Teaching Heat to High School Students

ECE 445 Design Document

Team #26

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1. Introduction

1.1 Problem:

In the middle and high school stages, the traditional teaching method for thermodynamics heavily relies on theoretical explanations, where teachers impart knowledge of thermodynamics through formulas and corresponding exercises. However, as an integral part of physics, thermodynamics entails many abstract concepts, which can be relatively challenging for students who are just introduced to it. The use of teaching aids can help students visualize the taught content, leading to reinforcement of learning [1]. Such concretization is crucial in teaching thermodynamics and can significantly deepen students' understanding of its concepts. Moreover, interactive teaching aids can enhance student engagement, igniting their enthusiasm for learning thermodynamics and thereby strengthening the effectiveness of their studies [2].

Recently, many researchers and educators have attempted to improve the way thermodynamics is taught. For instance, Wang et al. [3] introduced some advanced mathematical methods in the university-level heat transfer classroom, elucidating the fundamental principles of heat conduction through the analytical solutions of differential equations, significantly enhancing the teaching quality. However, this teaching model, which incorporates mathematical methods, is challenging to implement in middle and high school settings due to students' lack of advanced mathematical knowledge, making it difficult for them to intuitively understand thermodynamics from a mathematical perspective. Umam et al. [4] designed an experimental device that converts thermal energy into electrical energy, linking these two abstract concepts in the classroom, which received high praise from the majority of students. This experimental apparatus is more suitable for use in middle and high school classrooms, yet it still has many areas for improvement, such as lack of intuitive conversion and insufficient entertainment value. Overall, an innovative thermal teaching aid that is safe, engaging, and capable of visually demonstrating thermodynamics concepts remains scarce and highly needed.

1.2 Solution:

We propose to design and manufacture an integrated thermal experiment platform. This platform is primarily divided into two parts: a thermoelectric subsystem and a thermal conduction and convection subsystem. The thermoelectric system includes a thermoelectric plate array, a control module, and an LED array. When students touch the thermoelectric plate array, corresponding sections on the LED array will light up. The thermal conduction and convection system include rods made of different metal materials, thermal sensors with displays, a control module, and a heater. When students touch or activate the heater to heat one end of the rod, the display will show the temperature distribution within the rod.

The platform aims to provide students with hands-on learning experiences to visually demonstrate key concepts of heat transfer and thermal energy conversion. Through practical experiments, students will deepen their understanding of thermal conduction, convection, and thermoelectricity. The platform will feature interactive demonstrations and experiments, allowing students to explore these concepts firsthand, fostering curiosity and interest in the field of thermal science.

1.3 High-level requirements list:

The platform must effectively demonstrate concepts of heat conduction, convection, and thermoelectricity.
The platform must be safe for use in educational environments, with appropriate protective measures such as insulation and heat insulation to prevent accidents or injuries.
The platform needs to provide an intuitive interface and controls for students and teachers, with simple setup and operation, facilitating learning without technical difficulties.
The platform needs to be portable, relatively easy to move and transport, for use in different classrooms or educational environments.
The platform needs to have strong interactivity: attracting student participation during thermal experiments, with features that encourage exploration and experimentation.

2. Design

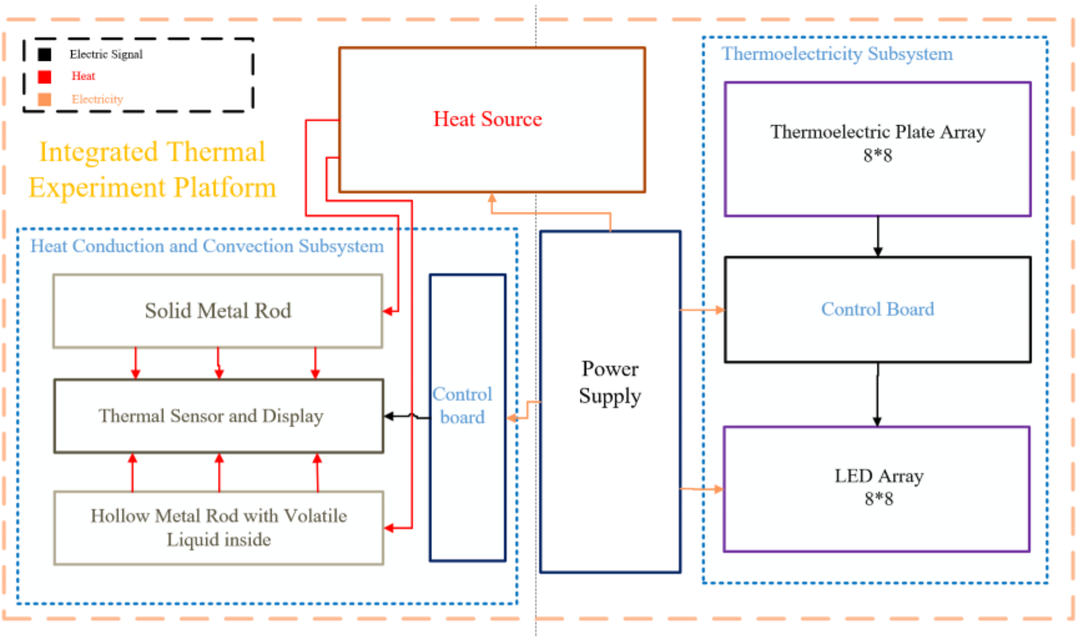

Fig 1. Block Diagram

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.

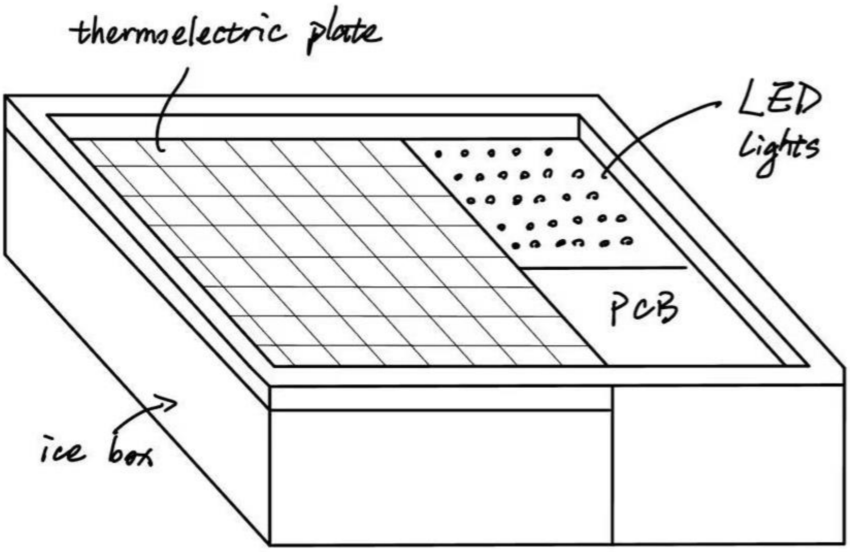

Fig 2. Thermoelectricity subsystem

2.1.1 Thermoelectric plate array

Nodes will be powered by the temperature difference of two sides of each thermoelectric plate. We choose 23mm*23mm*4.1mm thermoelectric plate and combine them into an 8*8 arrays. It is powered by hands or other heat source with higher temperature and on the other sides is cooled by ice bags to make sure the temperature difference is sufficient. 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. While for ice bag, it could reduce the temperature of one side of thermoelectric plate to 2-8℃. Therefore, the input temperature difference would be in the range of 10-100℃.

Requirement	Verification
1. Each thermoelectric plate output 0.4-3V open-circuit voltage 2. The 8*8 plates working separately. 3. The delay should be less than 3s. 4. It must work in at an environment temperature of at least 30℃	1. A. Put hand in room temperature (can use fingers which has lower temperature) and ice bag on two sides of thermoelectric plate. B. Measure the open-circuit voltage with a voltmeter, ensuring that it is higher than 0.38V C. Change hands to a cup of boiled water to produce around 100℃ temperature difference. Measure the open-circuit voltage and ensure that it is lower than 4.4V

	2. A. Using the voltmeter to make sure every plate working separately without disturbing each other. 3. A. Put heat source in various temperature and ice bag on two sides. B. Measure the time for the open-circuit voltage to reach its equilibrium (about 5% to final voltage) with voltmeter and timer, ensuring it is less than 3s. 4. A. When the outside temperature is higher than 30°C, put our device outdoor and let it directly exposed under the sunshine to heat the thermoelectric plates. B. Place the hands onto the plates and connect it with a voltmeter. C. Ensure the plate could produce enough open-circuit voltage of at least 0.4V

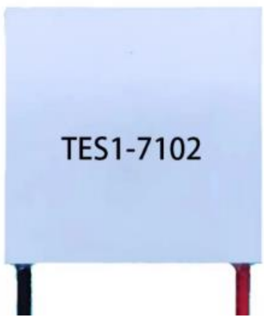

Fig 3. Thermoelectric Plate

2.1.2 Control board

This part 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. We choose SN74LS151N as multiplexer to integrate the 8 signals from thermoelectric plates to 1 signal, which is convenient for microcontroller to read and for PCB board to construct. As for microcontroller, STC8G1K08 was selected for its affordability and clock speeds of 11.0592MHz, enough for this project. Also, it could program on system through ISP interface to better control the multiplexers and circuits.

Requirement	Verification
1. Integrate every 8 signals of thermoelectric to one signal. 2. Microcontroller can be programmed through ISP interface and STC software to realize desired functions. 3. Output the signals Controlling LEDs	1. A. Directly connect the 8 input ports and power supply with 5V and 0V randomly B. Connect the output with the oscilloscope. C. Test whether the signal is integrated by 8 input signals. 2. A. Connect microcontroller to USB ISP bridge. B. Use STC-ISP software or other compatible programming software to program a simple code which can be easily tested by oscilloscope or voltmeter. C. Examine whether verification step in software is successful. D. Test whether program on microcontroller runs successfully with oscilloscope. 3. A. Write a simple code to control one LED light and connect them together. B. Ensure the LED could light the same as how it controls

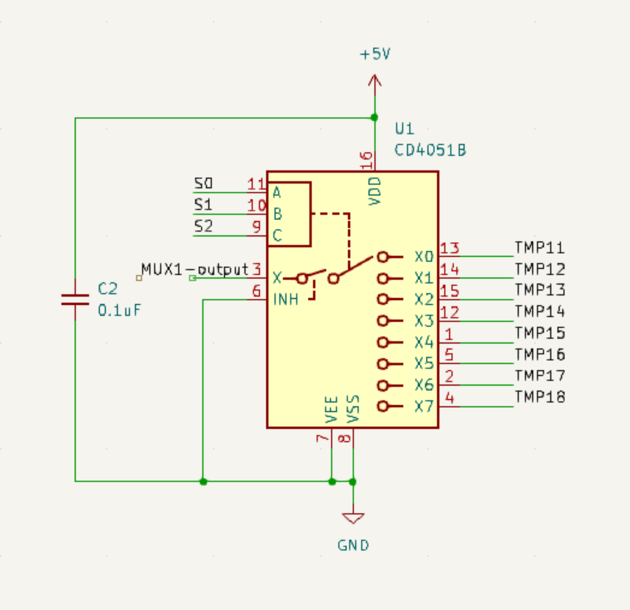

Fig 4. Control Board Schematic 1

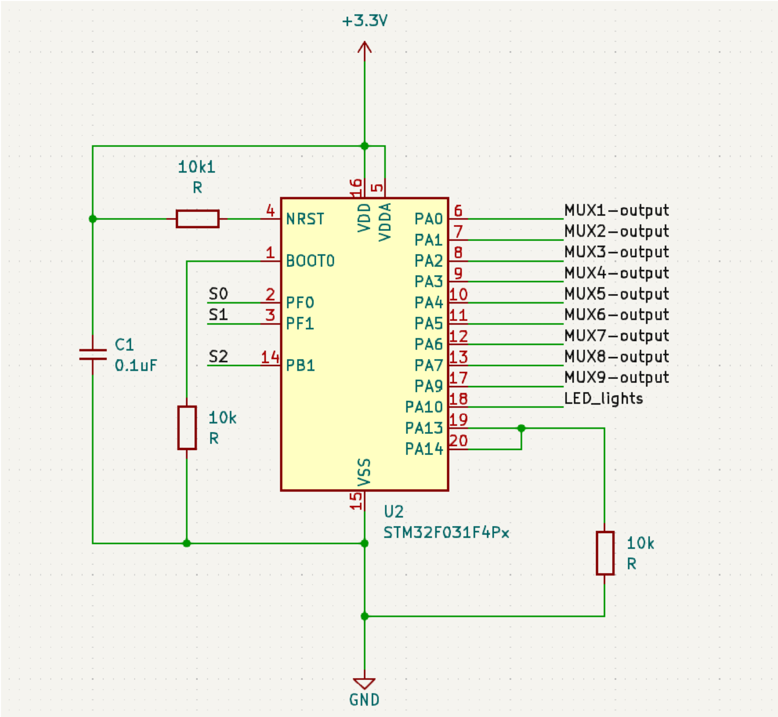

Fig 5. Control Board Schematic 2

2.1.3 LED array

This LED array 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.

Requirement	Verification
1. Display the desired colors for each LED light. 2. Must be visible from 3 meters away	1,2. A. Write a program in Arduino to let LED light display random color in every 3 second. B. Confirm that LED display and change each color smoothly without interfering other. C. Also ensure that LED is clearly visible out of 3 meters distance.

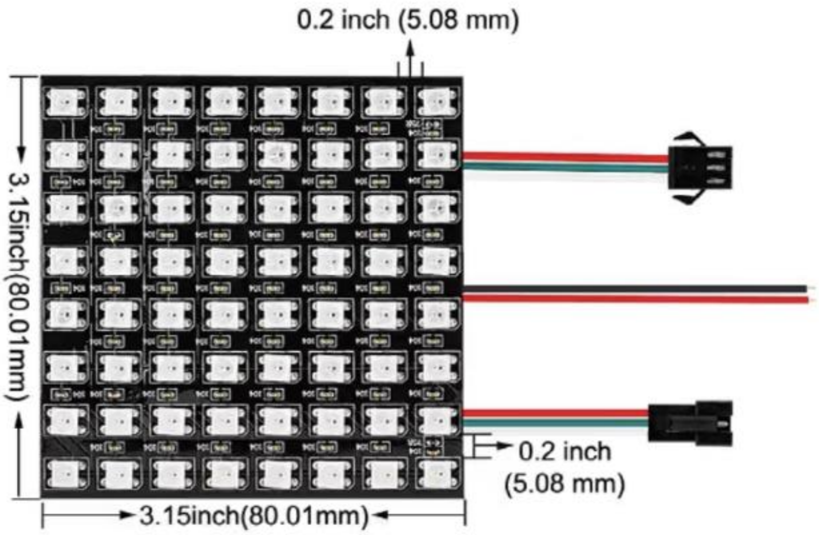

Fig 6. LED Array

2.2 Thermal Conduction and Convection Subsystem

This subsystem of our teaching program will showcase the differences in the conducti on of heat in different materials.When students put their hands or other heat source su ch as a cup filled with hot water on one side of the rod, heat will conduct from this sid e to the other and the Led lights uniformly distributed on the rod will light up if the th ermocouple connected to the Led lights reach a certain temperature.

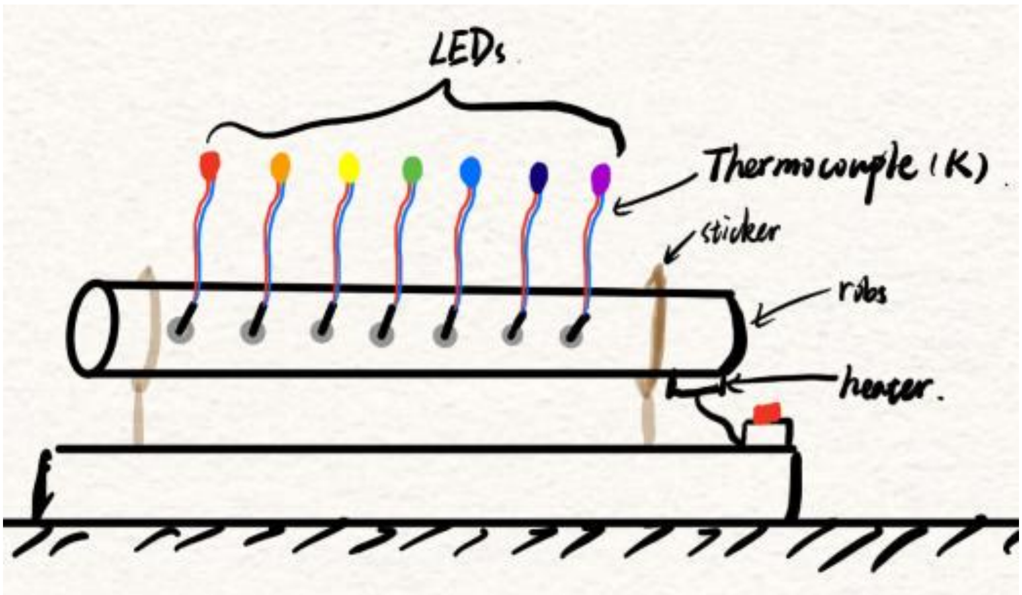

Fig 7. Thermal Conduction and Convection Subsystem

2.2.1 Thermal Conduction Sticks Array

Heat is conducted from one end of different materials to the other. We use copper pipe with built in thermal fluid, High Purity Tungsten Rod, wooden stick and Polytetrafluoroethylene rods as heat conduction teaching tool. It is powered by hands or other heat source with higher temperature on one side. Temperature for palm is around 30℃. However, body temperature specially for hands could be largely influenced by body conditions and environmental temperature is uncertain, which will cause inefficient heat conduction. As a result, we put the sticks into the ice and the temperature of stick will reduce to 2-8℃, which will cause huge temperature difference between the stick and hand.

Requirement	Verification
1. Each sticks work separately. 2. Temperature difference between he at source and rod should be greater than 10 degrees	1. Make sure there are no good conducto rs of heat between each stick. 2. put sticks into ice and reduce temperat ure of stick to 2-8℃ and the temperature of hands will be around 30℃. Thus, the temperatur e difference will be greater that 10℃

2.2.2 Heat Pipe Working Principle

A heat pipe is an efficient heat transfer device. It utilizes two processes, evaporation, and condensation, to transfer heat. The principle of operation can be divided into the following key steps:

1. Evaporation zone: At one end of the heat pipe (what we call the "evaporation zone") is heated by a heat source. Here, the working medium (e.g., water, alcohol, or other specific liquids) absorbs heat and evaporates into a gas.
2. Gas flow: Due to pressure differences, this evaporated gas automatically flows to the other end of the heat pipe, the "condensation zone.
3. Condensation zone: In the condensation zone, the gas encounters a relatively cold environment, where it releases heat and condenses back into a liquid state. This heat is usually transferred to a radiator or other cooling system in order to be dissipated.
4. Return to the evaporation zone: The working medium in its liquid state flows back to the evaporation zone again, either by capillary action or gravity, to start the process all over again.

Throughout the process, heat is efficiently transferred from the evaporating zone to the condensing zone, while the working medium circulates in between, forming a closed loop. Heat pipes are very efficient at transferring heat because the working medium inside the heat pipe is able to transfer a large amount of heat during evaporation and condensation. Simply put, a heat pipe is like a "superconductor" that utilizes the phase change of matter (from liquid to gas and back again) to transfer heat efficiently, and often more efficiently than a purely solid material.

2.3 Tolerance analysis

2.3.1 Thermoelectricity subsystem

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. However, the commercially available thermoelectric plate is all designed for refrigerating, their ability to produce electricity may vary largely, making it generates a large error in voltage based on temperature differences. This error caused may exceed out of the upper or lower limit of the microcontroller inputs.

According to Seebeck Effect, two different electrical conductors or semiconductors can cause a voltage difference between the two substances due to temperature differences. This is since the carrier energy is higher from at the hot end than at the cold end. The equation for the potential difference of Seebeck Effect is:

$$V = \int_{T_C}^{T_H} \left(S_B(T) - S_A(T)\right) dT \qquad Eq.1$$

Where, S_A and S_B are Seebeck coefficient for both materials and T_C and T_H represent their temperature at the end. If S_A and S_B do not vary with temperature or temperature changes in a small range, the above equation can be expressed as follows:

$$V = k(T_2 - T_1) \qquad Eq.2$$

Where k is a constant represents the difference of two Seebeck coefficient. This shows that the voltage is generated linearly with the temperature difference. So ideally, we assume that the Seebeck coefficient difference of two components of thermoelectric plate is k. In the part 2.1.1 we have claimed that the temperature difference of hands in normal condition is 20℃-35℃ and the ice bag could make the bottom of thermoelectric plate to 2℃-8℃, creating a temperature difference about 33℃-12℃. This difference may be growing higher to 90℃ when we put a cup of hot water on these plate array.

While for a STC8G1K08A microcontroller, the working voltage is in the range of 1.9V-5.5V [5]. To protect the microcontroller, we assume that the ADC voltage acquisition is in the interval from 20% minimum operating voltage to 80% maximum voltage, that is 0.38V-4.4V. Therefore, for every thermoelectric plate, the range of voltage is about 11.58 times, which is larger than 9 times the temperature difference could have.

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

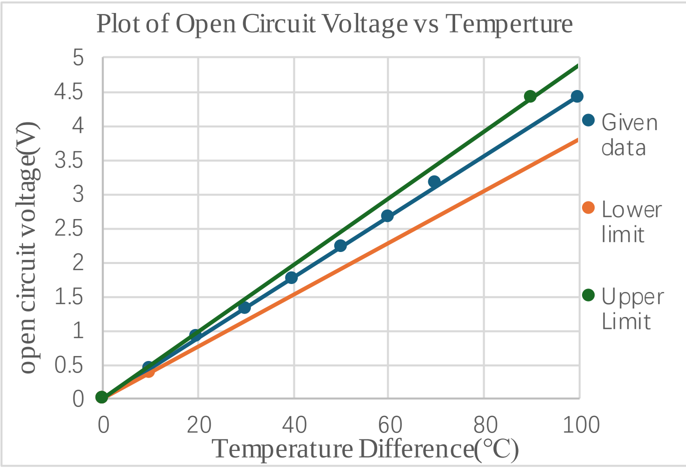

Fig 8. plots of specification and limited errors

So, from the data provided on the product specification, when the temperature difference is 10℃, the open circuit voltage is about 0.43V and is about 3.99 V for 90℃ difference. So that as shown in figure 2.1 for low temperature it can tolerate an error of over 13% and for high temperature the error could still be about 10%. These errors are all acceptable for the thermoelectric plates. Considering we still set a 20% input error for the protection of our microcontroller, we can draw a conclusion that this part in our design is able to work successfully both in normal conditions and for heat source lower than boiling water.

2.3.2 Thermal conduction and convection subsystem

A thermocouple is formed by connecting two conductors or semiconductors A and B of different materials to form a closed loop. As shown in Figure 1. Temperature t end for the temperature-sensitive end is called the measurement end, temperature t0 end for the connection instrumentation end is called the reference end or cold end, when the conductor A and B of the two clinging point t and t0 temperature difference exists between the two points of contact, in the loop to produce an electric potential EAB (t, t0), and thus the formation of electric current in the loop, a phenomenon known as the thermoelectric effect ". This electric potential is called thermal potential, thermocouple is to use this effect to work. The size of the thermoelectric potential and the size of the difference between t and t0. When the thermocouple of the two hot electrode material is known, by the thermocouple circuit thermoelectric potential distribution theory that the thermocouple ends of the thermoelectric potential difference can be expressed in the following formula:

$$EAB\ (t, t0) = EAB\ (t) - EAB\ (t0) \qquad Eq.3$$

Where EAB (t, t0) - thermocouple thermal potential; EAB (t)-thermal potential of the working end at temperature t; EAB (t0) - temperature is t0 when the cold end of the thermal potential.

From the above formula can be seen! When the working end of the measured medium temperature changes, the thermal potential changes, therefore, as long as the measurement of EAB (t, t0) and know EAB (t0) can be obtained EAB (t), the thermal potential sent to the display instrument for indication or recording, or sent to a microcomputer for processing, you can get the measurement end of the temperature t value.

To really understand the application of thermocouples it is necessary to mention several important properties of the thermocouple circuit:

The law of mass materials: a closed loop composed of a homogeneous material, regardless of how the temperature distribution of the length of the material in all places, the circuit does not generate thermal potential. This law requires that the two materials that make up the thermocouple must each be homogeneous, otherwise there would be an additional potential due to the temperature gradient along the length of the thermocouple, which would introduce error due to the unevenness of the thermocouple materials.

The law of intermediate conductors: insert a third homogeneous material (or materials) into the thermocouple circuit, and as long as the temperature of the connection point at both ends of the inserted material is the same, the inserted third material does not affect the thermal potential of the original circuit. This law shows that a thermocouple circuit can be pulled into an instrument that measures the thermal potential, as long as the instrument is at a stable ambient temperature. It also indicates that thermocouple joints can not only be welded, but can also be connected by borrowing a homogeneous isothermal conductor.

The law of intermediate temperature: two different materials composed of thermocouple circuit, its contact temperature were t and to when the thermal potential EAB (t, to) is equal to the thermocouple in the connection point temperature (t, tn) and (tn, to) when the corresponding thermal potential EAB (t, tn) and EAB (tn, to) the algebraic sum of which tn for the intermediate temperature. The law that when the thermocouple reference end temperature is not 0 ℃, as long as the thermal potential can be measured EAB (t, to), and to is known, can still use the thermocouple index table to find the measured temperature t value.

Connected conductor law: in the thermocouple circuit, if the thermocouple electrode material A and B were connected with the connection wires A1 and B1 (shown below), the temperature of each relevant point of contact for t, tn and to, then the circuit of the total thermal potential is equal to the thermocouple ends in the t and tn temperature conditions of the thermal potential EAB (t, tn) with the connection wires A1 and B1 ends in the tn and to temperature conditions The algebraic sum of the thermal potential EA1B1 (tn, to) at the ends of connecting wires A1 and B1 at the temperatures tn and to. Intermediate temperature law and connecting conductor law is the industrial thermocouple temperature measurement in the application of the theoretical basis for compensation wire.

T is temperature unit of temperature is degree centigrade unit of voltage is mV

T	0	-10	-20	-30	-40	-50	-60	-70	-80	-90	-95	-100
-200	-5. 8914	-6. 0346	-6. 1584	-6. 2618	-6. 3438	-6. 4036	-6. 4411	-6. 4577				
-100	-3. 5536	-3. 8523	-4. 1382	-4. 4106	-4. 669	-4. 9127	-5. 1412	-5. 354	-5. 5503	-5. 7297	-5. 8128	-5. 8914
0	0	-0. 3919	-0. 7775	-1. 1561	-1. 5269	-1. 8894	-2. 2428	-2. 5866	-2. 9201	-3. 2427	-3. 3996	-3. 5536
T	0	10	20	30	40	50	60	70	80	90	95	100
0	0	0. 3969	0. 7981	1. 2033	1. 6118	2. 0231	2. 4365	2. 8512	3. 2666	3. 6819	3. 8892	4. 0962
100	4. 0962	4. 5091	4. 9199	5. 3284	5. 7345	6. 1383	6. 5402	6. 9406	7. 34	7. 7391	7. 9387	8. 1385
200	8. 1385	8. 5386	8. 9399	9. 3427	9. 7472	10. 1534	10. 5613	10. 9709	11. 3821	11. 7947	12. 0015	12. 2086
300	12. 2086	12. 6236	13. 0396	13. 4566	13. 8745	14. 2931	14. 7126	15. 1327	15. 5536	15. 975	16. 186	16. 3971
400	16. 3971	16. 8198	17. 2431	17. 6669	18. 0911	18. 5158	18. 9409	19. 3663	19. 7921	20. 2181	20. 4312	20. 6443
500	20. 6443	21. 0706	21. 4971	21. 9236	22. 35	22. 7764	23. 2027	23. 6288	24. 0547	24. 4802	24. 6929	24. 9055
600	24. 9055	25. 3303	25. 7547	26. 1786	26. 602	27. 0249	27. 4471	27. 8686	28. 2895	28. 7096	28. 9194	29. 129
700	29. 129	29. 5476	29. 9653	30. 3822	30. 7983	31. 2135	31. 6277	32. 041	32. 4534	32. 8649	33. 0703	33. 2754
800	33. 2754	33. 6849	34. 0934	34. 501	34. 9075	35. 3131	35. 7177	36. 1212	36. 5238	36. 9254	37. 1258	37. 3259
900	37. 3259	37. 7255	38. 124	38. 5215	38. 918	39. 3135	39. 708	40. 1015	40. 4939	40. 8853	41. 0806	41. 2756

Thermocouple Allowable Error Calculation Formula:

The thermocouple tolerance formula expresses the difference between the actual temperature value and the thermocouple measurement as a percentage. The formula for calculating the allowable error for thermodynamic data is generally used as follows:

1. Thermocouple permissible error formula:

(1) 0°C to 600°C: Allowable error = +- (0.15% of temperature+ 0.3°C).

(2) 600 ° C ~ 1100 ° C: the allowable error = +- (0.2% temperature + 1.2 ° C);

2. Precautions:

(1) Where the thermocouple use in the process of measured error is greater than the above permissible range are likely to be thermocouple quality problems, should be immediately checked and tested.

(2) thermocouple minimum temperature test interval is generally 30° C ~ 40 ° C, in the minimum temperature test range, the allowable temperature error: +-2.2 ° C; (3) For thermocouple use in the process of measurement is greater than the above allowable range may be thermocouple quality problems should be checked immediately.

(3) For small temperature test, such as 0~200°C monitoring, can be used to the thermocouple withstand voltage test chamber for check

3. Cost

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:

$$4 * \frac{7\$}{hr} * \frac{10hr}{wk} * 16wks = 4{,}480\$ \qquad Eq. 4$$

The table below shows the estimated cost of various parts when we make prototype. We estimate that it will cost us 83.83$ for one prototype, and if we mass produce it, the cost is expected to drop to 58.55$.

Part	Cost (prototype)	Cost (bulk)
Thermoelectric plate array (TES1-7103)	0.76$*64=48.64$	0.5$*64=32$

PCB	3$	0.1$
LED array (WS2812B)	8$	7$
Microcontroller (STC8G1K08)	1$	0.8$
Multiplexer (SN74LS151N)	0.1$*8=0.8$	0.7$
Resistors, Capacitors, Crystals, ICs	5$	2$
Copper pipe 3mm*150mm	1.8$	1.5$
Copper pipe 8mm*150mm	1.5$	1.3$
Tungsten rod 5mm*150mm	6.3$	6$
Tungsten rod 3mm*150mm	4.8$	4.3$
PTFE rod 8mm*1000mm	0.83$	0.8$
PTFE rod 5mm*1000mm	0.76$	0.75$
Model k Thermocouple Probes	0.14$*10=1.4$	0.13$*10=1.3$
Total	**83.83$**	**58.55$**

4. Schedule

The project is divided into two parts, the thermoelectric subsystem and the heat conduction and convection subsystem. Kaihua and Tianyu are mainly responsible for the thermoelectric system, while Yongxin and Ziang are mainly responsible for the heat transfer system. These two subsystems also have some similar structures and functions, where all the team members work together to solve these problems.

Week	Kaihua Hu	Tianyu Feng
3/25	Make small prototype (1*8 thermoelectric plate)	Make small prototype (1*8 thermoelectric plate)
4/1	Extend prototype (1*8 to 8*8)	Designing PCBs for 8*8 prototype
4/8	Complete the prototype and perform initial tests	Test prototype and contact manufacturer for PCB manufacturing
4/15	Replacing some circuits in prototype with PCB	Replacing some circuits in prototype with PCB
4/22	Design and 3D print decorative parts	Improve circuit structure to ensure durability
4/29	Try programming to add functionality (different colors for different temperatures)	Try programming to add functionality (different colors for different temperatures)

5/6	Assemble two subsystems and battery	Assemble two subsystems and battery
5/13	Environmental test and final demo	Environmental test and final demo
5/20	Final report	Final report

Week	Yongxin Xie	Ziang Liu
3/25	Make small prototype	Make small prototype
4/1	Test and calculate the conductivity in different material	Test and calculate the conductivity in different material
4/8	Drill holes in the stick	Drill holes in the stick
4/15	Design and connect circuits	Design and connect circuits
4/22	Design and 3D print decorative parts	Design and 3D print decorative parts
4/29	Assemble Thermocouples Sticks and LEDs	Assemble Thermocouples Sticks and LEDs
5/6	Try programming to add functionality (LED lights up at a certain temperature)	Try programming to add functionality (LED lights up at a certain temperature)
5/13	Environmental test and final demo	Environmental test and final demo
5/20	Final report	Final report

5. Ethics and Safety

5.1 Ethics:

In developing an integrated thermal experiment platform aimed at enhancing the learning experience of high school students in thermodynamics, we address the ethical considerations essential for fostering an inclusive, safe, and respectful learning environment. Our commitment to ethical principles includes:

5.1.1 Inclusivity and Accessibility:

Ensuring that our platform is accessible and useful to all students, regardless of their physical abilities or learning styles. This entails designing interfaces and experiments that accommodate a wide range of users, promoting equal opportunities for learning and engagement.

5.1.2 Bias and Sensitivity:

Recognizing the potential for educational materials to reflect or perpetuate biases, we are committed to developing content that is culturally sensitive and free from stereotypes. Our goal is to provide an educational experience that respects and celebrates diversity.

5.2 Safety:

To address the safety concerns associated with our project, comprehensive measures are in place to ensure the well-being of all users. Key components of our safety strategy include:

5.2.1 Electrical Safety:

All electrical components will be securely insulated, with built-in safety features like circuit breakers to prevent overcurrent situations. A detailed Electrical Safety Manual will provide guidelines on safe operation and emergency protocols.

5.2.2 Thermal Safety:

Given the potential for burns from heaters or during experiments, we will implement safeguards such as thermal insulation and protective gear. A Lab Safety Document will outline procedures for safe handling of heat sources, including first aid measures for burns.

5.2.3 Mechanical Safety:

For any moving parts within the platform, we will employ shielding and safety guards to eliminate risks of injury. A Mechanical Safety Manual will guide users on interacting safely with the device.

Reference

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