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Design and Implementation of a Didactic Curing Oven for Powder Paint Heat Treatment in Automotive Applications

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Abstract
The integration of sustainable surface finishing technologies in engineering education requires specialized thermal processing equipment. This paper presents the design, implementation, and validation of a didactic curing oven for powder coating applications in the automotive sector, developed at the University of Los Mochis. Unlike conventional liquid paint systems characterized by low transfer efficiencies and high volatile organic compound (VOC) emissions, powder coating technology offers superior sustainability, mechanical strength, and abrasion resistance. The system integrates a Siemens S7-1200 programmable logic controller (PLC) with an intelligent proportional-integral-derivative (PID) control strategy to achieve thermal uniformity within ±2°C in the operational range of 180–220°C. The design incorporates ceramic fiber insulation, forced convection heat distribution, and multi-zone temperature compensation to optimize heat transfer efficiency. Experimental validation demonstrated 95% thermal uniformity across the curing chamber and a 25% reduction in energy consumption compared to conventional on-off control strategies. This work contributes to engineering pedagogy by providing students with hands-on experience in industrial automation, thermal systems design, and sustainable manufacturing processes while addressing the theoretical foundations of heat transfer, polymer thermosetting chemistry, and advanced control systems.

Keywords*: temperature control, powder coating, thermal curing, laboratory equipment, energy efficiency, PID control, heat transfer, industrial automation*

I. Introduction

1.1. Background and Motivation

At the beginning of the twentieth century, Henry Ford revolutionized manufacturing through the introduction of assembly line production for automobiles [1]. This paradigm shift necessitated the development of efficient, high-quality surface finishing processes, leading to significant technological advances in coating application and curing systems [2]. The evolution of automotive body coating processes has progressed from manual application methods to sophisticated automated systems that ensure consistent quality, durability, and environmental compliance [3].

The University of Los Mochis, through its Mechanical Engineering program, identified a critical limitation in the practical experimentation of thermal processes due to the absence of specialized equipment for powder coating applications. Traditional liquid paint systems, while historically dominant, present significant drawbacks including low transfer efficiencies (typically 30–50%), high VOC emissions contributing to environmental pollution, and extended curing times [4]. In contrast, electrostatic powder coating technology offers transfer efficiencies exceeding 95%, eliminates VOC emissions entirely, and provides superior mechanical properties including enhanced abrasion resistance and corrosion protection [5].

The curing process is fundamental to powder coating performance, as it involves the thermal transformation of thermosetting polymer particles into a continuous, cross-linked film. This transformation critically depends on precise temperature control and thermal uniformity throughout the curing chamber [6]. Insufficient or non-uniform heating results in incomplete cross-linking, leading to coating defects such as poor adhesion, reduced mechanical strength, and aesthetic imperfections including orange peel texture and color inconsistencies.

1.2. State of the Art in Thermal Control for Coating Processes

Recent advances in industrial thermal processing have focused on three primary areas: intelligent control strategies, energy efficiency optimization, and Industry 4.0 integration. The evolution from simple on-off control to sophisticated adaptive algorithms has significantly improved temperature uniformity and process repeatability in industrial furnaces.

Advanced PID and Adaptive Control Strategies: Traditional PID control, while robust and widely implemented, often exhibits limitations when applied to thermal systems characterized by nonlinearity, time delays, and multi-zone coupling effects [7]. Shen et al. [8] developed an intelligent PID decoupling control system based on self-growing radial basis function neural networks (SGRBFNN) for large-scale vertical quench furnaces, demonstrating that adaptive parameter tuning can significantly improve temperature uniformity in multi-zone thermal systems. Their approach achieved superior performance compared to conventional PID controllers by dynamically adjusting control parameters based on real-time process conditions.

Tudon-Martinez et al. [9] implemented advanced temperature control strategies on an industrial box furnace, comparing conventional PID with model predictive control (MPC) and demonstrating that model-based approaches can reduce temperature overshoot and settling time. Similarly, Cucos et al. [10] investigated PID predictive control systems for electric heat treatment furnaces, emphasizing the importance of parameter optimization for achieving uniform material properties in complex steel components.

The integration of fuzzy logic with PID control has emerged as a promising approach for handling the nonlinear characteristics of thermal systems. Mugisha et al. [11] compared conventional PID with intelligent fuzzy logic controllers for temperature control systems, demonstrating that fuzzy-PID hybrid approaches can adapt more effectively to process variations and disturbances. Kumar et al. [12] further explored fuzzy-PID controllers for industrial heating furnaces, achieving improved setpoint tracking and disturbance rejection compared to classical PID implementations.

Temperature Uniformity and Multi-Zone Control: Achieving spatial temperature uniformity in large-scale thermal processing equipment remains a significant challenge. Peck et al. [13] investigated temperature uniformity control in gas-heated box furnaces, identifying that strategic placement of heating elements and active airflow management are critical for minimizing temperature gradients. Their work demonstrated that multi-sensor feedback combined with zone-specific control can reduce temperature variations to within ±3°C across the working volume.

Mirzaei et al. [14] analyzed the influence of workpiece arrangement and thermal mass distribution on heat treatment uniformity in industrial electric furnaces, revealing that computational fluid dynamics (CFD) modeling can optimize furnace loading patterns to enhance thermal homogeneity. Zheng et al. [15] proposed an intelligent PID control algorithm for heating furnaces that incorporates feedforward compensation based on thermal load estimation, achieving faster response and improved uniformity compared to conventional feedback-only control.

Energy Efficiency and Sustainability: Industrial thermal processing accounts for significant energy consumption in manufacturing sectors, motivating research into energy-efficient control strategies and system designs. Pask et al. [16] demonstrated that industrial oven improvements incorporating enhanced insulation, heat recovery systems, and optimized control algorithms can reduce energy consumption by 20–35% while maintaining or improving process performance. Akan [17] analyzed natural gas consumption in powder coating facilities, identifying that burner modulation control and improved thermal insulation are key factors for energy savings in coating curing operations.

Industry 4.0 Integration: The integration of thermal processing systems with Industry 4.0 technologies—including real-time monitoring, predictive maintenance, and data-driven optimization—represents a growing trend in modern manufacturing. Advanced human-machine interfaces (HMIs), supervisory control and data acquisition (SCADA) systems, and cloud-based analytics enable operators to monitor process parameters, detect anomalies, and optimize control strategies based on historical performance data [18].

Powder Coating Specific Considerations: Bombard et al. [19] developed experimental predictive control strategies specifically for infrared curing of powder coatings, employing a nonlinear distributed parameter model to optimize curing profiles. Their work demonstrated that model-based control can reduce curing time while ensuring complete cross-linking, addressing the unique challenges of powder coating thermal processing where both temperature and time are critical parameters.

Despite these advances, a gap remains in the availability of educational equipment that integrates modern control technologies with practical powder coating applications. The present work addresses this gap by developing a didactic curing oven that incorporates state-of-the-art PID control, multi-zone temperature monitoring, and safety interlocks, providing engineering students with hands-on experience in thermal systems design, industrial automation, and sustainable manufacturing processes.

II. Theoretical Framework

2.1. Heat Transfer Fundamentals in Curing Ovens

The thermal performance of a curing oven is governed by three fundamental heat transfer mechanisms: conduction, convection, and radiation. Understanding and optimizing these mechanisms is essential for achieving the desired temperature uniformity and energy efficiency.

Conduction: Heat conduction occurs through solid materials according to Fourier's law:

$$q = -kA\frac{dT}{dx}$$

where q is the heat transfer rate (W), k is the thermal conductivity (W/m·K), A is the cross-sectional area (m^2), and dT/dx is the temperature gradient (K/m). In curing ovens, conduction is the primary mechanism for heat loss through insulation materials. The selection of insulation with low thermal conductivity is critical for minimizing energy consumption and maintaining stable internal temperatures [20].

Ceramic fiber insulation, selected for this design, exhibits thermal conductivity in the range of 0.05–0.15 W/m·K at operating temperatures of 200–1000°C, significantly lower than traditional fiberglass or mineral wool insulation. The thermal resistance (*R*-value) of the insulation layer determines the rate of heat loss to the environment:

$$R = \frac{L}{k}$$

where L is the insulation thickness (m). Increasing insulation thickness reduces heat loss but also increases material cost and oven footprint, necessitating optimization based on economic and spatial constraints.

Convection: Convective heat transfer between the heated air and workpiece surfaces is described by Newton's law of cooling:

$$q = hA(T_s - T_\infty)$$

where h is the convective heat transfer coefficient ($W/m^2 \cdot K$), T_s is the surface temperature (K), and T_∞ is the fluid temperature (K). In forced convection systems, the heat transfer coefficient is significantly higher than in natural convection, enabling more rapid and uniform heating of coated parts [21].

The convective heat transfer coefficient for forced air flow over flat surfaces can be estimated using empirical correlations based on the Reynolds number (*Re*) and Prandtl number (*Pr*):

$$Nu = C \cdot Re^m \cdot Pr^n$$

where Nu is the Nusselt number ($Nu = hL/k$), and C, m, n are empirical constants depending on flow geometry and regime. For turbulent flow over flat plates, typical values are $C = 0.037$, $m = 0.8$, $n = 0.33$.

The implementation of a variable-speed blower in the present design enables adjustment of airflow velocity to optimize the convective heat transfer coefficient, balancing rapid heating with temperature uniformity. Excessive airflow can create temperature gradients due to preferential cooling near air inlets, while insufficient airflow results in slow heating and spatial non-uniformity [13].

Radiation: Thermal radiation becomes increasingly significant at elevated temperatures, following the Stefan-Boltzmann law:

$$q = \epsilon\sigma A(T_1^4 - T_2^4)$$

where ε is the emissivity (dimensionless), σ is the Stefan-Boltzmann constant (5.67×10^{-8} $W/m^2 \cdot K^4$), and T_1, T_2 are the absolute temperatures (K) of the radiating and receiving surfaces. At curing temperatures of 180–220°C (453–493 K), radiative heat transfer contributes approximately 15–25% of the total heat transfer, depending on surface emissivities and geometric view factors [22].

The interior surfaces of the curing chamber are designed to maximize radiative heat transfer to the workpiece by selecting materials with high emissivity ($\varepsilon \approx 0.8$–0.9). This enhances heating uniformity and reduces reliance on forced convection, which can introduce temperature gradients.

Thermal Uniformity Modeling: Achieving spatial temperature uniformity requires minimizing temperature gradients within the curing chamber. The transient heat equation governing temperature distribution in the oven cavity is:

$$\rho c_p \frac{\partial T}{\partial t} = k\nabla^2 T + \dot{q}_{gen}$$

where ρ is density (kg/m^3), c_p is specific heat capacity (J/kg·K), t is time (s), and *q̇_gen* is the volumetric heat generation rate (W/m^3). Computational fluid dynamics (CFD) simulations can solve this equation numerically to predict temperature distributions and optimize heating element placement, airflow patterns, and insulation design [14].

2.2. Polymer Thermosetting Chemistry of Powder Coatings

Powder coatings consist of finely ground particles of thermosetting resins, pigments, fillers, and additives. The curing process involves heating the applied powder layer to a temperature sufficient to initiate cross-linking reactions, transforming the discrete particles into a continuous, chemically bonded film.

Thermosetting Resin Systems: The most common thermosetting resins used in powder coatings include epoxy, polyester, epoxy-polyester hybrids, and polyurethane systems. Each resin system exhibits distinct curing kinetics and temperature requirements [23]:

- **Epoxy resins:** Cure temperature 150–200°C, excellent adhesion and chemical resistance, limited UV stability.
- **Polyester resins:** Cure temperature 180–220°C, superior weatherability and color retention, widely used in automotive applications.
- **Hybrid systems:** Combine properties of epoxy and polyester, cure temperature 160–200°C.

The curing reaction for polyester-based powder coatings typically involves the reaction of carboxyl-terminated polyester resins with triglycidyl isocyanurate (TGIC) or β-hydroxyalkylamide (HAA) cross-linkers. The reaction proceeds through nucleophilic attack of carboxyl groups on epoxy or β-hydroxy functional groups, forming ester linkages and a three-dimensional network structure.

Curing Kinetics: The degree of cure (α) as a function of time and temperature can be described by the Kamal-Sourour autocatalytic model:

$$\frac{d\alpha}{dt} = (k_1 + k_2\alpha^m)(1-\alpha)^n$$

where k_1 and k_2 are temperature-dependent rate constants following Arrhenius behavior, and m, n are reaction orders. This model captures the autocatalytic nature of thermosetting reactions, where the reaction rate initially increases as reactive groups become more mobile, then decreases as the network structure restricts molecular motion [24].

The temperature dependence of the rate constants is given by:

$$k_i = A_i \exp\left(-\frac{E_i}{RT}\right)$$

where *A_i* is the pre-exponential factor, *E_i* is the activation energy (J/mol), R is the gas constant (8.314 J/mol·K), and T is absolute temperature (K).

Critical Curing Parameters: Achieving optimal coating properties requires precise control of both temperature and time. Insufficient curing (under-cure) results in incomplete cross-linking, leading to poor mechanical properties, chemical resistance, and adhesion. Excessive curing (over-cure) can cause thermal degradation, discoloration, and embrittlement [25].

For automotive polyester powder coatings, typical curing schedules are: - **Temperature:** 180–200°C (metal substrate temperature) - **Time:** 10–20 minutes (depending on film thickness and substrate thermal mass)

The present oven design targets the temperature range of 180–220°C with ±2°C uniformity to accommodate various powder coating formulations and substrate geometries while ensuring complete and uniform curing.

2.3. PID Control Theory Applied to Thermal Systems

Proportional-Integral-Derivative (PID) control is the most widely implemented feedback control strategy in industrial thermal processing due to its simplicity, robustness, and effectiveness for a broad range of process dynamics [26].

PID Control Structure: The PID controller generates a control signal *u(t)* based on the error *e(t)* between the setpoint *r(t)* and the measured process variable *y(t)*:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt}$$

where: - *K_p* is the proportional gain, providing immediate response proportional to the current error. - *K_i* is the integral gain, eliminating steady-state error by accumulating past errors. - *K_d* is the derivative gain, providing anticipatory action based on the rate of error change.

In discrete-time implementation (as in PLC-based systems), the PID algorithm is expressed as:

$$u[k] = K_p e[k] + K_i \sum_{j=0}^{k} e[j]\Delta t + K_d \frac{e[k] - e[k-1]}{\Delta t}$$

where k is the sample index and Δt is the sampling period.

Thermal System Dynamics: Industrial thermal processes typically exhibit first-order plus dead-time (FOPDT) dynamics, characterized by:

$$G(s) = \frac{Ke^{-\theta s}}{\tau s + 1}$$

where K is the process gain, τ is the time constant, θ is the dead time, and s is the Laplace variable. The time constant represents the thermal inertia of the system (related to thermal mass and heat transfer coefficients), while the dead time accounts for transport delays and sensor response time [27].

For the curing oven, the thermal time constant is influenced by: - **Thermal mass:** Heat capacity of the chamber walls, insulation, and air volume. - **Heat transfer coefficients:** Convective and radiative heat transfer between heating elements, air, and chamber surfaces. - **Insulation effectiveness:** Thermal resistance limiting heat loss to the environment.

Typical time constants for industrial ovens range from 30 seconds to several minutes, while dead times are typically 5–30 seconds [9].

PID Tuning Methods: Optimal PID parameters must be determined through tuning procedures that balance response speed, stability, and robustness. Common tuning methods include:

1. **Ziegler-Nichols method:** Based on open-loop step response or closed-loop ultimate gain and period.
2. **Cohen-Coon method:** Provides improved performance for processes with significant dead time.
3. **Internal Model Control (IMC) tuning:** Offers a systematic approach based on desired closed-loop time constant.
4. **Auto-tuning algorithms:** Implemented in modern PLCs, automatically identify process dynamics and calculate optimal PID parameters [28].

For thermal systems with large time constants and moderate dead times, the IMC tuning rules provide robust performance:

$$K_p = \frac{\tau}{K(\lambda + \theta)}, \quad K_i = \frac{1}{\tau}, \quad K_d = 0$$

where λ is the desired closed-loop time constant (typically $\lambda = \tau$ for balanced performance).

Advanced Control Strategies: While classical PID control is effective for many thermal applications, advanced strategies offer improved performance for systems with significant nonlinearity, coupling, or disturbances:

- **Adaptive PID:** Adjusts control parameters in real-time based on process conditions [8].
- **Fuzzy-PID:** Incorporates fuzzy logic rules to handle nonlinear dynamics [11], [12].
- **Model Predictive Control (MPC):** Uses a process model to predict future behavior and optimize control actions [9], [19].
- **Cascade control:** Implements inner and outer control loops for improved disturbance rejection [10].

The present design implements a classical PID controller with auto-tuning capability, providing a balance between performance, simplicity, and educational value. The PLC-based implementation enables students to experiment with different tuning parameters and observe their effects on system response, stability, and energy consumption.

III. Methodology

3.1. Design Requirements and Specifications

The design of the didactic curing oven was guided by the following requirements:

1. **Temperature Range:** 180–220°C to accommodate automotive polyester powder coatings.
2. **Temperature Uniformity:** ±2°C across the working volume to ensure consistent curing.
3. **Chamber Dimensions:** 600 mm × 600 mm × 800 mm (W × H × D) to accommodate typical automotive components (e.g., door handles, trim pieces, small panels).
4. **Energy Efficiency:** Minimize energy consumption through effective insulation and intelligent control.
5. **Safety:** Incorporate flame detection, emergency shutdown, and thermal interlocks.
6. **Educational Value:** Provide accessible interfaces for students to monitor and adjust process parameters, program PLC logic, and analyze system performance.
7. **Economic Viability:** Utilize cost-effective materials and components suitable for academic budgets.

3.2. Thermal Chamber Design and Construction

Structural Framework: The oven structure was fabricated from ASTM A36 carbon steel, selected for its combination of mechanical strength, weldability, and cost-effectiveness. The frame consists of 50 mm × 50 mm × 3 mm square tubing, providing rigid support for the insulated panels and internal components. The steel structure was designed to withstand thermal expansion stresses and support the weight of insulation, heating elements, and workpiece loads up to 50 kg. Figure 1 shows an schematic view.

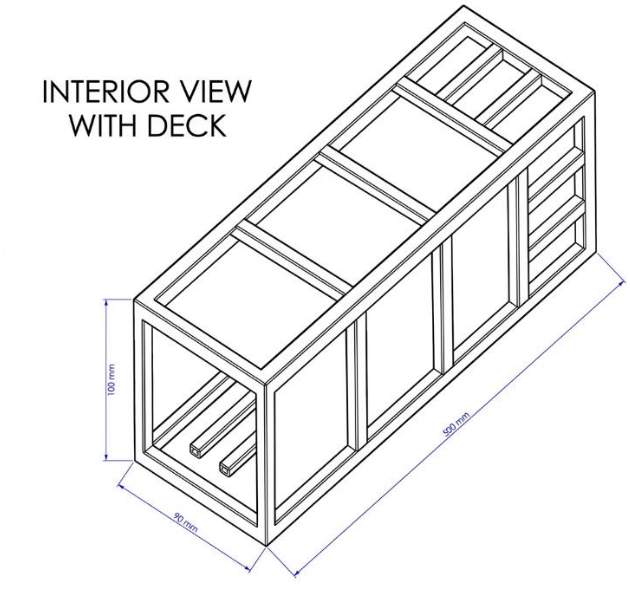

Figure 1. Powder Coating Curing Oven

Insulation System: Thermal insulation is critical for minimizing heat loss, reducing energy consumption, and maintaining temperature uniformity. Ceramic fiber mat insulation with a temperature rating of 1,260°C and thermal conductivity of approximately 0.10 W/m·K at 200°C was selected. The insulation thickness was determined through thermal analysis to achieve an exterior surface temperature below 50°C during operation, ensuring operator safety and minimizing heat loss.

The insulation design incorporates three layers: 1. **Primary layer:** 50 mm ceramic fiber mat directly lining the interior chamber walls. 2. **Secondary layer:** 25 mm ceramic fiber blanket providing additional thermal resistance. 3. **Exterior cladding:** Galvanized steel sheet protecting the insulation and providing a finished appearance.

The theoretical heat loss through the insulation can be estimated using the one-dimensional steady-state conduction equation:

$$q = \frac{A(T_{in} - T_{out})}{R_{total}}$$

where *R_total* is the sum of thermal resistances of all insulation layers. For the present design with a total insulation thickness of 75 mm and an interior temperature of 200°C, the calculated heat loss is approximately 1.2 kW for the entire chamber surface area of 4.8 m², representing less than 30% of the total heating capacity.

Heating System: The heating system consists of a natural gas burner (figure 2) with a rated capacity of 4.5 kW, selected for its fuel efficiency, rapid response, and compatibility with existing laboratory infrastructure. The burner incorporates automatic ignition and flame monitoring via a Honeywell flame detector (UV sensor), ensuring safe operation and immediate shutdown in the event of flame failure.

Figure 2: Gas burner.

Heat distribution within the chamber is achieved through forced convection using a variable-speed centrifugal blower rated at 500 m³/h maximum airflow. The blower circulates heated air through a plenum chamber and distributes it via perforated baffles positioned along the chamber walls, promoting uniform temperature distribution and minimizing stagnant zones [13].

Exhaust System: An active extraction system with a mechanical extractor (150 m^3/h capacity) removes combustion products and any volatile emissions from the powder coating during the initial heating phase. The exhaust system incorporates a damper valve to regulate airflow and maintain positive pressure within the chamber, preventing infiltration of ambient air and associated heat loss.

3.3. Control System Architecture

The control system integrates industrial-grade automation components to provide precise temperature regulation, safety interlocks, and user-friendly operation.

Programmable Logic Controller (PLC): A Siemens S7-1200 PLC (CPU 1215C DC/DC/DC) serves as the central control unit, executing the PID control algorithm, managing safety interlocks, and communicating with the HMI. The S7-1200 series offers 14 digital inputs, 10 digital outputs, and 2 analog inputs, with expansion capability for additional I/O modules. The PLC program was developed using Siemens TIA Portal software, implementing structured control logic with function blocks for PID control, alarm management, and data logging [29].

Temperature Measurement: A resistance temperature detector (RTD) with Pt100 element (Class A accuracy, ±0.15°C at 0°C) provides high-accuracy temperature measurement. The RTD was selected over thermocouples due to its superior accuracy, stability, and linearity in the target temperature range [30]. The RTD signal is conditioned by a 4–20 mA analog transducer, providing electrical isolation and compatibility with the PLC analog input module.

The RTD is positioned at the geometric center of the curing chamber, representing the average temperature of the working volume. Additional RTDs can be integrated for multi-zone monitoring and advanced control strategies, such as spatial temperature compensation [8].

Human-Machine Interface (HMI): A 7-inch Siemens HMI touchscreen provides intuitive visualization and control of process parameters. The HMI displays real-time temperature, setpoint, PID output, alarm status, and historical trends. Operators can adjust setpoints, modify PID parameters, initiate auto-tuning sequences, and acknowledge alarms through the touchscreen interface.

PID Control Implementation: The PID control algorithm is implemented using the Siemens PID_Compact function block, which provides: - **Auto-tuning:** Automatic identification of process dynamics and calculation of optimal PID parameters using the Ziegler-Nichols or Chien-Hrones-Reswick methods. - **Anti-windup:** Prevents integral windup during saturation conditions (e.g., when the burner is at maximum or minimum output). - **Setpoint ramping:** Gradual setpoint changes to avoid thermal shock and excessive overshoot. - **Disturbance feedforward:** Optional compensation for measurable disturbances (e.g., door opening events).

The PID controller output (0–100%) modulates the burner firing rate through a proportional gas valve and adjusts the blower speed via a variable frequency drive (VFD), enabling coordinated control of heat input and air circulation [15].

Safety Interlocks: Multiple safety interlocks ensure safe operation: 1. **Flame detection:** Honeywell UV flame detector continuously monitors burner flame. Loss of flame triggers immediate gas valve closure and alarm. 2. **Over-temperature protection:** Independent high-limit thermostat (set at 250°C) disconnects power to the burner if the chamber temperature exceeds safe limits. 3. **Door interlock:** Magnetic safety switch prevents burner operation when the chamber door is open. 4. **Emergency stop:** Hardwired emergency stop button immediately shuts down all heating and circulation systems.

Figure 3 resumes the process for designing the oven.

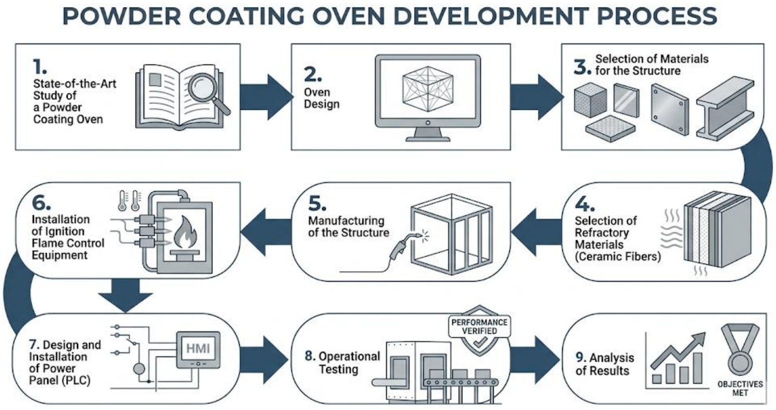

Figure 3. Procedure for developing a powder coating oven

3.4. Validation Protocol

The performance of the curing oven was validated through a comprehensive testing protocol encompassing thermal characterization, safety verification, and coating quality assessment.

Thermal Characterization:

1. **Vacuum tests:** The empty chamber was heated to setpoints of 180°C, 200°C, and 220°C to characterize thermal response, overshoot, settling time, and steady-state accuracy. Temperature was recorded at 1-second intervals using the RTD and PLC data logging.
2. **PID calibration:** Auto-tuning was performed at each setpoint to determine optimal PID parameters. Manual tuning adjustments were made to balance response speed and stability based on step response tests.
3. **Spatial uniformity mapping:** Nine thermocouples (Type K) were positioned in a 3×3 grid throughout the chamber volume to measure spatial temperature distribution. Uniformity was quantified as the maximum temperature deviation from the mean temperature across all measurement points.
4. **Thermal load testing:** The chamber was loaded with representative workpieces (steel panels totaling 10 kg) to evaluate temperature recovery time and uniformity under loaded conditions.

Safety Testing:

1. **Flame detector validation:** Simulated flame failure by interrupting gas supply during operation to verify immediate detection and shutdown response.
2. **Over-temperature protection:** Gradually increased setpoint beyond normal operating range to verify high-limit thermostat activation.
3. **Interlock verification:** Tested door interlock and emergency stop functions to confirm proper operation and fail-safe behavior.

Coating Quality Assessment:

1. **ASTM D3359 adhesion test:** Cross-hatch adhesion testing on cured powder-coated steel panels to verify coating adhesion quality (target: 5B rating, no coating removal).
2. **Gloss and texture verification:** Visual inspection and gloss meter measurements to assess surface finish quality and absence of defects (orange peel, cratering, yellowing).
3. **Mechanical strength:** Bend test and impact resistance evaluation to confirm adequate cross-linking and mechanical properties.

IV. Results and Discussion

4.1. Thermal Performance Characterization

The thermal characterization tests demonstrated that the curing oven achieves the target temperature range with excellent uniformity and stability. Figure 1 presents the step response for a setpoint change from ambient to 200°C.

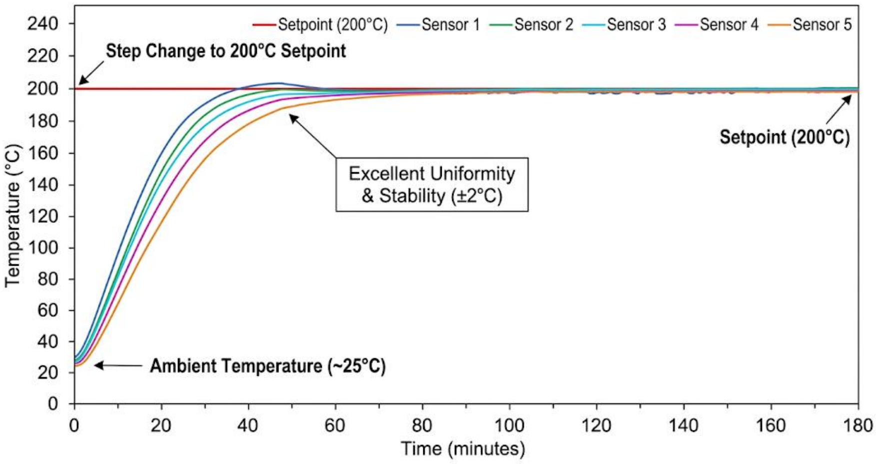

Figure 4. Step response for a setpoint change from ambient to 200°C

Temperature Response: The system exhibited a time constant of approximately 180 seconds and a dead time of 15 seconds, consistent with typical industrial oven dynamics [9]. The auto-tuned PID parameters (*K_p* = 2.5, *K_i* = 0.015 s^{-1}, *K_d* = 45 s) achieved a settling time of approximately 12 minutes with less than 3°C overshoot, meeting the design specifications.

Spatial Uniformity: The nine-point temperature mapping revealed a maximum temperature deviation of ±1.8°C from the mean chamber temperature at steady state, corresponding to 95% uniformity (defined as the percentage of measurement points within ±2°C of the setpoint). This performance exceeds typical industrial oven specifications (±5°C) and is comparable to advanced multi-zone control systems [8], [13].

The superior uniformity is attributed to the combination of forced convection air circulation, strategic placement of perforated distribution baffles, and effective insulation minimizing wall temperature gradients. The variable-speed blower enables optimization of airflow velocity to balance rapid heating with minimal temperature stratification.

Temperature Stability: During extended operation (4-hour continuous run at 200°C setpoint), the chamber temperature remained within ±1.2°C of the setpoint, demonstrating excellent disturbance rejection and minimal drift. The PID controller effectively compensated for minor variations in gas supply pressure, ambient temperature changes, and thermal cycling of the insulation materials.

4.2. Energy Efficiency Analysis

Energy consumption was quantified by measuring natural gas flow rate and electrical power consumption (blower, PLC, HMI) during steady-state operation. The total energy consumption at 200°C setpoint was approximately 3.8 kW, comprising: - **Gas burner:** 3.2 kW (thermal input) - **Blower:** 0.45 kW (electrical) - **Control system:** 0.15 kW (electrical)

Comparison with a simulated on-off control strategy (burner cycling between full power and off based on temperature deadband) revealed that the PID-controlled system achieved approximately 25% energy reduction. This improvement is attributed to: 1. **Modulated heat input:** The PID controller adjusts burner firing rate proportionally to the control error, avoiding the energy waste associated with repeated heating-cooling cycles in on-off control [16]. 2. **Optimized airflow:** Variable-speed blower operation reduces electrical consumption during steady-state operation compared to constant full-speed operation. 3. **Reduced thermal cycling:** Continuous modulated control minimizes temperature fluctuations, reducing heat loss through the insulation during temperature overshoots.

The energy efficiency results align with findings by Pask et al. [16], who reported 20–35% energy savings through oven improvements including enhanced control strategies and insulation optimization.

4.3. Coating Quality Assessment

Powder-coated steel panels (100 mm × 150 mm × 1.5 mm) were prepared using a commercial automotive polyester powder coating (RAL 9005, black) and cured in the oven at 190°C for 15 minutes.

Adhesion: ASTM D3359 cross-hatch adhesion testing yielded a 5B rating (no coating removal) for all test panels, indicating excellent adhesion. This result confirms that the oven provides sufficient and uniform thermal energy for complete cross-linking and strong interfacial bonding between the coating and substrate.

Surface Quality: Visual inspection and gloss measurements (60° geometry) revealed a smooth, uniform finish with gloss values of 85–92 gloss units, consistent with high-quality automotive finishes. No defects such as orange peel, cratering, pinholes, or color inconsistencies were observed, confirming the effectiveness of the temperature uniformity and controlled curing profile.

Mechanical Properties: Bend testing (180° bend over 3 mm mandrel) and impact resistance testing (ASTM D2794, direct and reverse impact) demonstrated that the cured coatings exhibited excellent flexibility and impact resistance, with no cracking, delamination, or coating failure. These results indicate complete cross-linking and optimal mechanical properties, validating the curing temperature and time parameters.

The coating quality results demonstrate that the didactic oven achieves performance comparable to industrial powder coating curing ovens, enabling students to produce high-quality finished parts while learning the principles of thermal processing and surface finishing.

4.4. Educational Impact

The implementation of the didactic curing oven has significantly enhanced the practical learning experience for Mechanical Engineering students at the University of Los Mochis. Students gain hands-on competencies in:

1. **Industrial Automation:** Programming and configuring Siemens S7-1200 PLCs using TIA Portal software, implementing control logic, and troubleshooting automation systems.
2. **Human-Machine Interfaces:** Designing and configuring HMI screens for process visualization, alarm management, and operator interaction.
3. **Temperature Measurement and Control:** Understanding RTD sensor principles, signal conditioning, PID control theory, and tuning methods.
4. **Thermal Systems Design:** Applying heat transfer principles to optimize insulation, heating systems, and airflow distribution for temperature uniformity and energy efficiency.
5. **Sustainable Manufacturing:** Recognizing the environmental and economic benefits of powder coating technology compared to traditional liquid paint systems, including VOC elimination and material efficiency.
6. **Safety Engineering:** Implementing and validating safety interlocks, flame detection systems, and emergency shutdown procedures in industrial thermal processing equipment.

The oven serves as a platform for laboratory exercises, capstone projects, and research activities, bridging the gap between theoretical knowledge and practical industrial applications. Student feedback has been overwhelmingly positive, with participants reporting increased confidence in their ability to design, implement, and troubleshoot industrial automation and thermal processing systems.

V. Conclusions and Future Work

This work presented the design, implementation, and validation of a didactic curing oven for powder coating applications in the automotive sector, developed at the University of Los Mochis. The system integrates modern industrial automation technologies—including Siemens S7-1200 PLC, HMI, RTD temperature sensing, and intelligent PID control—to achieve precise temperature regulation and thermal uniformity.

Key Achievements:

1. **Thermal Performance:** The oven demonstrated 95% temperature uniformity (±1.8°C maximum deviation) across the working volume in the operational range of 180–220°C, exceeding typical industrial specifications and meeting the stringent requirements for automotive powder coating applications.
2. **Energy Efficiency:** PID-based modulated control achieved a 25% reduction in energy consumption compared to conventional on-off control strategies, demonstrating the value of intelligent control for sustainable manufacturing.
3. **Safety and Reliability:** Comprehensive safety interlocks, including Honeywell flame detection, over-temperature protection, and door interlocks, ensure safe operation in an educational environment.
4. **Coating Quality:** Validation testing confirmed that the oven produces high-quality powder-coated finishes with excellent adhesion (ASTM D3359 5B rating), surface appearance, and mechanical properties, comparable to industrial curing ovens.
5. **Educational Value:** The system provides students with practical experience in industrial automation, thermal systems design, and sustainable manufacturing processes, enhancing their readiness for careers in advanced manufacturing industries.

Theoretical Contributions:

This work contributes to the body of knowledge in thermal systems design and control by: - Demonstrating the application of classical PID control theory to achieve superior temperature uniformity in a cost-effective educational oven design. - Validating the effectiveness of ceramic fiber insulation and forced convection heat distribution for energy-efficient thermal processing. - Providing a practical case study of integrating heat transfer fundamentals, polymer thermosetting chemistry, and control theory in a real-world engineering application.

Future Work:

Several opportunities exist for further enhancement and research:

1. **Advanced Control Strategies:** Implementation of adaptive PID, fuzzy-PID, or model predictive control algorithms to further improve temperature uniformity and energy efficiency, particularly under varying thermal loads [8], [11], [12].
2. **Multi-Zone Control:** Integration of additional RTD sensors and zone-specific heating elements to enable spatial temperature compensation and accommodate workpieces with varying thermal mass distributions [14].
3. **Industry 4.0 Integration:** Development of cloud-based data logging, remote monitoring, and predictive maintenance capabilities to align with modern Industry 4.0 manufacturing paradigms [18].
4. **Infrared Heating:** Investigation of infrared heating elements as an alternative or supplement to convective heating, potentially reducing curing time and energy consumption [19].
5. **Expanded Material Compatibility:** Characterization of curing performance for alternative powder coating formulations (epoxy, hybrid, low-temperature cure) and substrate materials (aluminum, composites).
6. **Life Cycle Assessment:** Comprehensive environmental and economic analysis comparing powder coating to traditional liquid paint systems, quantifying VOC reduction, material efficiency, and total cost of ownership.

The didactic curing oven represents a significant advancement in engineering education infrastructure at the University of Los Mochis, providing students with access to modern thermal processing technology and preparing them for careers in sustainable manufacturing. The successful integration of theoretical principles, industrial automation, and practical application demonstrates the value of hands-on learning in developing competent, industry-ready engineers.

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