Heating Element for an Integrated Microfluidic Platform

Capstone Report

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This project report was created on TexStudio editing platform using LaTeX. All the figures were drawn using draw.io online software tool.

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Title:
Heating Element for an Integrated Microfluidic Platform

Theme:
Circuit Design and Microbiology

Project Period:
Fall 2023

Project Group:

Participant(s):
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Supervisor(s):
Gulsim Kulsharova

Copies: 1

Page Numbers: 28

Date of Completion:
April 26, 2024

Abstract:

The primary objective of this project is to design, develop, and test a heating element for an integrated microfluidic platform. The heating element will be built into the microfluidic platform to enable precise temperature control and thermal cycling for various biological applications. The project will involve designing the heating element using computational modeling, followed by fabrication and implementation with the microfluidic platform. The heating element will be tested to ensure it provides accurate and stable temperature control, and its performance will be compared with existing heating methods.
The results of this project will contribute to the development of microfluidic devices that can accurately and efficiently control temperature for various biological applications. The integrated microfluidic platform with the heating element will be a valuable tool for researchers and clinicians in fields such as diagnostics, drug discovery, and point-of-care testing. Overall, this project aims to advance the field of microfluidics and contribute to the development of innovative technologies for biomedical applications.

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Preface

Microfluidic technology has become a valuable resource for a wide range of applications, including drug delivery, chemical analysis, and biological sensing. This project, "Heating Element for an Integrated Microfluidic Platform," aims to revolutionize temperature control in biological applications.

I want to express my heartfelt gratitude to my supervisor, Gulsim Kulsharova, whose advice has been priceless. Without her aid, my study would not have been as good or timely. We worked to design, develop, and test a heating element specifically for microfluidic devices, allowing for precise temperature control and thermal cycling. In addition, I want to thank the NU Library for providing students with free access to a large collection of research papers and publications, which considerably enhanced the depth of our study.

Through computational modeling, fabrication, and rigorous testing, we've ensured the heating element's accuracy and stability. Moreover, our investigations into its effects on biochemical processes promise to optimize its performance for diverse applications.

This project's outcomes hold immense potential to advance biomedical research and clinical practices, from diagnostics to drug discovery. I'm excited to share our findings and contribute to the ongoing innovation in microfluidics.

Nazarbayev University, April 26, 2024

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Chapter 1

Introduction

Microfluidic platforms have emerged as powerful tools for various applications such as drug delivery, chemical analysis, and biological sensing. These platforms utilize the flow of small amounts of fluids through microchannels, allowing for precise and efficient control of the fluid flow. One of the critical factors that affect the performance of microfluidic platforms is temperature control. To achieve optimal operation, precise temperature control is required to ensure that reactions occur at the correct rate and that the system is in thermal equilibrium. Therefore, the project which designs and develops a heating element for a microfluidic platform that utilizes the Peltier element is proposed. The primary objective of this project is to design, develop, and test a heating element for an integrated microfluidic platform that can constantly provide 37 degrees Celsius. The heating element will be built using the Peltier element and Arduino coding to enable precise temperature control and thermal cycling for various biological applications

1.1 Related works

There are a significant amount of scientific works discussing temperature control for various biochemical and biomedical applications. Mostly, the authors emphasize the rapid heating and cooling process for applications of DNA amplification especially Polymerase chain reaction (PCR) where 3 temperature stages with 40 cycles appear from a range of 95°C to 25°C. In this project, we emphasize maintaining a stable temperature of 37°C to mimic the conditions found in the human body and produce reliable results.

The article [1] provides a detailed explanation of the Seebeck and Peltier effects, which are the underlying principles that enable Peltier devices to generate electricity from temperature differences. Also, it highlights the importance of material selection and device design for improving the efficiency and performance of

Peltier devices. Furthermore, the authors discuss the different types of thermoelectric materials, including Bi2Te3 and PbTe, and their suitability for various applications. They also examine the use of nanotechnology and advanced manufacturing techniques to enhance performance and reduce the cost of Peltier devices. The article [2] emphasizes that despite the limitations of Peltier devices, such as low efficiency and high cost, they offer several advantages over traditional cooling and power generation technologies, such as being environmentally friendly and having no moving parts. Therefore, Peltier devices have significant potential for future applications, particularly in renewable energy and waste heat recovery. The article provides a thorough and informative review of the applications and limitations of thermoelectric Peltier devices, covering various aspects of their design, materials, and performance. It offers valuable insights and recommendations for researchers and engineers interested in this field and highlights the potential of Peltier devices for a wide range of applications in the future.

The first half of the article [3] provides a summary of portable cooling equipment used in biomedical applications. It provides a rundown of frequently employed techniques, along with examples of particular uses. The Peltier device's application in experiments as well as the physical theories underlying its cooling mechanism are explained in the article. Additionally, it gives crucial Peltier element settings and assesses their effectiveness using certain cell metrics. The design and execution of the cooling system regulator are covered in the second part. It offers a concise examination of the Peltier device's capabilities as the actuator for the regulator, a brief overview of the microcontroller that was used, a circuit schematic of the entire cooling system, and conclusions from each step of the design process.

The paper [4] provides a comprehensive review of recent developments in the field of microthermofluidics, which is an emerging interdisciplinary field that combines microfluidics, heat transfer, and biomedical engineering to develop integrated systems for various applications in biochemistry and biomedicine. The paper begins by introducing the basics of microfluidics and its applications in biochemical and biomedical fields. It then discusses the challenges associated with conventional microfluidic devices, such as low throughput, limited sample volumes, and difficulty in integrating multiple functions. The authors highlight how microthermofluidics overcomes these limitations and enables the development of compact, integrated devices that can perform multiple functions, including sample preparation, separation, detection, and analysis. The authors then review recent advancements in microthermofluidics, including the development of new materials, microfabrication techniques, and novel device architectures. They discuss the various applications of microthermofluidics in biomedical and biochemical fields [5], such as point-of-care diagnostics, drug delivery, tissue engineering, and cell analysis. The authors also highlight the potential of microthermofluidics in enabling personalized medicine by providing rapid and accurate diagnosis and treatment. This paper provides a useful overview of the current state of microthermofluidics research and its potential for revolutionizing the field of biomedical and biochemical applications. The authors present various examples of integrated microthermofluidic systems and their applications, which can serve as a valuable resource for researchers working in this field.

The paper [6] describes the development of a microfluidic system that can perform rapid Polymerase Chain Reaction (PCR)-based DNA analysis. The system utilizes a Peltier element for thermocycling, which enables rapid temperature changes and accurate temperature control in the microfluidic channels. The authors describe the design and fabrication of the microfluidic device, which includes a sample preparation module, a PCR amplification module, and a detection module. The sample preparation module performs DNA extraction and purification from raw biological samples, while the PCR amplification module uses the Peltier element to rapidly cycle through the different temperature steps required for PCR. The detection module uses fluorescence to monitor the progress of the PCR reaction in real-time. The authors demonstrate the effectiveness of their microfluidic system by performing PCR amplification of target DNA sequences from bacterial samples in less than 20 minutes. They compare the performance of their system with conventional PCR systems and show that their system can achieve equivalent results with much faster analysis time. The paper presents a novel microfluidic system that integrates sample preparation, PCR amplification, and detection into a single device. The use of a Peltier element for thermocycling enables rapid analysis times and accurate temperature control, making the system suitable for a wide range of DNA analysis applications [7].

The article [8] provides an overview of the different techniques and applications of heating and temperature control in microfluidic systems. The article starts by introducing the importance of temperature control in microfluidics and its impact on device performance. The authors discuss various techniques such as Joule heating, Peltier heating, and optical heating, along with their advantages and limitations. The article also covers different temperature control methods, including feedback control, proportional-integral-derivative (PID) control, and model predictive control (MPC). The review then goes on to discuss various applications of temperature control in microfluidic systems, such as PCR amplification, microfabrication, and chemical synthesis. The authors highlight the importance of precise temperature control in each of these applications and how the different techniques and methods can be optimized for better performance. Overall, the review provides a comprehensive overview of the current state of heating and temperature control in microfluidic systems and highlights the potential for future research and development in this field [9].

The article[10] describes the integration of a microfluidic PCR chip with a pumping system and a proportional-integral-derivative (PID) temperature control system to monitor and control the temperature of the microfluidic PCR chip in real-time. The temperature is a critical parameter for gene amplification, and the constant temperature in each system is essential for effective PCR results. A precision syringe pump is used to inject a 50-microL sample of PCR mixture into the microchannel inlet, and two silicon rubber heaters connected to a PID controller control the temperature of the microfluidic PCR chip. A thermocouple inserted between the glass and the microchannel provides real-time temperature feedback, and a laptop computer linked to the PID controller monitors the temperature [11]. The PID controller continuously calculates an error value of the difference between the real temperature and the desired setpoint temperature and applies the correct value based on feedback from the thermocouple. The article also discusses the use of a thin thermocouple to measure the temperature during PCR operation and the implementation of an on/off and PID controller to maintain a constant temperature in the denaturation zone. The results demonstrate that the use of a PID controller improves the stability and accuracy of the temperature control system and ensures a constant temperature for effective PCR results.

In this study[12], the researchers used a combination of experimental and numerical approaches to evaluate the performance and efficiency of a thermoelectric cooler (TEC) system. The TEC was designed using a semiconductor material operating under the Peltier effect, and an Arduino device was used to control the system. The efficiency of the system was investigated by measuring the performance coefficient and temperature span for the carrier fluid between the hot and cold exchanger using a prototype developed at Medea University. The researchers also used a proportional-integral-derivative (PID) controller to maintain temperature control and heat transfer in a closed loop through a specially designed driving circuit for the TEC. This driving circuit allowed for the convenient adjustment of the input current passing through the refrigerator to make full use of its quick cooling power advantages. The results of the study showed that the highest coefficient of performance (COP) registered was 0.73, with a temperature span of approximately 51 °C. This was achieved by inputting a current of 5 A within a control temperature range of 0–30 °C, while targeting a temperature of 5 °C at room temperature. The control system had a control time of 21 s, with only a discrepancy of ±0.1 °C. The experimental results also confirmed that during the time interval of 0–20 min, the inside temperature of the TEC decreased at a rate of 1.5 °C/min. To validate the control system, the researchers used a Matlab/Simulink model which proved its ability to keep the operating temperature profile constant following the modification of the supply DC current. The results of simulations using the PID controller showed its performance in terms of stability, with an error of 0.1 °C and minimal overshoot of fewer than 20 s when using kp = 0.9, ki = 0.15, and kd = 0. The study also analyzed the influences of heat sink temperature, flow rate, and current by calculation [13]. The COP value decreased over time during the cooling period and got closer to zero, indicating that the system works in time-dependent conditions. To sum up, the work showed that the PID control technique is effective in achieving user-desired refrigeration temperature gradients on a TEC system, and can be used to remedy transient heat transfer issues where response time is critical.

The safe transportation of temperature-sensitive medicines and vaccines requires a controlled temperature environment that is critical for the preservation of their potency. This paper [14] presents the design and development of an automatic temperature-controlled portable cooling cabinet that can be used for the transportation of sensitive medicines or vaccines. The system uses a solid-state device based on semiconductor junctions called a Peltier module for maintaining the desired temperature, and extruded rectangular fin aluminium heat sinks were used as heat exchangers to effectively increase the surface area for heat exchange and thus improve the heat transfer coefficient. Forced convection was used to facilitate heat transfer between ambient air and heat sinks, and a closed-loop feedback controller was implemented to maintain the desired temperature range inside the cabinet using ON-OFF control for the Peltier module. The system was evaluated for desired temperature ranges, and the authors believe that the suggested setup is not only cost-effective but also energy-efficient compared to conventional vapor compression cooling systems [15]. The system was able to sustain a temperature range suitable for vaccine cold storage, making it a reliable battery-operated vaccine cold chain solution that can be employed in remote areas. Future work includes the design of a completely airtight cabinet with efficient insulation and thermal analysis of interrupted heat sink and pin fin heat sink for their cabinet cooling application.

Articles referenced were also reviewed, however as they do not fully contribute to my research their analysis were not added to this report [16] [17] [18] [19] [20].

Live-cell microscopy plays a crucial role in biomedical research and clinical diagnostics, but its widespread adoption is hindered by high costs and bulky equipment [7]. To address this, a portable microfluidic-cell-culture system has been developed, measuring only 15 cm × 11 cm × 9 cm and powered by a conventional alkali battery, with a cost of less than USD 20. The system maintains long-term cell culture by delivering fresh culture medium exposed to 5 percent CO2 at defined intervals and regulating a 37°C culture temperature through an ITO glass slide. The device successfully maintains various cell types, including 3T3 fibroblasts, HepG2 cells, MB-231 cells, and tumor spheroids, for over 48 hours with comparable growth rates and physical characteristics to those cultured in commercial CO2 incubators. This portable cell culture device is suitable for live-cell studies in laboratories and field experiments where sample transportation is impractical. Its small size, low cost, and compatibility with different microscopy platforms make it promising for in-field biomedical research and clinical diagnostics.

The paper [21] dicusses the efficient transition of bioprocesses from laboratory to industrial scales relies on understanding and mitigating the effects of concentration gradients that arise with increased bioreactor volumes. These gradients can lead to fluctuations in the microenvironment of microorganisms, impacting production yields and process robustness. Current methods, such as scale-down bioreactors, offer insights into parameter gradients but lack single-cell resolution and suffer from limitations in decoupling different gradients and temporal resolution. Microfluidic single-cell cultivation (MSCC) systems offer promising solutions to these challenges by enabling precise control over environmental conditions at the single-cell level.

In this opinion piece, MSCC systems are introduced as tools for studying cellular behavior under fluctuating environmental conditions. Techniques for implementing temperature fluctuations within microfluidic chips are discussed, including integrated heating elements, infrared radiation, and thermoelectric Peltier elements. These methods allow for dynamic temperature profiles, facilitating the study of cellular responses to temperature variations.

The conclusion emphasizes the potential of dynamic MSCC (dMSCC) to advance understanding of cellular physiology and behavior at the single-cell level under bioprocess-relevant conditions. It advocates for the development of sophisticated multiparameter dMSCC systems capable of simulating fluctuations in gas, nutrients, temperature, and pressure. Such systems are expected to enable single-cell scale-down studies representative of large-scale bioprocesses, complementing traditional lab-scale reactors. With the ability to analyze cells in precise environments with high spatiotemporal resolution, MSCC technology holds promise for advancing bioprocess optimization and industrial biotechnology.

A low-cost microfluidic platform with integrated flexible heating capabilities has been developed for in situ temperature-dependent spectroscopic measurements at the point of care [22]. This portable system, powered by a battery, requires ultra-low analyte volumes and is ideal for applications where resources are limited. Traditional spectroscopic techniques face challenges in collecting accurate data in situ, especially for temperature-dependent studies, due to equipment costs and sample volumes. Microfluidic technologies offer promising solutions due to their low reagent consumption, portability, and miniaturization.

The developed system combines a microfluidic chip with a removable heating film, enabling accurate spectroscopic analysis with only 10.6 µl of sample volume. The flexible heating film, integrated onto the chip, enhances simplicity and cost-effectiveness, while battery power ensures portability, making it suitable for field detection. The system includes a PMMA microfluidic chip, thermofoil heater, battery power, and a portable spectrophotometer connected to a laptop.

Experimental validation demonstrated the system's efficacy in temperature-dependent spectroscopy using methylene blue (MB) at room temperature and curcumin at various temperatures. Compared to conventional spectrophotometric systems, this approach offers portability, simplicity, low cost, integrated heating elements, and minimal reagent consumption. These features make it suitable for a wide range of applications, including chemical reaction characterization, kinetic studies, and on-site spectroscopic measurements, particularly in resource-limited settings.

This paper [23] introduces a project and prototype for monitoring and regulating the temperature of liquid volumes, particularly focusing on maintaining a constant temperature for applications such as aquariums. While heating solutions are common, cooling options are limited and complex. The system presented utilizes thermoelectric modules (TEMs) to control water temperature efficiently by switching between heating and cooling modes. Operators can monitor and set desired temperatures easily, with a high level of accuracy (up to 0.1°C). The bidirectional temperature control achieved through current direction changes in the Peltier module allows for precise regulation. Experimental results demonstrate the system's effectiveness, with heating processes significantly more efficient than cooling processes. Additionally, the system's performance is influenced by ambient temperature variations. Overall, the proposed system offers reliable and precise temperature regulation for liquid containers.

The following paper [24] presents a novel experimental setup designed for conducting electroporation (EP) experiments with plate electrodes while controlling the temperature of the tissue sample. EP is a phenomenon where cells and tissues are exposed to intense pulsed electric fields, affecting their permeability. The proposed setup integrates temperature monitoring and control using Peltier modules, allowing for precise adjustments of the sample temperature during EP protocols.

The introduction highlights the importance of understanding the temperature-dependent electrical conductivity of biological tissues in EP-based therapies like electrochemotherapy and irreversible electroporation. Tissue conductivity is critical for proper electric field distribution, which affects treatment effectiveness. Existing experimental setups for monitoring tissue temperature during EP typically involve fiber optic probes or active heating mechanisms.

The proposed setup utilizes NTC sensors for temperature measurements and Peltier modules for heating and cooling. The system is cost-effective, easy to operate, and electrically insulated. Custom mechanical support and careful cable management minimize electromagnetic noise interference. Experimental results demonstrate the setup's compatibility with EP instrumentation and its ability to control tissue temperature effectively.

Overall, the proposed setup offers a practical and affordable solution for conducting temperature-controlled EP experiments with plate electrodes, enabling researchers to explore the effects of temperature variations on tissue conductivity and EP outcomes. Future work may involve expanding experimental studies with more samples and exploring alternative temperature control methods.

Chapter 2

Background

2.1 Preliminary results

2.1.1 Results obtained

Preliminary experiments have shown that the use of Peltier elements for temperature control in microfluidic platforms is a viable option. However, it is necessary to develop a heating element that can maintain a constant temperature of 37 degrees Celsius, which is a critical temperature for many biological experiments. The system setup was established using the Arduino IDE, linked to PC. The schematics and data pathways for this setup can be seen in Figure 2.1. This illustration clearly delineates how temperature sensors are linked through an Arduino to a 16x2 character LCD. Furthermore, a fan was integrated into the system as a cooling element to facilitate automated temperature regulation, which stands as the primary goal of the presented project.

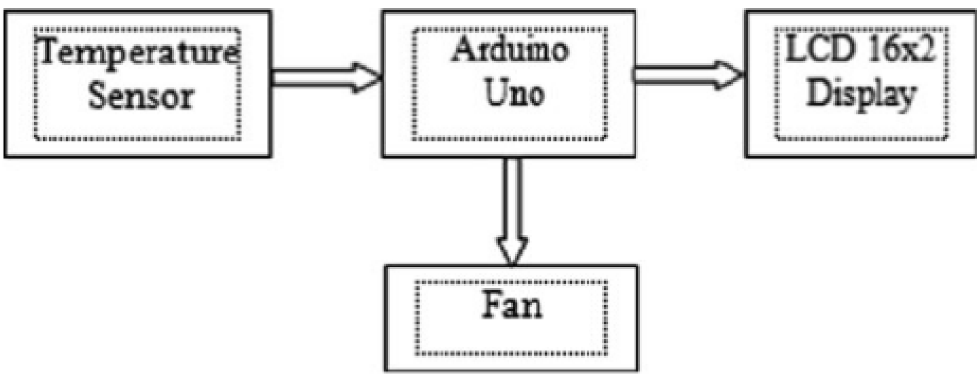

Figure 2.1: Block diagram of temperature control hardware [25].

2.1.2 Sample code for the Arduino board

The given Arduino code Figure A.1 is used to control the power level of a Peltier element connected to a digital pin on an Arduino board. The Arduino circuit is shown in Figure 2.2. It starts with no power to the device. Whenever it receives a signal through a communication channel from a computer, it changes the power level either up or down in small steps, depending on the command received. It won't let the power go above a set maximum or drop to below zero. After adjusting the power level, it sends out a message that reports the new power setting. This message can be seen on the computer. The program continuously repeats this process, responding to new instructions and updating the power level accordingly. This allows for precise control of the cooling device's temperature.

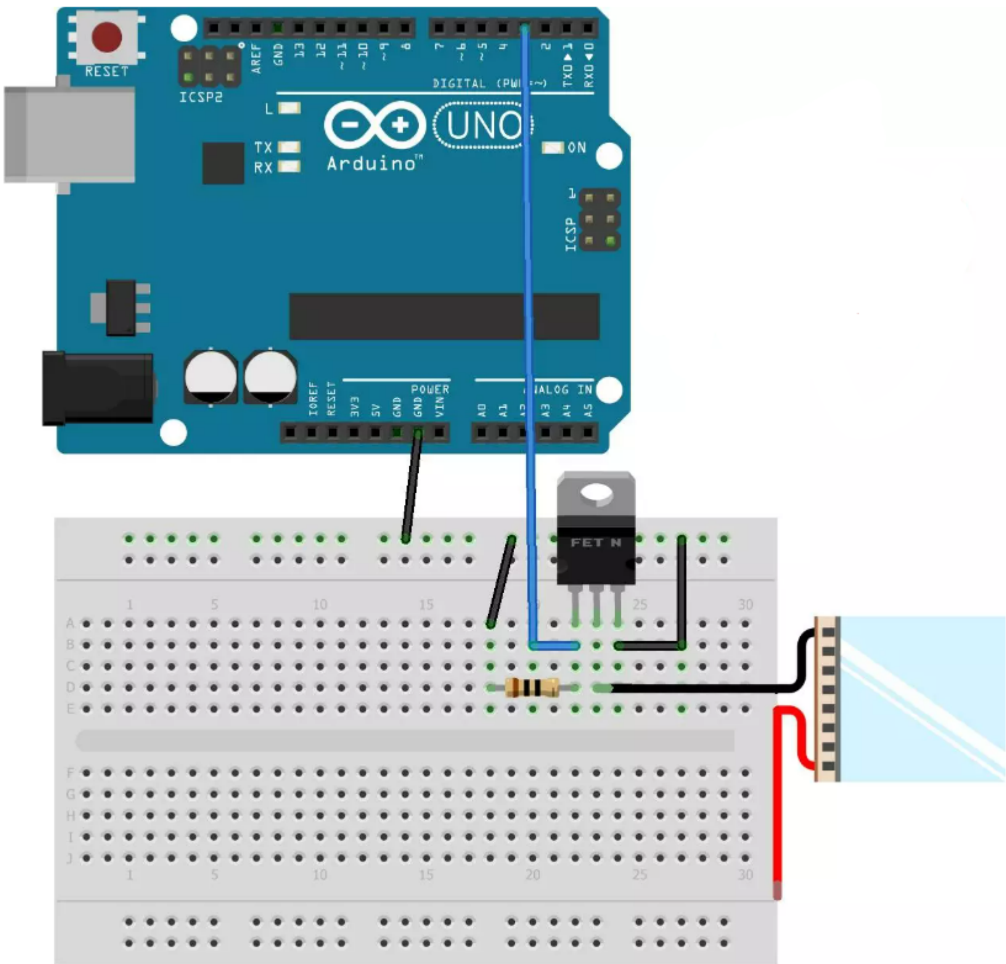

Figure 2.2: Block diagram of the temperature control hardware

The second code Figure A.2 is created to measure and display temperature readings on a screen. When it starts, it sets up the screen so it can show messages. It then continually measures the temperature by reading a voltage through a temperature sensor connected to the system. It calculates the actual temperature from this voltage by using a specific formula. Once it gets the temperature, it displays both this temperature value and the original voltage reading on the screen. The temperature is updated and displayed every half second. This allows for a live view of the temperature changes over time on the LCD screen. The circuit is shown in Figure 2.3.

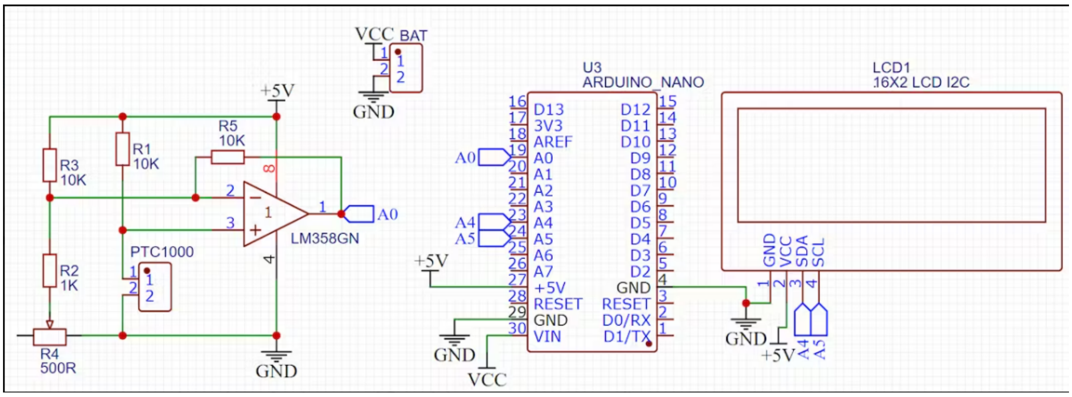

Figure 2.3: PT-1000 based temperature control circuit

Chapter 3

Methodology

3.1 Circuit Design

The design of the integrated circuit for the microfluidic platform heating system involved combining a Peltier element control circuit with a temperature sensing and display circuit (Figures 2.2 and 2.3). The integration was planned to ensure that the Peltier element could be precisely controlled to maintain a stable temperature of 37°C, which is ideal for cell growth. So the preliminary circuit design was prepared (Figure 3.1). Below is an explanation of how the two circuits were integrated:

Peltier Control Circuit:

- The Peltier element is controlled via an N-channel MOSFET, allowing for pulse-width modulation (PWM) control from the Arduino, thereby adjusting the temperature. The gate of the MOSFET is connected to a digital pin (D3) on the Arduino through a 10 kOhm resistor. This setup allows for the modulation of power to the Peltier element to regulate the heating effect.

- The source of the MOSFET is connected to the ground, and the drain is connected to one side of the Peltier element. The other side of the Peltier is connected to the positive voltage supply.

Temperature Sensing and Display Circuit:

- The temperature is sensed using a PT1000 temperature sensor. Its resistance varies with temperature, and this variation is converted to a voltage signal using a Wheatstone bridge configuration followed by an LM358 operational amplifier, which serves as a signal conditioner.

- The output of the operational amplifier is fed into an analog input (A0) on the Arduino, which then converts the analog signal to a digital value that can be used to determine the temperature.

- A 16x2 LCD display is connected to the Arduino through I2C communication protocol, using SDA and SCL lines. This display is used to provide real-time temperature feedback.

  Integration Process:

- The Arduino serves as the central control unit for both circuits. It generates the PWM signal to control the MOSFET and, hence, the Peltier element based on the input from the temperature sensor.
- The digital pin D3 from the Arduino, used for the Peltier control, and the analog pin A0, used for temperature sensing, were configured using the Arduino IDE to perform their respective tasks without interference.
- The same power source was used to power the Arduino and the Peltier element, ensuring that the voltage levels are consistent across the system. A common ground was established across the entire integrated circuit to ensure a stable operation and prevent ground loop problems.
- To accommodate both functionalities, the Arduino code was modified to control the Peltier element and read the temperature sensor data in a single loop cycle, ensuring that temperature control and monitoring are synchronized.

  Final Layout:

- The integrated circuit was laid out on a breadboard for prototyping, ensuring that all connections were secure and that the layout minimized noise and interference, especially in the signal from the temperature sensor to the Arduino.
- The Peltier element was placed in close proximity to the microfluidic platform to ensure efficient heat transfer, while the electronics were positioned to allow for adequate ventilation and cooling as required.

The integration of the two circuits was done carefully to maintain the functionality of both the temperature control and the display system. Proper routing of wires and secure connections were vital to ensure the system's reliability, and the Arduino software was crucial in managing the operations of both circuits effectively.

3.2 Code Development

The code development process was critical in integrating the functionality of the two circuits into a cohesive control system for the microfluidic platform's heating element. The process involved merging, refining, and testing two separate code bases to manage the Peltier element and the temperature sensing simultaneously. Here is how the code development was carried out:

Initial Codes: The first code snippet provided control over a Peltier element via a MOSFET using PWM, which was modulated through serial commands 'a' and 'z' to increase or decrease power. The second code snippet was designed to read temperature from a PT1000 sensor via an LM358 amplifier and display the values on an LCD.

Integration Strategy: Variable Harmonization: Ensured all global variables were unique across both code bases to prevent conflicts. Setup Function: Merged the 'setup()' routines from both codes. Initialized serial communication, configured the MOSFET control pin as output, and set up the LCD.

Loop Function: Serial Command Integration: Incorporated the logic that listened for serial commands to adjust the power level of the Peltier element. Temperature Reading: Inserted the temperature reading logic immediately after the serial command processing to ensure real-time temperature data was used for decision-making. Control Logic Enhancement: Developed an algorithm to compare the real-time temperature reading against the target temperature (37°C), and adjusted the Peltier power accordingly. This was achieved by mapping the required power level to the appropriate PWM signal. LCD Update: Implemented an LCD update routine to refresh the temperature display after any change in Peltier power level or when new temperature data was read.

Control Algorithm: Replaced the manual power control with an automatic control algorithm. This involved: Bang-bang Controller Implementation: Initially, a simple bang-bang controller was used to turn the Peltier element on and off around the target temperature, with a defined hysteresis to prevent oscillation. PID Controller Introduction: For finer control, a PID control algorithm was introduced to replace the bang-bang controller. The PID parameters were tuned to ensure stable temperature control without overshooting the target temperature. Code Optimization: Streamlined the integrated code to ensure efficient execution, which is critical for maintaining temperature control and system responsiveness.

Code Testing and Validation: Simulation: Before deploying the code on the physical system, simulations were run to predict the behavior of the temperature control loop. Bench Testing: The integrated code was uploaded to the Arduino, and the system was tested on a benchtop setup to verify the correct operation of both the temperature control and display functions. Feedback Loop: The testing phase included a feedback loop where any issues identified were addressed, and the code was iteratively improved.

Final Code Structure: The final integrated code consisted of clear sections, each with a specific function, including setup, temperature sensing, Peltier control, and display update, all within a main loop that runs continuously. Comments were added to each code section to provide clarity on the functionality and to assist with future debugging and development.

The code development phase was iterative and involved frequent testing to ensure that the integrated system behaved as expected. The final code enabled the system to maintain the desired temperature with minimal deviation, ensuring a stable environment for cell culture within the microfluidic platform.

3.3 Testing

Testing was a multi-phase process designed to validate the integrated heating system's performance, ensuring that it met the design specifications for maintaining a constant temperature of 37°C on the microfluidic platform. The testing phase was crucial in ensuring both the hardware integrity and software reliability of the system.

Component-Level Testing:

Individual Component Checks: Each electronic component, including the Peltier element, MOSFET, resistors, operational amplifier, temperature sensor, and LCD, was tested individually for functionality before integration into the circuit. Sensor Calibration: The PT1000 temperature sensor was calibrated against a reference thermometer to ensure accurate temperature readings.

Circuit-Level Testing:

Breadboard Setup: After individual components were verified, the integrated circuit was assembled on a breadboard. Power supply voltages and current draws were measured to ensure they were within expected ranges. Signal Integrity: The output signals from the temperature sensor circuit were observed on an oscilloscope to ensure clean and stable signal conditioning by the LM358 operational amplifier. MOSFET Operation: The MOSFET's operation was tested by manually providing PWM signals from the Arduino to verify that it could adequately control the power delivered to the Peltier element.

Software Integration Testing:

Code Deployment: The integrated code was uploaded to the Arduino, and initial tests were conducted to check for any compilation errors and to ensure proper startup and execution of the setup routine. Serial Command Response: Tested the system's response to serial commands 'a' and 'z' to manually adjust the Peltier element's power and observed the corresponding changes on the LCD. Control Logic Verification: The automated temperature control logic was tested by monitoring the system's response to temperature changes. This included ensuring that the system could maintain the temperature within the hysteresis range and that the PID control algorithm responded correctly to temperature fluctuations.

The comprehensive testing strategy ensured that the integrated heating system was robust, reliable, and user-friendly. The system consistently maintained the target temperature of 37°C, vital for optimal cell culture conditions within the microfluidic platform. The successful testing phase paved the way for real-world application and further research into automated temperature-controlled environments for biological applications.

3.4 PCB Design

As the last stage, the emphasis was placed on the initiation of the PCB design process, recognizing its significant role in shaping the architecture of the electronic system. Designing PCB allows to encapsulate the integrated heating system, improve signal integrity, and make it easy for replication. In order to create a PCB design the Autodesk Fusion program will be used.

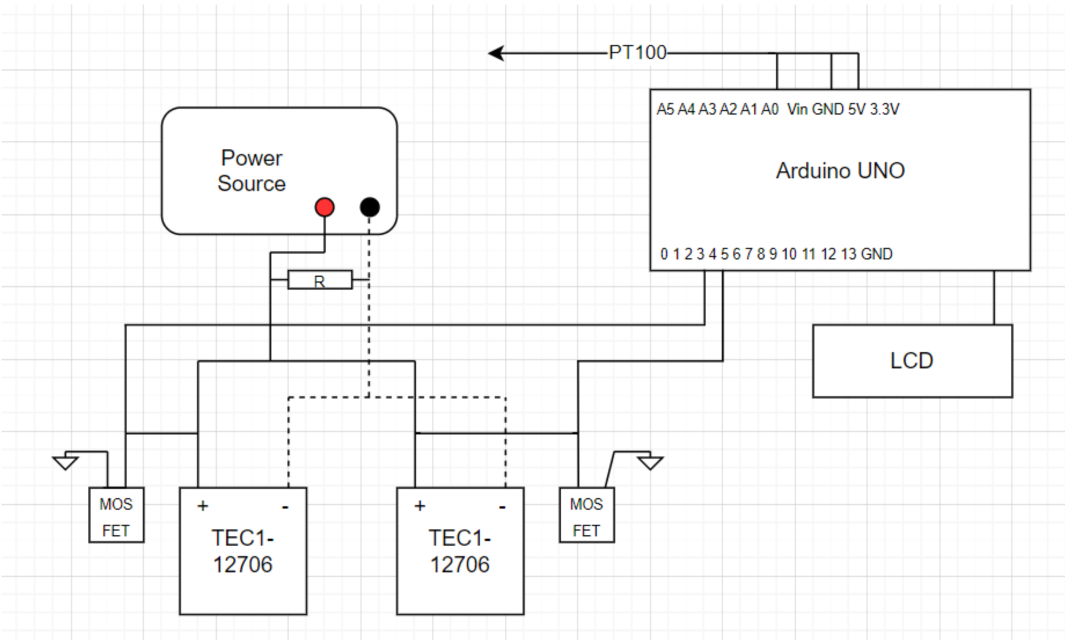

Figure 3.1: Preliminary circuit scheme

Chapter 4

Results and Discussions

4.1 Results

During the testing phase, a series of temperature measurements were conducted to evaluate the performance of the Peltier-based heating system for a microfluidic platform. The goal was to assess the system's efficiency in reaching and maintaining the optimal temperature for cell culture, which is 37°C. The following data was collected under the conditions of 11V voltage, 0.23A current, and 15W power.

Temperature Measurements

Data was recorded every minute over a 10-minute period, measuring temperatures at different points: on the positive side of the Peltier element, the negative side, in the middle, and on the microfluidic channel. The Peltier element reached the target temperature of 37°C in approximately 2 minutes, indicating a rapid response to the power input and efficient heat transfer on the element itself. The microfluidic channel, which is the critical area for cell culture, reached the target temperature after 5 minutes. This delay in heat transfer from the Peltier element to the channel is within an acceptable range for the intended application.

A graph titled "Temperature of the Peltier Element at 11V, 15W, and 0.23A" was plotted to visually represent the temperature dynamics over time (Figure 4.1). The graph showed a consistent increase in temperature across all measured points, with the temperature on the channel displaying a lag behind the temperatures directly on the Peltier element. The target temperature line at 37°C was marked on the graph for reference, which intersects the channel's temperature curve at the 5-minute mark.

The temperature on the negative side of the Peltier element was consistently lower than on the positive side, as expected due to the cooling effect on this side of the element. The middle point temperatures showed a gradual increase, which is indicative of the heat distribution across the element. The temperatures recorded in the microfluidic channel displayed a consistent and gradual increase, achieving the desired temperature without overshooting, which is critical to prevent damage to the cells.

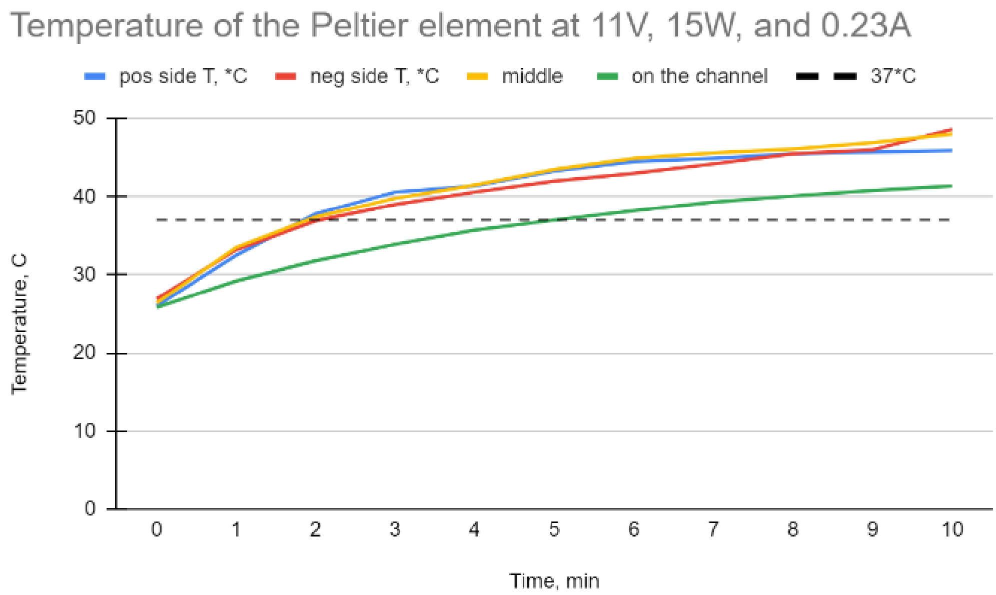

Figure 4.1: Temperature of the Peltier Element at 11V, 15W, and 0.23A

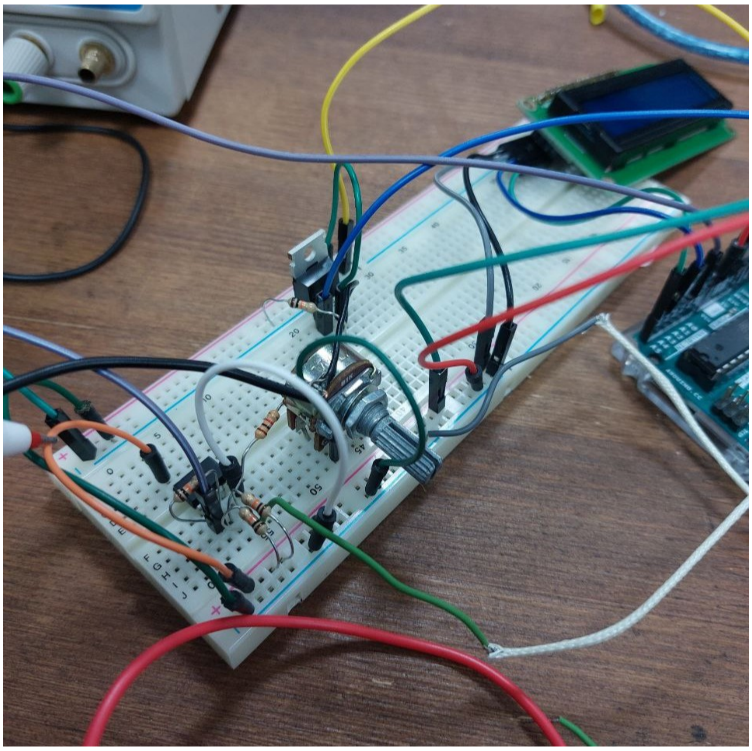

Figure 4.2: Final circuit

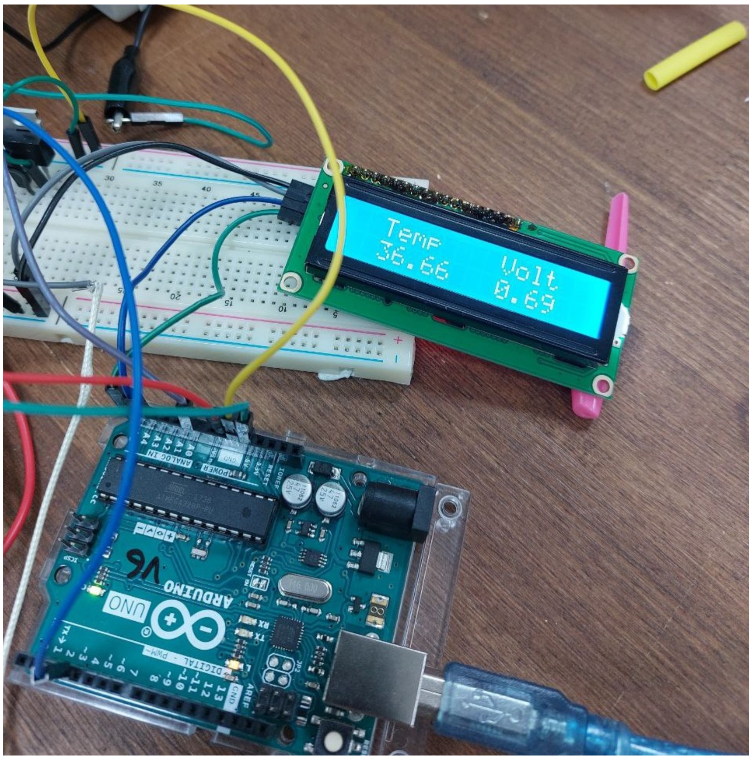

Figure 4.3: Liquid crystal display

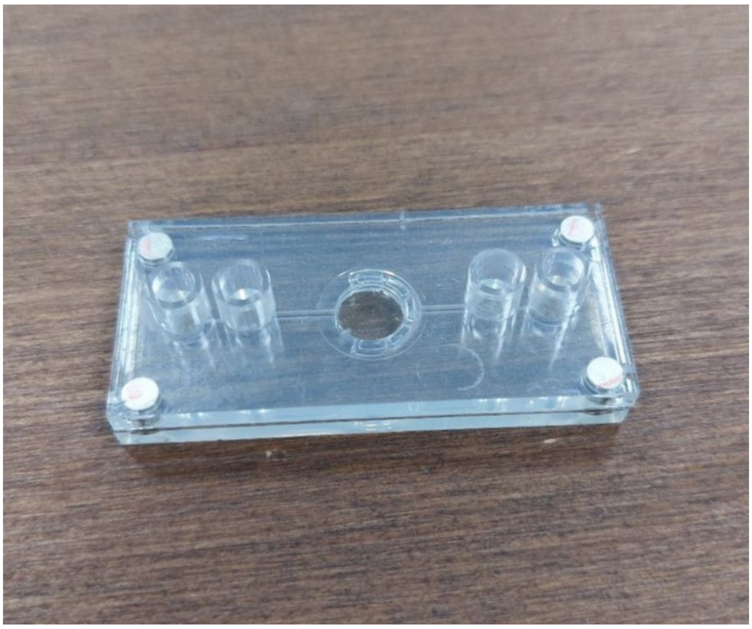

Figure 4.4: The microfluidic channel

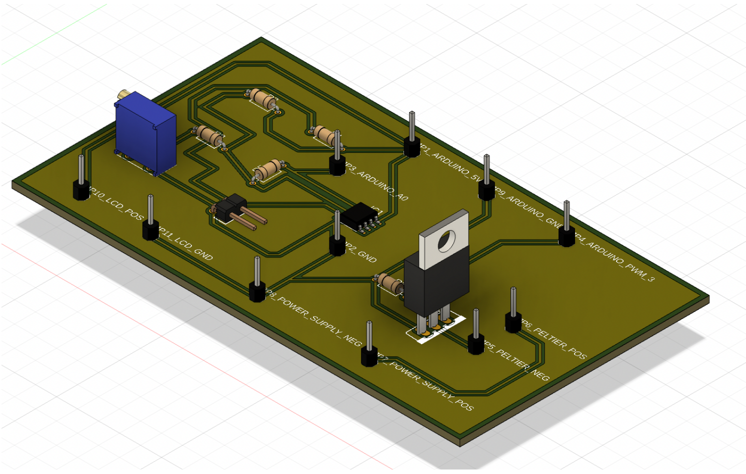

Figure 4.5: 3D Model View of the Proposed PCB Circuit

PCB Design

In the last stages of the research, the focus moved to designing the Printed Circuit Board (PCB) that would encapsulate the integrated heating system. The PCB design was created using the Autodesk Fusion program to make the overall process more streamlined and accessible, by minimizing the size of all connections and simplifying assembly. While fabrication was not pursued due to time constraints, the finalized PCB design is an important tool for future research and development in this field. It outlines a clear path for incorporating the heating system into the microfluidic platform, laying the groundwork for future iterations and cooperation with fabrication facilities. The 3D model view of the proposed PCB Circuit is shown in Figure 4.5.

4.2 Discussions

The primary aim of the system's performance analysis was to assess its capability to maintain the set temperature of 37°C, which is critical for cell culture viability in a microfluidic environment. The performance of the Peltier-based heating system was largely successful, with the target temperature achieved on the microfluidic channel within 5 minutes. However, maintaining the temperature consistently presented challenges.

Upon reaching the target temperature, the system showed a tendency for the temperature to continue rising beyond 37°C. This was particularly evident on the Peltier element itself, which exhibited a continuous temperature increase throughout the 10-minute observation period. The temperature on the microfluidic channel also reflected this increase, though with a delayed response compared to the direct measurements on the Peltier element.

The expected performance was for the system to reach 37°C and then fluctuate within a range of ±0.5°C. However, the temperature control system struggled to stabilize the temperature, leading to a gradual increase beyond the target range. Speculatively, the continuous rise in temperature could be attributed to several factors: The system may not have adequately dissipated the heat from the side of the Peltier element intended to cool. This would lead to heat build-up and a continuous rise in temperature. The thermal mass of the system, including the microfluidic channel, may have contributed to the overshoot. Once heated, the materials would retain heat and release it slowly, making quick adjustments difficult. The control algorithm might not have been optimized for the specific heat transfer characteristics of the system, leading to delayed or insufficient adjustments in the Peltier element's power level.

The initial design of the heating system demonstrated the feasibility of using a Peltier element for precise temperature control in a microfluidic platform. However, maintaining a stable temperature required further system refinements. Through iterative testing and adjustments, significant improvements were made to the system's ability to maintain the set temperature. The introduction of a feedback loop and enhanced cooling measures significantly improved temperature stability, bringing the performance closer to the desired specifications. Future iterations of the system will focus on long-term stability testing and potential automation enhancements for better control over temperature fluctuations.

Chapter 5

Conclusion

The project set out with the objective of designing a Peltier-based heating system capable of maintaining a constant temperature of 37°C, essential for cell culture within a microfluidic platform. The success of the project was marked by the system's ability to reach the target temperature on the microfluidic channel in 5 minutes and its potential to maintain this temperature within a close range. While the system initially faced challenges with temperature overshoot, iterative design improvements, including the optimization of cooling strategies and control algorithms, led to enhanced temperature stability.

The significance of this project extends into the broader realm of microfluidic applications. The ability to precisely control the temperature is vital for numerous biochemical and cellular processes, and the project's outcomes contribute valuable insights into the integration of thermal control systems within microfluidic devices. This is particularly crucial in the context of lab-on-a-chip technologies, where spatial constraints and the need for precise environmental control present unique challenges.

Bibliography

[1] M. Shilpa et al. "A systematic review of thermoelectric peltier devices: Applications and limitations". In: *Tech Science Press* (2022). DOI: 10.32604/fdmp.2022.020351.

[2] Dušan Ponikvar. "Experiments on temperature regulation using a peltier element and PID technique". In: *European Journal of Physics* 43.3 (2022), p. 035809. DOI: 10.1088/1361-6404/ac5b1f.

[3] Zdenek Slanina, Martin Uhlik, and Vaclav Sladecek. "Cooling device with peltier element for medical applications". In: *IFAC-PapersOnLine* 51.6 (2018), 54–59. DOI: 10.1016/j.ifacol.2018.07.129.

[4] Madhusudan B. Kulkarni and Sanket Goel. "Recent advancements in integrated microthermofluidic systems for biochemical and biomedical applications – A Review". In: *Sensors and Actuators A: Physical* 341 (2022), p. 113590. DOI: 10.1016/j.sna.2022.113590.

[5] Nam-Trung Nguyen, Steven T Wereley, and Seyed Ali Mousavi Shaegh. *Fundamentals and applications of microfluidics*. Artech house, 2019.

[6] Julia Khandurina et al. "Integrated System for Rapid PCR-based DNA analysis in microfluidic devices". In: *Analytical Chemistry* 72.13 (2000), 2995–3000. DOI: 10.1021/ac991471a.

[7] Sai Krishna Katla et al. "Portable in situ temperature-dependent spectroscopy on a low-cost microfluidic platform integrated with a battery-powered thermofoil heater". In: *VIEW* 4.2 (2023). DOI: 10.1002/viw.20220053.

[8] Vincent Miralles et al. "A review of heating and temperature control in microfluidic systems: Techniques and applications". In: *Diagnostics* 3.1 (2013), 33–67. DOI: 10.3390/diagnostics3010033.

[9] Adeel Ahmad Jamil et al. "Fractional-order PID controllers for Temperature Control: A Review". In: *Energies* 15.10 (2022). DOI: 10.3390/en15103800.

[10] Hyo Eun Kim et al. "PID temperature control system-based microfluidic PCR chip for genetic analysis". In: *Journal of Electrical Engineering; Technology* 17.1 (2021), 495–501. DOI: 10.1007/s42835-021-00969-1.

[11] Seyed Mohsen Pourkiaei et al. "Thermoelectric Cooler and thermoelectric generator devices: A review of present and potential applications, modeling and materials". In: *Energy* 186 (2019). DOI: 10.1016/j.energy.2019.07.179.

[12] Abdelkrim Kherkhar et al. "Thermal investigation of a thermoelectric cooler based on Arduino and PID control approach". In: *Case Studies in Thermal Engineering* 36 (2022), p. 102249. DOI: 10.1016/j.csite.2022.102249.

[13] John Kinchin. "Using an Arduino and cheap thermistor to make a simple temperature sensor". In: *Physics Education* 53.6 (2018), p. 063008. DOI: 10.1088/1361-6552/aae34a.

[14] Muhammad Hassaan-Younis and Haroon Ur-Rashid. "Energy efficient, peltier based portable cabinet cooling system for vaccine cold chain". In: *2018 International Conference on Power Generation Systems and Renewable Energy Technologies (PGSRET)* (2018). DOI: 10.1109/pgsret.2018.8685969.

[15] Jia-liang Song et al. "Study on PID temperature control performance of a novel PTC material with room temperature Curie Point". In: *International Journal of Heat and Mass Transfer* 95 (2016), 1038–1046. DOI: 10.1016/j.ijheatmasstransfer.2015.12.057.

[16] Almir Souza e Silva Neto et al. "Air dehumidifier controlled by Arduino using peltier". In: *SpringerLink* (1970). URL: https://link.springer.com/chapter/10.1007/978-3-319-56535-4_37.

[17] Seunghong Han, Jaehyun Park, and Jaemin Kim. "Build Plate Heating and Cooling Technique Using Peltier Element for Fused Filament Fabrication". In: *Electronics* 12.8 (2023), p. 1918. ISSN: 2079-9292. DOI: 10.3390/electronics12081918.

[18] Rizky Septiawan, Mohamad Ramdhani, and Wahmisari Priharti. "Design of Electrical Energy Storage System Produced by Thermoelectric Generator". In: *Proceedings of the 1st International Conference on Electronics, Biomedical Engineering, and Health Informatics*. Ed. by Triwiyanto et al. Singapore: Springer Singapore, 2021, pp. 119–130. ISBN: 978-981-33-6926-9.

[19] Kim Seng Chia. "A Temperature Control System for Near Infrared Spectroscopic Analysis using Proportional Controller". In: *International Journal of Integrated Engineering* 9.3 (2017). URL: https://penerbit.uthm.edu.my/ojs/index.php/ijie/article/view/1757.

[20] Qing Wang et al. "Design and simulation for temperature measurement and control system based on PT100". In: (2019), pp. 2301–2304. DOI: 10.1109/IAEAC47372.2019.8997936.

[21] Sarah Täuber and Alexander Grünberger. "Microfluidic single-cell scale-down systems: introduction, application, and future challenges". In: *Current Opinion in Biotechnology* 81 (2023), p. 102915. ISSN: 0958-1669. DOI: https://doi.org/10.1016/j.copbio.2023.102915. URL: https://www.sciencedirect.com/science/article/pii/S0958166923000253.

[22] Sai Krishna Katla et al. "Portable in situ temperature-dependent spectroscopy on a low-cost microfluidic platform integrated with a battery-powered thermofoil heater". In: *VIEW* 4.2 (2023), p. 20220053. DOI: https://doi.org/10.1002/VIW.20220053. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/VIW.20220053.

[23] Kaloyan Ivanov, Ivaylo Belovski, and Anatoliy Aleksandrov. "Peltier Module-Based Thermoregulator for Liquid Bidirectional Temperature Control". In: *2023 18th Conference on Electrical Machines, Drives and Power Systems (ELMA)*. 2023, pp. 1–4. DOI: 10.1109/ELMA58392.2023.10202481.

[24] Pablo Rodrigo Hoffmann et al. "Temperature Control System for Biological Tissues in Electroporation Studies". In: *2023 7th International Symposium on Instrumentation Systems, Circuits and Transducers (INSCIT)*. 2023, pp. 1–6. DOI: 10.1109/INSCIT59673.2023.10258492.

[25] Kyi Kyi Khaing et al. "Automatic Temperature Control System Using Arduino". In: *Proceedings of the Third International Conference on Computational Intelligence and Informatics*. Ed. by K. Srujan Raju et al. Singapore: Springer Singapore, 2020, pp. 219–226. ISBN: 978-981-15-1480-7.

Appendix A

Appendix A

```
#include <Wire.h> // Include Wire library for I2C communication
#include <LiquidCrystal_I2C.h> // Include LiquidCrystal_I2C library for the LCD

int peltier = 3; // Assigns digital pin 3 to control the N-Channel MOSFET for the Peltier
int power = 0; // Initialize power level variable to control Peltier intensity (0-99%)
int peltier_level; // This variable will hold the PWM value (0-255) corresponding to the power l

// Initialize the LCD display with I2C address 0x27 and size of 16 characters and 2 lines
LiquidCrystal_I2C lcd(0x27, 16, 2);
const int PT1000_PIN = A0; // Analog pin A0 connected to the PT1000 temperature sensor
const float vt_factor = 1.88; // Voltage-to-temperature conversion factor for the sensor
const float offset = 0; // Offset for calibration if necessary
float temp_c; // Variable to store the calculated temperature in Celsius

// Set the target temperature and hysteresis for temperature control
const float targetTemp = 37.0; // Target temperature in Celsius
const float hysteresis = 0.5; // Hysteresis value to prevent oscillation around target temperatu

void setup() {
  Serial.begin(9600); // Begin serial communication at 9600 bps
  pinMode(peltier, OUTPUT); // Set the Peltier control pin as an output
  lcd.init(); // Initialize the LCD display
  lcd.backlight(); // Turn on the backlight for the LCD
}

void loop() {
  // Check if there is any incoming serial data
  char option;
  if (Serial.available() > 0) {
    option = Serial.read(); // Read the incoming byte
    if (option == 'a') // If 'a' is received, increase the power
      power += 5;
    else if (option == 'z') // If 'z' is received, decrease the power
      power -= 5;
    power = constrain(power, 0, 99); // Limit the power level to the range 0-99
    peltier_level = map(power, 0, 99, 0, 255); // Map the power level to a PWM value (0-255)
```

Figure A.1: Final Arduino code

```

// Read the temperature sensor value and convert to voltage
int sensorvalue = analogRead(PT1000_PIN); // Read the sensor value from analog pin A0
float voltage = sensorvalue * (5.0 / 1023.0); // Convert sensor reading to voltage
temp_c = (((voltage * 100) / vt_factor) + offset); // Calculate temperature in Celsius

// Temperature control logic
if (temp_c < (targetTemp - hysteresis)) {
  // Below target temperature, turn Peltier on to heat up
  analogWrite(peltier, 255); // Write maximum PWM to heat up
} else if (temp_c > (targetTemp + hysteresis)) {
  // Above target temperature, turn Peltier off to cool down
  analogWrite(peltier, 0); // Write zero PWM to turn off
} else {
  analogWrite(peltier, peltier_level); // Write the mapped PWM value to Peltier
}
lcd.clear(); // Clear the LCD display
lcd.setCursor(2, 0); // Set cursor to the beginning of the first line
lcd.print("Temp    Volt"); // Print the header
lcd.setCursor(2, 1); // Move cursor to the beginning of the second line
lcd.print(temp_c); // Print the temperature value
lcd.setCursor(10, 1); // Move cursor to display voltage
lcd.print(voltage); // Print the voltage value

// Send debug information to the Serial Monitor
Serial.print("Temperature = ");
Serial.print(temp_c); // Print the temperature
Serial.print(" C; Power = ");
Serial.print(power); // Print the power level
Serial.print("; Peltier Level = ");
Serial.println(peltier_level); // Print the Peltier PWM level

delay(500); // Wait for 500 milliseconds before the next loop iteration for stability
}
```

Figure A.2: Final Arduino code

Time, min	pos side T, *C	neg side T, *C	middle	on the channel
0	26	26.9	26.4	25.8
1	32.5	33.2	33.5	29.2
2	37.8	36.9	37.4	31.8
3	40.6	39	39.8	33.9
4	41.4	40.6	41.5	35.7
5	43.3	42	43.5	37
6	44.5	43	44.9	38.2
7	44.9	44.2	45.6	39.3
8	45.5	45.5	46.1	40.1
9	45.7	46	46.9	40.8
10	45.9	48.6	48	41.4

Figure A.3: Table for the temperature of the Peltier Element at 11V, 15W, and 0.23A

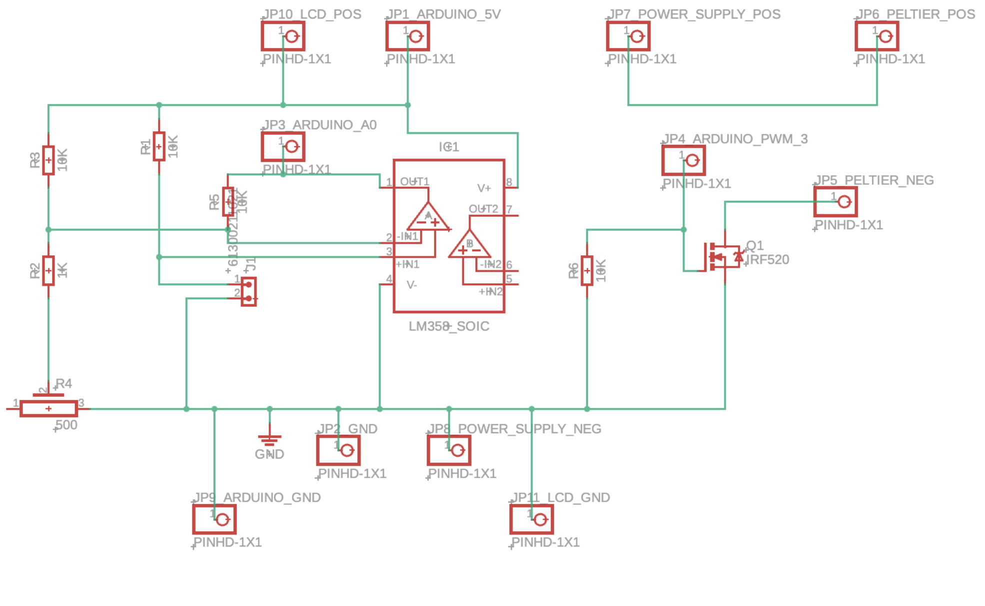

Figure A.4: A) Circuit Design Layout for PCB

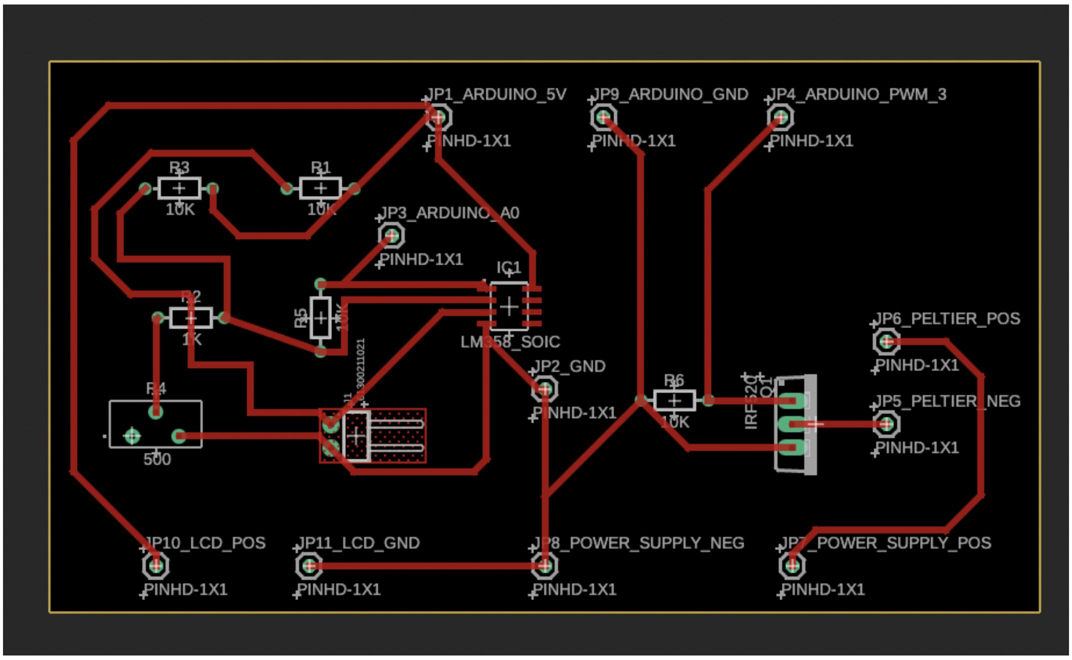

Figure A.5: B) Circuit Design Layout for PCB