ECE 445

SENIOR DESIGN LABORATORY

FINAL REPORT

Self-Heating Bed

Team #44

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Abstract

This project investigates the design and development of a cost-effective and accessible temperature-controlled sleep system. Drawing inspiration from commercially available systems such as Eight Sleep and BedJet, this project prioritizes affordability by leveraging readily available and inexpensive components.

Temperature-controlled sleep environments have demonstrated significant benefits, including improved sleep quality, enhanced cardiovascular recovery [1], and increased overall feelings of rest and rejuvenation. However, The current high price point of these systems creates a significant barrier to entry for many consumers.

We aimed to address this limitation by developing a high-performance and affordable temperature-controlled sleep system, making personalized sleep environments more accessible to a wider population.

Contents

1 Introduction

1.1 Problem

Maintaining an optimal sleeping temperature is essential for restful and uninterrupted sleep. Traditional methods of temperature control, such as adjusting thermostats, using fans, or adding layers often fail to provide personalized comfort or involve considerable energy costs[2]. This discomfort not only affects the quality of sleep but also contributes to daytime fatigue, decreased productivity, and long-term health consequences such as stress and weakened immune function[3].

As such, a field has arisen to target climate specifically while one is sleeping. Competitors in this field consist of water-based temperature regulation systems, which, while effective, come with significant drawbacks[1]. They pose a risk of leaks that can damage mattresses and bedding, particularly with more expensive or delicate materials like memory foam. These systems are also prohibitively expensive, both in terms of upfront costs and ongoing maintenance.

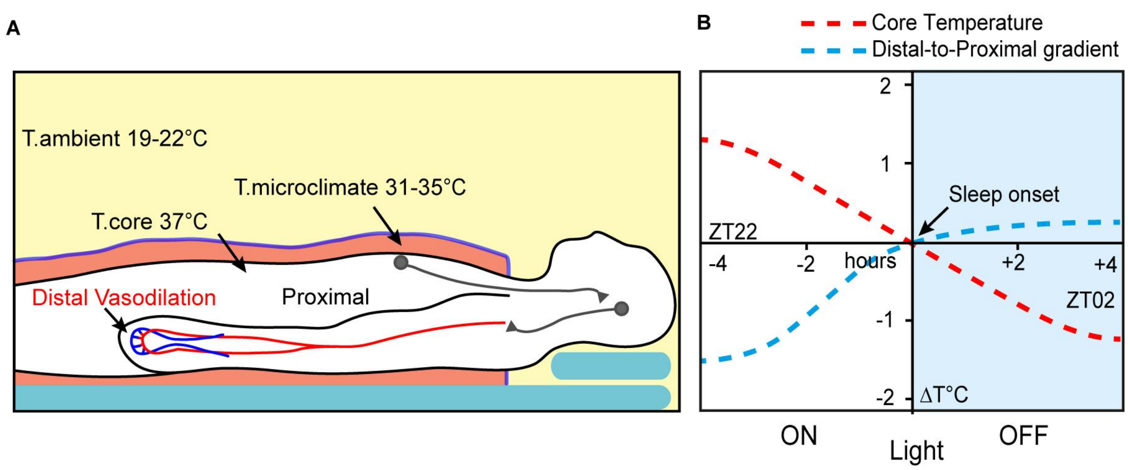

Figure 1: Optimal Temperatures While Sleeping

1.2 Solution

The proposed system consists of a central heating system stored underneath the bed, attached to a vent that clamps onto the foot of the bed and allows for circulation through a fan unit in the central heating system. This creates a modular system that may be used for heating or cooling by circulation.The vent directs air underneath your blanket, creating a temperature controlled zone. The project is divided into three subsystems:

1. Heating
2. Ventilation
3. Control

Each will be expanded on below. A brief overview and interactions between the subsystems is provided as well. Below is a mix of photos and renders to show our final enclosure.

Figure 2: Fabricated Enclosure Intake

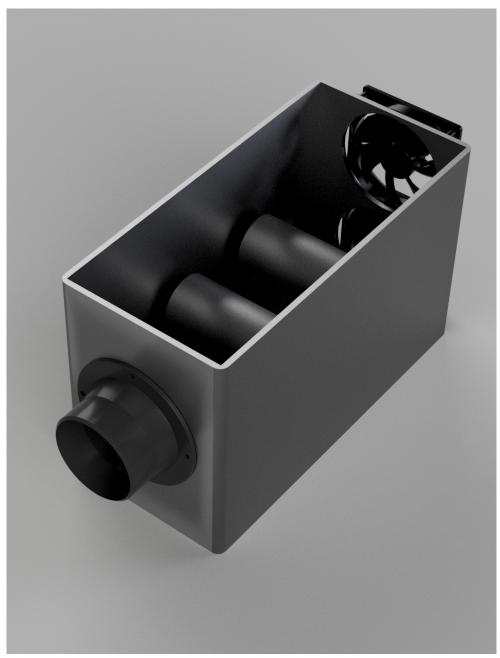

Figure 3: Exhaust Side View

1.3 High-level Requirements

As a mark of success, the project should be able to fulfill these three requirements:

1. Be able to modulate the temperature of its surroundings (defined as the temperature within a square box of the bed) within 3 degrees Fahrenheit of what the user inputs
2. Have a quiet air ventilation system, measured around 50-60 decibels (when sleeping, noise around one should not exceed 60)
   (a) To assess this system, we will use our phone microphones at head level on a bed, checking the decibels at night when only the system is in use.
3. Not power hungry and able to subsist off of the wattage of a normal fan and heater (1000-1500W).
   (a) To assess this system, we can check the input through power monitoring at the AC Input through a smart plug

2 Subsystem Overviews and Design

2.1 Block Diagram

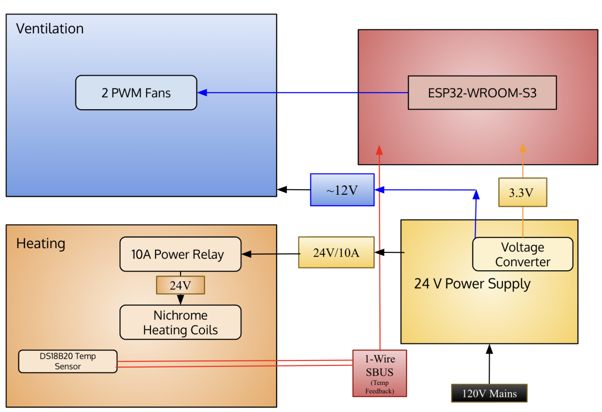

Figure 4: Block Diagram

2.2 Subsystem 1 - Heating

We settled on nichrome(nickel-chromium) wires, which can be found in hair dryers and toasters, are the ideal way to create our heating element. Nichrome is a metal alloy primarily composed of nickel and chromium, with various grades available. The most common types are nichrome-80 and nichrome-60, containing approximately 80% and 60% nickel, respectively. Both have a maximum operating temperature between 1100°C and 1200°C and melting points above 1400°C. [1] The chromium in nichrome forms an oxide layer on the surface, providing protection against corrosion. Its corrosion resistance, high melting point, and higher resistivity compared to other metals make nichrome an ideal material for electrical heating elements. The flexibility of the nichrome wire is why we chose to use it in our project, it enabled us to wrap it around steel pipes and act as the core heating element in our heating subsystem.[1] To heat the coil, voltage is applied on both sides of the wire. The nichrome is powered through a 24V 10A relay, that is controlled by the ESP32 in our control system.

We powered the nichrome with a constant voltage supply, the steady-state voltage/temperature relationship looks like the following:

$$\Delta T = \theta * \frac{V^2}{pL^2}$$

$\rho =$ resistivity or resistance per unit length $(constant)$

L = length of the wire

$\theta =$ the radial thermal resistance of the wire to ambient per reciprocal unit length

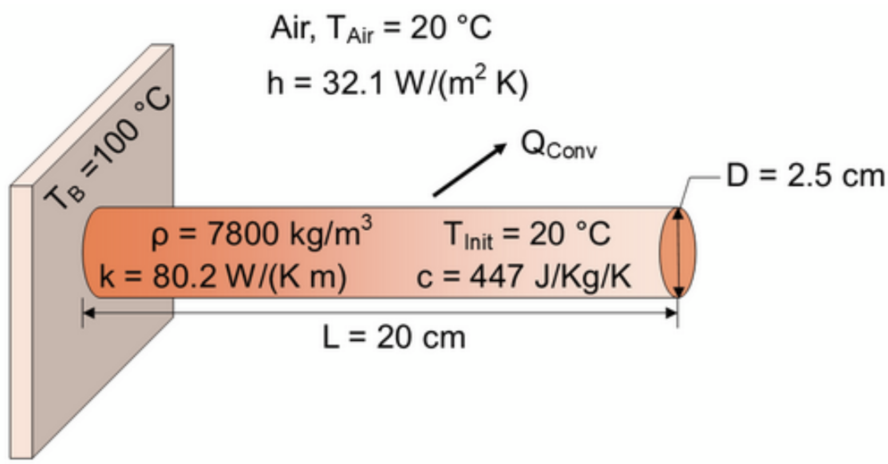

Figure 5: Thermal Model of Nichrome

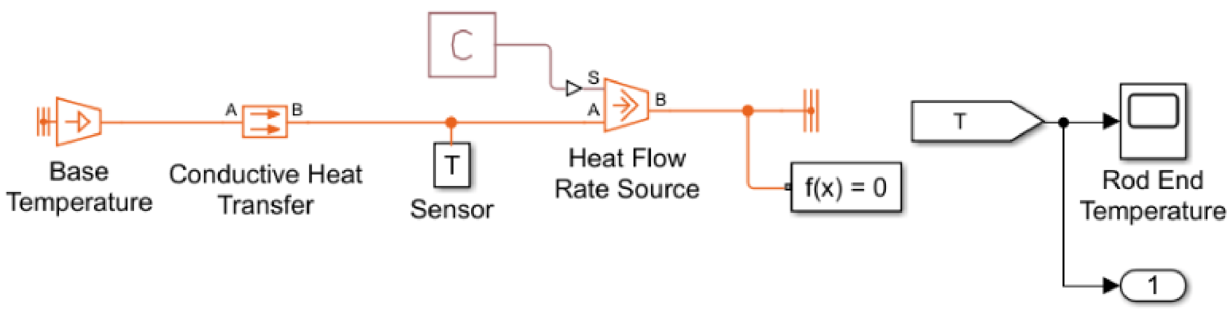

Figure 6: Steady State Heat Conduction Flow Diagram

The diagram in Figure 6 illustrates a **steady-state heat conduction flow diagram**, modeling heat transfer through the heating element (nichrome) under steady-state conditions. The process begins with a *Base Temperature*, which undergoes *Conductive Heat Transfer*, represented by the corresponding block in the diagram. A temperature sensor is included to monitor and measure the heat at specific points in the system.

2.2.1 Subsystem 1 - Requirements and Testing

Requirement	Verification
• The enclosure's temperature was maintained below 200°F to ensure safe and efficient operation of the system components and prevent overheating. • It was critical to keep the temperature within the circuitry enclosure below 150°F to avoid damage to sensitive electronic components and ensure long-term reliability. • The air directed toward the user was regulated to a maximum temperature of 110°F to provide a safe and comfortable experience while adhering to user safety standards.	• A precise temperature sensor, specifically the DS18B20, was employed as the primary measurement tool. This sensor plays a key role in accurately monitoring the operating temperatures and ensuring compliance with the outlined thermal limits. • We included a relay-based control mechanism to control the ON/OFF state of the heating element. This allows for precise adjustments to maintain the desired temperature ranges efficiently and effectively.

2.3 Subsystem 2 - Ventilation

One of our primary design objectives was to develop a ventilation system capable of efficiently moving air through insulated tubing while maintaining noise levels below 60 dB. Initially, we considered commercial blower solutions, but budget constraints and noise concerns led us to select two high-CFM 12V 120mm fans. These fans feature PWM (Pulse Width Modulation) capabilities, enabling precise speed control via our ESP32 microcontroller.

Figure 7: PWM Based Ventilation System

As you can see from Figure 8 and 9, the intake is by the fans, which pulls in fresh,ambient temperature air, pushes it over the hot nichrome, wrapped around steel tubing, and then forces it out of the exhuast vent, into the tubing.

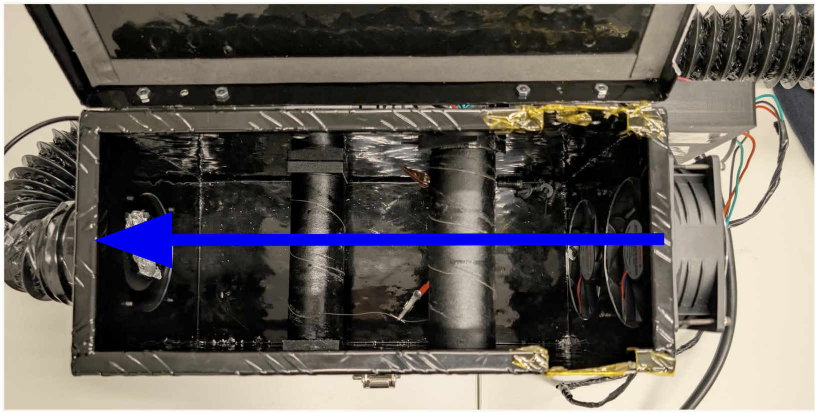

Figure 8: Airflow Direction

2.3.1 Subsystem 2 - Requirements and Testing

Requirement	Verification
• Must be able to observe and monitor changes in temperature • Ensure that system operates within safe/desired limits.	• We installed sensors to measure the ambient, intake and exhaust temperatures. By measuring the temperature Δ between the intake and exhaust air, we quantified how much the air was being heated. In our testing, we were able to take in air at 70°F and exhaust at 98°F, representing a 28 degree Δ.
• Ensure that ESP is able to control and modulate PWM Fans in order to control airflow	• We began our verification by using a oscilloscope to read the wave signal out of the ESP32's IO pin. We then adjusted its frequency, resolution, and duty cycle until we achieved a change in the fan speed. Finally, we worked to create a PWM curve that worked with our nichrome heating element, and reacted to the temperature sensor readings, to achieve our ideal exhaust temperature.

2.4 Subsystem 3 - Control System

Our central objective for the control system was using an MCU for power control and sensor input for intelligent temperature tracking and response. The PCB is the main part of the control system, acting as an administrator to the other subsystems for monitoring their consumption of power alongside performing calculations based on the data it receives over time.

Designing the PCB for this system required careful consideration of several factors to ensure robust performance. The preliminary issue was delivering power to the peripherals such as the ESP and fans. As our power converter was 24V 20A initially, we looked into multiple step-downs, the most efficient of which were buck converters. Looking through our options, we decided on the TPS563300ADDA. For communicating with ESP, a CP2102 module was used in conjunction with a USB-C port, converting directly from the twin data lines to a normal serial connection. The temperature sensors used was a DS18B20, a digital sensor capable of outputting a temperature range of -55C to 125C. Perfect for our needs and specific for ambient temperature sensing, we implemented this on our PCB as a 1-Wire Data Bus, communicating with multiple sensors through one IO on the ESP.

In maintaining the heating element, we intended on using a power MOSFET (IRFZ44N) in our design to switch the nichrome on and off based on power inputs from the ESP. This extended to our fans as well; although we could simply reduce the duty cycle to 0, we thought it would be best to have a cutoff for the fan power as another of the same MOSFETs.

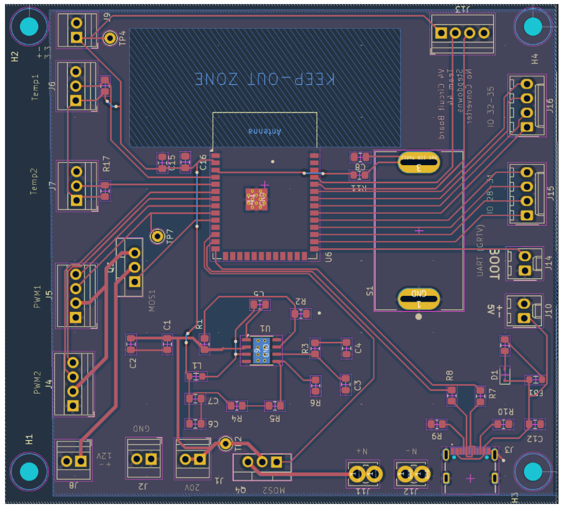

Figure 9: Final PCB Design

2.4.1 Subsystem 3 - Requirements and Testing

Requirement	Verification
• We must maintain control over the power delivery to both the heating and ventilation systems. The ESP32 must be able to monitor the various sensors placed around the enclosure and throughout the system, ensuring that all measurements and parameters were accurately tracked. Based on these inputs, it is responsible for regulating the power supply to remain within safe operating limits. This approach helps safeguard the system from potential damage, while maintaining optimal conditions inside the enclosure.	• The main way to test this system are control points on the IC to track the communication protocols, with use of an oscilloscope in the lab. Additionally, we checked if this is working in conjunction with the ventilation or heating systems - decreasing the resistance of the heating element provides a significant increase in temperature. Since we are also monitoring the sensors, we can use an external heat source to test the sensor output. In our case, we used a space heater to shift the temperature higher and allow our MCU to read the temperature from the sensor (that should be changing the longer it is close to the space heater).

3 Design

3.1 Subsystem 1: Heating

The resistivity of nichrome is significantly higher than that of other common metals such as copper or aluminum. This allows for the generation of heat at lower current levels, reducing power requirements. Using Ohm's Law and the power equation:

$$P = I^2 R$$

where P is power (in watts), I is current (in amperes), and R is resistance (in ohms). By increasing the resistance R through nichrome, the same heating effect can be achieved with lower current.

To determine the optimal nichrome configuration, we tested multiple wire gauges and lengths, as summarized in Table 1. The 24 AWG nichrome wire with a length of 45 cm (highlighted in green) emerged as the best option. It produced sufficient heat (254.88 W) while maintaining a manageable current draw of 10.62 A, remaining well below the melting point of the wire and within the safe operating range of our relay system. Longer lengths (e.g., 106 cm) exhibited excessive resistance, reducing heat output, while shorter lengths of thicker wire (e.g., 18 AWG at 24 cm) melted under high current loads. The selected configuration balanced heat generation, power efficiency, and durability.

Gauge	Length (cm)	Res. (Ω)	Heat	Melted ?	Amps	Power (W)
18	106	2.3	Yes	No	10.43	250.43
18	54	0.94	No	Yes	20	376
18	24	0.33	Yes	Yes	20	132
24	45	1.6	Yes	No	10.62	254.88
24	54	3.1	Yes*	No	7.74	185.81
24	106	5.83	Yes*	No	4.12	98.80

Table 1: Test results for different nichrome wire gauges and lengths under a 24V power supply. The green-highlighted row represents the final selected configuration. *Limited heating.

Heating Subsystem Implementation

We found the Nichrome wires to be highly flexible, which allowed us to wrap it around steel pipes to create a compact, distributed heating element. However, an initial design oversight was the failure to account for steel's high electrical conductivity. This resulted in electrical shorts at various contact points between the nichrome and steel, leading to some regions not getting hot. To address this, we applied a Rustoleum coating to the steel as an insulation barrier, which largely reduced the short-circuit problems.

The nichrome wire is powered by a 24V, 10A relay, which is controlled by the ESP32 microcontroller in the system. The relay served as an intermediary to toggle the heating element ON or OFF based on the temperature feedback from the sensors, ensuring precise thermal regulation.

To sum it up, the selection of nichrome wires was based on a balance of thermal efficiency, durability, and practicality. Combined with the ESP32-controlled relay system and precise temperature monitoring, our heating subsystem achieves reliable performance while minimizing energy consumption and maintaining user safety.

3.2 Subsystem 2: Ventilation

Through experimentation, we determined that the fans operated with a PWM frequency of 25 kHz and an 8-bit resolution. By varying the duty cycle of the PWM signal, we achieved precise control over fan speeds.

The last piece in the ventilation system design involved configuring the PWM system to operate the fans automatically. We needed to balance speed, sound, and airflow to heat the nichrome wire to the required temperature without allowing it to melt.

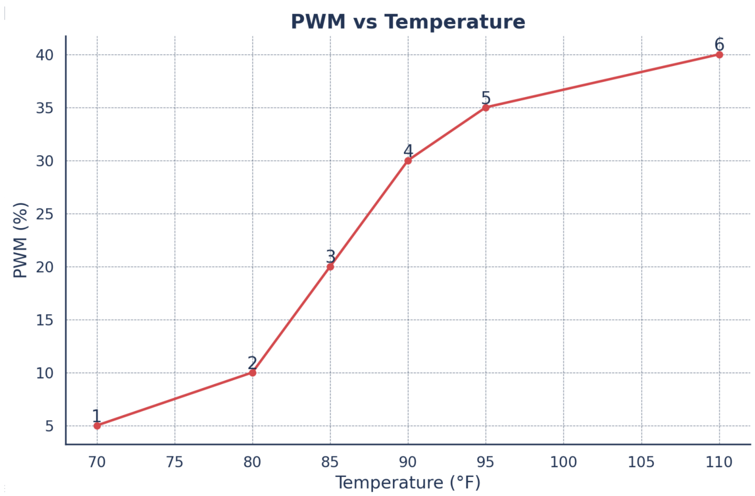

Figure 10: Final PWM Curve

A 6-stage PWM curve, depicted in Figure 10, proved optimal for our system. This curve facilitated temperature deltas of up to approximately 30°F, effectively fulfilling our temperature modulation requirement. The measured temperature reflects the exhaust vent temperature, enabling continuous adjustments based on the user's environment. To enhance safety, a sixth point has been added as the final rightmost point on the curve. This safeguard triggers an immediate increase in fan speed, maximizing heat exhaust and cooling the nichrome wire if the air temperature exceeds safe operating limits.

3.3 Subsystem 3: Control

We paid special attention to the layout of high-current traces, such as those feeding the heating coils, and decided it was best to use separate converters. Additionally, we integrated a series of test points and diagnostic headers on the PCB, allowing for straightforward troubleshooting and calibration of the sensor inputs and output signals. Together, these considerations contributed to a system that not only delivered precise and consistent temperature control, but also maintained operational safety and long-term reliability.

For the switching element, we initially decided to use a MOSFET to turn the heating element on and off. However, we realized that V_{gs} was not high enough to support the power we were inputting across it, as our MOSFET was constantly in the saturation range when we pulsed it. As a result, the MOSFET burnt quickly under use since R_{ds} was slightly too large. To solve this, we switched to an off-board relay that allowed 3.3V input with a physical switch between on/off for the nichrome. The relay worked well for our purposes and was an ideal way to solve the overheating issue.

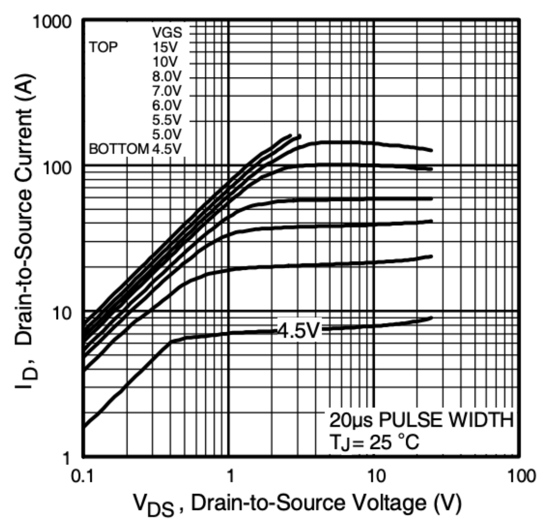

Figure 11: MOSFET I_d vs V_{ds} Curve

4 Cost and Schedule

4.1 Bill of Materials

Part #	Description	Manufacturer	Quantity	Cost
1	ESP32	Supply Shop	1	$0
2	TPS54336ADDA	Digikey	3	$2.11
3	Nichrome Wire	Amazon	1	$6.99
4	DS18S20	Digikey	4	$40.00
5	Wathai 12038 120MM Fan	Wathai	2	$40.00
6	3-Pin Screw Mount	Mikroe	2	$2.28
7	Steel Piping	Machine Shop	1Ft	$3.99
8	Enclosure	Confote	1	$60.99
9	Dryer Exhaust Vent + Insulated Ducting	Yijuhou	1	$9.99
10	30V Relay	Amazon	1	1.99
11	Rustoleum	Amazon	1	12.99
12	AC Power Cord	Amazon	1	20.48

Overall, our total cost is $219.23, which is slightly over budget.

4.1.1 Labor Costs

Each Person makes 50$ an hour, with a 2.5x multiplier for overhead costs. At 80 hours worked, $50 x 2.5 x 80 = $10000

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4.2 Schedule

Week	**Agenda**
9/29	Finish Design Document/Proposal regrade
10/6	Finish first iteration of PCB, order ICs for PCB, get enclosure from shop/amazon
10/13	Order first iteration of PCB (Monday), revise for next iteration, start signal coding for ESP32 and fans
10/20	Test PCB (if board arrives), start tests for nichrome, review PID feedback system
10/27	Ordered second iteration of PCB if revision needed, finalized voltage settings for heating elements
11/3	Finalized interaction of sensors with PID system, started assembly of venting to the enclosure
11/10	Finalized fan system signals, finalized assembly for mock demo
11/17	Mock demo week, have enclosure ready with PCB final iteration ready to solder/soldered
11/24	Break
12/2	Final demos, make presentation for next week
12/9	Final presentations

5 Conclusion and Reflection

5.1 Accomplishments

Overall, this project was a success. We achieved all three of our main goals and created a working product. We faced some challenges during the project, but we were able to overcome them through research and by talking to other students. The final product meets the standards we set for ourselves, in the high level requirements at the start. Our final prototype was able to module the temperature within 3 degrees of 95°F, operate below 750W consistently ($\approx$ 400W calculated), and measure in under 60dB based on microphones we used for testing.

5.2 Improvements and Looking Forward

While we successfully met the high-level requirements of our project, there are still areas in which we can improve our design. Notably, the overall efficiency of our heating system proved to be suboptimal. This inefficiency can be attributed to subpar material choices made during the design phase, as well as a sub-optimal heating element.

To minimize losses in future iterations, we could either reorient the nichrome wires or switch entirely to infrared panels. The current perpendicular orientation of the nichrome wires to the airflow results in a suboptimal utilization of the heated surface, causing a 50% temperature loss. By running these wires parallel to the airflow, as seen in devices like toasters or hair dryers, we could increase the contact area between the nichrome and the blown air, thereby improving heating efficiency. Alternatively, the adoption of infrared heating could be explored. Preliminary findings suggest that infrared panels are more effective at heating objects than air. By retaining our steel pipe design, we could use the panels to heat the pipes directly, which would, in turn, heat the air—serving as a viable replacement for the nichrome setup, however further research into the efficiency of this system would be required.

Lastly, thermal energy was lost to the metal enclosure. This issue can be addressed by replacing the metal enclosure with one made from ABS or another heat-resistant plastic. Such a change would reduce both thermal loss and the material costs of the project.

5.3 Ethics and Safety

Adhering to IEEE safety standards[4], all components of our design operate below the 40V threshold. To enhance safety, we implemented a temperature monitoring system. If operating temperatures exceed safe limits, the heating system immediately shuts down, and fan speeds are increased to facilitate rapid cooling and introduce fresh air.

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