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MORALITY BEFORE KNOWLEDGE

Design and fabrication of a 20 kilogram capacity cassava-based bioethanol distillation apparatus with 2.4 liter bioethanol output

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ABSTRACT

Background: The depletion of fossil fuel resources and growing environmental concerns have sparked interest in renewable energy sources like bioethanol. Cassava, an abundant crop in many tropical regions, shows promise as a feedstock for bioethanol production. This study aimed to design and fabricate an efficient small-scale distillation apparatus for producing bioethanol from cassava. **Methods:** A distillation apparatus with 20 kg cassava capacity was designed and constructed using locally available materials. Key components included a distillation tank, condenser, cooling tower system, and burner. The apparatus was tested using fermented cassava mash to evaluate its performance in bioethanol production. **Findings:** The fabricated apparatus successfully produced 2.4 liters of bioethanol with 65% purity from 20 kg of cassava feedstock. Optimal distillation temperature was found to be 70°C, balancing ethanol yield and purity. Heat transfer calculations indicated 576 kW of cooling capacity was required in the condenser. The cooling tower system achieved 63% thermal efficiency. **Conclusion:** The designed distillation apparatus demonstrates the feasibility of small-scale bioethanol production from cassava. Further optimization of the distillation process and heat recovery systems could improve efficiency. This technology shows potential for decentralized biofuel production to meet local energy needs in cassava-producing regions. **Novelty/Originality of this study:** The study on designing small-scale distillation equipment for bioethanol production from cassava successfully demonstrated practical and affordable applications for decentralized biofuel production in cassava-producing areas.

KEYWORDS: bioethanol; biofuel; cooling tower; distillation; renewable energy.

1. Introduction

The depletion of non-renewable energy resources has become an increasingly critical issue as global energy consumption continues to rise with economic growth and population expansion (Kadir, 1995). Fossil fuels remain the primary energy source worldwide, leading to serious challenges for many developing countries facing limited supplies and growing demand (Wardhanu, 2011). This energy scarcity is exacerbated by the rising use of gasoline-powered vehicles. According to Indonesian Police Statistics (2009), the number of motor vehicles in Indonesia reached 61,956,009 in 2009, resulting in increased petroleum fuel consumption. The Ministry of Energy and Mineral Resources (2009) has reported that current fuel reserves cannot be relied upon for an extended period. Furthermore, global warming caused by fossil fuel combustion poses escalating environmental threats, spurring the development of renewable alternative fuels and energy conservation technologies

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(Bayhaqi, 2006). The potential environmental hazards include pollution from fossil fuel combustion emissions, which can impact human and animal health as well as flora. Harmful gases such as CO, NOx, and unburned hydrocarbons (UHC), along with metallic elements like lead (Pb), are of particular concern. The dramatic increase in CO2 molecules also contributes significantly to global warming potential (Dunan, 2009).

Awareness of these serious threats has intensified research aimed at developing more sustainable and environmentally friendly energy sources and carriers. Biomass energy represents a promising form of renewable energy derived from diverse organic materials, including agricultural and forestry products and residues as well as domestic and agricultural waste (Mott, 1990). Biomass can be used directly as an energy source or converted into biofuels. Unlike fossil fuels, biomass utilization does not lead to net CO2 accumulation in the atmosphere, as the CO2 released during combustion is recaptured through photosynthesis in the growth of new biomass (Sutalaksana, 2006). While direct biomass combustion is relatively inefficient, conversion to biofuels like biogas, bioethanol, and biodiesel offers improved energy utilization. Bioethanol and biodiesel, in particular, show potential as long-term replacements for petroleum-based fuels. Bioethanol, produced through fermentation of biomass, represents a promising alternative to address fossil fuel dependence (PT Sinarmas Bio Energy, 2021). Approximately 93% of global bioethanol production utilizes fermentation processes. Bioethanol offers several advantages over conventional fuels and its applications continue to expand.As a plant-based fuel, bioethanol can help reduce environmental pollution and dependence on fossil resources. It can be produced from a variety of abundant biological materials in Indonesia, including sugar and starch-rich crops like cassava, sugarcane, sorghum, sweet potatoes, and others (Widiarto, 2008). Many of these feedstocks are common food crops that are readily available.

Bioethanol is considered more environmentally friendly because the CO2 produced from engine exhaust can be absorbed by plants, which are then used as raw materials for fuel production, creating a carbon-neutral cycle unlike the accumulation caused by petroleum fuel use (Assauri, 1995). Additionally, bioethanol has a high octane number of 135, compared to 98 for premium gasoline. The higher octane rating provides improved combustion stability and power output. More complete combustion also reduces carbon monoxide emissions - a 3% bioethanol blend can lower CO emissions to just 1.35%. Bioethanol can increase combustion efficiency due to its 35% oxygen content and reduce exhaust emissions of carbon monoxide, nitrogen oxides and other gases by 19-25% (Yaws, 1999). Cassava (Manihot esculenta) represents a particularly promising bioethanol feedstock for development in Indonesia. Although not native to the country, cassava has been widely cultivated by Indonesian farmers since its introduction by Dutch colonists in the early 19th century. This familiarity makes cassava well-suited for expansion as a bioethanol feedstock. Currently, much of Indonesia's cassava crop is exported to the US and Europe for industrial ethanol and starch production. As the world's fourth-largest cassava producer, with 19.5 million tons harvested from 1.24 million hectares in 2005, Indonesia has significant potential for domestic bioethanol production from this crop (Sularso, 2004).

Domestically, cassava is primarily used for animal feed and traditional foods after rice and corn. As a result, cassava prices are highly volatile and often unprofitable for farmers. Developing the bioethanol industry could help stabilize cassava prices and improve farmer incomes while addressing future renewable energy needs. This approach has the potential to make Indonesia energy independent through sustainable biofuel production (Perry, 1998). The objective of this research is to design and fabricate an efficient small-scale bioethanol distillation apparatus utilizing cassava as the feedstock. By developing appropriate technologies for bioethanol production from locally available crops like cassava, this study aims to contribute to sustainable biofuel development in Indonesia. The specific goals include: Designing a 20 kg capacity cassava-based bioethanol distillation system; Fabricating and assembling the designed distillation apparatus; Evaluating the performance of the distillation system in terms of bioethanol yield and purity; and Analyzing the energy requirements and efficiency of the distillation process

This research seeks to demonstrate the technical feasibility of small-scale bioethanol production from cassava, providing valuable insights to support the expansion of domestic biofuel industries. By enhancing bioethanol production capabilities, this work can help reduce fossil fuel dependence, mitigate environmental impacts, and promote rural economic development through value-added processing of agricultural products.

1.1 Bioethanol production methods

Several studies have explored various methods for bioethanol production from plant-based feedstocks. Previously study investigated bioethanol production from corn using hydrolysis and fermentation. The process involved hydrolyzing ground corn to glucose using 0.1 N HCl catalyst, followed by fermentation with 6 grams of Saccharomyces cerevisiae yeast and 4 grams of urea for 3 days. Distillation at 78-80°C yielded an ethanol concentration of 9.27%. From 60 grams of cassava peel flour, 12 ml of 9.27% ethanol was obtained, representing a 22.15% yield.

Indra (2012) developed an extractor machine to facilitate sugarcane juice extraction for bioethanol fermentation. The study utilized a fermentation tank with a thermometer to monitor internal temperature. Heat transfer calculations were performed using conduction and convection principles. The fermentation process ran for 35 days, achieving a 9% alcohol content as measured by an alcoholmeter. Higher ambient temperatures were found to accelerate the fermentation process.

Winarso (2015) conducted research on a bioethanol dehydrator machine using synthetic 3A zeolite as an adsorbent. The study aimed to produce fuel-grade ethanol with over 99% concentration through advanced separation methods including azeotropic distillation, pervaporation membranes, and adsorption. The dehydrator development involved three stages: 1) equipment design, 2) fabrication based on specifications, and 3) performance testing to achieve minimum 99% bioethanol purity.

Susilo et al. (2018) investigated bioethanol production from potato peels through hydrolysis, detoxification, fermentation, and distillation steps. Hydrolysis used sulfuric acid at 100°C for 1 hour. Detoxification involved adding NH_4OH to the hydrolysate before fermentation. Distillation was conducted at 100°C, with distillate collected between 78-84°C and analyzed by gas chromatography. Results showed reducing sugar contents of 15.85% and 15.58% with and without NH_4OH addition, respectively. Ethanol yields from 5 grams of dried potato peels after 4, 5, 6, and 7 days of fermentation were 3.54%, 4.85%, 5.35%, and 6.15%, respectively.

1.2 Bioethanol distillation process

The principle of bioethanol distillation involves separating liquids based on differences in boiling points. For ethanol-water mixtures, ethanol boils at 78°C while water boils at 100°C. This temperature difference allows for separation of ethanol from the fermentation broth (Holman, 1991). In the distillation process, the fermented liquid is heated to ethanol's boiling point, typically 79-81°C. Ethanol vapors are collected and passed through a condenser tube where the temperature is lowered below the boiling point, causing the ethanol to condense back into liquid form. This condensed ethanol is then collected in a receiving vessel (Feigenbaum, 1991).

Careful temperature control is critical to maximize ethanol concentration. Maintaining the temperature at ethanol's boiling point helps achieve higher purity. However, some water vapor is inevitably carried over, limiting the maximum achievable concentration to around 95% through simple distillation. Further dehydration processes are required to reach fuel-grade ethanol levels above 99% (Russel et al., 1996). While the distillation principle appears straightforward, practical implementation at larger scales presents challenges. Designing an efficient distillation apparatus requires balancing factors like heat transfer, vapor flow, and condensation to optimize ethanol recovery and purity. Energy efficiency is also an important consideration in distillation system design (Garvin & Davis, 1996).

2. Methods

2.1 Apparatus design and fabrication

The bioethanol distillation apparatus was designed using SolidWorks 2014 software. The main components include: Base frame, Water cooling tank, Measuring cylinder, Product tub, Condenser pipe, Condenser tank, Distillation kettle, Gas burner and Water pum.

The distillation tank was fabricated from 304 grade stainless steel with a thickness of 5 mm, a diameter of 300 mm, and a height of 600 mm. This material was chosen for its corrosion resistance and durability in contact with ethanol vapor (Sularso, 2004). The tank was equipped with a thermometer and pressure gauge to monitor process conditions. A spiral tube condenser was designed to efficiently cool and condense the ethanol vapor. The condenser consisted of a 6 mm diameter copper tube with a total length of 15,000 mm, coiled inside a stainless steel shell with dimensions of 150 mm diameter and 600 mm height. Copper was selected for its excellent thermal conductivity (Holman, 1991).

The cooling tower system was incorporated to provide a continuous supply of cool water for the condenser. It consisted of an induced draft, counter-flow design with a capacity matching the heat removal requirements of the condenser. The cooling tower was constructed using corrosion-resistant materials suitable for outdoor use (Andrew Smith Hallidie, 1988). A gas burner system was designed to provide controlled heating for the distillation process. The burner was sized to deliver sufficient heat input for maintaining the optimal distillation temperature range of 68-70°C (Richana, 2011). The supporting frame was constructed from 40 mm x 40 mm x 4 mm steel angle bars, providing a stable platform for all components. The frame was designed to allow easy access for operation and maintenance.

2.2 Experimental procedure

Twenty kilograms of cassava were processed to produce a fermented mash. This fermented material was loaded into the distillation kettle and heated using the gas burner. Temperature was closely monitored and maintained between 68-70°C to optimize ethanol vaporization. Ethanol vapors passed through the condenser cooled by circulating water from the cooling tower. Condensed ethanol was collected in the product tub and measured. The distillation process continued until ethanol production ceased. Multiple experimental runs were conducted at different temperature setpoints (68°C, 70°C, 75°C) to evaluate the impact on bioethanol yield and purity. Samples were analyzed for ethanol content using an alcoholmeter. The performance of the fabricated distillation apparatus was evaluated using the following procedure: (1) 20 kg of fermented cassava mash (6-12% ethanol content) was loaded into the distillation tank. (2) The cooling water circulation system was activated. (3) The gas burner was ignited and adjusted to gradually heat the mash to the target distillation temperature (68-70°C). (4) Distillation was allowed to proceed for approximately 4 hours, with regular monitoring of temperature and pressure. (5) The distillate (ethanol) was collected and its volume measured. (6) Ethanol concentration in the distillate was determined using an alcoholmeter.

The experiment was repeated three times to ensure reproducibility. Energy consumption was estimated based on the quantity of LPG fuel used during the distillation process.

2.3 Performance analysis

The performance of the distillation apparatus was evaluated based on the following parameters: Bioethanol yield (L/kg cassava), Ethanol purity (% v/v), Energy consumption, and Distillation efficiency. Heat transfer calculations were performed to determine the energy requirements for the distillation process. The cooling tower performance was assessed in terms of approach, range, and thermal efficiency.

Several key parameters were calculated to assess the performance of the distillation apparatus: (1) Ethanol yield: The volume of ethanol produced per kg of cassava feedstock; (2) Ethanol purity: The concentration of ethanol in the final distillate; (3) Energy efficiency: The ratio of energy content in the produced ethanol to the energy input from the burner; (4) Heat transfer in the condenser: Calculated using the following equation (Holman, 1991); (5) Cooling tower efficiency: Determined using the approach and range method (Perry & Green, 1997) (see Eq. 1).

$$Q = m \times cp \times \Delta T \qquad \text{(Eq. 1)}$$

Where:
Q = Heat transferred (kJ)
m = Mass flow rate (kg/s)
cp = Specific heat capacity (kJ/kg·K)
ΔT = Temperature difference (K)

The results were analyzed to identify optimal operating conditions and potential areas for improvement in the distillation process.

3. Results and Discussion

3.1 Results

3.1.1 Design of bioethanol distillation apparatus

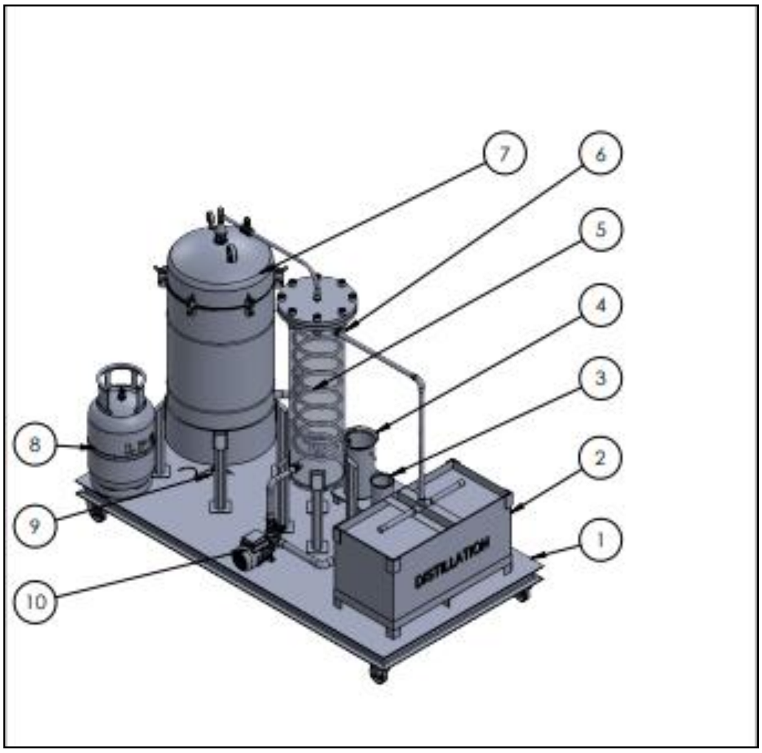

Fig. 1. Presents the design schematic of the bioethanol distillation apparatus.

Based on Fig. 1, the essential components of the system include a base frame (1 pc), water cooling tank (1 pc), measuring cylinder (1 pc), product tub (1 pc), pipe condenser (1 pc), condenser tank (1 pc), distillation kettle (1 pc), gas supply (1 pc), burner (1 pc), and water pump (1 pc). These components work together to facilitate the distillation process.

3.1.2 Components of bioethanol distillation apparatus

The bioethanol distillation apparatus comprises multiple components with distinct functions and characteristics. First, the base frame is constructed from a stainless steel plate with a thickness of 1.5 millimeters, a length of 2080 millimeters, and a width of 1080 millimeters. This sturdy frame provides a stable foundation for the distillation system.

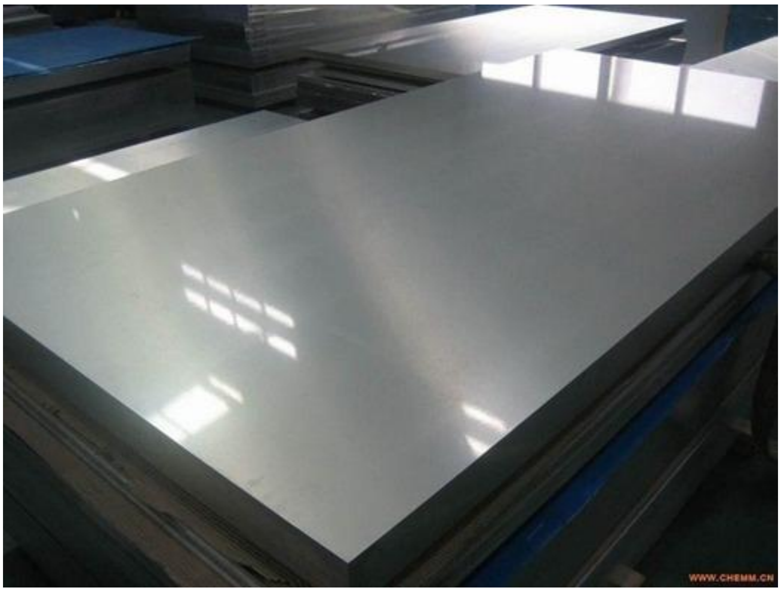

Fig. 2. The base frame design

Second (see Fig. 3), the water cooling tank is constructed from acrylic with a thickness of 4 mm ± 0.1 mm, a length of 600 mm, a width of 400 mm, and a height of 400 mm. This tank functions to cool water used as a coolant in the condenser, ensuring efficient operation of the distillation system.

Fig 3**.** The water cooling tank design.

Third (see Fig. 4), the measuring cylinder is used to accurately measure the level of distilled bioethanol produced by the system. This component is essential for monitoring the output of the distillation process.

Fig. 4. The measuring cylinder design.

Fourth (see Fig. 5), the product tub acts as a container for the condensed bioethanol product, collecting the distilled liquid after it passes through the condenser.

Fig 5. The product tub design.

Fifth (see Fig. 6), the pipe condenser is designed to facilitate the flow of vaporized bioethanol, allowing it to condense into a liquid phase.

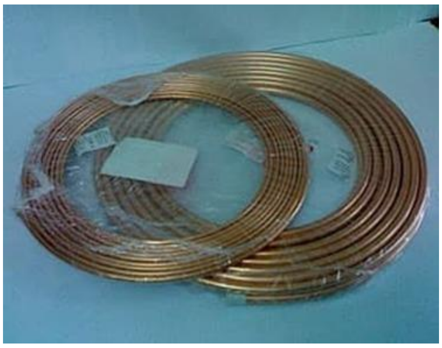

Fig 6. The pipe condenser design.

Sixth (see Fig. 7), the condenser tank is constructed from a stainless steel plate with a thickness of 5 mm ± 0.1 mm, a diameter of 150 mm, and a height of 600 mm. This tank uses 30°C water as a coolant to convert vaporized bioethanol into a liquid state.

Figure 7. The condenser tank design.

Seventh (see Fig. 8), the distillation kettle is constructed from a stainless steel plate with a thickness of 5 mm ± 0.1 mm, a diameter of 300 mm, and a height of 600 mm.

Fig 8. The distillation kettle design.

Eighth (see Fig. 9), The system utilizes LPG gas as fuel for the burner, which heats the bottom product in the distillation kettle. This heating process vaporizes the bioethanol, initiating the distillation process.

Fig 9. The gas supply and burner design.

Ninth (see Fig. 10), the water pump is a single-phase electric motor, type DB-125D 12-4, with specifications of 220/350 volts, 0.5 horsepower (0.37 kW), 1.93 amps, and 2850 revolutions per minute.

Fig 10. The water pump design.

3.1.3 Operating principle

The bioethanol distillation process involves heating the fermentation liquid to ethanol's boiling point (approximately 79°C, typically 80-81°C). Vaporized ethanol is channeled through a tube where its temperature is reduced below the boiling point, causing condensation. The condensed ethanol is collected in receptacles.

3.1.3.1 Component calculations for bioethanol distillation apparatus

a. Mass balance for 20 kg/h capacity bioethanol plant

Beer typically contains an ethanol concentration ranging from 6% to 12% (Ricardo, 2016). The desired ethanol purity in this process is 60%. Given a beer input of 20 kg/h, the top product would have an ethanol concentration of 12%, while the bottom product would contain 88% of the ethanol (Table. 1).

$$[\text{mass in}] = [\text{mass out}] \tag{Eq. 2}$$

Table 1. The mass balance for bioethanol production.

Component	Inlet		Outlet			
			Top Product (Bioethanol)		Bottom Product (Water)	
	kmol/h	kg/h	kmol/h	kg/h	kmol/h	kg/h
Beer	222,05	20,00	-	-	-	-
Bioethanol	-	-	52,09	2,40	-	-
Water	-	-	-	-	976,95	17,60
Total	222,05	20,00	52,09	2,40	976,95	17,60
Kg/h	20		20			

b. Bioethanol condenser calculations

The design parameters for the spiral-type condenser include a diameter of 150 mm, a height of 600 mm, a pipe diameter of 6 mm, a pipe length of 15,000 mm, and a single coil encircling the condenser tank. As shown in Figure 11, the inlet water temperature is 30°C, the outlet water temperature is 38°C, the ethanol vapor temperature is 68°C, the ethanol condensation temperature is 60°C, the inlet pressure is 27.34 kPa, the outlet pressure is 19.93 kPa, and the ethanol flow rate is 2.40 kg/h (8,640 kg/s).

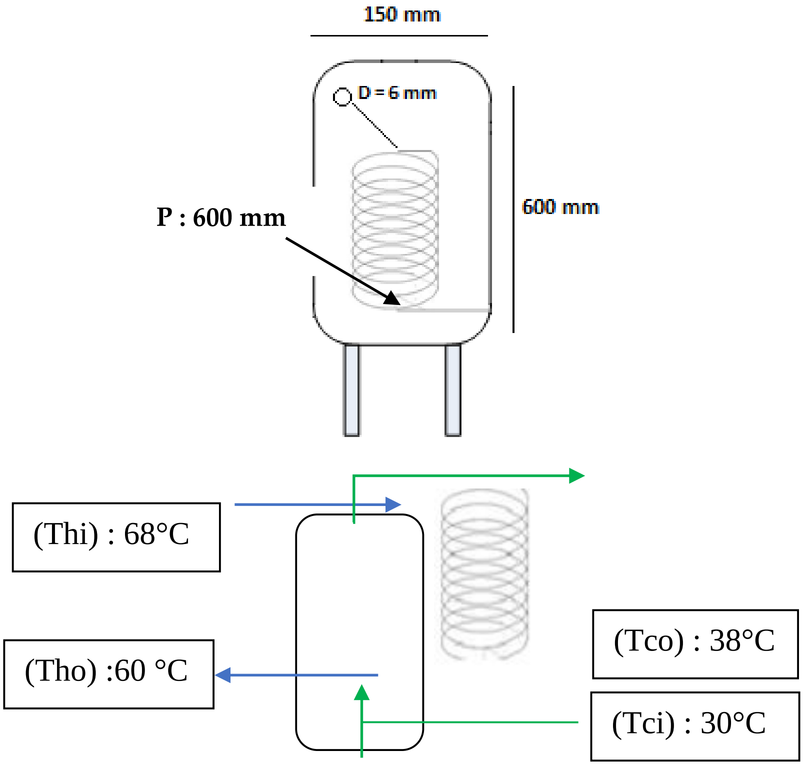

Fig. 11. The heat transfer schematic in the condenser.

The heat released by ethanol vapor, Qh, can be calculated using the equation:

$$Qh = mh \times cph \times \Delta Th$$

(Eq. 3)

where cph is the specific heat capacity of ethanol at 78°C (3,704 J/kgK). Substituting the given values, Qh is found to be 576,046 kW. The heat received by water, Qc, can be calculated assuming Qc equals Qh. Using the equation:

$$Qc = mc \times cpc \times (Tco - Tci)$$

(Eq. 4)

where cpc is the specific heat capacity of water, the required mass flow rate of water, mc, is calculated to be 17,206 kg/s, assuming:
Qc = Qh: mc = Qh / [cpc × (Tco - Tci)]
= 576,046 kJ/s / [4.185 kJ/kgK × (311.15 - 303.15) K]
= 17,206 kg/s

c. Heating load for distillation tank

Assuming a total weight of 20 kg, tank dimensions of 600 mm height, 2 mm thickness, and 300 mm diameter, and using stainless steel 304 material. The heat received, Q, can be calculated using the equation:

$$Q = m \times cp \times \Delta T$$

(Eq. 5)

In this case, with a mass flow rate of 20 kg/s, a specific heat capacity of 55,334 J/kgK, and a temperature difference of 38 K, the heat transfer rate is calculated to be 42,053 kJ/s, equivalent to 42,053 kW. The overall heat transfer coefficient, denoted as U, is a crucial parameter that can be determined using the equation:

$$Q = A \times U \times \Delta T, \tag{Eq. 6}$$

The overall heat transfer coefficient (U) is a measure of how efficiently heat can be transferred between the tank and the beer. It depends on factors such as the tank's surface area (A) and the temperature difference (ΔT). To calculate U, the tank's surface area is determined using the formula:

$$A = \pi \times r2; Q = m \times U \tag{Eq. 7}$$

For the given scenario, the tank surface area is calculated as $A = \pi \times r2 = 70{,}650$ mm2, and the overall heat transfer coefficient $U = 63{,}840$ W/m2K. Then, to determine the total heat required for beer vaporization to bioethanol, the equation $Q = m \times U$ is used, where m is the mass and U is 20,102 kW/kg.

For the LPG requirement for the burner, the heating value of the gas is provided as Hv = 6.58 kWh/L = 0.074 kW/kg (Source: Perry's Table 9-30, p. 9-31). Then, the gas requirement is then calculated as 20,102 kW/kg × 0.074 kW/kg = 155 g.

d. Cooling tower efficiency for bioethanol vapor condensation

The cooling tower efficiency for bioethanol vapor condensation was calculated based on various operational parameters. The range, calculated as the difference between the inlet and outlet water temperatures, was 8°C.

$$Range = Tw,in - Tw,out = 38°C - 30°C = 8°C \tag{Eq. 8}$$

The approach, calculated as the difference between the outlet water temperature and the wet bulb temperature, was 5°C.

$$Approach = Tw,out - Twb = 30°C - 25°C = 5°C \tag{Eq. 9}$$

Thermal efficiency calculation is:

$$\begin{aligned} \mu &= [(\mathrm{Tw,in} - \mathrm{Tw,out}) / (\mathrm{Tw,in} - \mathrm{Twbwb})] \times 100\% \\ &= [(38°\mathrm{C} - 30°\mathrm{C}) / (38°\mathrm{C} - 33°\mathrm{C})] \times 100\% = 63\% \end{aligned} \tag{Eq. 10}$$

The thermal efficiency of the cooling tower was 63%, indicating that it effectively cooled the water. Besides, water mass flow rate (L) calculation is:

$$L = Qwater \times \rho water\ at\ 38°C = 204\ m3/h \times 0.9930\ kg/m3 = 202.57\ kg/h = 0.056\ kg/s \tag{Eq. 11}$$

The water mass flow rate was calculated to be 202.57 kg/h or 0.056 kg/s. This was determined by multiplying the volumetric flow rate of water (204 m3/h) by the density of water at 38°C (0.9930 kg/m3).

Then, cooling capacity (Qw) of cooling tower calculation is:

$$\begin{aligned} Q &= m \times cp \times \Delta T \\ &= 17{,}206\ kg/s \times 1.005\ kJ/kg.K \times 8\ K \\ &= 138{,}336{,}240\ kW \end{aligned} \tag{Eq. 12}$$

The cooling capacity of the cooling tower was calculated to be 138,336,240 kW using Eq. 12. This equation states that the cooling capacity (Q) is equal to the mass flow rate of water (m)

multiplied by the specific heat capacity of water (cp) and the temperature difference (ΔT) between the inlet and outlet water.
Moreover, air mass flow rate (G) calculation is:

$$\begin{aligned} G &= Q_{air} \times \rho_{air} = 345.6\ m3/h \times 1.29\ kg/m3 \\ &= 445.82\ kg/h = 0.12\ kg/s \end{aligned}$$

(Eq. 13)

The air mass flow rate (G) was calculated to be 445.82 kg/h or 0.12 kg/s by multiplying the volumetric flow rate of air (Qair) by the density of air (ρair). Then, water to air flow ratio (L/G) calculation is L/G = 0.056 kg/s / 0.12 kg/s = 0.45.
Evaporation loss calculation is:

$$E = R \times 1/100 \times \Delta T / 5.8\ (m3/h)$$

(Eq. 14)

The evaporation loss (E) was calculated to be 0.33% using Equation 14. This equation states that the evaporation loss is equal to the recirculation flow rate (R) multiplied by 0.01, multiplied by the temperature difference (ΔT) between the inlet and outlet water, and divided by 5.8. Then, The windage loss was calculated to be 0.33% of the flow rate, which is equal to 0.007 m3/h.

The blowdown loss (B) was estimated to be 0.22. The drift loss (D) was estimated to be between 0.1% and 0.3% of the water mass flow rate (L) for an induced draft cooling tower without drift eliminators. The actual value of drift loss was calculated to be between 0.0203 and 0.0061. Then, make-up water flow rate calculation is:

$$\begin{aligned} Make\text{-}up &= B + D + E \\ &= 0.22 + 0.0061 + 0.07 \\ &= 0.29\ m3/h \\ &= 7.10\ m3/day \end{aligned}$$

(Eq. 15)

The make-up water flow rate was calculated to be 0.29 m3/h or 7.10 m3/day by adding the blowdown loss, drift loss, and evaporation loss. Then, performance efficiency of the cooling tower was calculated to be:

$$\begin{aligned} Performance\ Rate &= (actual\ output / plan) \times 100\% \\ &= (1.86\ m3/h / 2.04\ m3/h) \times 100\% \\ &= 91.18\% \end{aligned}$$

(Eq. 16)

The power requirement for the cooling tower circulation pump was calculated based on the pump specifications. The pump has a voltage of 220 V, a frequency of 50 Hz, a pipe diameter of 1 inch (25.4 mm), a maximum head of 35 m, a power of 125 W, a flow rate of 2.04 m3/h (34 L/min), a speed of 2850 rpm, and an efficiency of 91.18%. Then, the pressure head (Hk) for the pump was calculated to be:

$$Hk = (34\ L/min) / (9.8 \times 2) - (28\ L/min) / (9.8 \times 2) = 0.30\ L/min$$

(Eq. 17)

e. Cooling tower pump power calculations

The hydraulic power (HHP) required for the pump can be calculated using Eq. 18.

$$\begin{aligned} HHP &= (Q \times H \times \lambda) / 75 \\ &= (2.04\ m3/h \times 35 \times 1) / 75 \end{aligned}$$

$$= 0.95$$

(Eq. 18)

The hydraulic power (HHP) was calculated to be 0.95. This equation states that the hydraulic power is equal to the flow rate (Q) multiplied by the head (H) and the specific gravity of the fluid (λ), divided by 75.

Then, The brake horsepower (BHP) required can be calculated using Equation 19.

$$BHP = HHP / \eta = (2.04\ m3/s \times 35 \times 1) / (75 \times 0.94) = 1.04$$

(Eq. 19)

Therefore, overall pump efficiency (η) was calculated to be: $\eta = 0.91 \times 0.88 \times 0.96 \times 0.92 = 70.73\%$

3.1.4. Fabrication process of distillation apparatus

The fabrication process of the bioethanol distillation apparatus involves several steps. First, angle iron is cut using a cutting grinder to match the planned design for the machine frame construction. Next, electric arc welding is used to join the cut angle iron pieces together to form the machine frame. After welding, the frame is ground to smooth out any uneven surfaces. Then, the machine components are assembled according to the planned design and combined based on their respective functions. Finally, the main component parts of the machine are integrated to ensure that the apparatus functions according to the design specifications.

3.1.5 Distillation apparatus testing

The heating or vaporization process in the bioethanol distillation kettle demonstrates that temperature significantly influences both the quantity and purity of bioethanol produced. Table 2 presents the testing results.

Table 2. Bioethanol apparatus productivity test results

Distillation Temperature	Bioethanol Yield	Purity
68°C	1 liter	75%
70°C	2.2 liter	65%
75°C	3 liter	40-50%

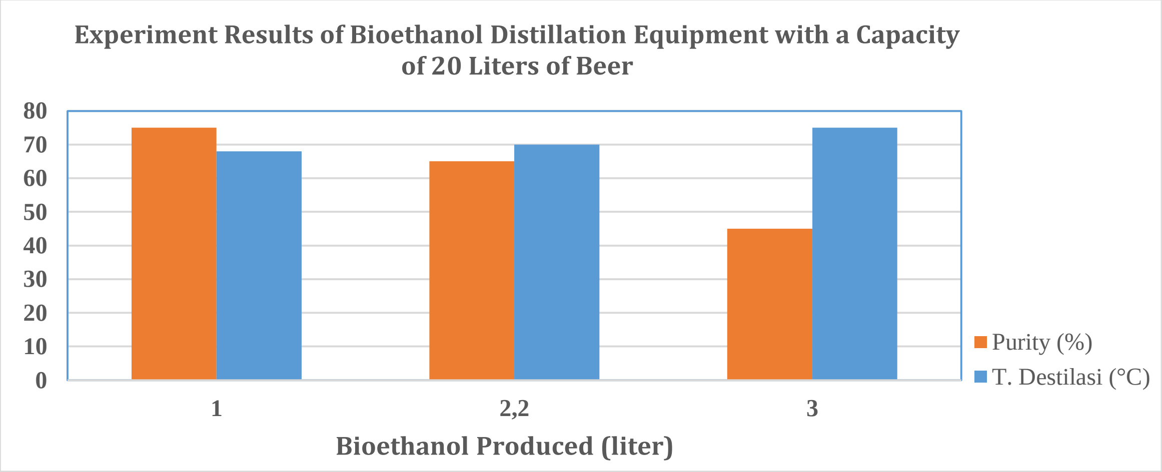

Fig. 12. The distillation experiment results.

The bioethanol production process utilizing 20 kg of cassava and 20 liters of fermentation solution, the yield was 2.4 liters of bioethanol with 60% purity. In conclusion, the designed and fabricated bioethanol distillation apparatus demonstrated effective performance in converting cassava-based feedstock to bioethanol. The comprehensive calculations and experimental results provide a solid foundation for understanding the system's performance and identifying areas for potential optimization in future iterations of the design.

(a) Raw Material (b) Bioethanol Distillation Equipment (c) Bioethanol

Fig. 13**.** The bioethanol production process

3.2 Discussion

The design and fabrication of a bioethanol distillation apparatus with a capacity of 20 kg was executed using Solid Works 2014 software for the initial design phase. The distillation tank dimensions were calculated to be 300 mm in diameter and 600 mm in height, constructed from SS 304 stainless steel (Mott, 1990). The production process involved a series of steps including material cutting, frame welding, grinding, component assembly, and final apparatus assembly. Testing of the distillation apparatus utilized fermented cassava tape solution as the input material. A 20 kg batch of cassava yielded 2.4 liters of bioethanol at a temperature of 70°C, achieving a purity of 65% (Susilo et al., 2018). The energy source for the burner was liquefied petroleum gas (LPG), with a calculated consumption of 155 grams to heat the system sufficiently (Perry, 1998). Optimization of the distillation process to achieve bioethanol purities exceeding 60% would require implementing a double distillation (two-stage distillation) system, potentially yielding high-purity product up to 90% (Setiawan, 2018).

The cooling system performance was evaluated to determine the approach and range values relative to the design specifications, identify areas of energy inefficiency, and propose improvements. Accurate measurement of the cooling tower's operational parameters is essential for assessing its performance (Holman, 1999). These parameters include wet bulb air temperature (Twb), dry bulb air temperature (Tdb), cooling tower inlet water temperature (Tw,in), cooling tower outlet water temperature (Tw,out), outlet air temperature (Ta,out), water mass flow rate (L), and air mass flow rate (G) (Holman, 1999). The cooling tower performance metrics evaluated included range, approach, thermal efficiency (μ), cooling capacity (Qw), evaporation loss, blowdown loss, drift loss, and make-up water flow rate (Sularso, 2004). The range, which is the difference between the inlet and outlet water temperatures, was calculated to be 8°C. A higher range indicates the cooling tower's effectiveness in reducing the water temperature (Sularso, 2004). The approach, defined as the difference between the outlet water temperature and the ambient wet bulb temperature, was determined to be 5°C. A lower approach value signifies better cooling tower performance (Sularso, 2004).

Thermal efficiency (μ), expressed as a percentage, is the ratio of the actual range to the ideal range. The ideal range is the difference between the inlet water temperature and the ambient wet bulb temperature (Sularso, 2004). The cooling capacity (Qw) represents the amount of heat removed from the water, calculated using the water mass flow rate, specific heat capacity, and temperature difference (Sularso, 2004). Evaporation loss is the quantity of water evaporated to achieve cooling, influenced by the latent heat of vaporization (Sularso, 2004). Blowdown loss occurs due to the discharge of a portion of the circulating water to prevent the concentration of dissolved solids, which can lead to scale formation and obstruct the water circulation (Sularso, 2004). Drift loss is the loss of water droplets entrained in the air stream passing through the cooling tower (Sularso, 2004). This loss can be minimized by installing drift eliminators. Make-up water flow rate is the rate at which fresh water is added to compensate for the total losses occurring in the cooling process (Sularso, 2004). Calculating the air-to-water flow ratio (L/G) is crucial for cooling tower performance evaluation (Sularso, 2004).

The distillation process's efficiency was significantly influenced by the operating temperature, affecting both the quantity and purity of the bioethanol produced (Susilo et al., 2018). At a temperature of 68°C, 1 liter of bioethanol was obtained with a purity of 75%. Increasing the temperature to 70°C yielded 2.2 liters of bioethanol with a purity of 65%. Further increasing the temperature to 75°C resulted in 3 liters of bioethanol; however, the purity decreased to 40-50% (Susilo et al., 2018). These findings emphasize the importance of precise temperature control to optimize the bioethanol yield and purity. The utilization of cassava as a feedstock for bioethanol production demonstrates the potential for converting agricultural resources into renewable energy (Wardhanu, 2011). The fermentation process, which converts the sugars present in cassava into ethanol, plays a crucial role in the overall efficiency of the bioethanol production system (Richana, 2011). Optimizing the fermentation conditions, such as temperature, pH, and inoculum concentration, can enhance the ethanol yield and reduce the production time (Cheng et al., 2009).

The distillation process, which separates the ethanol from the fermented mixture, is a critical step in obtaining high-purity bioethanol (Khak et al., 2014). The design of the distillation apparatus significantly influences the product quality and energy efficiency of the process (Setiawan, 2018). The use of a double distillation system can further purify the bioethanol, achieving purities up to 90% (Setiawan, 2018). However, implementing a double distillation system requires additional energy input and increases the complexity of the process (Setiawan, 2018). The cooling system's performance directly impacts the efficiency of the distillation process (Sularso, 2004). Adequate cooling is necessary to condense the ethanol vapors and maintain the desired product purity (Sularso, 2004). The cooling tower's effectiveness in rejecting heat from the circulating water depends on various factors, such as the ambient air conditions, water flow rate, and air flow rate (Sularso, 2004). Optimizing the cooling tower's performance can lead to improved energy efficiency and reduced water consumption (Sularso, 2004). The integration of renewable energy sources, such as solar or biomass, can further enhance the sustainability of the bioethanol production process (Kadir, 1995). Utilizing waste heat from the distillation process for preheating the feedstock or generating steam can improve the overall energy efficiency (Kadir, 1995). Implementing heat recovery systems can reduce the external energy input required for the process (Kadir, 1995).

Life cycle assessment (LCA) studies have shown that bioethanol production from cassava has a lower environmental impact compared to fossil fuels (Wardhanu, 2011). However, the sustainability of cassava-based bioethanol depends on various factors, such as land use change, fertilizer application, and water consumption (Wardhanu, 2011). Sustainable agricultural practices and efficient use of resources are essential to minimize the environmental footprint of bioethanol production (Wardhanu, 2011).The economic viability of small-scale bioethanol production systems, like the one presented in this study, depends on several factors, including feedstock availability, production efficiency, and market demand (Bayhaqi, 2006). Government policies and incentives play a crucial role in promoting the adoption of bioethanol as a renewable fuel (Bayhaqi, 2006). Establishing a robust supply chain and developing local markets for bioethanol can enhance the economic sustainability of small-scale production systems (Bayhaqi, 2006).

Future research should focus on optimizing the bioethanol production process to improve yield, purity, and energy efficiency (Susilo et al., 2018). Investigating the use of alternative feedstocks, such as agricultural wastes or lignocellulosic biomass, can expand the raw material base for bioethanol production (Richana, 2011). Developing advanced fermentation technologies, such as continuous fermentation or immobilized cell systems, can enhance the productivity and reduce the production costs (Cheng et al., 2009).

In conclusion, the design and fabrication of a small-scale bioethanol distillation apparatus using cassava as a feedstock demonstrate the potential for producing renewable fuel from agricultural resources. The performance of the distillation process and the cooling system significantly influence the yield and purity of the bioethanol product. Optimizing the operating conditions, implementing efficient heat recovery systems, and adopting sustainable agricultural practices are essential for the economic and environmental viability of bioethanol production. Further research and development efforts are necessary to enhance the efficiency and sustainability of small-scale bioethanol production systems, contributing to the transition towards a low-carbon energy future.

4. Conclusions

This study successfully designed, fabricated, and tested a small-scale bioethanol distillation apparatus utilizing cassava as feedstock. The system demonstrated capability to produce 2.4 L of 65% purity bioethanol from 20 kg of cassava when operated at 70°C. Key findings and conclusions include: Distillation temperature significantly impacts ethanol yield and purity, with 70°C providing optimal balance for the given apparatus design; The fabricated system achieved a bioethanol yield of 0.12 L/kg cassava, comparable to other small-scale distillation setups reported in literature; Energy analysis revealed efficient heat utilization, with LPG consumption of 155 g per batch; The cooling tower system effectively managed heat removal, demonstrating 91.18% efficiency; and Further optimization could potentially improve ethanol yield and purity, such as implementing a double distillation process.

This research contributes to the development of appropriate technologies for small-scale bioethanol production, supporting efforts to promote sustainable biofuel industries. Future work should focus on enhancing system efficiency, exploring methods to increase ethanol purity, and evaluating economic feasibility for rural implementation. The successful demonstration of cassava-based bioethanol production using locally fabricated equipment provides a foundation for expanding domestic biofuel capabilities in Indonesia. By utilizing abundant agricultural resources like cassava, this approach can contribute to energy security, environmental sustainability, and rural economic development.

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Author Contribution

Conceptualization, M Z. & G.H.; Methodology, M Z. & G.H.; Software, Z. & G.H.; Validation, M Z. & G.H.; Formal Analysis, Z; Investigations, Z.; Resources, Z; Data Curation, , I.H.; Writing – Original Draft Preparation, Z. & G.H.; Writing – Review & Editing, M Z. & G.H.;.; Visualization, M.B.R.P.

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