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Design and Development of an Ethanol Dehydrator Prototype Using Zeolite 3Å Molecular Sieves

Raihan Aprila[1]✉, Annisa Dede Azahra[2], Rosalina[3], Regna Tri Jayanti[4]

[1, 2, 3, 4] Department of Chemical Engineering, Politeknik ATI Padang, Padang, Indonesia

✉ **Corresponding Author :** Raihan Aprila (e-mail: raihanaprila03@gmail.com)

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ABSTRACT

Conventional distillation cannot surpass the ethanol-water azeotropic limit (95–96%), necessitating advanced dehydration for fuel grade ethanol (FGE) production per SNI 7390-2012 (≥99.5%). This study designed, fabricated, and evaluated a laboratory-scale ethanol dehydrator prototype featuring a novel 65° inclined horizontal adsorption column filled with 3Å zeolite molecular sieve a configuration not previously reported for ethanol dehydration. Product purity was measured using Gas Chromatography (Shimadzu GC-2010, FID). Under optimal first-run conditions, the system elevated ethanol purity from 96% to 99.79%, successfully meeting the FGE standard. Average vaporizer energy efficiency reached 42.49%, and maximum zeolite adsorption capacity was 0.1277 g water/g zeolite. The 65° inclined column design effectively minimized channeling and outperformed conventional vertical configurations, demonstrating its potential as a practical, low-infrastructure solution for community-scale bioethanol purification.

INTRODUCTION

Indonesia's high dependence on fossil fuels with energy demand reaching 263,690 BOE in 2023 (U.S. Department of Energy, 2025) combined with its Nationally Determined Contribution (NDC) commitments, has driven the rapid development of renewable energy, including bioethanol. Bioethanol produced from fermentation of biomass, including glucose, carbohydrates, and lignocellulose (Jayakumar et al., 2023), typically yields only 5–10% (v/v) ethanol (Kazemi Shariat Panahi et al., 2022), far below the fuel grade ethanol (FGE) standard of ≥99.5% set by SNI 7390-2012 (Saputro et al., 2023). Conventional distillation can only raise ethanol concentration to 95–96%, at which point the ethanol-water mixture reaches its azeotropic equilibrium and further separation becomes impossible (Loy et al., 2015), necessitating an advanced post-distillation purification step (Karimi et al., 2021; Saini et al., 2020).

Vapor-phase adsorption using 3Å zeolite molecular sieve has been established as an effective post-distillation method to overcome the azeotropic barrier. Its uniform 3Å pore size selectively adsorbs water molecules (2.8Å) while excluding ethanol (4.4Å), offering high capacity, thermal stability, and regenerability (Al Ezzi & Ma, 2017; Chaibi et al., 2021). Previous studies have reported FGE-grade purities of 99.40% (Handrian et al., 2018), 99.60% (Susilo et al., 2020), and 99.72% (Winarso & Nugraha, 2015). However, a critical research gap remains: existing systems predominantly employ vertical column configurations susceptible to channeling, or liquid-phase immersion methods that require extended contact times, both limiting throughput and operational continuity. No prior study has investigated a 65° inclined horizontal adsorption column for ethanol dehydration a configuration that exploits gravitational effects to distribute vapor more uniformly across the zeolite bed and prevent liquid accumulation, representing the key novelty of this work.

To address these limitations, this study designs and tests a prototype ethanol dehydrator incorporating a novel 65° inclined horizontal adsorption column. This configuration is intended to minimize channeling, optimize vapor-adsorbent contact, and improve liquid drainage during the process. The system has a 2-liter per batch capacity and employs a REX C-400 PID thermostat for stable temperature control at 80°C. Zeolite quantity was determined from empirically measured adsorption capacity (0.1466 g water/g zeolite), ensuring proportional column dimensions based on actual rather than theoretical performance. Therefore, this study has three specific objectives: (1) to design and fabricate a laboratory-scale ethanol dehydrator prototype with a novel 65° inclined horizontal adsorption column as its key innovation; (2) to evaluate the vaporizer energy efficiency and zeolite adsorption capacity under repeated batch operation and thermal regeneration; and (3) to assess whether the system can achieve SNI 7390-2012 fuel grade ethanol purity (≥99.5%) under laboratory-scale conditions.

RESEARCH METHODS

This research was conducted to design, build, and test a prototype ethanol dehydrator that uses zeolite molecular sieve 3Å as an adsorbent to increase the ethanol content from 96% to at least 99.5% in accordance with the FGE standard (SNI 7390-2012). The research was carried out in two phases: preliminary research to determine zeolite adsorption capacity, and full-scale dehydrator design and performance testing.

Preliminary Research

Prior to designing the device, preliminary research was conducted to determine the adsorption capacity of the zeolite adsorbent. New 3Å zeolite (20 grams) was activated by heating at 220°C for 2 hours in an oven, as activation temperature significantly influences zeolite adsorption capacity (Flores-céspedes et al., 2025), then cooled in a desiccator for 30-45 minutes. A laboratory-scale adsorption column (20 cm length, 2 cm diameter) was filled with 20 grams of activated zeolite. Ethanol vapor (96%, 100 mL) was passed through the column at 78-80°C. Three repetitions were conducted, and adsorption capacity was calculated as the ratio of mass increase of zeolite to initial zeolite mass ($q = \Delta mass / initial\ mass$). The preliminary study yielded an average adsorption capacity of 0.1466 g water/g zeolite (standard deviation = 0.00076 g/g), which served as the basis for calculating zeolite requirements for the full-scale design.

Dehydrator Design

The dehydrator was designed with two main units: a vaporizer column and an adsorber column. The vaporizer column dimensions were calculated based on a 2-liter working volume with a 20% safety factor, using the formula $V = (\pi/4)D^2L + (11/12)D^3$ with a height-to-diameter ratio of $L = 3D$. The column is made of 304 stainless steel (diameter 10.2 cm, height 30 cm) and equipped with a 400-watt tubular heater controlled by a REX C-400 thermostat (type K thermocouple) maintaining 80°C ± 1°C.

The adsorber column was designed as an innovative horizontal configuration with a 65° inclination. Zeolite requirement was calculated as: mass zeolite = mass of water in sample / adsorption capacity = 80 g / 0.1466 g/g = 1023 g (for 1.5 L of 96% ethanol feed). Column dimensions were determined using $V = (1/4)\pi D^2H$ with a 10% safety factor and $L = 4D$ ratio, resulting in a horizontal adsorber column made of SS 304 (diameter 7.6 cm, length 35 cm) filled with 1023 grams of 3Å zeolite molecular sieve at a 65° angle.

Materials and Procedure

The material used was commercial ethanol with a concentration of 96%. The zeolite molecular sieve 3Å used was synthetic zeolite with a uniform pore size of 3 Angstroms, activated by heating at 220°C for 2–3 hours, following standard activation procedures for synthetic zeolite molecular sieves (Zha et al., 2024). Testing was conducted with 1.5 liters of 96% ethanol feed per batch. The vaporizer was heated to 80°C using automatic PID control, and ethanol vapor was directed to the adsorber column. Three experimental batches were conducted, each consisting of three consecutive runs without zeolite regeneration between runs (9 runs total). Zeolite regeneration between batches was performed at 220°C for 2 hours in an oven.

Measurement Techniques

The ethanol content before and after dehydration was measured using Gas Chromatography (Shimadzu GC-2010) with a direct injection method using a Hydrogen Flame Ionization Detector (FID). Operating parameters including temperature, pressure, and heating power were recorded periodically. Zeolite adsorption capacity was calculated from the mass difference before and after adsorption. Vaporizer energy efficiency was determined as the ratio of theoretical energy needed for ethanol evaporation to the actual electrical energy consumed (400 W × 1 hour = 400 Wh). Theoretical energy includes sensible heat (heating from 28°C to 80°C) and latent heat of evaporation.

RESULTS AND DISCUSSION

The prototype ethanol dehydrator was successfully designed and constructed in compliance with the calculated specifications. The integrated system comprising a vaporizer column and a novel 65° inclined horizontal adsorption column, both fabricated from 304 stainless steel operates on a vaporization-adsorption principle: liquid ethanol feed is first vaporized, then directed through a 3Å zeolite bed that selectively adsorbs water molecules (2.8Å) while excluding ethanol (4.4Å), effectively breaking the azeotropic equilibrium.

Vaporizer Column Specifications

The vaporizer column specifications are summarized in Table 1. The actual internal volume of 2.45 L closely matches the target of 2.4 L, with the 0.45 L headspace serving as a vapor-liquid disengagement zone a critical design feature that prevents liquid entrainment into the adsorption column. The 400 W U-shaped tubular heater is paired with a REX C-400 PID thermostat (type K thermocouple) to maintain 80°C ± 0.5°C; however, partial submersion of the heater during operation reduces effective heat transfer, which is the primary contributor to the observed sub-50% energy efficiency discussed in Section 3.3. System pressure is monitored by a 0–2.5 bar gauge, while a 1″ SS ball valve regulates vapor flow to the adsorption column and a ½″ stop valve drains liquid residue after each run.

Table 1. Vaporizer Column Specifications

Parameter	Specification	Consideration
Material	SS 304	Corrosion resistant, stable at high temperature
Type	Vertical cylinder	Facilitates vapor-liquid separation
Diameter	10.2 cm	Calculated based on target volume and height ratio
Height	30 cm	Based on cylinder volume formula with 20% safety factor
Total Volume	2.45 L	Actual cylinder volume
Working Volume	2 L	Feed capacity per batch
Heater	Tubular heater 400 W	U-shaped for maximum heat transfer surface area
Temp. Control	Thermocouple type K & REX C-400	PID control, maintains 80°C ± 0.5°C
Pressure Gauge	0–2.5 bar	Safety monitoring during operation
Control Valve	Ball Valve 1" (SS 304)	Regulate vapor flow to adsorption column

Adsorber Column Specifications

The adsorber column specifications are presented in Table 2. The central innovation of this study is the 65° inclined horizontal configuration, selected on the basis of fluid dynamics principles: the inclination allows gravity to drain condensate toward the outlet while preventing liquid pooling within the zeolite bed a common failure mode in conventional vertical columns (Handrian et al., 2018). The 1023 g zeolite loading (bulk density 0.75 g/cm³) occupies approximately 86% of the internal volume, leaving 14% free space at each end as vapor distribution chambers. A 20-mesh SS screen at each end retains the 3–5 mm zeolite pellets and ensures uniform vapor distribution across the full bed cross-section. Critically, this inclined downward-flow design forces vapor to traverse the entire bed length before exiting, maximizing contact time. In contrast to vertical fixed-bed designs (Handrian et al., 2018; Winarso & Nugraha, 2015), this configuration eliminates gravitational vapor shortcutting; compared to horizontal immersion systems (Susilo et al., 2020), it eliminates the need for extended soaking times. Zeolite pellet size and binder composition also significantly influence adsorption performance (Ulfah et al., 2023), which is why standardized synthetic 3Å zeolite pellets were selected for this study.

Table 2. Adsorber Column Specifications

Parameter	Specification	Consideration
Material	SS 304	Corrosion resistant
Type	Horizontal 65°	Fluid distribution optimization
Diameter	7.6 cm	Availability of materials
Length	35 cm	Based on zeolite requirement calculation
Thickness	1 mm	Availability of materials
Adsorbent zone	30 cm	Effective adsorption zone
Zeolite partition	SS plate (20 mesh)	Preventing zeolite migration
Safety zone	2.5 cm each end	Steam distribution chamber
Zeolite mass	1023 g	Based on empirical adsorption capacity

Vaporizer Energy Efficiency

The vaporizer maintained stable operation at 80°C ± 0.5°C with a 15–20 minute heat-up time from ambient (28°C). Energy efficiency was defined as the ratio of theoretical evaporation energy (sensible heat from 28°C to 80°C plus latent heat of vaporization) to the actual electrical energy supplied (400 W × 1 h = 400 Wh). As no power meter was available, installed heater capacity was used as a conservative estimate. Table 3 presents the results.

As shown in Table 3, energy efficiency ranged from 40.71% to 47.09%, with batch averages of 41.70% (Batch 1), 41.94% (Batch 2), and 43.84% (Batch 3), yielding an overall average of 42.49%. The 2% improvement from Batch 2 to Batch 3 is directly attributable to a vapor leak identified and repaired before Batch 3, confirming that system integrity is critical for thermal performance. The low overall efficiency (below 50%) is primarily caused by the absence of wall insulation on the vaporizer, estimated to account for 30–35% of total heat loss; additional losses arise from heat dissipation at flanged joints and the heat sink effect of the SS column walls. Within each batch, efficiency tended to decrease across runs as the residual liquid became progressively water-enriched. These results are consistent with Winarso & Nugraha (2015), who reported ~45% thermal efficiency for a similar-scale dehydrator, and with Handrian et al. (2018), who identified heat loss as the primary efficiency constraint in laboratory-scale systems. Practically, adding external thermal insulation is a low-cost intervention estimated to improve efficiency to above 60%.

Table 3. Energy Supply Efficiency (Installed heater capacity 400 W)

Batch	Experiment	Evaporated Mass (kg)	Q Calculate (W)	Efficiency (%)
Batch 1	1	0.63826	165.29	41.32
	2	0.66299	171.70	42.93
	3	0.63097	163.41	40.85
	Average	0.64407	166.80	41.70
Batch 2	1	0.65793	170.39	42.60
	2	0.65664	170.06	42.52
	3	0.62875	162.83	40.71
	Average	0.64407	167.76	41.94
Batch 3	1	0.64007	165.77	41.44
	2	0.72726	188.35	47.09

3	0.66399	171.96	42.99
Average	0.67711	175.36	43.84

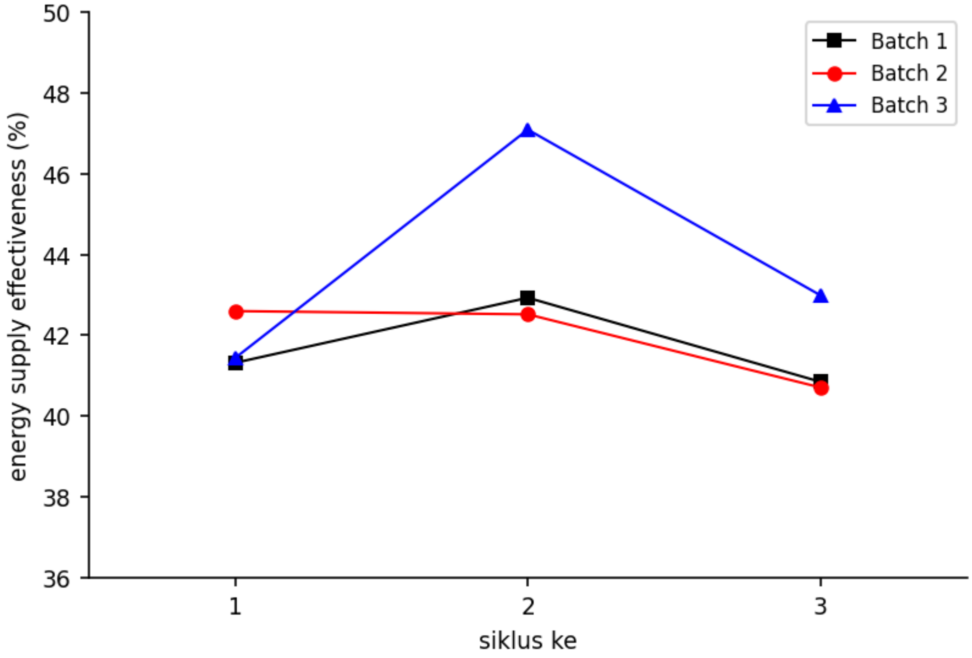

Figure 1. Energy supply efficiency curve

Zeolite Adsorption Capacity

Zeolite adsorption capacity (q = Δmass/initial mass) is the primary performance metric of this system, directly determining the volume of water removable per batch. Table 4 presents the complete dataset.

Table 4 reveals a consistent pattern across all batches. First-run capacity peaked at 0.1128–0.1277 g/g (average 0.1197 g/g), confirming good zeolite quality and falling within the reported literature range of 0.12–0.17 g/g for 3Å zeolite (Tabero & Gabruś, 2023). However, capacity fell sharply in Run 2 (to only 22–28% of Run 1 values) and Run 3 (to 16–18%), indicating near-complete zeolite saturation after the first run. Theoretically, 1023 g of zeolite at 0.12 g/g capacity should adsorb up to 122.8 g of water sufficient for approximately two full cycles of a 1.5 L feed (which contains ~60 g water). The faster-than-expected saturation suggests incomplete vapor-zeolite contact or early structural changes in the zeolite. Importantly, first-run capacity progressively increased across batches: 0.1128 g/g (Batch 1) → 0.1186 g/g (Batch 2, +5.1%) → 0.1277 g/g (Batch 3, +13.2%). Contrary to expectations, this does not reflect improved zeolite performance; as reported by Tabero & Gabruś (2023), repeated thermal regeneration causes structural modification that broadens pore selectivity, allowing ethanol molecules to enter previously water-selective pores and inflate the measured mass uptake. This interpretation is definitively supported by the inverse trend in product purity: despite higher mass uptake in Batch 3, first-run purity declined from 99.79% (Batch 1) to 98.95% (Batch 3).

The peak adsorption capacity of 0.1277 g/g in this study compares favorably with reported values: Gabruis et al. (2018) reported 0.12–0.15 g/g for 3Å zeolite under various regeneration conditions, and Susilo et al. (2020) obtained 0.11–0.13 g/g via the immersion method. The vapor-phase approach used here thus achieves the upper end of this range, attributable to the efficient vapor-zeolite contact enabled by the 65° inclined column design. The saturation signal is unambiguous by Run 3 of each batch: product purity (96–97%) nearly equals feed concentration (95–96%), confirming that the zeolite functions only as a vapor conduit at this stage and must be regenerated before the next batch.

Table 4. Zeolite Adsorption Capacity

Batch	Experiment	Zeolite Mass Before (g)	Zeolite Mass After (g)	q (g water/g zeolite)
Batch 1	1	1023.35	1138.75	0.1128
	2	1138.75	1177.81	0.0343
	3	1177.81	1203.27	0.0216
Batch 2	1	1023.25	1144.62	0.1186
	2	1144.62	1175.10	0.0266
	3	1175.10	1198.07	0.0195
Batch 3	1	1023.26	1153.88	0.1277
	2	1153.88	1188.73	0.0302
	3	1188.73	1214.22	0.0214

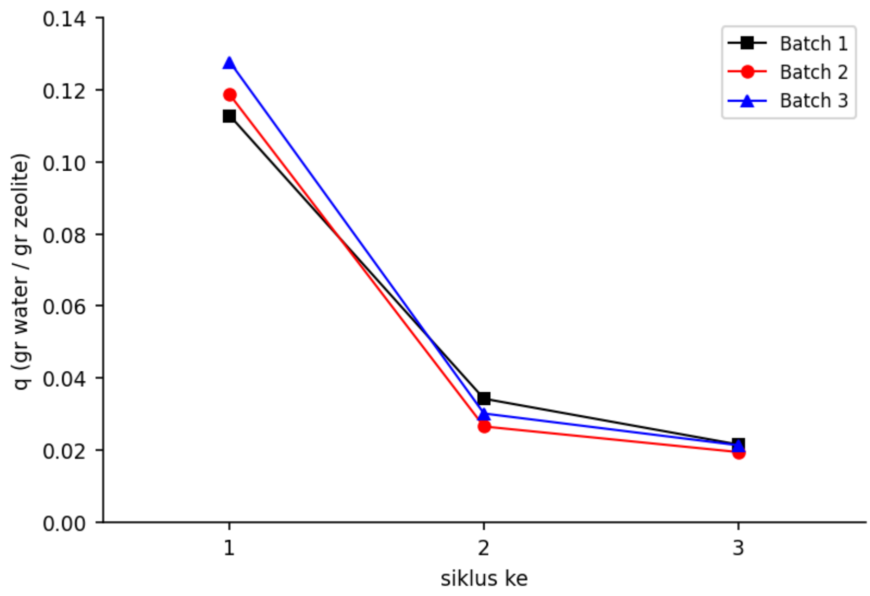

Figure 2. Adsorption capacity curve for each experiment

Ethanol Product Quality

Ethanol product purity, measured by Gas Chromatography (Shimadzu GC-2010, FID), is the ultimate performance criterion of the dehydrator. Table 5 summarizes all nine experimental results.

The highest purity achieved was 99.79% (Batch 1 Run 1), exceeding the SNI 7390-2012 FGE threshold of ≥99.5% and surpassing previous benchmarks including Handrian et al. (2018) at 99.40% and Winarso & Nugraha (2015) at 99.72%. Batch 2 Run 1 produced 99.45% marginally below the threshold while Batch 3 Run 1 yielded 98.95%. Of nine total runs, only one (Batch 1 Run 1) fully met the SNI standard, with Batch 2 Run 1 approaching it. Purity declined sharply within each batch from 99.79% → 98.64% → 97.19% in Batch 1, mirroring the zeolite saturation pattern in Table 4 confirming that product quality is directly governed by available adsorption capacity. By Run 3 of each batch, purity approached feed concentration (~96%), confirming complete zeolite saturation.

The progressive decline in first-run purity across batches 99.79% (Batch 1) → 99.45% (Batch 2) → 98.95% (Batch 3) confirms the cumulative negative effect of repeated thermal regeneration on zeolite selectivity, as discussed in Section 3.4. This trend underscores a key limitation of single-column batch systems and emphasizes the need for optimized regeneration protocols or thermally more stable zeolite types for sustained multi-batch performance.

Comparing with prior studies, the 99.79% purity achieved here exceeds Handrian et al. (2018) at 99.40%, and is competitive with Winarso & Nugraha (2015) at 99.72% and Susilo et al. (2020) at 99.60%, while employing a simpler, lower-cost apparatus without pressure swing equipment. This confirms that the 65° inclined horizontal adsorption column is effective and competitive for ethanol dehydration. However, achieving consistent FGE-grade purity across multiple runs requires either a larger zeolite bed, a dual-column alternating adsorption system, or optimized regeneration conditions directions supported by van Kampen et al. (2021) and Rafael et al. (2022). The 65° inclined column design demonstrably minimized channeling and outperformed conventional vertical configurations, confirming the novelty and effectiveness of this approach. Thermal regeneration at 220°C progressively altered zeolite selectivity, causing first-run purity to decline from 99.79% (Batch 1) to 98.95% (Batch 3), indicating that regeneration conditions require optimization for multi-batch operation. From a practical standpoint, this prototype is immediately applicable as a low-infrastructure solution for community-scale bioethanol purification; adding wall insulation alone is estimated to raise energy efficiency above 60%. For further development, future work should incorporate a dual-column alternating regeneration system for continuous FGE-grade production, and apply XRD/FTIR characterization to elucidate structural changes in zeolite induced by repeated thermal regeneration.

CONCLUSION

This study successfully designed, fabricated, and evaluated a laboratory-scale ethanol dehydrator prototype incorporating a novel 65° inclined horizontal adsorption column filled with 3Å zeolite molecular sieve a configuration not previously reported for ethanol dehydration and the primary novelty of this work. Under optimal first-run conditions, the system elevated ethanol purity from 96% to 99.79%, meeting the SNI 7390-2012 FGE standard (≥99.5%), with an average vaporizer energy efficiency of 42.49% and a peak zeolite adsorption capacity of 0.1277 g water/g zeolite. The inclined column design demonstrably minimized channeling and outperformed conventional vertical configurations, confirming its technical effectiveness. However, zeolite selectivity declined progressively with each thermal regeneration cycle at 220°C, causing first-run purity to drop from 99.79% (Batch 1) to 98.95% (Batch 3), indicating that regeneration conditions require further optimization. Practically, this prototype is directly applicable as a low-cost, low-infrastructure solution for community-scale bioethanol purification; the addition of wall insulation alone is estimated to raise energy efficiency above 60%. Future work should incorporate a dual-column alternating regeneration system and apply XRD/FTIR characterization to elucidate zeolite structural changes induced by repeated thermal regeneration.

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