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DESIGN OF INTEGRATED DISTILLATION-DEHYDRATION PROTOTYPE FOR BIOETHANOL WITH FLEXIBLE COLUMN AND CAPILLARY CONDENSER

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Abstract. The production of high-purity bioethanol remains a challenge, particularly when the feedstock originates from traditional fermentation processes such as *cap tikus*. This study presents an integrated distillation–dehydration prototype that enables simultaneous vapor separation and moisture removal within a single columnn – an innovation that combines a flexible dual-layer adsorbent chamber and a capillary-type condenser tio improve mass and heat transfer performance. The prototype consists of three main components: a boiler with a diameter and height of 500 mm, a distillation–dehydration column with a diameter of 101.6 mm and a height of 1000 mm designed for flexibility to accommodate various adsorbents, and a shell-and-tube condenser 1200 mm long equipped with 19 capillary tubes of 8 mm diameter. Heat is supplied by a "1000-eye" gas burner that ensures uniform thermal distribution at the boiler base. Preliminary testing with 10.8 L of *cap tikus* (25% alcohol) produced 94 mL of distillate in 3 hours, with a stable of 5 °C temperature gradient along the column. The resulting distillate reached alcohol 87% purity, demonstrating the capability of the integrated system to enhance dehydration performance. Despite performance limitations caused by heat losses in the boiler and vapor-flow resistance witihn the zeolite-packed column, theprototype shows promising thermal and separation characteristics and is ready for futher optimization to increase distillation rate and energy efficiency.

Keywords: Bioethanol, Capillary Tube Condenser, Distillation-Dehydration, Flexible Column, Prototype Design

1. INTRODUCTION

Indonesia continues to strengthen the development of renewable fuels, including bioethanol, as part of its national energy diversification strategy. Government programs targeting E5–E10 gasoline blends indicate a growing demand for fuel-grade ethanol, yet national production capacity remains limited due to constraints in technology readiness and feedstock availability [1]-[5]. Traditional fermentation products such as *cap tikus* represent a potential local ethanol source; however, they typically contain only 20–38% ethanol before purification, with some samples reported at below 25% [6]-[8]. These concentrations are far from the >95% purity required for fuel applications, indicating the need for effective purification technologies suited to decentralized or small-scale processing contexts. Conventional distillation is widely used to increase ethanol concentration, but thermodynamic limitations prevent separation beyond the azeotropic point (~90-95%), making an additional dehydration step essential [3]. Adsorptive dehydration using zeolite (particularly zeolite 3A) has been shown to efficiently remove residual water from ethanol due to its highly selective pore structure [9]-[12]. Recent reviews emphasize that adsorption remains one of the most effective pathways for producing fuel-grade ethanol, and new advancements continue to strengthen its role in integrated separation systems [4], [5]. Despite this, most studies treat distillation and adsorption as separate units, requiring multiple stages and introducing additional thermal losses.

To address these inefficiencies, integrated distillation-adsorption systems have been proposed, offering reductions in equipment count, energy consumption, and heat loss by combining vapor generation and dehydration within the same column [13], [14]. However, such integrated configurations remain underexplored, particularly for local feedstocks such as *cap tikus*, and few studies have evaluated column temperature gradients, vapor–adsorbent mass-transfer behavior, or distillation efficiency under practical operating conditions. Previous work on single-column reflux distillation for *cap tikus* achieved ethanol purities of only ~96-96.5% without a dehydration unit [8], indicating the need to incorporate an adsorptive medium directly within the column. Furthermore, optimization of column configuration, zeolite density, and operating temperature has been shown to significantly influence the achievable bioethanol purity in integrated systems [12]. Despite this, the application of simultaneous distillation-dehydration to traditional fermentation feedstocks like *cap tikus* remains rarely reported, particularly with respect to yield performance, final purity, and energy consumption [15].

Another key design consideration relates to the heating system. While many laboratory-scale distillation studies rely on electric heaters or industrial thermal systems, LPG-based gas burners offer practical advantages for small-scale and rural applications, including lower operating costs, rapid heating response, and easier temperature control [16]-[18]. Nevertheless, their effectiveness depends strongly on boiler geometry, heat distribution, and thermal insulation, all of which influence vapor formation and stability. Studies on small-scale distillation columns further indicate that thermal boundary conditions and wall heat losses can significantly impact separation performance, potentially reducing vapor flow rate and adsorption effectiveness when not properly managed [7]. Based on these gaps, this study focuses on the design and construction of a laboratory-scale integrated distillation-dehydration system equipped with a flexible dual-layer adsorbent chamber and a capillary-type condenser. The measurable objectives of this research are: (1) to design a practical, low-cost prototype capable of increasing ethanol purity from low-concentration feedstock such as *cap tikus* through a single-column distillation–adsorption mechanism; and (2) to evaluate its preliminary performance, including distillate purity, temperature profile behavior, and distillation rate under gas-fired operation. This prototype is expected to serve as a foundation for optimizing integrated separation systems and supporting the development of decentralized bioethanol production technologies in Indonesia.

2. METHODS

This study was carried out through four main stages: design specification, instrument identification, prototype fabrication, and preliminary performance testing. The overall research flow is shown in Figure 1. Functional criteria were established to ensure that each subsystem (boiler, column, condenser) performed within its expected operational limits before the prototype was evaluated. These criteria included: (i) steady steam flow from the boiler to the column without leaks; (ii) the condenser outlet temperature was maintained below 30 ºC; (iii) no leaks at any connections; (iv) cooling water flowed through each capillary tube gap without leaks entering the tube; and (iv) initial distillate was produced within a reasonable heating time (<40 minutes). If one or more of these criteria were not met, the fabrication phase was repeated to correct the identified issues.

2.1 Materials and Tools

The essential materials and tools used for developing the prototype are summarized in Table 1. The table presents only essential components of the integrated distillation–dehydration prototype, including the main structural elements, measurement instruments, heating and cooling systems, and fabrication tools. Listing these items with their key specifications provides a clear overview of the physical resources required for prototype construction and ensures replicability for future studies.

Table 1. Materials and Tools

Category	Item/Instrument	Key Specifications
Main Components	Stainless steel boiler	Ø 500 mm; height 500 mm; SS 304; conical top
	Distillation–dehydration column	Ø 101.6 mm; height 1000 mm; SS 304; two adsorbent chambers
	Capillary condenser	Shell Ø 101.6 mm; length 1200 mm; 19 tubes (Ø 8 mm); SS 304
	Support frame	HSS iron; welded
Adsorbent	Zeolite 4A	Granular; 100 g x 2 layers
Heating System	LPG “1000-eye” burner	Multi-flame; adjustable valve
Cooling System	Water tank + hoses	150 L; ambient cooling
	Water pump	DB-125; max. capacity: 27 L/minute; suction height: 8 m
Measurements	Thermometer (T1, T2)	WIPRO Bimetal Thermometer; Range 0-100 ºC; Ø 76.2 mm

Category	Item/Instrument	Key Specifications
	Alcoholmeter	Allafrance Alcoholmeter; 0-100%; accuracy ±2; calibration temperature: 20 °C
	Distillate container	Erlenmeyer Pyrex; 1000 mL
	Stopwatch	Smartphone timer
	Pressure gauge	0-350 psi (0-25 bar)
Fabrication Tools	SMAW welding machine	For frame and component welding
	Grinder, drill, cutter	Metal fabrication tools

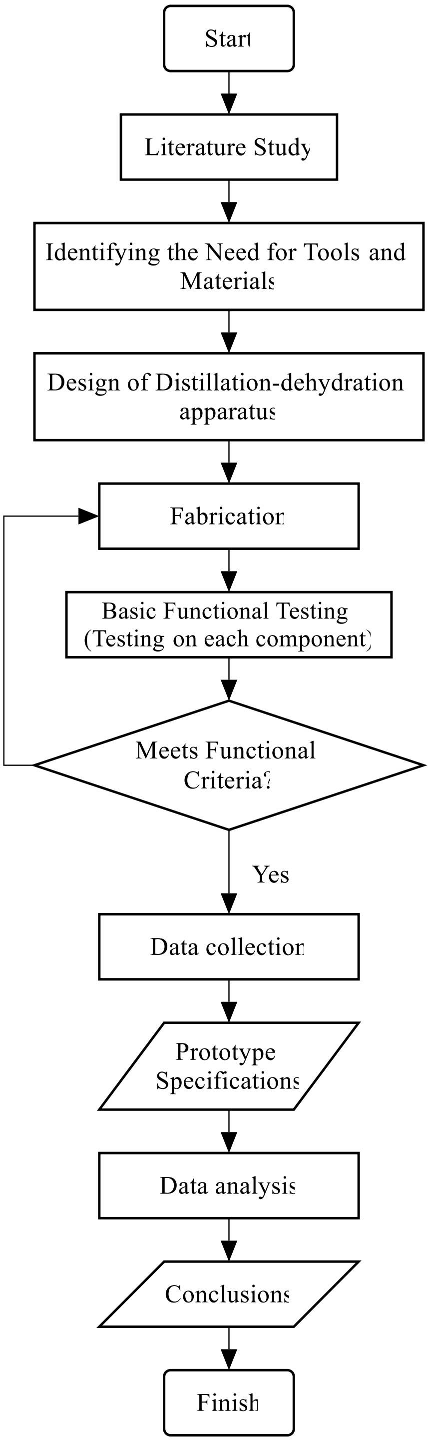


Figure 1. Research flowchart

2.2 Design of Distillation-Dehydration System

The conceptual and dimensional design of the apparatus was developed using Microsoft PowerPoint 2024, which served as a 2D schematic drafting tool for generating scaled engineering layouts. Although PowerPoint is not a conventional CAD platform, it enables precise manipulation of geometric elements, allowing all principal dimensions – such as boiler diameter, column height, condenser length, and capillary-tube arrangement – to be defined manually based on predetermined measurements. As the objective of this study was prototype construction rather than computational simulation or tolerance-critical machining, the schematic-based approach was sufficient to represent the structural configuration and spatial relationships among components. The final prototype dimensions were validated during assembly, confirming that the drafting method adequately supported the accuracy required for the development of a functional laboratory-scale distillation–dehydration system.

2.3 Fabrication

The distillation-dehydration apparatus was fabricated at the Welding Laboratory of the Agricultural Machinery and Equipment Study Program, Politeknik Gorontalo. The fabrication process included the construction of the boiler, column, and condenser installation using stainless steel welding techniques. Fittings, valves, and connectors were installed to ensure the system's operational flexibility and ease of maintenance. Before operation, a functional test was conducted on each component, particularly the boiler, distillation-dehydration column, condenser, and cooling water circulation system. This test aimed to check for leaks in these components and ensure there was no steam/water loss at the connections.

2.4 Determination of Distillation-Dehydration Equipment Specifications

The specifications of the distillation–dehydration apparatus were determined by analyzing process requirements related to target ethanol purity, batch feed capacity, and thermal efficiency. Literature data and basic thermodynamic estimations were used to define the necessary boiler volume, column dimensions, and condenser heat-transfer area. Material selection and structural flexibility were prioritized to ensure compatibility with multiple adsorbents and repeated laboratory use. The column was therefore designed with removable adsorbent compartments to support testing under different dehydration configurations. Overall, the resulting specifications were formulated to produce an efficient and adaptable system suitable for processing ethanol from traditional fermentation feedstocks.

2.5 Operating Parameters

The operating parameters applied during the initial performance test of the prototype are presented in Table 2. These parameters describe the thermodynamic conditions, feed characteristics, adsorbent configuration, and output variables measured during a 3-hour distillation–dehydration run. The summarized values provide a quantitative basis for assessing the system’s functional behavior and identifying factors influencing vapor generation, mass transfer, and distillate yield.

Table 2. Operating Parameters of Distillation-Dehydration System

Parameter	Value/Condition
Feed volume	10.8 L *cap tikus*
Initial alcohol content	25% v/v
Heating source	LPG “1000-eye burner”
Average boiler temperature	78-80 ºC
Column temperatures	T1 ≈ 80 ºC; T2 < T1
Cooling-water temperature	< 30 ºC
Adsorbent mass	100 g x 2 layers (Zeolite 4A)
Time opeartion	180 minutes

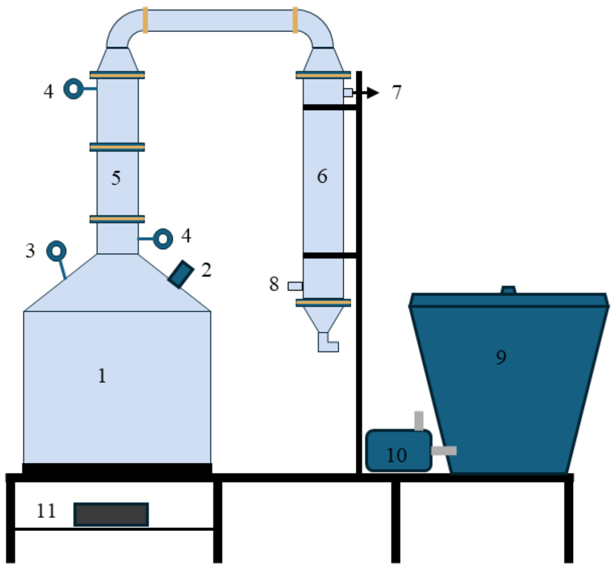
2.6 Data Analysis Technique

The analysis of experimental data in this study was carried out through a structured procedure encompassing data processing, performance evaluation, and measurement validation. Temperature data recorded at the lower (T1) and upper (T2) sections of the column were collected at 5-minute intervals and subsequently plotted as time–temperature profiles to observe heating dynamics, thermal stabilization, and column temperature gradients throughout the distillation–dehydration process. Distillate production was monitored by measuring the cumulative volume collected during the 3-hour operation, enabling calculation of the distillation rate in mL/h. The ethanol concentration of the distillate was determined using a calibrated alcoholmeter to quantify purification effectiveness.

3. RESULTS AND DISCUSSION

3.1 Bioethanol Distillation-Dehydration Equipment Specifications

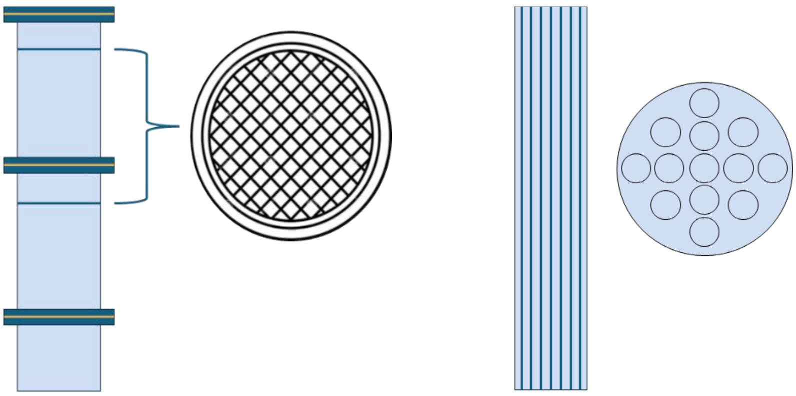
The design of the tool is carried out by determining the functional specifications of the distillation-dehydration tool equipped with several components as presented in Figure 2. The bioethanol distillation-dehydration tool series consists of: (1) a boiler tube that functions as a heating place for the cap tikus feed to produce ethanol vapor, (2) a feed input pipe to enter liquid raw materials, (3) a manometer to monitor the pressure in the boiler, (4) a thermometer to measure the operating temperature, (5) a distillation-dehydration column filled with zeolite 3A as an adsorbent, (6) a condenser to cool the vapor into a liquid distillate, (7 and 8) circulating water that enters and exits through the condenser for the condensation process, (9) a water reservoir as a source of coolant circulation, (10) a water pump to maintain a continuous flow of coolant circulation, and (11) a gas stove as the main heat source. This design allows the distillation and dehydration processes to take place simultaneously, so that the system is simpler in increasing the ethanol content in the raw materials. Among these components, the distillation-dehydration column and condenser are very important components in increasing the ethanol content.



Information:
1. Boiler tube
2. Feed/raw material input
3. Manometer
4. Thermometer
5. Distillation-dehydration column
6. Condenser
7. Water outlet pipe
8. Water inlet pipe
9. Water reservoir
10. Water pump
11. Gas stove

Figure 2. Design of bioethanol distillation-dehydration equipment

The distillation-dehydration column is designed in a vertical cylindrical shape equipped with an internal chamber to accommodate the adsorbent material (Figure 3(a)). The placement of the adsorbent in this column aims to improve the separation process, especially in the ethanol dehydration stage, by utilizing the selective properties of the adsorbent material towards water molecules. The condenser is designed with a double pipe system (shell and tube) consisting of a number of small pipes on the inside and one large pipe as the outer sheath (Figure 3(b)). The small pipes function as a flow path for the distilled ethanol vapor which then undergoes a cooling process so that it condenses into a liquid phase. Meanwhile, cooling water flows through the large pipe on the outside, filling the gaps around the small pipes, so that heat transfer occurs efficiently. The working principle of this condenser is based on the forced convection mechanism of the cooling water flow and heat conduction through the pipe walls, which results in a decrease in the temperature of the ethanol vapor to its condensation point.



(a) (b)

Figure 3. Main component design: (a) distillation-dehydration column and (b) condenser

A bioethanol distillation-dehydration equipment has been successfully designed and fabricated with the primary goal of producing high-purity ethanol. The design integrates the distillation and dehydration processes in a single column, reducing the need for additional equipment while minimizing heat loss. The apparatus's working principle is based on heating the raw material, cap tikus, which has a relatively high ethanol content. Evaporation and separation of the ethanol-water mixture occur in a column containing 4A zeolite adsorbent, and recondensation of the ethanol vapor occurs through a water-cooled condenser. The apparatus's configuration is compact, utilizing a metal support frame for stability and ease of operation on a laboratory scale. The design of the distillation-dehydration apparatus can be seen in Figure 4. The energy source used to heat the raw material is a gas stove.

The bioethanol distillation-dehydration tool designed in this research consists of several main components with the following technical specifications:

1. Main/Support frame
   This frame (Figure 4) serves as a base for the boiler, motor, and reservoir, as well as a condenser support. The main frame measures 1750x520 mm, with a height of 300 mm from the bottom of the boiler base. The lower part of the main frame is made of angle iron, while the condenser support is made of hollow iron coated with anti-rust paint for increased durability.
2. Boiler
   The vertical cylindrical boiler (Figure 5) is made of 304 grade stainless steel with a plate thickness of 2 mm. This material was chosen for its resistance to corrosion and chemical reactions with ethanol. This boiler has a diameter of 500 mm and a height of 500 mm, thus the boiler can hold a maximum liquid material capacity of 98.125 L. The boiler is equipped with a feed inlet for entering liquid raw materials (mouse cap), as well as a steam outlet connected to the distillation column and the distillation residue outlet.
3. Distillation-dehydration column
   The column is a vertical cylindrical tube (Figure 6(a)) made of 304 stainless steel with a diameter of 101.6 mm and a height of 1000 mm. The inside of the column is equipped with a filling chamber of 3 mm particle size zeolite 3A adsorbent, with a maximum filling capacity of 500 grams for each section. This column is designed to be able to perform two functions simultaneously, namely distillation to separate ethanol from water based on boiling point, and dehydration to absorb water molecules using zeolite. The column structure consists of several segments that can be removed to facilitate filling and replacing the adsorbent. This design also allows the flexibility of using various types of adsorbent materials, such as zeolite or porous geopolymer, according to research needs. The steam flow will come into direct contact with the adsorbent layer so that the water content in the ethanol can be reduced, producing ethanol with a higher purity. With this design, the column not only functions as a separation medium based on boiling point, but also integrates an adsorption mechanism as a dehydration stage.

Figure 4. Design results of bioethanol distillation-dehydration equipment

Figure 5. Boiler design

4. Condenser
   The condenser (Figure 6(b)) is designed using a shell and tube type design with a total length of 1200 mm and an outer diameter of 101.6 mm. There are 19 stainless steel pipes on the inside with a diameter of 10 mm each, where the ethanol vapor is flowed and then condensed. Cooling water is flowed in the opposite direction (counter-current flow) through the outer space of the pipe which is circulated by a water pump. The multi-pipe design on the inside allows for an increase in the heat transfer surface area, so that the condensation efficiency becomes more optimal [19]-[21]. This is because it allows an increase in the heat transfer surface area, so that condensation is more effective, thermal resistance is reduced, and the operating temperature is stable [22]. With this design, the ethanol vapor coming out of the distillation column can be condensed quickly and stably, producing ethanol liquid with a purity that meets the target dehydration process.
5. Water reservoir tank
   The tank, made of polyethylene (PE) (Figure 7), has a total volume of 150 L and serves as a reservoir for cooling water that is circulated to the condenser. Water from this reservoir is circulated to the condenser using a water pump with a maximum capacity of 27 L/minute and 200 Watts of electrical power.

(a) (b)

Figure 6. Component design: (a) distillation-dehydration column and (b) condenser

Figure 7. Water tank and pump

6. Heat source
   The heat used for evaporation of the raw materials is a gas stove with a "1000 eye" stove specification (Figure 8). The use of the "1000 eye" type gas stove was chosen as the main heat source for the 50 cm diameter boiler because it is able to produce an even flame distribution across the entire surface of the tube base. The multi-burner design of this stove allows heat to be distributed homogeneously, thereby minimizing temperature gradients and speeding up the heating process. With a relatively high combustion power, this type of gas stove is suitable for large-capacity boilers that require significant thermal energy to evaporate the fermentation solution.

Figure 8. Stove “1000 eyes”

In addition to heat distribution, the use of a gas stove offers advantages in terms of operational flexibility and energy costs. This system does not require a high-power electrical installation like resistive heaters, and is easier to operate in both laboratory and field conditions. Heat transfer efficiency can be increased by adjusting the distance between the flame and the boiler base, allowing for more controlled gas consumption without reducing the distillation rate. Therefore, the "1000-eye" gas stove is a practical and economical alternative for heating in the design of bioethanol distillation-dehydration equipment.

3.2 Discussion

Design and Construction of the Bioethanol Distillation–Dehydration System

The bioethanol distillation-dehydration apparatus is designed with special designs for several main components, such as the distillation-dehydration column and condenser. The designed distillation-dehydration column has a length of 1000 mm and a diameter of 101.6 cm so that it provides an adequate height-to-diameter (H/D) ratio for vapor-liquid phase separation and adsorptive interactions in the vapor-upflow. Modern packed bed design studies have shown that column geometry (H/D) and filling distribution have a significant effect on the pressure drop and contact profile between the gas and solid phases, which in turn determine the mass transfer efficiency in adsorptive/distillative applications [23], [24]. Zeolite is a superior adsorbent in separation technology because its microporous structure allows high selectivity towards water molecules in ethanol-water mixtures. Recent studies have confirmed that optimizing the use of zeolites can replace conventional energy-intensive separation methods, making them more sustainable [25]. Therefore, this column is designed with two adsorbent holding chambers (one at the bottom and one at the top) to avoid the accumulation of adsorbent mass at one point and to maintain the porosity distribution along the bed, thereby reducing the risk of channeling and unwanted vapor flow reduction [26]. Thus, this design can expand the vapor-adsorbent contact so that the dehydration efficiency is increased according to the principle of zeolite-based separation optimization.

On the other hand, the dimensions and position of the distillation-dehydration column structure play a role in the evaporation mechanism and vapor contact with the adsorbent. Research on scaling up adsorption columns [27] shows that column dimensions, especially diameter and height, affect the saturation time, residence time, and volume of solution that can be processed, while the adsorption capacity remains relatively constant. This is in line with the design of the distillation-dehydration column in this study, where the vertical configuration was chosen to maximize the contact between the ethanol-water vapor and the zeolite layer. Meanwhile, a modeling study of a gas adsorption column [28] confirmed that the adsorption dynamics can be accurately predicted using a 1-D pseudo-homogeneous approach, which is also relevant to analyzing the adsorption behavior of ethanol vapor in a vertical column. Thus, the design of the distillation-dehydration column used is not only supported by empirical considerations, but also in accordance with theoretical approaches in the literature.

Another key component that plays a significant role in this system is the condenser. The condenser design in this study has an outer diameter of 10.16 cm and a length of 120 cm, with 19 capillary tubes of 0.8 cm diameter inside, providing an internal heat transfer surface area of approximately 0.57 m2 from the capillary tubes alone. This capillary structure increases the internal heat transfer coefficient by reducing the condensate film thickness and increasing the turbulence of the vapor flow relative to the tube surface, resulting in a faster and more efficient condensation process. Previous research related to shell-and-tube condensers has shown that increasing the number of tubes and reducing the tube diameter can significantly increase the heat transfer rate and condensation effectiveness [29]. In addition, long vertical condenser tubes with optimized surface structures result in an increase in the condensation coefficient of up to 20-60% compared to similar plain tubes [30]. With this configuration, the condenser design in the bioethanol distillation-dehydration apparatus is expected to produce a more stable condensate product and prevent vapor from escaping without being adequately condensed.

Preliminary Performance Evaluation and Analysis of Factors Affecting Process Efficiency

Based on the preliminary testing results, a total of 10,800 mL of Cap Tikus (alcohol 25% v/v) was introduced into the boiler, and the corresponding data are presented in Figure 9. The figure of experimental results shows the variation of temperatures at the lower (T1) and upper (T2) parts of the column throughout the distillation–dehydration process, with data recorded at 5-minute intervals. During the initial phase (0-34 minutes), both T1 and T2 gradually increased toward the boiling point of ethanol, as indicated by the appearance of the first distillate droplet at 34 minutes. Once the system reached the operational phase (≥ 40 minutes), T1 stabilized at approximately 86 ºC and T2 at around 81 ºC, with an average temperature difference of about 5 ºC. This condition indicates the formation of a consistent temperature gradient within the column, which is essential for effective vapor separation and adsorption. Nevertheless, the total distillate volume obtained after 3 hours of heating was only 94 mL, indicating limited heat and mass transfer efficiency within the system that requires further optimization.

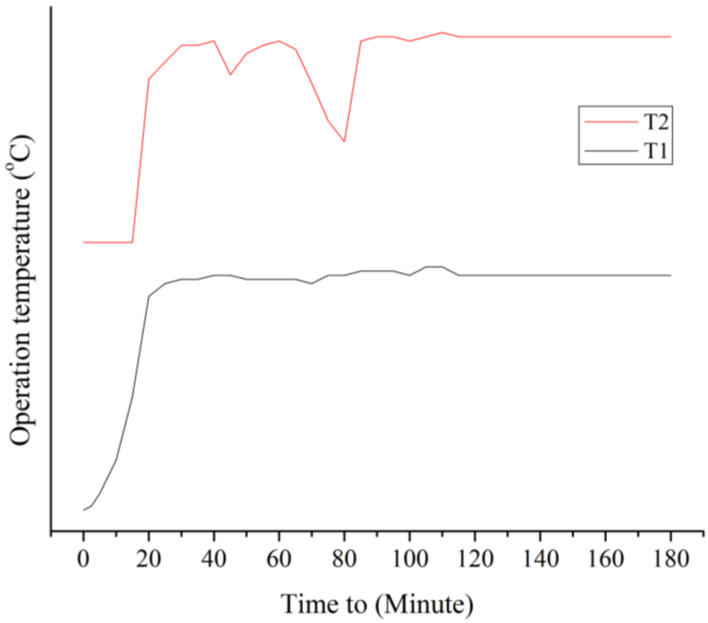


Figure 9. Time versus temperature of distillation-dehydration process

The flow of ethanol vapor from the boiler to the condenser required approximately 15 minutes from the onset of boiling (t = 00:20:00, T1 = 81 °C, and T2 = 71 °C) until the vapor condensed into liquid distillate at 34 minutes. The total distillate collected over 3 hours was 94 mL, equivalent to 31.3 mL/h (or approximately 38.7 mL/h when calculated from the first drop), indicating a relatively low effective vapor rate compared to the feed volume. While the condenser temperature was maintained low and stable at 26 °C, the main limitation is presumed to lie in heat transfer within the boiler, including losses by conduction, convection, and radiation due to insufficient insulation and non-uniform flame distribution. Previous studies have reported that vapor flow resistance in packed columns increases with higher adsorbent density and uneven flow distribution, leading to reduced vapor velocity and product throughput [31,32]. Moreover, thermal conditions of the column wall significantly influence separation performance, as heat losses may trigger premature condensation and internal reflux, hindering vapor transport toward the condenser [33]. This phenomenon is consistent with the experimental findings showing a temperature gradient of about 5 °C between the lower and upper sections of the column, indicating that mass transfer occurred but was not yet optimal. Furthermore, column performance simulations have demonstrated that non-idealities arising from mass transfer resistance must be considered in design and analysis, as they directly affect separation efficiency and temperature distribution along the column [34].

The distillation–dehydration column design with a total height of 1000 mm in this study provides a sufficient residence time for ethanol vapor to interact with the adsorbent layers. However, the total height of the zeolite bed, approximately 30 mm (3 cm), remains relatively low, thereby limiting the adsorption capacity and accelerating the occurrence of breakthrough. Several studies have shown that increasing the bed height to 4-5 cm can significantly extend the breakthrough time and enhance adsorption capacity, although this must be balanced with an appropriate control of the vapor flow rate to prevent excessive flow resistance [35-37]. Furthermore, both the vapor flow rate and initial vapor concentration play important roles, as higher values tend to accelerate adsorbent saturation due to shorter contact times and increased mass loading [38].

Another critical aspect influencing the quantity of bioethanol produced is the headspace ratio within the boiler. A low liquid filling ratio leads to a significant portion of the thermal energy being dissipated to heat the gas in the upper space, thereby reducing heat transfer efficiency and delaying the establishment of stable vapor formation. The overall thermal system efficiency increases only up to an optimum point before declining due to ineffective heat distribution [39]. In addition, experimental results have shown substantial heat loss in columns with a high surface-area-to-volume ratio, which reduces the actual vapor load [40]. A large headspace volume also tends to produce non-uniform vapor flow patterns and increases the likelihood of internal condensation along the column wall or within the adsorbent bed, causing part of the vapor to revert to liquid before reaching the condenser [41,42]. These conditions necessitate an optimal headspace ratio to balance heat transfer efficiency to the liquid phase and vapor expansion space, thereby improving the evaporation rate. Therefore, in the preliminary test case (boiler filled at approximately 10.8% of its total volume), the low product volume (94 mL over 3 hours) indicates heat losses and vapor formation inefficiency resulting from the excessive headspace. Determining the optimal headspace ratio is thus essential to maintain thermal efficiency, vapor flow stability, and high bioethanol productivity. Design improvements through increasing the liquid filling ratio, enhancing boiler insulation, and optimizing adsorbent configuration in the column are expected to improve the distillation rate and separation efficiency. Consequently, the overall performance of the distillation–dehydration system can be significantly enhanced through integrated control of thermal, hydrodynamic, and mass transfer characteristics.

Design improvements through increasing the liquid filling ratio, enhancing boiler insulation, and optimizing adsorbent configuration in the column are expected to improve the distillation rate and separation efficiency. Consequently, the overall performance of the distillation–dehydration system can be significantly enhanced through integrated control of thermal, hydrodynamic, and mass-transfer characteristics. In this study, despite the limited vapor production, the distillation–dehydration process successfully increased the ethanol concentration of cap tikus from 25% to 87%, demonstrating that the prototype is capable of achieving substantial purification even under suboptimal operating conditions.

4. CONCLUSION

A bioethanol distillation–dehydration prototype integrating both separation stages within a single column has been successfully designed and fabricated. The system consists of a 500 mm x 500 mm stainless-steel boiler, a 1000 mm x 101.6 mm distillation–dehydration column with flexible adsorbent compartments, and a 1200 mm capillary-type condenser containing 19 tubes of 8 mm diameter. The "1000-eye" LPG burner provided uniform thermal distribution necessary for stable vapor generation. Preliminary testing using 10.8 L of cap tikus produced 94 mL of distillate over 3 hours, with a consistent column temperature gradient of approximately 5 °C. Despite the low yield, the system successfully increased ethanol concentration from 25% to 87%, demonstrating that the integrated column effectively enhances dehydration performance even under non-optimal heating conditions. The observed limitations indicate the need for improvements in boiler insulation, liquid filling ratio, and adsorbent configuration to enhance vapor generation and separation efficiency. Overall, the prototype shows strong potential for further optimization and serves as a foundational platform for subsequent performance validation and scale-up studies in local bioethanol production.

5. ACKNOWLEDGEMENT

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6. REFERENCES

[1] Admin, "Indonesia plans to launch 5% bioethanol mix of fuel in three years", 7 Dec. 2022. [Online]. Available: https://www.astra-agro.co.id/2022/12/07/indonesia-plans-to-launch-5-bioethanol-mix-of-fuel-in-three-years/. [Accessed: 7 Jul. 2025].

[2] Enerdata, "Indonesia starts selling gasoline with 5% bioethanol", 6 Jul. 2023. [Online]. Available: https://www.enerdata.net/publications/daily-energy-news/indonesia-starts-selling-gasoline-5-bioethanol.html. [Accessed: 7 Jul. 2025].

[3] Ibai, "Indonesia to target 10 bioethanol blend in fuel by 2030", 11 Sep. 2024. [Online]. Available: https://www.ibai.or.id/news/item/6002-indonesia-to-target-10-bioethanol-blend-in-fuel-by-2030.html/. [Accessed: 7 Jul. 2025].

[4] F. Nangoy dan B. Christina, "Analysis-Indonesia faces ethanol feedstock hurdle to repeat biodiesel success", 6 Apr. 2023. [Online]. Available: https://theprint.in/environment/analysis-indonesia-faces-ethanol-feedstock-hurdle-to-repeat-biodiesel-success/1500955/. [Accessed: 7 Jul. 2025].

[5] J. Isaac, "Aprobi urges regulatory clarity as Indonesia targets 500 bioethanol plants", 24 Apr. 2025. [Online]. Available: https://indonesiabusinesspost.com/4167/policy-and-governance/aprobi-urges-regulatory-clarity-as-indonesia-targets-500-bioethanol-plants/. [Accessed: 7 Jul. 2025].

[6] L. V. Lintong, D. Deeng dan W. E. Mamosey, "Perubahan Nilai Budaya Masyarakat Cap Tikus di desa Talaitad Utara Kecamatan Suluun Tareran Kabupaten Minahasa Selatan," *Jurnal Holistik,* vol. 15, no. 4, pp. 1-16, 2022.

[7] N. F. Tambayong, O. E. H. Laoh dan O. Porajow, "Analisis Usaha Cap Tikus di Desa Poopo Kecamatan Passi Timur Kabupaten Bolaang Mongondow," *Agr-sosioekonomi,* vol. 12, no. 2, pp. 77-86, 2016.

[8] F. Wenur dan Y. Waromi, "Studi Pengolahan Bioetanol Tradisional dari Nira Aren di Minahasa Selatan," *Jurnal Teknologi Pertanian,* vol. 8, no. 2, pp. 1-7, 2017.

[9] M. Subandriyo dan F. A. Putri, "The effect of various zeolites as an adsorbent for bioethanol purification using a fixed bed adsorption column," *International Journal of Technology,* vol. 11, no. 7, pp. 1300-1308, 2020.

[10] Khaidir, D. Setyaningsih dan H. Haerudin, "Modifikasi Zeolit Alat sebagai Material Molekular Sieve pada Proses Dehidrasi Bioetanol," *Jurnal Zeolit Indonesia,* vol. 8, no. 2, pp. 97-105, 2009.

[11] S. B. Ginting dan J. Kristian, "Ethanol Dehydration in Fixed Bed Column Using Pellet Adsorbent from Lampung Natural Zeolite," *Jurnal Rekayasa Kimia dan Lingkungan,* vol. 17, no. 1, pp. 53-63, 2022.

[12] H. Hargono, N. A. Handayani, S. D. Andani, E. Wardani, U. A. Fisama dan K. S. Seng, "Adsorption method using zeolite to produce fuel-grade bioethanol," *International Journal of Renewable Energy Development,* vol. 12, no. 4, pp. 808-815, 2023.

[13] A. Rahmanulloh, "Biofuels Annual," Foreign Agricultural Service, United States Department of Agriculture, Jakarta, 2023.

[14] Grains, "Ethanol market profiles – Indonesia", 13 May 2014. [Online]. Available: https://grains.org/bioethanol/ethanol-market-profiles/indonesia/. [Accessed: 7 Jul. 2025].

[15] Y. Sumampouw, H. S. Kolibu dan S. H. J. Tongkukut, "Pembuatan Bioetanol dengan Teknik Destilasi Refluks Satu Kolom," *Jurnal Ilmiah Sains,* vol. 15, no. 2, pp. 154-158, 2015.

[16] E. O'Rear, D. Webb, J. Kneifel dan C. O'Fallon, "Gas vs electric: Heating system fuel source implications on low-energy single-family dwelling sustainability performance," *Journal of Building Engineering,* vol. 25, no. 2019, p. 100779, 2019.

[17] Australian Energyr Upgrades, "Gas vs. Electric: Which Heating System is More Efficient?", 9 Apr. 2024. [Online]. Available: https://australianenergyupgrades.com.au/gas-vs-electric-which-heating-system-is-more-efficient/. [Accessed: 7 Jul. 2025].

[18] A. Brui, "Electric Boiler vs Gas Boiler: Which is Better?", 9 Apr. 2025. [Online]. Available: https://www.greenmatch.co.uk/boilers/compare/types/electric-vs-gas. [Accessed: 7 Jul. 2025].

[19] B. L. Rakshith(a), L. G. Asirvatham, A. A. Angeline, J. A. P. S. Raj, J. R. Bose, P. J. B. Princess, S. Gautam, O. Mahian, G. Ribatski dan S. Wongwises, "Cooling of power electronic devices using rectangular flat heat

pipes with externally and internally cooled condensor," *Applied Thermal Engineering,* vol. 236, no. Part B, p. 121474, 2024.

[20] B. L. Rakshith(b), L. G. Asirvatham, A. A. Angeline, J. P. S. Raj, J. R. Bose dan S. Wongwises, "Experimental investigation on the heat transfer performance of flat heat pipe embedded with internally cooled condensor," *International Journal of Heat and Mass Transfer,* vol. 230, no. 2024, p. 125728, 2024.

[21] P. Dong, G. Wang, W. Yu, E. Liu dan Y. Han, "Investigation on heat transfer performance of flat plate micro-heat pipe phase change heat storage/release device," *Green Energy and Resources,* vol. 2, no. 2, p. 100071, 2024.

[22] J. Jose dan T. K. Hotta, "Thermal performance analysis and optimization of a heat pipe-based electronic thermal management system using experimental data-driven neuro-genetic technique," *Thermal Science and Engineering Progress,* vol. 54, no. 2024, p. 102860, 2024.

[23] V. Jurado-Davila, J. T. De Oliveira, D. Estumano dan L. A. Féris, "Fixed-bed column for phosphate adsorption combining experimental observation, mathematical simulation, and statistics: Classical and Bayesian," *Separation and Purification Technology,* vol. 317, no. 2023, p. 123914, 2023.

[24] V. Stampi-Bombelli dan M. Mazzotti, "Exploring Geometric Properties and Cycle Design in Packed Bed and Monolith Contactors Using Temperature-Vacuum Swing Adsorption Modeling for Direct Air Capture," *Industrial & Engineering Chemistry Research,* vol. 63, no. 2024, pp. 19728-19743, 2024.

[25] E. Pérez-Botella, S. Valencia dan F. Rey, "Zeolites in Adsorption Processes: State of the Art and Future Prospects," *Chemical Reviews,* vol. 122, no. 24, pp. 17647-17695, 2022.

[26] V. Stampi-Bombelli, A. Storione, Q. Grossmann dan M. Mazzotti, "On Comparing Packed Beds and Monoliths for CO2 Capture from Air Through Experiments, Theory, and Modeling," *Industrial & Engineering Chemistry Research,* vol. 63, no. 2024, pp. 11637-11653, 2024.

[27] D. Juela, M. Vera, C. Cruzat, A. Astudillo dan E. Vanegas, "A new approach for scaling up fixed-bed adsorption columns for aqueous systems: A case of antibiotic removal on natural adsorbent," *Process Safety and Environmental Protection,* vol. 159, no. 2022, pp. 953-963, 2022.

[28] F. J. G. Ortiz, M. B. Rodríguez dan R. T. Yang, "Modeling of fixed-bed columns for gas physical adsorption," *Chemical Engineering Journal,* vol. 378, no. 2019, p. 121985, 2019.

[29] Z. Rifaldo, B. Hafid, Z. Husin, E. H. Wijayanto dan M. Idris, "Heat Transfer Analysis in Shell and Tube Type Condenser," *Journal of Mechanical Engineering, Manufactures, Materials and Energy,* vol. 8, no. 1, pp. 67-74, 2024.

[30] Z. Chen, K. Zhang dan N. Wang, "Experimental Investigation of Large-Scale Vertically Coated Tubes for Enhanced Air–Steam Condensation Heat Transfer," *Energies,* vol. 17, no. 4759, pp. 1-15, 2024.

[31] Y. Cao, H. A. Dhahad, A. Khandakar, M. E. H. Chowdury, M. A. Ayari, S. M. Alizadeh dan B. Vaferi, "Employing computational fluid dynamics technique for analyzing the PACK-1300XY with methanol and isopropanol mixture," *Scientific Reports,* vol. 12, no. 6588, pp. 1-11, 2022.

[32] A. Surmi, A. Mohd Shariff dan S. S. M. Lock, "Comprehensive Analysis of Pressure Drop Phenomena in Rotating Packed Bed Distillation: An In-Depth Investigation," *ACS Omega,* vol. 9, no. 26, pp. 28105-28113, 2024.

[33] R. Staud, K. Schroder, K. Mesarek, J. Schroder, R. Herbst, K. Jasch dan S. Scholl, "Impact of thermal column wall conditions and subcooled reflux on separation performance in miniplant distillation columns," *Separation and Purification Technology,* vol. 358, no. 2025, p. 130479, 2025.

[34] H. Poortalari, F. Varaminian dan J. Karimi Sabet, "A packed distillation column performance simulation by modified equilibrium stage model based on multicomponent packing efficiencies," *Progress in Engineering Thermodynamics and Kinetics,* vol. 1, no. 2, pp. 1-19, 2024.

[35] A. S. Kovo, S. Alaya-Ibrahim, A. S. Abdulkareem, O. D. Adeniyi, T. C. Egbosiuba, J. O. Tijani, M. Saheed, B. O. Okafor dan Y. S. Adeyinka, "Column adsorption of biological oxygen demand, chemical oxygen demand and total organic carbon from wastewater by magnetite nanoparticles-zeolite A composite," *Heliyon,* vol. 9, no. 2, p. e13095, 2023.

[36] A. Samanth, R. Vinayagam, T. Varadavenkatesan dan R. Selvaraj, "Fixed bed column adsorption systems to remove 2,4-Dichlorophenoxyacetic acid herbicide from aqueous solutions using magnetic activated carbon," *Environmental Research,* vol. 261, no. 2024, p. 119696, 2024.

[37] L. Meina, M. Qiao, Q. Zhang, S. Xu dan D. Wang, "Study on the dynamic adsorption and recycling of phosphorus by Fe–Mn oxide/mulberry branch biochar composite adsorbent," *Scientific Reports,* vol. 14, no. 1, p. 1235, 2024.

[38] S. E. Marranea, K. Dânoun, Y. Essamlali, S. Aboulhrouz, S. Sair, O. Amadine, I. Jioui, A. Rhihila dan M. Zahouily, "Fixed-bed adsorption of Pb(II) and Cu(II) from multi-metal aqueous systems onto cellulose-g-hydroxyapatite granules: optimization using response surface methodology," *RSC Advances,* vol. 13, no. 2023, pp. 31935-31947, 2023.

[39] B. Shahzamanian, S. Varga, J. Soares, A. I. Palmero-Marrero dan A. C. Oliveira, "Theoretical performance assessment of a multi-effect distillation system integrated with thermal vapour compression unit running on solar energy," *International Journal of Low-Carbon Technologies,* vol. 19, no. 2024, pp. 908-921, 2024.
[40] L. M. Ränger, Y. Waibel dan T. Grützner, "Experimental Investigation of Heat Losses in a Pilot-Scale Multiple Dividing Wall Distillation Column with Three Parallel Sections," *Chemiengineering,* vol. 7, no. 68, pp. 1-16, 2023.
[41] R. Hu, C. Duan dan Y. Lan, "Investigating the Effects of Distillation System, Geographical Origin, and Aging Time on Aroma Characteristics in Brandy Using an Untargeted Metabonomic Approach," *Foods,* vol. 13, no. 1922, pp. 1-15, 2024.
[42] N. M. Tahir, J. Zhang dan M. Armstrong, "Control of Heat-Integrated Distillation Columns: Review, Trends, and Challenges for Future Research," *Processes,* vol. 13, no. 17, pp. 1-33, 2025.