Teaching Heat to High School Students

ECE 445 Design Document

Team #26

Kaihua Hu, Tianyu Feng, Yongxin Xie, Ziang Liu

Sponsor: Wee-Liat Ong

May 10, 2024

Abstract

In the middle or high school stages, a versatile thermal teaching aid is still lacking. In this project, we have developed an integrated thermal lab platform, which can demonstrate concepts of heat conduction, convection, and thermoelectricity. This lab platform is divided into two subsystems: the thermoelectric subsystem and the heat transfer subsystem. In the thermoelectric system, we control an LED array by processing signals from 64 small thermoelectric plates to display the temperature distribution on the plate. In the heat transfer subsystem, we use thermocouples to detect the temperature of different materials' metal rods or heat pipes at different coordinates and display the temperature using LEDs. It is worth noting that students can touch the thermoelectric plates or metal rods to directly feel the thermal changes. Considering its impressive interactivity and visualization capabilities, this thermal lab platform will be an ideal candidate for future middle and high school teaching aids.

Contents

Abstract ii

Contents iii

1. Introduction 1

2. Design 3

2.1. Design Procedure 3
2.1.1. Thermoelectricity subsystem 3

2.1.2. Heat conduction and convection subsystem 5

2.2. Design Detail 5
2.2.1. Thermoelectricity subsystem 5

2.2.2. Thermal Conduction and Convection Subsystem 7

3. Design Verification 8

3.1. Thermoelectricity subsystem 8
3.1.1. Thermoelectric plate array 8

3.1.2. Control Board 8

3.1.3. LED array 9

3.2. Heat conduction and convection subsystem 9
3.2.1. Thermocouple 10

3.2.2. Control board 10

4. Cost 11

4.1. Parts 11
4.2. Labor 11
5. Conclusion 12

5.1. Accomplishment 12
5.2. Uncertainty 12
5.3. Ethic and Safety 12
5.4. Future Work 13
References 14

1. Introduction

Various types of experimental teaching aids are widely used in middle and high school stages, with a significant positive impact on stimulating students' interest in learning and enhancing teaching quality. However, there is still a notable lack of versatile thermal teaching aids available on the market. Traditional thermodynamics teaching methods primarily rely on theoretical explanations, making it challenging for students to grasp concepts from some teaching aids effectively as in other subjects. Therefore, the development of a versatile thermal experimental teaching aid can effectively improve the teaching efficiency in the field of thermodynamics.

In recent years, many researchers and educators have been striving to improve thermodynamics teaching methods. For example, Umam et al. [3] designed an experimental device that converts heat energy into electrical energy as a teaching aid, which received favorable feedback from most students, although issues such as lack of intuitive conversion and insufficient enjoyment were noted. Wang et al. [4] introduced advanced mathematical methods in the university heat transfer course, elucidating the fundamental principles of heat conduction through the analytical solution of differential equations, but this method is not suitable for middle and high school classrooms.

In this project, we have developed an integrated thermal experiment platform that effectively demonstrates concepts of heat conduction, convection, and thermoelectricity to students. Unlike traditional thermodynamics teaching aids that simply present knowledge, we focus on enhancing interactivity between the lab platform and students, as well as improving learning efficiency by visualizing thermodynamic concepts. As shown in the block diagram below, the platform is mainly divided into two subsystems: the thermoelectric subsystem and the heat transfer subsystem. To ensure the safety and stability of this lab platform, making it more suitable for using in classroom, we have removed the radiation subsystem originally included in the design. The thermoelectric subsystem consists of a thermal plate array, a control module, and an LED array. When students touch the thermal plate array, the corresponding parts of the LED array light up. The heat transfer subsystem includes rods and heat pipes made of different metal materials, an LED display, thermal sensors, a control module, and a heater. When students touch or activate the heater to heat one end of the rod, LEDs will display temperature differences at different positions of the rod. It is worth noting that students can directly touch the thermal plates and heat-conducting rods to sense heat changes when using this thermal lab platform, enabling them to independently complete thermal experiments without encountering operational difficulties or safety hazards. Combining the intuitiveness and fun of visualizing heat changes through LEDs, this thermal lab platform holds great potential in the field of thermodynamics education.

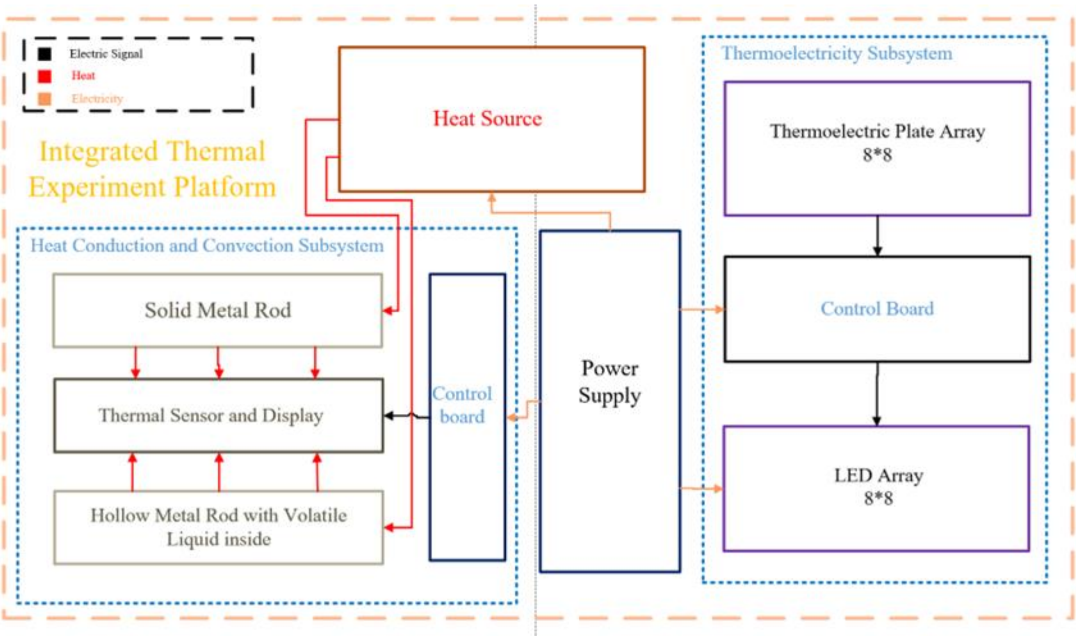

Figure 1.1 block diagram

2. Design

2.1. Design Procedure

2.1.1. Thermoelectricity subsystem

The thermoelectric system primarily demonstrates to students the concept that temperature differences can be converted into electrical energy using thermoelectric plates. As shown in Figure 2.1.1, this system mainly consists of a large thermoelectric plate composed of 64 small thermoelectric plates, a control board, and an LED array. When students put their hands or other heat sources (such as cups filled with hot water) on the thermoelectric plate, the LED lights illuminate, displaying the shape of the hand or other heat source.

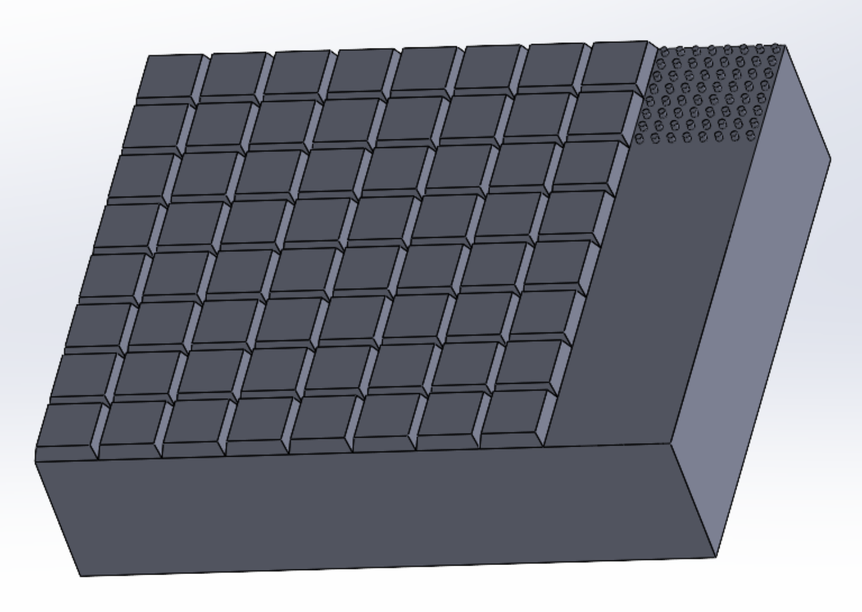

Figure 2.1 Thermoelectricity subsystem

Initially, we intended to power the entire subsystem through the electrical energy generated by the thermoelectric plates. However, after testing thermoelectric plates of different types and sizes, we abandoned this idea and decided to add additional power sources. Considering that we need to use this lab platform in middle school classrooms, without using ice blocks, students touch the thermoelectric plate with their hands, resulting in a temperature difference of approximately 5-15°C between the two sides of the thermoelectric plate. According to our test results, a 20mm*20mm thermoelectric plate can generate approximately 0.2-0.6v of voltage under these conditions, which is insufficient to power the LED array. To facilitate the daily use of the system, we detect the electrical signals generated by the thermoelectric plates through a microcontroller and use them to control the LED array, thus avoiding the need for ice blocks.

Regarding how to display temperature changes on the thermoelectric plate, we also went through a series of changes. Initially, the shape of the LEDs was fixed, meaning that when students touched the thermoelectric plate, a fixed shape, such as "ZJUI," would light up. To enhance interaction with students, we chose to display the temperature distribution on the thermoelectric plate. We used an 8*8 LED array and a large thermoelectric plate composed of 64 small thermoelectric plates, with each small thermoelectric plate connected to the corresponding LED on the LED array. Therefore, when students touch a position on the large thermoelectric plate, the corresponding position on the LED array lights up. This design gives students more freedom to explore and enhances interaction.

We used 64 small thermoelectric plates, each requiring a different interface, while common microprocessors typically have fewer than 20 input ports. Initially, we wanted to use multiplexer to aggregate several signals into one, but in actual testing, the instability of the electrical signals from the thermoelectric plates worsened after passing through the multiplexer. Therefore, we abandoned the use of a multiplexer to address the issue of insufficient interfaces. As shown in the circuit diagrams 2.1.2 and 2.1.3 below, we used four microcontrollers, with one microcontroller serving as the host, connecting the LED array and 16 small thermoelectric plates. Additionally, the other three microcontrollers each process signals from 16 small thermoelectric plates and input the processed signals into the host.

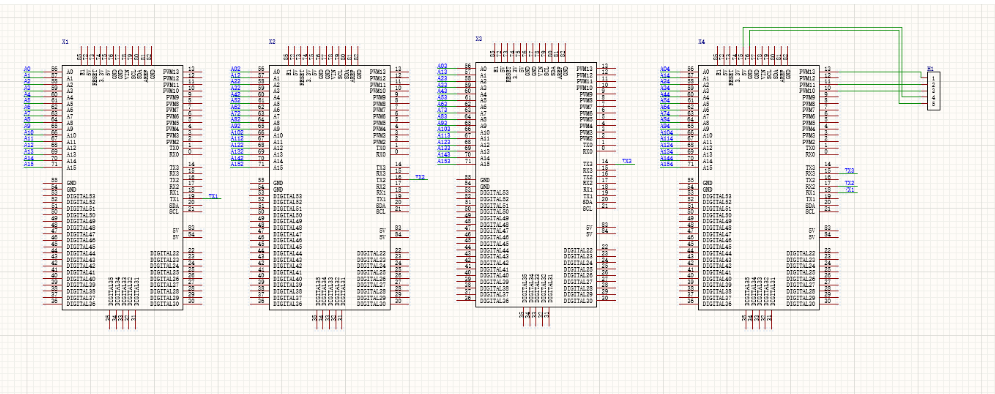

Figure 2.2 PCB Schematic 1

Figure 2.3 PCB Schematic 2

2.1.2. Heat conduction and convection subsystem

Heat conduction shows students that heat can be conducted through a medium and how the efficiency of heat conduction varies from medium to medium. Our device uses 3 temperature sensors, microcontroller real-time detection of their temperature, the data will be displayed on the screen. This is to facilitate the display of the specific each sensor temperature, but also easy to tune. At the same time according to the temperature difference and temperature conduction efficiency, the microcontroller controls the LED display different colors for illustration. When students put their hands or other heat sources (such as cups filled with hot water) on side of the conductor bar， temperature conducts from one section to the other and the thermal sensor picks up the temperature and displays it on the screen and the led will light up.

Initially, we started to use a memory metal flower to show the change in temperature. Memory metal flowers will open when they reach a specific temperature, however thi s is very much influenced by the temperature of the outside environment, which mean s that it is possible that the high temperature of the environment causes the flowers to open rather than the temperature of the hand coming from the conductor rod. Then we wanted to demonstrate thermal conductivity by connecting the led with a thermocoup le. The thermocouple probe reaches a certain temperature the LED lights up. However , the body temperature is 36 to 37 degrees Celsius and the temperature difference betw een the body and the environment is 10 to 15 degrees Celsius. This is not a large temp erature difference and does not visualize the temperature difference very well. So, we use a thermal sensor plus a screen that can display the temperature, which will be mor e intuitive.

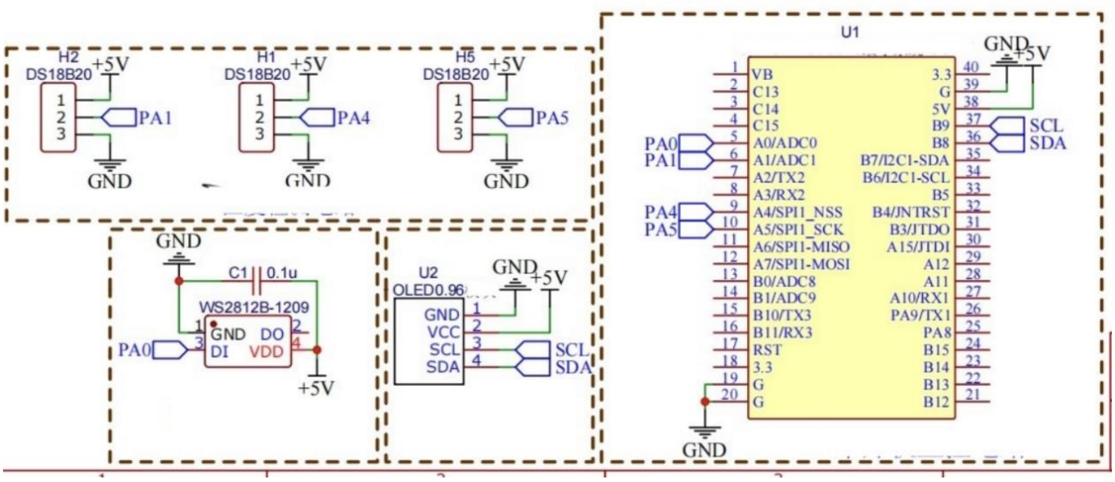

Figure 2.4 PCB Schematic

2.2. Design Detail

2.2.1. Thermoelectricity subsystem

This subsystem of our teaching program will showcase conversion of thermal energy into electrical energy through thermoelectric materials. When students put their hands or other heat source such as a cup filled with hot water on the thermoelectric plates, the LEDs be lighted displaying a shape of hands and showing the temperature of heat source by different colors.

Inspired by the ability of thermoelectric material to transfer electrical and thermal energy to each other, we decided to utilize the commercially available low power refrigeration plate in the market to make a heat-to-electricity device to transfer heat and then light LED. This subsystem is an 8*8 array of the thermoelectric plates which is corresponding to a LED and can control its light using a microcontroller.

The commercially available thermoelectric plate is usually designed for refrigerating, but it could also produce a voltage with temperature according to Seebeck Effect. After testing the voltages generated by different sizes of thermoelectric plates at different temperature differences, we choose 20mm*20mm*4.1mm thermoelectric plate and combine them into an 8*8 arrays. This choice was made to select the right size in order to generate enough voltages for the microcontroller and also to control the size of the plate in order to increase the number of thermoelectric plates per unit area with the aim of increasing the resolution ratio, thereby obtaining better performance. For our chosen thermoelectric plate, the detailed parameter is shown below.

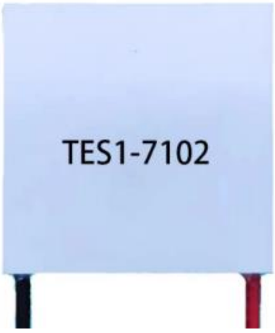

Figure 2.5 Thermoelectric Plate

Temperature difference(℃)	Open circuit voltage(V)
0	0
10	0.43
20	0.9
30	1.32
40	1.76
50	2.21
60	2.67
70	3.15
100	4.42

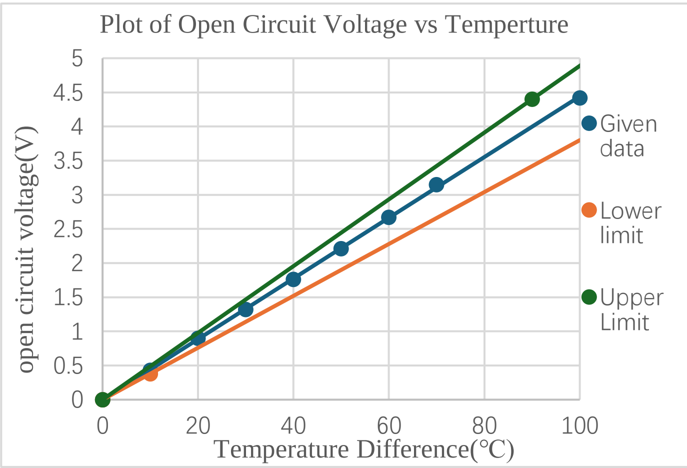

Figure 2.5 plots of specification and limited errors

For LED array, it consists of 8*8 LEDs corresponding to the thermoelectricity plate array. It can receive the signals and data processed by microcontroller and light different colors according to the temperature difference sensed by thermoelectric plate. Therefore, we choose WS2812B which is an intelligent control LED light source. This LED light was chosen for its three primary colors could achieve 256 brightness display, scan frequency not less than 400Hz/s and receive speed at 800kbps. It also integrated LED, control circuit and RGB chips, allowing the circuit to be simpler and easier to assemble.

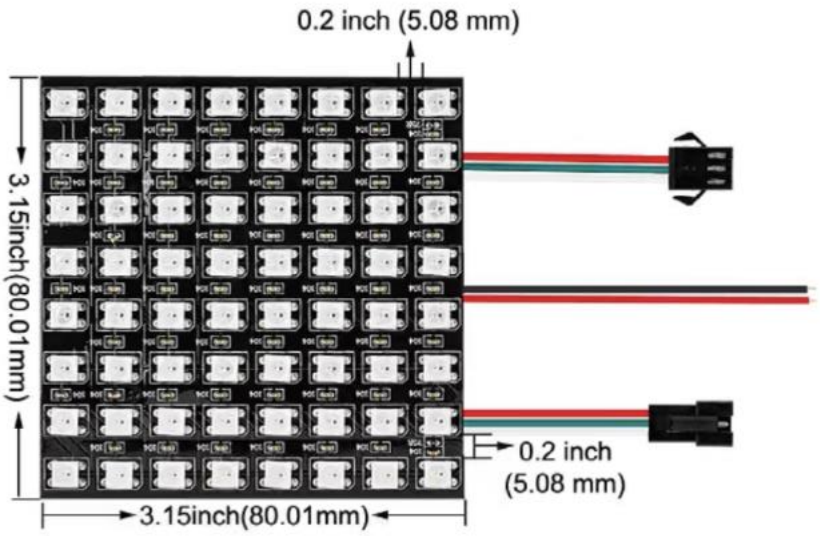

Figure 2.6 LED Array

2.2.2. Thermal Conduction and Convection Subsystem

This subsystem will demonstrate that heat transfers and has different effects depending on the material. When the student heats the conductor bar with their hand or other heat source, the display will show the temperature at three different locations on the conductor bar and the LEDs will change color at different temperature differences.

We thought about the different uses of various thermal conductive materials and how easy it would be to show the effect of heat transfer using different materials for the conductor bars. We used thermal sensors to measure the temperature and used lights and display data to show this.

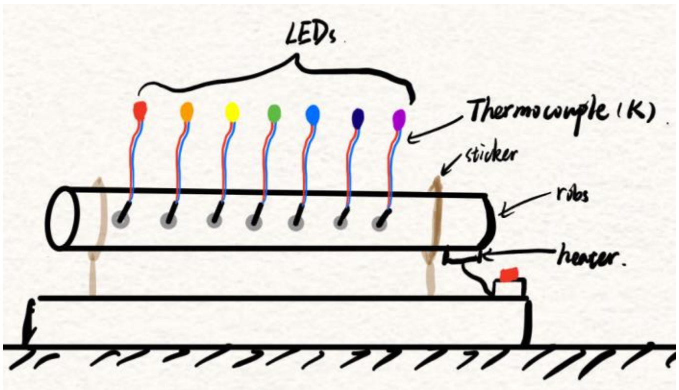

Figure 2.7 Thermal Conduction and Convection Subsystem

3. Design Verification

3.1. Thermoelectricity subsystem

3.1.1. Thermoelectric plate array

In our original design, we plan to use ice bags to make sure the temperature difference is sufficient, however, we found that a small temperature difference could be easily detected. Besides, it is difficult to power the system with the extra voltage it generates. Through our research we found that, temperature for palm is around 30℃ and for fingers it could be around 25℃ under the room temperature, but body temperature specially for hands could be largely changed by environmental temperature and body conditions. So, even without the ice bags, the voltage generated could still be at least 0.4V, which is enough for the subsystem. We also tested this as well and the results were just as calculated.

Therefore, unlike in our Requirement and Verification Table in design document, we discarded the idea of using ice packs and the desired temperature difference has been reduced which is no longer between 0.4V-3V as written in requirement. Besides, the other requirements are well satisfied, and the verifications have also been done well.

3.1.2. Control Board

This module is a PCB board that consists of several multiplexers and a microcontroller, which receive 64 signals from thermoelectric array module and output one signal to control LED array module. This module has changed a lot from the previous in design document. At first, we scheduled to use multiplexers to integrate every 8 signals into one signal, but in the process of verification, we found that the signals processed by multiplexer could not retain its original voltage, and it would be changed to high voltages and low voltages instead. Therefore, the plan of using multiplexer was discarded, and we will add the number of microcontrollers to solve this problem.

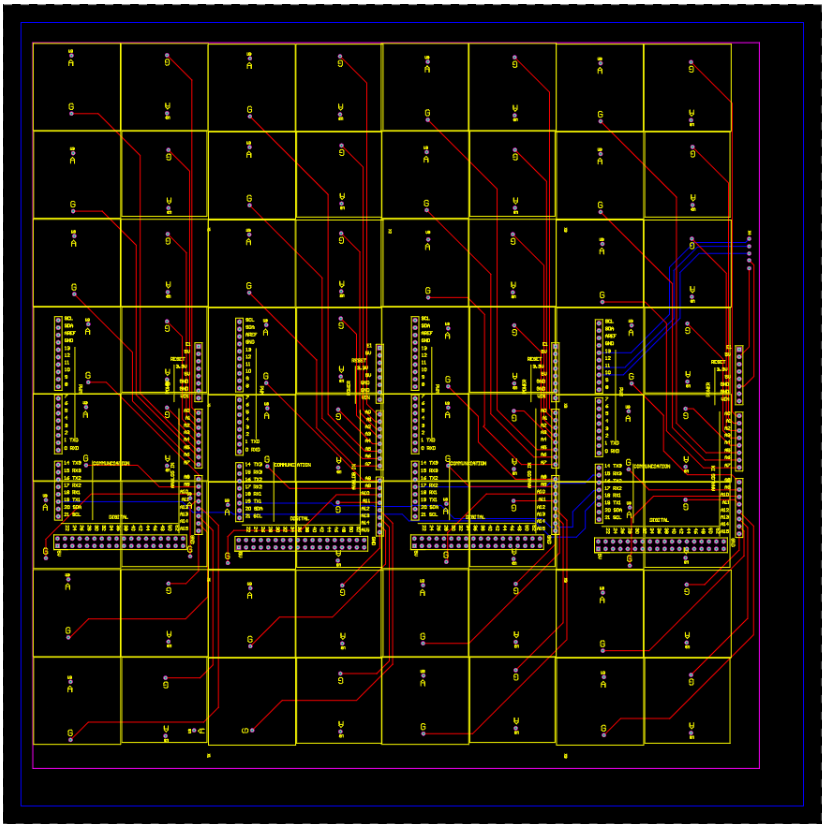

Figure 3.1PCB layout

3.1.3. LED array

In the process of verification, this module works smoothly and has almost no problem. Each LED light could work smoothly and individually and also display the desired colors controlled by microcontrollers. For its display performance, its luminance is sufficient and even when we decrease the input voltage to 1/16 of maximum values, the luminance is still enough and could be clearly visible out of 3 meters.

3.2. Heat conduction and convection subsystem

The rate of heat conduction in solids, also known as thermal conductivity, is the amount of heat transferred per unit time, per unit thickness of solid material, per unit temperature difference. The formula is as follows: $k = Q/(A * \Delta T * t)$ where: k is the thermal conductivity in W/(m-K); Q is the amount of heat transferred in J; A is the area of heat transfer in m^2; ΔT is the temperature difference in K; and t is the time. Suppose we have a metal rod of length L and cross-sectional area A. A power P is applied at one end and a temperature change needs to be detected at the other end. The heat transfer problem can be approximated as a linear heat transfer problem by considering the bar as a rectangular column. First, calculate the heat Q from the power and time: $Q = P * t$. Then, calculate the heat conduction velocity k from the heat conduction equation: $k = Q / (A * \Delta T * L)$ where ΔT is the temperature difference between the two ends of the bar. Next, based on the heat transfer rate k, we can estimate the time it takes for the other end to sense the temperature change: $t' = L / (k * \Delta T)$ Substituting the known data into the formula, we can calculate the time t' it takes for the other end of the metal rod to sense the temperature change.

3.2.1. Thermocouple

The DS18B20 is encapsulated with a sealant with high thermal conductivity, which ensures high sensitivity of the temperature sensor and very low temperature delay. The temperature sensor supports a "1-wire" interface and measures temperatures from -55°@-+125° with an accuracy of 0.5° cover a range of -10 to +85°C. The field temperature is directly transmitted as a "1-wire" digital signal. Digital

The field temperature is directly transmitted in a "one wire bus" digital way, which greatly improves the system's anti-jamming property. Suitable for field temperature measurement in harsh environments. This is different from the beginning of the choice of thermocouple temperature measurement, due to the field temperature is more difficult to measure we choose to use DS18B20.

3.2.2. Control board

We used an STM32F103C8T6 microcontroller as the core and three circuits including a temperature detection circuit, a display circuit and a WS2812 circuit. Due to the poor results of the previous experiments, we chose to visualize the temperature size directly on the display.

4. Cost

4.1. Parts

The table below shows the estimated cost of various parts. We estimate that it will cost us 132.09$ for one, and if we mass produce it, the cost is expected to drop to 106.8$.

Part	Manufacturer	Retail Cost($)	Bulk Purchase Cost($)	Actual Cost($)
Thermoeletric Plate (TES1-4903)	Jiequ Trading Co.	0.94*64=60.16	0.7*64=44.8	0.9*64=57.6
PCB	Jiepei PCB Co.	10.5	7	10.5
LED array (MAX7219)	Pairui Lianhe Technology Co.	0.76	0.7	0.76
Resistors, Capacitors, Crystals, Ics	TeleSky Co.	5	3	5
Microcontroller (ATmega2560)	Xinwei Electronic Technology Co.	9.13*4=36.52	8*4=32	9.13*4=36.52
Universal board	TeleSky Co.	2.1	1.5	2.1
Microcontroller (STM32F103C8T6)	TeleSky Co.	6.3	5.8	6.3
OLED	TeleSky Co.	4.8	4.5	4.8
Thermal probe (DS18B20)	Dallas Semiconductor Co.	1.7*3=5.1	1.5*3=4.5	1.7*3=5.1
LED RGB light (WS2812)	XGBTEL Co.	3.5	3	3.5
Total		134.74	106.8	132.09

4.2. Labor

Our fixed development costs are estimated to be 7$/hour, 10 hours/week for four people. Ignoring some additional labor costs, our R&D costs are approximately:

$$4 * \frac{7\$}{hr} * \frac{10hr}{wk} * 16wks * 2.5 = 11{,}200\$$$

5. Conclusion

5.1. Accomplishment

In summary, we have innovatively developed a thermal lab platform suitable for middle and high school classrooms, which effectively demonstrates the concepts of heat convection, conduction, and thermoelectricity to students. By visualizing heat changes through LEDs, students gain a more vivid and concrete understanding of thermodynamic concepts. The LED displays the temperature distribution on the thermoelectric plate and the heat-conducting rod, thus dynamically changing in real-time as students perform different operations, enhancing interactivity. By increasing the accuracy and sensitivity of thermal sensors, the lab platform can demonstrate excellent experimental results at room temperature. Combined with the electrical safety resulting from reasonable encapsulation and appearance design, the thermal lab platform ensures high safety levels, with minimal risk of injury to students even when operating independently. Its application in middle and high school classrooms is highly appealing due to its safety and effectiveness.

5.2. Uncertainty

It's worth noting that in the thermoelectric subsystem, the relatively large area of the small thermoelectric plates we use (20mm*20mm) can result in graphics with rough edges and insufficient clarity. This issue can be effectively addressed by reducing the size of the thermoelectric plates to increase the number of thermoelectric plates per unit area. Also, the corresponding increase in the number of LED arrays is necessary to significantly enhance the resolution of the LED display screen, thus better illustrating the thermal distribution on the large thermoelectric plate.

In the heat transfer subsystem, we currently only use three thermal sensors simultaneously and utilize LEDs to display the temperature differences between these sensors. However, this approach does not adequately capture the overall temperature curve inside the heat-conducting rod. By increasing the number of thermal sensors and introducing a display screen to showcase the temperature curve inside the heat-conducting rod, we can better demonstrate the diverse thermal conductivity properties of different materials.

5.3. Ethic and Safety

In developing a thermoelectric teaching aid, it is crucial to adhere to ethical standards set forth by the IEEE [5] and ACM [6] by ensuring the design prioritizes public safety and environmental sustainability. The highest voltage is set to only 5V in our design, which is no harm to human body. Also, the material and components are choosing to consider their environmental sustainability and would not be discarded randomly. We should transparently disclose any potential conflicts of interest and respect intellectual property rights through proper acknowledgment and licensing of all hardware and software components. Rigorous testing should be conducted to maintain high standards of quality and performance, with honest representation of the aid's capabilities and limitations to avoid misleading users. Moreover, we should aim to enhance educational outcomes in STEM and promote professional development, ensuring that the benefits of the teaching aid are accessible without discrimination, thereby supporting an inclusive learning environment. This comprehensive approach will not only uphold ethical engineering practices but also contribute positively to societal and environmental well-being.

5.4. Future Work

In future work, we can continue to enhance the thermal lab platform to further improve its performance and functionality. In our thermoelectric subsystem, we currently use an external power source to supply power to the microcontroller, which to some extent does not demonstrate the concept of converting heat energy into electrical energy. Thermoelectric plates can generate electricity with temperature difference. However, due to limitations in the efficiency of thermoelectric plates and the relatively small temperature difference from sources such as the human body and room temperature, we currently only utilize this energy to generate signals and display them on LEDs. However, if we could improve the thermoelectric plates and use microcontrollers and LED displays with lower power consumption, the thermoelectric subsystem could potentially power itself through the electricity generated by the thermoelectric plates, thereby better illustrating the concept of thermoelectric conversion.

Furthermore, this thermal lab platform aims to enhance the quality of thermodynamics teaching in middle and high school classrooms. To achieve this goal, it is necessary to develop corresponding teaching support materials and resources. For example, when using the heat transfer subsystem, teachers could play instructional videos explaining Fourier's law of heat conduction. Through continuous improvement and innovation, the thermal lab platform will become an essential tool in future teaching, providing students and teachers with richer and more in-depth learning and teaching experiences.

References

[1] Ordu, U. B. A., “The role of Teaching and Learning AIDS/Methods in a changing world.,” *Bulgarian Comparative Education Society.*, 2021.

[2] J. S. Lee, “The relationship between student engagement and academic performance: is it a myth or reality?,” *The Journal of Educational Research*, vol. 107, no. 3, pp. 177–185, Nov. 2013, doi: 10.1080/00220671.2013.807491.

[3] S. Wang *et al.*, “Integration of recent developments in transient heat conduction and mass transfer for solid sphere into teaching,” *Computer Applications in Engineering Education*, vol. 30, no. 5, pp. 1526–1546, Jun. 2022, doi: 10.1002/cae.22542.

[4] D. K. Umam, S. Saehana, A. Kade, and Yunanli, “Development of Thermal Energy Conversion Devices into Electrical Energy as Physics Learning Teaching Aids,” Journal of Physics: Conference Series, vol. 2126, no. 1, p. 012011, Nov. 2021, doi: 10.1088/1742-6596/2126/1/012011.

[5]IEEE, “IEEE Code of Ethics,” ieee.org, Jun. 2020. https://www.ieee.org/about/corporate/governance/p7-8.html

[6]“The ACM Code of Ethics arose from the experiences, values and aspirations of computing professionals around the world, and captures the conscience of the profession. It affirms an obligation of computing professionals to use their skills for the benefit of society.,” www.acm.org. https://www.acm.org/about-acm/code-of-ethics-in-chinese (accessed Apr. 15, 2024).