it will be used for domestic purpose and the sludge waste will be used as organic manure. A Fermenter is a biochemical reactor used for controlling performance of a microbial metabolic reaction to produce useful products in addition to the biomass formed. Mathematical modeling and simulation are widely used to gain insights into biotechnological processes. Thus, to reduce the amount of experimental work, it is necessary to design, control as well as optimize the process.

The Fermentation process is classified according to the operating mode. The reactors are labeled as a batch reactor and a continuous stirred tank reactor. The reagents are charged at the start of the reaction and the products are withdrawn at the end of the reaction in batch mode. In the continuously stirred tank reactor, the reactants are continuously charged, and the products are continuously removed. It operates below uniform situation of low substrate and high product concentrations. Bioreactor is a consistent mixed tank reactor where a few organic responses happen in a liquid medium.

### 1.2 Motivation

The main motive of this project is the use of waste, i.e. biodegradable waste. This can be fermented to get the biomass products. Many isolated villages in India are the shortfall of energy. This motivated to use waste as a raw material to energies those villages. The waste can be recycled and it helps us to keep the environment clean, healthy, the use of renewable energy, i.e. biomass is less effective when compared to conventional energy. The sources of bio recyclable wastes are forests, villages, food wastes in functions and hotels. It helps to get various products like methane gas for cooking, also that the remaining substrate can be used as the fertilizer. The control of fermenter helps to get high yield.

### 1.3 Problem statement

- Waste management as well as the energy crisis.
- The increase of waste nowadays due to increase in the population.
- The use of conventional energy sources such as coal, petroleum, etc. causes more pollution and increase in global warming.
- Rapid depletion of non-renewable energy sources like coal, gas, petroleum, etc.
- In fermenters the temperature is always varying along with the biomass concentration will vary.
- The dilution rate should be maintained if it is higher than the maximum growth rate, so the cell growth rate will be reduced.
- Input feed should be properly diluted if not the decomposition won't take properly.

### 1.4 Objectives of proposed system

The objectives of this project listed as

- Control, the concentration of biomass by varying the feed dilution rate.
- Control of fermenter temperature by varying the jacket dilution rate.
- Proportional (P), proportional plus integral (PI), proportional plus integral plus Derivative(PID) controller combinations along with the Fuzzy controller is used
- The accuracy and efficiency of the controllers were analyzed.

## II. LITERATURE SURVEY

Literature survey is an essential for any undertaking; it helps growing new ideas for carrying out of the task. Document research is necessary to carry out project work in stages. The investigative approach for this project was based on the previous results of the published literature review. The literature review was conducted using existing articles, IEEE articles and reviews.

### 2.1 Literature overview

**Ahmad Ashoori, Amir Hosein Ghods, Ali Khaki-Sedigh, Mohammad Reza Bakhtiari [1]** has proposed "Model predictive control of a non-linear fed-batch fermentation process" developed a model for producing different antibiotics. Goal is to control temperature, PH, dissolved oxygen. The Model predictive control is performed to determine the control signal by minimizing the cost function.

**Mats Akesson, Per Hagander, Jan Peter Axelsson [2]** has illustrated "A pulse technique for control of fed-batch fermentations" The strategy of controlling the feed rate of the fed-batch fermentation substrate is presented; the main idea is to make the forward speed pulse to assess the response of the dissolved oxygen signal.

**K. Serebrinsky, B. Hirmas, J. Munizaga, and F, Pedreros [3]** has estimated "Model structures for batch and fed-batch ethanol fermentations" estimate the model parameters and then use these values to simulate and optimize a fed batch culture. Analyze batch and fed batch kinetic models and find a single model structure that is unique for both types of crops and suitable for all temperatures.

**NS Mkondweni and R Tzoneva [4]** has presented "Programme for monitoring and control of a fed-batch fermentation process for the production of yeast" here SCADA system is used for automatic control of the fed batch fermentation process for yeast production, hardware and software parts for the data acquisition and changes to control system set points are described and discussed. The LABVIEW code is used.

**Dr. Riyadh R. Alsabti, Dr. Ittehad F. Tobyia, Ziad T. Al-Ismaeel [5]** has studied "Control of continuous stirred tank fermenter" is attempted to provide programs for the study of the dynamics and control of the continuous stirred tank fermenter, here mathematical model on mass and heat balance is developed.

### 2.2 Summary of literature survey

The Literature survey summary explains various methods of controlling a fermenter or bioreactor. After analyzing the papers, a quality model is designed for fermenter, which is briefly explained in the coming subsequent sections.

#### 2.2.1 Merits:

- In the continuous stirred tank fermenter, the reagents are constantly charged, and the products are continuously extracted.
- The substance is very much mixed and uniform all through.

#### 2.2.2 Limitations:

- In batch, reagents are loaded at the start of the reaction and discarded at the end of the reaction.

## III. METHODOLOGY

The dynamic as well as the steady state simulation model of the continuous stirred tank reactor is based on the mass and energy balance equations of the fermenter as well as the jacket. For simulation, these balance equations are required to build the fermenter. The biochemical reaction takes place between the biomass (the microorganism of the living body) and the substrate (the food of the microorganism of the living body for its sustenance) to produce biomass.

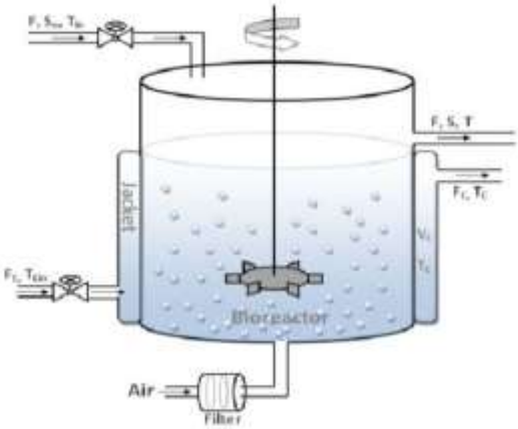


**Fig 1:** Schematic diagram of jacketed bioreactor

**3.1 Assumptions for the proposed model:**

Assumptions were made to formulate the mass and heat balance for the continuous stirred tank fermenter

- The feed substrate may be very diluted with water so that the properties of the water can be applied.
- The specific growth rate is considered constant with temperature, since the temperature deviations are very small in the control analysis.
- The constant heat generated with the aid of using agitation and the heat losses is negligible.
- The inlet temperature of air is the same as the fermentation temperature and the air is saturated with water, so that the heat loss by evaporation may be negligible.

**3.2 Derivation of mass balance equation:**

Accumulation rate = in by flow - out by flow + generation

Substrate mass balance $\frac{d(VS)}{dt} = FS_0 - FS - Vr$

where, V is the volume of the fermenter.

S is concentration of the substrate in the fermenter.

$S_0$ is the concentration of substrate in the feed.

F is the volumetric flow of the inlet and outlet flow.

r is the rate of substrate consumption by the cell.

Yield is defined as $Y_{X/S} = \frac{Mass\ of\ cell\ produce}{mass\ of\ substrate\ consumed}$

The rate of substrate consumption by the cell is given by, $r = \frac{\mu X}{Y_{X/S}}$

where, X is the concentration of biomass in the fermenter.

μ is the specific growth rate.

$Y_{X/S}$ is yield of biomass on substrate.

The substrate mass balance equation can be rewrite as $\frac{dS}{dt} = \frac{F}{V}S_0 - \frac{F}{V}S - r$

by substituting r in the above equation and then consider F/V as dilution rate D

$$\frac{dS}{dt} = DS_0 - DS - \frac{\mu X}{Y_{X/S}}$$

$$\frac{dS}{dt} = D(S_0 - S) - \frac{\mu X}{Y_{X/S}}$$

The growth inhibition of the substrate is expressed by the following formula:

$$\mu = \frac{\mu_{max} S}{K_m + S + K_I S^2}$$

where, S substrate concentration in fermenter.

$K_I$ is the inhibition constant. [9]

$K_m$ is Monod coefficient. [8]

μ is a specific growth rate.

$\mu_{max}$ is the maximum growth rate.

substituting the above μ value equation becomes

$$\frac{dS}{dt} = S_0 D - SD - \frac{\mu_{max} S}{Y_{\frac{X}{S}}(K_m + S + K_I S^2)} X$$

where, S is Substrate concentration in fermenter.

$S_0$ is Substrate concentration in feed.

D is the rate of dilution of the inlet and outlet stream.

$\mu_{max}$ is the maximum growth rate.

$K_m$ is the coefficient of Monod. [8]

$Y_{x/s}$ is the yield of biomass on the substrate.

X is the concentration of biomass in the fermenter.

$K_I$ is the Inhibition constant. [9]

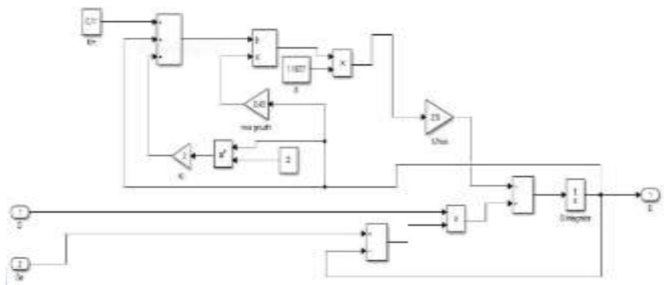

**Fig 2:** A Simulink model of the mass balance equation

Based on the derived mass balance equation, the simulation is made as shown in the above Fig 2. It is the part of the complete continuous stirred tank fermenter then it will be combined with the heat balance equation of fermenter and jacket.

**3.3 Heat balance equation of fermenter:**

In the bioreactor, heat can be added or removed from the microbial fluid. The two main heat transfer configuration vessels are (a) outer jacket (b) the inner coil. The jacket system external fermentation selected in this study

General heat balance of the fermentation broth is

$$Q_{acc} = Q_g + Q_a - Q_{ex} - Q_{ev} - Q_{sen}$$

The heat rate $(Q_g)$ is estimated according to the yield or performance factor($Y_A$)

$$Q_g = \mu \frac{X_1}{Y_A}$$

heat of agitation $(Q_a)$ is given by,

$$Q_a = \frac{P_{wa}}{V}$$

heat of evaporation $(Q_{ev})$ is given by,

$$Q_{ev} = \frac{F_g \rho_g (H_1 - H_2) L_{at}}{V}$$

If there is no aeration in the system i.e. $F_g = 0$ or no evaporation of water is allowed i.e. $H_1$-$H_2$= 0, then the heat of evaporation is zero, so that heat can be estimated by using saturated air flow at the fermentation temperature.

Net sensible heat in the $(Q_{sen})$ fermentation tank is,

$$Q_{sen} = DC_p(T - T_i)$$

heat accumulation $(Q_{acc})$ is given by,

$$Q_{acc} = V\rho C_p \frac{dT}{dt}$$

The exchange of heat $(Q_{ex})$ is given by,

$$Q_{ex} = \frac{UA}{V}(T - T_c)$$

By substituting all the sub equations in the main equation, the final equation becomes,

$$\frac{dT}{dt} = D(T_{in} - T) + \frac{D(S_0 - S)Y_{X/S}}{\rho C_p Y_A} - \left[\frac{UA}{\rho C_p V}\left(T - \left(\frac{T_{Cin} + T_C}{2}\right)\right)\right]$$

Where, $Y_A = \frac{Y_{X/S}}{H_{CS} - Y_{X/S}H_{bp}}$

$H_{cs}$ is the thermal combustion of the substrate.

$H_{bp}$ is heat for the produced biomass.

T is the temperature of the fermenter.

$T_{in}$ is the temperature of the feed.

$C_p$ is the specific heat of the process liquid.

$Y_A$ is the coefficient generated by heat.

$\rho$ is the density of the process liquid

U is the overall heat transfer coefficient.

A is the required heat transfer zone.

V is the Volume of the fermenter.

$Tc_{in}$ is the inlet temperature of the cooling water.

Tc is the outlet temperature of the cooling water.

**3.4 Heat balance equation of jacket**

$$Q_{acc} = Q_{in} - Q_{out} + Q_{ex}$$

$$\frac{dT_C}{dt} = D_C(T_{Cin} - T_c) + \frac{UA}{\rho_c Cp_c V}\left(T - \left(\frac{T_{cin} + T_c}{2}\right)\right)$$

where, $D_c$ is the Dilution rate of inlet cooling water.

$Cp_c$ is Specific heat of cooling water.

$\rho_c$ is Density of cooling water in jacket.

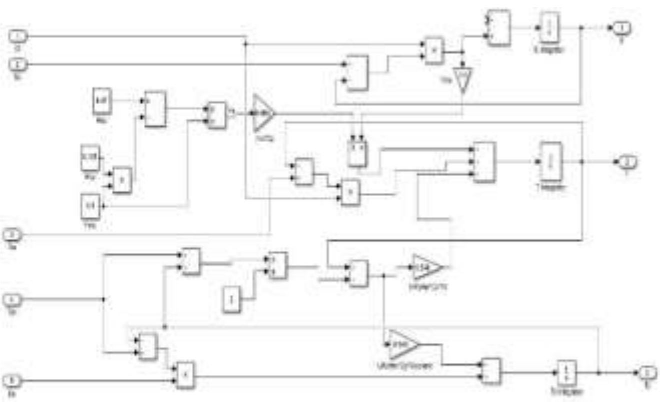

**Fig 3:** Simulink model of the heat balance equation of fermenter and jacket

Based on the derivation both the heat balance equation of fermenter and jacket simulation is shown in the above Fig 3. It is the part of continuous stirred tank fermenter it is combined with the mass balance equation to form the complete fermenter.

### 3.5 Simulation of continuous stirred tank bioreactor

By using the derived non-linear equations, i.e. substrate mass balance, heat balance and jacket heat balance equations, with the desired values

The equations are presented in a SIMULINK model subsystem as shown in Figure 4

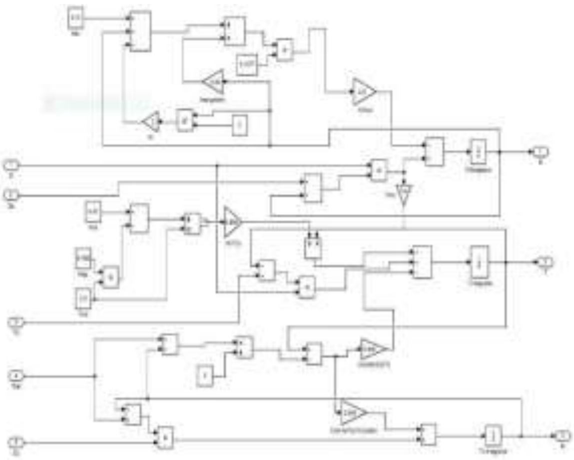

**Fig 4:** Continuous Stirred Tank Bioreactor model in SIMULINK

### 3.6 Design of PID controller system

At present, the feedback controller is the most commonly used control algorithm in the industry. It is generally used to control the process, including the heating and cooling system, liquid level monitoring, and pressure control. In PID control, it need to specify the process variable and the set point must be specified. The process variable in the system parameter you want to control, such as temperature, concentration, and set point is the required value of the parameter you want to control. The PID regulator compares the value of the controlled variable with the set point value. The most important types of industrial feedback controllers include: P, P along with the PID controller.

$$U(t) = K_c\left(E(t) + \frac{1}{\tau_I}\int_0^t E(t)dt + \tau_D\frac{dE(t)}{dt}\right)$$

where, $K_C$ is the proportional constant

$\tau_I$ is the integral time constant

$\tau_D$ is the derivative time constant

E(t) is the error (the desired value – the actual output value)

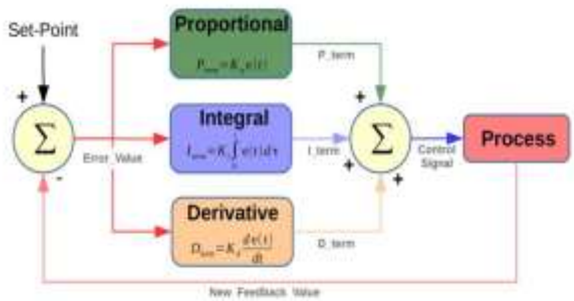


**Fig 5:** The basic Simulink model of PID controller

### 3.7 Design of fuzzy controller

The control system is based on fuzzy logic, a mathematical system that analyzes the values of analog inputs in terms of logical variables that assume continuous values between 0 and 1. The fuzzy logic controller as four parts: Fuzzification, Rule base, Inference, and Defuzzification. The Fuzzification transfers the sharp values into the club notes of the linguistic term.

The basic rule is a group of propositions containing linguistic variables, the rules are expressed in the form of "if then" or "if and then". The interface combines the records received from the Fuzzification with the rule base and drives the fuzzy reasoning process. Defuzzification process to form a crisp output.

By considering the 3 membership function the fuzzy logic controller is designed for concentration control positive small, positive medium, positive big is made based on the input feed and output feedback. The gain is used after the fuzzy logic controller to boost up the signal. In the similar manner, the temperature is controlled when the temperature is low output biomass concentration also low. Fuzzy base rule is formed by low, medium and high.

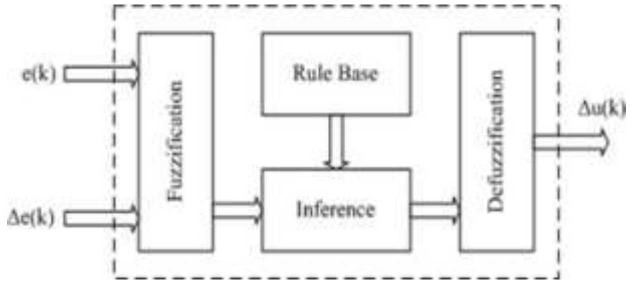


**Fig 6:** Simulink model of Fuzzy controller

### 3.8 Parameters

- Step response: It is how a system respond to the step input. The time behavior of a general system when its input move from 0 to 1 in a relatively short time.
- Threshold level: The amount of measurement change required for a measuring instrument to react to a change in measurement output or achieve a defined result.
- Rising time: The amount of time it takes for a response to go from x to y percent of its ultimate value.
- Settling time: The quantity of time it takes for the output to stabilize within a certain tolerance zone.
- Steady state error: The deviation of the system output from the desired response during steady state. Due to the particular time, the output response value is subtracted from the actual set point or threshold level.
  Steady state error = set point or threshold level – output value (at a given time)
- Efficiency: It is the ratio of output value to input value, then multiply by 100.
  Efficiency = (output/input) x100

### 3.9 Control of biomass concentration and bioreactor temperature

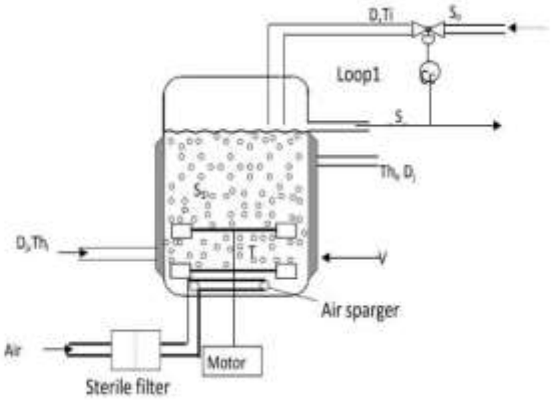


**Fig 7:** Biomass concentration control

$S_0$ is Substrate concentration in feed
D is the Dilution rate of inlet and outlet stream
$T_i$ or $T_{in}$ is Temperature of the feed
S is Substrate concentration in bioreactor
$Th_0$ or $T_C$ is the Output temperature of cooling water
$D_J$ or $D_c$ is the Dilution rate of, inlet cooling water
V is the Volume of the bioreactor
$Th_i$ or $Tc_{in}$ is Input temperature of cooling water

The concentration of biomass is controlled by manipulating the dilution rate of feed, uses overflow technology to adjust the reactor lag. The control scheme is shown in Fig 7.

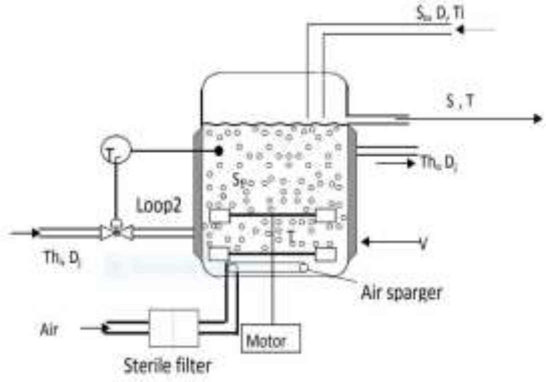


**Fig 8:** Bioreactor temperature control

$S_o$ is Substrate concentration in feed
D is the Dilution rate of inlet and outlet stream
$T_I$ OT $T_{in}$ is Temperature of the feed
S is Substrate concentration in bioreactor
T is Temperature of bioreactor
$Th_o$ or $T_c$ is Output temperature of cooling water
$D_J$ or $D_c$ is the Dilution rate of inlet cooling water
V is Volume of bioreactor
$Th_i$ or $Tc_{in}$ is Input temperature of cooling water

The temperature of the bioreactor is controlled by manipulating the dilution rate of the cooling water. The control scheme is shown in fig 8.

This program controls two variables, separately manipulating the dilution rate of feed and the dilution rate of the jacket to adjust the biomass concentration and the temperature of the fermenter tank respectively as shown in the Simulink model of fig 9 and fig 10 using different controllers.

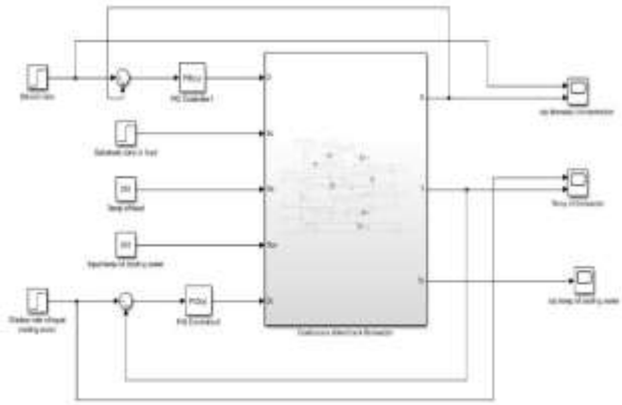

**Fig 9:** PID control model

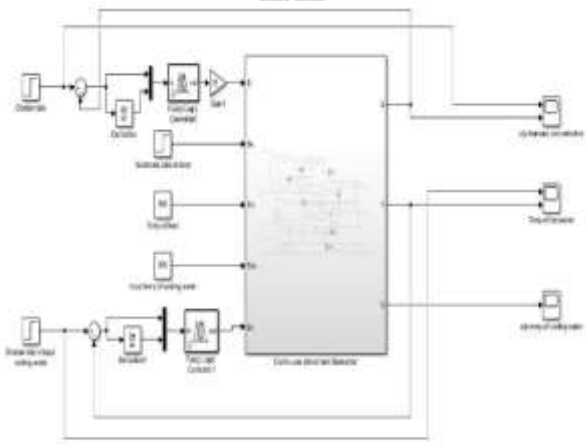

**Fig 10:** Fuzzy control mode

## IV. RESULTS AND DISCUSSION

The proposed setup is designed and tested in Simulink MATLAB. The following sections describe the various results. The tuned waveforms of the output response of the bioreactor are plotted. The step response is used in order to show how the temperature and concentration is maintained at the particular threshold to get maximum yield. The step response of controller is shown as follows,

### 4.1 Control of output biomass concentration

#### 4.1.1 Without controller response

A continuous stirred tank fermenter is designed without the controller. A MATLAB SIMULINK model developed. It is simulated using the step input it represent the biomass concentration in concentration control. The step response without the controller is shown in Fig 11.

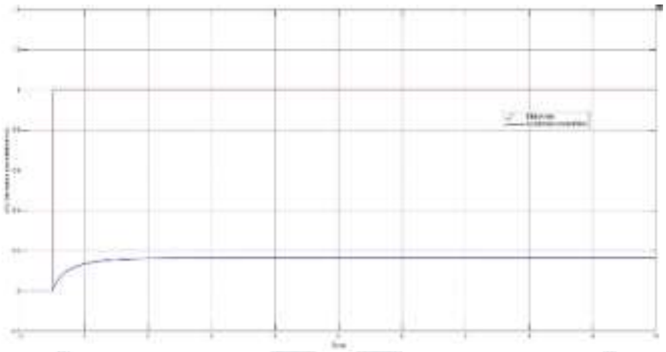

**Fig 11:** The Step response for change in dilution rate without controller.

The response shown in the Fig 11, the output concentration is controlled without the controller. The graph is output biomass concentration v/s time. The rising time is 688.000ms, settling time is 2s. The rising time and settling time is more without the controller. So next by using controllers the output response accuracy is evaluated.

#### 4.1.2 P controller response

The parameters of P controller, the values will be assigned in blocks to implement and simulate the process of the controller. The step response of controller P is shown below,

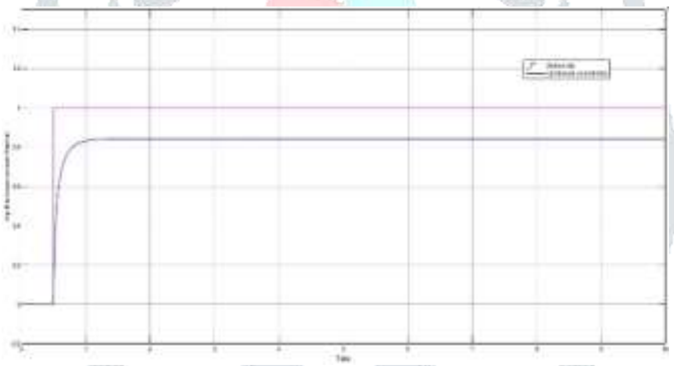

**Fig 12:** Step response for change in dilution rate using P controller

The response shown in Fig 12, the output biomass concentration is controlled by using P controller. The graph is output biomass concentration v/s time. The P=20, the rising time is 193.178ms, settling time is 1.5s. By using P controller, the offset will be more, and steady state error is more so, next PI controller is used.

#### 4.1.3 PI controller response

The parameters of PI controller, the values will be assigned in blocks to implement and simulate the process of the controller. The step response of the PI controller is shown below,

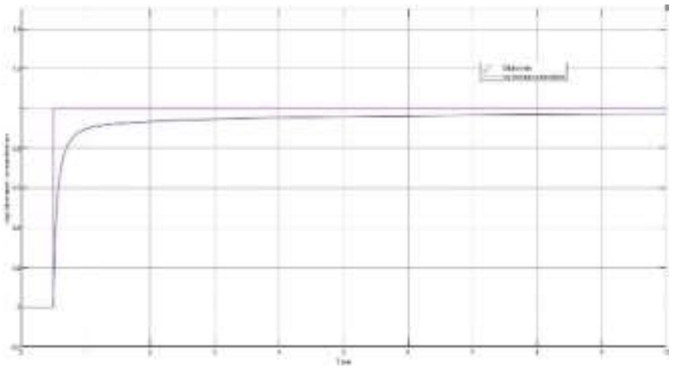

**Fig 13:** Step response for change in dilution rate using PI controller

The response shown in Fig 13, the output biomass concentration is controlled by using PI controller. The graph is the output biomass concentration v/s time. P=30, I= 20, the rising time is 269.347ms, settling time is 1.2s. By using the PI controller, the offset is reduced, and steady state is reduced not completely eliminated so, next PID controller is used.

### 4.1.4 PID controller response

PID controller parameters, values will be assigned in blocks to implement and simulate the controller process. The step response of the PID regulator is shown below,

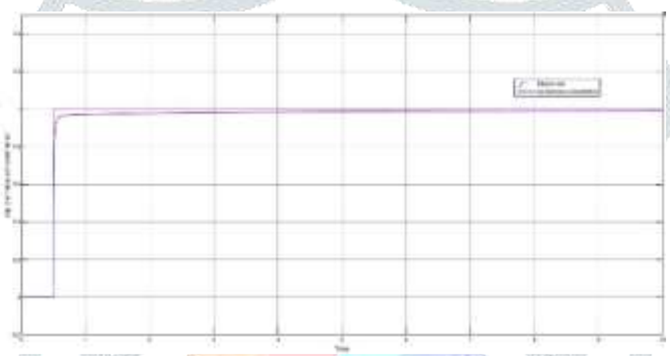

**Fig 14:** Step response for change in dilution rate using PID controller

The response shown in Fig 14, the output biomass concentration is controlled by PID controller. The graph is output biomass concentration v/s time. The P=300, I=250 and D=20. The rising time is 22.660ms, settling time is 0.731s. By using the PID controller, it almost reaches the threshold level, then the Fuzzy controller is used.

### 4.1.5 Fuzzy controller response

The Fuzzy controller parameters, values will be assigned in blocks to implement and simulate the process of the controller. The step response of the Fuzzy controller is shown below,

**Table 1:** Fuzzy rule base for Biomass concentration control

| Output | PS | PM | PB |
|---|---|---|---|
| PS | PS | PB | PB |
| PM | PS | PB | PB |
| PB | PB | PB | PB |

Where, the table which is shown above will be the output parameters for fuzzy rule, in that PS signifies Positive small, PM signifies positive medium and PB signifies Positive big.

**Fig 15:** Step response for change in dilution rate using Fuzzy logic controller

According to the response shown in Fig 15, the output biomass concentration is controlled by the Fuzzy controller. The graph is output biomass concentration v/s time. The rising time is 19.394ms, settling time is 0.586s.

By using the Fuzzy controller, the system is stable compared to PID controller the offset and steady state error is almost eliminated when compared to PID controller.
All the controller's step response is shown in the single graph as shown in Fig 16

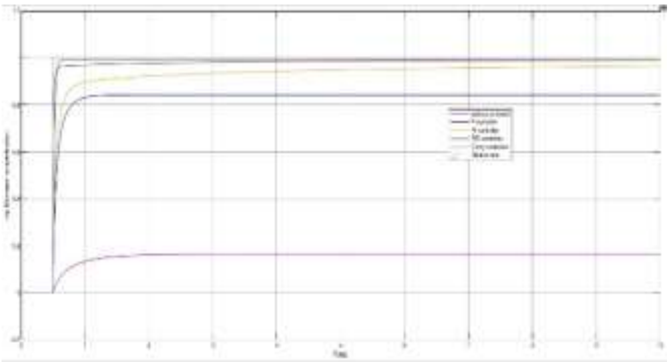

**Fig 16:** The Step response of the P, PI, PID and Fuzzy controller for change in dilution rate

**Table 2:** Comparison of different controllers for output biomass concentration control

| Controller | Rising time (ms) | Settling time (s) | Steady state error (t=3s) | Efficiency (%) |
|---|---|---|---|---|
| WITHOUT CONTROLLER | 688.000 | 2 | 0.83 | 17 |
| P | 193.178 | 1.5 | 0.16 | 84 |
| PI | 269.347 | 1.2 | 0.08 | 92 |
| PID | 22.660 | 0.731 | 0.05 | 95 |
| FUZZY | 19.394 | 0.586 | 0.01 | 99 |

As shown in the above table, comparing the different controllers with two parameters like rising time and settling time to check stability and accuracy of the system. The Fuzzy controller is best for controlling the biomass concentration of the bioreactor by varying the dilution rate when compares to other controllers because it can be seen that the steady state error also decreased also the efficiency of the Fuzzy controller is almost 100%. So Fuzzy is better than other controllers.

**4.2 Control of bioreactor temperature**

**4.2.1 Step response without controller**

The simulation the continuous stirred tank fermenter is designed without the controller. The step response without the controller is shown in Fig 17.

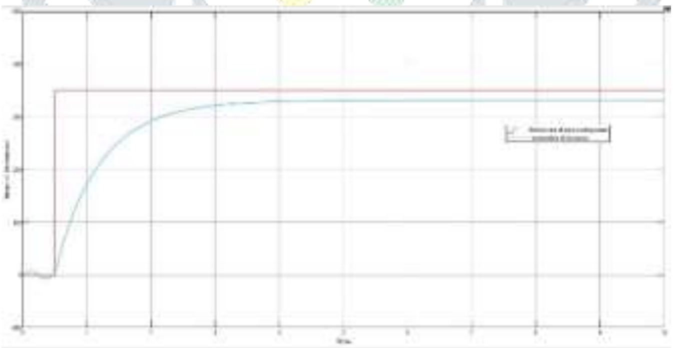

**Fig 17:** Step response for change in the dilution rate of input cooling water without the controller

The response shown in the Fig 17, the bioreactor temperature is controlled without the controller. The graph is bioreactor temperature v/s time. The rising time is 1.531s, settling time is 3s. The offset error is more and also the steady state error is present without the controller so next the controller is implemented.

**4.2.2 Step response of P controller**

The parameters of P controller, the values will be assigned in blocks to implement and simulate the process of the controller. The step response of the P controller is shown below,

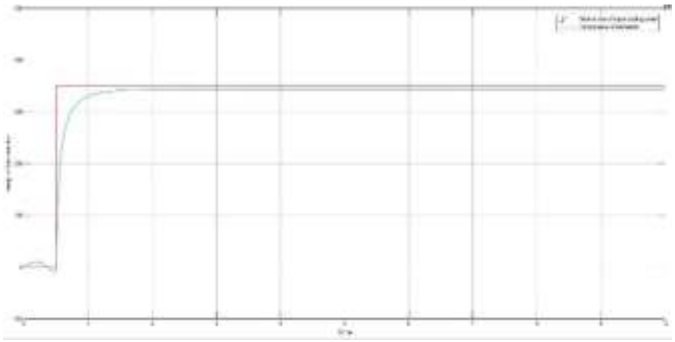

**Fig 18:** Step response for change in the dilution rate of input cooling water using P controller

The response shown in Fig 18, the bioreactor temperature is controlled by P controller. The graph is bioreactor temperature v/s time. P=0.5, the rising time is 270.429ms, settling time is 2s. By using P controller, the oscillation delay is present, and it takes more time to settle, so next the PI controller is used.

### 4.2.3 Step response of PI controller

The parameters of PI controller, the values will be assigned in blocks to implement and simulate the process of the controller. The step response of the PI controller is shown below,

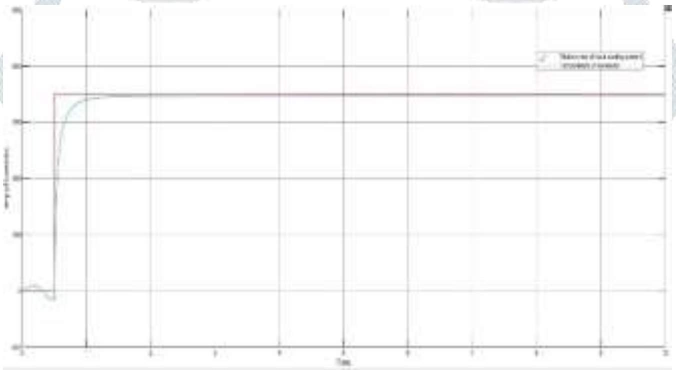

**Fig 19:** Step response for change in the dilution rate of input cooling water using PI controller

The response shown in Fig 19, the bioreactor temperature is controlled by PI controller. The graph is bioreactor temperature v/s time. P=0.5, I=0.5. The rising time is 195.118ms, settling time is 2.5s. By using PI controller, rising time is reduced when compared to P controller and settling time also reduced, still oscillation delay time is present so next the PID controller is used.

### 4.2.4 Step response of PID controller

The parameters of PID controller, the values will be assigned in blocks to implement and simulate the process of the controller. The step response of the PID controller is shown below,

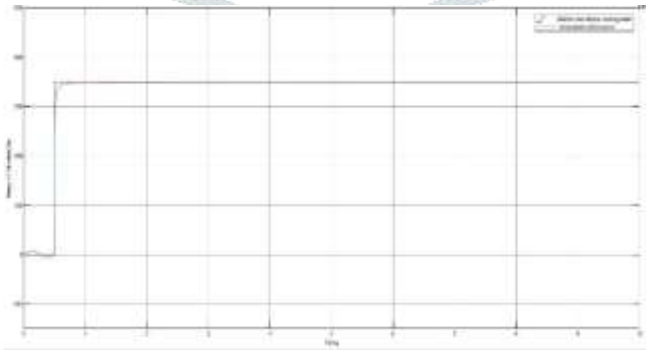

**Fig 20:** Step response for change in the dilution rate of input cooling water using the PID controller

The response shown in Fig 20, the bioreactor temperature is controlled by PID controller. The graph is bioreactor temperature v/s time. P=0.5, I=0.5 and D=0.1. The rising time is 22.583ms, settling time is 0.8s. By using the PID controller, the offset is reduced compared to other two controllers and also the settling time also reduced, so next the Fuzzy controller is used.

### 4.2.5 Step response of Fuzzy controller

The parameters of Fuzzy controller, the values will be assigned in blocks to implement and simulate the process of the controller. The step response of the Fuzzy controller is shown below,

**Table 3:** Fuzzy rule base for temperature control

| Output | L | M | H |
|---|---|---|---|
| L | L | H | H |
| M | L | H | H |
| H | H | H | H |

Where, the table which shown above will be the output parameters for fuzzy rule, in that L signifies Low, M signifies Medium and H signifies High.

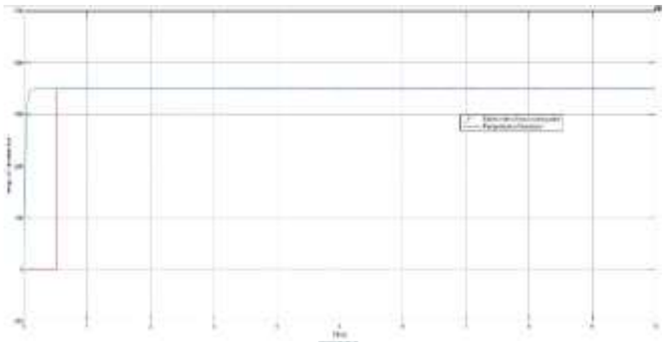

**Fig 21:** Step response for change in the dilution rate of input cooling water using the Fuzzy logic controller

The response in Fig 21, the bioreactor temperature is controlled by the Fuzzy controller. The graph is the temperature of bioreactor v/s time. The rising time is 21.076, settling time is 0.1s. By using Fuzzy controller, the system is stable compared to PID controller the offset and steady state error is completely eliminated and the oscillation delay is eliminated so the system is more accurate when compared to other controller

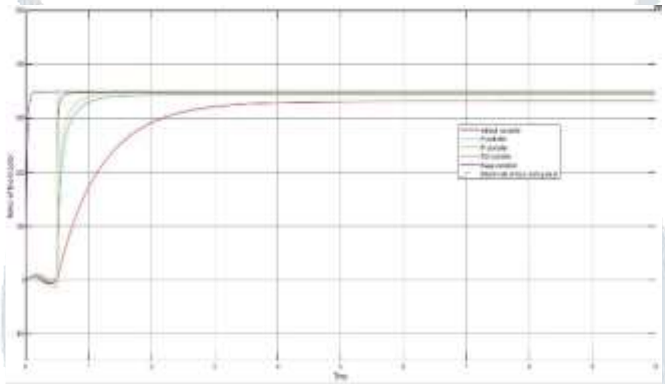

**Fig 20:** Step response of P, PI, PID controller for change in dilution rate of input cooling water

**Table 4:** Comparison of different controller for temperature control

| Controller | Rising time (ms) | Settling time (s) | Steady state error (t=3s) | Efficiency (%) |
|---|---|---|---|---|
| WITHOUT CONTROLLER | 1.531 s | 3 | 30 | 91.4 |
| P | 270.429 | 2 | 10 | 97.1 |
| PI | 195.118 | 2.5 | 5 | 98.5 |
| PID | 22.583 | 0.8 | 0 | 100 |
| FUZZY | 21.076 | 0.1 | 0 | 100 |

As shown in the above table, comparing the different controllers with the parameters like Rising time, Settling time. The Fuzzy controller is best for controlling bioreactor temperature. The Steady state error is zero for PID and the Fuzzy controller, but in the PID controller, it has some time delay, but in fuzzy the delay time is eliminated so the Fuzzy controller is better than other controllers.
From the transient response curves in the results, it is seen that any change in substrate concentration feed and dilution of inlet and outlet stream has effect on biomass concentration and fermenter temperature, while change in the dilution rate of inlet cooling water affect only fermenter temperature and as no effect on biomass concentration.

### 4.3 Advantages of the proposed system

- Good content mixing and adaptable operation conditions.
- Continuous operation.
- Good temperature control.

- Good control.
- Simplicity of construction.
- Low in operation cost.
- Simple to clean.
- Simple industrial availability.

### 4.4 Limitations of the proposed system

- Sealing rings and bearings are required.
- Dimensional limitations are imposed by the motor size, shaft length and weight.

### 4.5 Applications of proposed system

- Used in domestic application like cooking fuel.
- Biogas as a vehicle fuel.
- Biogas for the power generation.
- For Pumping water and other applications.
- Stirred tank bioreactors are commonly used in fermentation industry.

## V. CONCLUSION

In the current work, the continuous stirred tank bioreactor or fermenter biomass concentration as well as temperature are controlled by P, PI, PID along with the fuzzy logic controller. The fuzzy results were found to be more suitable than the P, PI, PID controllers. The results also illustrated the great stability of Fuzzy to follow the variation of the set point change and settle through the small period compared to other controllers as shown in results. It is observed that the response almost reaches the threshold level. It represents that the Fuzzy controller is good when compared to other controllers. The Fuzzy logic controller is more suitable when compared with P, PI, along with the PID controller it provides the best response for concentration and temperature control. By observing the response of all the controllers the performance of the fuzzy logic controller is better than other controllers because it reaches the required yield.

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## APPENDIX

$S_0$ = 3 g/l, $K_m$ = 0.11 g/l
$k_1$ = 2 g/l, D = 0.2 $hr^{-1}$
$\mu_m$ = 0.48 $hr^{-}$1, $YX_{/S}$ = 0.4 g.cell/g.sub
$T_{in}$ = 308 K. $\rho$ = 999 g/l
$C_p$ = 0.001 Kcal/g.K
$Tc_{in}$ = 297 K
$H_{cs}$ = 4.47 Kcal/g.sub
$H_{bp}$ = 5.165 Kcal/g.bio
UA/V = 0.546 $W/m^3$.K
$D_c$ = 0.5 $hr^{-1}$
P - Proportional
PI - Proportional Integral
PID – Proportional Integral Derivative