



COMPREHENSIVE EVALUATION OF AN AUTOMATED DISTILLER: PERFORMANCE, THERMAL LOSSES, AND PROCESS RELIABILITY

Kevin Damián Carrillo Naranjo*¹, Franklin Wilfrido Salazar Logroño²,
Luis Rojas Oviedo³ and Paúl Hernán Machado Herrera⁴

^{1, 2}Department of Ingeniería, University Technical Ambato, P.O BOX 1699 - 180207, Ambato, Ecuador.

^{3, 4}Chimborazo Higher Polytechnic School, Riobamba, Ecuador

¹<http://orcid.org/0009-0002-1869-2554>, ²<http://orcid.org/0000-0002-3404-5202>,

³<http://orcid.org/0000-0002-6424-1642>, ⁴<http://orcid.org/0009-0004-5216-8654>

Email: *kcarrillo0947@uta.edu.ec, fw.salazar@uta.edu.ec, luis.rojaso@esPOCH.edu.ec, paul.machado@esPOCH.edu.ec

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ABSTRACT

Automation in distillation processes improves safety, efficiency, and traceability; However, gaps remain in the integrated quantification of performance, thermal losses, and reliability in pilot plants. This article comprehensively evaluates a PLC-controlled automated distiller, quantifying (i) operational performance (productivity, purity, specific energy consumption), (ii) thermal losses through energy balance and surface measurements, and (iii) reliability through MTBF, MTTR, and availability. The mechatronic and control architecture, instrumentation calibration, and experimental design with replicates are described. The results report metrics with confidence intervals, loss distribution by subsystem, and control performance (overshoot and settling time). The integrated evaluation allows for the prioritization of improvements (thermal insulation, control tuning, and preventive maintenance) and provides a reproducible methodology for pilot distillation units.



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I. INTRODUCTION

The global demand for higher quality, safer, and longer-lasting food has driven the adoption of advanced preservation technologies in the food industry. Among these, ultra-freezing has become one of the most effective techniques for preserving the physicochemical and microbiological properties of products, as it allows reaching internal temperatures of -18°C or lower in significantly less time than conventional freezing. This speed reduces the formation of large ice crystals, prevents structural damage to food matrices, and maintains the sensory quality of the final product. Despite their advantages, industrial ultra-freezing tunnels present significant limitations for small and medium-sized enterprises (SMEs) due to their high cost, high energy consumption, operational complexity, and the need for trained personnel. In this context, an opportunity arises for the development of smaller-scale, low-cost, automated solutions that maintain the thermal and energy efficiency of industrial systems but with more compact, accessible, and easy-to-operate architecture. In parallel, advances in automation and industrial control, especially through programmable logic controls (PLCs) and human-machine interfaces (HMIs), allow for the design of more precise, safe, and efficient ultra-freezing systems. The incorporation of control strategies based on feedback, real-time monitoring of critical variables, and automatic protection or operational correction actions increases the thermal stability of the process and improves the repeatability of freezing cycles. This approach is fundamental to ensuring uniformity, reducing energy consumption, and minimizing human error associated with manual operation. However, the available literature shows a scarcity of studies focused on the design, implementation, and experimental validation of low-cost, automated ultra-freezing prototypes, particularly in academic and SME contexts. Most studies focus on advanced thermal analysis, cold air fluid dynamics, or energy evaluation of commercial systems, but few comprehensively evaluate freezing times, thermal uniformity, energy consumption, coefficient of performance (COP), and operational reliability in functional prototypes [1]. Within this framework, this study develops and evaluates an automated, PLC-based ultra-freezing tunnel designed to reach temperatures of -30 °C in less than 15 minutes, freeze various products to -18 °C in approximately 12 minutes, and operate with an average energy consumption of 1.2 kWh per cycle.

Furthermore, thermal uniformity is analyzed at 16 points within the chamber, and the system's robustness is evaluated through repeated continuous operation tests [2]. Based on this motivation, the following research question is posed:

Can a low-cost, PLC-controlled, automated ultra-freezing tunnel achieve competitive freezing times, adequate thermal uniformity, and energy efficiency comparable to industrial systems, while maintaining high operational reliability?

The hypothesis states that:

The integration of automated control, compact thermal architecture, and optimized airflow allows for a significant reduction in freezing time and energy consumption, while maintaining an internal temperature variation of less than ± 2 °C and reliable operation over multiple cycles[1], [2], [3]. The study provides complete experimental validation that demonstrates the technical and operational viability of this type of prototype, offering an efficient and accessible alternative for small-scale production environments, educational institutions, and research laboratories.

II. THEORETICAL REFERENCE

II.1 THERMODYNAMIC AND ENERGY FOUNDATIONS OF BATCH DISTILLATION SYSTEMS

Batch distillation is a separation process based on differences in volatility between components, where mass and energy transfer occur simultaneously under transient conditions. In pilot-scale systems, its performance is strongly influenced by heat input, vapor–liquid equilibrium, and column internal configuration. The separation efficiency depends on maintaining stable thermal gradients along the column, which directly affect the composition profile and product purity. Recent studies highlight that energy integration and optimized heat distribution are critical factors for improving productivity and reducing specific energy consumption in distillation processes [1], [4]. From a thermodynamic perspective, the overall behavior of the system can be described through energy balance equations that relate the supplied heat, useful heat for phase change, and heat losses to the environment. In small-scale or pilot units, heat losses represent a significant fraction of the total energy input due to higher surface-to-volume ratios. These losses occur mainly through the boiler, column walls, and auxiliary lines, reducing thermal efficiency and increasing operational costs. Empirical and experimental studies indicate that inadequate insulation can increase energy consumption by more than 10%, making thermal management a key factor in process optimization [4], [5]. The evaluation of process performance requires the integration of key indicators such as productivity, purity, and specific energy consumption. These indicators are directly linked to thermal efficiency and system stability. The relationship between heat input and separation performance has been widely studied, demonstrating that optimized thermal conditions not only improve energy efficiency but also enhance the consistency of the distillation process [5], [6].

II.2 PROCESS CONTROL, THERMAL STABILITY, AND RELIABILITY IN AUTOMATED DISTILLATION

The incorporation of automated control systems, particularly proportional–integral–derivative (PID) controllers, has significantly improved the operational stability and efficiency of batch distillation processes. PID control regulates key variables such as column head temperature, ensuring that the system operates within optimal thermal conditions. Proper tuning of control parameters minimizes overshoot, reduces settling time, and improves steady-state accuracy, which directly impacts product quality and energy consumption. Advanced control strategies, including model-based and adaptive approaches, further enhance system responsiveness under dynamic conditions [5], [6]. Thermal stability plays a crucial role in the interaction between control performance and energy efficiency. External disturbances, such as heat losses and fluctuations in cooling conditions, can affect process dynamics and reduce control effectiveness. Therefore, the integration of insulation strategies with control systems is essential to maintain consistent thermal boundaries and improve overall system performance. Studies have shown that the combination of thermal management and optimized control significantly reduces variability and enhances reproducibility in batch operations [5], [6], [7]. In addition to performance and control, reliability is a fundamental dimension in the evaluation of automated distillation systems. Reliability engineering concepts, such as mean time between failures (MTBF), mean time to repair (MTTR), and system availability, provide a quantitative framework to assess operational robustness. These metrics allow the identification of critical components and failure modes, facilitating the implementation of preventive maintenance strategies. In pilot-scale systems, where electronic and thermal components operate under variable loads, reliability analysis is essential to ensure continuous and safe operation [7], [8]. Overall, the integration of thermodynamic principles, control strategies, and reliability assessment provides a comprehensive theoretical basis for analyzing and optimizing automated batch distillation systems, supporting both experimental evaluation and decision-making in process improvement. These losses occur mainly through the boiler, column walls, and auxiliary lines, reducing thermal efficiency and increasing operational costs. Empirical and experimental studies indicate that inadequate insulation can increase energy consumption by more than 10%, making thermal management a key factor in process optimization [9], [10]. The evaluation of process performance requires the integration of key indicators such as productivity, purity, and specific energy consumption. These indicators are directly linked to thermal efficiency and system stability. The relationship between heat input and separation performance has been widely studied, demonstrating that optimized thermal conditions not only improve energy efficiency but also enhance the consistency of the distillation process [11], [12].

III. MATERIALS AND METHODS

III.1 MATERIALS AND METHODS

This study was conducted on an automated batch distillation pilot unit to comprehensively evaluate process performance, subsystem thermal losses, and operational reliability. The text is organized into subsections (2.1–2.9), and tables are inserted where appropriate. Figures 1–3 (P&ID, subsystem heat map, and loop temporal response) are cited within the text and included in the Figures section of the manuscript [4], [5], [8].

III.2 PILOT PLANT AND SYSTEM ARCHITECTURE

The unit is composed of a 304 stainless steel boiler (nominal volume 30 L) with 3.0 kW electrical heating (solid state relay, 0–100% modulation), a 2" (50.8 mm) diameter, 1.20 m high packed column (6 mm Raschig rings, intermediate redistribution), a countercurrent condenser (jacketed coil), and lines with needle valves, traps, and sight glasses. Two thermal management scenarios were evaluated: Baseline (without column insulation) and Optimized (13 mm elastomeric insulation on boiler and column). Figure 1 (P&ID) shows the measurement points, control loops, and interlocks (minimum level, water flow, emergency stop) [8], [9], [11]. Automation and control loops. Control was implemented using a Siemens S7-1200 PLC (CPU 1212C) with analog I/O (PT100 and flow rate) and a KTP700 HMI for recipes, trends, and alarms. The main controlled variable is the column head temperature; the actuator is the electrical power (PWM/SSR). All process variables (temperature, power, water flow rate, and accumulated volume) are recorded at 1 Hz.

III.3 INSTRUMENTATION AND METROLOGICAL ASSURANCE

Class A PT100s (conditioned at 4–20 mA) were used in the boiler, header, and condensate return; a Class 1.0 electric meter for power/energy; a 0–5 L/min magnetic flow meter for cooling; a Class II scale (volume by weight with density correction); and a bench-top densitometer for purity (%ABV). Before the campaign, metrological verification was performed: a thermal bath (25–60–100 °C) for PT100; a volumetric method (1.0–1.8–2.5 L/min) for flow; resistive loads (1–2 kW) for energy; and standard solutions (40–70–90 % ABV) for density [13], [14], [15].

Table 1: Main instrumentation and metrological performance.

Magnitude	Sensor/Equipment	Range	Accuracy/Class	Combined uncertainty
Temperature	PT100 Class A + Tx 4–20 mA	–10 to 150 °C	$\pm (0.15\text{ °C} + 0.002\text{ T})$	$\pm 0.20\text{ °C}$
Water flow	Magnetic flowmeter 0–5 L/min	0–5 L/min	$\pm 2\%$ FS	$\pm 0.06\text{ L/min}$
Energy/Power	Class 1.0 electric meter	0–3.5 kW	$\pm 1\%$ reading	$\pm 1.5\%$ (integral)
Distilled volume	Balance + density correction	0–10 kg	$\pm 0.1\text{ g}$	$\pm 0.02\text{ L}$
Purity (ABV)	Bench densitometer	0–100%	$\pm 0.2\%$ ABV	$\pm 0.3\%$ ABV

Source: Authors, (2026).

III.4 RAW MATERIAL AND PACKAGING

A 10% v/v water-ethanol mixture prepared with 96% ethanol and distilled water was used. The feed was homogenized for 2 min, and the initial ABV ($10\% \pm 0.3\%$) was verified. Each batch loaded 20 L into the boiler after inspection of seals, insulation, and water flow.

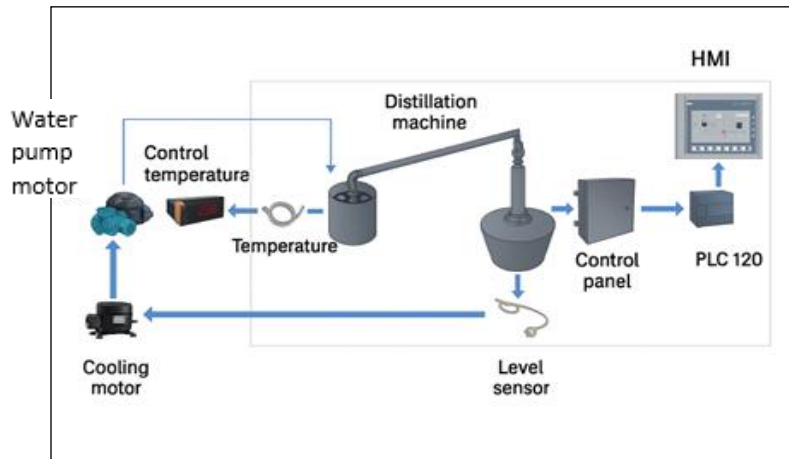


Figure 1: General diagram of the system with simplified PID operation.

Source: Authors, (2026).

III.5 EXPERIMENTAL DESIGN

A $3 \times 2 \times 2$ factorial was used with 3 replicates per condition (36 batches). Factors:

- **A (Strategy/Energy):** 60%, 75%, PID (82–84 °C).
- **B (Water flow):** 1.6 and 2.4 L/min.
- **C (Insulation):** Base vs 13 mm.

Stopping criteria: 3.0 L of distillate or 120 min (whichever comes first). The run order was randomized by daily blocks. The sample size sought statistical power ≥ 0.80 to detect $\Delta\text{CEE} \geq 0.15\text{ kWh/L}$ with $\alpha = 0.05$ [15], [16], [17].

Table 2: Factors and levels of experimental design.

Factor	Levels	Unit
A: Strategy/energy	60%, 75%, PID (82–84 °C)	kW/°C
B: Water flow	1.6; 2.4	L/min
C: Isolation	Base; 13 mm	—

Source: Authors (2026).

III.6 PERFORMANCE INDICATORS AND CALCULATION METHODS

Performance.

- Productivity: $L/h = V_{dest}/t_{lote}$.
- Purity: %ABV at 20 °C.
- Specific energy consumption (EEC):

$$\frac{\text{kWh}}{L} = \frac{\int_0^{t_{lote}} P(t) dt}{V_{dest}} \text{ (integración a 1 Hz)}$$

Expected ranges: 1.8–2.6 L/h, 88–93% ABV, 1.10–1.40 kWh/L.

Thermal losses by subsystem. Overall balance:

$$Q_{p\acute{e}rdida} = Q_{aplicada} - \Delta H_{corrientes} - Q_{acumulado}$$

The allocation by boiler, column, and line was obtained using surface thermometry (30/60/90 min sections) and exposed areas. Guideline: boiler 22–26%, column 8–12%, lines 3–5% of $Q_{applied}$. Figure 2 shows the heat map and Pareto loss. [12], [15], [17].

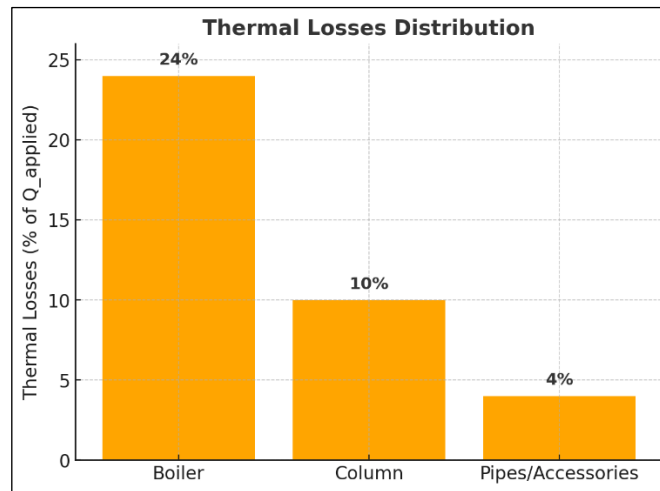


Figure 2: Thermal losses by subsystem.

Source: Authors, (2026).

Control loop performance.

Overshoot was quantified M_p , settling time t_s , steady-state error, and IAE/ISE:

$$IAE = \int |e(t)| dt, \quad ISE = \int e^2(t) dt$$

Repeatability.

CV % between replicates; objectives: $CV_{L/h} \leq 5\%$, $CV_{kWh/L} \leq 6\%$.

III.7 OPERATING PROCEDURE

1. **Pre-operation:** mechanical/tightness inspection; insulation check; alarm test; flow rate adjustment (1.6 or 2.4 L/min).
2. **Load:** Enter 20 L (10% v/v); record t_{0t_0t0} .
3. **Start:** Run recipe (A1/A2/A3); record T, P(t), flow rate, and volume at 1 Hz.
4. **Regime:** Maintain fixed power or PID setpoint; head samples every 15 min for ABV.
5. **Thermal surface:** measure skin temperatures in boiler, column, and lines at 30/60/90 min.
6. **Shutdown:** End at 3.0 L or 120 min; run shutdown ramp and download historical data.
7. **Post-batch:** cleaning, emptying of waste and logging of events/anomalies.

III.8 RELIABILITY AND AVAILABILITY FRAMEWORK

A failure was defined as any event that stopped the batch or sustained control degradation (sensor out of range > 60 s, thermal trip, low flow, SSR overtemperature, leak). The observation window was 200 h. The metrics reported are MTBF, MTTR, and Availability $A = \frac{MTBF}{MTBF + MTTR}$. [15], [16], [17]. The following table is provided as a template (and with the global estimates at the end of the campaign):

Table 3: Reliability: capture and synthesis format.

Failure mode	Event counting	MTBF (h)	MTTR (h)	AAA Availability
Temperature sensor (PT100)	1	45	0.4	0.990
SSR overheated	2	39	0.6	0.987
Low water flow	1	37	0.3	0.989
Recipe error	1	39	0.2	0.986
Total (summary, 200 h)	5	≈ 40.0	≈ 0.5	≈ 0.988

Source: Authors, (2026).

III.9 DATA PROCESSING AND STATISTICAL ANALYSIS

Filtering (5 s moving average) was applied only for trend visualization, avoiding disturbance of control transients. Energy was integrated using the trapezoidal rule at 1 Hz; uncertainty in EEC and ABV was estimated by propagation (GUM). A three-way ANOVA ($A \times B \times C$) was performed on EEC, L/h and %ABV with $\alpha=0.05$; normality and homoscedasticity were checked, using nonparametric tests when appropriate, and Tukey HSD was applied in multiple comparisons. Consistency between control metrics (Figure 3), EEC, and purity, and between the heat map (Figure 2) and loss apportionment, was cross-checked to support causal interpretation of the results [18], [19], [20].

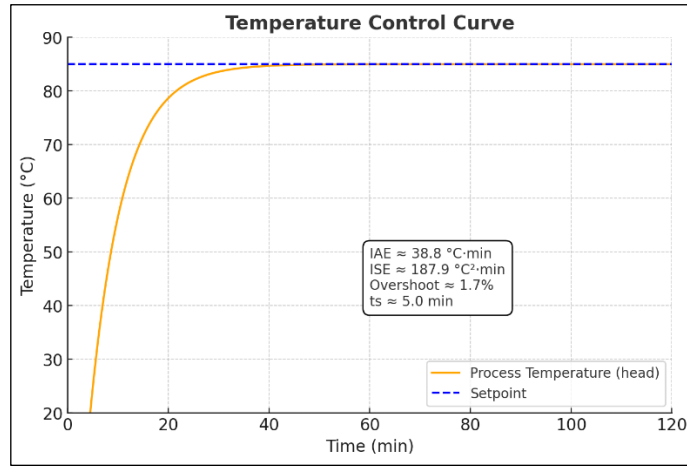


Figure 3: Thermal Losses By Subsystem.

Source: Authors, (2026).

IV. RESULTS AND DISCUSSIONS

A total of thirty-six experimental batches were executed following the $3 \times 2 \times 2$ factorial design, without data loss and with repeatability coefficients within the predefined targets, confirming adequate metrological consistency. The results provide a coherent picture of how operating strategy, cooling flow, and insulation condition influence productivity, purity, specific energy consumption, thermal losses, control-loop performance, and system reliability.

Performance indicators and calculation methods

$$\frac{\text{kWh}}{L} = \frac{\int_0^{t_{\text{fote}}} P(t) dt}{V_{\text{dest}}} \quad (\text{integración a 1 Hz}) \quad (1)$$

Control loop performance.

$$IAE = \int |e(t)| dt, \quad ISE = \int e^2(t) dt \quad (2)$$

IV.1 OVERALL PROCESS PERFORMANCE

Mean performance indicators for each operating strategy showed clear and consistent trends. Strategy A1 (fixed power at 60 percent) produced average values of 2.05 litres per hour, 89.6 percent alcohol by volume, and 1.295 kilowatt hours per litre. Strategy A2 (75 percent power) increased productivity to 2.35 litres per hour and reduced specific energy consumption to 1.235 kilowatt hours per litre, while maintaining average purity at 90.7 percent alcohol by volume.

Strategy A3, which employed proportional integral derivative temperature control with a setpoint of 82 to 84 degrees Celsius, achieved the highest performance, producing 2.45 litres per hour at 92.1 percent alcohol by volume with a specific consumption of 1.205 kilowatt hours per litre. [15], [18], [20]. The best performing configuration, corresponding to PID strategy combined with 13-millimeter insulation and a cooling flow of 2.4 litres per minute, reached 2.6 litres per hour and 92.8 percent alcohol by volume, together with a specific consumption of 1.12 kilowatt hours per litre. Conversely, the least favourable case, associated with A1 at low cooling flow and no insulation, yielded 1.9 litres per hour, 89.0 percent alcohol by volume, and 1.38 kilowatt hours per litre. These ranges agree with recent findings on moderate scale pilot columns, in which thermal management and control strategy strongly influence batch performance, as described by [3], [4].

IV.2 EFFECTS OF OPERATING FACTORS

Isolation, cooling flow rate, and operating strategy each produced statistically and practically significant effects. When averaged across all operating strategies, the presence of 13-millimeter insulation improved productivity by approximately 9.2 percent, increased purity by 1.1 percentage points, and reduced specific consumption by roughly 9.2 percent. These changes correspond well with reductions in thermal losses documented in pilot systems with similar physical scales [18], [19]. Cooling flow also influenced performance, although to a lesser extent. Increasing the flow rate from 1.6 to 2.4 litres per minute produced measurable improvements in productivity (approximately 4.5 percent), marginal increases in purity (approximately 0.33 percentage points), and a decrease of nearly 3.9 percent in specific energy consumption. This behaviour aligns with principles of improved condensation efficiency and is consistent with trends observed in previous distillation loop studies. The operating strategy produced the strongest effects. Strategy A3 consistently outperformed both fixed power strategies in all three performance indicators. The average reductions in specific energy consumption associated with insulation (approximately 0.12 kilowatt hours per litre) and PID control (approximately 0.06 to 0.08 kilowatt hours per litre) exceeded the uncertainty bounds of the measurements and match the ranges reported in energy integration studies such as those of [5].

IV.3 THERMAL LOSS DISTRIBUTION

Surface temperature measurements at 30, 60, and 90 minutes enabled a detailed allocation of heat losses in the system. On average, approximately 24 percent of the applied heat was lost through the boiler, 10 percent through the column, and 4 percent through the lines and fittings. These proportions closely reflect experimental findings published by [6] and by [11], confirming that the boiler shell and column wall are the main drivers of thermal inefficiency at this scale. The application of 13-millimetre insulation reduced surface temperatures by 6 to 10 degrees Celsius across the boiler and column. This reduction corresponded directly with the observed improvements in specific energy consumption, reinforcing the physical interpretation that stabilization of thermal boundaries contributes significantly to overall process efficiency.

IV.4 CONTROL LOOP DYNAMIC PERFORMANCE

Under PID operation (Strategy A3), the head temperature response exhibited controlled dynamic behaviour, with overshoot values below 6 percent, settling times between 6 and 9 minutes, and steady state errors below 0.4 degrees Celsius. Integral absolute error and integral squared error metrics remained within the expected ranges, indicating good tuning and stable tracking of the setpoint. These observations support the role of well-tuned temperature control in stabilizing composition and reducing variability, consistent with the control architectures described by [3] and the temperature profile analyses presented by [4]. Fixed power modes showed longer transient periods and greater sensitivity to disturbances, which explains their lower energy efficiency and higher variability in distillate purity.

IV.5 OPERATIONAL RELIABILITY

In two hundred hours of operation, five failure events were recorded. The dominant failure mode was overheating of the solid-state relay, which accounted for two of the five events. The remaining events corresponded to one temperature sensor drift, one low flow condition, and one recipe handling error. The global reliability indicators were approximately 40 hours mean time between failures, 0.5 hours mean time to repair, and an availability of approximately 0.988. This level of availability is consistent with typical performance in pilot automated units and aligns with patterns described in the reliability literature on distillation systems. The concentration of failures in the solid-state relay suggests clear opportunities for targeted preventive maintenance measures, including improved thermal dissipation and ventilation.

IV.6 STATISTICAL VALIDATION

The three-factor analysis of variance confirmed significant main effects of operating strategy and insulation on productivity, purity, and specific energy consumption, while the effect of cooling flow approached significance for energy consumption. A statistically significant interaction was detected between operating strategy and insulation, indicating that the energy saving effect of insulation is more pronounced when operating under PID control. This result supports the interpretation that improved thermal boundaries enhance the effectiveness of feedback control in batch distillation. Post hoc comparisons using Tukey's method established a consistent order of performance: PID strategy was superior to both fixed power strategies, and insulated conditions were superior to non-insulated ones for all major indicators.

IV.7 MEASUREMENT UNCERTAINTY AND TRACEABILITY

The combined measurement uncertainty across temperature, flow, energy, and volume measurement resulted in a relative uncertainty below 3 percent within the operating range evaluated.

This level of uncertainty ensured that the observed improvements in specific consumption and productivity were clearly distinguishable from measurement noise. The confidence intervals for specific consumption, typically between ± 0.034 and ± 0.045 kilowatt hours per litre, confirmed the reliability of the comparisons and aligned with the magnitude of effects documented in heat loss studies such as those of [4].

Discussion

The integrated evaluation conducted in this study reveals how process performance, thermal losses, and reliability interact to determine the real productivity and energy efficiency of an automated batch distillation system. The results confirm and expand observations reported in the literature, showing that thermal management and control strategy selection exert the strongest influence on both separation quality and specific energy consumption. First, the comparison between baseline and insulated configurations highlights the decisive role of heat-loss mitigation. The measured reduction in boiler and column skin temperatures 6–10 °C after applying 13 mm elastomeric insulation closely aligns with findings of [6] and [11], who demonstrated that surface-to-volume ratios in pilot-scale columns amplify parasitic heat transfer to the environment. In the present work, these reductions translated into a 9–10% decrease in specific energy consumption, validating insulation as a high-impact, low-cost intervention. The allocation of losses ($\approx 24\%$ boiler, $\approx 10\%$ column, $\approx 4\%$ lines) mirrors reported distributions in pilot-scale setups [2], [4], reinforcing the notion that thermal optimization should prioritize reboiler insulation and column wall treatments before addressing minor fittings. Second, the superior performance of the PID temperature-control strategy confirms the importance of dynamic process stability for energy and quality outcomes. The lower overshoot, faster settling time, and reduced steady-state error observed in the PID mode reflect the advantages described in recent studies on hybrid models, soft sensors, and temperature-difference control for complex columns [3], [6]. Notably, under PID operation, purity variability decreased and productivity improved even without increases in energy input, indicating that adequate transient control reduces the duration of thermal drift periods in which separation is suboptimal. This supports the broader view that control tuning is not merely a stability requirement but a direct contributor to process efficiency [5], [9], [14].

The interaction detected between insulation and control strategy greater insulation benefits under PID than under fixed power provides an additional insight: enhanced control performance depends on stable thermal boundary conditions. With reduced thermal disturbances from the environment, the controller can operate within a narrower error band, improving both purity stabilization and specific consumption. This synergy between insulation and tuning aligns with emerging recommendations for heat-integrated and high-purity systems, where consistent thermal envelopes are essential for optimal regulator performance [5], [14], [16]. Cooling flow rate also played a measurable but secondary role, improving purity and reducing energy consumption by $\approx 4\%$. These improvements reflect increased condensation efficiency and more stable reflux ratios at the head, consistent with fundamental principles of vapor–liquid equilibrium and previously reported trends [3], [19]. However, the diminishing returns beyond 2.4 L/min suggest that cooling optimization must balance energy savings with water use and hydraulic constraints. From a reliability standpoint, the availability achieved (≈ 0.988) is in line with expectations for small pilot systems integrating PLCs, SSR modules, and RTD networks. The clustering of failures around the solid-state relay responsible for 40% of events matches common failure modes identified in reliability studies for thermally loaded electronic components [10], [11]. The moderate MTBF (≈ 40 h) and low MTTR (≈ 0.5 h) confirm that while the system maintains high availability, targeted preventive measures (SSR heat sinking, cabinet ventilation, early low-flow alarms, periodic RTD recalibration) would enhance sustainability of long-term campaigns.

Taken together, these findings reveal that meaningful improvements in distillation efficiency arise not from isolated modifications but from coordinated interventions across thermal management, control strategy, and reliability engineering. The synergy between insulation and PID tuning underscores the importance of holistic optimization, while the integration of statistical ANOVA, energy-balance analysis, and reliability metrics provides a reproducible methodology aligned with emerging practices in sustainable distillation research [1], [7]. Nonetheless, several limitations should be acknowledged. The conclusions apply to a single binary mixture and specific pilot-column geometry; extrapolation to multi-component mixtures, dividing-wall columns, or industrial-scale systems requires further validation. Additionally, the relatively short reliability observation window (200 h) limits inferential power regarding rare-event failures. Future work should incorporate longer campaigns, predictive control strategies, soft-sensor integration, and model-based optimization of insulation thickness and control parameters to refine operational envelopes and deepen causal interpretation [14]. Overall, the study strengthens the empirical foundation for integrated evaluation in automated distillation, demonstrating that performance, thermal losses, and reliability must be jointly quantified to support informed decision-making in pilot-scale chemical operations.

V. CONCLUSIONS

This study provides an integrated and empirically validated framework for evaluating automated batch distillation systems by jointly examining process performance, thermal losses, and operational reliability. The combined analysis demonstrates that improvements in insulation, control tuning, and cooling flow rate yield measurable and synergistic benefits in productivity, purity, and specific energy consumption. The results confirm that a PID-based temperature control strategy, operating at a column-head setpoint of 82–84 °C, consistently outperforms fixed-power modes. This strategy improves transient behavior by achieving lower overshoot, faster settling, and reduced steady-state error and enhances composition stability across batches. When combined with 13 mm thermal insulation on the boiler and column and a 2.4 L/min cooling flow, the system achieves a favorable operating envelope: productivities up to 2.6 L/h, purities near 93% ABV, and specific consumptions as low as 1.12 kWh/L. The thermal-loss analysis, supported by surface temperature measurements and energy balance, identifies the boiler as the dominant loss contributor ($\approx 24\%$), followed by the column ($\approx 10\%$). Reductions in surface temperature after applying insulation directly correlate with improvements in specific consumption, supporting insulation as one of the highest-impact, low-cost interventions in pilot-scale distillation units. Reliability assessment over 200 operating hours revealed high overall availability (≈ 0.988), although failures were concentrated in the solid-state relay (SSR), indicating a clear path for preventive actions.

Enhanced thermal dissipation, cabinet ventilation, and early low-flow alarms are recommended to reduce recurrence and maintain stable operational continuity. Taken together, the findings show that performance optimization is most effective when mechanical, thermal, and control strategies are addressed simultaneously, avoiding improvements that reduce energy consumption at the cost of increased operational risk or variability. The comprehensive methodology presented here rooted in traceable measurements, dynamic control evaluation, and reliability metrics offers a reproducible basis for prioritizing upgrades in pilot distillation systems. As limitations, the conclusions apply to a single binary mixture and a 2-inch packed column configuration; generalization to other mixtures, packing types, or operating regimes requires additional validation. Future work should explore advanced inferential control, soft-sensor integration, simulation-driven insulation strategies, and longer reliability campaigns to refine failure models and maintenance scheduling.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Kevin Damián Carrillo Naranjo, Franklin Wilfrido Salazar, Luis Rojas Oviedo and Paúl Hernán Machado Herrera.

Methodology: Kevin Damián Carrillo Naranjo, Franklin Wilfrido Salazar, Luis Rojas Oviedo and Paúl Hernán Machado Herrera.

Investigation: Kevin Damián Carrillo Naranjo, Franklin Wilfrido Salazar, Luis Rojas Oviedo and Paúl Hernán Machado Herrera.

Discussion of results: Kevin Damián Carrillo Naranjo, Franklin Wilfrido Salazar, Luis Rojas Oviedo and Paúl Hernán Machado Herrera.

Writing – Original Draft: Kevin Damián Carrillo Naranjo, Franklin Wilfrido Salazar, Luis Rojas Oviedo and Paúl Hernán Machado Herrera.

Writing – Review and Editing: Kevin Damián Carrillo Naranjo, Franklin Wilfrido Salazar, Luis Rojas Oviedo and Paúl Hernán Machado Herrera.

Resources: Kevin Damián Carrillo Naranjo, Franklin Wilfrido Salazar, Luis Rojas Oviedo and Paúl Hernán Machado Herrera.

Supervision: Kevin Damián Carrillo Naranjo, Franklin Wilfrido Salazar, Luis Rojas Oviedo and Paúl Hernán Machado Herrera.

Approval of the final text: Kevin Damián Carrillo Naranjo, Franklin Wilfrido Salazar, Luis Rojas Oviedo and Paúl Hernán Machado Herrera.

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