Department of Electrical, Computer, and Biomedical Engineering

EEN365 Control Systems

Course Project

Spring 2025

Design and Implementation of a Heat Chamber with Closed-loop Temperature Control

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Introduction

Heated chambers are widely used in real-world engineering and industrial applications where precise thermal control is essential. These applications range from electronics testing, environmental simulation, and food preservation to chemical reactions and materials processing. In manufacturing and quality assurance, heated chambers ensure products can withstand temperature fluctuations. In research, they provide controlled environments for thermal experiments and sensor calibration. Understanding the thermal behavior of such systems and designing reliable control strategies are fundamental for modern engineering solutions.

In this project, the students are tasked to design, model, simulate, and implement a compact heat chamber system (Figure 1) with closed-loop PID temperature control. The project includes theoretical modeling and practical experimentation. Students will evaluate system stability, transient and steady-state performances.

System Design and Construction

- Construct a 20×20×20 cm cubic heat chamber using foam insulated walls (e.g., Styrofoam).
- Mount a metallic heat-spreading plate at the bottom, attached to a wooden base (e.g., MDF).
- Install a wirewound resistor (e.g., 6 Ω, 50 W) as the heating element and fix it on the metallic plate using screws or thermal adhesive/glue.
- Place a suitable temperature sensor (e.g., TMP36 or LM35) in the center of the chamber volume.
- Include a small (e.g., 40x40x10mm) 12V DC fan and vents to enforce air circulation.
- Regulate the voltage across the wirewound resistor by varying the duty cycle of the PWM signals generated from the microcontroller. Similarly, the fan speed can be controlled by adjusting the PWM duty cycle.

- The PWM signals are used to drive both the heating element and the ventilation fan via logic-level N-channel MOSFETs, with appropriate supporting components including a series current-limiting resistor, pull-down resistor, and flyback diode, as illustrated in Figure 2.

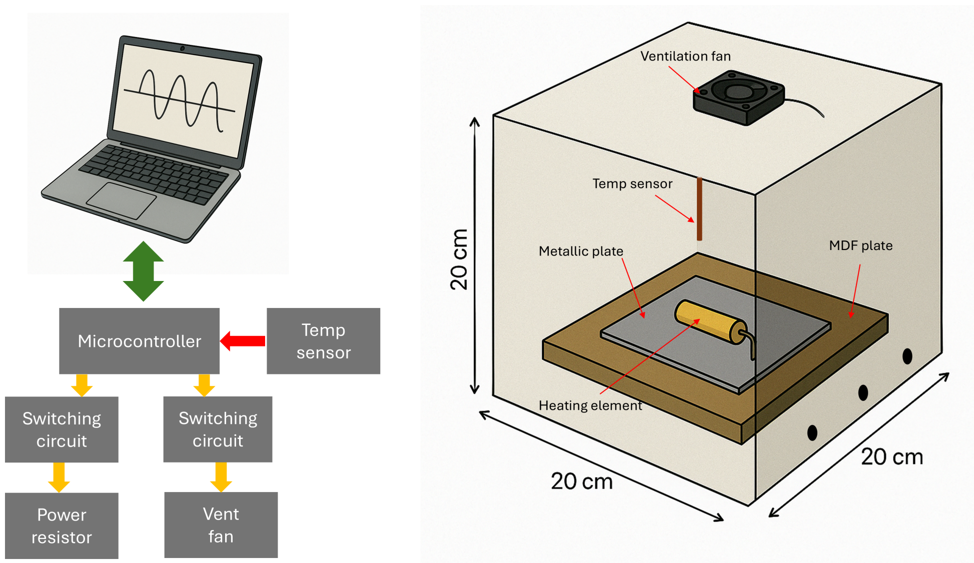

Figure 1: 3D model of the foam-insulated heat chamber with hardware-software interface diagram.

Mathematical Modeling

The thermal behavior of the system is modeled using the principle of energy conservation applied to a lumped thermal mass. The governing equation is derived from a thermal energy balance, equating the rate of thermal energy storage in the chamber to the net heat input from the heating element minus the heat lost to the surroundings. The following modeling assumptions are applied: (1) the air inside the chamber is well mixed, resulting in uniform temperature distribution; (2) heat losses occur primarily through conduction and natural convection via the chamber walls; (3) radiation effects are negligible at the expected operating temperatures; and (4) the heater behaves as an ideal controllable heat source.

Energy Balance Equation

We begin the modeling of the thermal system by applying the first law of thermodynamics to a lumped-capacitance thermal chamber. The rate of change of thermal energy stored inside the chamber $dU(t)/dt$ is equal to the net heat input minus the heat lost to the environment.

$$\frac{dU(t)}{dt} = \dot{Q}_{in}(t) - \dot{Q}_{loss}(t) - \dot{Q}_{f}(t)$$

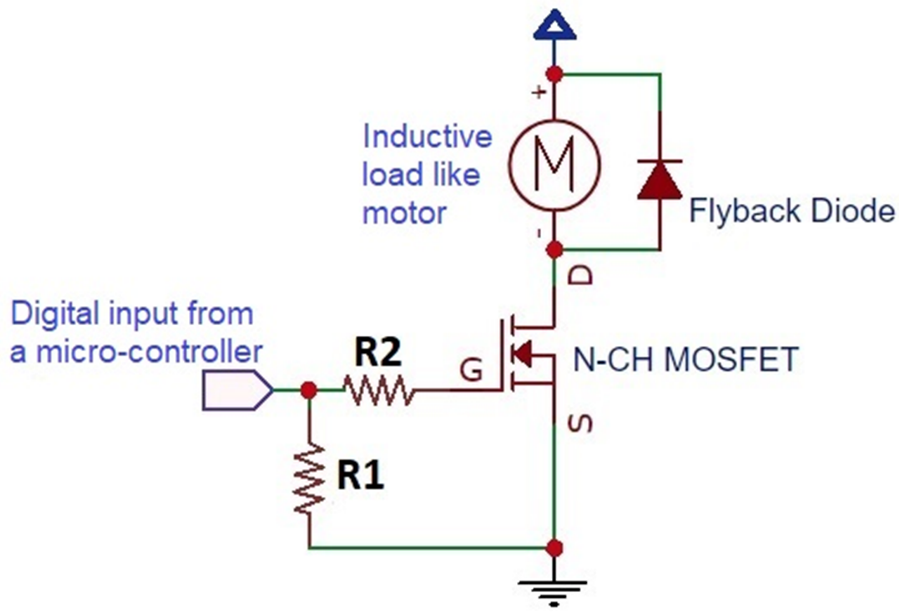

Figure 2: Switching circuit.

which can be further decomposed into

$$C_{th} \cdot \frac{d\theta(t)}{dt} = \dot{Q}_{in}(t) - \dot{Q}_{loss}(t) - \dot{Q}_f(t)$$

where:

- C_{th} is the thermal capacitance of the chamber [J/°C]
- $\theta(t)$ is the chamber internal temperature at time t [°C]
- $\dot{Q}_{in}(t)$ is the input heat power from the power resistor [W]
- $\dot{Q}_{loss}(t)$ is the heat loss to ambient [W]
- $\dot{Q}_f(t)$ is the heat power removed by the ventilation fan in [W]

Assuming the majority of the heat loss occurs due to conduction through the chamber walls to the ambient surroundings, which is proportional to the temperature difference between the chamber internal temperature $\theta(t)$ and ambient temperature θ_a:

$$\dot{Q}_{loss}(t) = \frac{\theta(t) - \theta_a}{R_{th}},$$

where R_{th} represents the thermal resistance of the chamber walls and it is described as $R_{th} = \ell/k.A$, where ℓ, k, and A represent the chamber wall thickness in [m], the thermal conductivity of material in [W/m.°C], and the surface area of each wall in [m^2]. The energy balance equation becomes

$$C_{th} \cdot \frac{d\theta(t)}{dt} = \dot{Q}_{in}(t) - \frac{\theta(t) - \theta_a}{R_{th}} - \dot{Q}_f(t)$$

This is the governing differential equation of the system. Note that the thermal capacitance C_{th} represents the system capability to store thermal energy and it can be calculated as the product of the mass of the thermal energy storing material– in this case the trapped air – m_a in [kg] and the specific heat capacity c_p in [J/kg.°C]. The external thermal power $\dot{Q}_{in}$ can be provided by a power resistor where

$$\dot{Q}_{in} = i(t)^2 R = \frac{v(t)^2}{R}.$$

where $i(t)$, $v(t)$, and R represent the current, voltage, and the ohmic resistance of the resistor.

A ventilation DC fan is utilized to cool down the chamber through air exchange with the surrounds. The heat removal rate by the fan can be given by

$$\dot{Q}_f(t) = \dot{m}_a(t) c_p (\theta(t) - \theta_a),$$

where $\dot{m}_a$ is the mass flow rate of air in [kg/s], which can be evaluated as $\dot{m}_a(t) = \rho_a \dot{V}(t)$. The parameter ρ_a is air density in [kg/m^3] and the variable $\dot{V}(t)$ is the volumetric airflow rate in [m^3/s]. The maximum DC fan volumetric airflow rate can be estimated using its CFM (cubic feet per minute) rating.

Performance Evaluation

Evaluate system based on:

- Closed-loop stability
- Reference tracking capability
- Transient response: rise time, settling time, overshoot
- Steady-state error

Reporting and Documentation

Prepare a technical report that includes the following key sections:

- **Introduction**
- **Motivation**
- **Materials and Methods**
  - Mathematical modeling, including transfer function and state-space representation

  - Control system architecture
  - Experimental setup design
  - Software development and PID controller implementation

- **Results and Discussion**
  - Time response plots for various reference signals
  - Stability analysis
  - Transient and steady-state performance evaluation

- **Conclusion**
- **Team Members' Contributions**
- **Appendices**
  - Microcontroller code
  - System photographs
  - Bill of Materials (BOM)
  - Additional supporting materials

Deliverables

1. Functional heat chamber prototype
2. Arduino/Raspberry Pi PID implementation code
3. Technical report (PDF)

Evaluation Criteria

- Demonstration (50%)
- Technical report (50%)

Optional Bonus

- Develop a GUI (MATLAB or Python) for live plotting, OR
- Integration of a digital display interface to show both the setpoint (desired temperature) and the actual chamber temperature in real-time.

Equipment Suggestions

- $https://besomi.com/ae_en/pcrx0248-50w-6-ohm-aluminum-wirewound-power-resistor-chassis-mount-heat-dissipating.html$

Important Dates

- Demonstration: 5th June
- Report Submission deadline: 10th June