(2022), 1 (3): 238–247 **Scientica** 3021-8209
Jurnal Ilmiah Sain dan Teknologi

# Reactor Design for Ethanol Production from Cassava Starch by Fermentation Method

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**Abstract (English)**
Ethanol ($C_2H_5OH$) serves as an alternative fuel and industrial feedstock. Bioethanol, produced from cassava starch, reduces dependence on fossil fuels and greenhouse gas emissions. This research explores the design of a reactor and stirrer for ethanol production from cassava starch via the fermentation method. The reactor is an upright cylinder with a flat top and a conical bottom, having a total volume of 57.4192 $ft^3$, a reactor height of 2.0993 ft, and a cylinder thickness of 0.0685 in. The stirrer is an axial turbine impeller with a power of 1653 Hp. The bioethanol production process involves hydrolysis, fermentation, and purification. Through mass balance analysis, the reactor operates for one hour at 105°C and 1 atm pressure with a total inlet of 2866.09 lb/h. Simulation of the fermentation model considered parameters such as the maximum rate of enzyme reaction (Vmax) and the maximum specific growth rate (μmax). The calculation results show that the reactor and stirrer design can be applied efficiently, ensuring optimal performance in ethanol production from cassava starch. In conclusion, this design can be applied for ethanol production efficiently, while simulations show that Vmax and μmax are key factors in batch biochemical reactor design**.**

**Article History**
*Submitted: 17 Desember 2023*
*Accepted: 23 Desember 2023*
*Published: 24 desember 2023:*

**Key Words**
ethanol, cassava starch, reactor design, fermentation.

**Abstrak (Indonesia)**
Etanol ($C_2H_5OH$) berperan sebagai bahan bakar alternatif dan bahan baku industri. Bioetanol, dihasilkan dari pati singkong, mengurangi ketergantungan pada bahan bakar fosil dan emisi gas rumah kaca. Penelitian ini mengeksplorasi desain reaktor dan pengaduk untuk produksi etanol dari pati singkong melalui metode fermentasi. Reaktor berbentuk silinder tegak dengan bagian atas datar dan bagian bawah kerucut, memiliki total volume sebesar 57.4192 $ft^3$, tinggi reaktor 2.0993 ft, dan ketebalan silinder 0.0685 in. Pengaduk berupa impeller axial turbine dengan daya 1653 Hp. Proses produksi bioetanol melibatkan hidrolisis, fermentasi, dan pemurnian. Melalui analisis keseimbangan massa, reaktor beroperasi selama satu jam pada suhu 105°C dan tekanan 1 atm dengan total zat masuk 2866.09 lb/h. Simulasi model fermentasi mempertimbangkan parameter seperti laju maksimum reaksi enzim (Vmax) dan laju pertumbuhan spesifik maksimum (μmax). Hasil perhitungan menunjukkan bahwa desain reaktor dan pengaduk dapat diterapkan dengan efisien, memastikan kinerja optimal dalam produksi etanol dari pati singkong. Kesimpulannya, desain ini dapat diaplikasikan untuk produksi etanol secara efisien, sementara simulasi menunjukkan bahwa Vmax dan μmax adalah faktor kunci dalam desain reaktor biokimia batch.

**Sejarah Artikel**
*Submitted: 17 Desember 2023*
*Accepted: 23 Desember 2023*
*Published: 24 desember 2023*

**Kata Kunci**
etanol, pati singkong, desain reaktor, fermentasi.

## Introduction

Ethanol, with the chemical formula $C_2H_5OH$, is an alcohol compound known as a volatile, flammable, and colorless liquid. These properties make it have various uses, one of which is as an alternative fuel to gasoline. In addition, ethanol is also used in the pharmaceutical, cosmetic, and food industries (Santoso, 2022).

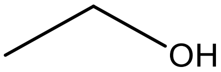


**Figure 1. Chemical structure of ethanol**

Bioethanol, on the other hand, is a variant of ethanol produced from biomass materials such as starch, sugar, and cellulose. With the potential to reduce dependence on fossil fuels and reduce greenhouse gas emissions, bioethanol plays an important role in sustainability efforts (Burhani et al, 2019).

The bioethanol production process from cassava starch involves three main stages, namely hydrolysis, fermentation, and purification. In the hydrolysis stage, cassava starch is converted into simple sugars such as glucose and fructose, using enzymes or acids. The fermentation stage involves converting the hydrolyzed sugars into ethanol through the activity of microorganisms, particularly yeast (Saccharomyces cerevisiae), under anaerobic conditions. The bioethanol fermentation reaction can be explained as follows (Vasić et al, 2021):

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$$

The purification stage is carried out to remove impurities such as water, acids, and bases, using methods such as distillation, absorption, and ion exchange.

Fermentation reactor design is a crucial aspect in the pre-design of a bioethanol plant from cassava starch, which aims to produce ethanol with high yield and optimal quality. Several key factors need to be considered in designing bioethanol fermentation reactors, including reactor types such as batch reactors, semibatch reactors, and continuous reactors, each of which is appropriate for the scale of production (Kusmiyati and Mulia, 2014).

The reactor size should be adjusted to the production capacity of the plant to avoid low ethanol yield or high production costs. The operating conditions of the reactor, such as temperature, pH, and composition of the fermentation medium, must be adjusted to the needs of the microorganisms involved in the fermentation process. An adequate aeration system is a must, considering that fermentation requires oxygen for the growth and metabolism of microorganisms (Imawanto et al, 2020).

In this article, we will comprehensively discuss the reactor design in the pre-design of a bioethanol plant from cassava starch, involving aspects such as reactor type, reactor size, operating conditions, and aeration system. The purpose of this article is to explain the design of reactor and stirrer for ethanol production from cassava starch by fermentation method. The article also discusses other types of reactors that can be used for this process.

## Method

### *Ethanol Synthesis*

Starch is a polysaccharide consisting of long glucose chains. To be converted into ethanol, starch must first be hydrolyzed into simple sugars, namely glucose. Starch hydrolysis can be done using acid catalysts or enzymes. After hydrolysis, the resulting glucose is then fermented by yeast. Yeast is a microorganism that can convert glucose into ethanol and carbon dioxide. Fermentation takes place at 25-30°C for 24-48 hours. After fermentation is complete, ethanol can be separated.

Figure 2 illustrates the process of ethanol formation and Figure 3 shows the reaction mechanism that occurs.

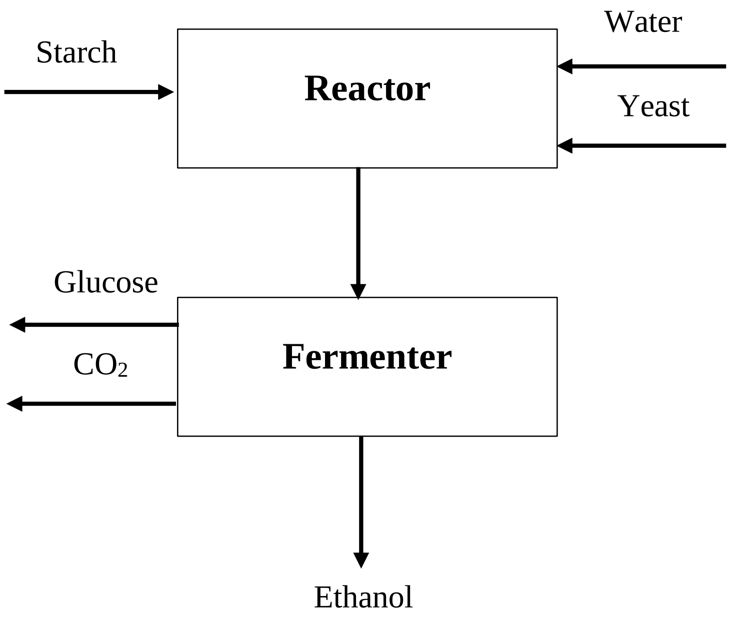



**Figure 2 ethanol manufacturing scheme**

$$C_6H_{10}O_5 + H_2O \rightarrow C_6H_{12}O_6$$

$$C_6H_{12}O_6 + Yeast \rightarrow 2C_2H_5OH + 2CO_2$$

**Figure 3 Reaction mechanism of ethanol fermentation from cassava starch**

***Reactor Design***

The reactor is an upright cylinder with a flat top and a conical bottom. The reactor will operate at 105°C and 1 atm pressure for 1 hour. The reactor is made of stainless steel SA 240 Grade M Type 316 and has a permit stress of 18750 psi. Double blunt welded joints are used for the construction of the reactor. The corrosion factor for the reactor is 0.0625. The amount of material entering the reactor is 2866.09 lb/h and the volumetric rate is 62.39 ft³/h. The stirrer is an axial turbine with 4 blades at a 45° angle. The stirrer impeller is made of SA 240 Grade M Type 316 high alloy steel and the stirrer shaft is made of SAE 1020 Hot Roller Steel. Details of the specification assumptions can be found in table 1.

**Table 1** Assumptions of specifications design of reactor and stirrer

| Specifications | Reactor |
|---|---|
| Type | Upright cylinder with standard dished top and conical bottom with 120˚ apex angle |
| Temperature | 105˚C |
| Pressure | 1 atm |
| Operation time | 1 hour |

| | |
|---|---|
| Construction time | Stainless steel SA 240 Grade M Type 316 |
| Allowable Stress ($f$) | 18750 |
| Welding | Double welded butt joint |
| Corrosion Factor | 0.0625 |
| Amount incoming substance | 2866.09 lb/h |
| Volumetric rate | 62.39 $ft^3$/h |

| | Stirrer |
|---|---|
| Type | Axial Turbine with 4 Blades at an Angle of 45˚ |
| Impeller material | High Alloy steel SA 240 Grade M type 316 |
| Shaft material | Hot Roller Steel SAE 1020 |

The reactor operated for one hour at room temperature and pressure with a total incoming substance of 2866.09 lb/h. The mass balance analysis process was performed by utilizing Microsoft Excel application for data collection using equations 1-18. Table 2 presents the calculated parameters for the reactor and stirrer. (Anggraini, 2018).

**Table 2** Calculation of reactor and stirrer parameters

| Section | Parameters | Equation | Eq |
|---|---|---|---|
| Dimension of reactor | Total Volume of Reactor | $Total\ Vol.of\ reactor = precursor\ vol. + 20\% \times blank\ psace\ Vol.$ <br> Where <br> Total vol. of reactor ($ft^3$) | (1) |
| | Vessel dimension ($d_i$) | $Total\ Vol. = V_{bottom\ lid} + V_{cylinder} + V_{top\ lid}$ <br> $Total\ Vol. = \left(\frac{\pi d_i^3}{24\tan\left(\frac{1}{2}\alpha\right)}\right) + \left(\frac{\pi d_i^3}{4} \times Lc\right) + 0.0847 d_i^3$ <br> Where <br> α = 60˚ <br> $L_c$ = 1.5 <br> $d_i$ (in) | (2) |
| | Volume of liquid in the cylinder ($V_{lc}$) | $V_{lc} = V_{liquid} - V_{bottom\ lid}$ <br> Where <br> $V_{lc}$ ($ft^3$) | (3) |
| | Height of liquid in the cylinder ($H_{lc}$) | $H_{lc} = \frac{V_{lc}}{\left(\frac{\pi}{4}\right) d_i^2}$ <br> Where <br> $H_{lc}$ (in) | (4) |
| | Pressure of design ($P_i$) | $P_i = P_{atm} + P_{hydrostatic}$ <br> $P_i = 14{,}7\ psia + \left(\frac{\rho(HL-1)}{144}\right) psia$ <br> Where <br> $HL$ = 5.1463 <br> $P_i$ (psig) | (5) |
| | Cylinder thickness ($t_c$) and $d_o$ | $t_c = \left(\frac{p_i \times d_i}{2(f \times E - 0.6P_i)}\right) + C$ <br> Where | (6) |

| | | | |
|---|---|---|---|
| | standardization | $f$ = 18750<br>$E$ = 0.8<br>$C$ = 1/16<br>$d_o = d_i + 2t_c$<br>Where<br>$d_o$ (ft) | |
| | Height of cylinder ($L_c$) | $Total\ Vol. = V_{bottom\ lid} + V_{cylinder} + V_{top\ lid}$<br>$Total\ Vol. = \left(\frac{\pi d_i^3}{24\tan\left(\frac{1}{2}\alpha\right)}\right) + \left(\frac{\pi d_i^3}{4} \times Lc\right) + 0.0847 d_i^3$<br>$L_c$ (in) | (7) |
| | Dimension of top lid | $th_t = \frac{0.885 \times P_i \times d_i}{2(f \times E - 0.1P_i)} + C$<br>Where<br>$th_t$ = top lid thickness (in)<br>$h_t = 0.169 \times d_i$<br>Where<br>$h_t$ = height of top lid (in) | (8) |
| | Dimension bottom lid | $th_b = \frac{P_i \times d_i}{2(f \times E - 0.16)\cos\left(\frac{1}{2}\alpha\right)} + C$<br>Where<br>$\alpha$ = 120°<br>$th_b$ = bottom lid thickness (in)<br>$h_b = \left(\frac{\frac{1}{2}h_t}{\tan\left(\frac{1}{2\alpha}\right)}\right)$<br>Where<br>$\alpha$ = 120°<br>$h_b$ = height of bottom lid (in) | (9) |
| | Height of reactor | $Height\ of\ reactor = h_t + L_c + +h_b + s_f$<br>Where<br>$s_f$ = 2.5<br>Height of rector (ft) | (10) |
| Stirrer | Impeller diameter ($D_a$) | $\frac{D_a}{D_t} = 0.5$<br>Where<br>$D_t$ = 77.6250<br>Impeller diameter (ft) | (11) |
| | Impeller height from the bottom of the tank ($Z_i$) | $\frac{Z_i}{D_t} = \frac{1}{3}$<br>Where<br>Impeller diameter from the bottom of the tank (ft) | (12) |
| | Impeller length ($l$) | $\frac{l}{D_a} = \frac{1}{4}$<br>Where<br>Impeller length (ft) | (13) |
| | Impeller width ($W$) | $\frac{W}{D_a} = \frac{1}{5}$<br>Where | (14) |

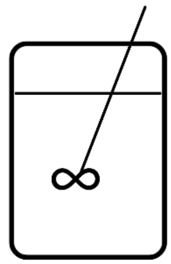
| | | |
|---|---|---|
| | Impeller width (ft) | |
| Number of stirrer ($n$) | $$n = \frac{H_{liquid}}{2 \times D_a^2}$$ Where $H_{liquid}$ = 61.7559 | (15) |
| The stirring power ($H$) | $$P = \frac{\varphi \times \rho \times n^3 \times D_i^5}{g_c}$$ Where $\varphi$ = 0.9, $g_c$ = 32.2 lb.ft/s$^2$.lbf, $P$ (Hp) $$H = (0.1 + 0.15)P + P$$ Where 0.1 = estimation of the amount of power leakage in the process and bearing from the input power; 0.15 = estimation of the amount of belt or gear leakage form input power; $H$ (Hp) | (16) |
| Shaft diameter of stirrer ($D$) | $$D^3 = \frac{16 \times T}{\pi \times S}$$ $$T = \frac{63025 \times H}{N}$$ $$S = 20\% \times 36000\ lb/in^2$$ Where $S$ = maximum allowable design shearing stress (lb/in$^2$); $N$ = stirrer rotation = 100 rpm; $T$ = torsion moment (lb.in); $\pi$ = 3; $D$ (in) | (17) |
| Shaft length of stirrer ($L$) | $$L = h + (l - Z_i)$$ Where $h = L_c + h_t$; $L$ (ft) | (18) |

***Other Reactor Types***

Batch bioreactors are used in the fermentation process to produce ethanol from cassava starch. The batch bioreactor was developed based on the mole balance design equation for reactors, which gives the mass flow rate of the reacting species minus the mass flow rate of the reacting species plus the rate of chemical formation of species or biochemical reactions in the system equal to the rate of mass accumulation in the system. The development method used is based on the assumptions:

a. No mass flow of material into or out of the reactor
b. Reaction specie changes with time
c. The reactor is well mixed and there is no spatial variation in the reactor volume
d. For most liquid phase reactions, density changes during the reaction are usually small and negligible (i.e. V = Vo)
e. Batch bioreactors are operated isothermally, as most fermentation processes are carried out at either room temperature or slightly above room temperature.
f. The specific heat capacity is constant.

g. The batch bioreactor is designed to be a cylindrical vessel with a height of 50 cm and a diameter of 30 cm. The design is based on a small-scale laboratory setup. However, the vessel will still provide considerable output and will not take up much space when the bioreactor is fully installed.
h. Model equation:




## Result and Discussion

The reactor that can be used in the process of making ethanol from cassava starch by fermentation reaction is an upright cylindrical reactor with a flat top and a conical bottom. The reactor dimensions are selected based on the required volume and design pressure. The thickness of the cylinder wall, top cap, and bottom cap are determined based on strength calculations to withstand the operating pressure. This reactor is sufficient for small to medium scale ethanol production. The reactor can be made of stainless steel material that is resistant to corrosion and easy to clean. The fermentation process is carried out in the reactor with controlled temperature and pH. Fermentation microorganisms will convert cassava starch into ethanol and carbon dioxide. Ethanol can then be separated from the reaction mixture by distillation method.

**Table 3** Reactor parameters designed based on calculations.

| No | Parameters | Results |
|---|---|---|
| 1 | Total volume of reactor | 57.4192 $ft^3$ |
| 2 | Vessel dimension ($d_i$) | 42.0153 in |
| 3 | Volume of liquid in the cylinder ($V_{lc}$) | 42.6924 $ft^3$ |
| 4 | Height of liquid in the cylinder ($H_{lc}$) | 53.2364 in |
| 5 | Pressure of design ($P_i$) | 4.3040 psig |
| 6 | Cylinder thickness ($t_c$) | 0.0685 in |
| 7 | $D_o$ standardization | 42.1524 in |
| 8 | Height of cylinder ($L_c$) | 4.7130 in |
| 9 | Top lid thickness ($th_t$) | 0.0678 in |
| 10 | Height of top lid ($h_t$) | 7.1006 in |
| 11 | Bottom lid thickness ($th_b$) | 0.0745 in |
| 12 | Height of bottom lid ($h_b$) | 12.1431 in |
| 13 | Height of reactor | 2.0993 ft |

Based on the calculation, table 3 shows the parameters of the designed reactor. By using a well-designed reactor and an optimized fermentation process, ethanol production from cassava starch can be an efficient and environmentally friendly endeavor. The ethanol produced can be used as biofuel or raw material for various industrial products.

Stirrer is a crucial component in the ethanol production reactor from cassava starch through fermentation method. Its functions are very diverse, including maintaining the homogeneity of the reaction mixture, increasing heat transfer between phases, and accelerating the fermentation reaction rate. With this important role, the stirrer becomes one of the strategic elements in ensuring the efficiency and success of the ethanol production process from cassava starch, because it is able to support key processes in the reactor.

**Table 4** Stirrer parameters designed based on calculations.

| No | Parameters | Results |
|---|---|---|
| 1 | Impeller diameter ($D_a$) | 38.8125 ft |
| 2 | Impeller height from the bottom of the tank ($Z_i$) | 25.875 ft |
| 3 | Impeller lenght ($l$) | 9.7031 ft |
| 4 | Impeller width ($W$) | 7.7625 ft |
| 5 | Number of stirrer ($n$) | 1 piece |
| 6 | The stirring power ($H$) | 1653 Hp |
| 7 | Shaft diameter of stirrer ($D$) | 9.1734 in |
| 8 | Shaft lenght of stirrer ($L$) | 3.8311 ft |

Based on the calculation results shown in table 4, the stirrer is in the form of an impeller with a diameter large enough to ensure the homogeneity of the reaction mixture in the reactor. The distance of the impeller from the bottom of the reactor is chosen so as not to disturb the fluid flow in the reactor, while the required stirring power is large enough to overcome the viscosity of the reaction mixture. The stirrer is made of stainless steel which is resistant to corrosion and easy to clean. Driven by an electric motor with adjustable speed, the stirring speed should be adjusted according to the operating conditions of the reactor to ensure optimal fermentation performance. With the use of a well-designed stirrer, the fermentation process in the ethanol production reactor from cassava starch can run efficiently and produce high-quality ethanol.

### *Other Reactor Types*

The purpose of simulation is to make a comparison of the real experimental data presented for the real process and check the adequacy of the model and model assumptions underlying the creation of the bioreactor. Therefore, the kinetics data for simulation and validation of the mathematical model of cassava starch fermentation to ethanol in a batch system were obtained based on the research of Manikandan et al. (2010). The parameter values used to simulate are listed in Table 5.

**Table 5** Model Validation Parameters

| Parameter | Information | Mark |
|---|---|---|
| Vmax | Maximum rate or speed of enzyme reaction | $35.50\frac{gmol}{l.hr}$ |
| km | Michaelis-Menten constant | $826.45\frac{gmol}{l}$ |
| | Coefficient formation product related | $2.67\frac{gproduct}{gr\ biomass - hr}$ |
| | The growth of the coefficient of product formation is related to growth | $0\ .062\frac{gproduct}{gr\ biomass - hr}$ |
| Ymax | Growth rate Specific maximum | 0.10049 (/ hr ) |
| Kd | Coefficient endogenous decay | 0.01416 (/hour) |
| YCx /Cs | Cell weight yield per unit weight of substrate used | $10.104\frac{Kg\ Cx}{Kg\ Cs}$ |
| M.S | Coefficient maintenance | 0.00540 |
| YCP/CS | Product weight yield per unit weight of substrate used | 0.0543 KgCp / KgCs |

The maximum rate or speed of enzyme reaction when varied has an influence on the batch reaction time required to achieve a certain substrate concentration relative to the enzymatic conversion of substrate to product. The higher the maximum rate or speed of enzyme reaction, the faster the batch reaction time required to achieve a certain substrate concentration relative to the enzymatic conversion of substrate into product and vice versa. Effect of maximum specific growth rate (μmax) of microbial cells on the batch reaction time required to achieve a certain product concentration profile. The higher the maximum specific growth rate of microbial cells, the faster the batch reaction time required to achieve a given product concentration profile, and vice versa. Therefore, operating a reactor with a higher μmax value will produce more product in a short period of time.

An increase in the maximum reaction rate or speed (Vmax) of enzyme activity promotes the conversion of substrate to product quickly and rapidly, and an increase in the maximum specific growth rate (μmax) of microbial cells rapidly increases the concentration of microbial cells at a faster rate and vice versa. An increase in the maximum specific growth rate (μmax) of microbial cells also increases the concentration of the product. Thus, it can be concluded that the parameters (Vmax) and (μmax) are key factors in batch biochemical reactor design, as they are useful for predicting the most appropriate batch reaction conditions and bioreactor efficiency.

## Conclusion

This research focuses on the design of reactor and stirrer for ethanol production from cassava starch through fermentation method. The designed reactor is an upright cylinder with a flat top and conical bottom with specifications of total volume of reactor of 57.4192 $ft^3$ with height of reactor of 2.0993 ft and cylinder thickness of 0.0685 in. The stirrer is a single impeller axial turbine with a power of 1653 Hp. The reactor and stirrer parameters are designed based on calculations and simulated to ensure optimal performance. Based on the calculation results, it can be concluded that the design and performance analysis of the reactor are applicable. Other types of reactors are also discussed and compared with the designed reactor. The simulation results show that the maximum reaction rate (Vmax) and maximum specific growth rate (μmax) are the key factors in the design of batch biochemical reactors.

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