MODELLING AND DESIGN OF IMC BASED CONTROLLER FOR FERMENTATION PROCESS USED FOR THE PRODUCTION OF ETHANOL

Yashwini.V.V[1], S.Nagarajan[2], S.Sobana[3]
yashwini.vijay.24@gmail.com, hod.eie@eec.srmrmp.edu.in, sobbana.subramani@gmail.com
Department of Electronics and Instrumentation Engineering
Easwari Engineering College (Autonomous Institution), Chennai-600 089

Abstract - In this paper, efficient production of ethanol from corn by using fermentation process is discussed. A mathematical model is developed for the above-mentioned process and the challenges in adjusting the specific growth rate(μ_{max}) has been addressed. Also, the rate or velocity of growth of the microbial cells which is the key affecting factor of the substrate concentration is adjusted for optimum results. On successful design of the mathematical model, the concentration of ethanol is controlled by using four different controllers out of which one suitable controller is considered as the ideal controller for the production of ethanol from corn.

Keywords: Ethanol, Fermentation, Specific growth rate, Maximum Velocity or rate of reaction of enzymes, Concentration of Product.

1. INTRODUCTION

The era is turning itself towards bio-degradable products. Even the fuels used in vehicles are changing from diesel and gasoline to biofuels. Ethanol is one such biofuel that is evolving nowadays. Scientists and researchers have found several biological products from which ethanol can be obtained. Amongst all suggested materials, corn is commonly used due to it high availability, less cost and high yield. Sapna, D.P. Chaudhary briefed a study of how corn is converted into ethanol. In their research they discussed on different types of corn grinding(milling). They have also given a short gist about various fermenters used for production of ethanol. In this paper, the uses of ethanol are listed down clearly, especially it points out on how important biofuel is for the future. Mohammad Emal Qazizada (2016) proposed a design of a Batch Stirred Fermenter for the production of ethanol. This paper considers ethanol production using yeast under anaerobic respiration (also known as fermentation process). The author affirms that this system produces high substrate concentration and about 82% of product yield. Also, he says that this system can be used to design larger scale batch stirred reactors. Mominur Rahman proposed a paper on comparative study on production of bioethanol from banana and yam peel. The paper thus proposed considers banana peel and yam peels as the substrates for growth of the fungi. In this paper, the fungi Aspergillus Niger was used for hydrolysis and the hydrolysate were then treated with Zymomonas Mobilis for fermentation to take place. The result of the experimentation revealed that the density of bioethanol produced by banana peel was 133.5g/l and that produced by yam peel was 146.33g/l. This proves that the production of bioethanol from banana peel was less than that of yam peel.

2. PROPOSED SYSTEM

The proposed system gives insights of designing a mathematical model for the conversion of Corn to Ethanol. With the obtained results of the modelled open loop system, system identification is done and the values for an open loop transfer function obtained. The output curve obtained from the open loop model and the open loop transfer function is compared to ensure that the system works correctly. With these, the open loop part of the proposed system gets done. To make the system as a closed loop one, P Controller, PI Controller, PID Controller and IMC based PID Controller is incorporated and outputs were compared and the most suitable controller was considered as the best controller for ethanol production using corn by fermentation process.

Initially, the input for the system is corn kernels. These kernels are then subjected to milling process. In this process the kernels are grinded either by wet-milling or dry-milling process. In dry milling process the corn is simply grinded and so this method is considered as a cost-effective method. In wet milling, the kernels are soaked in a particular solution and then the corn is grinded. Though this process is tedious compared to the previous method, this method is employed worldwide. Now the ground corn kernels are subjected to Gelatinization process. In this process, the crushed corn is added to water to make a gelatinous corn slurry. Thus, at this stage a liquefication process is obtained thereby creating way for partial hydrolysis.
One of the most important steps in production of ethanol from corn is Saccharification. This process is done to breakdown the hydrolysis into glucose monomers. Therefore, the glucose thus obtained is treated with yeast, a single-celled microorganism of the Fungi Family in the absence of respiration to produce ethanol. The conversion of Glucose to Ethanol in the presence of Anaerobic respiration is called as Fermentation.

3. MATHEMATICAL EQUATION INVOLVED IN MODELLING

The initial concentration of microbial cells is given as input to the designed first principle model. This is denoted as C_{xvo}.This value is maintained as a constant throughout the process.

By using this C_{xvo} the equation of viable cells otherwise known as microbial cells which are employed for the process of fermentation is given by,

$$\frac{dC_{XV}}{dt} = \mu_{max} C_{XVO} - K_d C_{xvo} \quad \text{(from reference [4])} \qquad \ldots\ldots.. (2)$$

The output obtained from the above equation is given as the input for the concentration of substrate (corn that has been converted to glucose) as well as for the concentration of the final product (Concentration of Ethanol). Similar to the viable microbial cells, the mathematical modelling contains certain non-viable cells also which is given by the equation,

$$\frac{dC_{xd}}{dt} = K_d C_{xv} \quad \text{(from reference [4])} \ldots\ldots.. (3)$$

The Concentration of Substrate (C_s) is given by the equation,

$$C_s = \frac{C_{xvo}}{e^{\frac{tVmax - C_{xvo} - C_{xv}}{Km}}} \quad \text{(from reference [4])} \ldots\ldots..(4)$$

The final product- Concentration of Ethanol (Cp) is given by the equation,

$$\frac{dC_p}{dt} = \alpha \mu_{max} C_{xv} + \beta C_{xv} \quad \text{(From Reference [4])} \ldots\ldots(5)$$

The values for each of the parameters in the equation is given in the table below. These Values (represented in table 1) are obtained from previous Journals and Literatures.

Parameter	Description	Value
V_{max}	Maximum rate or velocity of reaction of the enzymes	35.50(gmol/l.hr)
μ_{max}	Maximum Specific growth	0.10049/hr
α	Growth related product formation coefficient	2.67g product/g biomass

β	Non-growth related product formation coefficient	0.062g product/g of biomass
K_m	Michaeis-Menten Constant	826.45 gmol/l
K_d	Endogenous Decay Coefficient	0.01416/hr

Table 1. Parameters for Model Validation

4. SOFTWARE DESCRIPTION

A simulation is an act of reciprocating a real-time operation of a process or system. Simulation is used in many situations, such as testing, training, learning and optimizing a new technology. Simulation is one way in which the results of the future system can be predicted well in advance. MATLAB is one of the commonly used Simulink platforms in engineering field. MATLAB is a high-performance language for technical computing. It integrates computation, visualization, and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation. For this project, we have used MATLAB R2019b.

5. OPEN LOOP SYSTEM

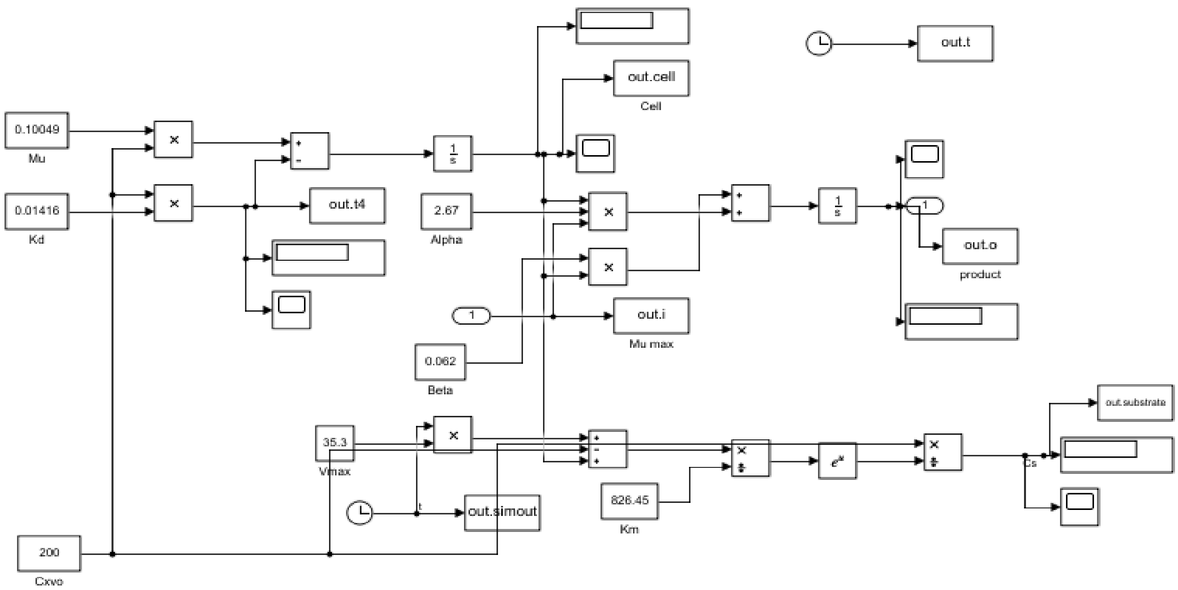

Fig.1. Open Loop System of the Plant

This Simulink model(Figure 1) is the modelling that was performed for the proposed system. The major input blocks are initial concentration (C_{xvo}), Maximum Specific growth rate(μ_{max}), Maximum rate/Velocity of reaction(V_{max}). Other inputs are growth related product information (α), non-growth related product information (β), Michaeis-Menten constant (K_m) and Endogenous Decay Co-efficient (K_d). Except μ_{max} and V_{max} all other inputs are kept as constants. The values of the inputs are displayed in Table 3.1. After obtaining the final output (product), the whole model is selected, a subsystem is created from it.

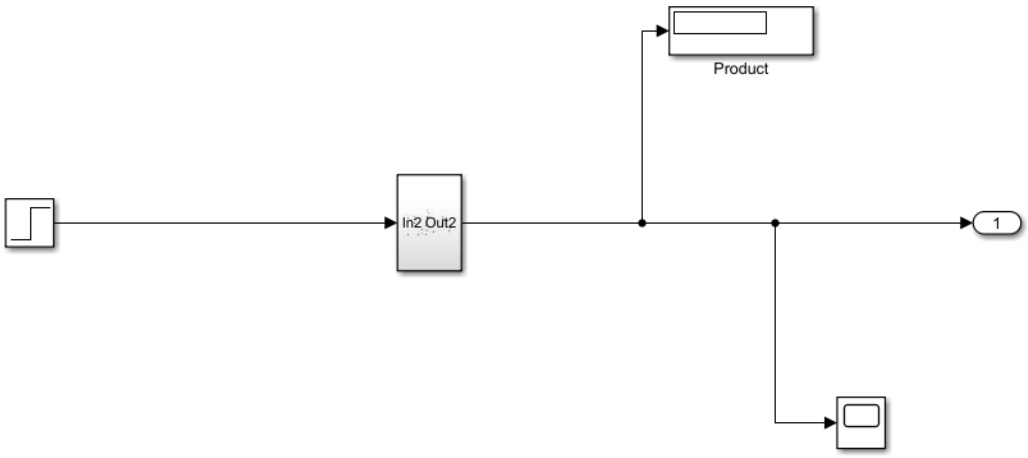

Fig.2. Subsystem of the Plant

The figure 2 depicts the model after the subsystem has been created. The input considered for the subsystem is Specific Growth Rate of the Microbial Cell (μ_{max}) and the output is taken as concentration of ethanol production (C_p).

A step input of value μ_{max}= 0.10049/hour is given to the plant and for that specific growth rate the output (concentration of ethanol production) obtained was 28,510 g/l. The simulation time is set to 100 hours. On the completion of this process, a first order open loop curve is obtained which can be viewed using scope. Using this curve, a first order process with dead time equation needs to be obtained. For that, manual system identification is done.

The First order process with dead time is expressed as,

$$\frac{\boldsymbol{Y(s)}}{\boldsymbol{C(s)}} = \frac{\boldsymbol{K_p e^{-t_d s}}}{\boldsymbol{1+\tau_p s}} \quad \text{…….. (6)}$$

The next step is the find the values for K_p, t_d and τ_p so that an open loop transfer function can be obtained which is the initial step to develop a closed loop model. These values can be found from the following formulae,

i. The value of K_p is found by $K_p = \frac{B}{A}$ where B is the output at steady state and A is the input at steady state of the process reaction curve.
ii. The value of t_d is the time elapsed until the system responded.
iii. The value of τ_p is found by $\tau_p = \frac{B}{S}$ where S is the slope of the sigmoidal curve at the point of inflection and B is the output at steady state.

From the output of simulated model, the values of B, A, S values were found to be 28510, 0.10049 and 3000 respectively. The values of K_p, t_d and τ_p are obtained as 283709.822, 21.6hr and 57.02hr respectively which were found using the values of output at steady state, input at steady state and Slope. So, now the First order process with dead time for the proposed system came be written as,

$$\frac{Y(s)}{C(s)} = \frac{283709.822\ e^{-21.6s}}{57.02s+1} \quad \text{………(7)}$$

Using this transfer function, an open loop model for the proposed system is created. The below diagram represents the model which was modelled using the obtained transfer function.

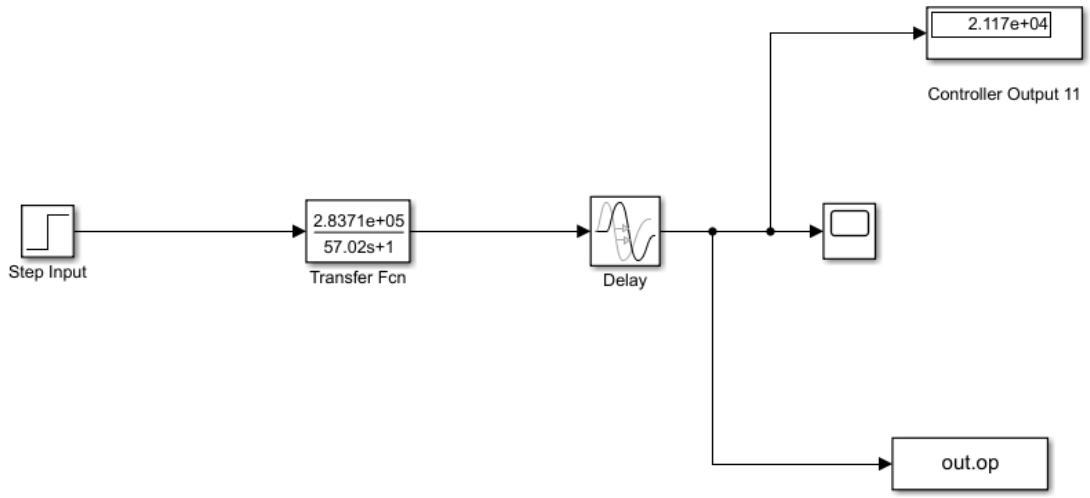

Fig 3. Open Loop Transfer Function

The step input given to the system is Specific growth rate and the output obtained is the final product (Concentration of Ethanol). The output of the plant and the output obtained after designing the transfer function is compared for accuracy so that a closed loop model can be derived from the obtained results.

6. CLOSED LOOP MODEL

In this closed loop model, four controllers are being compared. They are P controller, PI controller, PID controller and IMC based PID controller. Amongst these four, the one that provides quicker output with lesser settling time and with minimal errors will be considered as the optimum controller for this fermentation process.

To design a controller, the most important step is to tune a controller. For this system, Cohen-Coon controller tuning is performed. The values of K_p, t_d and τ_p are already calculated and so these values can be substituted in the Cohen-Coon formula. For an IMC based PID Controller, Pade approximation of time delay is being used to calculate the parameters to tune the controller. The formula is as follows:

$$K_c = \frac{(\tau + \theta/2)}{K_p\ (\tau_f + \theta/2)}$$

$$T_i = \frac{\theta}{2} + \tau$$

$$T_d = \frac{\tau\theta}{2[\frac{\theta}{2}+\tau]}$$

where $\tau_f = 0.1$, $\theta = t_d$, $\tau = \tau_p$

Now, on substituting the values of K_p, t_d and τ_p in the above formulae, the values for tuning the controllers are obtained. This can be performed in the 'Editor' page of MATLAB.

The below programs were run for obtaining the values of tuning parameters:

For P- Controller:

```
k=283709.822;
t=57.02;
td=21.6;
Process_Gain=k
Time_Constant=t
Delay_Time=td
kc1=[(1/k)*(t/td)]*[1+(td/(3*t))]
```

For PI-Controller:

```
k=283709.822;
t=57.02;
td=21.6;
Process_Gain=k
Time_Constant=t
Delay_Time=td
kc2=[(1/k)*(t/td)]*[0.9+(td/(12*t))]
ti2=td*[(30+(3*td/t))/(9+(20*td/t))]
```

For PID-Controller:

```
k=283709.822;
t=57.02;
td=21.6;
Process_Gain=k
Time_Constant=t
Delay_Time=td
kc=[(1/k)*(t/td)]*[4/3+(td/(4*t))]
ti=td*[(32+6*td/t)/(13+(8*td/t))]
td1=td*[4/(11+(2*td/t))]
```

For IMC based PID Controller:

k=283709.822;
t=57.02;
td=21.6;
Process_Gain=k
Time_Constant=t
Delay_Time=td
kc=(t+(td/2))/k*(τ_f+(td/2))
ti3=(td/2)+td
td2=(t*td)/2[(td/2)+t]

After running the programs, the values displayed in the table below were obtained:

Proportional Controller	Proportional Integral Controller	Proportional Integral Derivative Controller	IMC based Proportional Integral Derivative Controller
K_c= 1.0480e-05	K_c=8.6679e-06	K_c =1.3287e-05	K_c=0.002
-	T_i=40.5728	T_i=46.1803	T_i=67.82
-	-	T_d=7.3484	T_d=9.080

Table 2. Parameters for Controllers

The values in table 2 are used to tune the respective controllers. By modelling a closed loop system by using the controllers and by considering the manipulating variable as Specific growth rate of the microbial cell, the concentration of ethanol production can be controlled.

The following Simulink models depicts the models of the P, PI, PID and IMC based PID Controllers.

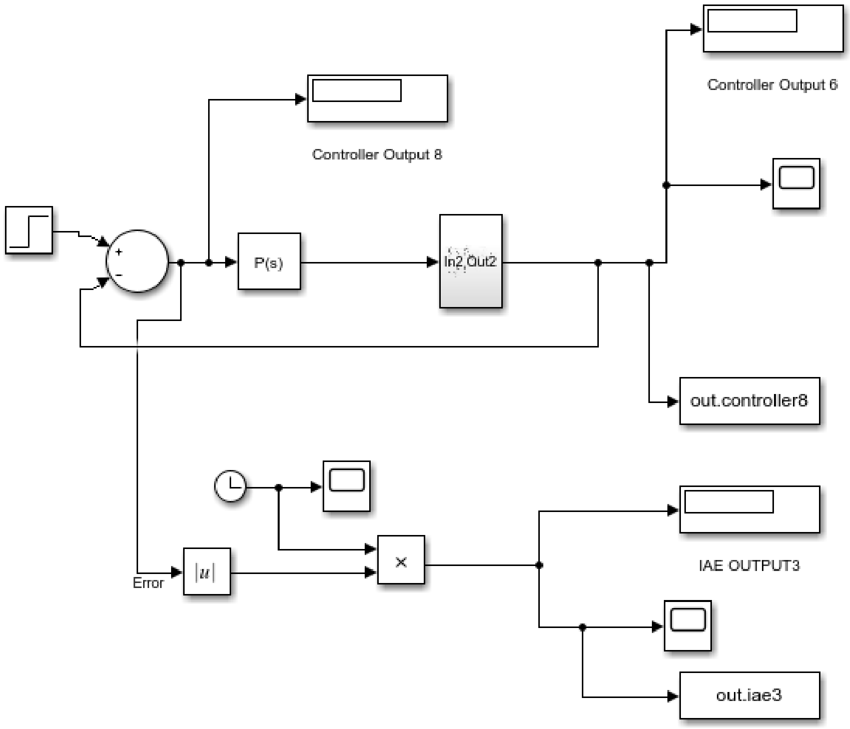

Fig 4. P Controller

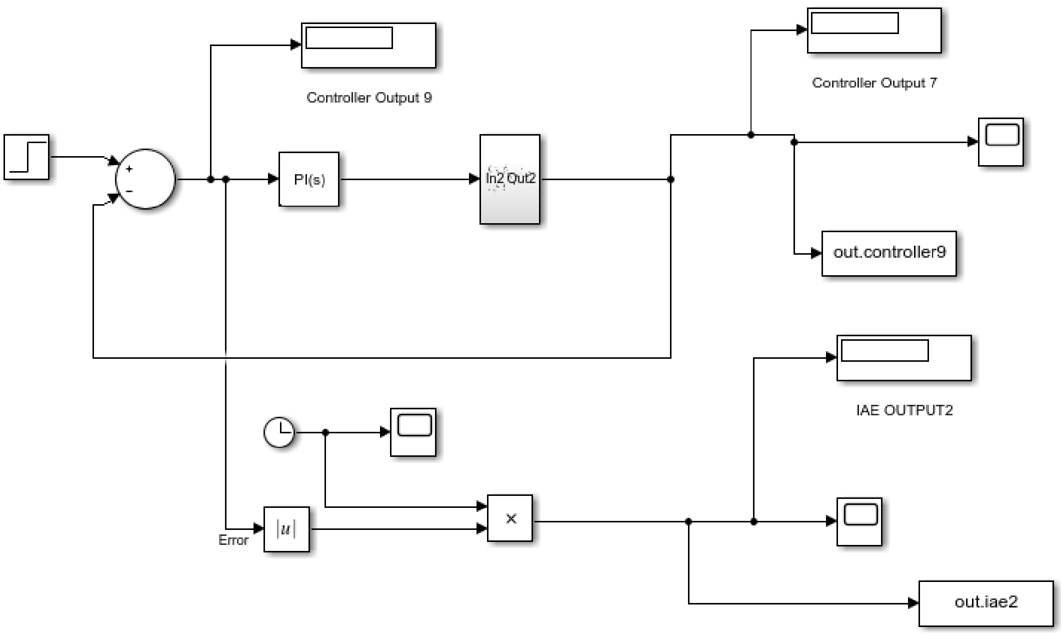

Fig.5 PI Controller

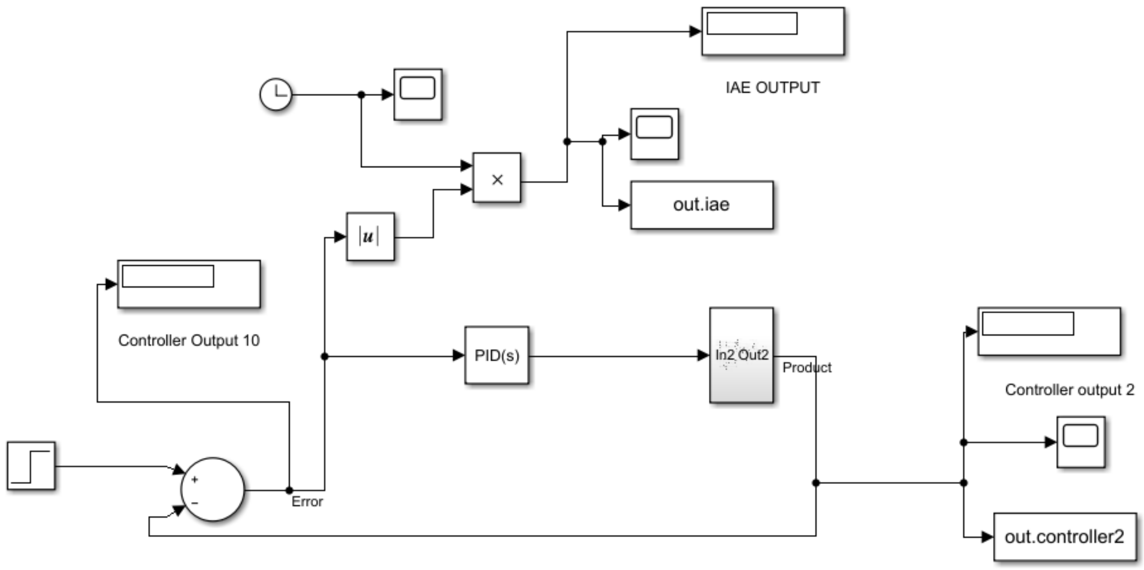

Fig.6 PID Controller

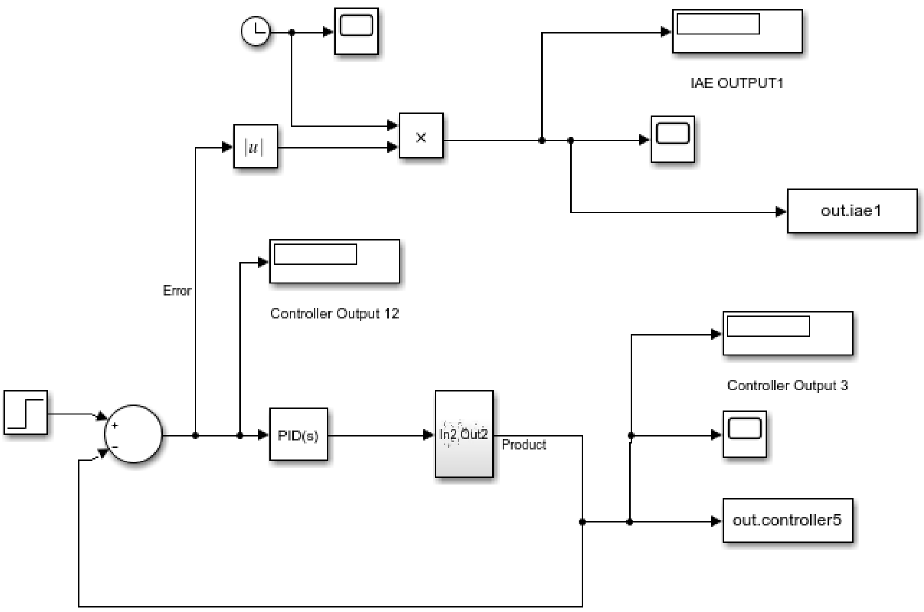

Fig 7.IMC based PID Controller

Along with the controller outputs, the Integral Absolute Error (IAE) output is also obtained. This helps in determining the error obtained from each controller and which eventually leads to choosing the controller that provides the least error.

7. RESULTS AND DISCUSSIONS

Open Loop Response:

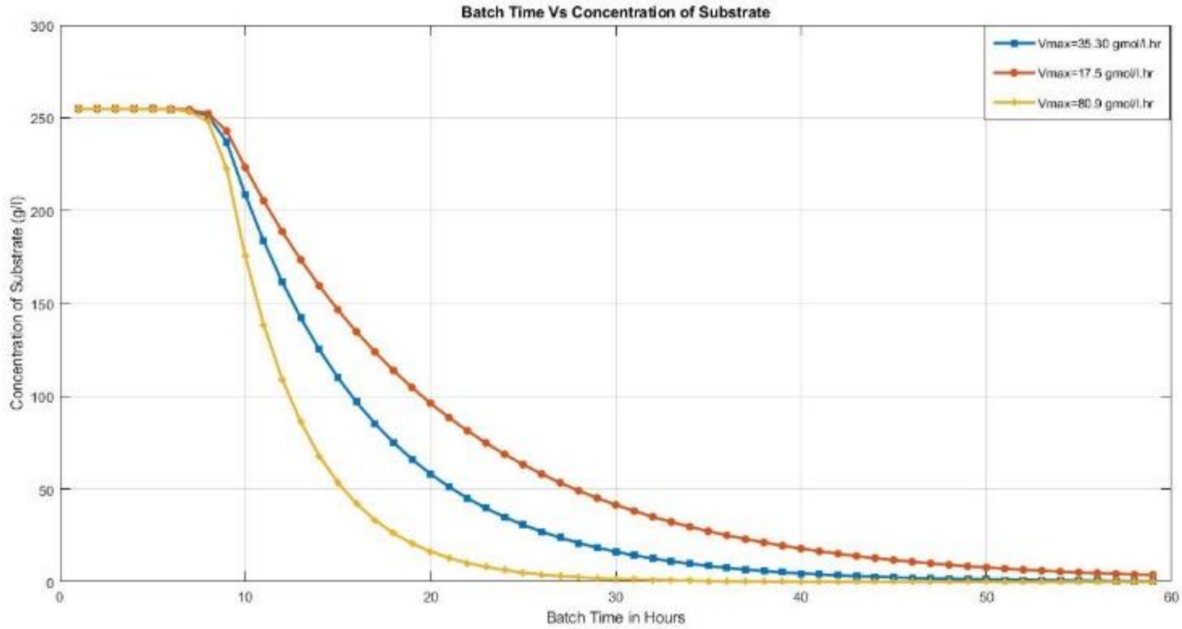

Fig 8. Effect of maximum rate or velocity

The figure 8 shows the effect of maximum rate or velocity (Vmax) of reaction of enzymes on batch reaction time. The value of Maximum rate or velocity of reaction is varied as V_{max}=35.50gmol/l.hr, 17.5gmol/l.hr, 80.9gmol/l.hr such that it has its effect on the batch reaction time which in turn affects the Concentration of the substrate. Higher the value of V_{max}, quicker is the batch time required for the given substrate to convert into product.

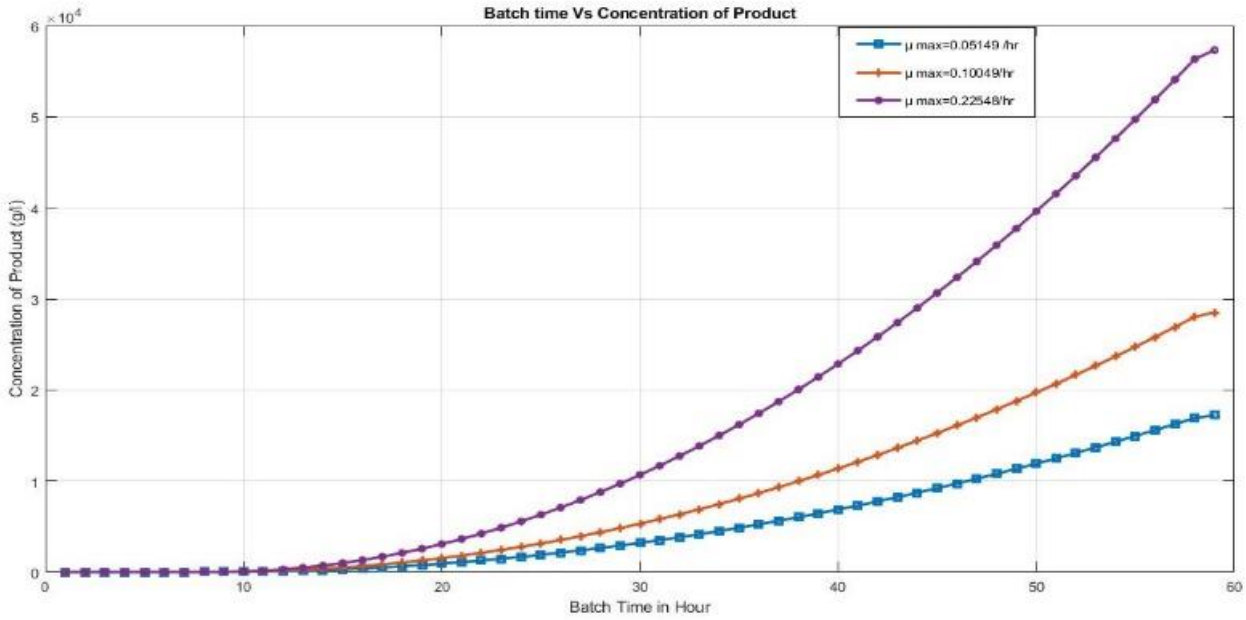

Fig 9. Effect of the maximum specific growth rate (μmax)

The figure 9 shows the effect of the maximum specific growth rate(μmax) of microbial cells on batch time and the concentration of product. The value of Maximum specific growth rate is varied as μ_{max}=0.10049/hr, 0.22548/hr, 0.05149/hr such that it affects the batch reaction time which has its effect on the concentration of the product. Larger the value of μ_{max} quicker is the batch reaction time required to achieve a given product concentration.

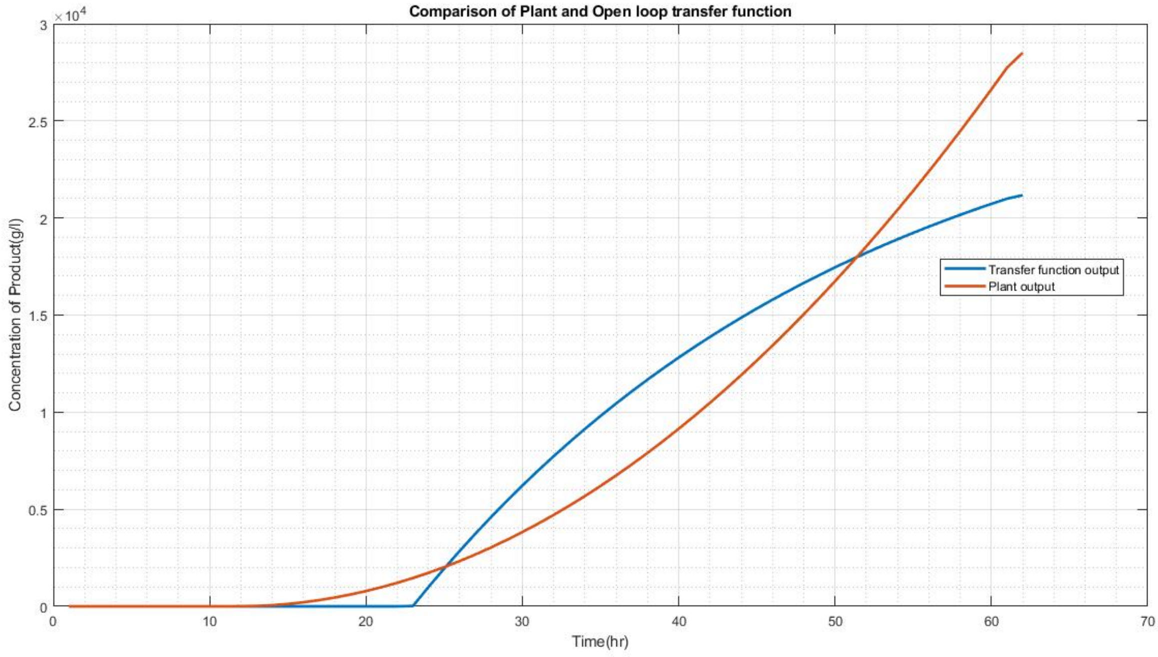

Fig 10. Comparison of Plant and Open Loop Transfer Function

The figure 10 represents the comparison between the plant output and open loop transfer function output. Both the outputs were found to be increasing as time increased. For a time = 100 hrs, the output of the plant was found to be 28200 g/l and the open loop transfer function was found to be 21120 g/l.

Closed Loop Response:

The output response of all controllers is taken for a time period of 100 hours. The set point given was 22000g/l. The following outputs were obtained. Also, for each controller, the Integral Absolute Error is also found out.

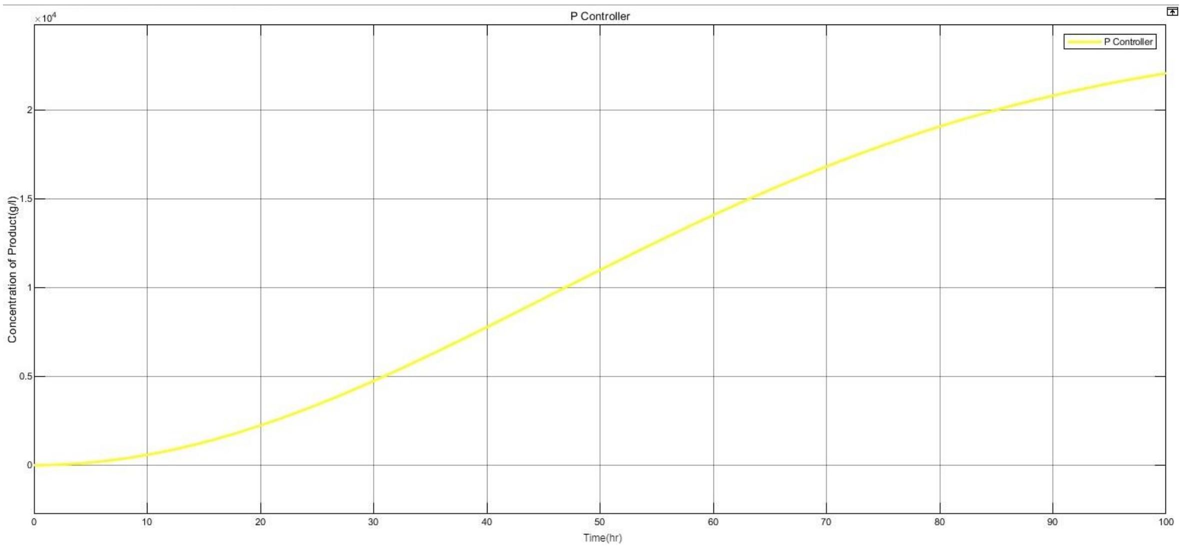

Fig 11. Output response of P Controller

The figure 11 shows the output of the P type controller used for this system. This controller did not settle down at the set point rather it was increasing continuously as the time increased. So, this controller is not suitable for the production of ethanol.

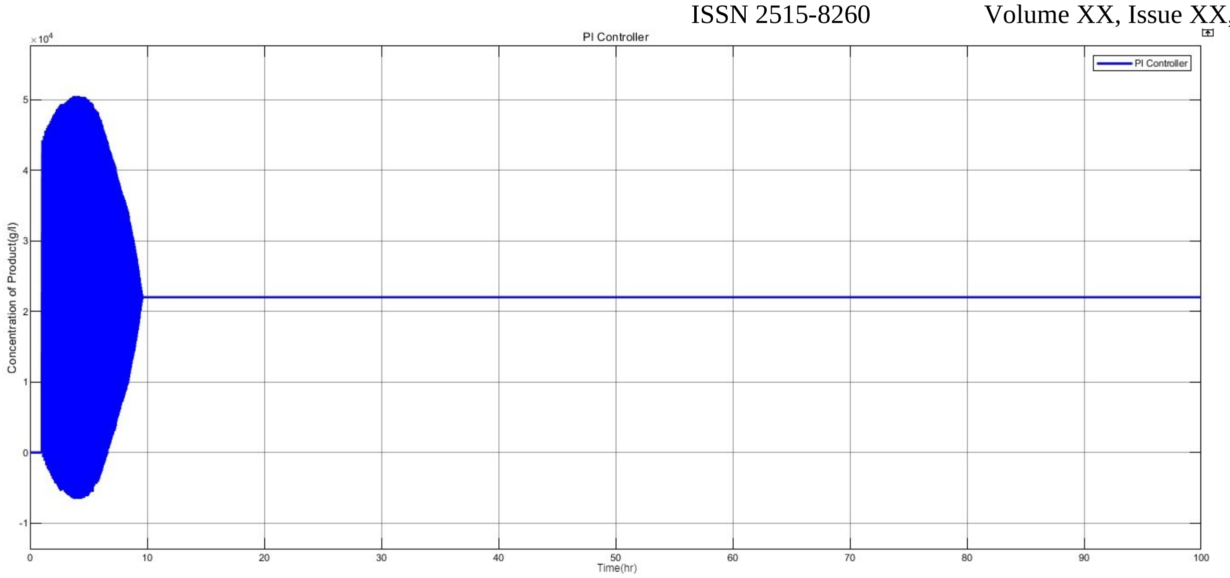

Fig 12. Output response of PI Controller

The figure 12 depicts the output response obtained from a PI-controller. In this controller, though the response graph settles at the required set point, the time taken for settling is too long when compared to other controllers. It takes almost 10 hours to settle at 22000g/l.

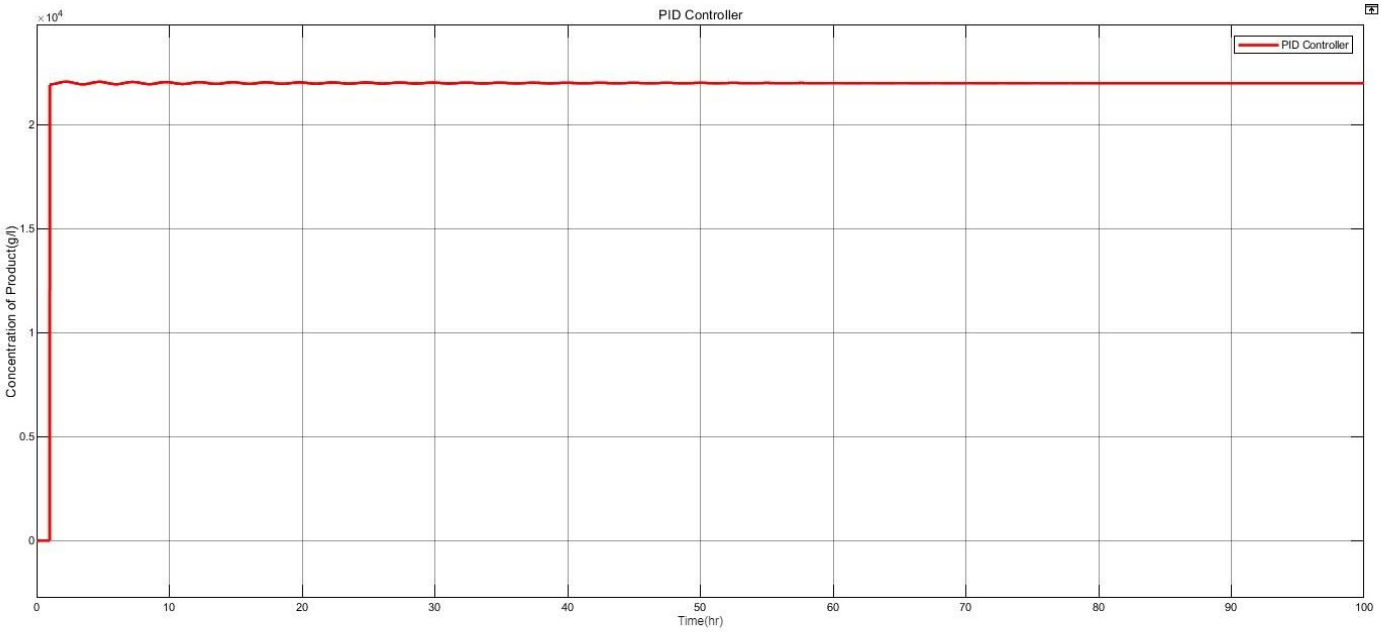

Fig 13. Output response of PID Controller

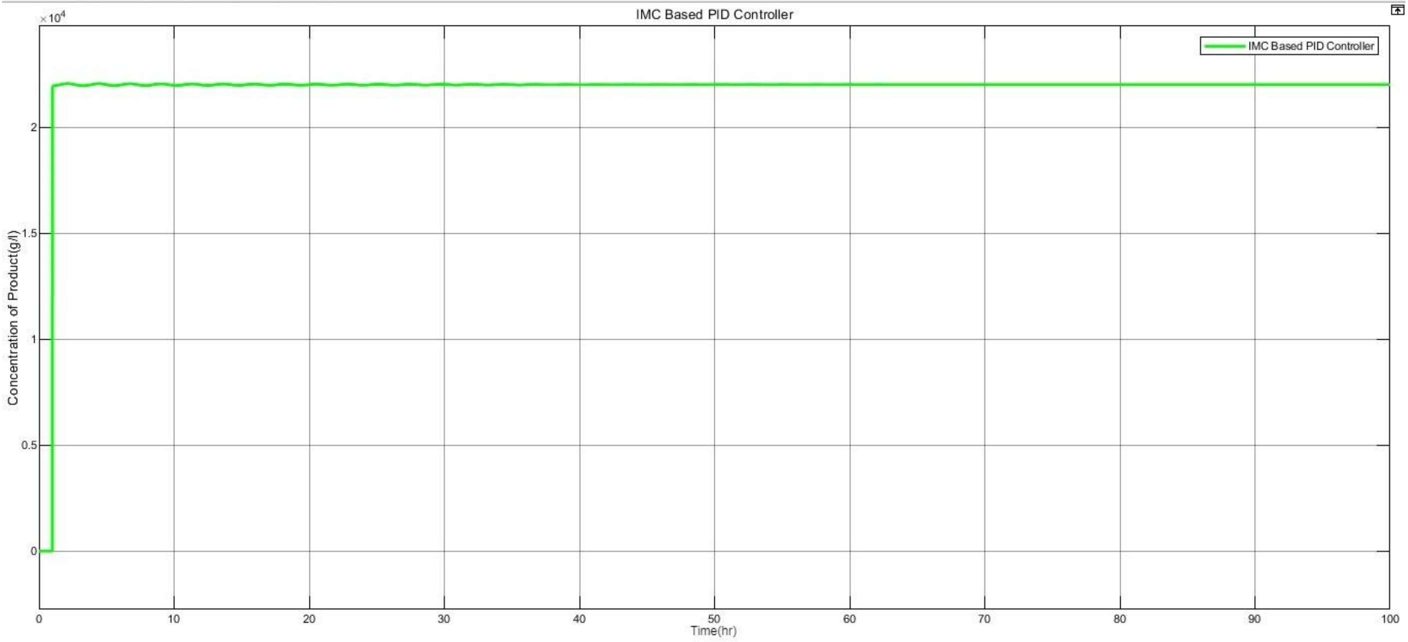

Fig 14. Output response of IMC based PID Controller

Figures 13 and 14 shows the response of PID Controller and IMC based PID Controller. It can be observed that both the controllers have almost similar outputs. But, when IAE is considered, there is much difference in the output. This is addressed in the IAE Tabulation.

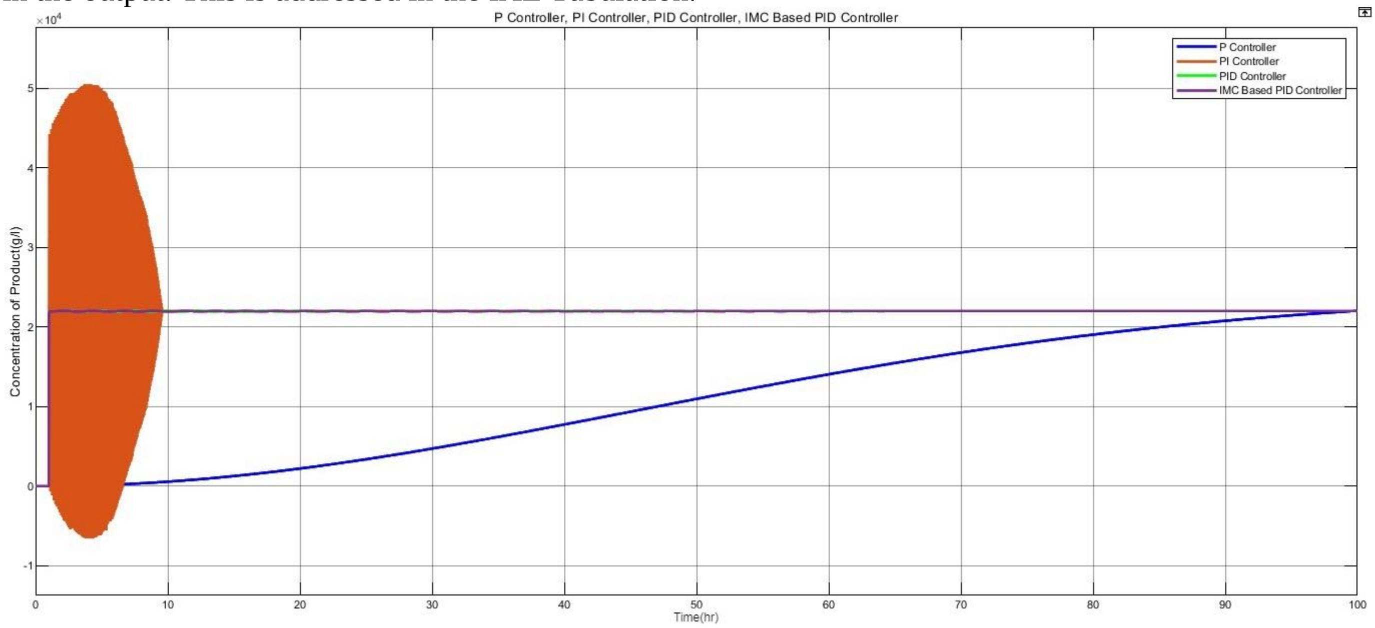

Fig 15. Comparison of P, PI, PID and IMC based PID Controller

	P-Controller	PI-Controller	PID-Controller	IMC based PID-Controller
IAE Values	**5204**	**0**	**7.655**	**2.68**

Table 3. Calculated IAE Values

The table 3 represents the calculated IAE values from each controller. It can be observed that the IMC based PID controller produces the least error. Also, one contradictory fact can be observed that the IAE value of PI Controller is obtained to be zero. But then this cannot be concluded as the suitable controller for the proposed system because PI Controller as seen in fig.12 produces oscillations for about 10 hours and settles only after that. Hence the PI Controller has longer settling time and so even if the IAE value is 0 for this controller, it is not selected to be the suitable one.

8. CONCLUSION

This study predicted the effects of various operating kinetic parameters on the batch time profile for the whole conversion process of substrate(corn) to product(ethanol) with the following observations: The simulated output shows that the batch time profile required for conversion of substrate to product were 15,20,21hrs based upon the values of Maximum rate or velocity of reaction and the maximum specific growth rate. An increase in the maximum rate or velocity of reaction (V_{max})promotes quick and rapid conversion of the substrate into product. An increase in the maximum specific growth rate (μ_{max}) of the microbial cells also increases the concentration of the product. Thus, it can be concluded that μ_{max} and V_{max} are the key factors in reaction conditions and efficiency of this fermentation process.
Also, when controller design is considered, the IMC based PID Controller shows quicker settling time and low errors when compared with P, PI and PID Controllers. So, IMC based PID Controller is considered to be the appropriate controller for the proposed system.

9. FUTURE SCOPE

The project as of now has been developed with the production of ethanol from corn alone. In future the same project can be improvised by using multiple input sources such as stock of sugarcane, cassava and a controller can be designed to determine on which feedstock the production of ethanol is efficient. Adding to that, intelligent controllers can also be implemented to optimize the production of ethanol from corn.

10. REFERENCES

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