Indian Institute of Technology Bombay

Department of Electrical Engineering

Academic Session: 2021-22, Semester: II

Course Project Report

Course: EE 344: Electronic Design Lab

Project Group No: MON-KT-3-3

Students:

Sl	Roll No.	Name	Email
1	190070049	Rathour Param Jitendrakumar	190070049@iitb.ac.in
2	19D070042	Panyam Sweeya Goud	19D070042@iitb.ac.in

Project Mentors: Prof.Kushal R. Tuckley

Project Title: Temperature Controller Using Heating Element and PWM Control

Date of Submission: 2022-07-11

This project aims to conceptualize and design a temperature controller for a multipurpose oven. Such ovens can be used for baking food. So, the desired temperature range is 90-260°C, which includes ovens from cool ovens (90°C) to hot ovens (200–230°C). The primary motivation is to build a low-cost, easy-to-maintain, accurate, and a reliable system. This is accomplished using a heating element, which generates heat; a driver circuit which helps in controlling larger voltages with help of smaller voltages; a thermocouple which measures temperature and a feedback system which regulates the heat to maintain it at a particular temperature which is user-specified. This project is executed and tested in Simscape™ (MATLAB), which will also enable anyone in the future to build this as a working product. The aim was successful.

Contents

1 Introduction

1.1 Project Goal

The aim is to simulate a oven with a temperature controller to maintain any temperature in the range 90-500°C with 2-3% accuracy and achieve this temperature in a reasonable time (2 minutes).

1.2 Possible Application - Food Baking

Different types of food requires different temperatures for baking. For example, custard will need a 'slow' oven (150-160°C), bread requires 'moderate' oven (180-190°C) and pastries a 'very hot' oven (230-260°C)[1]. This project will eliminate the need of multiple kinds of ovens and replace it with a custom temperature controlled oven.

2 System Overview

2.1 Basic Idea

The key idea in achieving the desired mass (say food) temperature (T_d) is that we can control the Duty Cycle of Pulse Width Modulator's output voltage. The driver circuit drives this voltage to the heating element. And accordingly, temperature of heating element is set to T_h. The temperature of mass (T_o) is generally lesser than T_h. So the system needs to determine T_h such that $T_o = T_d$. So, negative feedback is needed. The thermocouple measures T_o and sends it to the microcontroller. If $T_o > T_d$, the microcontroller sends a signal to turn OFF PWM. Otherwise, it will generate a signal that appropriately modifies the duty cycle of PWM and turn ON PWM if it was OFF before.

Note. *Instead of temperature of mass as feedback, to suite our application (1.2) we can take temperature of air as feedback. See 6.2 for more details.*

The block diagram 1.

2.2 Subsystems

Microcontroller A μC is essential for simple temperature setup of the oven. It is used for taking input from user (the set-point), generate input signals for PWM, interfacing with the thermocouple and doing simple calculations with involved signals. It also plays a major role in control mechanism of the system.

Pulse Width Modulator (PWM) This is the core element of our system. It uses PWM to output suitable voltage according to the required temperature. The SG3525A-D IC we use also provides feedback compensation to prevent overshoots and oscillations.

Control Mechanism This is an predominantly a PWM controller which will control the the voltage of coil responsible for the heater's temperature.

Power Driver This circuit will drive the output of the pulse width modulator to the heating element.

Oven A Muffle furnace where the object to be heated is isolated from the heating element.

Temperature sensor A Type K Thermocouple with a temperature range (-200 °C to +1350 °C) will be used for temperature sensing. The received signal from the Thermocouple is processed for interfacing with microcontroller using SPI.

2.3 Physical Realisation

See 2.

2.4 Simulink Model

See 3.

3 Project Implementation

4 Subsystems Designs

4.1 Microcontroller

Arduino UNO based on the ATmega328P is a classic choice. It is a low-cost, easy-to-use hands-on device with many functionalities. The Microcontroller will use the input provided by the user (set-point) to generate the required input signal for Pulse Width Modulator. It receives the temperature readings via interfacing with the thermocouple. After input is provided by user, the microcontroller sends this signal to PWM. Initially, this signal will turn ON the PWM and set the Duty Cycle to some fixed value. Then, it will receive the temperature measurement from the Thermocouple. Depending on the temperature readings, it will send a new signal to PWM.

It also has important role in the Control Mechanism which is discussed in Section 4.3.

4.1.1 Simulation

We have used simulink to do the arithmetic, these tasks will be done by a microcontroller physically.

- Set Desired temperature of Oven T_d (input from user)
- Receive the temperature of mass from thermocouple T_o (using SPI)
- Set the Duty Cycle for the PWM generator as $(T_o - T_d)/600$, 600 because we want the maximum temperature to which it is heated is 600. It should consider boundary cases too set duty cycle 0 when $T_o > T_d$ and set duty cycle 0.8 when $T_o > 600°C$.

4.2 Pulse Width Modulator

SG3525A is a series of pulse width modulator ICs that are used to switching power supplies. This implements PWM using a comparator to control the Duty cycle. It also provides support for feedback compensation using an External RC network to prevent overshoots and oscillations. Additional features such as instantaneous turn off, dead time adjustment are provided.

4.2.1 Simulation

We used the PWM generator block to generate PWM signals with input Duty Cycle as shown in 14b. It is a ‘up’ counter working on the principle as shown in 14c. Whenever the ramp is greater than the input number/600, the signal becomes zero.

4.3 Control Mechanism

The subsystem will implement the following

Account for temperature difference (PWM control) This is done by calculating the difference between desired temperature of mass T_d and it’s measured temperature T_o. The microcontroller will modify the duty cycle of PWM signal appropriately. Simulated both proportional control and ON/OFF control.

A PID controller was also simulated but it requires long time for tuning. If time permits, We will also tune and implement PID.

Accounting for overheating of Oven This happens when $T_o > T_d$. To reduce T_o, the coil is completely switched OFF by turning OFF the Pulse Width Modulator. The Microcontroller will send the corresponding signal to PWM to turn OFF utilizing it’s the Fast turn−off[2] feature. The PWM have to be turned ON when T_o becomes less than T_d.

Avoiding overshoots and oscillations R-C network is connected to the input of Error Amplifier provided by IC to prevent overshoots and oscillation.

4.3.1 Simulation

The PWM generator will give 0 duty cycle (output voltage = 0) when $T_o > T_d$ and so the coil is completely switched OFF. When $T_o > 600°C$, we will give 1 duty cycle (output voltage = 1), but high duty cycle is not good for the IC and so we have set the max possible duty cycle as 0.8.

4.4 Oven

A muffle-furnace-type oven is a suitable candidate for this temperature controller system. The object is isolated from the heating element, fuel, gases and other combustion products. It has a chamber with proper insulation to minimise loss by radiation, an appropriately insulated door with efficient locking. As the oven temperature can go as high as 300°C, ceramic fibre blankets are suitable as insulation. The oven will contain a refractory material inside a groove where heating element can be placed. The thermocouple for temperature sensing is also placed in this hot area. The other subsystems are placed outside the oven except the fan which is kept inside to improve air flow.

An example oven, is shown in Figure 4a

4.4.1 Simulation

We have made our simple oven 4b with 32 bricks (8in · 4in · 2.25in). We have vertically stacked 4 bricks together. So, all 4 sides of oven wall has height 9in. And 2 bricks are stacked horizontally (along their length) which gives outer length and breadth as 16in. Inner length is 16in and breadth is 8in, as one side of bricks take up the width (4in) of adjacent bricks. Also, heat transfer between Oven Walls, Mass and Resistive Wire is modelled using convection and radiative transfer as shown in 16a.

4.5 Driver Circuit

The max output current of the IC is 500mA[2]. This isn't high enough for the heating element. As, we may required upto 15A current for the heating element. Hence, a driver circuit is needed to drive the heating element. The IC provides the driver outputs but they are limited to max current of 100mA[2]. So, IC is used as Single−Ended Supply with driver outputs (PIN 11, 14) grounded. Instead, external driver with input as IC's output voltage is preferred. P-channel IRF9540 MOSFET is suitable candidate. It is enough powerful and can handle current upto 19A. The connection is as shown in Figure 5. The output of IC is used as input to MOSFET and a Resistance-based heating element is its load (R_L). And, R_5 is 100-Ω protection resistor.

4.5.1 Simulation

For simulation, we have ensured that current doesn't exceed 16A. So that the system works in a house with 3 phase power supply. This subsection is a work in progress. Currently, we have converted a 1V amplitude PWM signal into $440V$ PWM signal using gain block. We will be implementing the MOSFET-based driver circuit.

4.6 Heating Element

The temperature range for oven is 90-500°C. As the temperature for heating element is higher than oven, max temperature of heating element should be atleast 1000°C. We will be using Resistance Heating Alloys as Heating Element. These are further divided into Austenitic Alloys NiCr, NiCrFe (called NIKROTHAL) and Ferritic Alloys FeCrAl (called KANTHAL). Even though both has maximum temperature in air 1000ºC, KANTHAL is chosen due to following advantages over NIKROTHAL.

- 2-4 times longer life when operated at same temperature.
- Easier to change when the oven is hot.
- Higher resistivity which implies KANTHAL coil is considering lighter among elements with same cross-section.
- Other desirable properties like Higher surface load and higher yield strength.

Heating elements work by producing heat as current passes through the resistance ($P \propto I^2R$). The heat changes temperature which changes the Resistivity of heating element. Figure 6 shows the variation of resistivity with Temperature for selecting heating elements. As resistivity varies, resistance changes which in turn increases heat (so, temperature). So, a control mechanism is needed to keep the temperature constant. A linear change in resistivity is desired (like in KANTHAL D) as then a simple proportional control mechanism can be used to maintain temperature. Considering all the above aspects, **KANTHAL D** coil is suitable. It will be placed at the inside of the muffle and driven by power MOSFET.

4.6.1 Calculations

Below are the supporting arguments for using Kanthal-D as heating element using example of a tubular element for flat iron (Page 84[3]). For $P = 1000W$ load and voltage of 220V the calculations are as follows:
The resistance is given by

$$R = \frac{U^2}{P} = \frac{220^2}{1000} = 48.4\Omega$$

A tubular element is a cylindrical covering the coil and has diameter d = 8mm and tube length l = 300mm. The effective tube length inside the cylindrical covering after subtracting the terminal length is $\approx$ 250mm (300-(2 $\cdot$ 25mm)). The surface load of a heating conductor (p), is power divided by its surface area of heating conductor.

$$p = \frac{P}{\pi \cdot d \cdot l \cdot 0.01} = \frac{1000}{\pi \cdot 8 \cdot 250 \cdot 0.01} = 15.91\frac{W}{m^2}$$

Here as the heating element is placed inside the cylindrical covering for the coil we need to have 3 times higher surface load compared to tube.

$$p_{\text{coil}} = p_{\text{tube}} \cdot 3 = 3 \cdot 15.91 = 47.73\frac{W}{cm^2}$$

So, back calculating the surface area of the coil, which is basically wire wounded, we use

$$A = \frac{P}{p} = \frac{1000}{47.73} = 20.951cm^2$$

Crosschecking it with the datasheet of Kanthal-D[3] for checking its compatibility, the temperature factor of resistance (C_t) at room temperature is 1.05. The temperature factor

$$C_t = \frac{\text{resistance at a particular temperature } T}{\text{resistance at } 20°\text{C}} = \frac{R_T}{R_{20}} = \frac{48.4}{1.05} = 46.0952\Omega$$

The ratio of Area and resistance at 20 is

$$= \frac{20.951}{46.0952} = 0.4545\frac{cm^2}{\Omega}$$

Now referring to the table of Kanthal-D Page 52[3], we get its essential parameters. The ratio of area and resistance (0.4545) is close to 0.493; hence we can use Kanthal-D. The parameters are as shown in 1. And the mass of the resistive element will be 0.06326kg from [4].

4.6.2 Simulation

As shown in 16a, we created a custom Simscape™ component which is a variant of thermal mass component with the facility of controlling the specific heat of the mass with a signal. We also simulated the change in resistivities and specific heat of wire with the increase in temperature by using the Lookup Table feature of simulink as shown in 3a.

4.7 Temperature sensor

The max temperature required for the oven is around 500°C; the popular temperature sensor LM35 can measure at most 150°C; hence a thermocouple is chosen as it has good accuracy. There are several types of thermocouples with different temperature ranges and materials as mentioned in the table below. The most suitable thermocouple types are K, J, N, R, S, B, T, E. Looking at the temperature range in Table 2, Type K and N can be used for this oven, as their ranges are −180°C to 1370°C, −270°C to 1300°C respectively. We have preferred type K as they are most common for general purposes as they are slightly cheaper and have a slightly higher max temperature (can help in case of overheating) compared with type N. The MAX31855 K-type Thermocouple module is selected. It is also compatible with Arduino and has a low cost.

4.7.1 Thermocouple Insulation

It is essential to get a accurate reading of temperature as we are using it for feedback. So, all Thermocouple wires must be insulated except the sensors to avoid false temperature reading.

As shown in Figure 7a, without thermocouple tip protection the reaction time is in the order of 100ms. Hence, the microcontroller have to either wait 100ms to sent the next PWM signal or we can use the insulation.

Very few insulators are suitable for high temperature range oven (≈ 500°C). Nextel ceramic fiber is a good candidate.

4.7.2 Temperature Measurement

The MAX31855 module provides a SPI read only interface to most micro-controllers as shown in 7b. It outputs thermoelectric voltages V_{out}.

$$V_{\text{out}} = (41.276\mu V/°C) \cdot (T_R - T_{\text{ambient}}) \tag{1}$$

Where, T_{ambient} is the temperature of device. So, the measured temperature T_R is

$$T_R = T_{\text{ambient}} + \frac{V_{\text{out}}}{(41.276\mu V/°C)} \tag{2}$$

4.8 Bill of Materials (BoM)

S.No	Product	Part No	Quantity	Amount(Rs)	Link
1	Arduino Uno R3	EC-2111	1	399.00	ElectronicsComp
2	Pulse Width Modulator - IC SG3525A	EC-0551	1	42.00	ElectronicsComp
3	KANTHAL D Coil	HFL030499	1	80.00	IndiaMart
4	MAX31855 Module with K Type Thermocouple Sensor	EC-7646	1	959.00	ElectronicsComp
5	IRF9540N MOSFET	EC-0301	1	34.00	ElectronicsComp
6	Bricks	-	As required	100.00	Indiamart
7	Op Amps, Resistors, Capacitors	-	As required	-	-

Total = Rs 1614

5 Testing and Evaluation

For this, we created a custom signal that will change T_d with time and observed the behaviour of the system (Mass feedback). Fig 8 shows that as the rate of temperature change, changes suddenly around $50s$. Then around $150s$ cooling starts but as we don't have a proper cooling system, this happens very slowly.

The model was evaluated using Simscape™ by creating models of physical systems within the Simulink® environment.

6 Experiments and Results

6.1 Selection of Control Mechanism

Figure 9 and **??** shows a comparison of ON/OFF control and P control output plots at different T_d.

6.1.1 Proportional control

Proportional control saturates to a temperature less than T_d, a helpful property when the mass temperature can not be changed drastically.

Steady State Error It gives Steady State Error (reaches till $99.37°C, 197.8°C, 294.8°C$ for $T_d = 100, 200, 300°C$, respectively). Hence, Proportional control is not desired. This can be fixed by multiplying the set temperature with a pre-calculated normalizing constant, but even better approach would be PID control.

6.1.2 ON/OFF control

ON/OFF gives good results (less time taken to heat up), but it too has a slight issue. Once the desired temperature is reached, the system will keep on oscillating ON and OFF as. As the duty cycle for maintaining that temperature might be different.

Hysterisis As shown in 11, ON/OFF without PWM shows temperature fluctuations $\pm 3°C$. This temperature fluctuations decreases ($\pm 2°C, \pm 0.3°C, \pm 0.01°C$) as PWM frequency increases (0.02 Hz, 0.1 Hz, 50Hz respectively). ON/OFF without PWM was achieved by removing the PWM generator from the block.

So for now, we are continuing with ON/OFF.

6.2 Feedback Technique Based Results

Usually, the system take the mass temperature as feedback. To get best results, it is required that the thermocouple touches the mass (or atleast its container). With this, our system has many applications in boiling, melting or modifying elements in any way till 700°C. But in our specific example, the oven temperatures denotes temperature of air and not mass (Also, connecting and disconnecting thermocouple is not a burden the users will want especially when dealing with foods). So, the feedback would be air's temperature. The only change in our system will be to move thermocouple from mass and keep it in air. As, air has a high specific heat, it takes more time to heat up. So, for such kind of application, the rise time will be more and also the maximum possible temperature decreases than previous case. Hence, our system will be helpful only for 'cool', 'very slow' and 'slow' ovens where it achieves the desired temperature.

We see that max temperature possible to reach within 500 seconds is close to 600°C for feedback through mass and 250°C through air.

7 Future Works

- Adding finer details to simulation model to make it more physically realizable eg., insulation layers, modelling oven with external atmosphere and heat flow between them.
- Implementing PID control and tune it using frequency-based auto-tuning feature of simulink.
- Working on mechanical design of a portable oven to further decrease heat losses.

Appendices

7.1 Simulation Models

All simulation files are available here.

References

[1] "Oven temperatures," *Wikipedia*, Last accessed on 11.04.2022. [Online]. Available: https://en.wikipedia.org/wiki/Oven%20temperatures

[2] "Sg3525a pulse width modulator control circuit," *ON Semiconductor Datasheet*, Last accessed on 11.04.2022. [Online]. Available: https://www.onsemi.com/pdf/datasheet/sg3525a-d.pdf

[3] "Kanthal® d wire ferritic resistance alloy," *KANTHAL*, no. 4, 1995-11-08. [Online]. Available: https://www.spacematdb.com/spacemat/manudatasheets/Kanthal%20D%20Data%20Sheet.pdf

[4] M. I. Neacă, "Comparative simulation of the dynamic regimes of resistive heating elements," in *2019 International Conference on Electromechanical and Energy Systems (SIELMEN)*, 2019, pp. 1–6.

[5] K. HAREENDRAN, "Pwm automatic heater controller," *electroschematics.com*, Last accessed on 11.04.2022. [Online]. Available: https://www.electroschematics.com/pwm-automatic-heater-controller/

[6] "Temperature controller basics handbook," *Instrumart*, Last accessed on 11.04.2022. [Online]. Available: https://www.instrumart.com/pages/283/temperature-controller-basics-handbook

[7] "Thermocouple types," *Design World Online*, Last accessed on 11.04.2022. [Online]. Available: https://www.designworldonline.com/thermocouple-types/

[8] "Thermocouple," *Wikipedia*, Last accessed on 11.04.2022. [Online]. Available: https://en.wikipedia.org/wiki/Thermocouple

[9] ForceTronics, "Designing a thermocouple based temperature measurement circuit part 1," *YouTube*, 2018. [Online]. Available: https://youtu.be/S4mbV36QZW4

[10] "Irf9540 power mosfet," *Vishay Siliconix Datasheet*, no. 91078, 2021. [Online]. Available: https://www.vishay.com/docs/91078/91078.pdf

[11] "Heating alloys for electric household appliances," *Kanthal Appliance Alloys Handbook*, 2003. [Online]. Available: http://www.west-l.com/uploads/tdpdf/06080303.pdf

[12] "Max31855 datasheet," *maxim integrated*, Last accessed on 11.04.2022. [Online]. Available: https://datasheets.maximintegrated.com/en/ds/MAX31855.pdf

[13] T. Channel, "How to wire pid for single or multiple heating elements," *YouTube*, 2020. [Online]. Available: https://youtu.be/mt4pxbG2_YQ

[14] MATLAB, "Getting started with simscape," *YouTube*, 2021. [Online]. Available: https://www.youtube.com/watch?v=fStr7rzsr3k

[15] "Pwm generator, generate pulse width modulated signal or waveform," *MathWorks*, Last accessed on 11.04.2022. [Online]. Available: https://in.mathworks.com/help/physmod/sps/ref/pwmgenerator.html

[16] Mitica, Iustinian, Neaca, Andreea, and Maria, "The modeling of the heating resistors in transient regime," 2011.

Tables

Table 1: KANTHAL D Wire Stock Item

Diameter (mm)	Resistance at 20°C (Ω)	cm^2/Ω at 20°C	Weight (g/m)	Surface area (cm^2/m)	Cross sectional area (mm^2)
0.30	19.1	0.493	0.512	9.42	0.0707

Table 2: Comparison of Types of Thermocouple

	Temperature range (°C)			
Type	**Continuous**		**Short-term**	
	Low	**High**	**Low**	**High**
K	0	+1100	−180	+1370
J	0	+750	−180	+800
N	0	+1100	−270	+1300
R	0	+1600	−50	+1700
S	0	+1600	−50	+1750
B	+200	+1700	0	+1820
T	−185	+300	−250	+400
E	0	+800	−40	+900
Chromel/AuFe	−272	+300	N/A	N/A

Figures

List of Figures

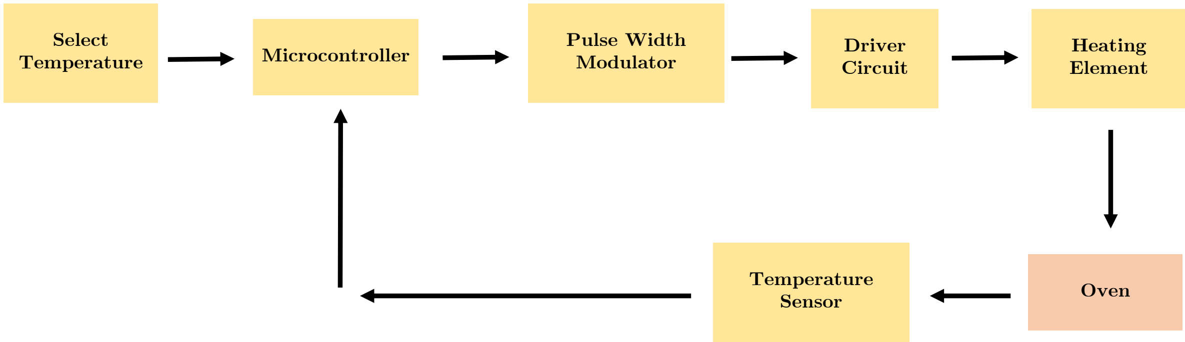


Figure 1: Block Diagram with major subsystems

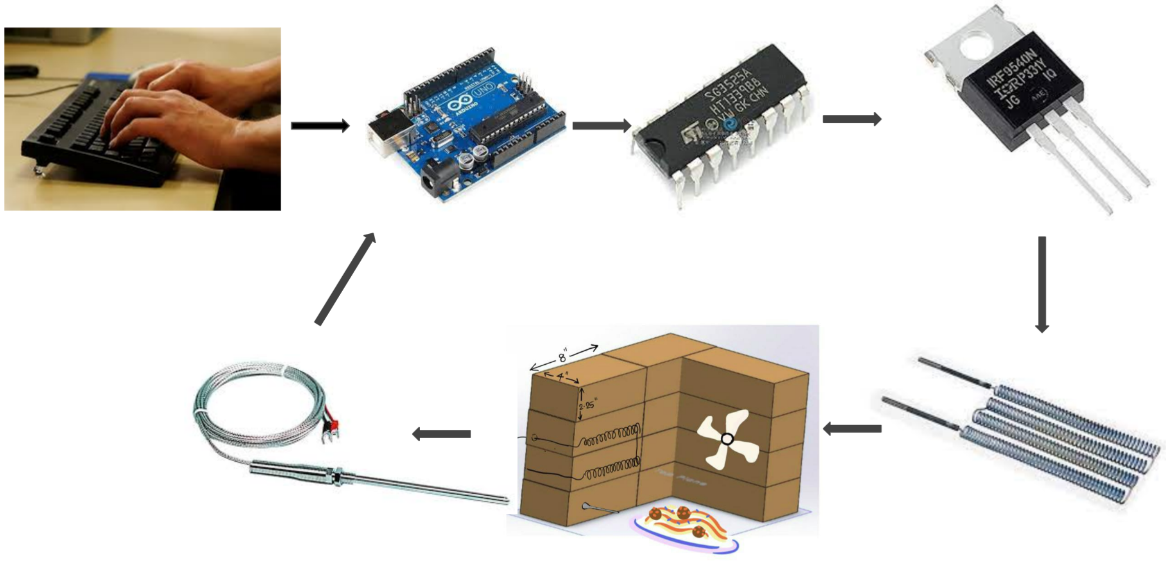
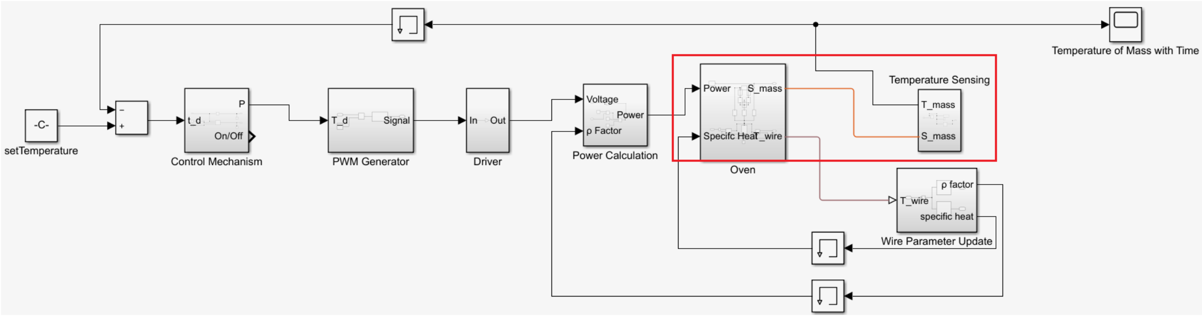
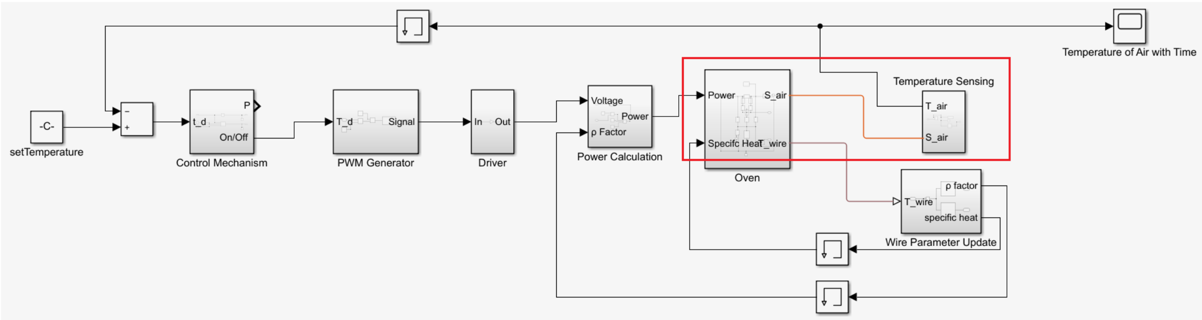


Figure 2: Block Diagram with major componenets Source



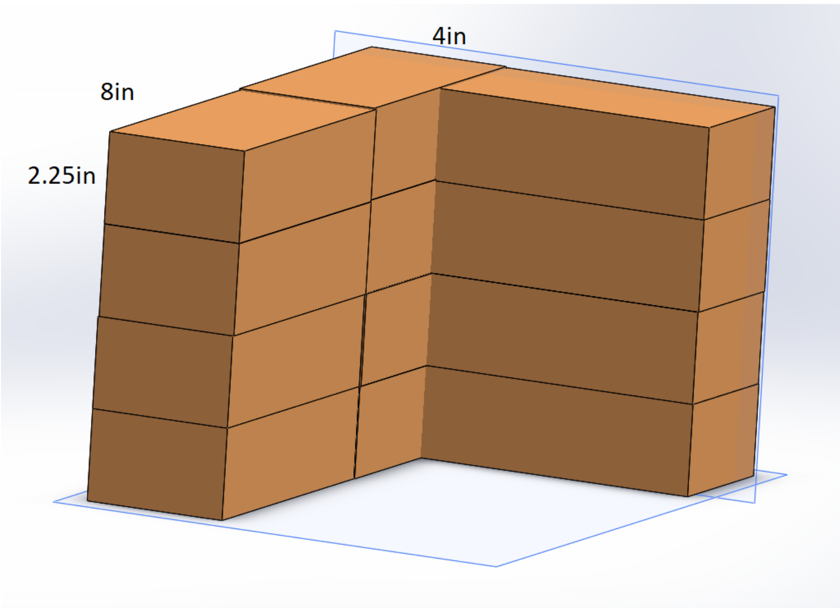
(a) General Temperature Controlled System (temperature feedback from mass)



(b) Air Oven (temperature feedback from air) with change highlighted

Figure 3: Simulink Model

(a) Example manufactured convection oven Source



(b) Oven Structure using Bricks (2 walls shown from an angle)

Figure 4: Oven Design

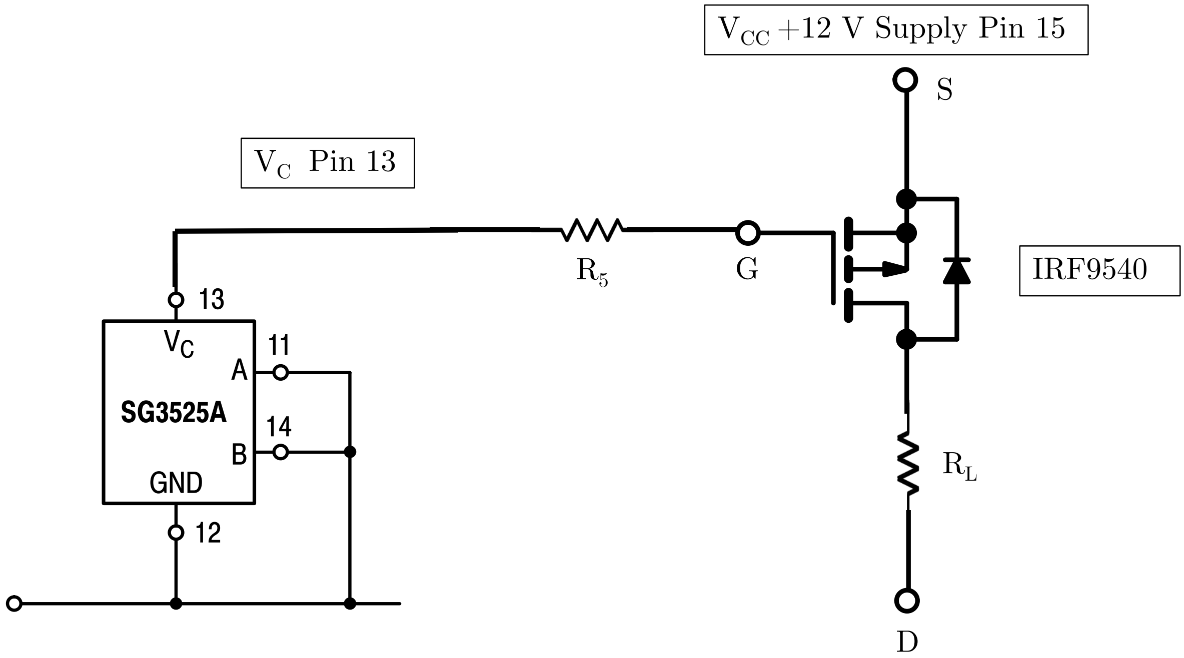


Figure 5: Driver Circuit with connections to IC SG3525A [2]

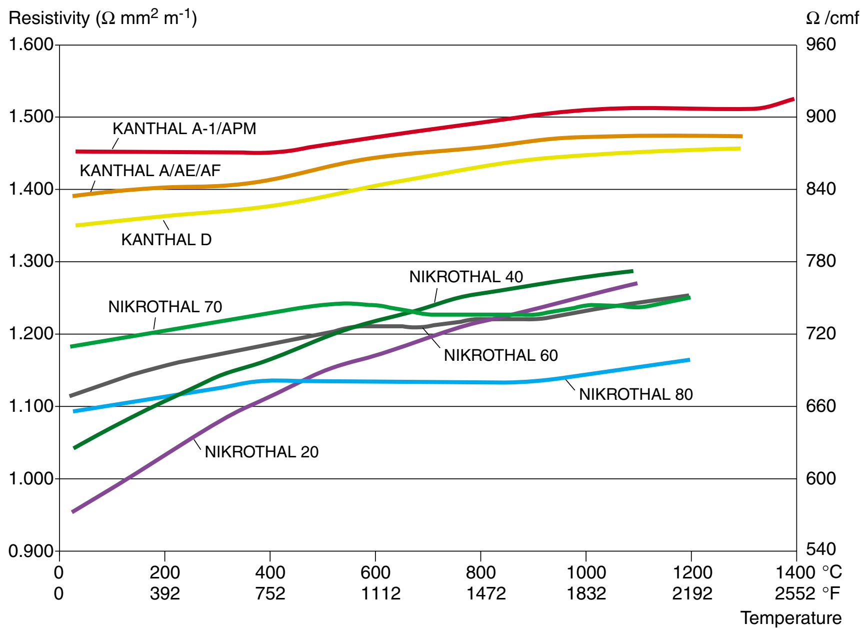
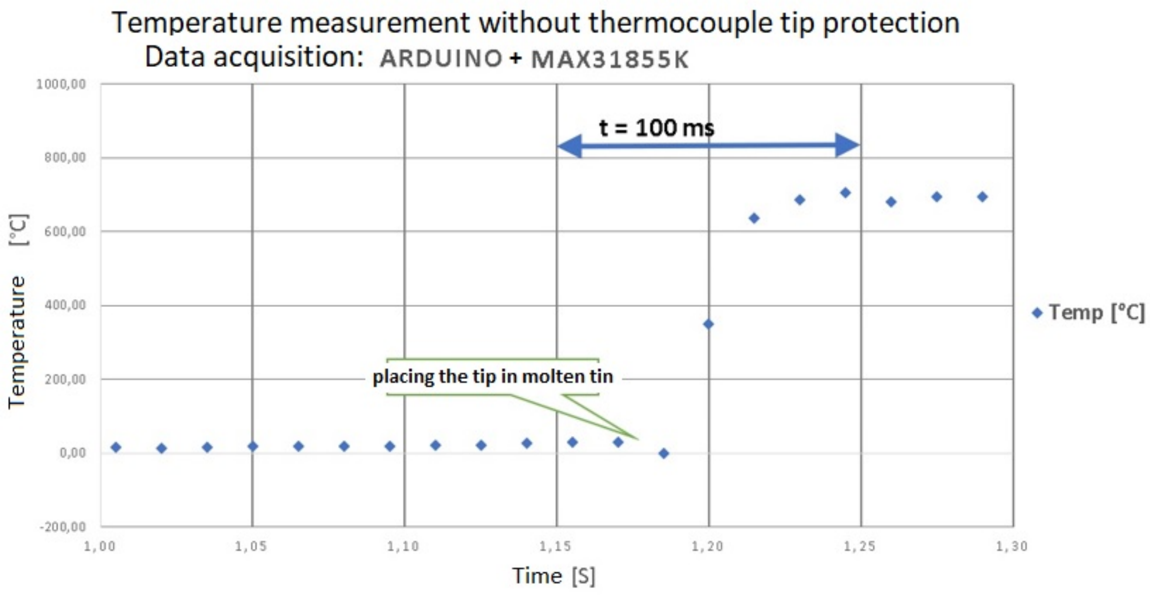
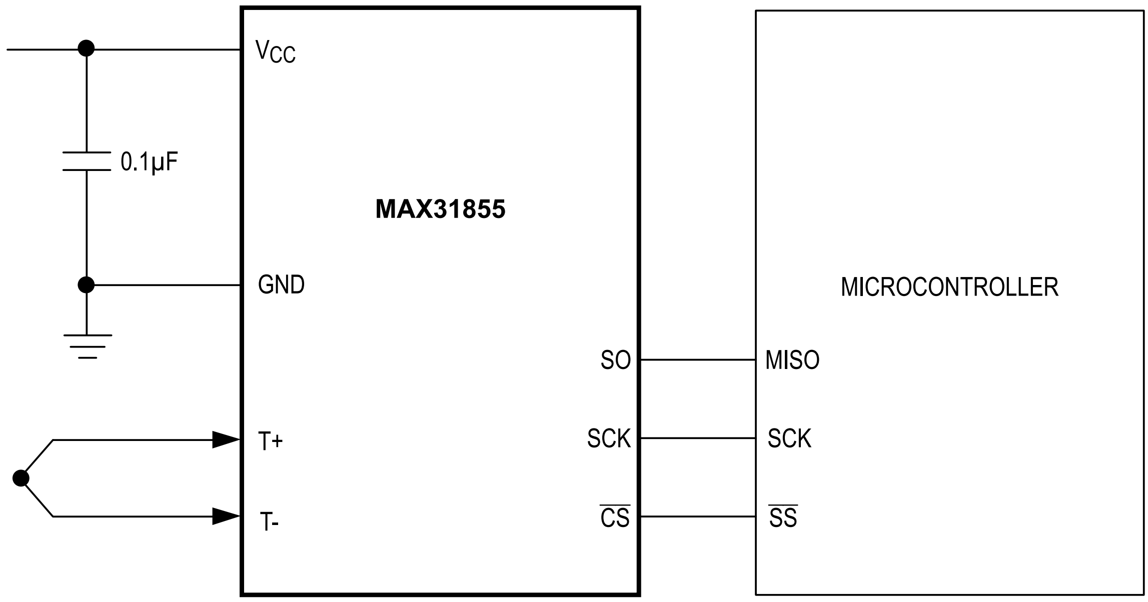


Figure 6: Resistivity vs. Temperature of various Heating Elements [11]

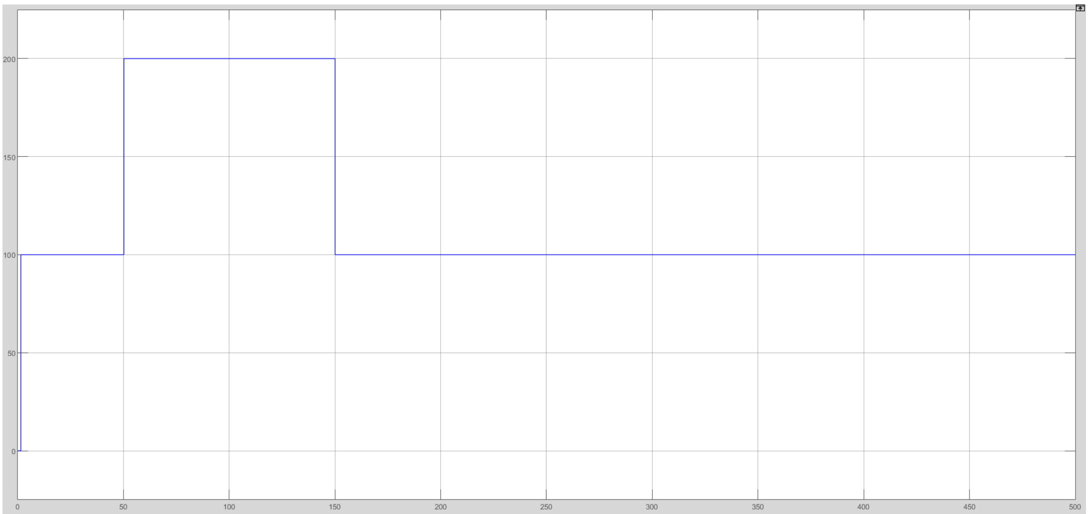


(a) Measurement without a tip cover [12]

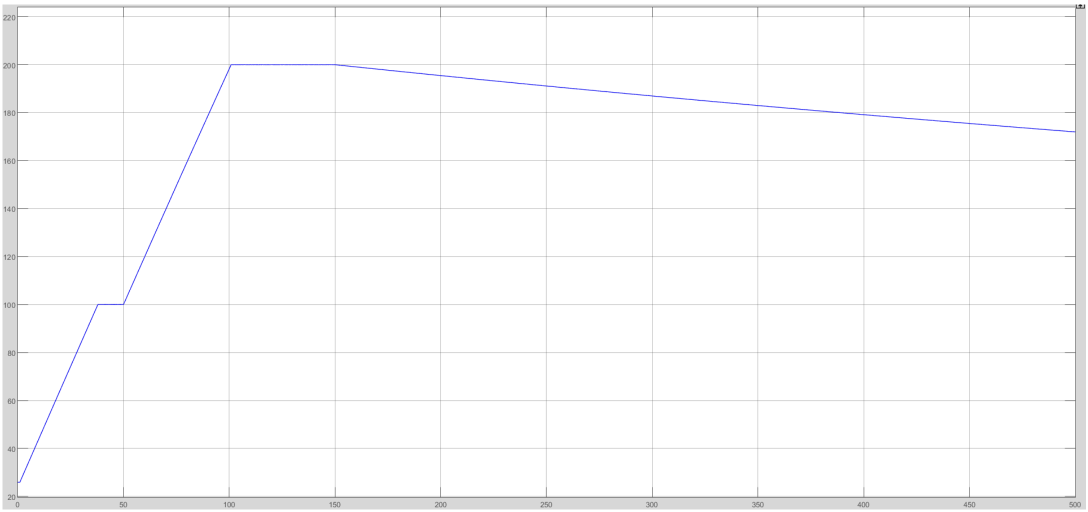


(b) Measurement Schematic

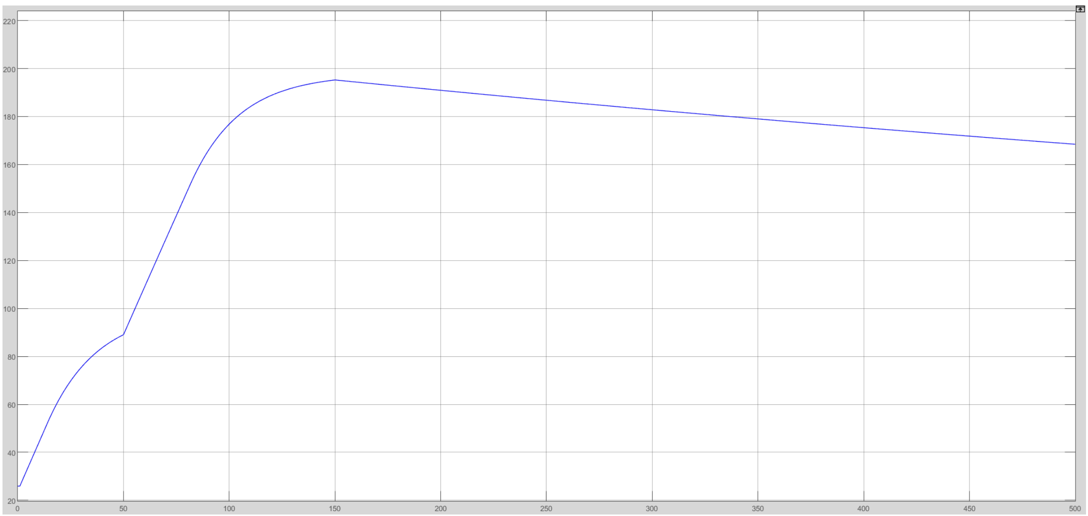
Figure 7: Thermocouple Temperature Measurement [12]



(a) Set temperature signal

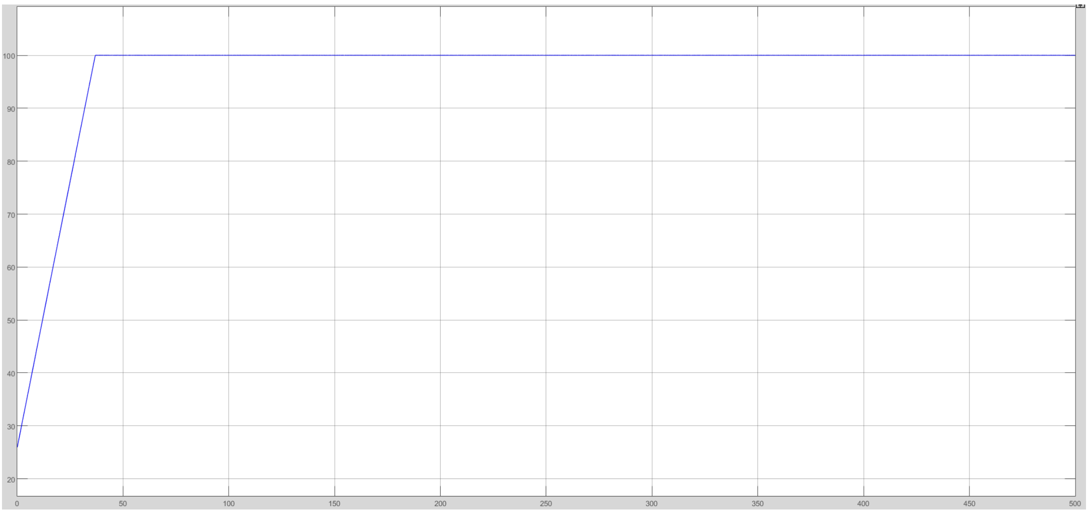


(b) ON/OFF control

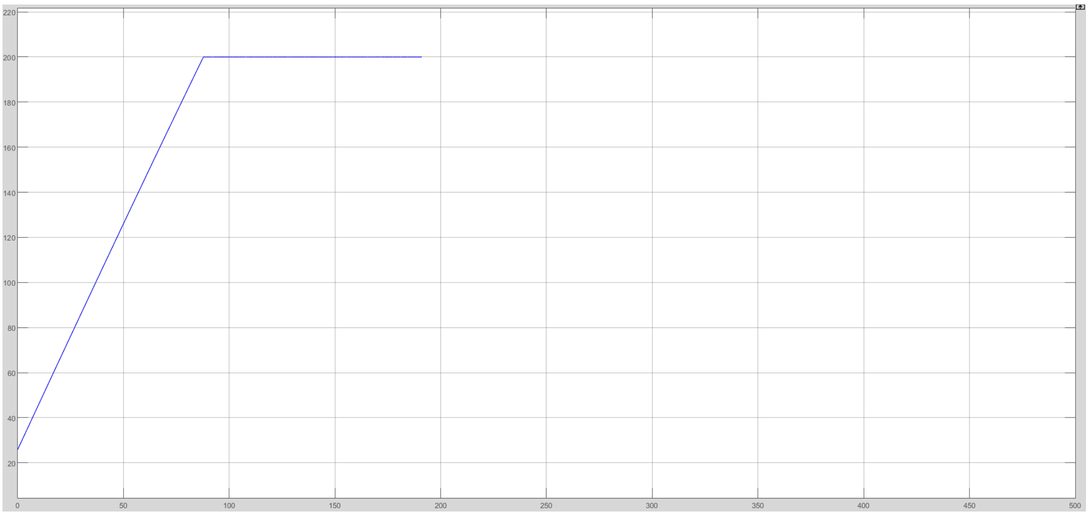


(c) P control

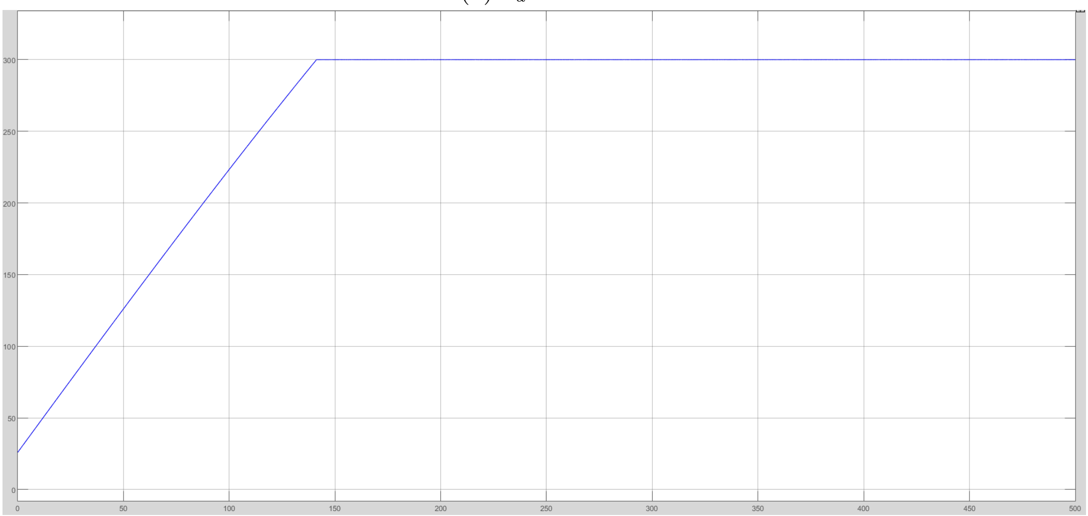
Figure 8: Changing T_d suddenly



(a) $T_d = 100°C$

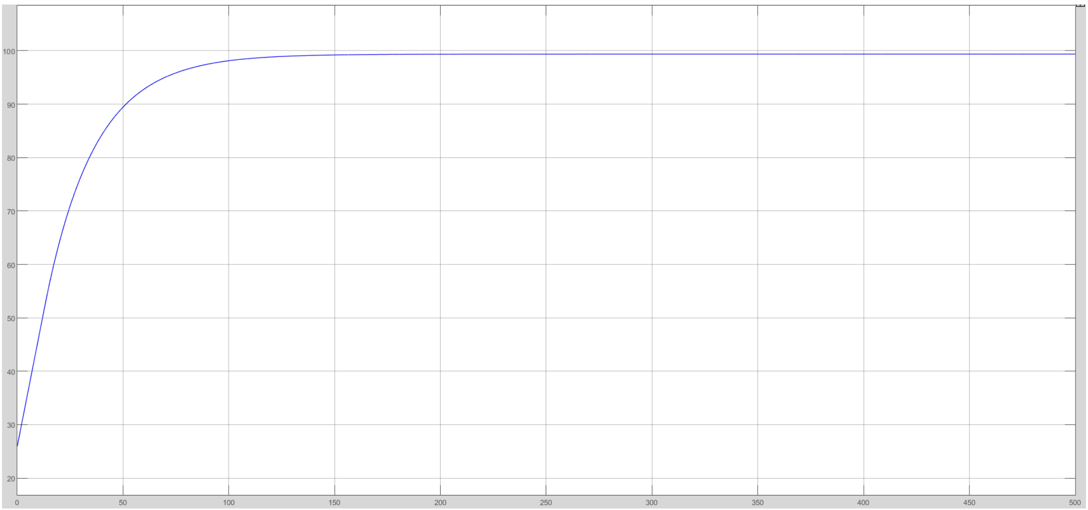


(b) $T_d = 200°C$

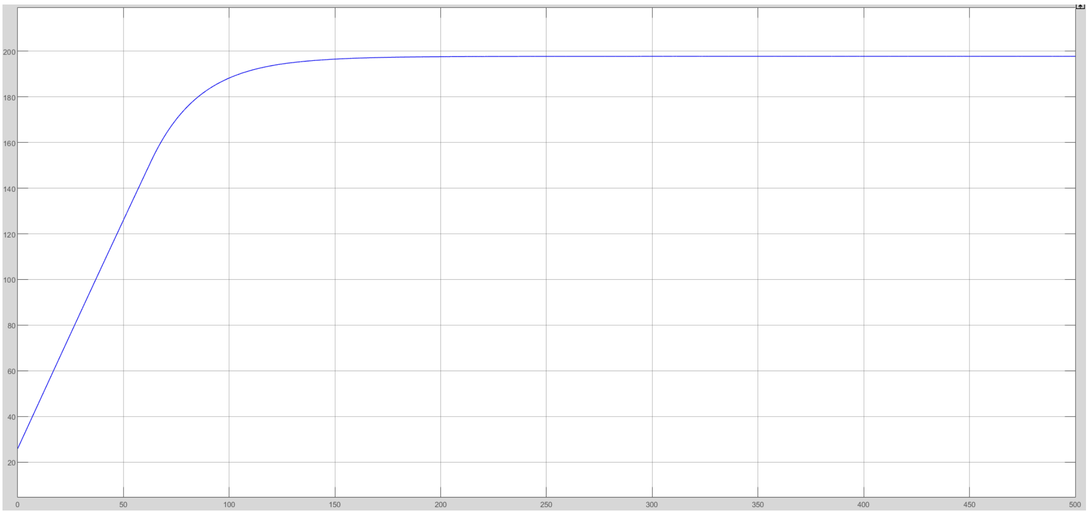


(c) $T_d = 300°C$

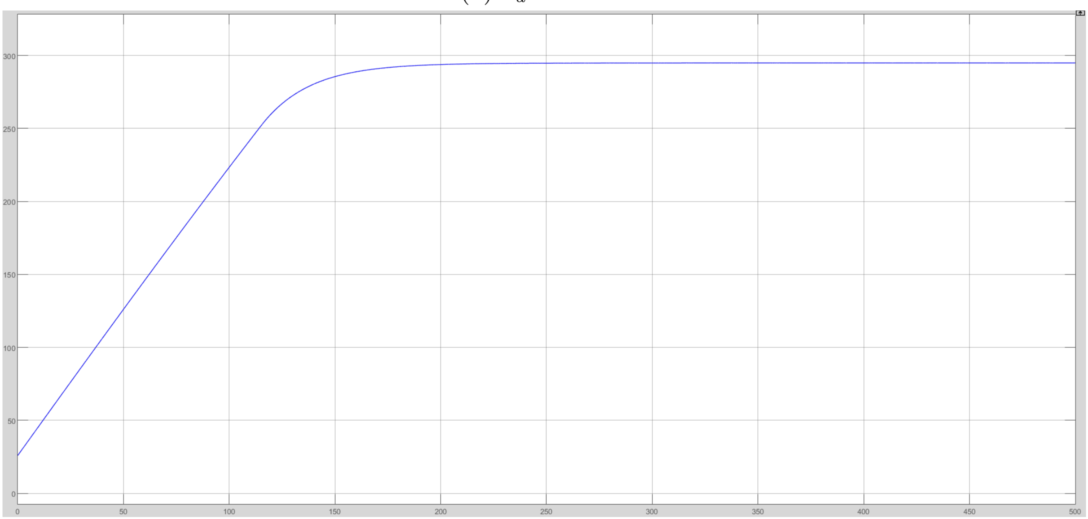
Figure 9: A comparison of ON/OFF control outputs at different T_d



(a) $T_d = 100°C$

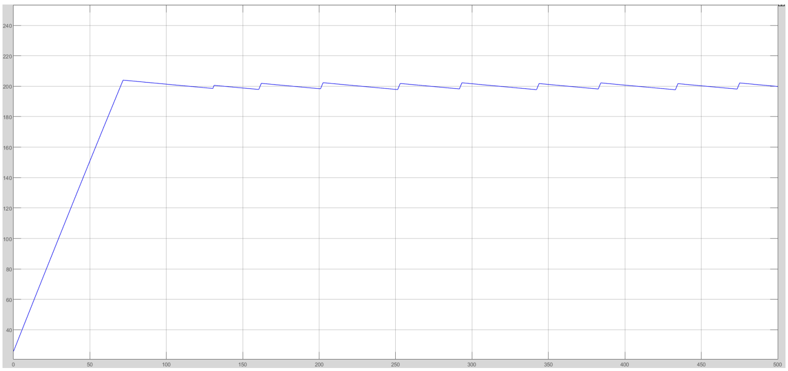


(b) $T_d = 200°C$

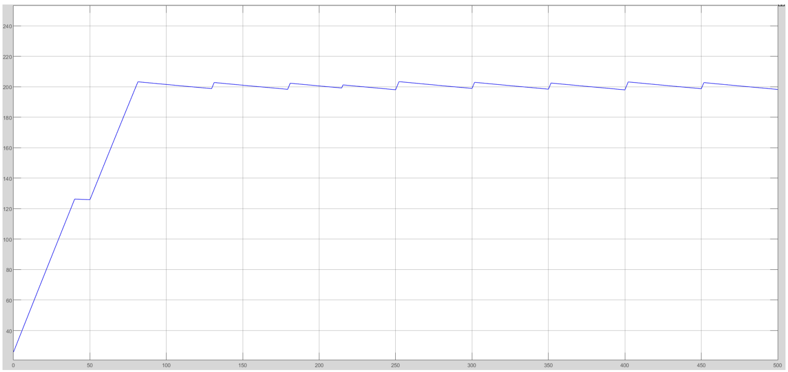


(c) $T_d = 300°C$

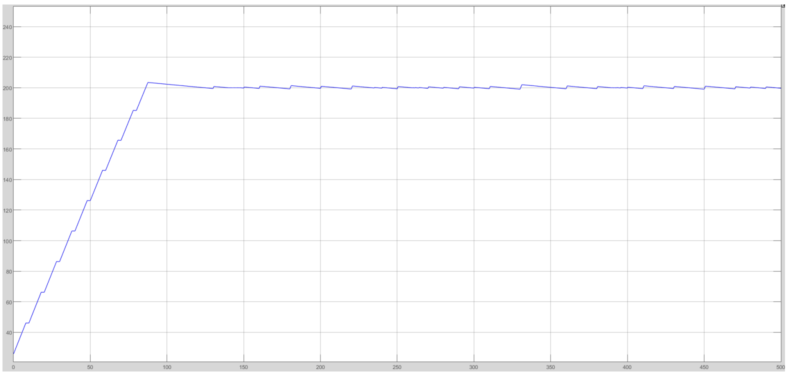
Figure 10: A comparison of P control outputs at different T_d



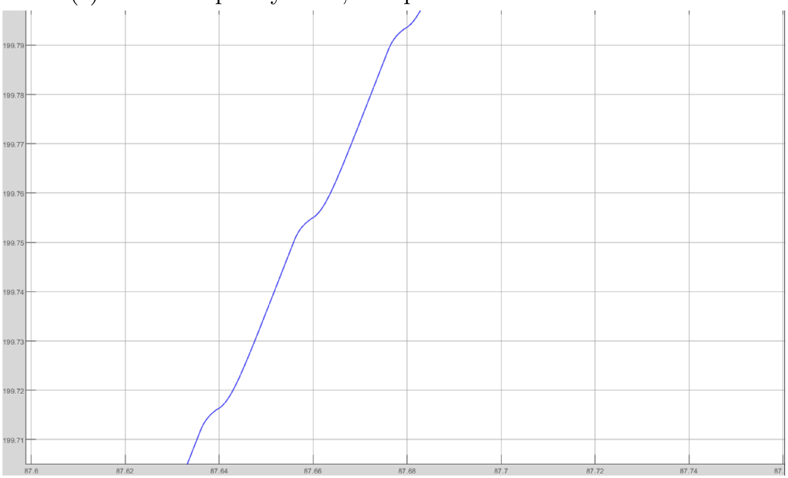
(a) No PWM, Temperature Fluctuation $\pm 2°C$



(b) PWM frequency 0.2 Hz,Temperature Fluctuation $\pm 2°C$

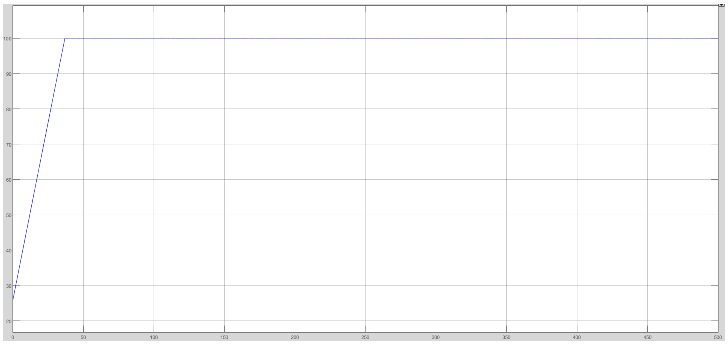


(c) PWM frequency 1 Hz, Temperature Fluctuation $\pm 0.3°C$

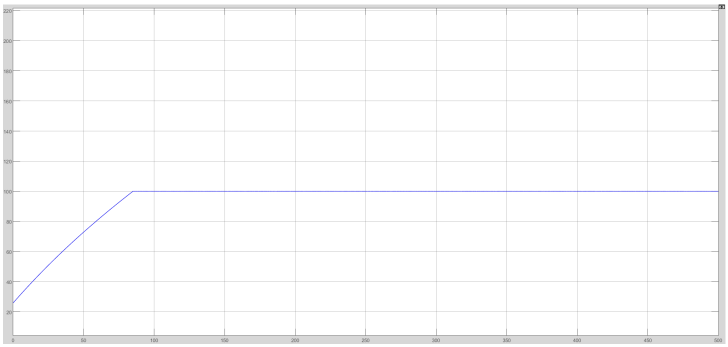


(d) PWM frequency 50 Hz, Temperature Fluctuation $\pm 0.02°C$
Observe the periodic behaviour which matches with 80% duty cycle.

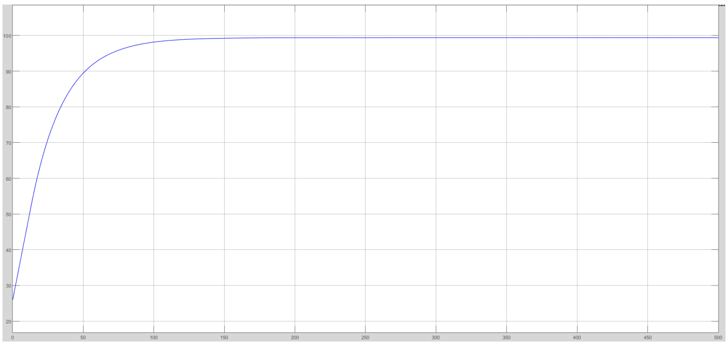
Figure 11: Hysteresis (Oscillatory Behaviour) of ON/OFF control at different frequencies.



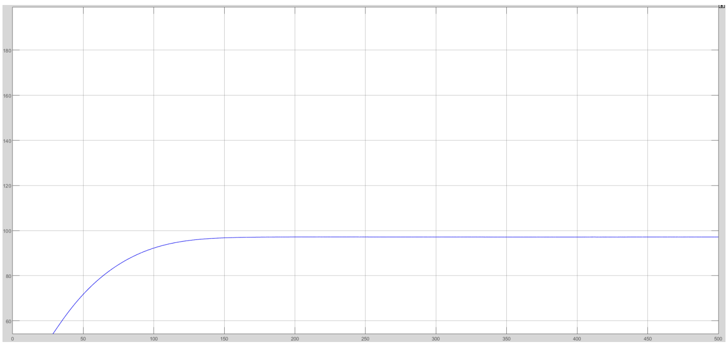
(a) ON/OFF control (Mass feedback)



(b) ON/OFF control (Air feedback)

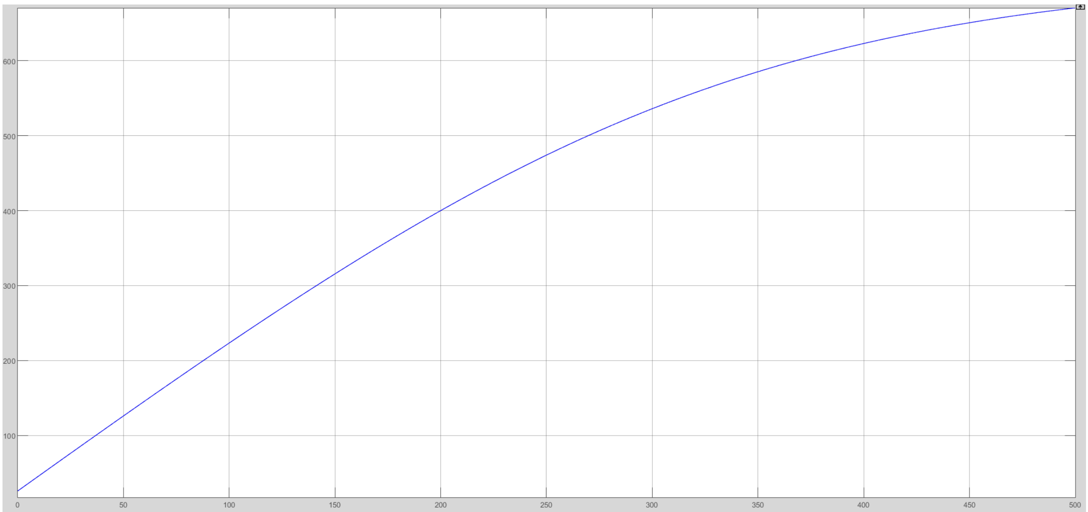


(c) P control (Mass feedback)

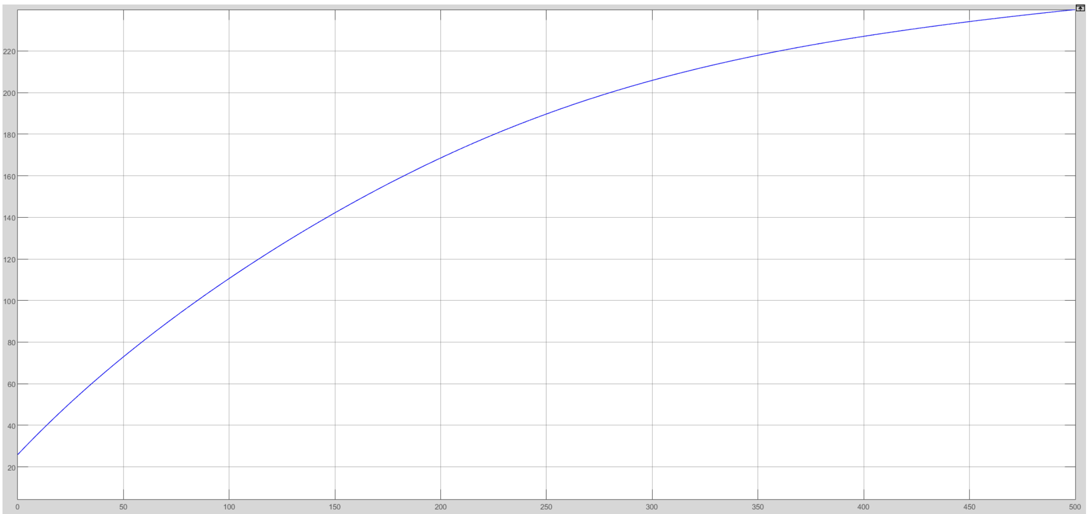


(d) P control (Air feedback)

Figure 12: Comparing different feedback points at $T_d = 100°C$

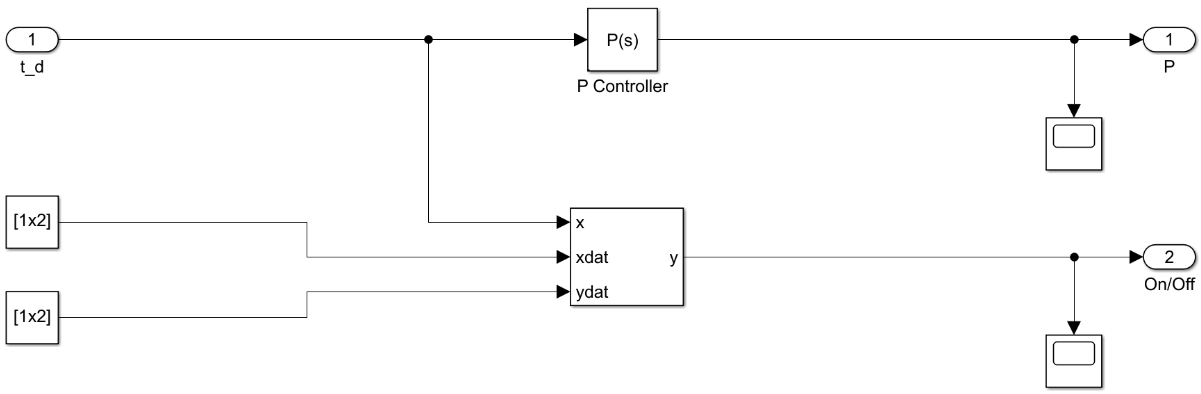


(a) ON/OFF control (Mass feedback)

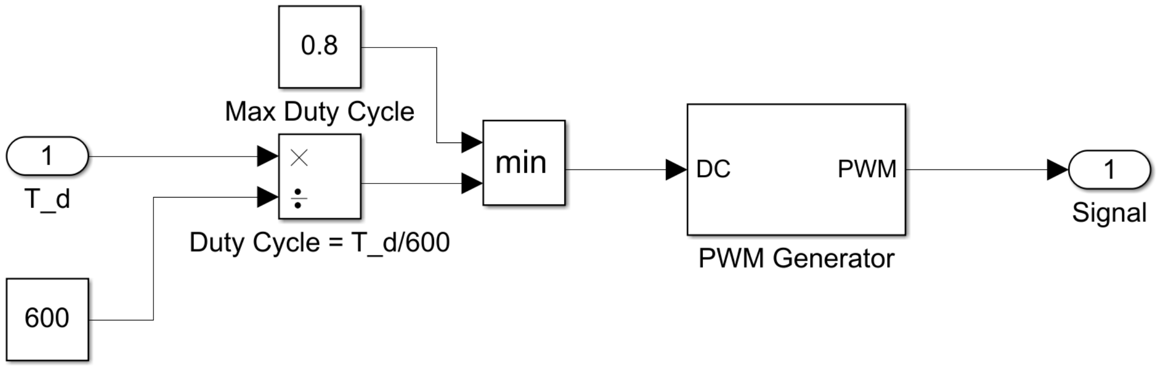


(b) ON/OFF control (Air feedback)

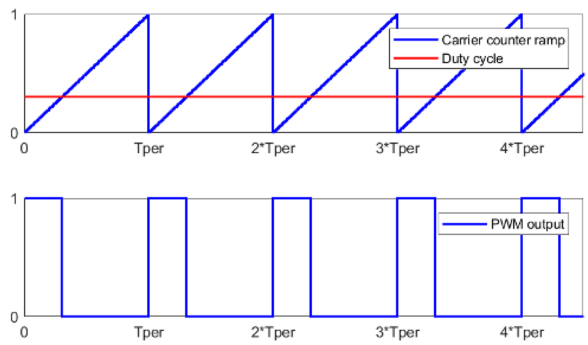
Figure 13: Comparing max temperatures reached within 500 seconds for different feedback points



(a) Control Mechanism

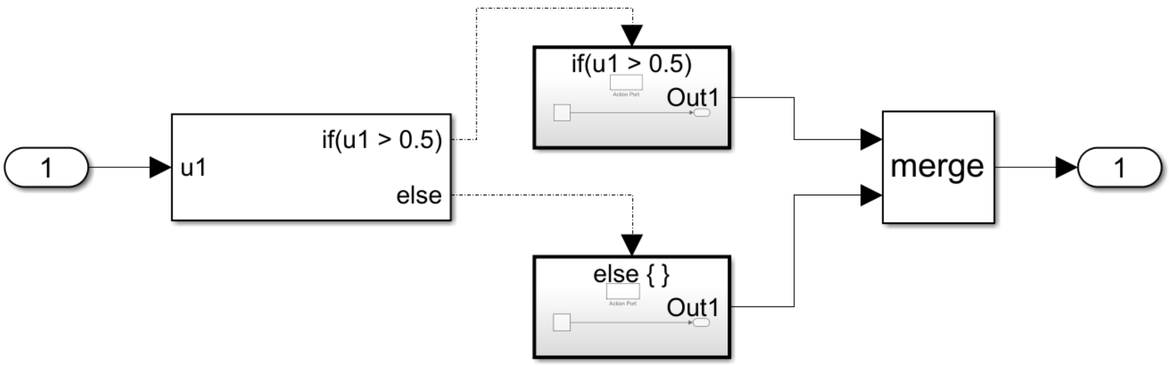


(b) PWM Generator

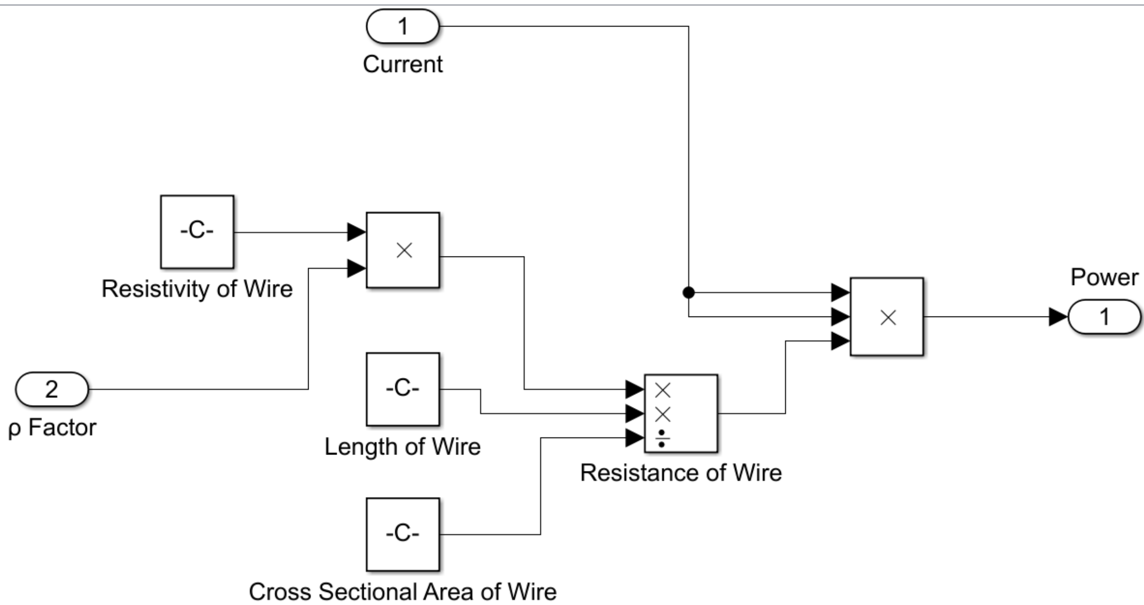


(c) PWM Generation Principle (Source)

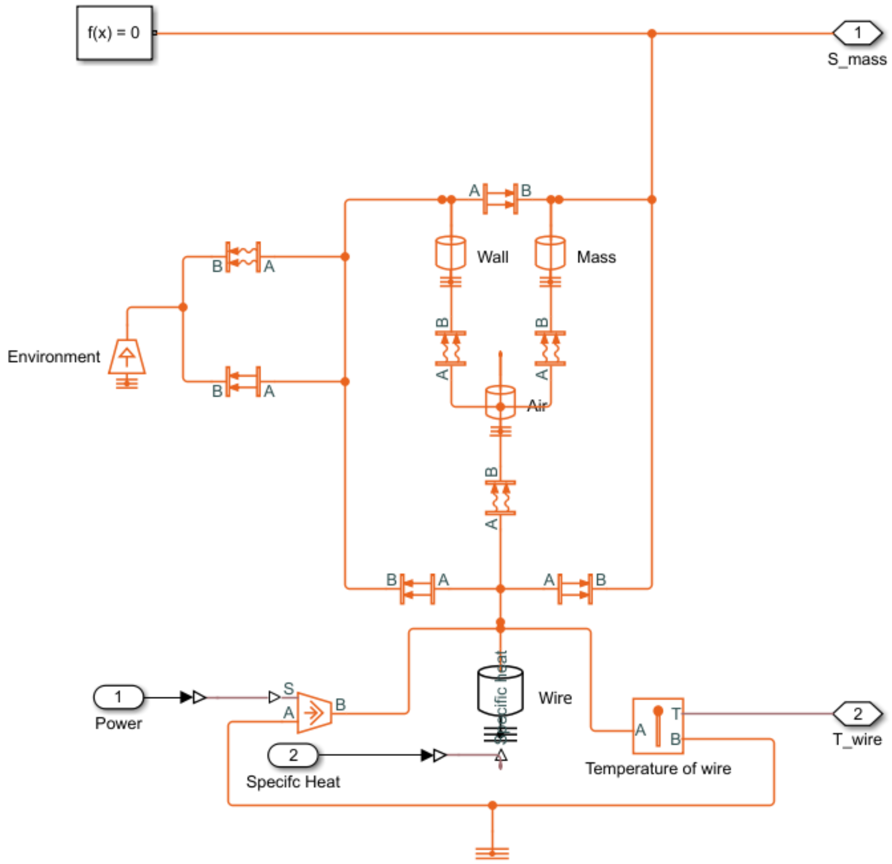
Figure 14: Pulse Width Modulator



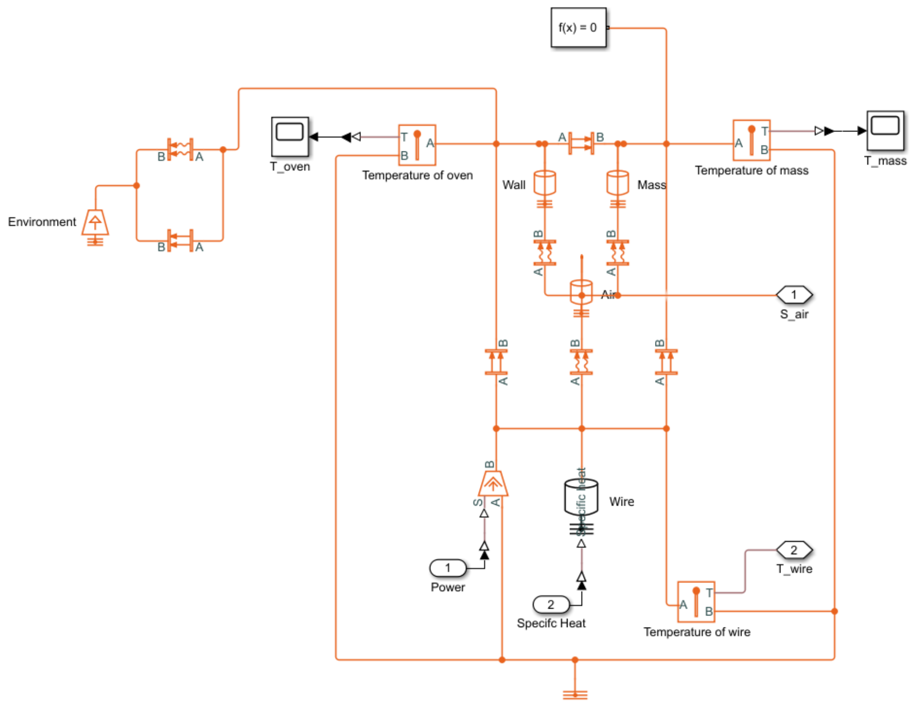
(a) Driver Circuit



(b) Power Calculations



(a) Air Oven



(b) Mass Oven

Figure 16: Oven Design

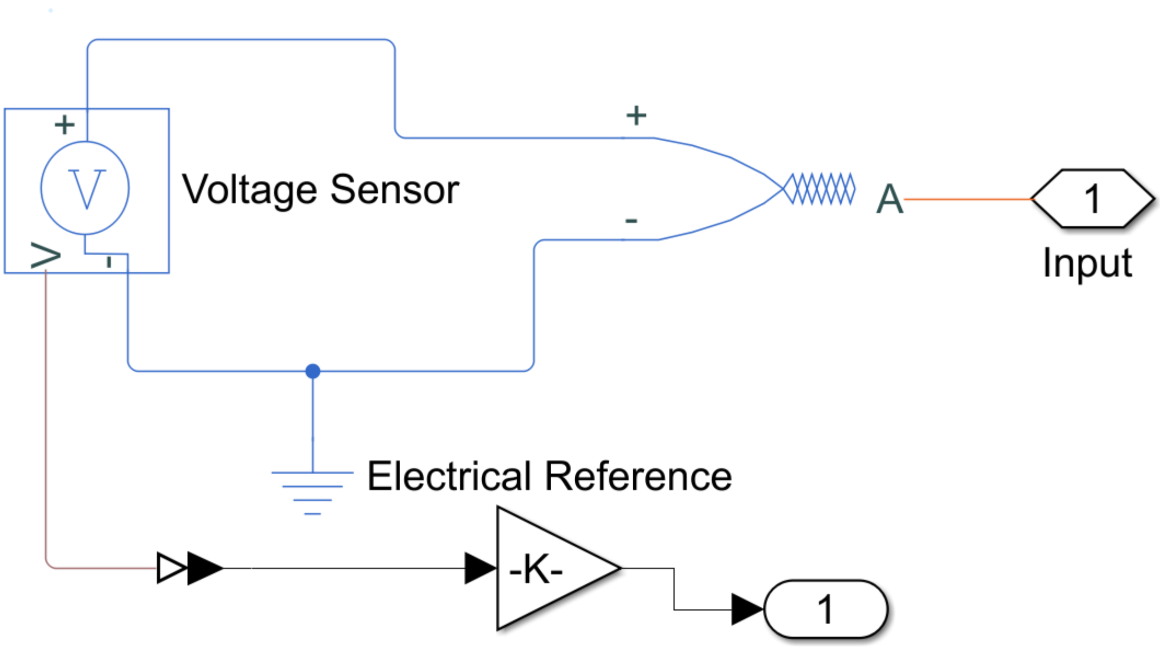


Figure 17: Thermocouple Measurement