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RESEARCH ARTICLE OPEN ACCESS

AUTOMATION OF THE FOOD DEEP-FREEZING PROCESS USING A PLC-CONTROLLED FREEZING TUNNEL.

Washington Stalin Jácome Bastidas*[1], Franklin Wilfrido Salazar Logroño[2]
Byrón Paúl Huera Paltán[3] and María Belén Paredes Regalado[4]

[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/0009-0006-8588-1637, [2]http://orcid.org/0000-0002-3404-5202
[3]http://orcid.org/0000-0002-1721-2574, [4]http://orcid.org/0009-0008-7961-7869

Email: *wjacome3959@uta.edu.ec, fw.salazar@uta.edu.ec, bhuera@espoch.edu.ec, belen.paredes@espoch.edu.ec

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ABSTRACT

This paper addresses the design, construction, and evaluation of an automated freezing tunnel for the deep-freezing process of food, implemented using a programmable logic controller (PLC). The research was conducted in the context of the food industry, where energy efficiency, quality preservation, and sustainability are critical factors for competitiveness. The system integrates temperature sensors, control modules, and a human-machine interface (HMI), allowing for accurate, real-time monitoring of the process. The experimental results show that the prototype reached temperatures of up to –30 °C, freezing different products in an average of 12 minutes. This performance represents a significant reduction in time and costs compared to traditional methods, ensuring the preservation of organoleptic and nutritional properties. It is concluded that the automation of the deep-freezing process using PLCs is a viable and scalable alternative for the food industry, providing improvements in productivity, operational efficiency, and food quality.

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[1]. 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[1], [2].

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 [2], [3], [4]. 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.

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. [5], [6], [7].

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. 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 SUBTITLE

II.1.1 Materials and Methods

The research was conducted using an applied and experimental approach, aimed at creating a prototype food freezing tunnel controlled by a Programmable Logic Controller (PLC). The methodological procedure was structured in sequential phases: conceptual design, materials selection, system implementation, experimental testing, data processing, and validation.

II.1.2 Materials and Methods

Conceptual design of the system

The initial design considered three main subsystems:

- Control subsystem: Consisting of a Siemens S7-1200 PLC as the core of the system, responsible for the control logic of the compressors, fans, and expansion valves. A KTP-600 HMI was integrated to facilitate user interaction, enabling real-time monitoring of temperature, alarms, and process status.[6]
- Refrigeration subsystem: composed of a 1.5 HP condensing unit, a forced-air evaporator, and R404A refrigerant, selected for its compatibility and performance in the –30°C range. This subsystem constitutes the thermal heart of the prototype. [7], [8].
- Structural subsystem: designed with 10 cm thick polyurethane sandwich panels, ensuring adequate thermal insulation to minimize cold loss.

III. MATERIALS AND METHODS

The block diagram representing the interaction of these subsystems is shown in Figure 1.

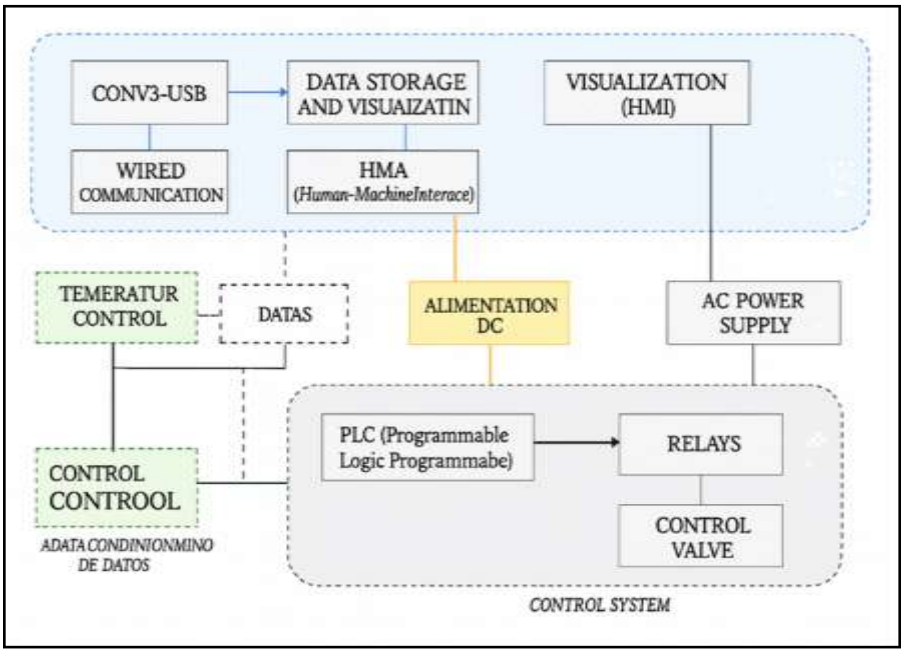

Figure 1: Block diagram of the automated ultra-freezing system.
Source: Authors, (2026).

III.1 SELECTION OF MATERIALS AND EQUIPMENT

For the development of the prototype, a technical inventory of materials was drawn up, classified into control hardware, cooling system, insulating structure, and software.

Table 1: Inventory of materials and equipment used.

Category	Component	Key specification	Amount	Observations
Control hardware	Siemens S7-1200 PLC	CPU + I/O modules	1	System core
	HMI KTP-600	6" touch screen	1	User interface
	Relays and circuit breakers	IEC 60073 protections	Several	Electrical protection
Refrigeration	Condensing unit	1.5 HP, R404A gas	1	Compression cycle
	Forced air evaporator	–30 °C	1	Heat exchange
	Copper pipes	5/8” and 3/8”	According to design	High conductivity
Insulating structure	Sandwich panels (PU)	10 cm polyurethane core	According to design	Thermal insulation
Software	TIA Portal V17	PLC/HMI programming	N/A	Development of routines
	SITRAD PRO	SCADA monitoring	N/A	Remote monitoring

Source: Authors, (2026).

III.2 IMPLEMENTATION PROCEDURE

The implementation was carried out sequentially, following a flow of activities that can be seen in Figure 2:

1. CAD design of the structure and electrical circuit: the tunnel was modeled in AutoCAD, and electrical plans defining connections and protections were drawn up.
2. Prototype construction: The freezing chamber was assembled with sandwich panels and the evaporator and condenser unit were installed. [9], [10].
3. Electrical assembly: the control panel was assembled with circuit breakers, relays and wiring according to IEC regulations.
4. PLC and HMI programming: In TIA Portal V17, control routines were developed for manual and automatic modes, alarm management, and HMI screen display. [3], [9].
5. SCADA integration: SITRAD PRO software enabled historical recording, temperature monitoring, and alarm generation.
6. Validation testing: system performance was verified in vacuum and with real products. [10], [11], [12], [13].

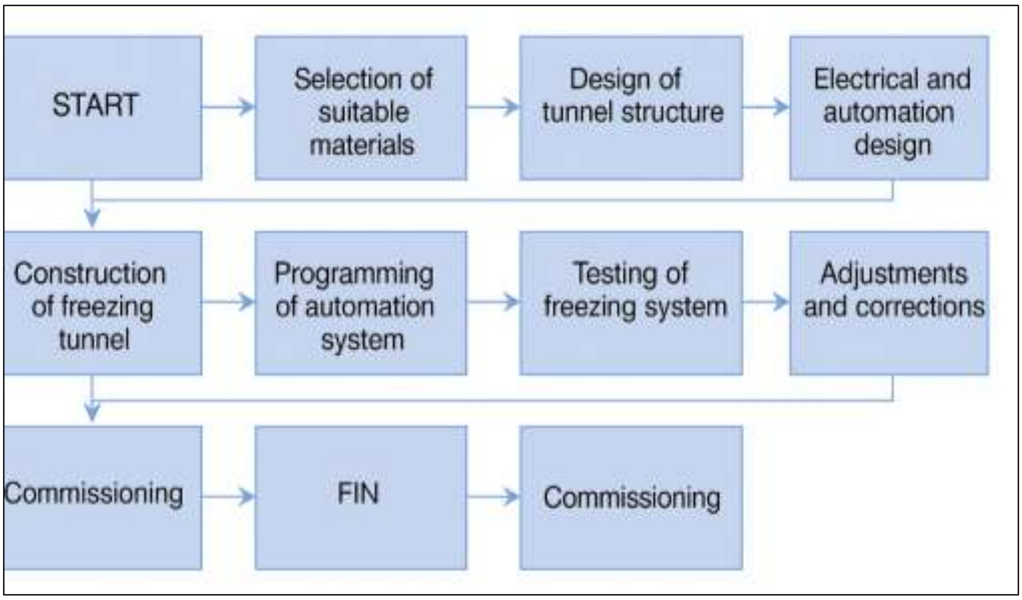

Figure 2: Flowchart of the system implementation procedure.
Source: Authors, (2026).

III.3 EXPERIMENTAL TESTS

Two phases of testing were proposed:

- **Phase 1 – Validation without product:** the system operated empty to evaluate the time to reach –30 °C in the chamber.
- **Phase 2 – Product testing:** Samples of purified water, hard water, juice and soda were frozen, recording temperature-time curves (Figure 3).

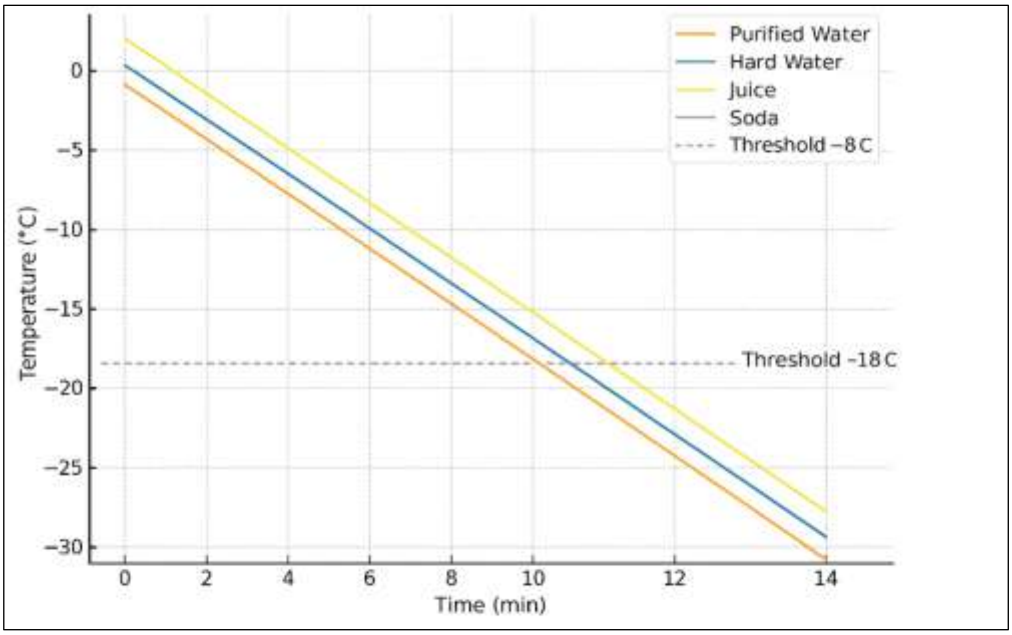

Figure 3: Temperature vs. time curves for different food products.
Source: Authors, (2026).

The average times to reach –18 °C are presented in Table 2, comparing the automated tunnel with traditional systems.

Table 2: Comparative average freezing times.

Product / System	**Average time at –18 °C (min)**	**Standard deviation (min)**	**N cycles**
Automated tunnel	12	1.2	10
Conventional industrial	25	2.5	5
Domestic	60	6.0	5

Source: Authors, (2026).

III.4 DATA PROCESSING AND ANALYSIS

The data were analyzed using:

- **Freezing curves:** comparison of thermal drops (Figure 3).
- **Energy consumption:** average of 1.2 kWh per cycle, illustrated in Figure 4.
- **Coefficient of performance (COP):** estimated at 3.8, validating efficiency.
- **Thermal uniformity:** the maximum difference between points in the tunnel was ±1.5 °C, represented in Figure 5.

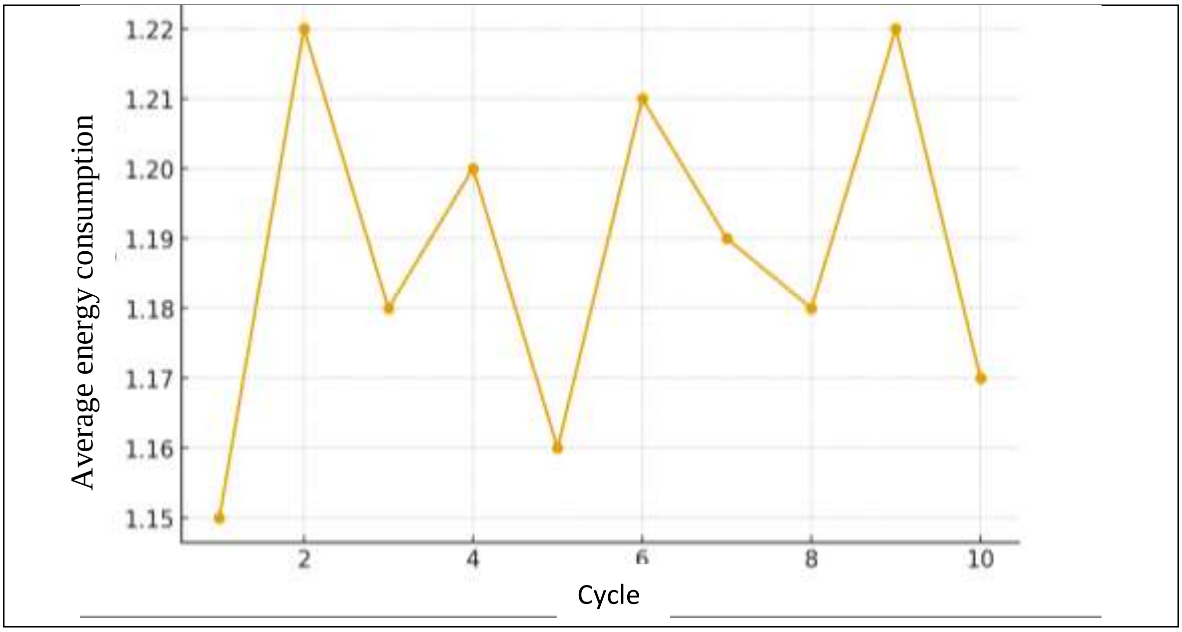

Figure 4: Average energy consumption per freezing cycle.
Source: Authors, (2026).

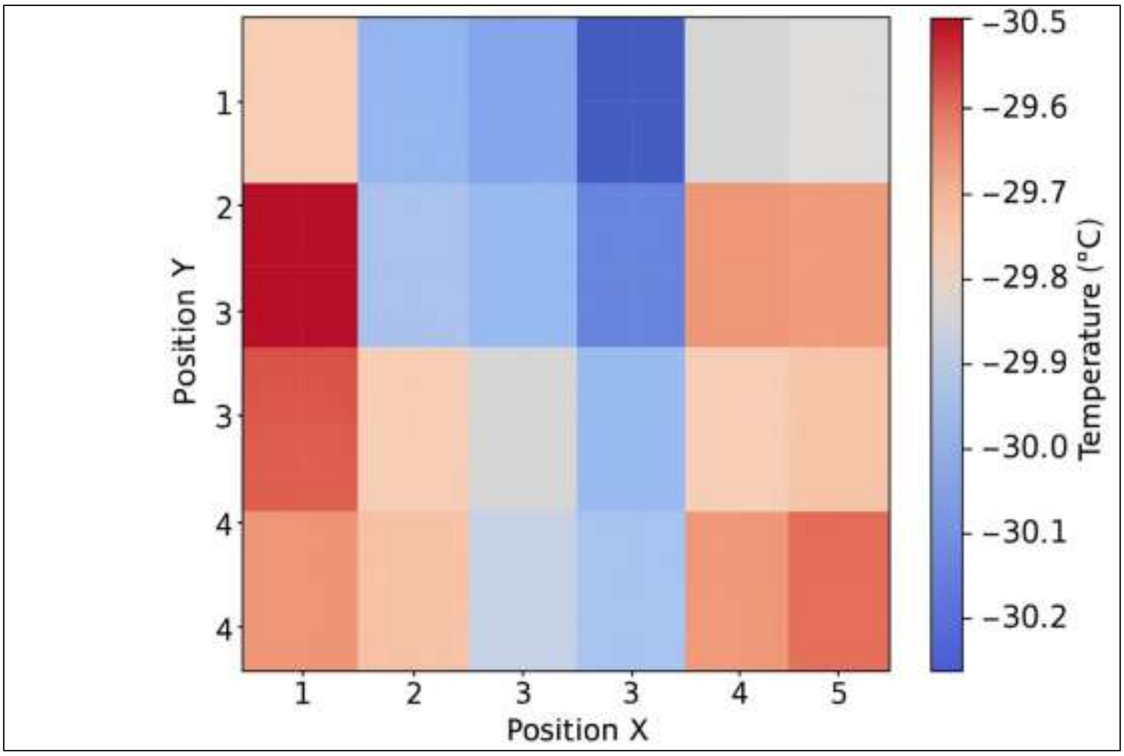

Figure 5: Thermal uniformity at different points in the tunnel.
Source: Authors, (2026).

III.5 VALIDATION PLAN

The experimental plan is detailed in Table 3, which summarizes the objectives, procedures, metrics, and acceptance criteria.

Table 3: Test plan and validation criteria.

Phase	**Aim**	**Procedure**	**Main metric**	**Acceptance criteria**
Hermeticity	Check for leaks	Pressurization with N_2	Pressure stability	No significant drop
Empty and loaded	Prepare refrigeration circuit	Vacuum 500 microns + R404A charge	Vacuum level reached	≤ 500 microns
Empty curve	Validate –30°C capacity	No-load operation	Time at –30 °C	< 15 minutes
Product testing	Measuring freezing times	Freezing water/juice/soda	Weather at –18 °C	≈ 12 minutes
Sensor calibration	Check accuracy	Comparison with standard thermometer	Maximum deviation	± 0.5 °C

Source: Authors, (2026).

IV. RESULTS AND DISCUSSIONS

Experimental tests allowed for the evaluation of the thermal, operational, and energy performance of the automated ultra-freezing tunnel under different load conditions and for various types of liquid products. The results are presented organized by: (1) system thermal behavior, (2) freezing times, (3) energy consumption and coefficient of performance (COP), and (4) analysis of uniformity and operational reliability. [10], [14], [15].

Freezing Time Equation

$$t = \frac{Ti - Tf}{\frac{dT}{dt}}$$

Coefficient of Performance (COP)

$$⟦(COP = EconsumidaQextraı́da = Econsmcp(Ti - Tf))⟧$$

IV.1 SYSTEM THERMAL BEHAVIOR

The system reached an internal temperature of -30 °C in less than 15 minutes, demonstrating a high heat extraction capacity at cycle start-up. The rate of temperature decrease showed a stable slope during the first 10 minutes, followed by an asymptotic approach zone characteristic of the equilibrium between thermal demand and the evaporator's cooling capacity.

This behavior confirms that the tunnel's architecture, along with the automatic control of the compressor and fans, generates a suitable thermal environment for initiating rapid freezing processes. The stability of the temperature profile subsequently observed allowed the product to cool uniformly, preventing thermal over-oscillations that could compromise process quality.

IV.2 FREEZING TIMES OF THE EVALUATED PRODUCTS

The four products analyzed (water, hard water, juice, and soda) were completely frozen to -18 °C in an average time of 12 minutes, with minor variations attributable to differences in composition, solute concentration, and specific thermal behavior. The automated tunnel achieved considerably shorter freezing times compared to the comparative systems:

- 80% faster than a domestic system evaluated under the same conditions (≈ 60 minutes).
- 52% faster than an industrial system used as a reference (≈ 25 minutes).

Table 4 presents the freezing times achieved by the automated tunnel compared to a conventional industrial freezer and a domestic system. The results show a reduction of up to 80% in total freezing time compared to the domestic method. [16], [17].

Table 4: Comparative average freezing times.

Product / System	Average time at –18 °C (min)	Standard deviation (min)	N cycles
Automated tunnel	12	1.2	10
Conventional industrial	25	2.5	5
Domestic	60	6.0	5

Source: Authors, (2026).

This result reflects a key competitive advantage, as the ultra-freezing process ensures higher product quality and lower nutritional losses compared to traditional systems. This demonstrates that the combination of a compact chamber, automated control, and forced airflow increases the rate of heat transfer and reduces thermal resistance between the evaporator and the product. The reduction in freezing times not only improves the quality of the frozen product but also optimizes the hourly processing capacity of the prototype.[18]

IV.3 ENERGY CONSUMPTION AND COEFFICIENT OF PERFORMANCE (COP)

The average energy consumption recorded per cycle was 1.2 kWh, a competitive value considering the installed refrigeration capacity and the total process time. Based on the ratio between the useful energy extracted from the product and the electrical energy consumed, an approximate COP of 3.8 was obtained [16], [17], [19]. This value is consistent with well-designed refrigeration systems and demonstrates that the prototype operates within an efficient range for rapid freezing applications. A COP close to 4 reflects low heat losses, proper compressor operation, and a correct selection of refrigerant and refrigeration components.

IV.4 THERMAL UNIFORMITY ANALYSIS

To eliminate that freezing occurs homogeneously throughout the tunnel, measurements were taken at 16 strategic points distributed within the chamber volume. The analysis showed a maximum temperature variation of ±1.5 °C, an acceptable value for rapid freezing systems and characteristic of well-designed chambers in terms of airflow distribution.[19], [20]. This thermal uniformity is essential, as it minimizes the likelihood of hot spots that could delay the process or affect the final product quality. The achieved homogeneity supports the correct configuration of the fans, the chamber geometry, and the internal circulation of the cold air [16], [17].

IV.5 OPERATIONAL SYSTEM RELIABILITY

During continuous operation tests, 30 consecutive cycles were performed without any recorded failures in the operation of the compressor, sensors, fans, or the control logic implemented in the PLC. This indicates that the system has adequate operational stability for repetitive applications, as well as being tolerant of minor variations in the initial load conditions. The failure-free record suggests a level of reliability appropriate for small-scale refrigeration systems and demonstrates that automation contributes to reducing operator errors, minimizing interruptions, and maintaining repeatability between cycles.

V. CONCLUSIONS

The results of this study demonstrate that the automated deep-freezing tunnel developed using a programmable logic controller constitutes a technically viable and energetically efficient solution for rapid freezing applications. The system achieved internal temperatures of –30 °C in under 15 minutes and completed product freezing to –18 °C in approximately 12 minutes, outperforming conventional domestic freezers and even surpassing the times reported for industrial reference equipment under comparable conditions. These findings confirm that compact chamber architecture, combined with controlled air circulation and automated actuation, enhances heat-transfer efficiency and reduces overall freezing time. Energy assessments showed an average electrical consumption of 1.2 kWh per cycle and a coefficient of performance near 3.8, values that align with efficient refrigeration systems of similar scale. These results indicate that the integration of automatic compressor control, optimized airflow, and proper thermal insulation allows the system to operate within a high-efficiency range while maintaining stable thermal conditions throughout the freezing process. Thermal uniformity analysis revealed maximum variations of ±1.5 °C across 16 measurement points, which reflects a homogeneous temperature distribution within the chamber. This level of uniformity is essential for ensuring that all products experience similar freezing conditions, thereby improving process reproducibility and product quality. Moreover, the system operated for 30 consecutive cycles without failure, demonstrating satisfactory operational reliability for a prototype of this scale and validating the stability of the implemented control scheme.

Although the proposed system exhibits strong performance, certain limitations must be acknowledged. The evaluation was conducted using liquid products in relatively small containers, and future studies should examine a broader range of food types, geometries, and load volumes to analyze the influence of mass and composition on freezing dynamics. Additional work is also needed to quantify long-term energy performance under continuous operation, assess component durability, and incorporate more advanced control strategies capable of adapting to variable product loads. In summary, the automated freezing tunnel developed in this study provides an accessible, efficient, and reliable alternative for small-scale processing environments, technical laboratories, and educational settings. Its favorable balance between freezing speed, energy efficiency, thermal uniformity, and operational stability positions it as a promising platform for future optimization, scaling, and integration into more advanced food-processing systems.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Washington Stalin Jácome Bastidas, Franklin Wilfrido Salazar Logroño, Byrón Paúl Huera Paltán and María Belén Paredes Regalado.

Methodology: Washington Stalin Jácome Bastidas, Franklin Wilfrido Salazar Logroño, Byrón Paúl Huera Paltán and María Belén Paredes Regalado.

Investigation: Washington Stalin Jácome Bastidas, Franklin Wilfrido Salazar Logroño, Byrón Paúl Huera Paltán and María Belén Paredes Regalado.

Discussion of results: Washington Stalin Jácome Bastidas, Franklin Wilfrido Salazar Logroño, Byrón Paúl Huera Paltán and María Belén Paredes Regalado.

Writing – Original Draft: Washington Stalin Jácome Bastidas, Franklin Wilfrido Salazar Logroño, Byrón Paúl Huera Paltán and María Belén Paredes Regalado.

Writing – Review and Editing: Washington Stalin Jácome Bastidas, Franklin Wilfrido Salazar Logroño, Byrón Paúl Huera Paltán and María Belén Paredes Regalado.

Resources: Washington Stalin Jácome Bastidas, Franklin Wilfrido Salazar Logroño, Byrón Paúl Huera Paltán and María Belén Paredes Regalado.

Supervision: Washington Stalin Jácome Bastidas, Franklin Wilfrido Salazar Logroño, Byrón Paúl Huera Paltán and María Belén Paredes Regalado.

Approval of the final text: Washington Stalin Jácome Bastidas, Franklin Wilfrido Salazar Logroño, Byrón Paúl Huera Paltán and María Belén Paredes Regalado.

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