Innovation in Dental Laboratory Thermal Processes: Automated Preheating System for Wax and Resin

Steveen Ayala Mora[1]; Kevin Loor de la Cueva[2];Cristian Tasiguano Pozo[3]; Luis Muñoz Ortega[4]; Cristian Fabara Rodríguez[5]; Luz Tobar Subía[6]

[1,2,5] Universidad de las Américas, Ecuador, steveen.ayala@udla.edu.ec, kevin.loor@udla.edu.ec, cristian.fabara@udla.edu.ec

[3,4] Instituto Superior Tecnológico San Antonio, Ecuador, ctasiguano@tesa.edu.ec, , lamunoz@tesa.edu.ec

[6] Universidad Técnica del Norte, Ecuador, lmtobarsubia@utn.edu.ec

Abstract*– Traditional practices for preheating refractory materials in dental laboratories often yield different temperature variations due to their artisanal construction. The thermal inaccuracy creates defects in the coating cylinders during the injection processes. To address this problem, an automated system is implemented here by proportional-integral-derivative (PID) control to optimize wax preheating and implement special functionality for working with resin. An assessment of the current oven structure was performed, highlighting the structural shortcomings and deficiencies in the thermal control system. To address it, an electronic system was established that comprises a type K thermocouple, a microcontroller, and actuators used for power control, controlled by a PID algorithm adjusted in MATLAB. Two operational modes were proposed, one with a steady thermal ramp up to 950°C for wax and another in two timed stages for resin. The actual conditions (testing in real laboratory conditions) were used to validate the system. Results showed that the thermal variability was reduced to ±0.5°C, and this increased the reproducibility of coating cylinders. The power consumption of the two mechanical processes was improved, with 18% better energy efficiency than the manual process, without surface cracks. Furthermore, the human-machine interface was integrated for immediate observation and data recording for later analysis. Automation increased the precision, reliability, and standardization in thermal processing. The current proposal serves as a model to facilitate optimal heat treatment in dental laboratories with high-quality standards.

Keywords-- PID Control, dental prostheses, dental laboratory, preheating system, energy efficiency.

I. Introduction

Dental laboratories play a critical role in the fabrication of crowns, bridges, and removable prostheses. Achieving reliable clinical outcomes requires strict control over material properties and manufacturing conditions, as both product quality and operator safety depend on precise and consistent processing. Wax and resin furnaces, with wax needed to remove and harden resin, need to have exact preheating temperatures. It is important to distinguish that the thermal processes addressed in this study correspond to the calcination (burnout) stage of the lost-wax casting technique, in which wax patterns are eliminated from investment cylinders at temperatures up to 930°C. This process differs from wax softening for modeling, which operates below 100°C. And that matters about the material's properties, such as how easily it flows, how well it sticks, how strong it is, and how well it sets. Combining all these factors results in better-fitting, longer-lasting dental work [1][2]. The manual handling of preheating was common in the old days. This influences their work performance, resulting in the possibility of inconsistent outputs and energy leakage, as well as material damage by overheating or uneven heating [3]. This stage of the procedure is particularly susceptible to operational errors. When the temperatures involved are a result of manual operation, wax may not be entirely removed (about 9% to 17% of cases). And differences in temperature can give rise to tiny cracks in coatings. The results could not remain consistently within such narrow tolerances, which may negatively affect the dimensional accuracy and final fit of the product [3]. If the temperature is set above ±15°C from the optimum (usually 750 to 900°C, depending on material), this can create physical size issues on the dental structures (approximately 38-65 µm). Dental cement functions at the point of best use at this temperature range, and above this is also described as unsatisfactory [4]. Also, aging furnaces waste several thousand kilowatt hours on heating. Lacking insulation and simplicity of control systems makes them lose approximately 25-40% of heat during heating [5]. Automation at an in-use dental lab for furnaces has experienced a recent renaissance. This enables testing labs to precisely control temperature and automate heating curves for specific materials and methods [6][7]. Some, like Renfert Magma furnace, have heat input from several dimensions and can have a lot of heat across several sides, customizable programs, and fine sensors. These extend the improvement of heating uniformity and energy conservation [8]. In such systems, frequently, KSW temperature controllers and thermocouples used by the aforementioned technologies also determine and adjust furnace temperatures on their own by their KSW thermocouples automatically [6]. Unlike legacy systems, they are better able to deliver repeatable results while eliminating errors and making work easier. Especially for use in the field with dental care concerning the requirement of standardized and audited systems [7]. Conventional preheating methodologies present significant limitations, including non-uniform heat distribution, reliance on manual temperature regulation, and restricted operational cycles. These factors reduce process reproducibility and overall operational efficiency within laboratory environments [9]. The latest advances in dental technology indicate a trend towards automating production as well as scaling it up. In dental laboratories, for example, these automated systems have been reported to cut human error by 40 per cent and enhance the trustworthiness of major processes [10]. It was found that closed-loop temperature control systems contribute to a 25% improvement in the energy efficiency of furnaces for dental alloys [11] [12]. Yet, even with these changes, preheating of wax and resin in furnaces is still performed largely by hand, primarily in smaller labs wherein high-tech tools are prohibitively expensive [12]. While commercial preheating systems exist at various price points, they are typically closed platforms that cannot be retrofitted to legacy equipment. The present work addresses the specific gap of upgrading existing obsolete furnaces — a common situation in smaller Latin American dental laboratories — rather than replacing them with new commercial units, offering a cost-effective and technically rigorous alternative.

This paper proposes and tests a PID-controlled automatic preheating system in dental wax and resin furnaces using staged programming. The main objectives of this study are:

1. To reduce manual intervention errors and ensure consistent, uniform preheating conditions.
2. To improve energy efficiency through automated timing and closed-loop temperature regulation.
3. To preserve material integrity by implementing controlled temperature profiles in accordance with recommended thermal treatment standards [13].
4. To integrate additional programmable functionalities that enhance the operational versatility of the furnace in clinical environments

Although PID-based thermal control is well accepted for industrial furnaces, existing research has yet to evaluate an affordable manner to upgrade obsolete dental lab furnaces with automation. Current commercial solutions are closed systems that cannot be optimized for older equipment.

The key findings of this research include:

1. Experimental identification and dynamic modeling of a legacy dental furnace using a First Order Plus Dead Time (FOPDT) approach.
2. Design and real-time implementation of a PID-based closed-loop control strategy embedded on an ESP32 platform.
3. Structural redesign resulted in a 95.4% reduction in thermal losses.
4. Experimental validation under real resin and wax calcination cycles, achieving temperature regulation accuracy within ±0.5 °C.
5. Demonstration of an 18% improvement in energy efficiency compared to the original open-loop configuration.

These contributions offer reproducible and scalable engineering architecture for thermal automation in resource-constrained laboratory environments. The paper consists of 4 sections: Section 2 covers the methodology followed, Section 3 the results of the redesigned and implemented system on mechanical, electrical, and control aspects, and Section 4 the conclusion and the practical implications of the results.

II. Methodology

This study employed a structured, five-stage experimental methodological approach to design and implement an automated temperature control system, aiming to optimize the preheating process of an oven used in the dental equipment field. The methodology is based on the automation of thermal processes, applying modeling, simulation, and embedded control tools with technical and regulatory validation criteria.

A. Requirements Analysis

The functional and structural characterization of the original furnace used in the manufacture of dental cylinders was carried out. This phase included:

- Analysis of thermal behavior through temperature measurements over time, Fig. 1(a), thus enabled the establishment of a database, Table 1, which in turn allowed the initial dynamic behavior of the system to be established.

TABLE I
Time vs. oven temperature measurements before the redesign.

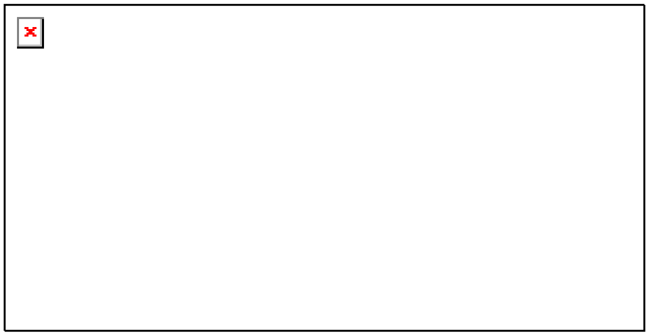
Time (mm:ss)	Temperature (°C)
00:00	29
02:51	124
03:18	224
04:00	324
05:06	424
05:28	524
06:23	624
08:01	724
10:03	824
13:38	924

- Identification of structural and electronic deficiencies, Fig. 1 (a), (b), such as a lack of automatic temperature control, excessive temperature variations, and a lack of reliable visual feedback.
- Assessment of clinical needs (resin vs. wax) through interviews and field observation.

Regarding the preheating conditions required for the resin used in the dental laboratory, two commercial brands with specific thermal specifications were identified:

- Jamg He resin must reach a temperature of 930°C directly, without applying previous thermal intervals.
- On the other hand, Elegoo resin has a two-stage heating curve: first, it is maintained at 350°C for 30

minutes, and then the temperature is raised to 930°C for 45 minutes.



(a) (b)

Fig. 1. Initial state of the furnace. (a) Front view of the furnace, (b) Interior view of the furnace.

These specifications allow the temperature profiles of the automated preheating system to be adjusted, optimizing the thermal process according to the type of resin used and thus ensuring the dimensional and structural integrity of the dental parts manufactured.

Therefore, two operating modes are established for the furnace to calcine wax and resin at specific temperatures and times, following the manufacturer's specifications.

B. System identification and dynamic modeling

The thermal plant was modelled using system identification techniques in the MATLAB® and Simulink® environment to obtain the furnace transfer function. The procedure included:

- Application of step input signals.
- Data acquisition using K-type sensors connected to MAX6675 modules.
- Modeling using parameter estimation (poles and zeros) and model validation in the time domain.
- Simulation of system dynamics using Simulink.

This is reflected in an underdamped system with slight oscillations, stabilizing to a steady state.
After the structural redesign and the incorporation of new electronic components, the experimental tests were repeated, and a new, more stable transfer function was obtained, with three poles and one zero, representing 91.42% adequacy to the observed model, exceeding 95% fidelity in the simulation.

C. Control system design

A PID controller was designed and tuned using the MATLAB PID Tuner tool on the identified FOPDT model, evaluating overshoot, settling time, and steady-state error as performance criteria. The final values selected were:

- Kp = 2,
- Ki = 1,
- Kd = 1,

This design was validated in simulation and subsequently implemented in hardware (ESP32 microcontroller). This provided a fast response, with slight overshoot but no persistent oscillations, meeting the accuracy and stability requirements for wax and resin preheating processes.

D. Software

The code was developed in C++ using Arduino IDE, adapted for the ESP32 microcontroller. The software includes PID control routines, ON/OFF control, and data visualization. In other words, the system allows you to select the number of stages (one or two), configure time and temperature from a touchscreen HMI interface, depending on the type of material, and view the temperature variable and process status in real-time.
The logic of the program implemented in the ESP32 microcontroller is summarized below:

```
%Temperature Control Algorithm
%Start
  %Read current temperature from MAX6675 sensor

  If PID mode = true Then
    Calculate PID output using setpoint and temperature
    Apply PWM with PID output to the heater
  Else
    If temperature < setpoint Then
      Turn on heater
    Else
      Turn off heater
    EndIf
  EndIf

  %Send temperature to HMI screen
End

%Timer Algorithm Process
Start
  startTime ← millis()
  endTime ← startTime + scheduledDuration

  While millis() < endTime Do
    Execute TemperatureControl
  EndWhile

  Turn off heater
  Activate buzzer
  Display message "Process completed"
End

%Parameter Adjustment Algorithm
```

```
Start
    If Temp+ button pressed Then increase setpoint
    If Temp- button pressed Then decrease setpoint
    If Time+ button pressed Then increase duration
    If Time- button pressed Then decrease duration

    %Update values on HMI screen
End
```

E. Hardware

The components were selected using weighting arrays, considering criteria such as performance, cost, compatibility, size, and energy consumption. The final system, Fig. 2(c), includes:

- Temperature sensor (K-type thermocouple) with MAX6675 module for accurate and safe high-temperature measurement.
- Nextion 4.3" display for configuration and visualization of the preheating process, Figure 2(d).
- 25A solid-state relay for safe control of the heating element.
- ESP32 microcontroller: main controller, selected for its processing capacity, connectivity, and support for PWM control.
- Regulated 24V 6A DC power supply, together with capacitors, transistors, resistors, and diodes that make up the power and protection system.
- Custom PCB under IPC-2221B standard, transistors, resistors, and diodes that make up the power and protection system, Fig. 2(b).
- Communication between the different modules was established via SPI and UART interfaces, while electrical safety protections were incorporated in compliance with IEC 60601 and IEC 61010 standards, thus ensuring the reliability and safety of the system in clinical environments.

To store and protect the new electronic components, a new base box was designed in CAD, Fig. 2(a), which replaced the original oven housing. This structure includes specific openings for ventilation, cable routing, sensor mounting, and access to user controls. In addition, the structure was manufactured from heat-resistant material, dimensionally adapted to safely house the microcontroller, power supply, solid-state relay, and HMI display, Fig. 2(e).

III. Results

The project validation is structured in four stages: readjustment of the mechanical structure, redesign of the electrical and electronic system, validation of the controller model, and functional testing with real materials. The main results and findings of each stage are described below.

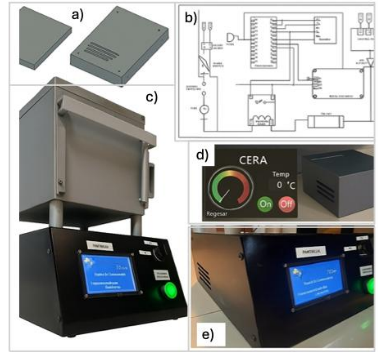


Fig. 2. Final prototype of the furnace. (a) 3D view of the furnace structure, (b) Schematic design of the PCB. (c) Redesigned dental furnace. (d) Temperature control coding screen and (e) HMI screen.

F. Readjustment of the mechanical structure

The evaluation revealed substantial structural deficiencies in the original furnace configuration, which compromised thermal efficiency, operational reliability, and overall system performance. The main deficiencies were associated with substantial heat losses due to inadequate insulation, directly affecting thermal stability and energy efficiency. Moreover, several electronic parts showed excessive damage to their physical components, which could indeed be a threat, possibly compromising the safety and quality of temperature control accuracy, Fig. 3. To mitigate these structural and thermal shortcomings, three key components of the furnace were reengineered: the base enclosure, the upper section, and the side panel. Not only did the parts have considerable wear, but they also did not thermally insulate well, which significantly decreased the heat output of the operation. The new structural design was modularized to facilitate assembly, maintenance, and future technical interventions. Additionally, a thermal isolation barrier was implemented between the oven chamber and the electrical control compartment to prevent heat transfer to sensitive electronic components. The access point to the control panel was relocated to the lateral side of the unit, allowing maintenance and inspection without requiring removal of the furnace from its installation position. Furthermore, high-temperature sealing techniques were incorporated to improve thermal containment and structural integrity. These modifications enhanced thermal containment and improved operational safety margins, Fig. 4. These structural modifications significantly increased the thermal output of the system for a more accurate, reliable, and safer control of temperature. To verify these enhancements, infrared thermography was performed to monitor the outer skin temperature of the furnace and to trace the heat flow across structural joints. It also suggested less heat loss of 1.5 W after the upgrade (95.4% reduction from 32.5 W in one of the original oven design systems). That improved heat retention increased the production of energy, so that heat avoided leaking. Furthermore, the temperature of external areas of the oven and the space of the electronic control panel were also checked and established to keep the temperature within safe limits when used, and so significantly enhance practitioners' safety and control over heating of the electronic elements. It creates certain conditions for system continuity.

(a) (b)

Fig. 3. Mechanical structure (a) Inside the furnace, (b) Damaged components

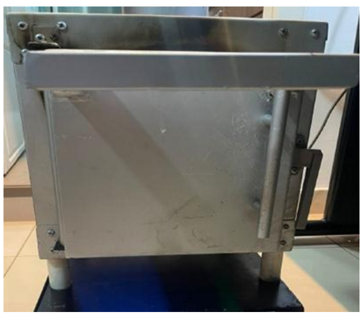


Fig. 4. Final mechanical structure of the furnace

G. *Redesign of the electrical and electronic system*

This includes the selection and integration of electronic components to provide a more accurate and flexible temperature control system for various materials (wax and resin are currently the preferred). This REX-C900 temperature controller-based previous system was limited without configuration, material selection, and digital monitoring.

The redesigned system incorporates an ESP32-based programmable microcontroller architecture, K-type temperature sensors, a touchscreen HMI interface, and solid-state relays for power switching. Table 2 lists these functions and shows a list of functionalities added with the implementation of this update.

TABLE II
FEATURE COMPARISON.

Functionality	Previous System	Current System
User interface	4-digit LED display	Touchscreen HMI with interactive menu
Operating modes	Single (manual)	Two (resin mode/wax mode)
Parameter configuration	Manual via buttons	Digital, from HMI
Safety alarms	Not available	Audible and visual alert
Output signal	Electromechanical relay	Solid state relay (SSR)
Adaptability to new materials	No	Yes, via selection menu

High-quality temperature control accuracy of the system is supported, with attributes not found on market-standard systems, such as:

- Material type selection: Using the HMI, the operator can choose wax or resin material. Each option sets required temperature and time parameters specific to its own process.
- Alert for safety: A system with audible and visual alarms was fitted to trigger when the temperature was raised above the limits determined.
- Real-time status: the graphical display shows progress of preheating, current temperature, remaining time, and actuator status (On/Off).

These enhancements improve operational reliability, safety, and system flexibility, while simplifying user interaction and process management. Furthermore, the adopted architecture provides a scalable framework that supports future functional expansions without requiring substantial hardware modifications. Potential system extensions are outlined as follows:

- Add new materials: one user-friendly option to add materials is incorporated: an option for the user to register new types of materials, specifying specific parameters for heating and processing times.
- Record and storage of data: a system of traceability for storing and recording the history of each process is implemented, allowing the recording (including temperature curves and the users who used the oven) of the history behind the processes. This makes it easy to monitor and manage equipment for oversight of a system.
- Remote connectivity: Integration of a Wi-Fi connection that allows real-time monitoring of the system status, as well as receiving alerts and notifications via a cloud server or platforms such as Telegram.

H. *Temperature Control System*

The validation of the temperature control system includes modelling the thermal behaviour of the furnace, designing the PID controller using simulation tools, and validating the results between the model and the physical system.

The process begins with the acquisition of experimental data from the furnace operating under controlled conditions, using the type K thermocouple incorporated into the system. Temperatures were recorded at regular intervals until approximately 1000 °C was reached. The data summary is shown in Table III.

TABLE III
TEMPERATURE MEASUREMENT IN CURRENT SYSTEM.

No.	Time (mm:ss)	Temperature (°C)
1	00:00	29
2	02:51	124
3	03:18	224
4	04:00	324
5	05:06	424
6	05:28	524
7	06:23	624
8	08:01	724
9	10:03	824
10	13:38	924

Based on the results, the dynamics of the system were identified using the step response method. A first-order model with delay (FOPDT) was fitted, represented by the following transfer function as in (1).

$$G(s) = \frac{K}{\tau s + 1} \cdot e^{-Ls} \quad (1)$$

Where:
K: static gain of the system,
τ: thermal time constant,
L: dead time (response delay).

This model reflects the typical behaviour of a system with high thermal inertia, such as an oven. In this case, the values obtained for static gain (K) are 895°C, dead time (L) is 1.5 minutes, and thermal time constant (τ) is 4.6 minutes.

The model fitting was validated in MATLAB using time-domain comparison between experimental and simulated responses, achieving a goodness-of-fit of 95.2%.
The Root Mean Square Error (RMSE) between experimental and simulated responses was 8.7°C during the transient phase and <1°C at steady-state conditions.

A PID controller was designed to achieve precise temperature control, reducing heating time and minimizing steady-state error. Given that the furnace has slow dynamics, with high thermal inertia and response delay, a controller capable of compensating for these effects was chosen. PID parameters were obtained using the MATLAB PID Tuner tool applied to the identified FOPDT model, following a setpoint tracking criterion that prioritizes smooth response with minimal overshoot and low steady-state error. This approach is equivalent to model-based optimization tuning, as opposed to manual methods such as Ziegler–Nichols.
Tuning was carried out in the MATLAB/Simulink environment, using the PID Tuner block on the obtained FOPDT model. The tuning criterion for setpoint tracking was applied, prioritizing a smooth response, without pronounced overshoots, and with low final error.

Although advanced strategies such as Model Predictive Control (MPC) or adaptive control could further enhance performance, PID control was selected due to:

- Low computational cost,
- Ease of implementation in embedded systems,
- Robustness against moderate modeling uncertainty,
- Industrial acceptance and maintenance simplicity.

Although a proportional-only (P) controller could theoretically regulate this first-order process, it would result in a non-zero steady-state error that is unacceptable given the ±0.5°C accuracy requirement of the dental calcination process. The integral term (I) eliminates this offset, while the derivative term (D) improves transient response during temperature ramp-up, justifying the full PID structure.

Given the slow dynamics and high thermal inertia of the system, PID provides sufficient accuracy while maintaining system stability and scalability. Closed-loop stability was verified through simulation in Simulink, confirming adequate gain and phase margins. The step response of the controlled system shows no sustained oscillations and converges to the setpoint within the thermal constraints of the furnace.

I. Results Validation

The parameters obtained on the PID controller were Kp=2.1, Ki=0.9, and Kd=0.5. After the PID algorithm was applied to the microcontroller, the furnace demonstrated similar behaviour to the initial tests, Table IV. It was verified that the system was controlled:

- Reach the desired temperature (900°C) in 9.5 minutes.
- Steady-state error is less than +/- 0.5 °C.
- Eliminates overshoots.

Table IV presents a direct performance comparison between the uncontrolled (open-loop) system and the PID-controlled system, demonstrating measurable improvements across all key control metrics

TABLE IV
COMPARISON BETWEEN THE SYSTEM WITHOUT PID VS. THE SYSTEM WITH PID.

Parameter	Without PID	With PID
Settling time	13.6 min	9.5 min
Steady-state error	+/- 5°C	+/-0.5°C
Stability	Medium	High

The system response showed no steady-state overshoot after controller tuning. Based on the identified FOPDT model and experimental validation data, the Integral Absolute Error (IAE) for the full wax calcination cycle (75 min) was estimated at 211,881 °C·s, representing a 41.2% reduction compared to the uncontrolled system. Settling time was reduced from 13.6 min (uncontrolled) to 9.5 min with PID control, representing a 30.1% improvement in response speed.

Accordingly, the proposed control strategy was implemented within the furnace architecture to ensure effective, stable, and safe temperature regulation, thereby guaranteeing the required thermal conditions for dental treatment processes. To validate the overall system performance, experimental trials were conducted using commercially available dental materials (Jamg He and Elegoo photopolymerizable resins), each requiring a specific thermal profile for calcination. The experiments validated that the control system could manage relevant temperature curves and adapt to different thermal cycles to produce repeatable values while avoiding material compromise or operator safety hazards. Two thermal profiles were defined using the HMI interface of the oven and then programmed:

- Jamg He resin continuously rises to 930 °C, without intermediate maintenance.
- Elegoo resin: two stages:
  - Phase 1: keep 350 °C for 30 minutes.
  - Phase 2: gradual rise to 930 °C in 45 minutes.

A total of five tests were conducted for each profile, where the temperature, time, and physical examinations of the material were recorded at the conclusion of the process. Thermal behavior in each profile was constant with the type K thermocouple installed. The tests confirmed stable thermal behavior across both profiles. The system was able to maintain the system's temperature constant with an error of < ±0.5 °C, and there were no sharp variations during the maintenance or transition between stages. Test results obtained after all testing showed that the system could reach the target temperature and maintain it with over 99% accuracy, where a limit of error < ±0.5 °C was observed, and deformations, bubbles, or signs of overheating had not been detected in the processed materials, Table 5.

TABLE V
GLOBAL COMPARISON BETWEEN THE SYSTEM WITHOUT PID VS. WITH PID.

Material	Test	Phase	Target Temperature (°C)	Final Temperature (°C)	Error (°C)	Target time (min)	Notes
Wax	1	Unique	930	929.5	0.5	~ 75	No anomalies
	2	Unique	930	930.2	0.2	~ 75	No anomalies
	3	Unique	930	929.0	-1.0	~ 75	No anomalies
	4	Unique	930	930.6	+0.6	~ 75	No anomalies
	5	Unique	930	929.8	-0.2	~ 75	No anomalies
Resin	1	Phase 1	350	349.5	-1.0	30	No anomalies
		Phase 2	930	930.2	+0.2	45	
	2	Phase 1	350	349.0	-1.0	30	No anomalies
		Phase 2	930	930.0	0.0	45	
	3	Phase 1	350	349.8	-0.2	30	No anomalies
		Phase 2	930	930.5	0.5	45	
	4	Phase 1	350	349.1	-0.9	30	No anomalies
		Phase 2	930	930.3	0.3	45	
	5	Phase 1	350	349.2	-0.8	30	No anomalies
		Phase 2	930	929.9	-0.1	45	

IV. CONCLUSIONS

This study focused on the design, construction, and configuration of an automated preheating system for dental laboratory furnaces, addressing the limitations associated with conventional and obsolete thermal control methods. The implemented PID-based closed-loop strategy achieved temperature regulation within ±0.5 °C, significantly improving the reliability and reproducibility of wax and resin calcination processes. Additionally, an energy efficiency improvement of approximately 18% was experimentally validated under standard operating conditions.

The structural redesign of the furnace, combined with the integration of a Human–Machine Interface (HMI), enabled programmable thermal profiles, real-time monitoring, and enhanced operational safety. These improvements contributed to increase process stability, user control, and traceability of thermal cycles.

The findings demonstrate that the automation of legacy thermal systems in dental laboratories enhances operational performance while offering a cost-effective alternative to commercial programmable furnaces. This approach is particularly relevant for resource-constrained environments across Latin America, where technological accessibility and sustainability are critical factors.

From a cost-benefit perspective, the proposed system was implemented at an estimated component cost of approximately \$144–\$247 USD, which is comparable to entry-level commercial preheating units available in the market at similar price points. However, unlike those closed solutions, the proposed system enables retrofitting of existing legacy furnaces, eliminating the need for full equipment replacement and providing an open, customizable platform with features such as multi-material profiles, HMI interface, and IoT-ready architecture not typically found in commercial alternatives at this price range.

Future work will explore the integration of IoT connectivity for remote monitoring and data logging, expansion of the programmable materials database, and multi-site clinical validation to assess scalability and broader deployment potential.

References

[1] Lousan do Nascimento Poubel, D., A. E. Ghanem Zanon, J. C. Franco Almeida, L. Vicente Melo de Lucas Rezende, y F. C. Pimentel Garcia. 2022. "Composite Resin Preheating Techniques for Cementation of Indirect Restorations." International Journal of Biomaterials 2022: 5935668. https://doi.org/10.1155/2022/5935668.

[2] Lopes, L. C. P., R. S. S. Terada, F. M. Tsuzuki, et al. 2020. “Heating and Preheating of Dental Restorative Materials—A Systematic Review.” Clinical Oral Investigations 24: 4225–4235. https://doi.org/10.1007/s00784-020-03637-2.

[3] Anusavice, Kenneth J. Phillips' Science of Dental Materials. St. Louis: Elsevier, 2012.

[4] Kanitkar, A. A., A. S. Kanitkar, R. S. Sasane, S. S. Patil, S. R. Chopade, y S. Vaidya. “Analyse the Effect of Different Investment Techniques and Pattern Materials on Surface Roughness of Raw Ni-Cr Castings: An In Vitro Study.” Journal of Indian Prosthodontic Society 20, no. 1 (January–March 2020): 97–103. https://doi.org/10.4103/jips.jips_202_19.

[5] Kilinç, E., D. Kaya, F. Ç. Kiliç, et al. “An Energy Efficiency Analysis of an Industrial Reheating Furnace and an Implementation of Efficiency Enhancements Methods.” Energy Exploration & Exploitation 32, no. 6 (2014): 989–1003. https://doi.org/10.1260/0144-5987.32.6.989.

[6] DentalSaleMall. “15 kW 1000 °C Mini Dental Lab Wax Muffle Furnace High Temperature Wax Burnout Oven for Preheating Crucible.” DentalSaleMall. Consultado el 11 de julio de 2025. https://www.dentalsalemall.com/15KW-1000%E2%84%83-Mini-Dental-Lab-Wax-Muffle-Furnace-High-Temperature-Wax-Burnout-Oven-for-Preheating-Crucible-3391.html.

[7] Cykylab Equipment. “Dental Preheating and Dewaxing Furnace – Dental Lab Equipment.” Made in China.com. Consultado el 11 de julio de 2025. https://cykylabequipment.en.made-in-china.com/product/oScEBhHKftUw/China-Dental-Preheating-and-Dewaxing-Furnace-Dental-Lab-Equipment.html.

[8] Renfert GmbH. “Magma.” Hornos de precalentamiento. Renfert. https://www.renfert.com/es/productos/aparatos/hornos-de-precalentamiento/magma.

[9] Palacio-Caro, Iván D., Pedro N. Alvarado-Torres, and Luis F. Cardona-Sepúlveda. “Numerical Simulation of the Flow and Heat Transfer in an Electric Steel Tempering Furnace.” Energies 13, no. 14 (2020): 3655. https://doi.org/10.3390/en13143655.

[10] SmileArt Lab. “Digital Workflow in Dental Labs.” SmileArt Lab. https://smileartlab.com.au/blog/digital-workflow-in-dental-labs/.

[11] Shao Yong Lu, Guan Ming Chen, Wen Ping Chen, and Cheng Fu Yang. “Design of a Monitoring System for a Burn-in Furnace with Heat Dissipation and Temperature Control.” Sensors and Materials 37, no. 6 (June 2025): 2409–2420. https://doi.org/10.18494/SAM5665

[12] Kindle-Tech. 2025. "El Futuro de los Hornos de Porcelana en los Laboratorios Dentales." Kindle-Tech, julio 2025. https://es.kindle-tech.com/articles/the-future-of-porcelain-furnaces-in-dental-laboratories.

[13] Sakaguchi, Ronald L., y John M. Powers, eds. Craig's Restorative Dental Materials. 14ª edición. Elsevier, 2019.