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Thermal analysis of PTC heaters

Thermography of PTC and Peltier heaters. Labview® based control and Matlab® Simulink simulations of PTC heaters.

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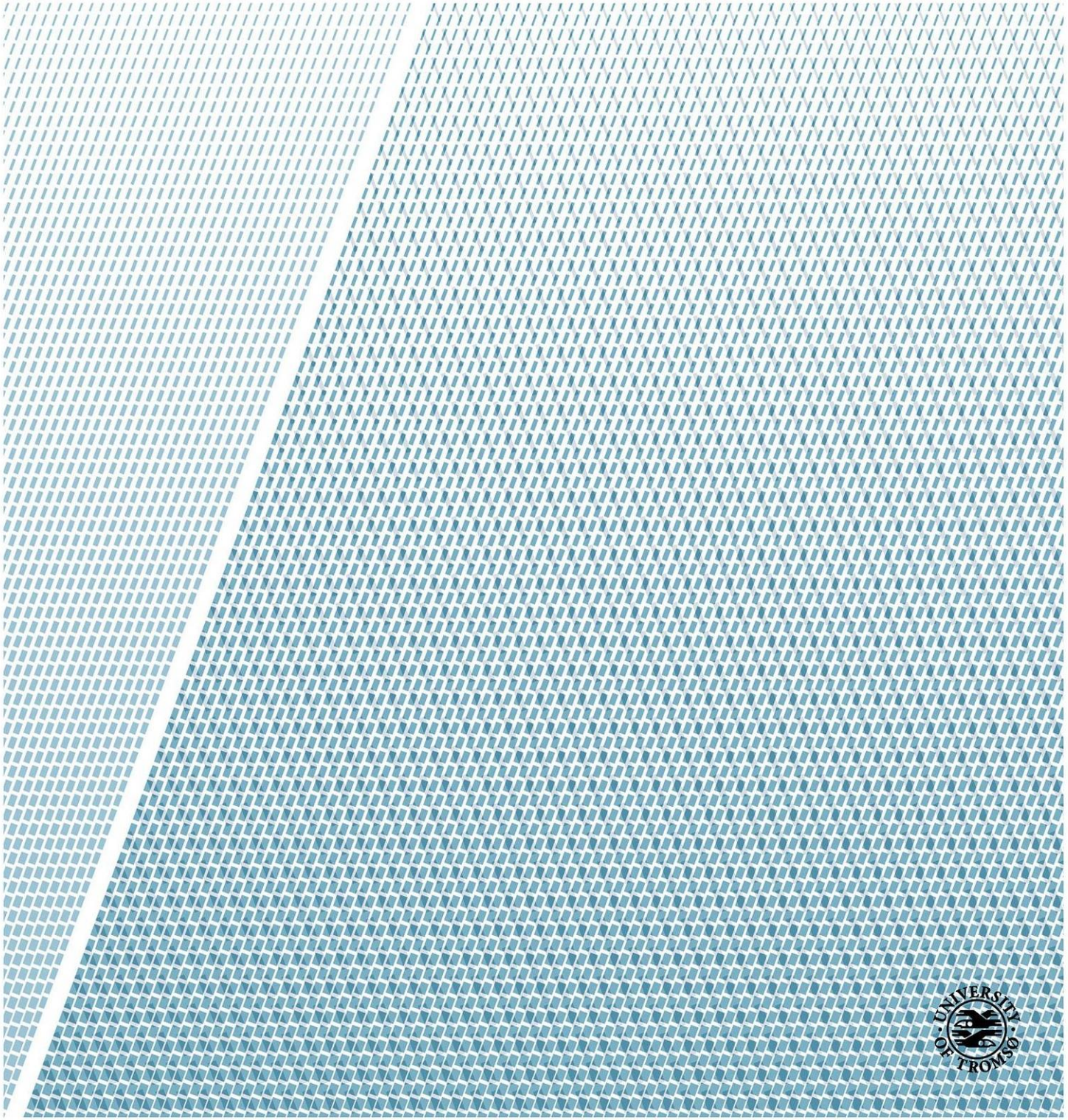

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Abstract

A large variety of heating devices are being used in the industry. Their usage depends upon the area of application. Two widely used smart heating devices are discussed in this study. These heating devices are Peltier/thermoelectric (TE) and Positive Temperature Coefficient (PTC) resistive heater. These heating devices have different physical principles. Their principle of operation, types and advantages are given in the literature.

This study provides detailed experimentation of PTC heater and Peltier device at room conditions and cold environment. The thermal response of both heating devices is discussed. Due to certain advantages, PTC heater is further analysed. The study has discussed two sensing methods for PTC heater. One is contact based sensing method and the other is non-contact sensing method. The advantage of introducing non-contact based sensing method is remote monitoring.

A PTC heater can be used in a customized temperature control industrial application. Infrared thermography is one of the ways to remotely monitor the temperature. An Infrared camera captures the infrared radiations that are emitted, transmitted or reflected from the heating devices. The infrared image contains the information about the complete temperature profile of the surface. This study contains experimental work on analysing a PTC resistive heating device using two temperature measuring methods. One is a contact measurement method using a miniature resistive temperature detector (RTD) namely pt100. The other is infrared thermography that is a non-contact based method. A prototype of temperature measurement and control system (TMCS) is developed. It is based on PID control system where pt100 is providing temperature feedback. The surface temperatures of the PTC resistive heater are recorded using TMCS and compared with the infrared temperature readings. The experiments are performed at room conditions and the cold environment conditions. The cold environment analysis of the PTC heater is done in an industrial cold environmental chamber at The Arctic University of Norway. The infrared thermography is performed using FLIR® T1030Sc high definition infrared camera. The experimental results of TMCS show a reasonable control system response. It has the steady state error around $\pm 0.3^{o}$C at room conditions and $\pm 0.6^{o}$C at cold environment conditions. In addition, TMCS and IR thermography results corresponds with

one another. A temperature offset of ±0.5^{o}C is observed between TMCS and IR readings. In addition, a model of PTC heater was simulated in MATLAB® Simulink. The simulation results of resistive heater correlates with the experimental results. Overall, the study shows that TMCS is a prototype that can be used for temperature measurement and control applications inside the room and cold environment conditions. The infrared thermography gives an advantage to remotely monitor and validate the control system.

This study can be implemented in the applications of smart heating and control. This study can also be utilized in de-icing systems operating in cold environment.

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Nomenclature

Symbols

I	$[A]$	Current
R	[Ω]	Ohm
V	$[V]$	Volt
U	[W/K]	Overall conductance
T_h	[K]	High Temperature
T_l	[K]	Low temperature
$\dot{Q}_p$	$[\,W/sec\,]$	Peltier heating or cooling rate of change
Q_j	$[W]$	Joule effect
Q_c	$[W]$	Conduction effect

Greek Symbols

ε	$[dimensionless]$	Thermal Emissivity
Ω	$[V/A]$	Ohm
α	$[dimensionless]$	Coefficient of energy absorbed
ρ	$[dimensionless]$	Coefficient of energy reflected

Abbreviations

AI	Analog input
AO	Analog output
AlGaAs	Aluminium gallium arsenide
DAQ	Data acquisition
DC	Direct current
GaAs	Gallium arsenide
HgCdTe	Mercury cadmium telluride
IR	Infrared
Incoloy	nickel-iron-chromium alloy
InSb	Indium antimonite
I/O	Input output
Jr.	Junior

PCB	Printed circuit board
PTC	Positive temperature coefficient
PID	Proportional, Integral, Derivative
NWIR	Narrow wave IR
NI	National Instruments
NUC	Non uniform correction
max.	Maximum
min.	Minimum
MWIR	Medium wave IR
MCT	Mercury cadmium telluride
LWIR	Long wave IR
ROI	Region of interest
RTD	Resistive temperature detector
Sec	Second
TMCS	Temperature measurement and control
VI	Virtual instrument
VLWIR	Very long wave IR
FPA	Focal plane array
pt	Platinum
QWIP	Quantum well infrared photon

Chapter 1

1. Introduction

A large variety of heating devices are being used in the industry. Their usage depends upon the area of application. Two widely used smart heating devices are discussed in this study. These heating devices are Peltier/thermoelectric (TE) and Positive Temperature Coefficient (PTC) heaters. These heating devices have different physical principles. Their principle of operation, types and advantages are given in the literature.

In this study, a laboratory scale experimental setup for Peltier and PTC heating device is built. Detailed experimentation and analysis of heating elements is performed. A laboratory scale prototype is developed to measure and control a PTC heater. The experimental setup is analysed in room conditions and cold environmental conditions. A simulation model is developed in *MATLAB® Simulink* and results are compared with the experimental findings.

1.1. Scope of Work

The scope of work is described in this section. This work included the following activities.

1. *Theory* of the following

    - Resistive heating elements
    - Peltier device
    - Resistance temperature Detectors for temperature sensing (RTD)
    - Infrared thermography (IRT)
    - A PID control system
    - DAQ device

    The theory includes the discussion on these devices and their characteristics. It also includes infrared basic theory and its application in thermal detection devices. Data acquisition devices and PID control system are discussed.

2. Making a laboratory scale *Experimental Setup* for heating devices. It also includes design and development of temperature measurement and control system (TMCS) for PTC heater. Preparing the TMCS hardware Setup inside cold environmental chamber and its cold proofing.

3. *Conduct* detailed experimentation to acquire thermal signatures of Peltier and PTC heaters' thermal units inside

    a. Room conditions
    b. Cold environmental conditions

4. Conducting the *Analysis* of heating devices. Perform experimental procedure to analyse the surface temperature of resistive heater at room and cold environment temperatures.

5. *Develop* simulation model for PTC heater in MATLAB® Simulink.

6. *Compare* the simulation results with experimental findings.

7. *Compile* the study in form of a thesis report.

1.2. Contents

The *introduction* is discussed in the first section of this thesis.

The second section of the thesis contains brief *theoretical background* of four components. It includes two heating devices (resistive and Peltier device), one temperature sensor namely resistance temperature detector (RTD) and an infrared camera.
This section also contains an overview of the proportional, integral and derivative (PID) control system. A PID control system is implemented in the Labview® software using a data acquisition (DAQ) device manufactured by National Instrumentation® (NI). A brief overview of a DAQ system is also given in theory section.

The third section of the thesis contains the *methodology* of the study. The method section describes how four setup components are used to perform experimentation. These four setup components are *temperature measurement and control system* (TMCS) of a resistive heater, Peltier device assembly, an *infrared camera* and *cold environment chamber*. This section contains device assembly, setup procedure and experimentation.

The fourth section of the thesis contains the *results and discussion*. It contains experimental results performed at room and cold environment conditions. The simulation model and results are described in this section.

The thesis is *concluded* in the fifth section. The contents of the thesis are also shown in Figure 1.

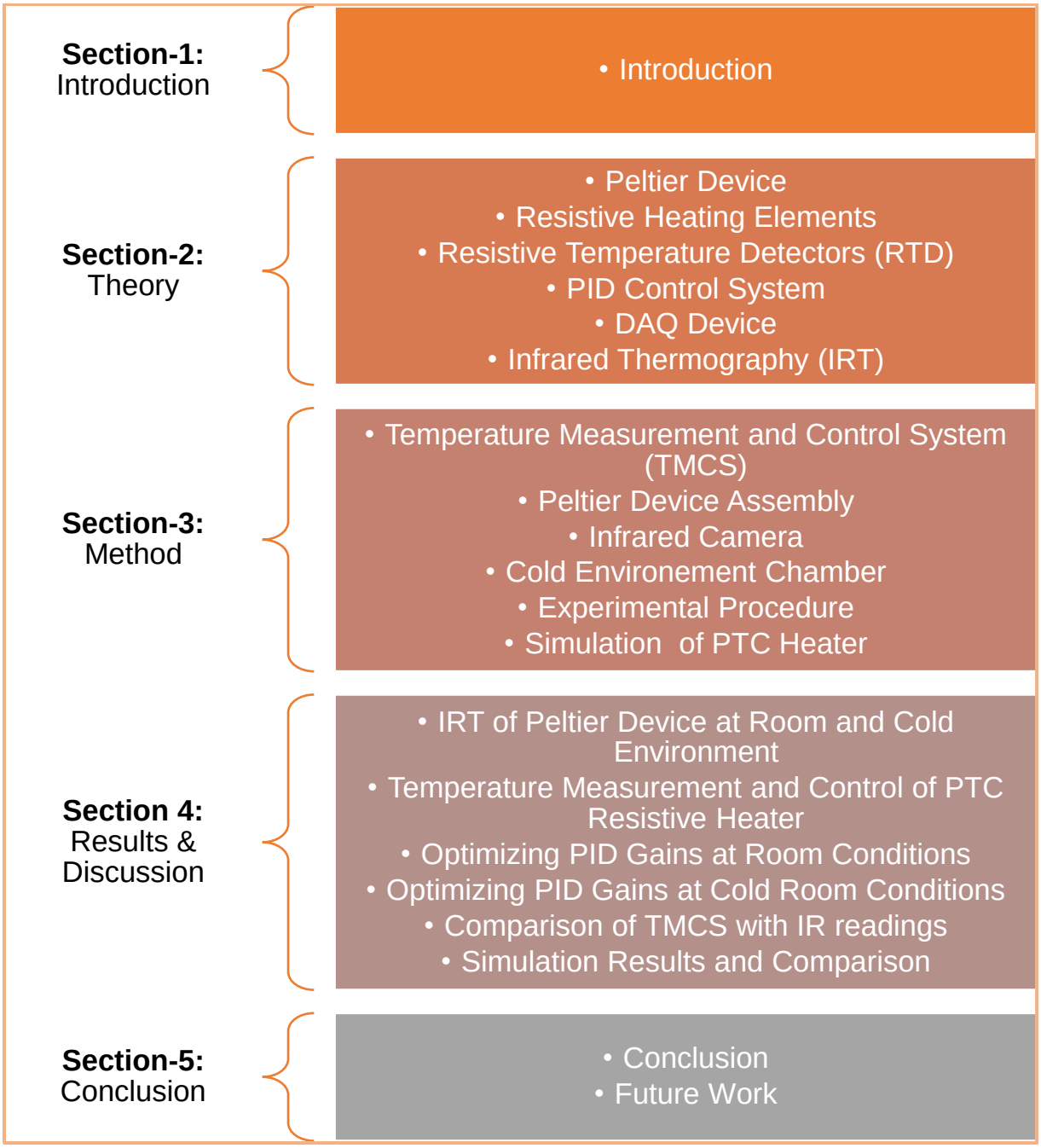


Figure 1 Contents

Chapter 2

2. Theory

2.1. Peltier Device

2.1.1. Introduction to peltier device

The Peltier device is also referred as thermoelectric module (TEM).The Peltier device uses the Peltier effect to generate heating and cooling at the same time. The thermoelectric module used for cooling purposes is also referred as Thermoelectric cooler (TEC).

The Peltier effect was discovered by French physicist Jean Charles Athanase Peltier in 1834. Peltier observed thermal effects produced at the junction of the two dissimilar conducting elements, whenever the electric current is passed through it. This phenomenon involves joule heating but cannot be solely explained by this phenomenon. It was also observed that the direction of the current plays an important role to produce heating and cooling [1].

Additionally, the Peltier device can be considered as a thermoelectric module which is a solid state heat pump. This technology was matured in 1960's with the rapid advancement in semiconductor technology including thermocouples and ceramic substrates [2].

2.1.2. Working principle

If electric current is passed through two different adjoining conductors, some of the electrons cross the junction from one conductor to another. This crossing continues until an electric field is generated which is large enough to prevent further electrons to flow across the junction. This electron flow is due to the Fermi level between the two conductors. The electrons flows from the higher fermi level to the lower one until both conductors have same fermi levels. The current passing through the junction results in either a forward or a reverse bias. This produces a temperature gradient resulting in hotter side and a colder side. If the temperature of the hotter junction is kept low by removing the heat, the temperature of the cold side can be cooled by tens of degrees [1].

A typical Peltier device contains number of N-type (excess of electrons) and P-type (deficiency of electrons and excess of holes) semiconductor junctions. These junctions are connected in series by metallic junctions (good conductors such as copper). They are connected thermally in parallel to create a hot side and a cold side. This forms a typical single-stage thermoelectric module [3]. The typical construction of a Peltier device is shown in Figure 2.

The difference in temperature between hot and cold side of a standard single-stage TEM can reach up to 70°C. However, with rapid advancement in semiconductor materials, this difference is being improved [2].

2.1.3. Physics of thermoelectric module

When direct current passes through a pair of thermocouples with their junction temperatures being maintained at different temperatures, four effects are observed namely Seebeck effect, Peltier effect, Joulean effect, and Conduction effect.

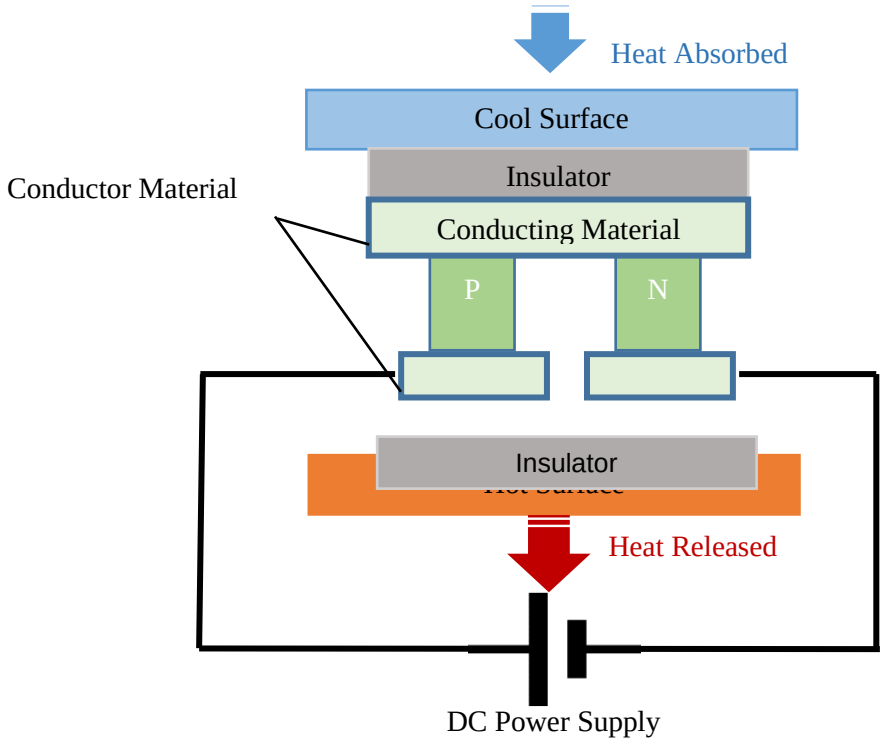


Figure 2 Thermoelectric/Peltier Device Construction

a. Seebeck effect

Electric potential is generated when different conductors are adjoined at different temperatures. This is known as seebeck effect. It is important to note that seeback effect is independent of the current flow and it always occurs when two electrical conductors or semiconductors are at different temperatures [4].

b. Peltier effect

When current passes through a pair of dissimilar electrical conductors or semiconductors, it creates thermal gradient between the junctions. One side of junction becomes cool and the other becomes hot. Peltier varied the current and observed the heating and cooling rate of change for different sets of elements. It was observed that

$$\dot{Q}_p \propto I \qquad (1)$$

where $\dot{Q}_p$ is the Peltier cooling or heating rate of change (W/sec) and I is the current (A). The proportionality constant in Eq. (4) is called Peltier coefficient Π_{ab} (W/sec/A) and is written as

$$\dot{Q}_p = \Pi_{ab} I \qquad (2)$$

where

$$\Pi_{ab} = \Pi_a - \Pi_b$$

Π_a and Π_b are the peltier coefficients of two conductors *a* and *b*.

c. Joule effect

The Joule effect is the phenomena of heat energy $Q_j(W)$ being dissipated across a conductor, when electric current flows through it. It can be related as

$$Q_j = I^2 R \qquad (3)$$

where I and R are current (A) and resistance (ohms) respectively.

d. Conduction effect

The heat conducts due to the temperature difference. The heat $Q_c(W)$ is transferred from hot end to the cold end is given by the relationship

$$Q_c = U(T_h - T_l) \qquad (4)$$

where U is the overall conductance (W/K) and T_h and T_l are high and low temperatures (K) respectively.

2.1.4. Types of TEM/ Peltier device:

The TEM/peltier devices are mostly used in the cooling applications. These thermoelectric coolers are available in two major types.

I. Single Stage TEM
II. Multistage TEM

I. Single stage TEM/Peltier device

The single stage peltier device is made of several p type and n type semiconductors connected thermally in parallel. The semiconductors are interconnected with good electrical conductor such as copper. In addition, filler material used on the top and bottom of semiconductors is an electrical insulator and a good thermal conductor. This filler ensures that there is minimum temperature difference between the surface and the semiconductor [4, 5]. The single stage peltier device is shown in Figure 3.

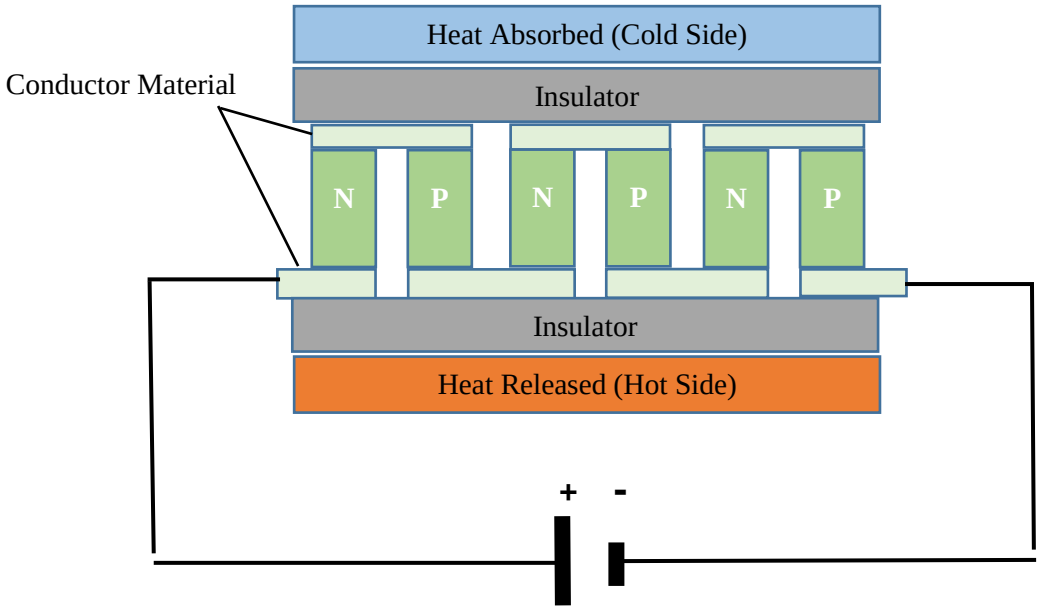


Figure 3: Single stage TEM/peltier device

II. Multi stage TEM/peltier device

If the desired differential temperature is not achieved by a single stage device, a multi stage peltier device is used. As evident from the name, these modules have multiple stages of TEM stacked in an array. Figure 4 shows a typical three stage peltier device. These devices are constructed in a pyramid shape because the lower stage must pump the heat dissipated by the upper stages. In addition there is an active heat load on the top stage [4].

Figure 4: Multi stage TEM/peltier device [6]

2.1.5. Application and advantages of thermoelectric modules:

Thermoelectric modules are used two major applications such as thermoelectric heating /cooling and energy generation as shown in Figure 5. Our focus is towards thermoelectric heating/cooling applications.

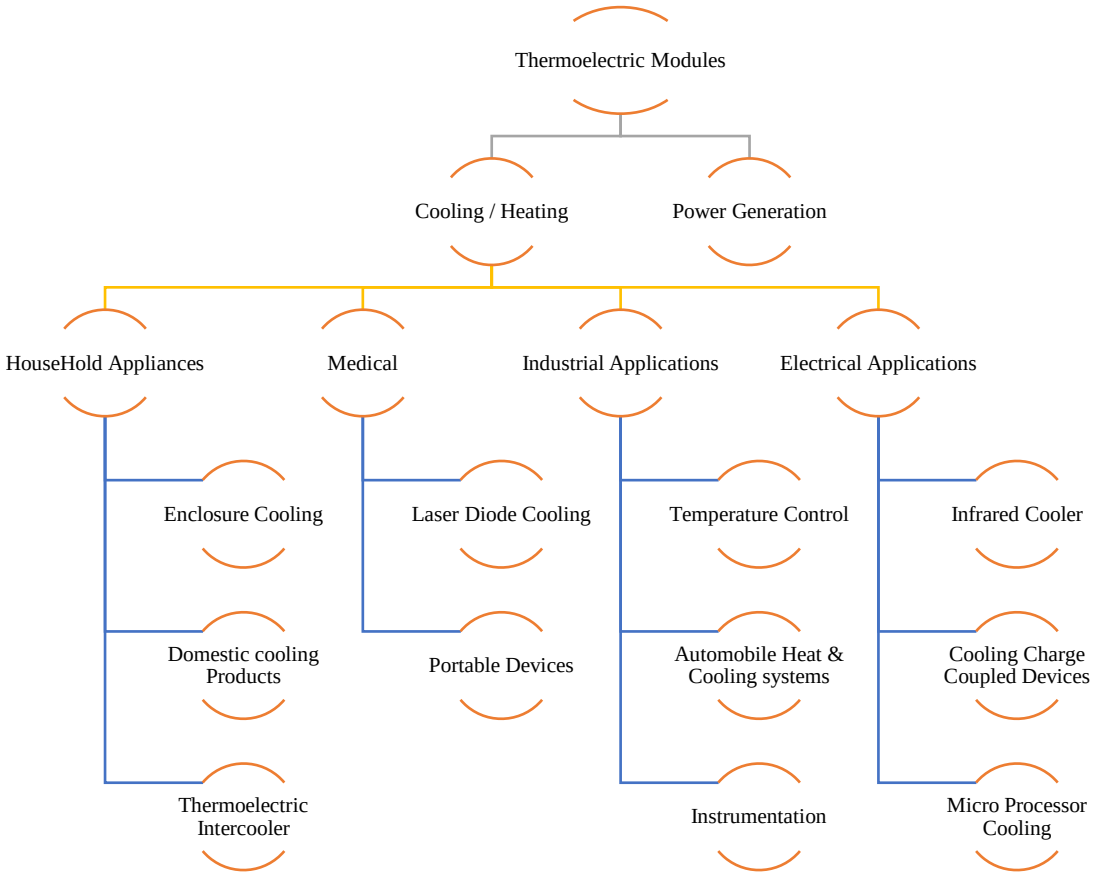


Figure 5: Application areas of TEM/ peltier device (adapted from [4, 7, 8])

Thermoelectric module are useful when there are following design parameters [8].

- Low cost
- Small size
- Less mounting space
- Compact design
- Less weight
- Safety
- Low power

However, the disadvantages of these devices are that they have low efficiency and are difficult to implement on a larger scale.

2.1.6. Mounting methods of peltier device

A peltier device is typically used with the heat sink. The heat sink can be installed on either sides depending upon the application. The general instructions for mounting the heat sink including some cautions are listed below [9].

1. Clean both surfaces of the peltier device with alcohol or similar chemicals.

2. Remove the dirt from the heat sink particularly from the fins.

3. Spread a thin layer of silicon grease (thermally conductive) on the contact surface.

4. Gently place the desired side of the peltier device onto the contact surface. Gently apply light pressure until the device adheres onto the heat sink surface. Ensure that no air gap remains between the contact surfaces.

5. If necessary, repeat the same procedure for the other surface of peltier device.

After the mounting, check for the device serviceability by measuring the resistance value.

2.2. Resistive Heating Elements

Resistive heating elements are the devices that operate on the principle of resistive heating also known as joule heating.

2.2.1. Joule heating

Current flowing through a conductor encounters resistance, and some electrical energy is transformed into thermal energy. This phenomena is known as *Joule heating*. The joule heating is caused due to the resistance of the element. Joule heating is also known as electrical heating or resistive heating. The amount of heat energy produced depends on the type of conductor.

2.2.2. Advantages and disadvantages of resistive heating elements

The advantages of electrical heating devices are discussed as follows.

a. Economical

The resistive heating devices are cheap and easy to fabricate. They also require less maintenance cost and can be easily produced on large industrial scale.

b. Ease of Operation and Control

The resistive heating elements have simple operating procedure. The design is not much complicated and can easily be automated and controlled.

c. Low Noise and Environment Friendly

The electrical mode of operation makes it emission free device. It has non movable parts hence it is noise free device.

d. Uniform Heating

These types of devices are ideal for uniform heating across the surface area. The heating elements are flexible to take any shape or angle.

e. Efficiency

The electrical resistance heating is quite efficient as compared to other modes of heating. Efficiency can be increased significantly with the careful selection of heating elements' type.

f. Cleanliness

Resistive heating devices are free of emissions and moving parts, so easy to clean, hence preferred to be used in medical equipment.

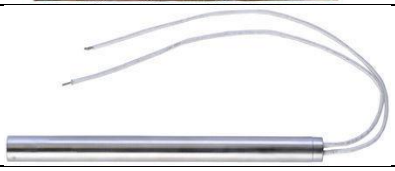
g. Disadvantages

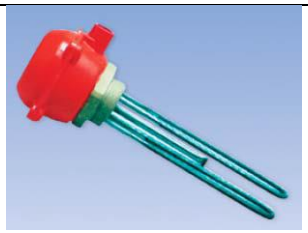
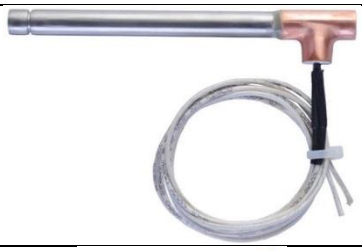
There are few drawbacks of the electrical heating devices. The high cost of electricity can make the operational cost more expensive as compared to other modes of heating. In case of short circuit, the electrical heating device can catch fire and cause a hazard.

2.2.3. Applications of resistive heating elements:

There is a wide range of applications of resistive heating devices on an industrial scale. Heat is required in our daily living which makes the application area even wider. The resistance heating devices are available in different types depending upon the specific application areas. These devices are generally used in automation, process and biomedical industry including a large variety of home appliances. The different types of resistive heating devices are discussed in the Table 1.

Table 1: Resistive heating devices and its Application (source [10])

Description	**Temperature Limit / Power**	**Application Area**	**Figure**
Mica heating pads	160°C	Heating dies, platens, molds, tanks, process machinery	
Quartz heating element	1kW	Multi-purpose process Heaters	
Enclosure heating element	240°C	Compact home, medical and industrial appliances	
Ceramic heating element	700°C	Wide range of industrial processes	
Heat tracing cable		Under floor heating	
Silicon drum heater	150°C	Pre heating and melting of process ingredients, viscosity control, ease of liquid flow, freeze protection, speed up chemical reactions	
Silicon rubber heater	250°C	Flexible heating	
Cartridge heaters	450°C	Localized heating in high vibration applications	

Tank heater	12KW	Hard water heating	
Air heater	500^{o}C	Drying, plastic welding, laminating, and heat sealing	
Nozzle heaters	350^{o}C	Heating cylindrical parts	

i. Mica heating pads

Mica heaters are best used on flat surfaces requiring heating where silicone or film heaters are not suitable for temperatures above 160°C.

ii. Quartz infrared heating pads

Quartz Infrared (IR) heating elements are enclosed in steel frame. They are suitable for medium wave infrared curing, heating and drying. The IR spectrum in which they operate is Medium wave infrared energy 1.5 to 5.6 microns. Heaters should be mounted with the quartz tubes in the horizontal plane. It is advisable that temperature monitoring and control unit should be used with such type of units [10].

iii. Enclosure heating element

The enclosure devices are based on positive temperature coefficient (PTC) elements. These type of heating elements are self-regulated. PTC heating elements are used as combined heating and temperature limiting device at the same time. They are housed inside a small alloy casing which allows efficient heat transmission to the thermal medium.

These elements are used as conduction/convection heaters and can be used where compactness and self-protection is required. These elements need small mounting space and are used for heating appliances in industrial/medical field including wide range of home appliances [10].

iv. Ceramic heating/infrared element

These heating elements are very energy efficient. Generally they convert 96% of the input power to heat and achieve maximum temperature of 700ºC. These heating elements provides longwave IR radiation. They have a working life of 5000 - 10,000 hours. Generally they are operated with monitoring and control units [10].

v. Heat tracing cables

The heat tracing cable provide high temperature. The temperature can be varied by choosing various cable layout options. The heat tracing cables are available in thin and flexible design which makes it easy to be used under the floor of small or complicated rooms [10].

vi. Silicone drum heater

The Silicon Drum Heaters are mostly used in process industry. Their design is simple and can be integrated easily. The heating element inside the silicone drum heater is a multi-strand nickel chromium. Generally, the heating element is insulated with fiberglass yarn. The fiberglass yarn is constructed in the shape of a tape. The fiberglass that is soaked with silicon is coated with these tapes to form several layers.

The silicon drum heaters has several advantages for instance it is easy to install and flexible enough to be wrapped around the structure. It is very useful for the improvement of the flow of highly viscous fluids [10].

vii. Silicone rubber heater

Silicon rubber heater mats are used to fulfil the heat requirement up to 250°C. They are reliable and robust heaters. They can be used in the applications that are exposed to vibrations. If they are used optimally, there life can exceed 10 years under various operating conditions. Theses heaters can be used over different types of surfaces. It is recommended to use them with temperature control units [10].

viii. Cartridge heater

Theses heaters are enclosed and cartridge shaped. They are used to achieve temperature up to 450ºC. They are constructed from Nickel-chromium resistance wire. These heaters are generally moisture resistant and they include fiberglass lead wire insulation. Cartridge heaters are suitable for localized heating requirement and also for the applications subject to high vibration [10].

ix. Tank heater

These heaters are constructed from Industrial graded Incoloy (nickel-iron-chromium alloy). They are generally immersed inside the liquid for heating purpose. They are equipped with thermostat for temperature control [10].

x. Air heater

Air heaters have an open coil with high temperature resistance wire. The air directly passes over the resistance wire for maximum heat transfer. The maximum temperature of approximately 500^{o}C can be produce in such type of heaters [10].

xi. Nozzle heaters

These heaters are sealed and shielded clamps for heating cylindrical parts. The application area is heating the cylindrical parts for instance press nozzles for injecting thermoplastic materials. They can provide maximum surface temperature up to 350^{o}C depending upon the working conditions [10].

2.3. Resistive Temperature Detector (RTD)

The resistive temperature detector (RTD's) are also known as resistance thermometers. The resistance thermometers are made from a pure metal. The electrical resistance of every metal is a function of temperature. Hence there is a typical response of the electrical resistance vs temperature for each metal. This response cannot be necessarily linear which is generally desired. RTD's are made of nickel, copper and mostly platinum, which has a stable linear response. The comparison of temperature vs electrical resistance for platinum, nickel and copper is given in the Figure 6.

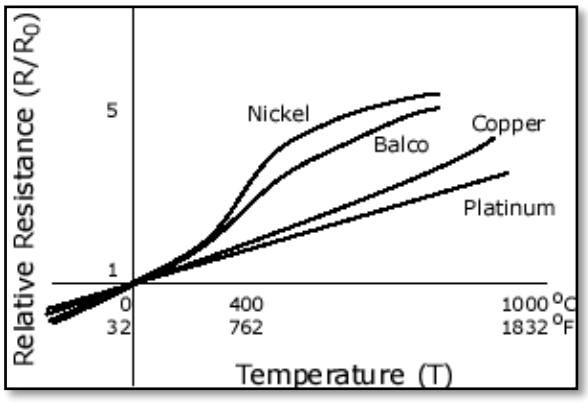


Figure 6: Temperature vs electrical resistance for platinum and other metals [11]

The relationship between the temperature and electrical resistance curve is shown in Figure 6. It gives us valid information about the temperature when the resistance of the metal is measured. The construction of a RTD is shown in Figure 7.

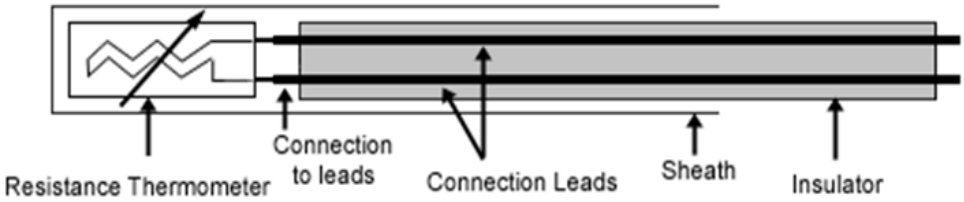


Figure 7: Typical construction of RTD [12]

The RTD is usually constructed using platinum winding on a ceramic or glass substrate. The windings are connected to the connection leads inside an insulator. The connection leads inside the insulator are encapsulated in a sheath. There are alternative configurations of RTD for instance a thin layer of metal inside multiple insulating layers (thin film RTD). The RTDs measure temperature based on change in the resistance of the metal windings with the change in temperature conditions. The thermal properties of the metal windings define the accuracy of the temperature being measured with an RTD. With the knowledge of the thermal properties of the metallic windings it is possible to predict the temperature at a measured resistance. The RTDs are active sensors and they require excitation from the outside source to produce a voltage drop across the wire. The wire resistance can be calculated from the voltage drop which corresponds to a specific temperature [12].

There are several types of RTDs commercially available which have the following attributes.

Attributes of RTD's

a. Wire material

The wire material of the RTD is selected according to the measuring temperature range and the environment in which the sensor is to be installed.

b. Physical construction

The physical construction of the RTD depends on the application. Generally it depends on the mounting requirements of the RTD, how much electrical isolation is required and the type of the medium in which the sensor is to be attached or immersed (liquid). Few of the examples of the RTD construction are given in Figure 8. These examples shows the different configuration of the metal windings on a substrate.

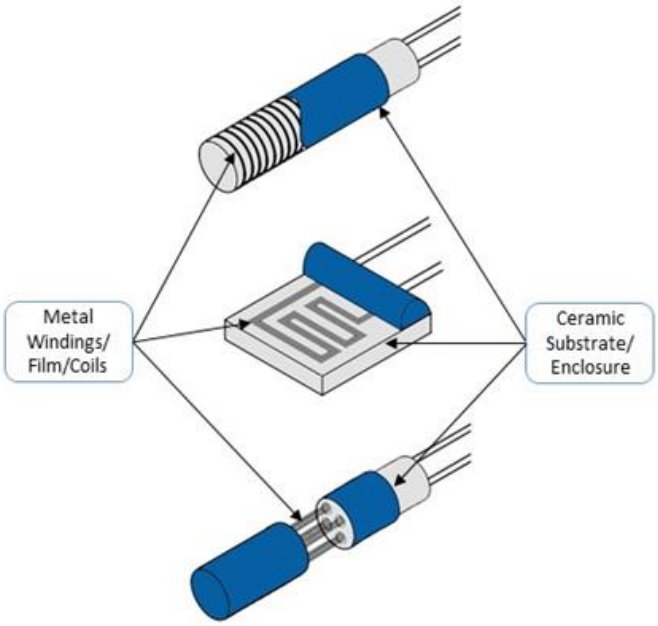


Figure 8: RTD various constructions [12]

c. Number of Lead Wires

Most of RTD instruments used Wheatstone bridge circuit for measurement purpose. Bridge contains RTD at one arm and other remaining three arms connected with standard resistances. Bridge is generally a resistance measuring device which converts the resistance of RTD into electrical signal.

Two wire configuration

In a two-wire RTD configuration, the excitation current is given and the voltage measurement is done from the same two leads. The temperature measurement accuracy can be affected if the resistance of the lead wires is significant enough relative to the measured resistance of the RTD element [12].

Three wire configuration

In a three wire configuration, characterization and correction for lead-wire resistance can be done by the hardware. This allows more accurate measurement. However, there is possibility of inaccurate measurement due to inconsistencies in the lead-wire resistance [12].

Four wire configuration

In this configuration of RTD, there is a separate path of excitation and resistance measurement. The advantage in this configuration is the correction of lead-wire resistance and isolation of noise inside the excitation source [12].

2.4. PID Control System

Control System: A control system is a system which controls the output to achieve a desired response. A simple control system is shown in the Figure 9. The output of the control system is controlled by varying the input.

Figure 9: A control system

The single block shown in Figure 9 represents a control system that can be further elaborated. There are two major types of control system based on the feedback mechanism namely

- Open Loop System
- Closed Loop System

Before describing the open and close loop system, it is important to know the key terminologies as shown in the Table 2.

Table 2: Key terminologies of a control system

Terminology	Description
Process Variable	The value obtained from the sensor in a feedback system
Set Point	The desired value of the control system set by the user
Actuator Output	The final output of the control system
Error	Difference between the set point and the process variable
P Gain	Proportional gain aims to minimize the error
I Gain	Integral gain aims to minimize the steady state error
D Gain	Derivative gain aims to resist the sudden change in the control system
Rise Time	The time taken by the control system to respond the change
Settling Time	The time after which the actuator output stabilizes
Steady State Error	The difference between the process variable and set point after the settling time

Overshoot	The maximum output amplitude of the control system as compared to the set point.
Tuning	The method to adjust the P,I and D gains to optimize the control system response

Open Loop System: In the open loop system the output is not given back to the input. The control system is independent of the output of the system (Figure 10).

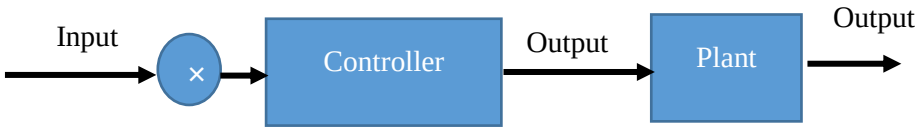


Figure 10: Open loop system

Closed Loop System: In the closed loop system the output is given back to the input. The closed loop control system is dependent of the output of the system (Figure 11).

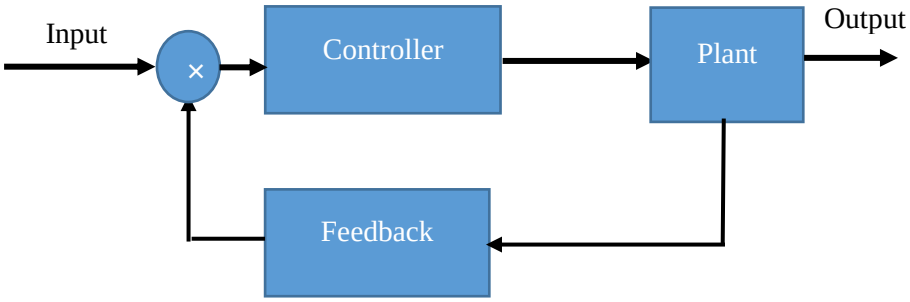


Figure 11: Closed loop system

2.5. Data Acquisition (DAQ)

Data acquisition (DAQ) is a process through which a physical phenomenon (mechanical or electrical) is measured using a computer. The measurement could be current, voltage, temperature, sound, pressure etc. There are three main components of a DAQ system [13].

a) Sensor
b) DAQ Device
c) Computer with programmable software

The components of the DAQ system is shown in Figure 12.

A signal produced by the sensor is acquired by the DAQ device. DAQ device acts as an interface between the computer and the incoming signals from the sensors. The role of the DAQ device is to digitize the signals such that computer can interpret them. The DAQ devices generally have the following components [13].

- Analog to digital converter
- Digital input/output (I/O) channels
- Analog I/O channels
- Counter/timers to count and generate digital pulses

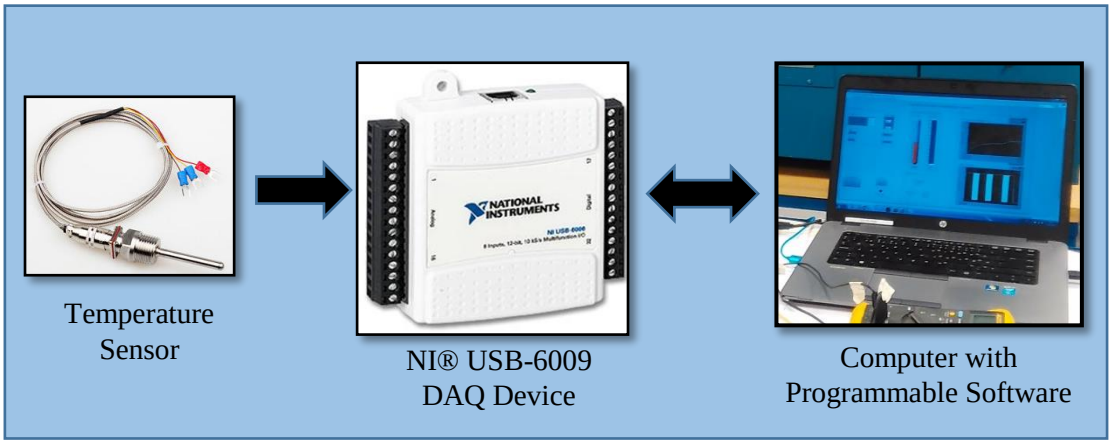


Figure 12: Components of a DAQ system

A computer with programmable software is used to control the operation of DAQ device. A DAQ system and computer are used for the following purposes

- Processing data
- Visualising Data
- Storing data

The DAQ systems are frequently used in the industrial applications for process measurement and control. A measurement and control DAQ system have the following advantages from the traditional systems [13].

- Computer provides the computational power to the DAQ system
- Interactive user interface and easy to monitor
- Provides flexibility to the system e.g. can add more sensors or DAQ devices
- Cost effective measurement solution

2.6. Infrared Thermography (IRT)

The Infrared thermography (IRT) is used to observe the thermal images produce as a result of infrared radiation emitted from the object. It is known that an object at a temperature above absolute zero (−273°C) emits electromagnetic radiation. These electromagnetic radiations fall into the specific electromagnetic spectrum known as Infra-red band. The wavelength of IR band ranges from 1 to 1000 μm [14]. The IR band is subdivided into narrow wave IR (NWIR), medium wave IR (MWIR), long wave IR (LWIR), and very long wave IR (VLWIR).

2.6.1. Physics of infrared thermography

To understand the physics of IR thermography, the following fundamental terms must be understood.

a. Kirchoff's law of conservation of energy

When the light is incident on an object, the energy will be dissipated in three ways. The energy will be absorbed, reflected and radiated by the object. According to the law of conservation of energy, this phenomena can be written as

$$\alpha + \rho + \tau = 1 \qquad (9)$$

where

$\alpha =$ coefficient of energy absorbed
$\rho =$ coefficient of energy reflected
$\tau =$ coefficient of energy transmitted

In most of the cases, the energy absorption is minimal. Generally, the material having good emittance are poor reflectors and vice versa.

b. Emittance/emissivity

A material with perfect emittance is a black body which has the emissivity ε = 1. However this is an ideal case whereas, in real the emittance is always less than 1. For instance the emissivity of human skin is 0.98. It can also be said that a good emitter is a good absorber of energy.

The emissivity ε (dimensionless) is defined as the ratio between the radiant flux exiting true radiating body M_r (W/m^2) and an ideal blackbody M_b (W/m^2) at the same temperature. The emittance phenomena is shown in the Figure 13.

$$\varepsilon = {}^{M_r}/_{M_b} \qquad (10)$$

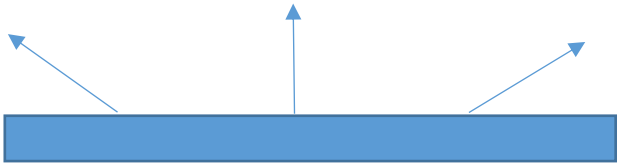


Figure 13: Emittance

c. Reflectance

The reflectance is the capability of the object to reflect light (Figure 14). For instance, first surface mirror is a good reflector.

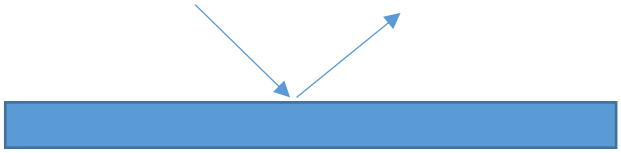


Figure 14: Reflectance

d. Heat and modes of transfer

The heat is a form of energy created from the molecular motion of the body. The molecular motion is the kinetic energy of the body and heat is total kinetic energy of the body. The heat energy is transferred from one medium to another by three different modes namely Conduction, Convection and Radiation. The conduction is heat transfer by molecular motion inside the material where the material property is not changed. The convection is heat transfer by the motion of fluid (air mass or liquid). The radiation is the transfer of energy by electromagnetic radiations.

e. Temperature

Temperature is defined as the degree of hotness and coldness of an object. It is the measure of the thermal energy present inside an object.

2.6.2. Infrared camera working principle

IR camera works on the basis of thermographic imaging. The main components of the IR camera include a lens, detector, video processing electronics and user interface control, as shown in Figure 15.

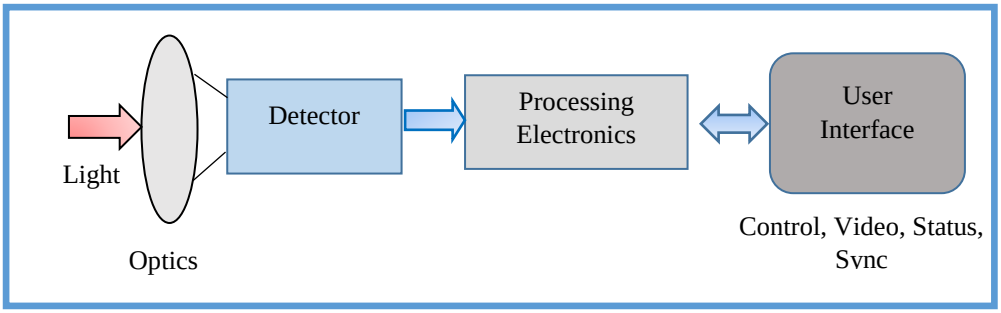


Figure 15: IR camera working principle [15]

The rays emitted from the target object falls on the IR camera lens. The lens focus the infrared rays on the detector element by means of a lens. The IR detectors used can be divided into two classes' namely thermal detectors and quantum detectors. The thermal detectors are sensitive to the incident energy flux. The commonly used thermal detector is the uncooled micro-bolometer which is constructed from a metal compound or semiconductor material. On the other hand sensitivity of quantum detectors depends on the photon absorption. The quantum detectors are constructed from the materials such as InSb, HgCdTe (MCT), and layered gallium arsenide/Aluminum gallium arsenide (GaAs/AlGaAs) for *quantum well infrared photon* (QWIP) detector. These detectors require strong cooling for the correct operation [16].

The detector comprises of the IR sensitive elements that are arranged in an array called the focal plane array (FPA). These array elements are miniature sized (µm) IR sensitive elements. The number of elements present inside an array determines the resolution of the IR imagery of the camera. The processing electronics translate the detector signals into infrared imagery. The processing electronics are responsible for controlling the parameters of the captured imagery. The user interface of the IR camera sends the instructions to the processing electronics. The commercially available IR cameras usually include the user interface software to compute the parameters such as scene temperature, calibration, external trigger input and imagery recording. The IR cameras require calibration to read out the correct temperature across of the target objects [15].

2.6.3. IRT application area

Figure 16 shows some of the main area where infrared thermography can be applied. It can be observed that IR thermography has a wide application potential.

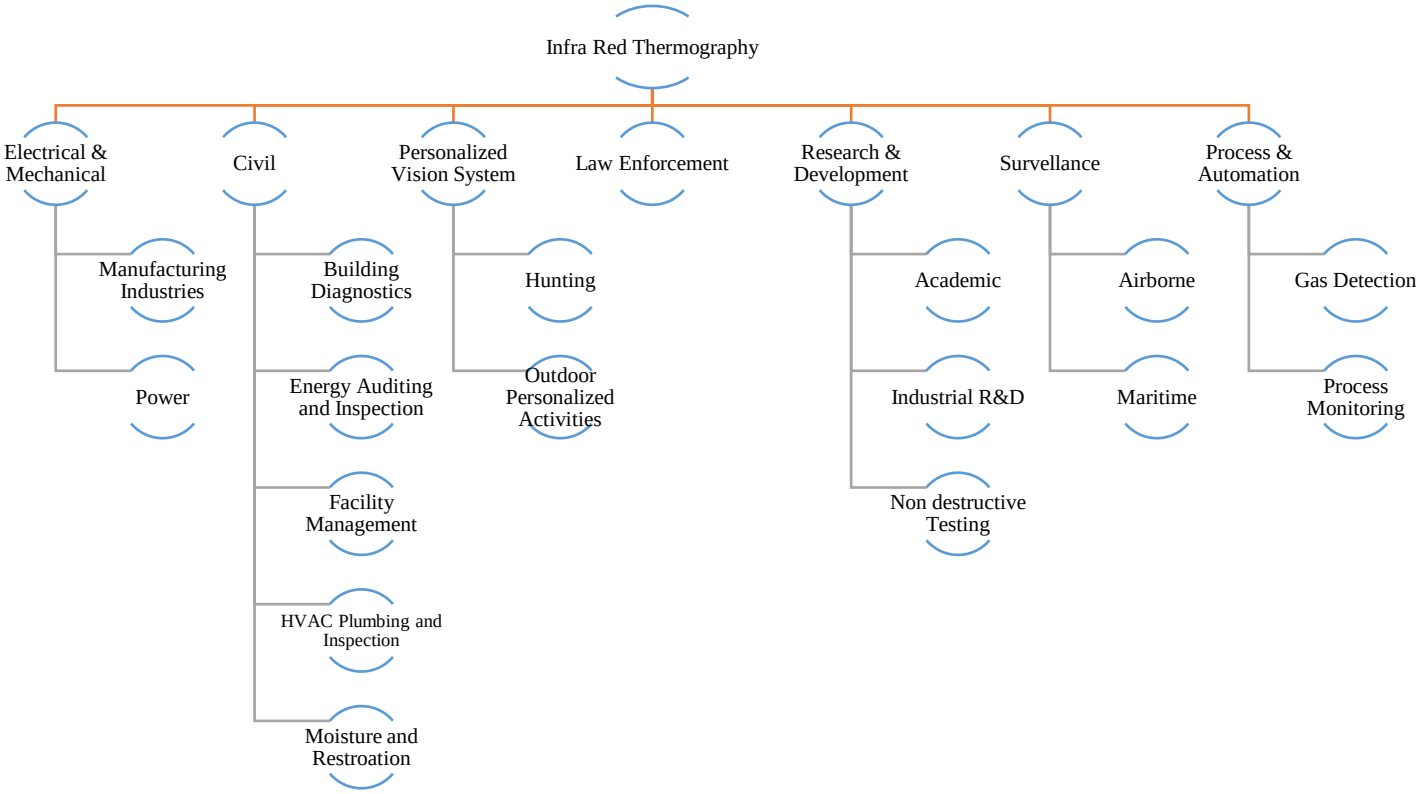


Figure 16: Infrared thermography (IRT) application area

2.7. Simulation of PTC Heater

2.7.1. PTC thermistor

The type of PTC thermistor model used in the MATLAB® Simscape® is a switching type thermistor. The resistance decreases with the rise in temperature until Curie temperature (T_c) or Curie point is reached. Curie temperature is the temperature above which certain materials lose their permanent magnetic properties. If the temperature of the PTC thermistor rises beyond Curie temperature, the resistance increases rapidly on the logarithmic scale. This is region on the right side of T_c as shown in the Figure 17.

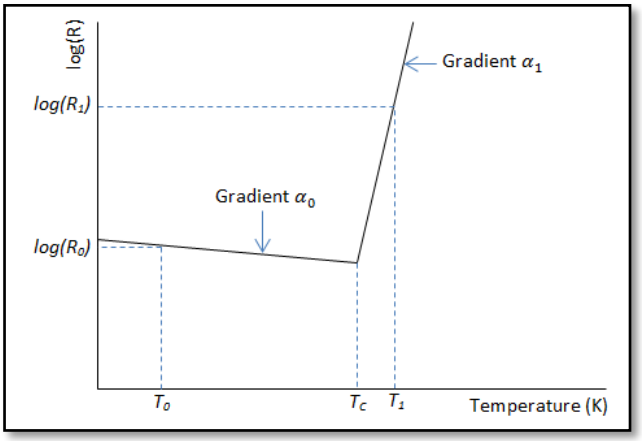


Figure 17: Resistance vs temperature plot of PTC thermistor [17]

The PTC thermistor model has two behaviours i.e. an electrical and thermal behaviour.

a. Electrical Behaviour

For a switching type PTC thermistor, the resistance R at temperature T is given by

$$R = \begin{cases} R_0 e^{\alpha_0 (T - T_0)} & at\ T < T_c \\ R_0 e^{\alpha_0 (T - T_1)} & at\ T \geq T_c \end{cases} \qquad (11)$$

T_c can be defined as

$$T_c = \frac{\log(R_1) - \log(R_0) + \alpha_0 T_0 - \alpha_1 T_1}{\alpha_0 - \alpha_1} \qquad (12)$$

where:

T_c is the Curie temperature (K)

R_0 is the resistance at nominal temperature T_0 (K)

R_1 is the resistance at reference temperature T_1 (Ω)

T_0 is the nominal temperature at which the resistance is quoted, usually room temperature (K)

Note: T_0 is less than the Curie temperature T_c

T_1 is the reference temperature (K), equal or greater than the Curie temperature T_c, it implies that at T_1 the PTC regime is in force

α_0 is the temperature coefficient at nominal temperature T_0

α_1 is the temperature coefficient at reference temperature T_1

b. Thermal Behaviour

The following equation describes the thermal behaviour of the PTC thermistor block.

$$Q = K_d t_c \frac{dT}{dt} \qquad (13)$$

where:

Q is the input net heat flow
K_d is the dissipation factor
t_c is the thermal time constant ()
$\frac{dT}{dt}$ is the rate of change of the temperature (K/sec)

2.7.2. Conductive heat transfer

The conductive heat transfer block in MATLAB® Simulink work on physical principle of heat transfer by conduction between two layers. The conductive heat transfer can be shown by Fourier law described in the equation as follows.

$$Q = k.\frac{A}{D}.(T_A - T_B) \qquad (14)$$

where

Q is the conductive heat flow
k is the thermal conductivity of material
A is the area normal to the heat flow direction
D is the distance between layers
T_A, T_B temperatures of the layers A and B

2.7.3. Convection heat transfer

The convection heat transfer block in MATLAB® Simulink is based on heat transfer by convection between two bodies by means of fluid motion. The convective heat transfer is governed by the Newton law of cooling. It is described in the following equation.

$$Q = h.A.(T_A - T_B) \qquad (15)$$

where,

Q is the convective heat flow
h is the convective heat transfer coefficient
A is the surface area
T_A, T_B is the temperatures of the bodies A and B

2.7.4. Radiative heat transfer

The radiative heat transfer block in MATLAB® Simulink represents a heat transfer by radiation between two bodies. The transfer is governed by the Stefan-Boltzmann law. It can be described from the following equation:

$$Q = k.A.(T_A{}^4 - T_B{}^4) \qquad (16)$$

where,

Q is the radiative heat flow
k is the radiative heat transfer coefficient
A is the surface area of emitting body
T_A, T_B is the temperatures of the bodies A and B

2.7.5. Thermal mass

The Thermal Mass block represents a thermal mass, which reflects the ability of a material or a combination of materials to store internal energy. The property is characterized by mass of the material and its specific heat. The thermal mass is described with the following equation:

$$Q = c.m.\frac{dT}{dt} \qquad (17)$$

Q is the heat flow
c is the specific heat of mass material
m is the surface area
T is the temperature
t is the time

Chapter 3

3. Method

The aim of this study is to analyse the thermal behaviour of a resistive heating device and peltier device in room and cold environmental conditions. In addition, measurement and control of a resistive heating device is implemented. The methodology of this study can be described in a simple block diagram shown below (Figure 18).

In order to measure and control the resistive heating device, a temperature measurement and control system (TMCS) was built. The TMCS was used in a series of experiments under different environmental conditions.

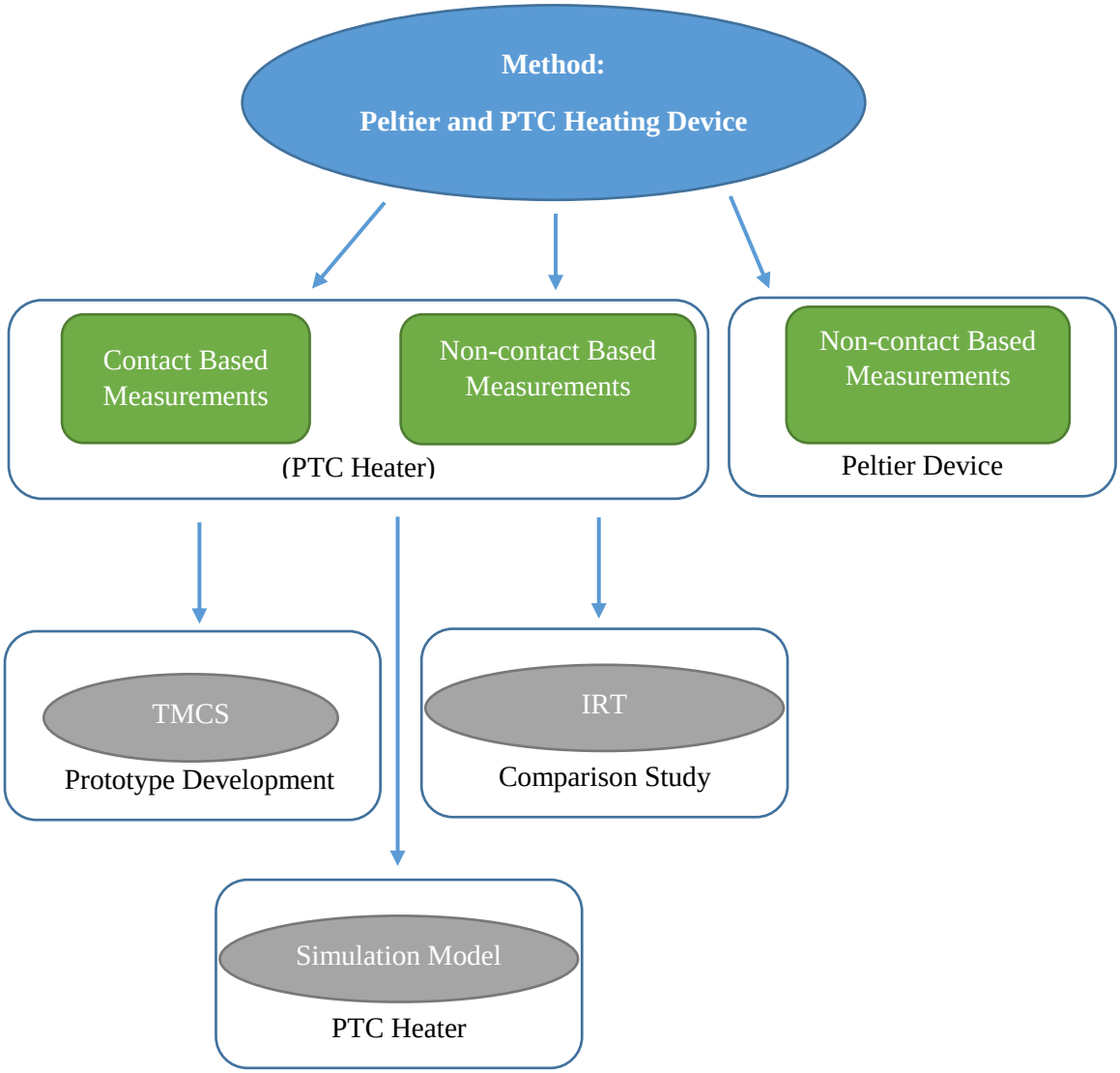


Figure 18: Methodology of the study

A PTC resistive heating device namely *DBK HP 05* is used for experimentation. Thermal response of this device is measured and then compared using two different methods. One is a contact based measurement/sensing method. A resistive temperature detector (RTD) namely pt100 is used for the contact based method. It is important to note that TMCS is built based on contact measurement method. TMCS uses feedback from pt100 to perform temperature measurement and control of resistive heating device. TMCS is described in detail in the following Section 3.1. The other sensing method is a non-contact method via infrared thermography. I have used FLIR® T1030Sc (high-definition) IR camera for this method. IR thermography is used for comparison purpose in our study. These two measurement/sensing methods are tested at room conditions (24^{o}C) as well as inside a controlled cold environment at -10^{o}C.

The experiments performed in this study consist of four major setup components as shown in Figure 19.

Figure 19: Setup components of experimental work

The temperature measurement and control system (TMCS) was designed and built in this thesis work. The cold environment chamber and FLIR® T1030Sc camera are commercial off the shelf setup components.

The scope of this work generated the tasks that can be summarized as follows.

- Mounting platform for peltier device

- Designing a customized temperature measurement and control system (TMCS) for resistive heating device
    - Prototyping of TMCS
        - Hardware
        - Software Interface
- Preparing the experimentation setup with the setup components
    - Peltier device
    - TMCS with resistive device
    - Infrared camera (FLIR® T1030Sc)
    - Cold environment chamber
- Performing a series of experiments using IRT to measure and analyse surface temperature of peltier device at
    - Room conditions
    - Cold environment conditions (-10^{o}C)
- Performing a series of experiments to measure surface temperature of resistive heating device at
    - Room conditions
    - Cold environment conditions (-10^{o}C)
    - Analysing the surface temperatures acquired from two different sensors i.e.
        - Resistive temperature detector (RTD)
        - FLIR® IR camera (T1030Sc)
- Developing simulation model of resistive heating device using MATLAB® Simulink®

3.1. Peltier Device Assembly

The peltier device is mostly used in cooling applications but it can also be used for heating purposes by using the hot side of the peltier device *TEC-12706*. The main specifications are listed in Table 3.

Table 3: TEC12706 Specifications

Specifications	**Unit**
Max Operating Temperature	138^{o}C
Power	50 Watts
Delta Temperature (Max)	75^{o}C approx.
V_{max}	16.4V
I_{max}	6A
Module Resistance	2.3Ω

For cooling applications, the peltier device is recommended to be used with the heat sink and fan to transfer the heat away from the hotter side, otherwise beyond a certain threshold level, both sides of the peltier device will be extremely heated causing the malfunctioning of the device.

In our work, we want to observe the heating capability of peltier device. We will keep the hot side up for the IR thermography. The heat sink on the hotter side is not attached since we need to monitor the surface temperature distribution. However the colder side of the peltier device is attached with a heat sink. This is done to maintain the temperature difference between the two sides of the peltier device. Figure 20 explains the assembly of the peltier device ready for IR observation.

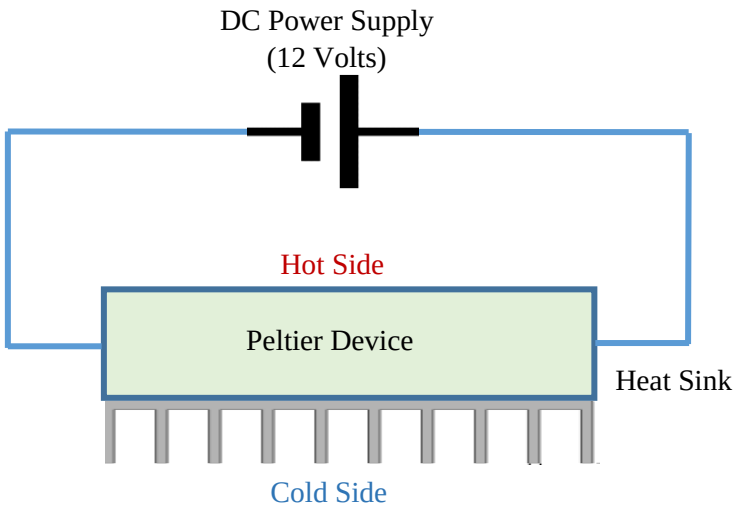


Figure 20: Peltier device assembly as a heating element

3.2. Temperature Measurement and Control System (TMCS) for PTC heater

A temperature measurement and control system (TMCS) was built to measure the thermal response of resistive heating device. TMCS assists to regulate the temperature of the resistive heater inside room and cold environmental conditions. Figure 21 shows the breakdown structure of the temperature measurement and control system (TMCS). TMCS comprises of two major components i.e. a hardware and a software interface. The hardware of TMCS is described in Section 3.2.1. The hardware includes the temperature control hardware, National instruments® data acquisition (DAQ) module (NI Mydaq), power unit and a heating device assembly. The subdivision of the hardware modules is also given in Figure 21.

The heating device assembly consists of the PTC resistive assembly and pt100 sensor (i.e. a resistive temperature detector- RTD). The power unit comprises of a constant current generator and a main power supply.

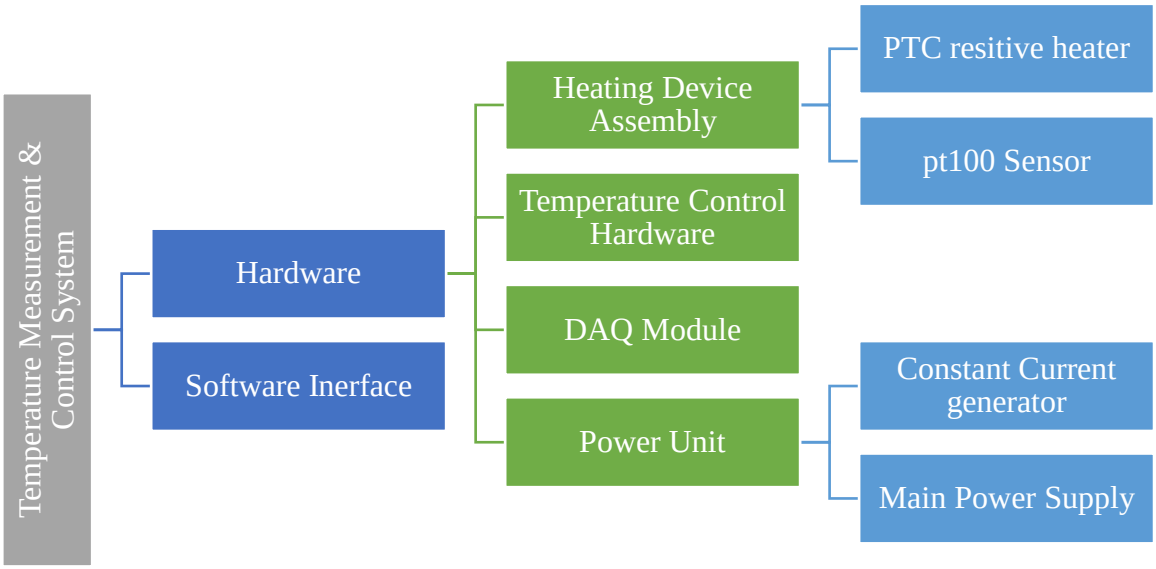


Figure 21: Breakdown structure of temperature measurement and control system (TMCS)

3.2.1. Hardware

The TMCS hardware consists of the following components

- Heating device Assembly
  - PTC heater (DBK HP 05)
  - pt100 sensor- a resistive temperature detector (RTD)
- Temperature control hardware (custom built)
- Data acquisition module
- Power unit
  - Constant current generator
  - Power supply

3.2.1.1. Heating device assembly

The heating device assembly of resistive device consists of a miniature sized and compact PTC heater. The major specifications of the resistive heater (DBK HP 05) are given in Table 4.

Table 4: DBK HP 05 specifications

Specification	Unit
Input Voltage	12-24VDC
Power Output	50 Watts
Max Output Temperature	100^{o}C

The resistive heater (DBK HP 05) was fixed on a wooden block. Top surface of the resistive element is kept exposed for IR thermographic measurements. The pt100 sensor is glued inside the resistive heater with a thermal conducting glue. The pt100 sensor is a typical resistive temperature detector. We have used a two wire pt100 sensor. The specification of a 2-wire pt100 sensor is shown in Table 5.

Table 5: 2-wire pt100 specifications

Specification	**Unit**
Excitation current	200 uA
Temperature measuring range	-50°C to 800°C
Resistance	18 to 390 Ω

A PTC heater with pt100 sensor makes the heating device assembly as shown in Figure 22.

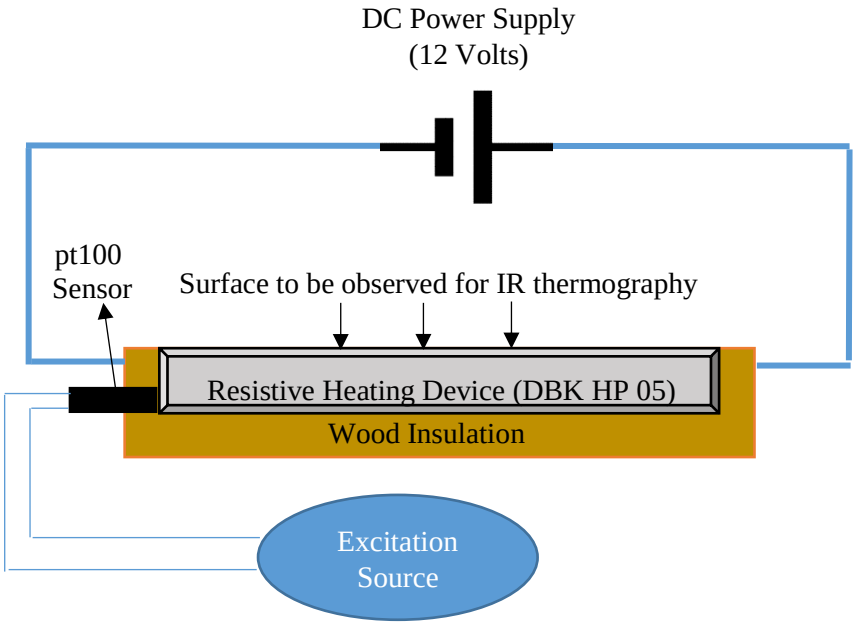


Figure 22: Heating device assembly

3.2.1.2. Temperature control hardware

Temperature control hardware is a printed circuit board (PCB) assembly with mechanical mountings. The breakdown of temperature control hardware is shown in Figure 23. Temperature control hardware performs the following tasks.

- Provide switching control for the resistive heater (DBK HP 05)
- Provides interconnection between the data acquisition module and pt100

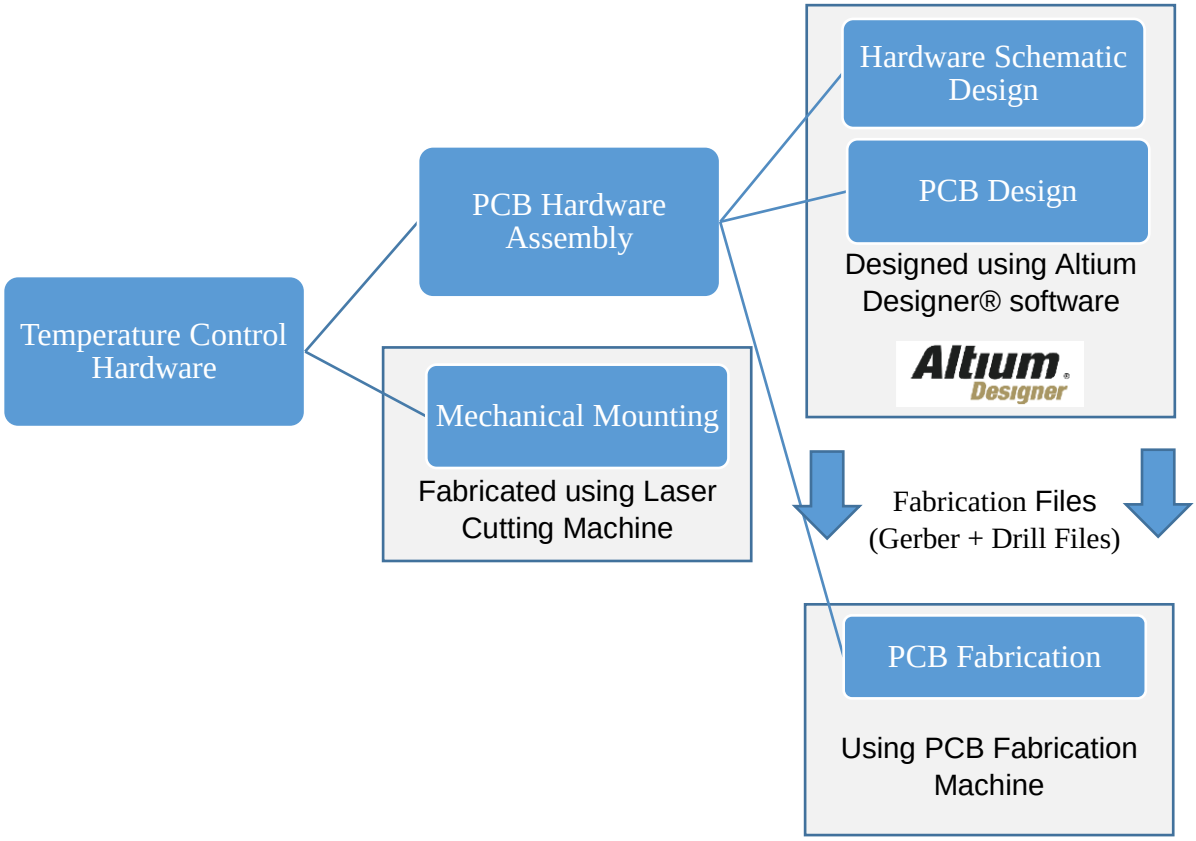


Figure 23: Breakdown: Temperature control hardware

The PCB hardware assembly of temperature control hardware was designed and fabricated using Altium® Designer software. The procedure to manufacture the PCB assembly is briefly described in the following steps.

Step-1: Designing the schematics file of the PCB assembly using Altium® Designer schematics environment. Designing includes

- Components selection using the existing library
- Component placement
- Designating the components
- Modifying component pads if necessary
- Wiring the components

The resulting schematic file of our temperature control hardware is shown in Figure 24.

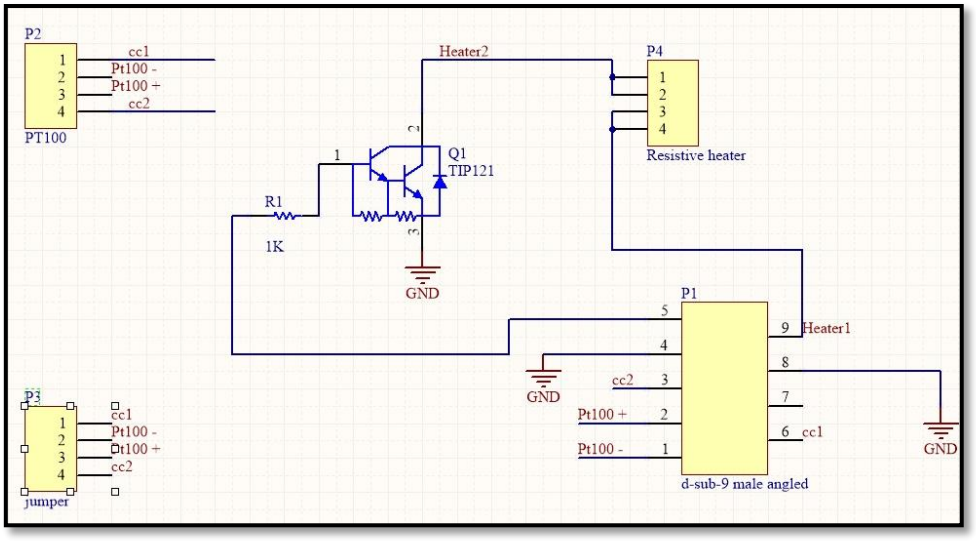


Figure 24: Schematic design of PCB Assembly

Step-2: Compile the schematic document by selecting ***Project → Compile Document.SchDoc*** in the main toolbar as shown in Figure 25. The message window will show the compile results.

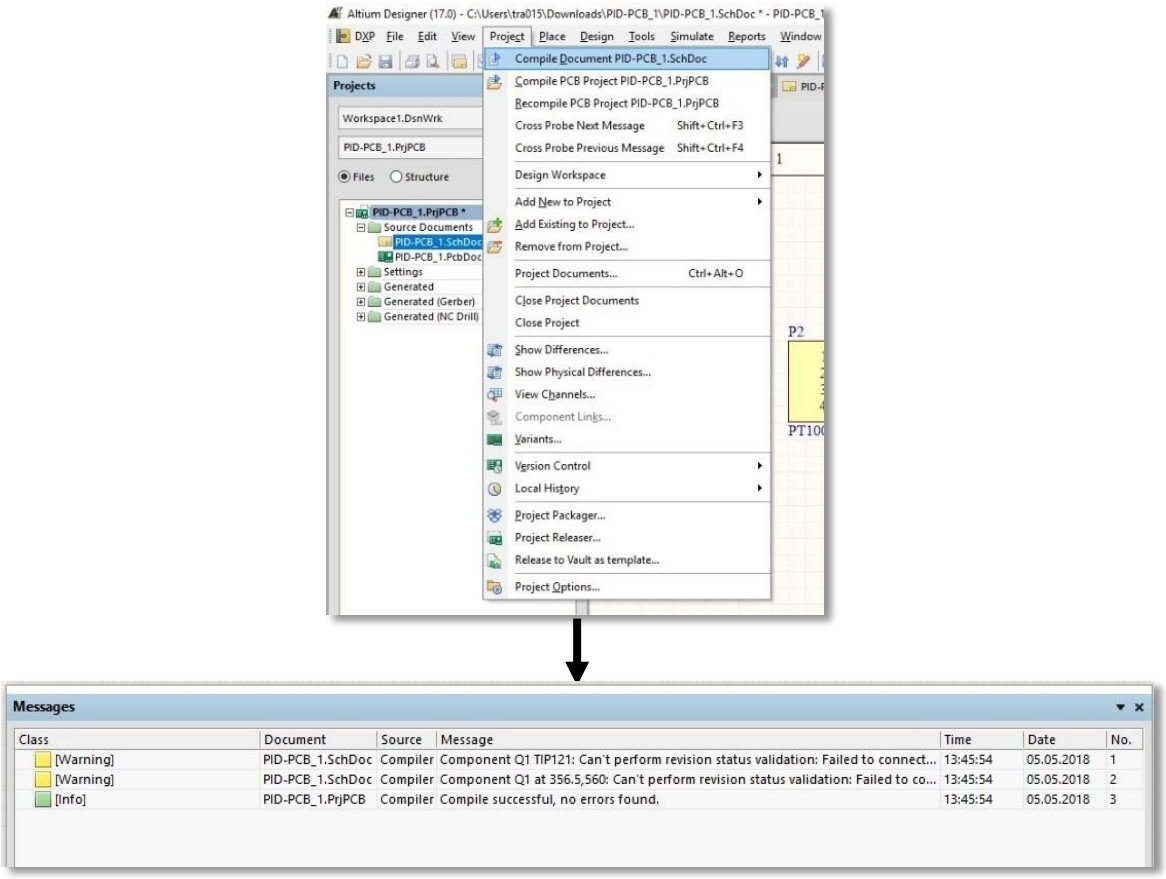


Figure 25: Compiling schematic file

Step-3: Transferring schematic file into the PCB file using Altium® transfer tool as shown in Figure 26.

Step-4: Designing the PCB file by performing the following tasks

- Defining the size of PCB (25mm x 35mm)
- Defining the boundary layer
- Placing the components
- Defining routing thickness and a ground layer (top layer)
- Perform routing on the bottom layer
- Run the design rules check for errors

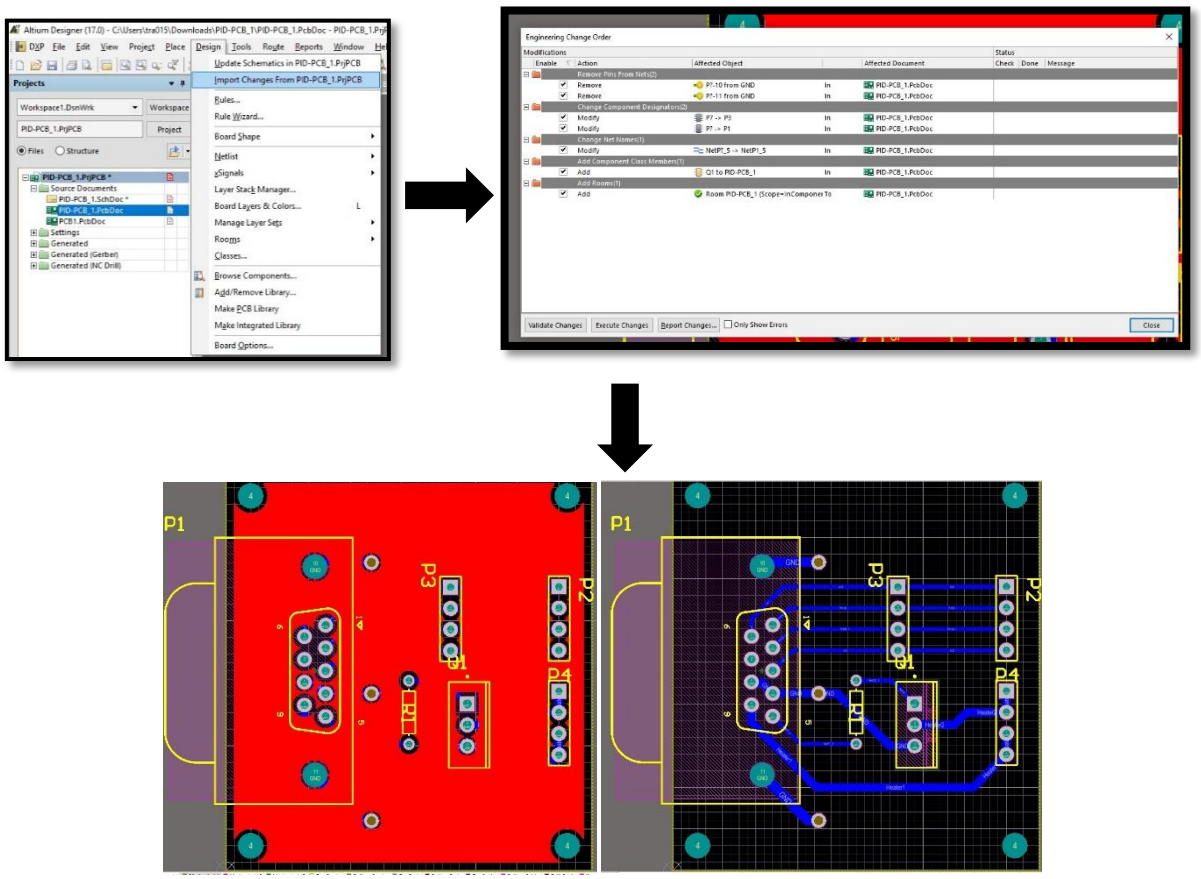


Figure 26: Transferring schematic file to a pcb file

Step-5: Generating the output files from PCB design file namely

- Gerber data files (*.gbl file)
  - Top layer
  - Bottom layer
  - Boundary layer

- Drill file (*.txt file)

Step-6: Transferring files mentioned in step-5 to the PCB manufacturing machine to make a two sided PCB.

Step-7: Soldering the components decided in step-1 on the PCB.

Step-8: Manufacture the insulating spacers using the laser cutting machine as shown in Figure 27.

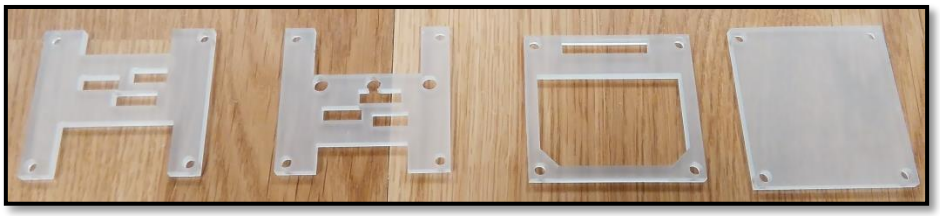


Figure 27: PCB insulating spacers manufactured using laser cutting machine

Step-9: Perform the connectivity checks on the PCB with soldered components.

Step-10: Assemble the PCB with insulating spacers to make Temperature Control Hardware as shown in Figure 28.

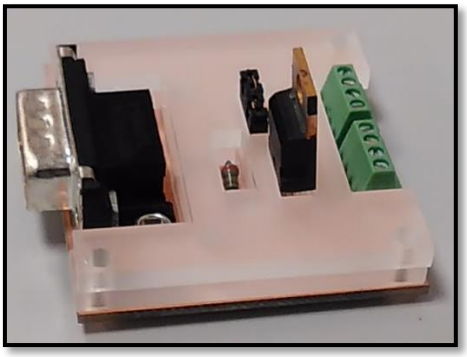


Figure 28: Temperature control hardware

3.2.1.3. Data acquisition (DAQ) module

The data acquisition module is used to performs two tasks

- Acquire the voltage output from pt100

- Drive the transistor inside the temperature control hardware to power On/Off the heating element (DBK HP 05)

NI® *MyDaq* module is used in TMCS hardware to perform the mentioned tasks. The connectivity of the MyDaq module inside the TMCS hardware is shown in the Figure 29.

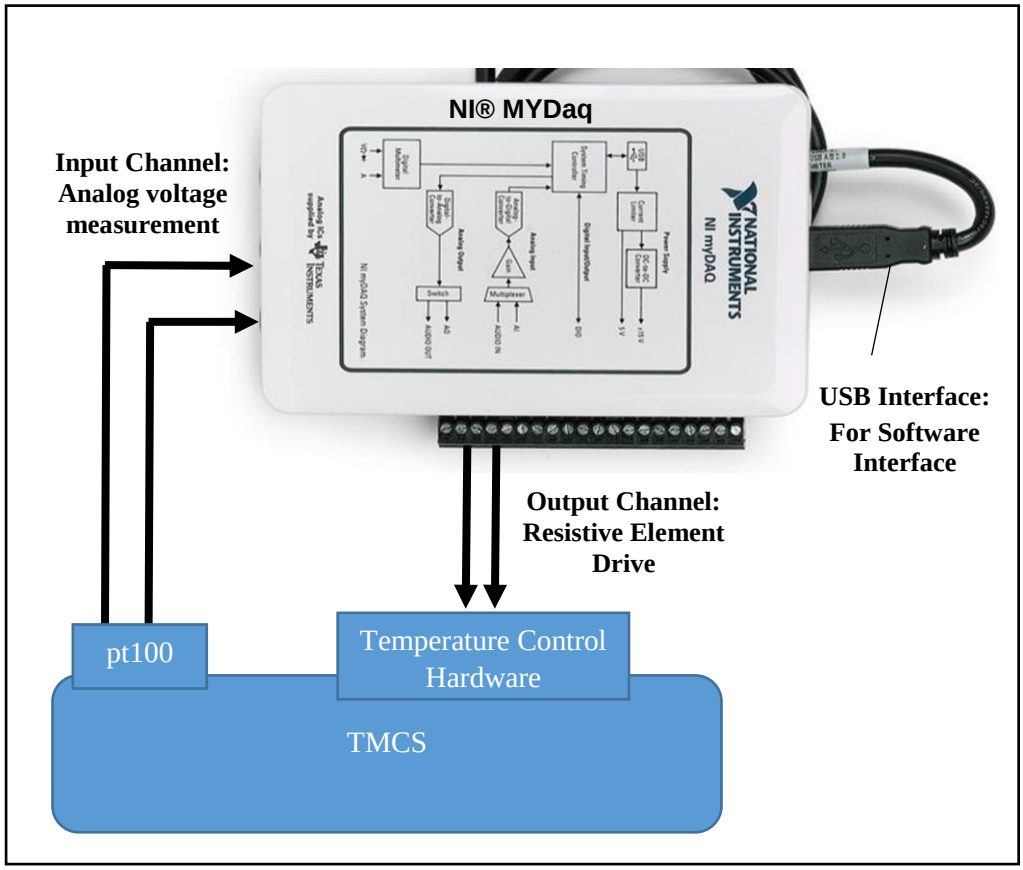


Figure 29: Connectivity of NI® MyDaq with TMCS

3.2.1.4. Power unit

The power unit of the hardware module is responsible for providing the power requirements to the TMCS. The power unit has two sub modules namely

- Power supply (DC) for resistive heater
- Constant current generator for the pt100

The variable DC power supply is used to power up the resistive heater. The constant current generator provides fixed 1mA of excitation current to the pt100 element. The constant current

generator is powered up by the power supply of the resistive heater. The connection diagram of power unit modules is shown in Figure 30.

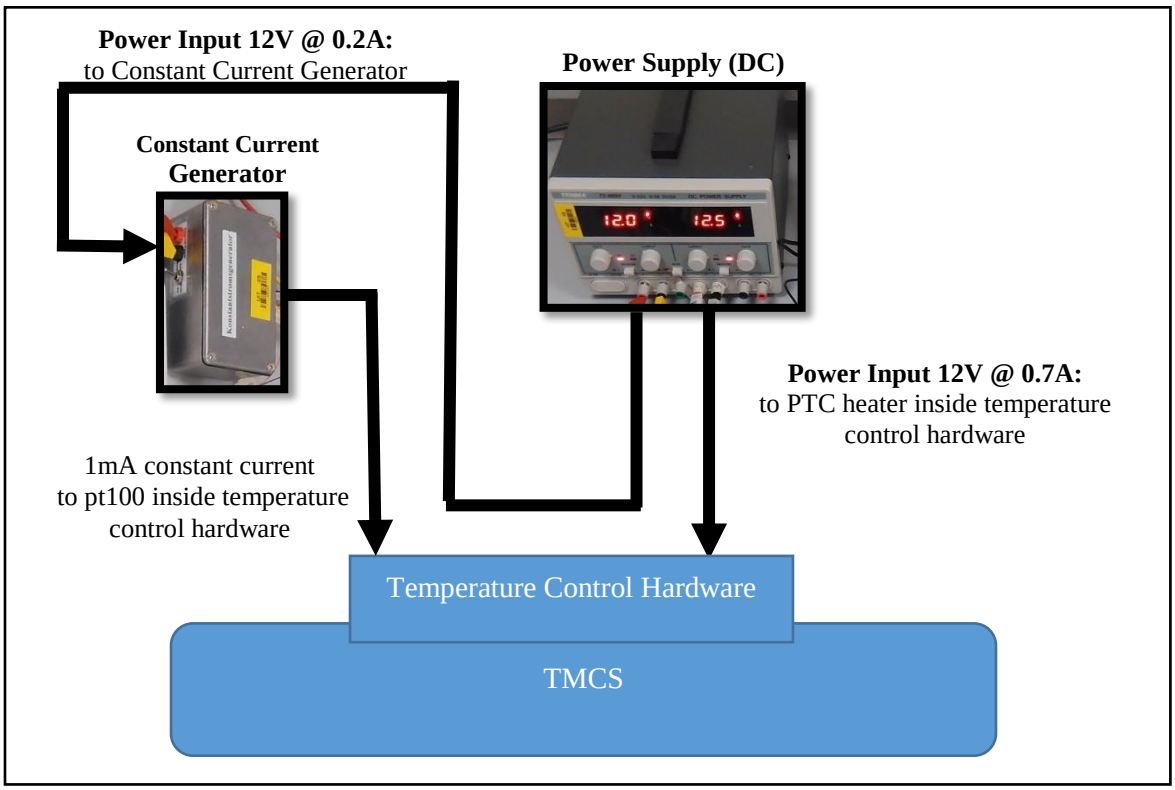


Figure 30: Connectivity of power unit modules

3.2.2. Software interface

The software interface of the TMCS is a user interface to monitor and control the temperature of resistive element (DBK HP 05). Figure 31 shows the screenshot of this software interface and its elements are marked with numbers.

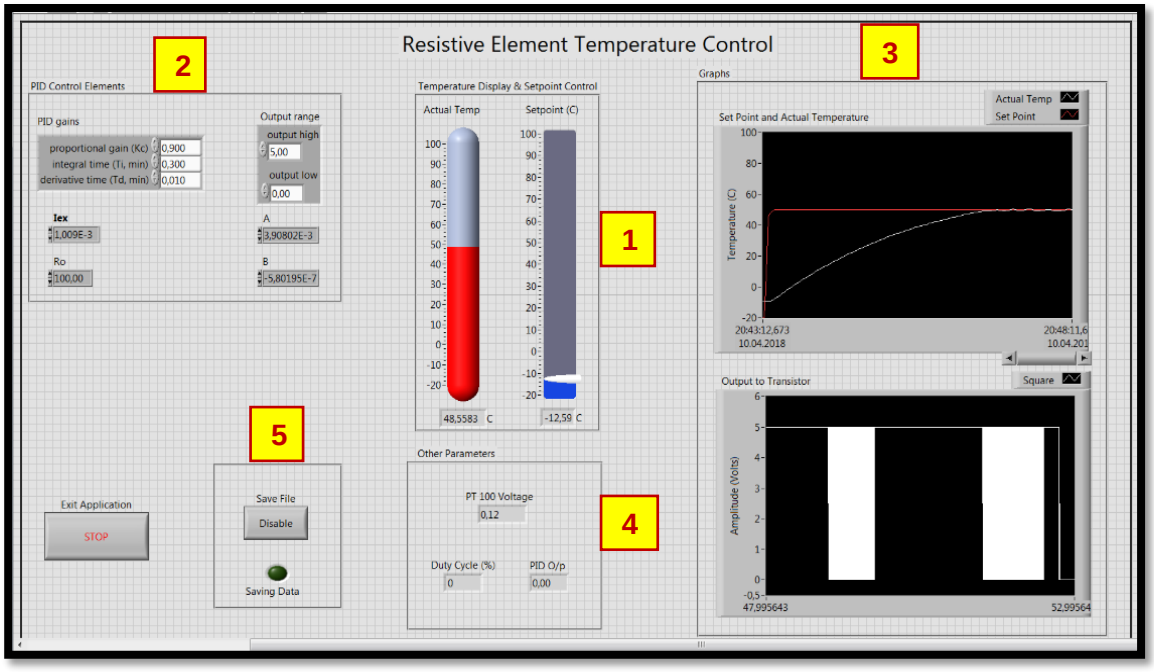
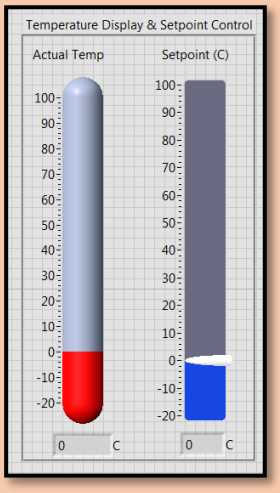
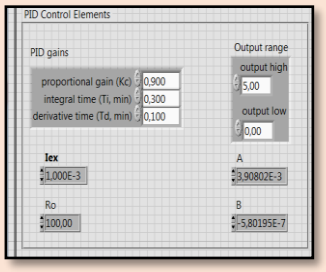
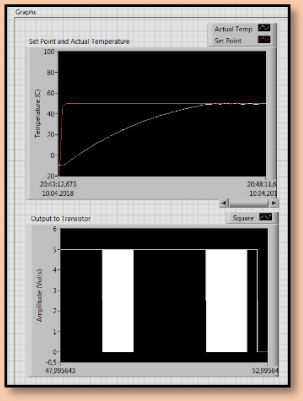
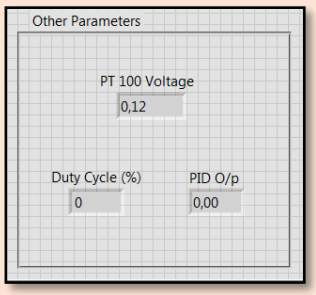
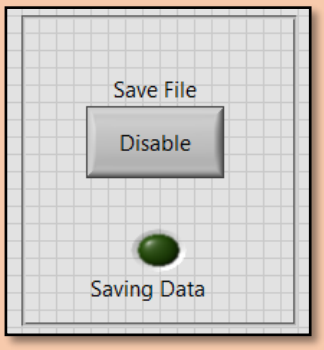


Figure 31: Software Interface of TMCS

The software interface contains the elements described in Table 6. Software interface elements which are numbered can be traced in the Figure 31.

Table 6: Software interface elements

No.	Element Name	Purpose	Figure
1	Temperature Display & Set point Control	Display the actual temperature of resistive heater (via pt100). Provides set point control to the user	

No.	Element Name	Purpose	Figure
2	PID Control Element	User input of P,I & D gains	
3	Graphs	Plot the set point and actual temperature of resistive heater simultaneously. Plot the voltage input to the resistive heater (i.e. voltage out of the TMCS to resistive heater)	
4	Miscellaneous Parameters	Display parameters of pt100 and PID output voltage.	
5	Data Logging	Data saving button with an indication available to the user	

The software was designed in the Labview® development environment. The development process of the software interface is shown in Figure 32. The LabView® virtual instrument (VI) is created using a LabView® block diagram, graphical code, and a front panel. The VI also gets the physical input through NI® MyDaq module. The output of the VI is our software interface where a user can define TMCS inputs and observe the outputs. In addition the VI send necessary output signals to NI® MyDaq.

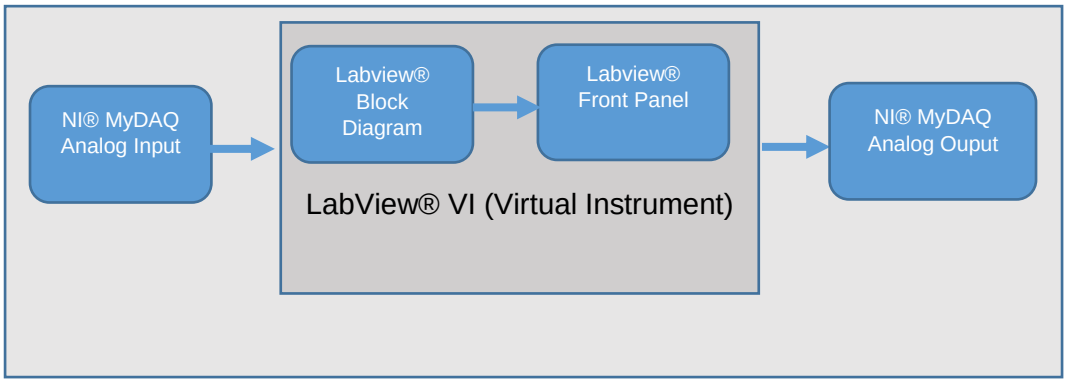


Figure 32: Process of the software interface development

The front panel is designed similar to the interface as shown in Figure 31. The screenshot of the block diagram created is shown in the Figure 33. The elements of the block diagram and their functionality is described in the Table 7. The elements of block diagram can be traced inside Figure 33.

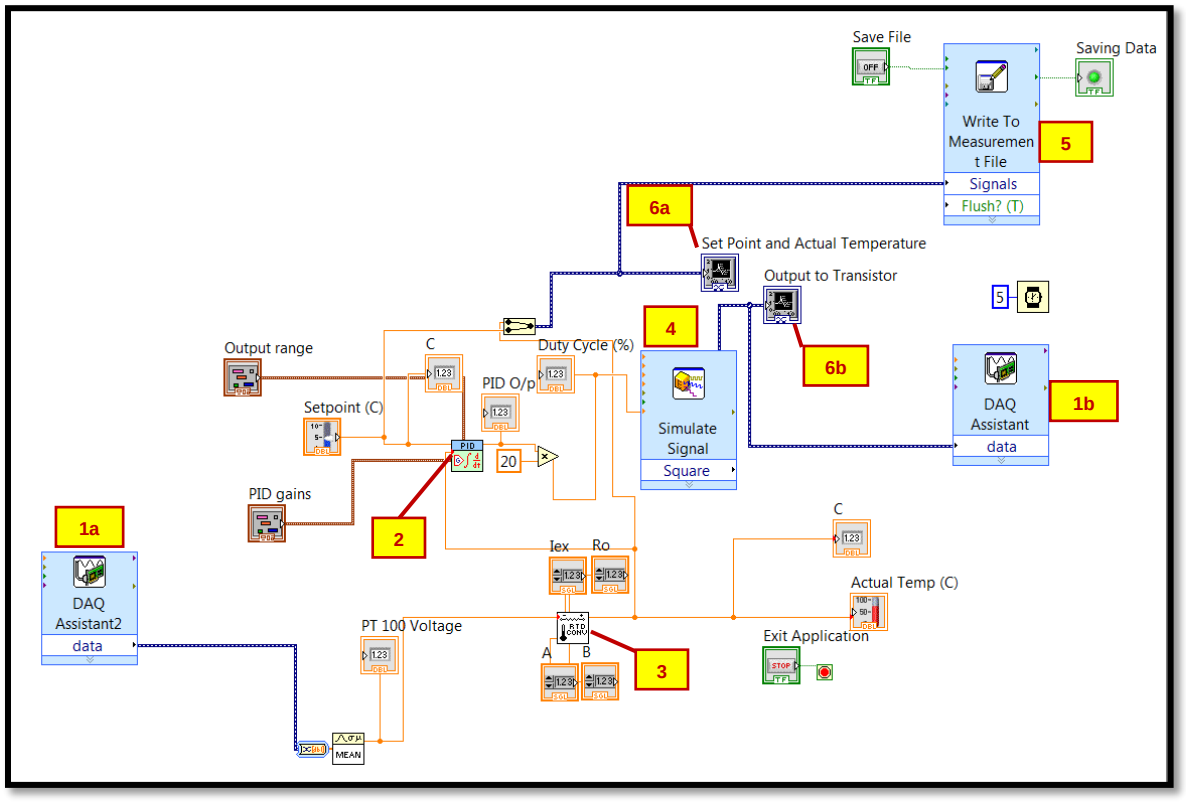
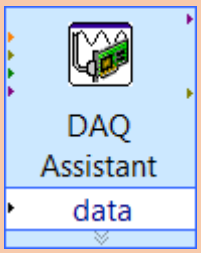
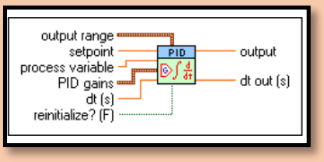
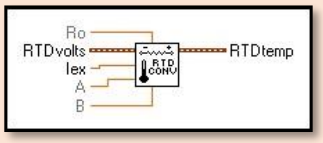
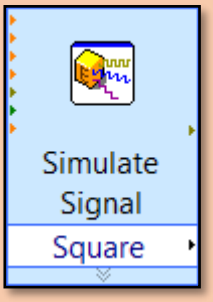
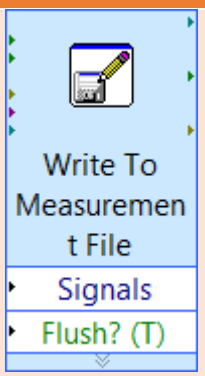
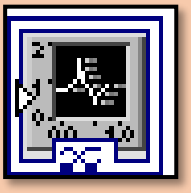


Figure 33: LabView® block diagram of the software interface

Table 7: Block diagram elements

No.	Element Name (VI)	Function	Figure
1a	DAQ Assistant	To configure analog input channel (AI1) of NI® MyDAQ in order to read pt100 voltage. • Voltage I/P range (0 to 300 mV) • Single Ended Input	
1b	DAQ Assistant	To configure analog ouput (AO1) channel of NI® MyDAQ in order to drive transistor of TMCS hardware. • Voltage O/P range (0 to 5V DC)	
2	PID	Implement PID controller for TMCS. • User I/P = P,I, D Gains • User I/P = Set Point Temperature • Output Range Value = 0 to 5	
3	Convert RTD Reading	Convert pt100 voltage (acquired via DAQ Assistant) to a temperature reading (°C). • RTD input = DAQ Assistant O/p • User input = Excitation current (mA) • RTD output= Temperature (-10 to 100°C)	
4	Simulate Signal	Generate the square wave based on the PID output. The Output of the simulate signal VI is given to DAQ Assistant. • Input value from PID VI = 0 to 100 • Output wave duty cycle = 0 to 100% • Output wave amplitude = 0 to 5	

No.	Element Name (VI)	Function	Figure
5	Write to Measurement File	Save the data to the excel file with time stamps. The following data is recorded • Set Point temperature data(°C) from PID VI • RTD output data(°C)	
6a	Waveform Chart	Plot the data of • Set point temperature (from PID VI) • Actual Temperature (from Convert RTD Reading VI)	
6b	Waveform Chart	Plot the data of • DAQ Assistant output channel	

3.3. Infrared Camera

One of the main setup component is infrared camera. FLIR® T1030Sc high definition camera is used to observe the resistive heater as shown in Figure 34. IR temperature monitoring is in addition to the pt100 sensor used in our work. FLIR® *Research IR* software is used to capture the sequence of thermographic images. This is done using specific tools of Research IR software. The thermographic images are saved and post processed to plots the surface temperature vs time readings of the resistive heater.

The infrared thermography setup and *Research IR* software interface are briefly described in this section.

Figure 34: FLIR® T1030Sc Camera

3.3.1. Infrared thermography setup

The Flir® IR camera was mounted on a stand to observe the heating devices. The viewing angle of the IR camera was kept 90 degrees to avoid reflection of light from the surface of the heating devices. This reflection can result inaccurate temperature readings.

Figure 35 shows the infrared thermography setup. The IR camera is powered on by its adapter cable which is connected at its back end. The camera is controlled by its customized research software (FLIR® *ResearchIR*). The camera communicates with this software via USB port

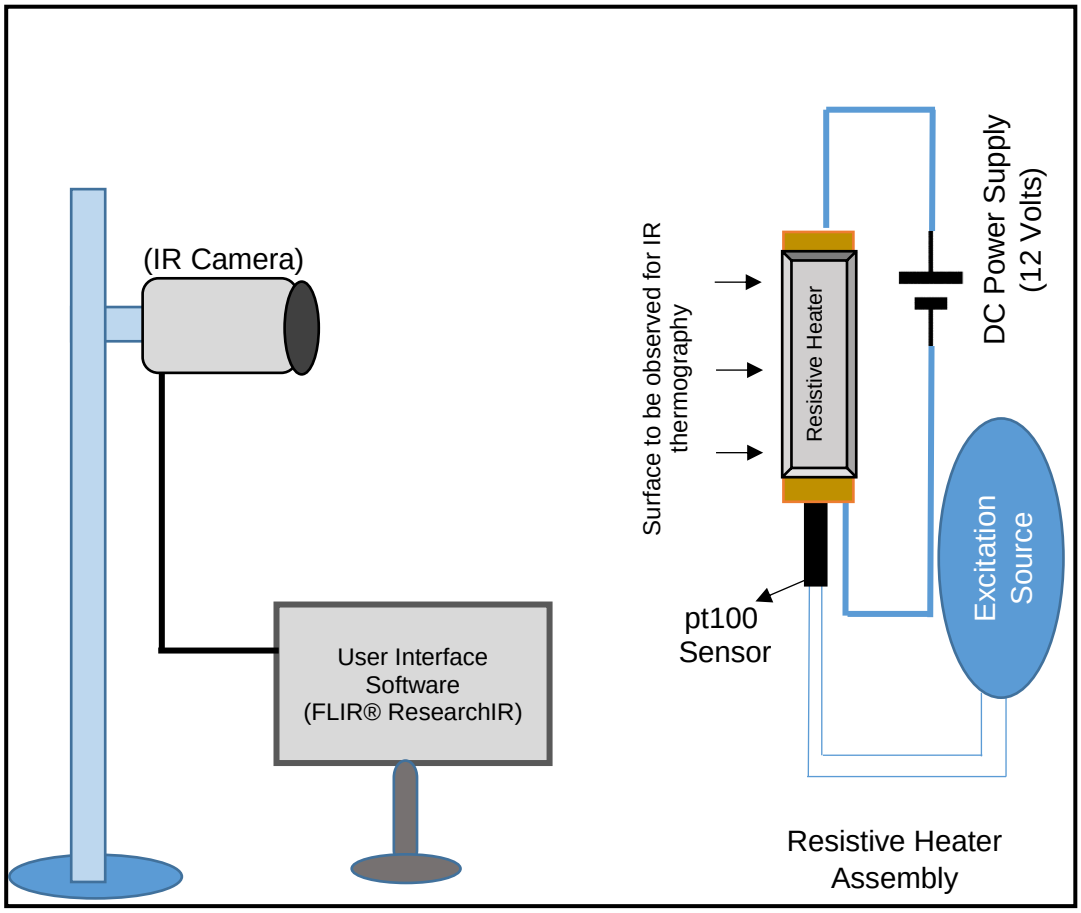


Figure 35: IR thermography setup

3.3.2. FLIR® *ResearchIR* setup

FLIR® *ResearchIR* is a customized software which is used to perform the IR image acquisition, recording and analysis. The following steps are required to operate the software and acquire infrared images. The multiple infrared images recorded in a single file is called as an IR sequence file.

Step-1: Opening FLIR® *ResearchIR* software from the desktop. As a result the main software screen displays along with the toolbars (Figure 36).

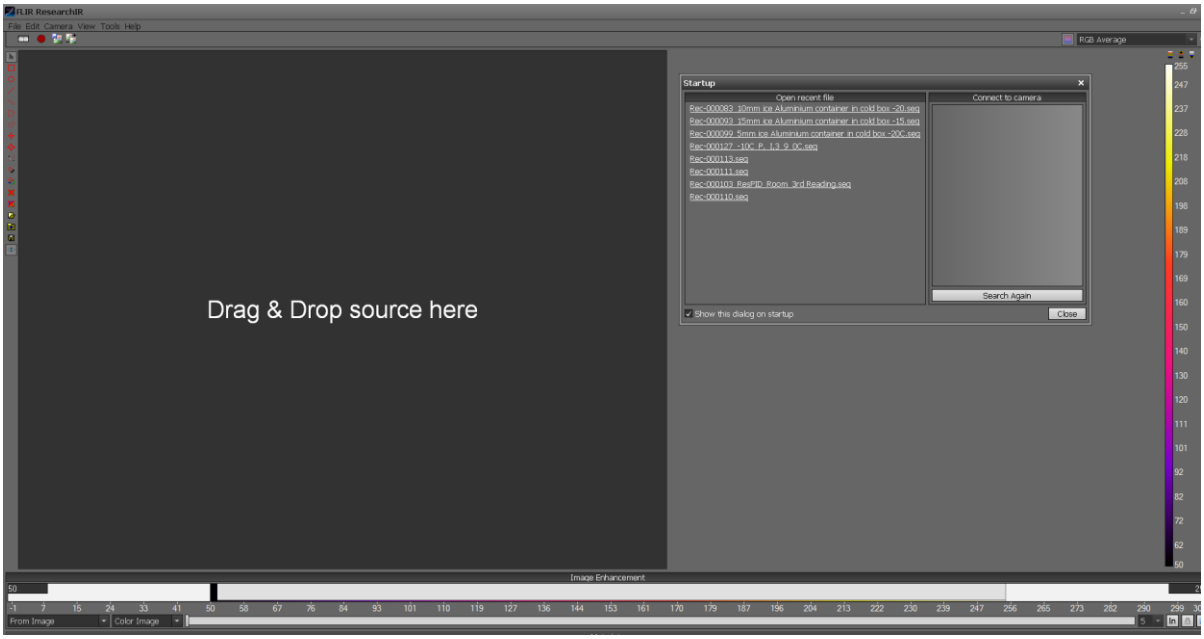


Figure 36: Screen display of the software interface

Step-2: Connecting live camera by selecting the*T1030Sc camera* displayed in the ***Connect to camera*** window (Figure 37).

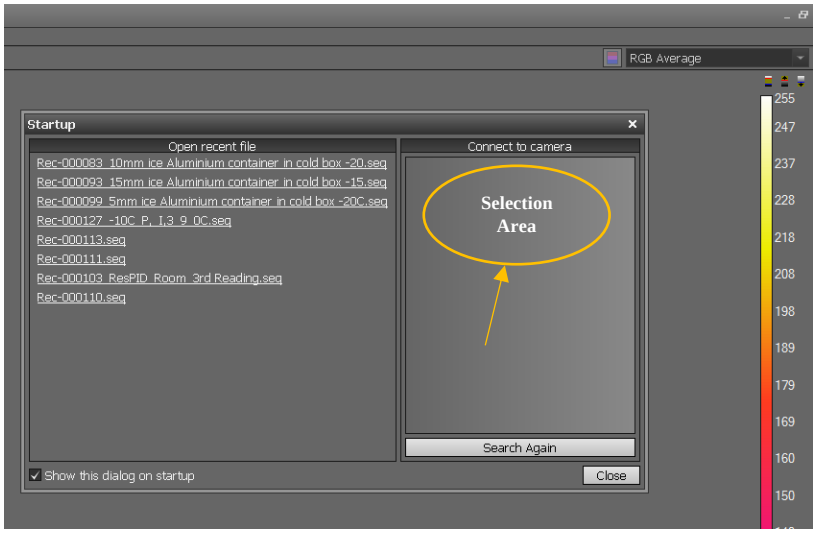


Figure 37: Camera device selection screen

After selecting the camera's name in the *Connect to camera* window (Figure 37), the live IR camera screen will appear as shown in Figure 38.

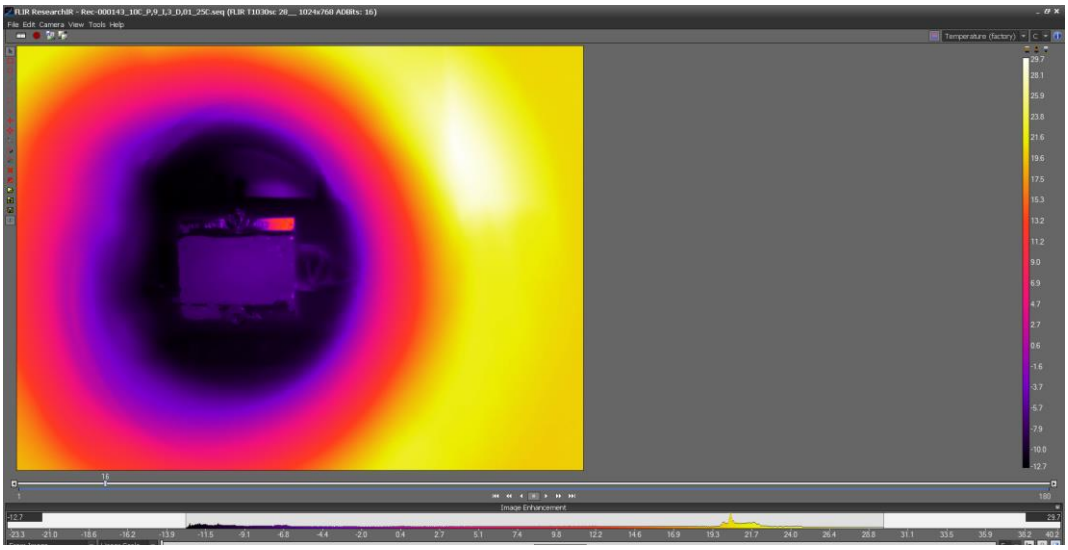


Figure 38: Live IR camera screen

Step-3: Setting the recording conditions by clicking ***Edit record settings*** present on tool bar present on the top left corner (Figure 39).

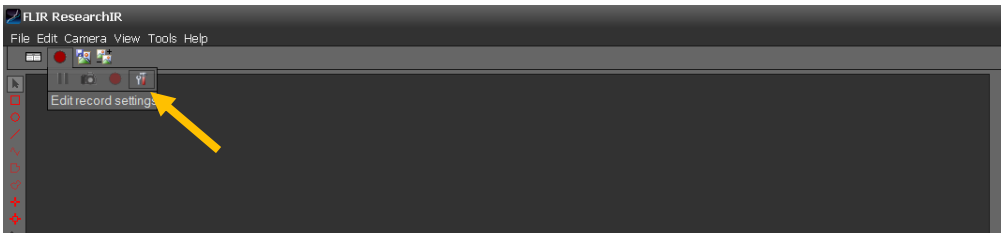


Figure 39: Edit record settings

A new window of ***Record Settings*** appears as shown in Figure 40. The parameters configured in this windows are as follows

- Record mode
- Record period
- Recording stop conditions
- Record directory

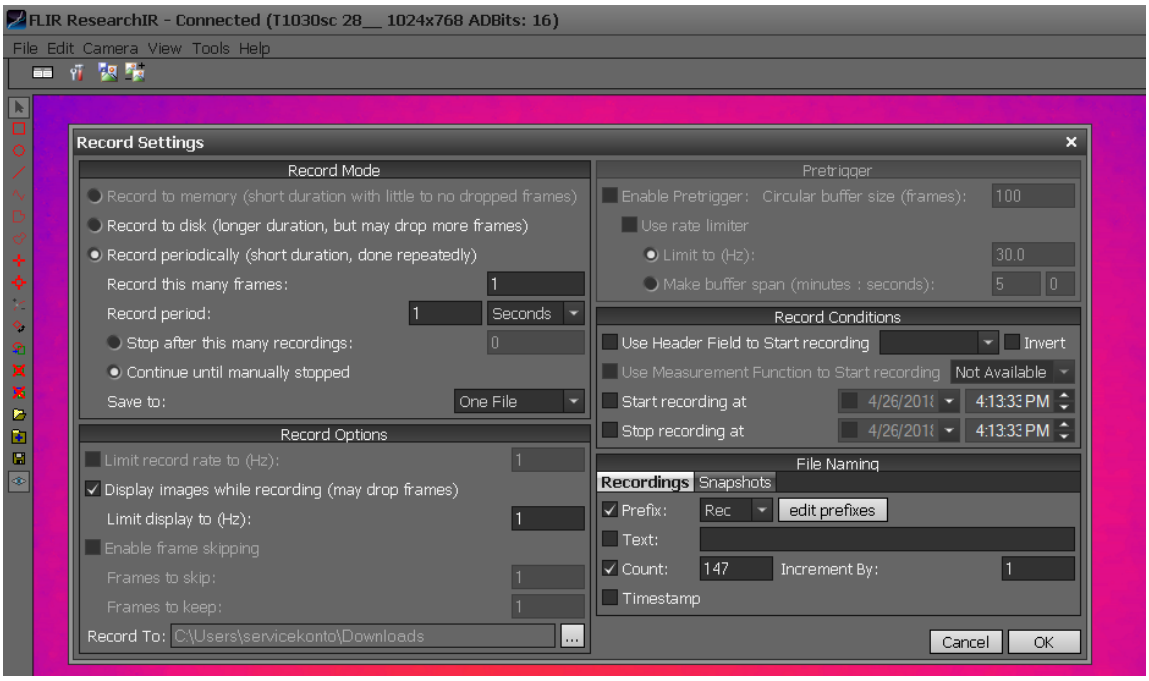


Figure 40: Record settings window

Step-4: Setting the frame rate (Hz) by selecting ***Camera → Control*** as shown in Figure 41.

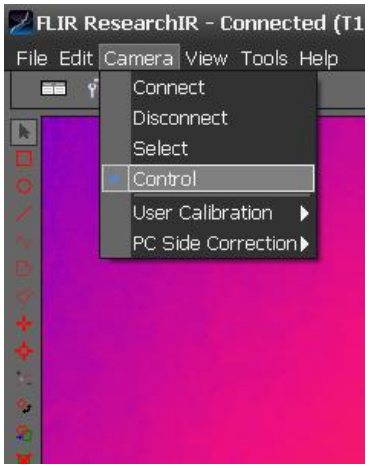


Figure 41: Camera control window

A new window ***T10XX Camera Controller*** appears as shown in Figure 42. Camera's frame rate is edited in this window.

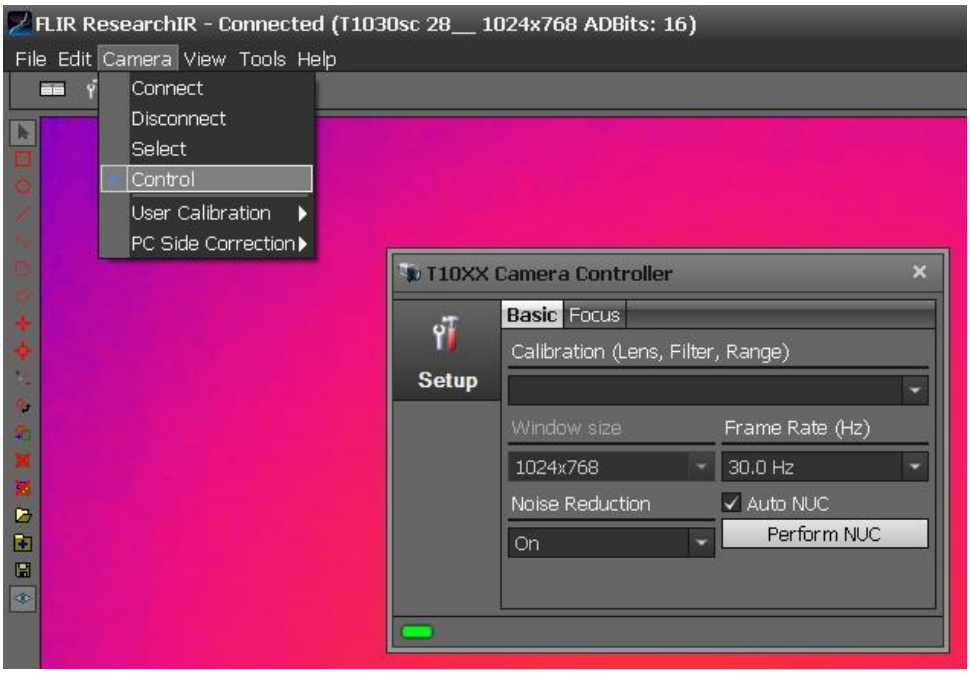


Figure 42: Frame rate (Hz) setting

Step-5: Starting the recording process by pressing the button in toolbar named ***Record a movie.*** The record button is highlighted yellow in the Figure 43.

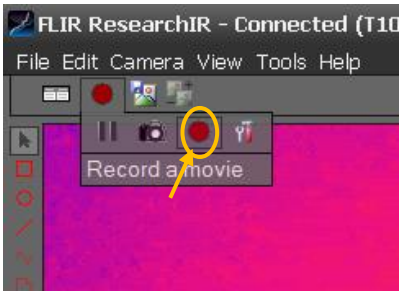


Figure 43: Recording an IR sequence

As soon as record button is pressed, a ***Recording*** window appears and recording can be stopped by pressing the stop button as shown in Figure 44.

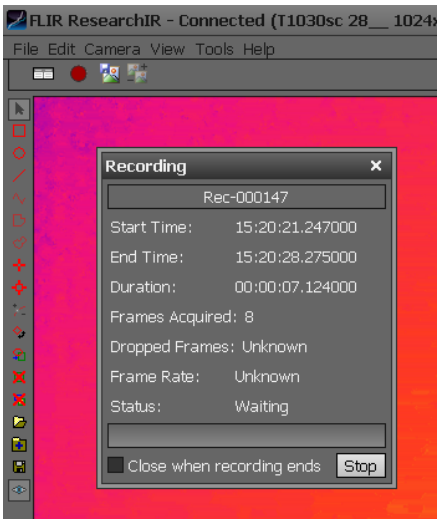


Figure 44: Recording window

Step-6: Replaying the recorded sequence by selecting ***File → Open*** in the main toolbar and opening the right directory as shown in Figure 45.

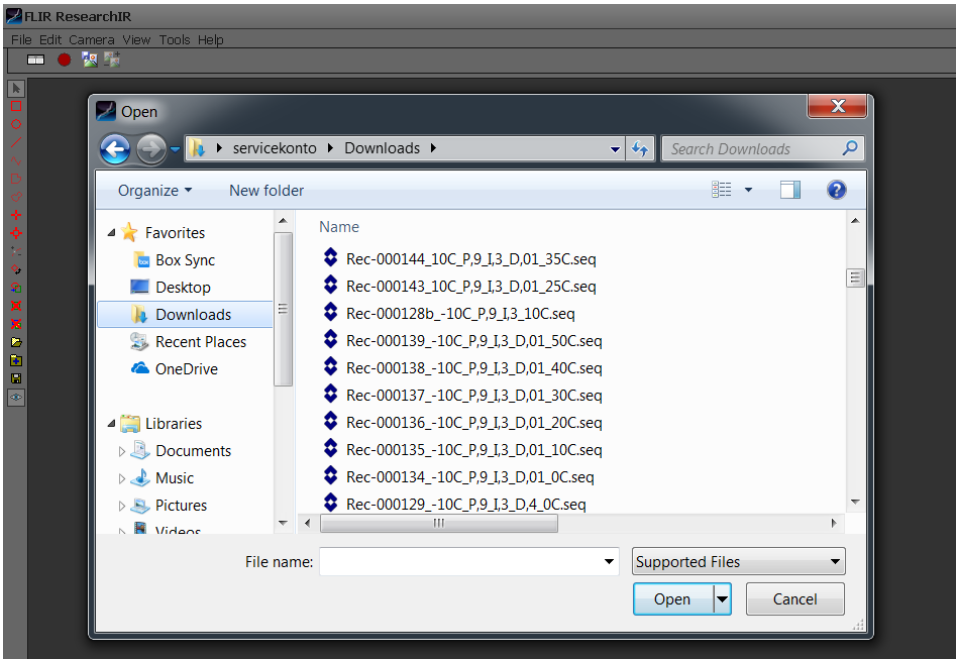


Figure 45: Replaying IR sequence file

Step-7: Entering the appropriate object parameters by selecting ***Tools → Object Parameters*** as shown in Figure 46. A new window ***Object Parameters*** will open as shown in Figure 47. The object parameters include

- Emissivity
- Reflected Temperature
- Atmospheric Temperature

- Distance of camera from the target
- Relative humidity
- External optics parameters

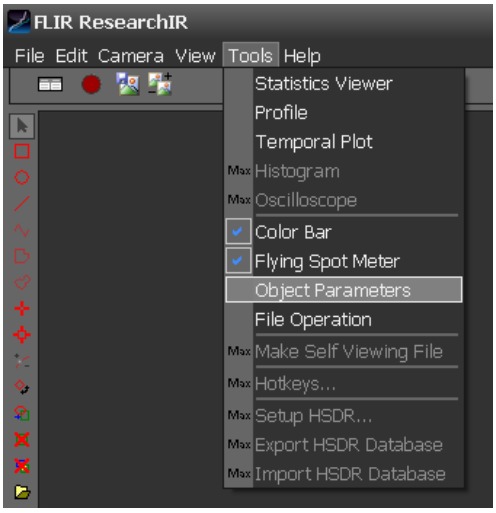


Figure 46: Selecting object parameters

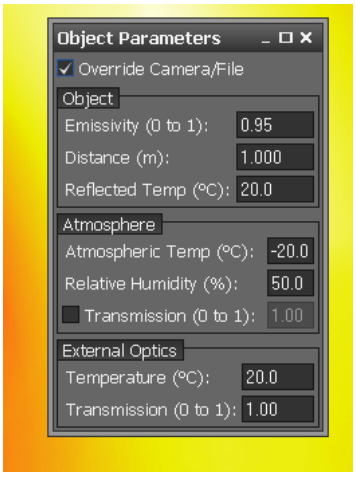


Figure 47: Editing object parameters

Step 8: Performing the IR image analysis using the ***Analysis*** toolbar available on left side of the software window (highlighted yellow) in Figure 48. There are several options available to assist the image analysis. The options used in this study are listed in the Table 8. It includes their symbols and description of their functionality.

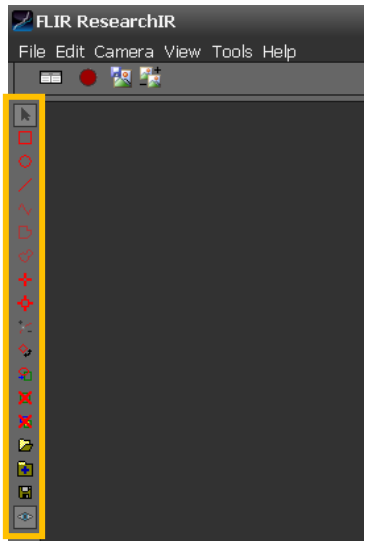


Figure 48: Analysis toolbar (highlighted yellow on the left side of the screen)

Table 8: Analysis toolbar description (adapted from [17])

Analysis Toolbar Name	Symbol	Description
Select/Edit ROI		With this tool selected, the user can mouse over an ROI. The ROI can be dragged to move it or the user can grab a "handle" to resize the ROI
Box ROI		Drawing an arbitrary rectangular box
Ellipse ROI [Max]		Draw an arbitrary ellipse
Line ROI [Max]		Draw a straight line
Bendable Line ROI [Max]		Draw a multi-segment line. Each left click adds a vertex. Right click to stop adding points. Using the Edit ROI tool the vertex points can be moved individually.
Polygon ROI [Max]		Draw a closed polygon. Left click to add a vertex. Right click to close the polygon. Using the Edit ROI tool the vertex points can be moved individually.
Freehand ROI [Max]		Draw a freehand shape. Hold down the left mouse button and drag to draw. Release the left button to close the ROI.
Spot Cursor ROI [Max]		This ROI reads the value of a single pixel.
Measurement Cursor ROI		Reads the average of a 3x3 box of pixels. Standard practice in thermography is to use a 3x3 block of pixels for measurements.

3.4. Cold Environmental Chamber

One part of the experimentation is to analyse the resistive device and peltier device inside cold environmental conditions. A *Cold Environmental Chamber* manufactured by *Tenney Jr.* is used for this purpose as shown in Figure 49. The cold environmental chamber is an enclosed box and equipment can be placed inside.

Figure 49: Cold Environmental Chamber (*Tenney Jr*)

The temperature of this environmental chamber can be regulated up to -50ºC. The environmental temperature at -10ºC was kept inside the chamber during the experiment. The setup of cold environmental chamber is shown in Figure 50.

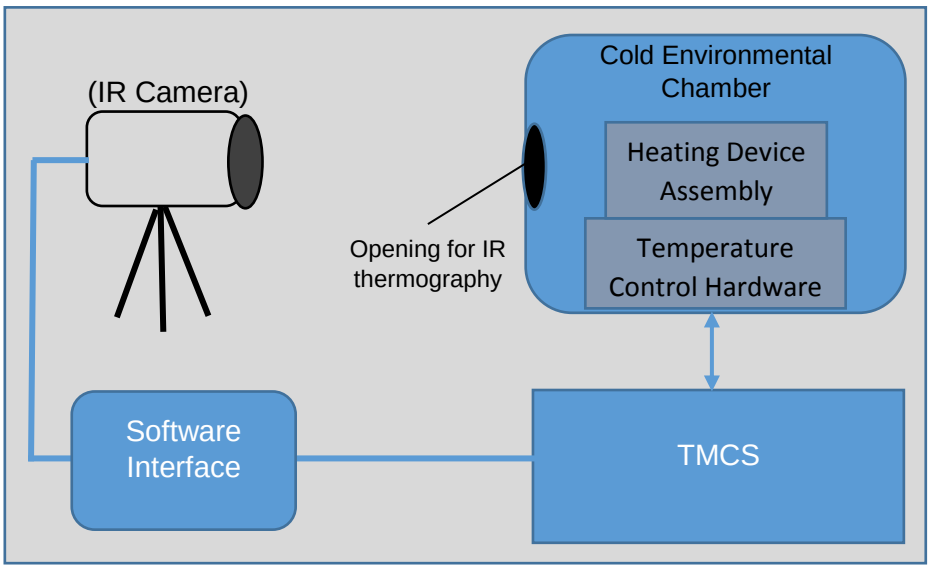


Figure 50: Cold environmental chamber in the experimental setup

The user software interface explained above was used to observe thermographic images of peltier and PTC resistive heating devices.

3.5. Experimental Procedure

The following tasks were performed in our experimental procedure

1. Calculating the Reflected Temperature for IR Camera
2. Acquiring thermal signatures of peltier device using IRT at room and cold environmental conditions
3. Measuring the resistive heater temperature without PID control at room and cold environmental conditions
4. Measuring the resistive heater temperature with PID control (using TMCS) at room and cold environmental conditions
5. The following set up component are used to perform the experimental procedure. They are described in section 3.1 to section 3.4. These are
    a) Peltier device
    b) TMCS with resistive device
    c) Infrared camera
    d) Cold environmental chamber

The cable connections for the above tasks are described in the following Table (Table 9).

Table 9: Connections for the experimental setup

Connection Type	**Pin No.**	**Terminal 1**	**Terminal 2**	**Signal**
Customize Rs232 cable (9-pin)	1	Rs232 9-pin PCB mounted (Figure 24)	NI® *MyDaq* VΩ (Hi)	Dc voltage (0-5V)
	2		NI® *MyDaq* VΩ (Comm)	Gnd
	3		Not connected	-
	4		NI® *MyDaq* channel-AO0	Analog output (volt)
	5		DC power supply (+ve)	Dc voltage (12V)
	6		DC power supply (-ve)	Gnd
	8		Constant current generator output (+ve)	Current (mA)
	9		Constant current generator output (-ve)	Current (mA)

Standard Power Lead Cables	-	Constant current generator (Power IN+)	Power supply DC (+)	DC voltage (12V)
	-	Constant current generator (Power IN-)	Power supply DC (-)	Gnd

3.5.1. Calculating reflected temperature for IR camera

The manufacturer of the IR camera (FLIR®) recommends to enter the *Reflected Temperature* measured by IR camera. It is apparent temperature caused due to the reflection of light. Hence, the reflected temperature of the testing environment is to be entered in the image settings. In our study, the reflected temperature will be calculated twice i.e. for room and cold environment conditions.

Figure 51: Setup for calculating reflected temperature at room conditions

The following procedure is used to calculate the reflected temperature. It is also described in the *ResearchIR*® manual.

1. A piece of commercial aluminium foil is crumbled and unfolded.
2. This aluminium foil is placed in front of the IR camera as shown in Figure 51

3. The emissivity value of the image is set to 1.
4. The entire image area is selected from the analysis toolbar using the square area (**BOX1)**.
5. The average temperature is recorded form the *Stats* toolbar which comes out to be 23.2^{o}C as encircled yellow in the in Figure 52.

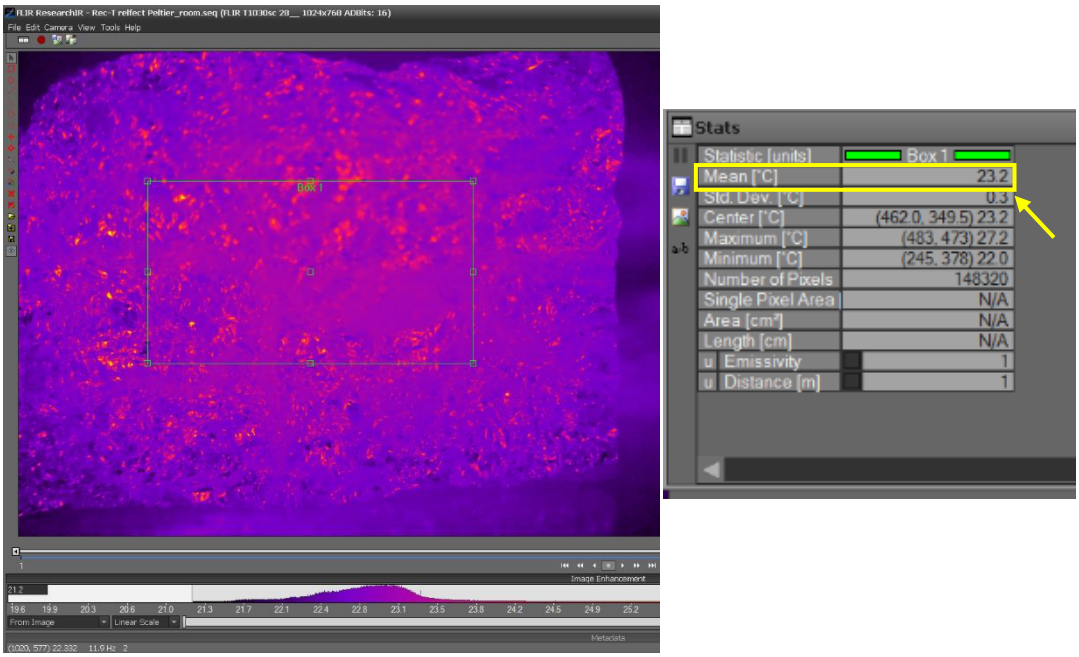


Figure 52: Calculating reflected temperature in FLIR® ResearchIR software at room conditions

6. Repeat steps 1 to 4 for calculating reflected temperature in cold environmental conditions. Figure 53 shows the setup for calculating reflected temperature in cold environmental conditions

Figure 53: Setup for calculating reflected temperature in cold environmental conditions

7. The average temperature is recorded form the *Stats* toolbar which comes out to be -0.5ºC as encircled yellow in the in Figure 54.

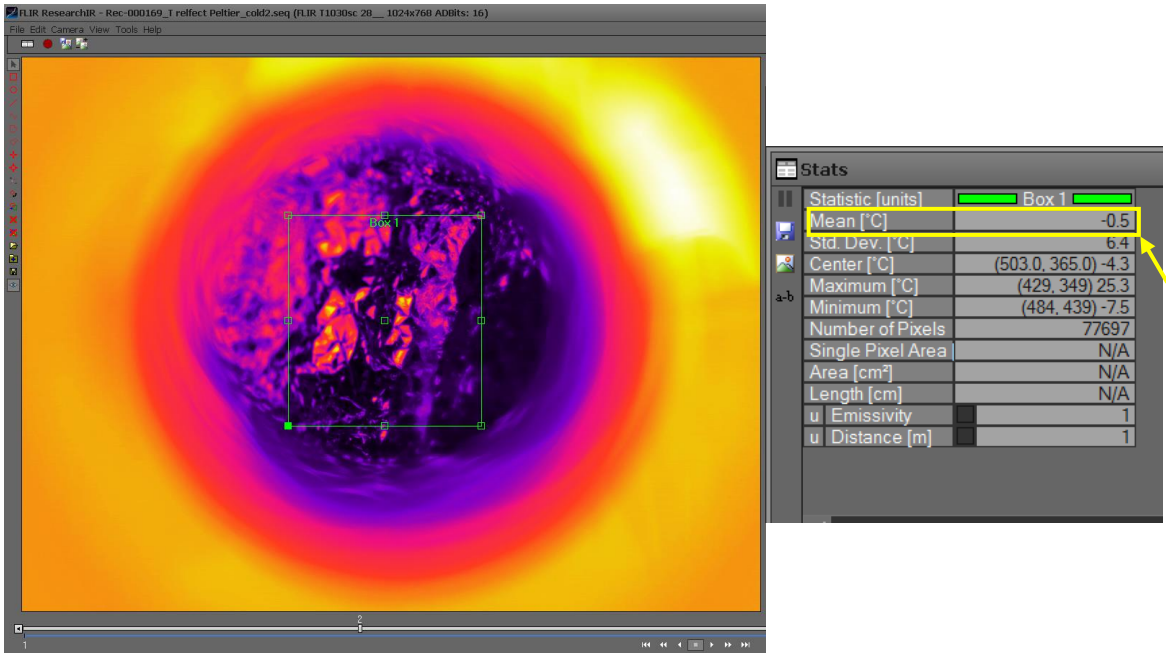


Figure 54: Calculating reflected temperature for IR camera with aluminium foil in cold environment conditions

As a result, the reflected temperature is set to 23.2ºC during experiments in room temperature. The reflected temperature is set to -0.5ºC during experiments in cold environment.

3.5.2. Thermal signature of peltier device using IRT at room and cold environmental conditions

The IR thermography of peltier device consists of the following components.

i. Peltier device TEC (12706)
ii. Aluminium heat sink
iii. 12V dc fixed power supply (20A max)
iv. Flir® camera T1030Sc with its power cable and adapter
v. Stand to mound Flir camera
vi. Standard USB to micro USB cable (Flir® camera connection)

The setup is shown in the Figure 55. The procedure of IRT of peltier device at room conditions is explained as follows.

1. Setting the image parameters

a. Emissivity = 0.95
b. Reflected temperature = 23.2ºC
c. Distance = 0.5 m
d. Atmospheric temperature = 24ºC

Rest of the parameters for instance relative humidity and external optics parameters were kept to default value.

2. Setting the following recording conditions

    a. Recording speed = 1 frame/sec
    b. Setting directory

3. Start recording of IR camera through *FLIR® ResearchIR* software

4. Power On peltier device
5. Wait for approximately 15 seconds
6. Power Off peltier device
7. Stop the recording

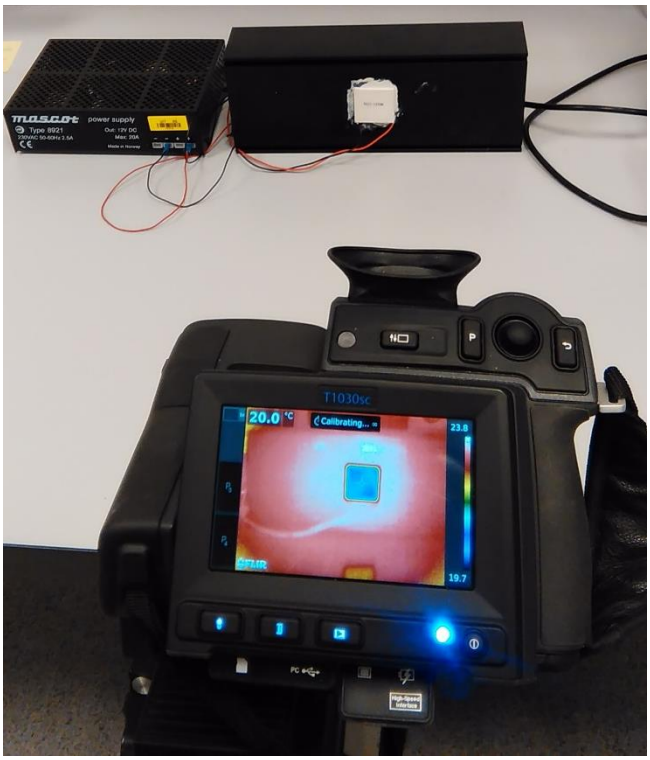


Figure 55: Setup of peltier device using IRT at room conditions

The procedure of IRT of peltier device in cold environment conditions is explained as follows.

1. Setting the image parameters
    a. Emissivity = 0.95
    b. Reflected temperature = -0.5^{o}C
    c. Distance = 0.5 m
    d. Atmospheric temperature = -10^{o}C

2. Place peltier device assembly inside cold environmental chamber
3. Repeat step 2 to 7 as described above.

3.5.3. Measuring resistive heater temperature without using PID at room conditions

The procedure to measure temperature profile of the resistive heater at 24^{o}C (room conditions) is as follows. Figure 56 shows the experimental setup at room conditions.

1. Attach heating device assembly of TMCS on a stand.
2. Perform necessary connections according to the Table 9.
3. Place IR camera facing towards heating device.
4. Repeat the steps 1 and 2 as described in Section 3.5.2.
5. Power on heating device assembly of TMCS
6. Start recording of IR camera through *FLIR® ResearchIR* software
7. Stop recording until resistive heater reaches its maximum temperature.

3.5.4. Measuring and controlling the resistive heater temperature with PID (using TMCS) at room conditions

The procedure to measure temperature profile of the resistive heater at 24^{o}C (room conditions) is as follows. Figure 56 shows the experimental setup at room conditions.

1. Repeat procedure given in 1 to 4 from section 3.5.3.
2. Run software interface of TMCS
3. In the software interface, set the values of
    a. P, I and D gains
    b. Excitation current of pt100 to 1mA
    c. Maximum output value = 5
    d. Minimum output value = 0

4. Power on the power module of TMCS hardware
5. Press the *Enable* button in the Save File region for data logging
6. Start recording of IR camera through *FLIR® ResearchIR* software
7. Scroll *Temperature Set point* bar to adjust restive heating temperature at 35^{o}C to 65^{o}C
8. Stop recording until resistive heater reaches its set point temperature
9. Set *Temperature Set point* bar to room temperature

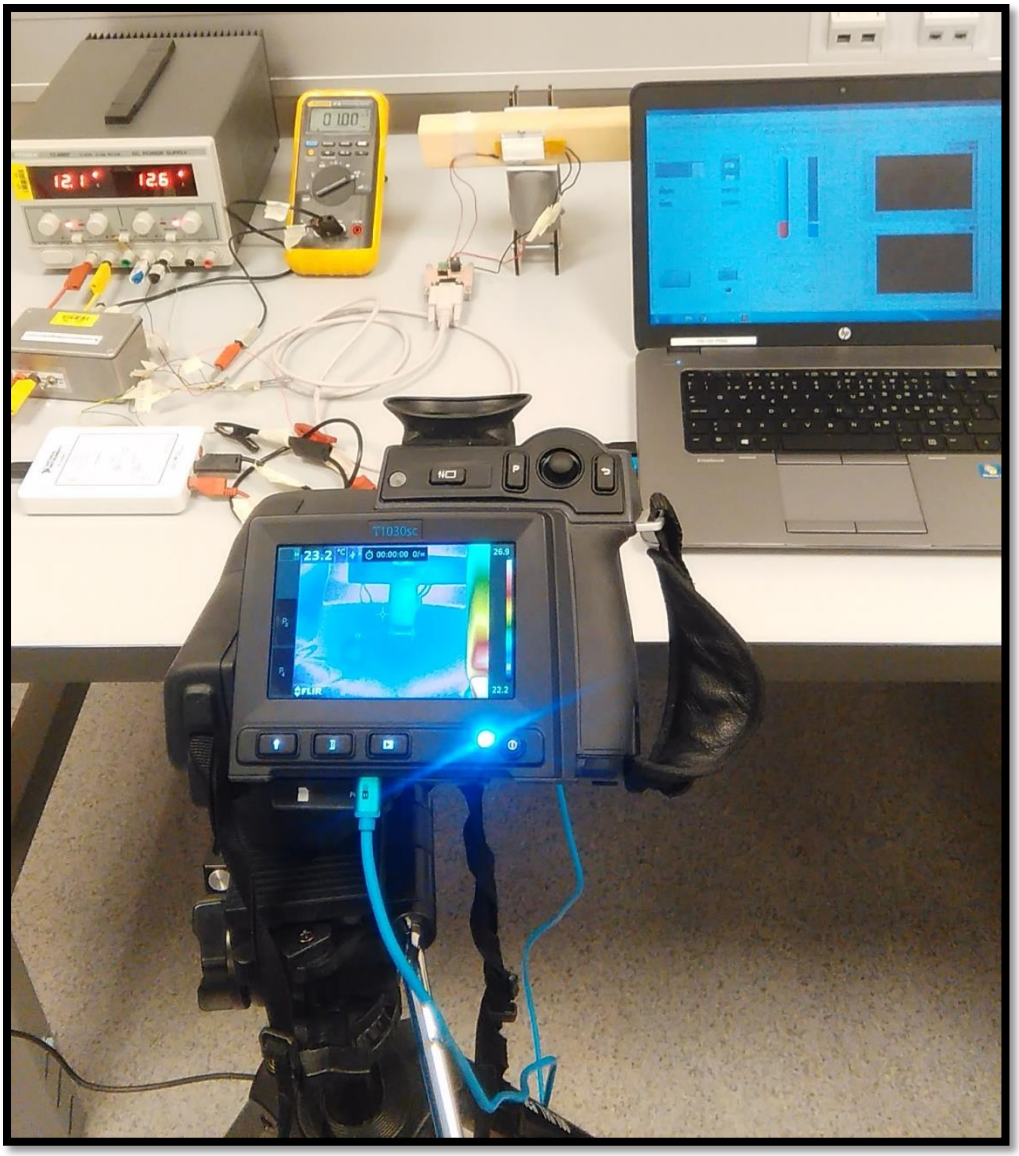


Figure 56: Experimental setup for room conditions (24^{o}C)

3.5.5. Measuring resistive heater temperature without using PID control in cold environment

The procedure to measure temperature profile of the resistive heater at -10^{o}C (cold environment conditions) is as follows.

1. Attach heating device assembly of TMCS on a stand.
2. Place heating device assembly and temperature control hardware inside cold environmental chamber
3. Perform necessary connections according to the table 9.
4. Place IR camera facing towards heating device.
5. Power on heating device assembly of TMCS
6. Start recording of IR camera through *FLIR® ResearchIR* software
7. Stop recording until resistive heater reaches its maximum temperature.

3.5.6. Measuring and controlling the resistive heater temperature with PID (using TMCS) at cold environmental conditions

Figure 57 shows the experimental setup in cold environmental conditions. The procedure to measure temperature profile of the resistive heater at -10^{o}C (cold environmental conditions) is as follows.

1. Repeat procedure given in 1 to 6 from section 3.5.5.
2. Scroll *Temperature Set point* bar to adjust restive heating temperature at -10 ^{o}C to 65^{o}C
3. Stop recording until resistive heater reaches its set point temperature
4. Set *Temperature Set point* bar to -10^{o}C

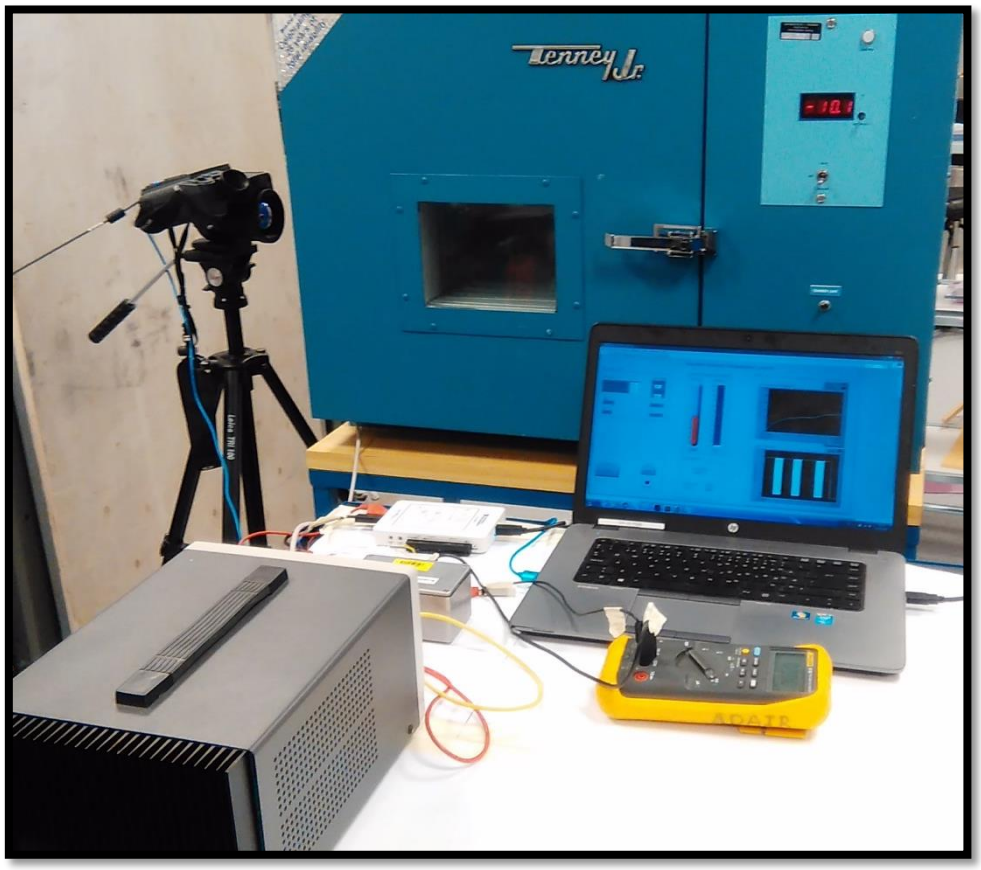


Figure 57: Experimental setup for cold environment (-10^{o}C)

3.6. MATLAB® Simulation of PTC Heater

3.6.1. Problem statement

The aim of this simulation is to simulate the thermal behaviour of a small-sized positive temperature coefficient (PTC) resistive heater.

The simulation is performed using MATLAB® software using its Simulink and Simscape tools. The PTC heater can be divided into two sub units.

i. PTC thermistor
ii. Thermal mass attached

The aim is to link these subunits to simulate PTC heater characteristics in room conditions and cold environment conditions and acquire temperature vs time plots. Finally, the simulated plots (Figure 86 and Figure 87) are compared with the experimental results of PTC heater temperature without PID gains (Figure 64 and Figure 65).

3.6.2. Specifications

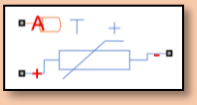
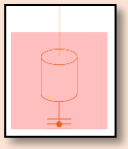
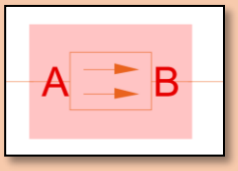
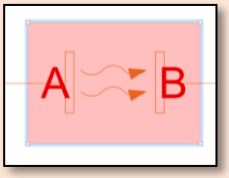
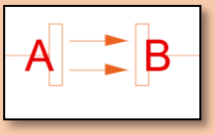
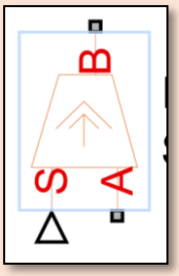
The specifications of the PTC heater's model is shown in Table 10. The thermal mass of the simulated PTC heater is same as the actual mass of PTC heater used in experimentation.

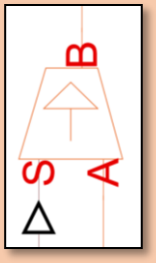
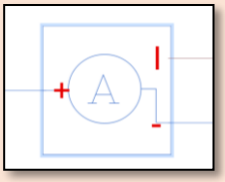
Table 10: Model specifications of PTC heater

Specifications	Description/Unit	Value
A. PTC Thermistor		
Nominal temperature	T_0 (K)	298
Reference temperature at T1	T_1 (K)	398
Thermal time constant	t_c (sec)	5
Initial temperature (Room)	T_0 (K)	298
B. Thermal Mass		
Mass	kg	0.050
Specific heat (Aluminium)	J/kg/K	800
C. Heat Transfer		
Area	cm^2	14
Thickness	cm	1
Thermal Conductivity	W/(m*K)	220

The MATLAB® Simulink® model of PTC heater is created using a Simscape tool box. In order to create the model, following major blocks are used as shown in the Table 11. The overview of the model is shown is in Figure 58.

Table 11: MATLAB® Simulink® blocks used to create PTC heater model

No.	Block Name	Purpose	Figure
1	PTC Thermistor	This block shows a switching type PTC thermistor having a thermal and electrical port.	
2	Thermal Mass	It shows a thermal mass and characterized by the object mass and its specific heat capacity.	
3	Conductive Heat Transfer	The block shows the heat transfer by conduction through a layer of material. The heat is transferred among two ports available.	
4	Convective Heat Transfer	The block shows the energy transfer by convection between two bodies due to fluid motion. The transfer is directly proportional to the convective heat transfer coefficient, surface area, and the temperature difference.	
5	Radiative Heat Transfer	The block shows the energy transfer by radiation between two surfaces.	
6	Ideal Heat Flow Source	The block shows an ideal source of thermal energy. It maintains specified heat flow at its outlet regardless of the temperature difference across the source. Connections A and B are thermal inlets and outlets. Port S represents the thermal signal port	

No.	Block Name	Purpose	Figure
7	Ideal Temperature Source	The block shows an ideal source of thermal energy that maintains a specified temperature at its outlet under all circumstances. Ports A and B are thermal ports corresponding to the source inlet and outlet, respectively. Port S is a physical signal port.	
8	Current Sensor	It is block that measures the current and converts into a physical signal. Port + and Port – are current measuring ports. Port I is the physical signal port.	

The PTC resistive assembly in the model is constructed by using a PTC thermistor block, attached to a thermal mass as shown in Figure 58. The thermal mass represents the aluminium plate attached to the PTC thermistor via conductive heat transfer block. The PTC thermistor is electrically powered and the heat dissipated inside is converted into a power (watts). This power is fed back to the thermal mass (aluminium plate). Hence, as soon as PTC thermistor is powered up the thermal mass attached to it heats up. The maximum temperature of PTC thermistor is set at 100^{o}C. In this manner, a one-dimensional PTC heater model is achieved.

3.6.3. PTC heater model at room temperature

The MATLAB® model of PTC heater is implemented as shown in Figure 58. The model is tested in room conditions. As discussed above, PTC heater assembly includes the PTC thermistor, thermal mass, current sensor and conductive heat transfer block. The thermal mass is exposed to the atmosphere (air) at room conditions via convective and radiative heat transfer block.

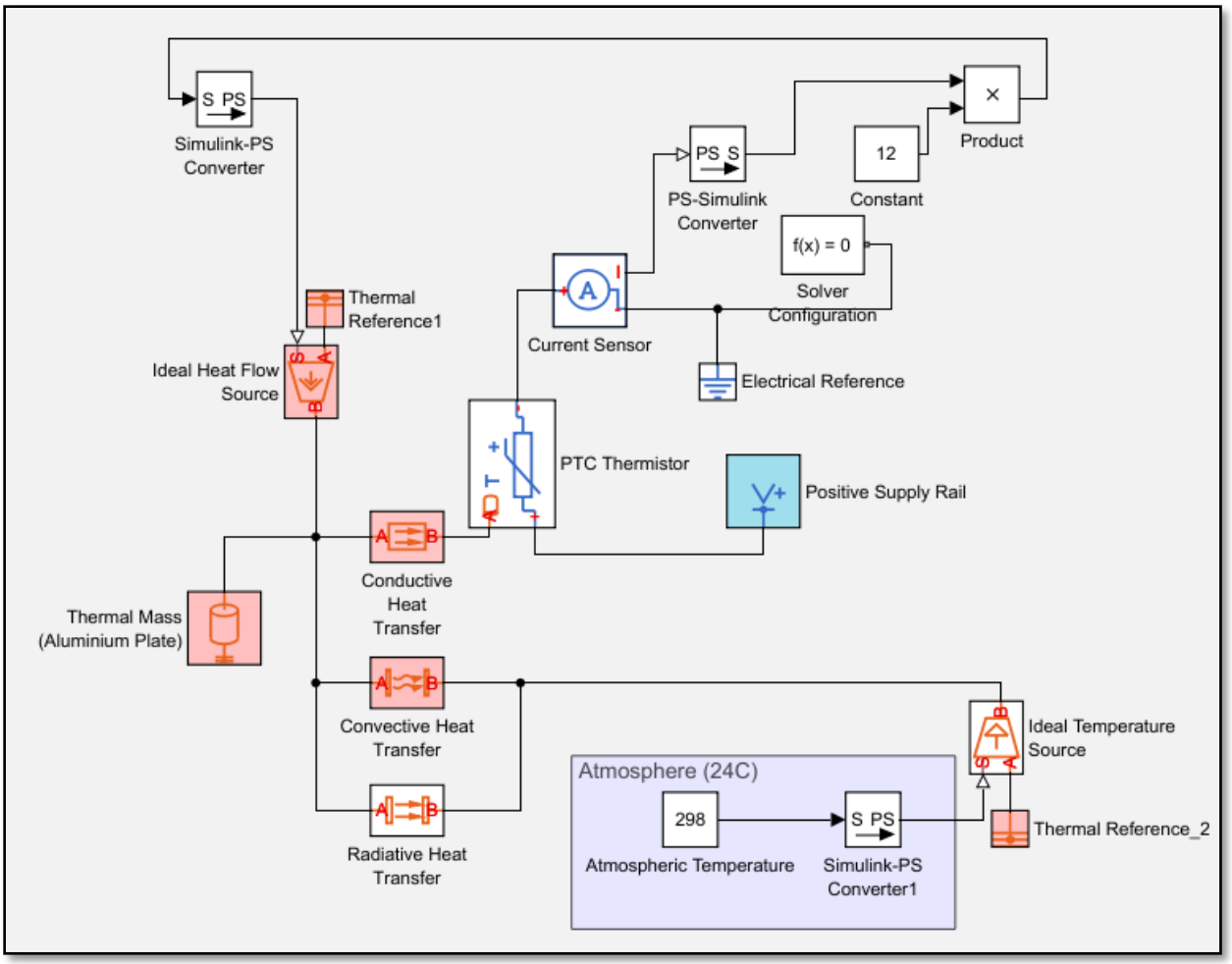


Figure 58: Model of PTC heater operating at room conditions

3.6.4. PTC heater model in cold environment (-10°C)

The similar model shown above is also tested in cold environment conditions. The air temperature of -10°C is introduced in the model as shown in Figure 59. The model is simulated in cold environmental conditions.

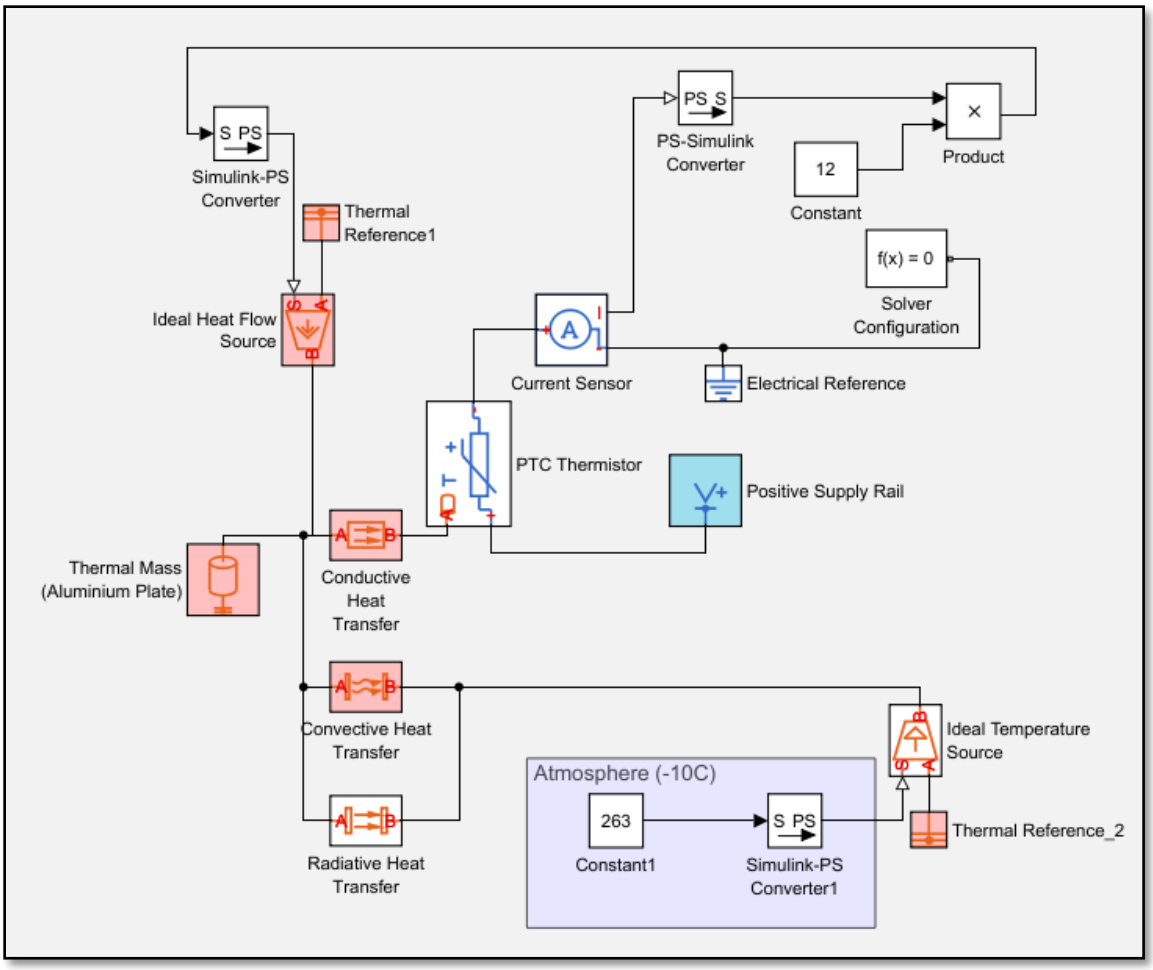


Figure 59 Model of PTC heater in cold environment conditions

Chapter 4

4. Results

4.1. Thermal Signature of Peltier Device in Room and Cold Environment

The temperature plots of peltier device are shown in Figure 60 and Figure 61 respectively. These are average surface temperature plots of peltier device vs time in room and cold environment (-10^{o}C). These plots shows that the surface temperature of peltier device rises sharply with time. For instance, peltier device reaches 100^{o}C within 10 seconds in room conditions. However it reaches 100^{o}C within 28 seconds in cold environment conditions (-10^{o}C). It can be concluded that peltier device takes more time to reach 100^{o}C in cold environment conditions. This is due to the effect of surrounding cold temperature.

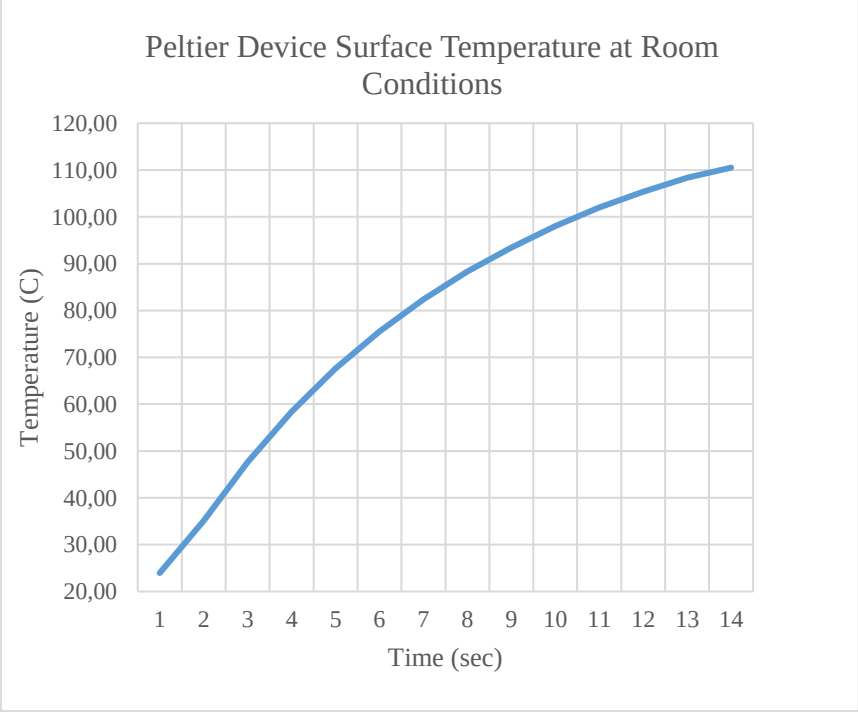


Figure 60: Temperature vs time plot of peltier device at room conditions using IRT

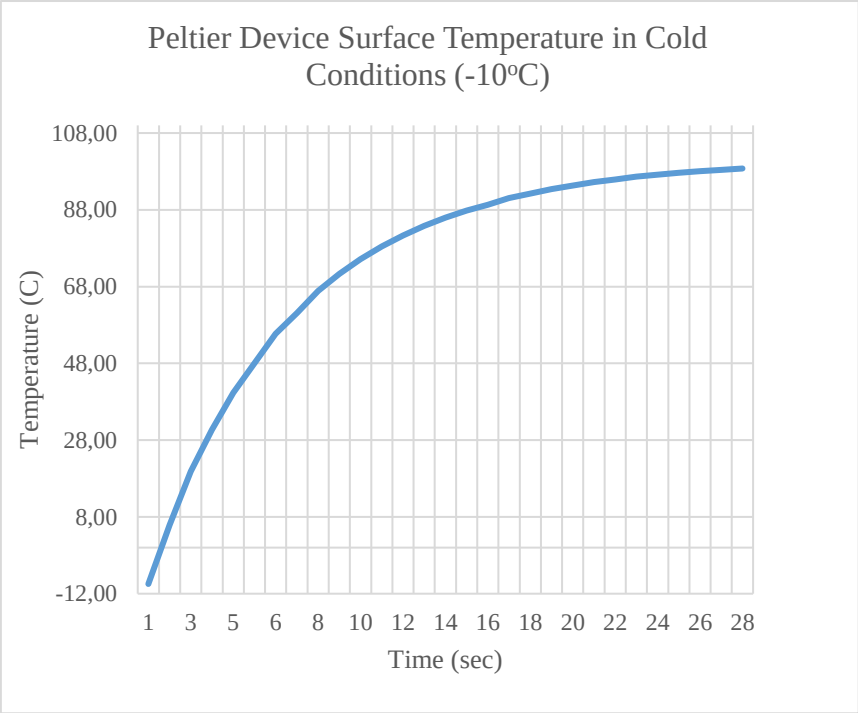


Figure 61: Temperature vs time plot for peltier device in cold environment using IRT

The IR images of peltier device in room conditions are shown in Figure 62. These are infrared images of peltier device's surface. The IR images of peltier device in cold environment (-10°C) are also shown in Figure 63.

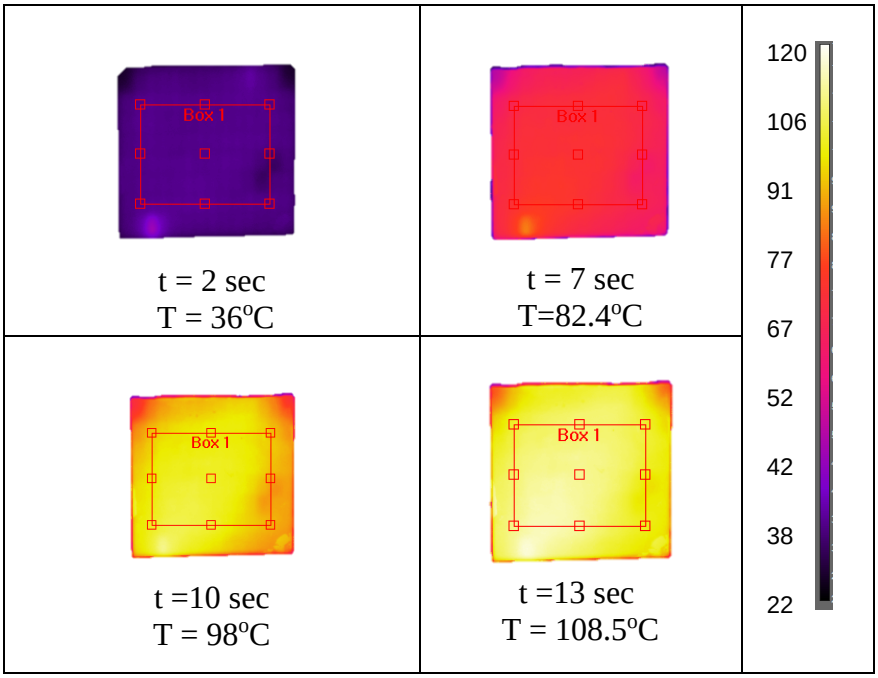


Figure 62: IR images of peltier device at room conditions (area average surface temperature)

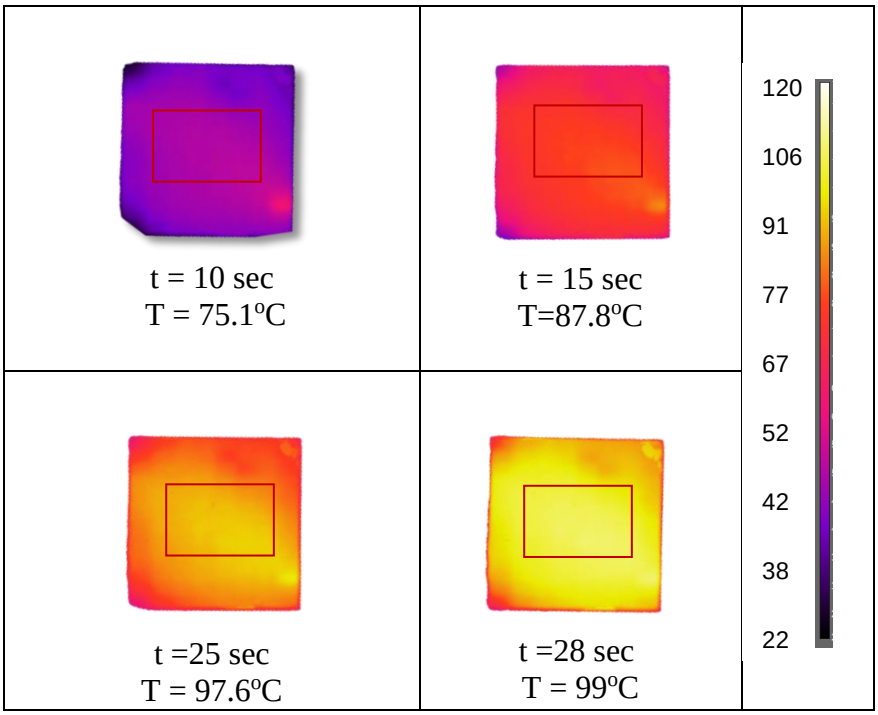


Figure 63: IR images of peltier device in cold environment (-10°C) (area average surface temperature)

It can be observed that the heating response of peltier device is fast as compared to the PTC heater inside room and cold environment. This can be observed by comparing Figure 60 and Figure 61 with Figure 64 and Figure 65. However, the peltier devices have low efficiency and are difficult to implement on large industrial scale as discussed in Section 2.1.5. On the other hand PTC heater is self-regulating, robust and can be implemented on for large scale industrial applications. Hence, the temperature measurement and control of PTC heater was further analysed in our study.

4.2. Temperature Measurement of PTC Heater without PID Control

Initially, the response of the PTC heater was observed without using PID control. The experiments were performed in room temperature and cold environmental conditions. At room conditions, the temperature response without using PID control is shown in Figure 64. Figure 64 shows that the temperature of PTC heater continue to rise until it reaches maximum temperature of 100°C. PTC heater maintains its temperature at 100°C. It takes 680 seconds (approximately) to reach 100°C (Figure 64).

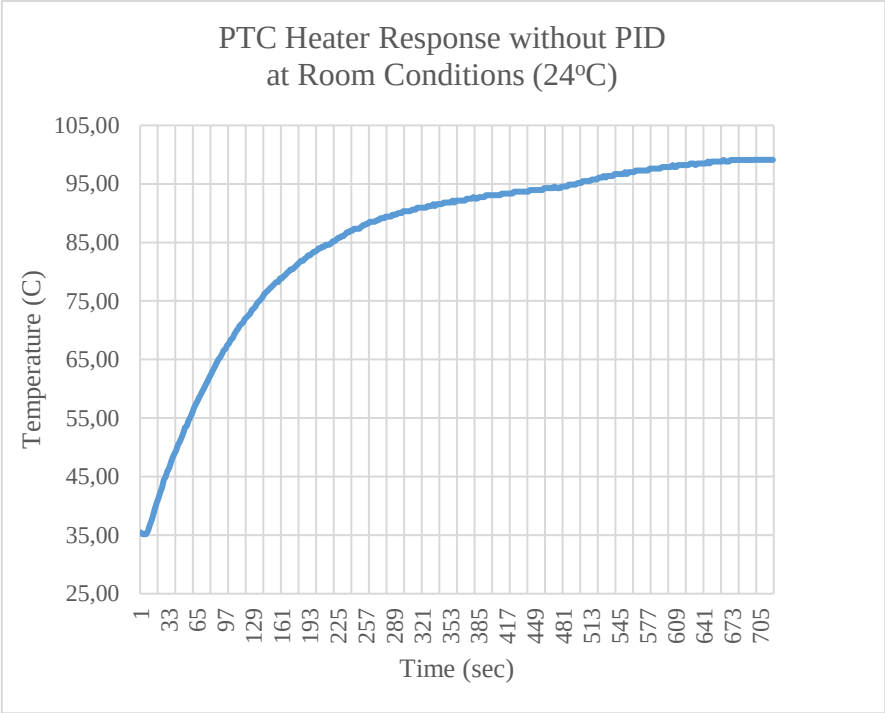


Figure 64: Temperature vs time plot for resistive heater (DBK HP05) without PID at room condition

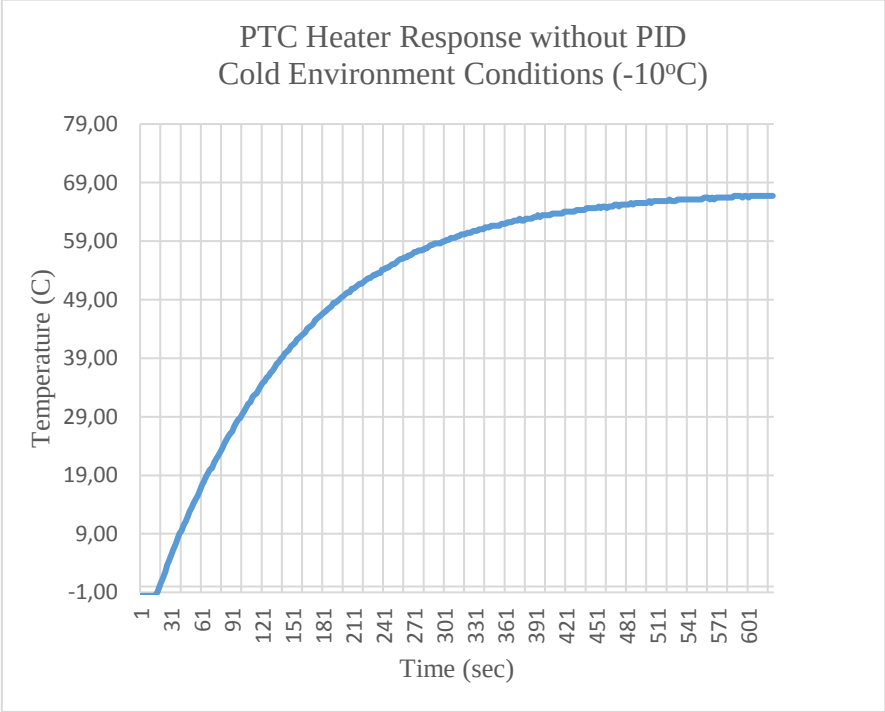


Figure 65: Temperature vs time plot for resistive heater (DBK HP05) without PID in cold environment

The PTC heater reaches maximum 100°C at room temperature and it reaches maximum 69°C in cold environment conditions (Figure 65).

4.2.1. Thermal signature of PTC heater in room and cold environment

The IR images of PTC heater in room and cold environment are shown in following figures (Figure 66 and Figure 67). These are infrared images of PTC heater's surface.

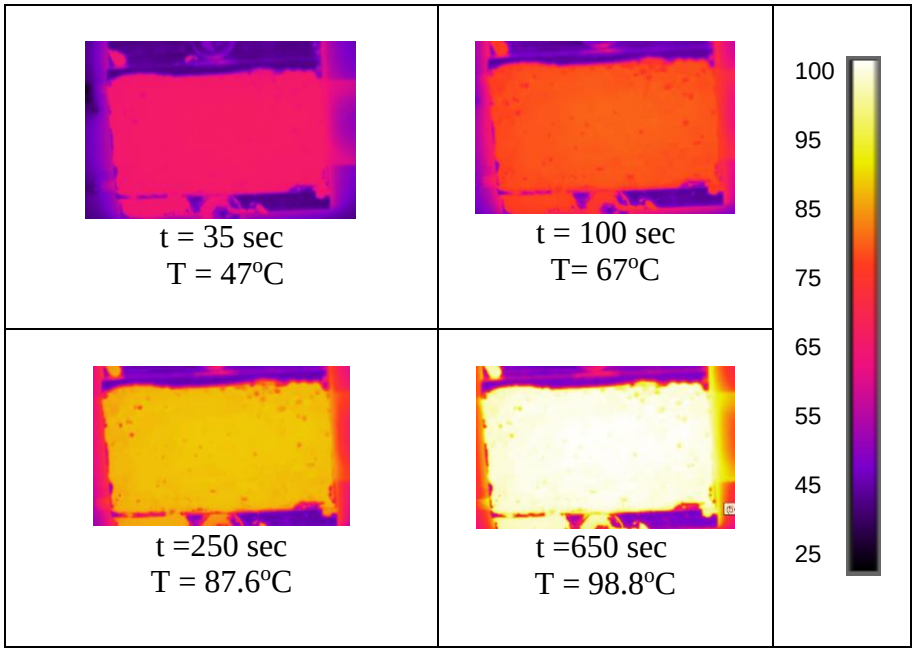


Figure 66: IR images of PTC heater at room conditions (24°C)
(area average surface temperature)

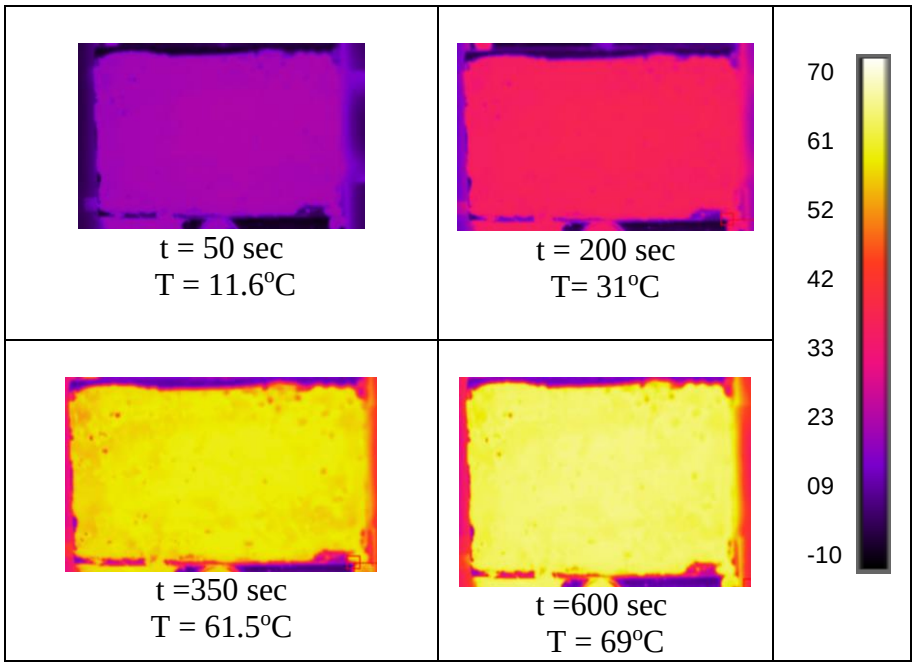


Figure 67: IR images of PTC heater in cold environment (-10°C) (area average surface temperature)

4.3. Temperature Measurement and Control of PTC Heater with PID Control

As discussed in Section 3.2, TMCS was built to measure and control the temperature of PTC heater. The experimental procedure is defined in Section 3.5. The series of experiments were performed in order to obtain optimum proportional, integral and derivative (PID) gain values. These values were optimized at the room temperature and inside the cold environment. The overview of the results is shown in Table 12, 13 and 14. In these tables, figure numbers are also mentioned. The figure numbers corresponds to a specific set point temperature with P, I and D gains.

Table 12 show the overview of results acquired at room conditions (24°C). Table 13 shows the overview of results acquired at cold environmental conditions (-10°C). Table 14 shows the addition of IRT measurements to the optimized PID results.

Table 12: Overview of results of temperature measurement and control system (TMCS) at room conditions (24°C)

Results at Room Conditions (24°C)						
Initial Temperature (°C)	Set Point (°C)	PID Gains			Corresponding Figure No.	Discussion Theme (Section 4.1)
		P	I	D		
24°C	-	0	0	0		Response without PID control
	35	1	0	0	68	Optimizing control system for P gain
	45	1	0	0	69	
	35	1	0.3	0	70	Optimizing control system for P and I gains
	45	1	0.3	0	71	
	35	1	0.3	0.4	-	Optimizing control system for P, I and D gains
	45	1	0.3	0.4	-	
	35	1	2	0	72	
	55	1	2	0	73	

Table 13: Overview of results of temperature measurement and control system (TMCS) at cold environmental conditions (-10°C)

Results at Cold Environmental Conditions (-10°C)						
Initial Temperature (°C)	Set Point (°C)	PID Gains			Corresponding Figure No.	Discussion Theme (Section 4.2)
		P	I	D		
-10°C	5	1	x	x	74	Optimizing control system for P gain
	5	1	0.4	x	75	Optimizing control system for P and I gains
	5	1	0.3	x	76	
	5	1	0.3	0.01	77	Error observed in the system with D gain
	15	1	0.3	0.01	78	Optimizing control system for P, I and D gains
	25	1	0.3	0.01	79	
	35	5	0.15	0	80	
	55	5	0.15	0	81	

Table 14: Overview of TMCS readings' comparison with infrared thermography

Room Conditions (24ºC)							
Initial Temperature (ºC)	Set Point (ºC)	PID Gains			Correspon-ding Figure No.	IRT Plot	Discussion Theme (Section 4.3)
		P	I	D			
24ºC	35	1	2	0	82	Included	IR temperature overlay on optimized PID gains
	55				83		
Cold Environmental Conditions (-10ºC)							
Initial Temperature (ºC)	Set Point (ºC)	PID Gains			Correspon-ding Figure	IRT Plot	Discussion Theme (Section 4.3)
		P	I	D			
-10ºC	35	5	0.15	0	84	Included	IR temperature overlay on optimized PID gains
	55				85		

4.3.1. Optimizing P, I and D gains at room conditions

Table 15 shows the summary of results using PID gains with TMCS. The temperatures are set at 35ºC, 45ºC and 55ºC. Table 15 shows that progressive tuning of P, I and D gains reduced the steady state error.

The optimization of P, I and D gains was done to minimize the steady state error. We have found the optimum values of P, I and D gains using trial and error method. Initially, I and D gains were set to 0. The P gain was increased gradually from 0 to 1. The P gain value greater than 1 was also tested. It was observed that by increasing P gain, TMCS tries to reach the set point temperature as soon as possible. However, only proportional (P) control is not enough to reach the set point temperature as shown in Figure 68 and Figure 69. Hence, Integral (I) controller is introduced to reduce the error. The value of I gain was increased gradually. It was observed that integral controller tries to reduce the error of TMCS. Thus, by introducing P and I controller, TMCS was able to reach the set point temperature as shown in Figure 70 to Figure 73. The derivative (D) controller is generally used to resist sudden changes. In our system, D gain was kept zero since introducing it did not have significant effect on the steady state error.

The optimum values of P=1, I=2 and D=0 were found for our system. The minimum steady state error (±0.3ºC) was achieved using these values at room conditions.

Table 15: Summary of results of the temperature control system (Room Conditions)

Room Conditions (24ºC)						
Initial Temperature (ºC)	Set Point (ºC)	PID Gains			*Steady State Error (ºC)	Figure Number
		P	I	D		
24	-	0	0	0	-	64
24	35	1	0	0	-2.99	68
24	45	1	0	0	-4.82	69
24	35	1	0.3	0	±0.6	70
24	45	1	0.3	0	±0.9	71
24	35	1	0.3	0.4	±0.5	-
24	45	1	0.3	0.4	±0.5	-
24	35	1	2	0	±0.3	72
24	55	1	2	0	±0.5	73
*Steady State Error = (Steady State Max. Temp. - Set Point) + (Set Point - Steady State Min. Temp.)						

Figure 68 to Figure 73 shows the temperature response of resistive device using PID gains at room temperature. These figures shows PTC resistive device temperature and set point temperature vs time. The PTC resistive device temperature is observed through TMCS (using pt100 sensor). Each figure (Figure 68 to Figure 73) shows these plots at a specific value of P, I and D.

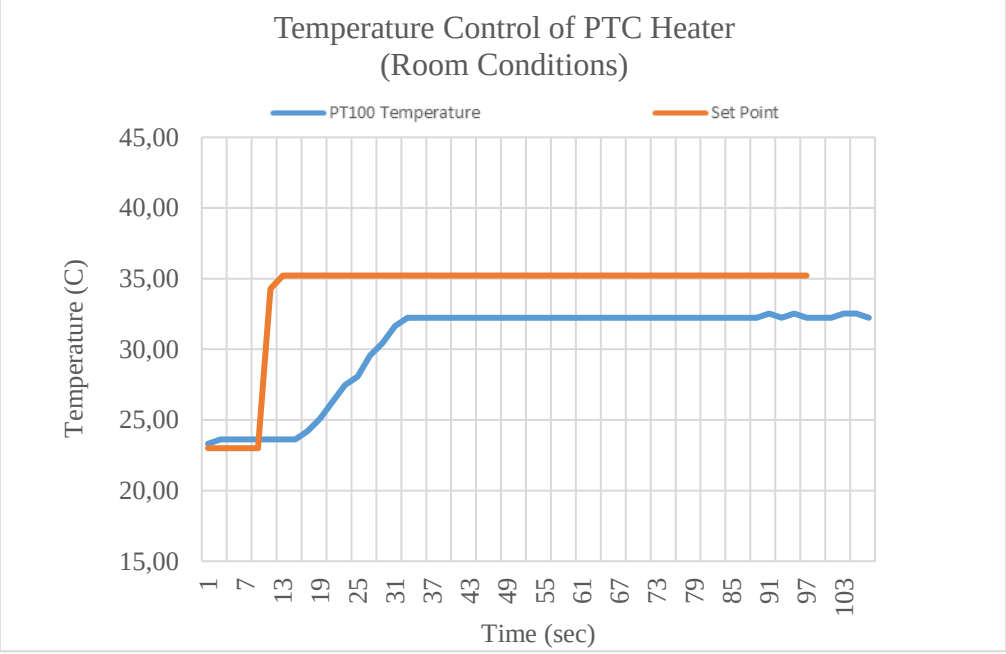


Figure 68: Temperature control of PTC heater (using TMCS) vs time (sec)
Gain P=1 I=0, D=0 Set point = 35ºC

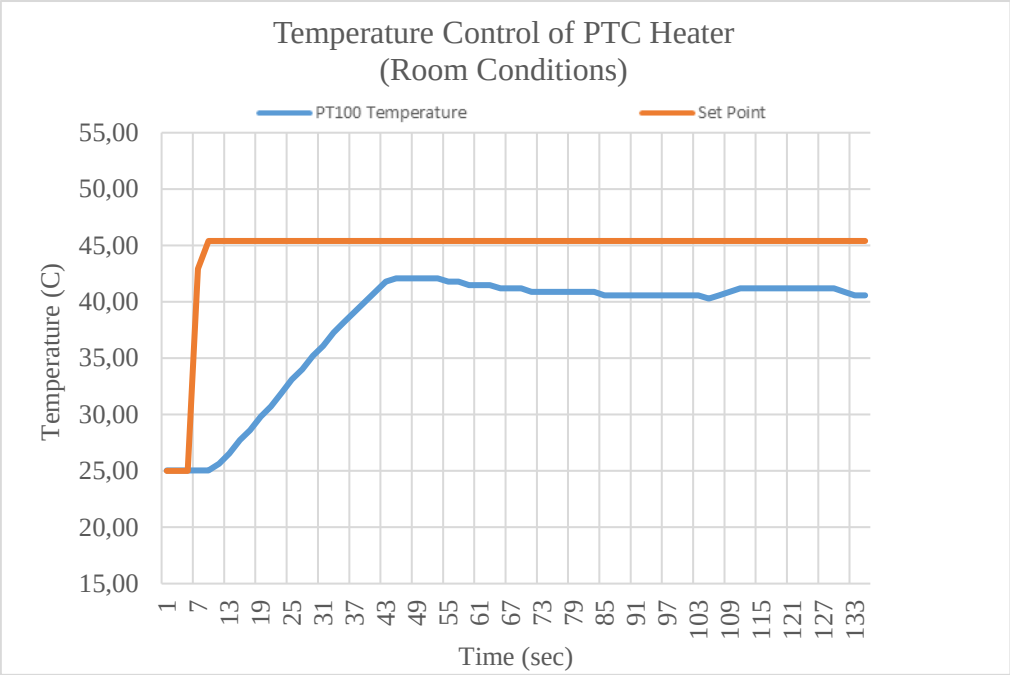


Figure 69: Temperature control of PTC heater (using TMCS) vs time (sec)
Gain P=1, I=0, D=0 Set point = 45ºC

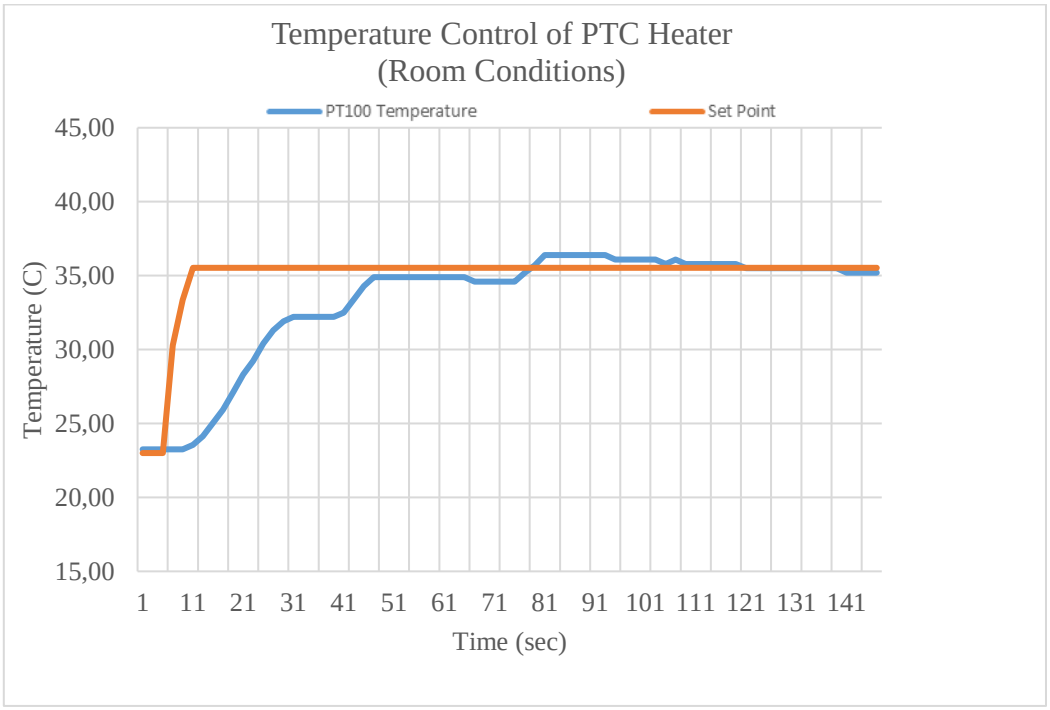


Figure 70: Temperature control of PTC heater (using TMCS) vs time (sec)
Gain P=1, I=0.3 Set point = 35ºC

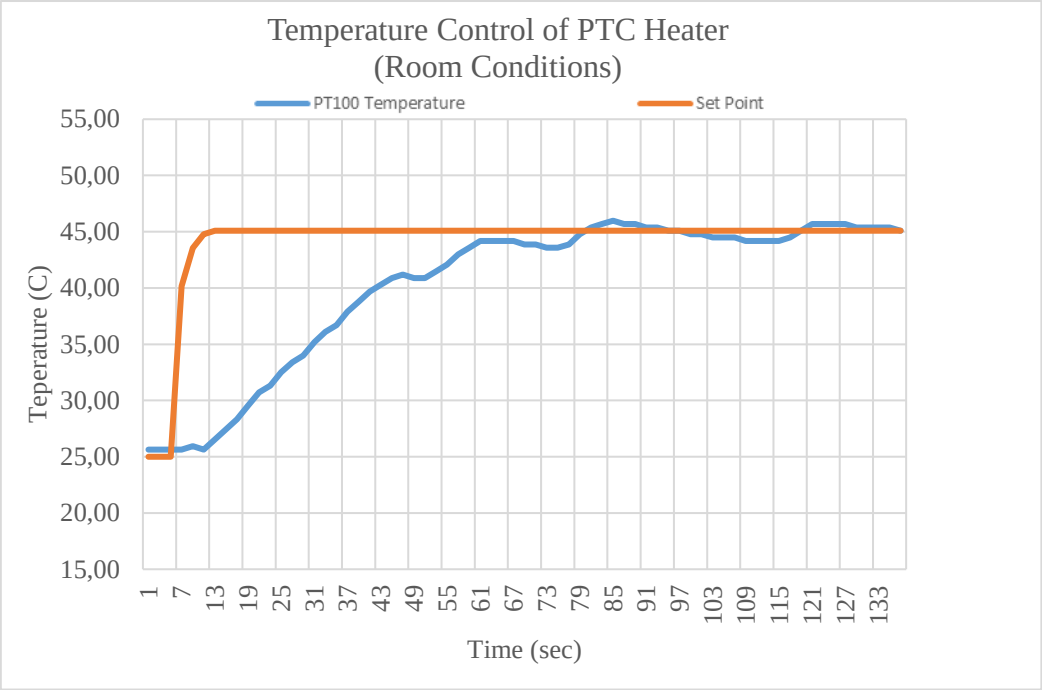


Figure 71: Temperature control of PTC heater (using TMCS) vs time (sec)
Gain P=1, I=0.3, D=0 Set point = 45°C

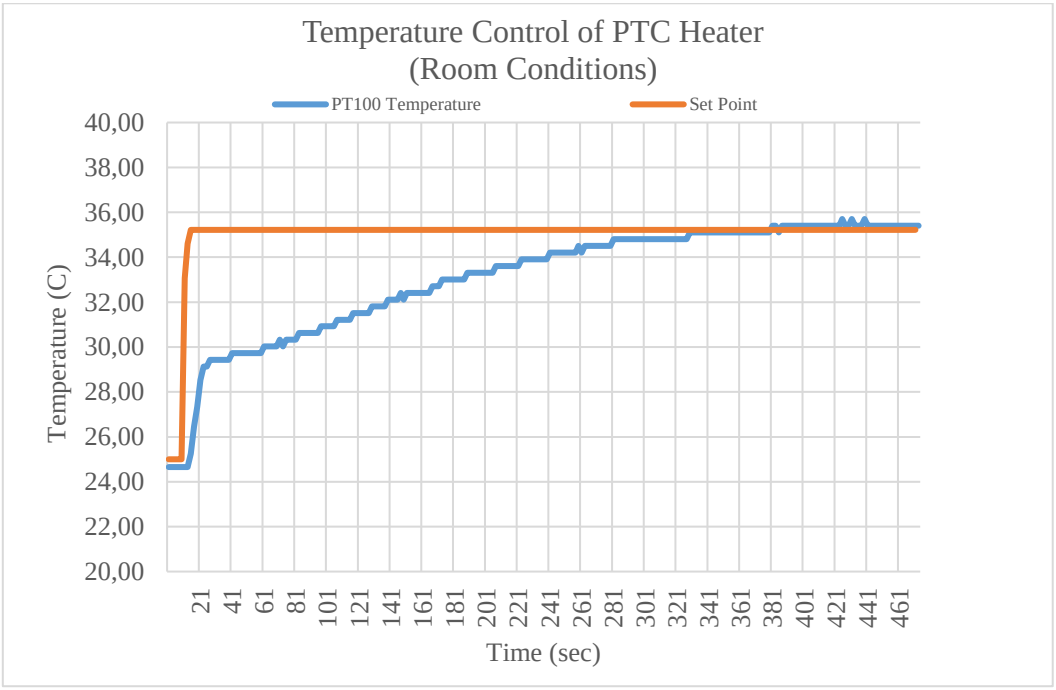


Figure 72: Temperature control of PTC heater (using TMCS) vs time (sec)
Gain P=1, I=2, D=0 Set point = 35°C

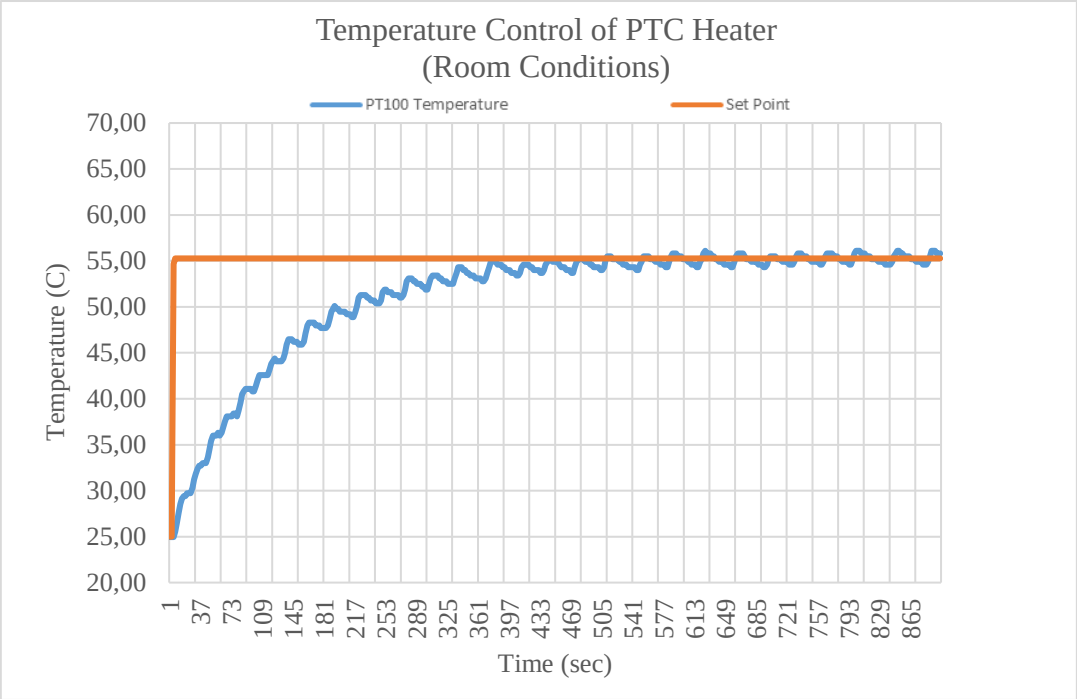


Figure 73: Temperature control of PTC heater (using TMCS) vs time (sec)
Gain P=1, I=2, D=0 Set point = 55°C

4.3.2. Optimizing P, I and D gains in cold environmental conditions

Further experiments were performed inside cold environment chamber. Its temperature was maintained at -10°C. Table 16 shows the summary of results when set point temperatures are 5°C, 15°C, 25°C, 35°C 45°C and 55°C. The P, I, and D gains were optimized inside the cold environment chamber in order to minimize the steady state error. The values of P, I and D were optimized progressively as shown in Table 16.

The optimizing of PID gains in cold environment was done using different sets of P, I and gains. It was found that the optimum PID gains in cold environment were different than the optimum gains at room conditions. Furthermore the steady state error of TMCS in cold environment is more than that of room conditions. The reason might be due to the harsh environmental conditions inside cold environment chamber.

It was observed that for a similar PID gain values, the error between set point and resistive heater device temperature was more in cold environment as compared to room conditions. For instance, at P=1, I=0 and D=0, the error (in cold environment) is about 4.5°C. On the other hand, this error is 3°C in room conditions for the same values of PID gains.

The cold environmental chamber is set at -10°C and it has a fan which produces gusts of cold air. This causes the resistive heater to cool down quickly due to cold temperature and forced convection. In order to reach the set point temperature, the P gain is increased to a higher value. However, only proportional (P) control is not enough to reduce the steady state error.

Hence Integral (I) controller is introduced to reduce the error. The optimum integral (I) gain of 0.15 was found. This value is smaller as compared to the one at room conditions (I=2). The reason could be due to comparatively larger optimum P gain (P=5) which takes the TMCS closer to the set point temperature. It was also observed that further increasing integral gain does not improve the system response. In cold environment conditions, the derivative gain was also kept zero since introducing it did not have significant effect on steady state error. The PI controller was adequate for our system.

The optimum values of P=5, I=0.15 and D=0 were found for our system. The minimum steady state error of ±0.6ºC was achieved using these values in cold environment (-10ºC).

Figure 74 to Figure 81 shows the plots of set point temperature and PTC heater temperature recorded from the pt100 sensor. Each figure (Figure 74 to Figure 81) shows these two plots at a specific value of P, I and D. It can be observed from Table 16 that progressive tuning of P, I and D gains has reduced the steady state error.

Table 16: Summary of results of the temperature control system (cold environment conditions)

Cold Environment Conditions (-10ºC)						
Initial Temperature (ºC)	Set Point (ºC)	PID Gains			*Steady State Error	Figure Number
		P	I	D		
-10	5	1	x	x	-3.89	74
-10	5	1	0.4	x	±1.1	75
-10	5	1	0.3	x	±0.75	76
-10	5	1	0.3	0.01	±0.74	77
-10	15	1	0.3	0.01	±0.74	78
-10	25	1	0.3	0.01	±0.75	79
-10	35	5	0.15	0	±0.6	80
-10	55	5	0.15	0	±0.6	81

*Steady State Error = (Steady State Max. Temp. - Set Point) + (Set Point - Steady State Min. Temp.)

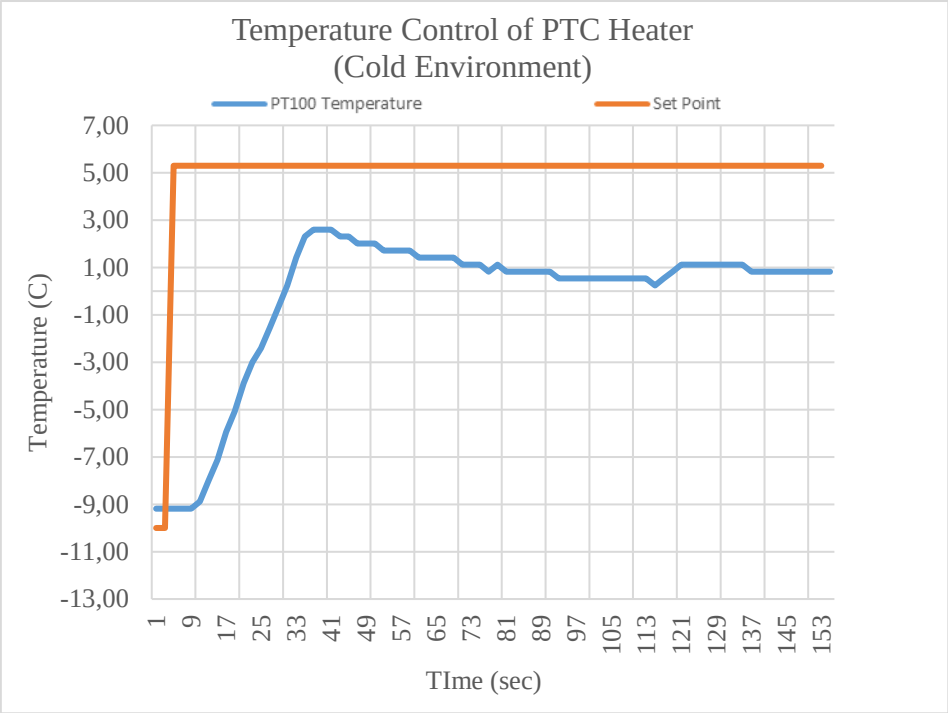


Figure 74: Temperature control of PTC heater (using TMCS) vs time (sec)
Gain P=1, I=0, D=0 Set point = 5ºC

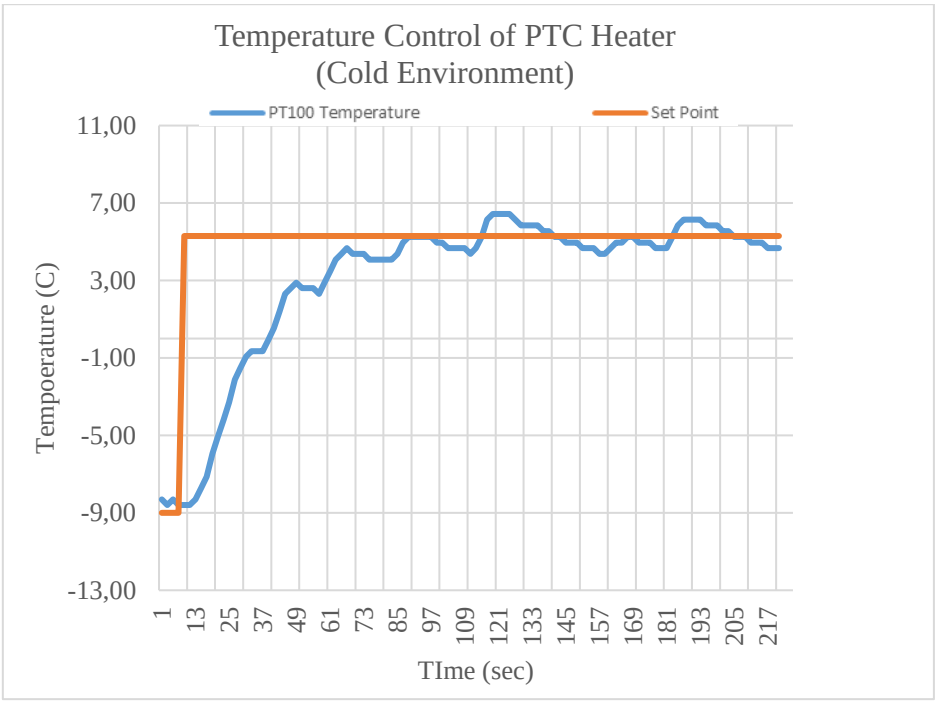


Figure 75: Temperature control of PTC heater (using TMCS) vs time (sec)
Gain P=1, I=0.4, D=0 Set point = 5ºC

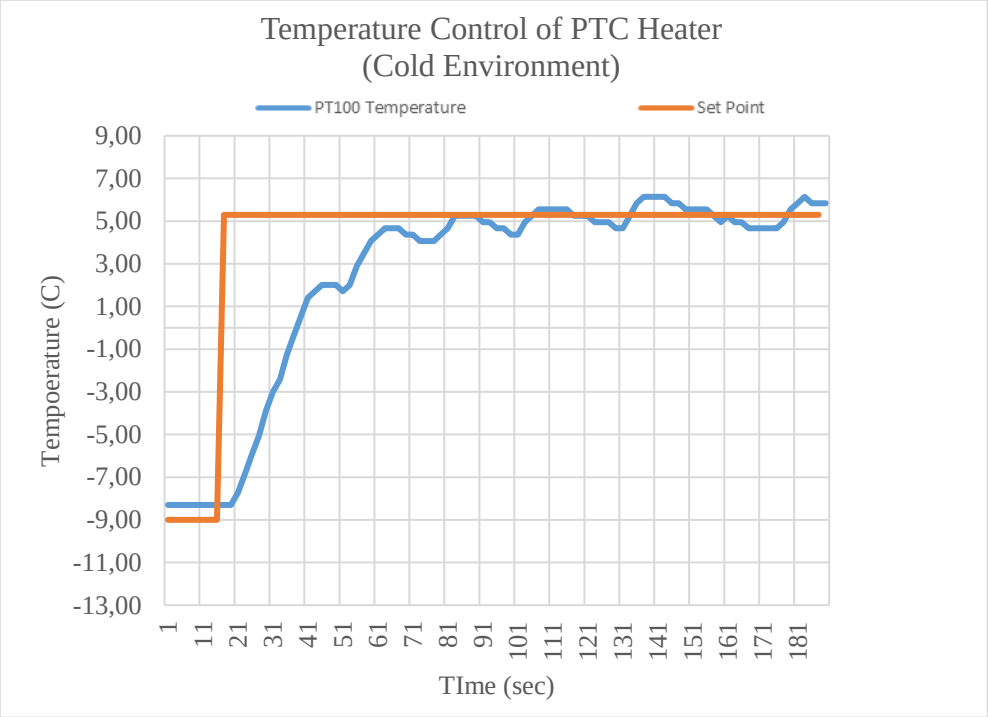


Figure 76: Temperature control of PTC heater (using TMCS) vs time (sec)
Gain P=1, I=0.3, D=0 Set point = 5^{o}C

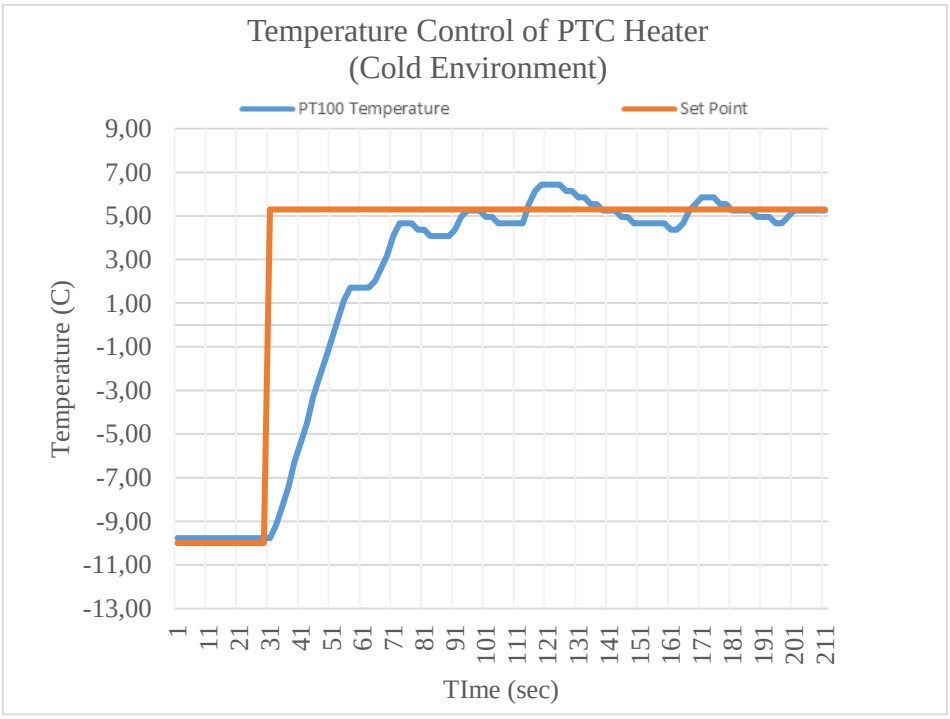


Figure 77: Temperature control of PTC heater (using TMCS) vs time (sec)
Gain P=1, I=0.3, D=0.01 Set point = 5^{o}C

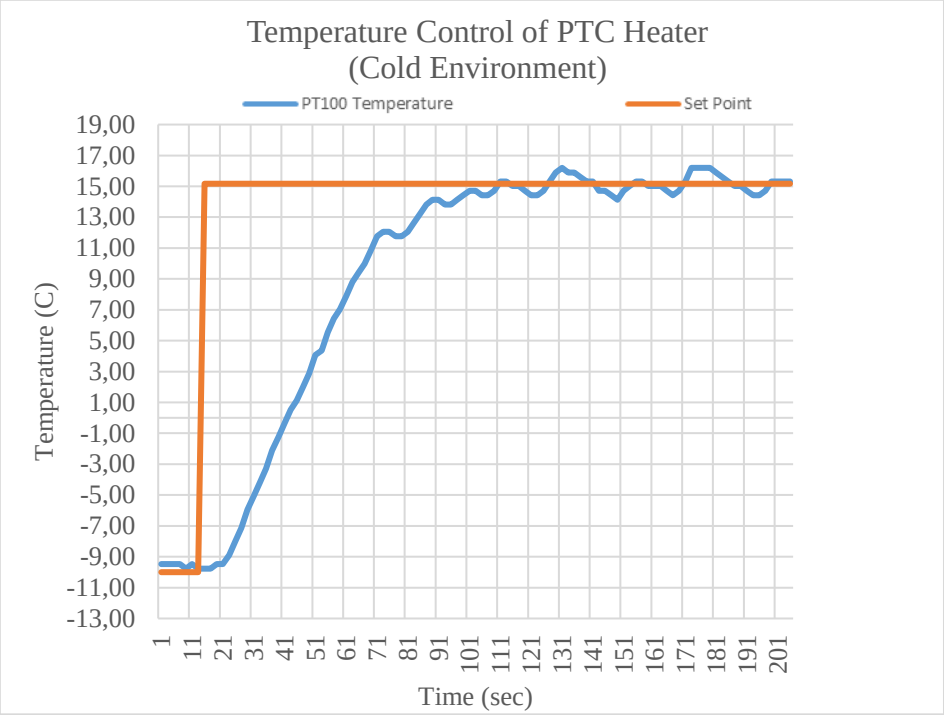


Figure 78: Temperature control of PTC heater (using TMCS) vs time (sec)
Gain P=1, I=0.3, D=0.01 Set point = 15ºC

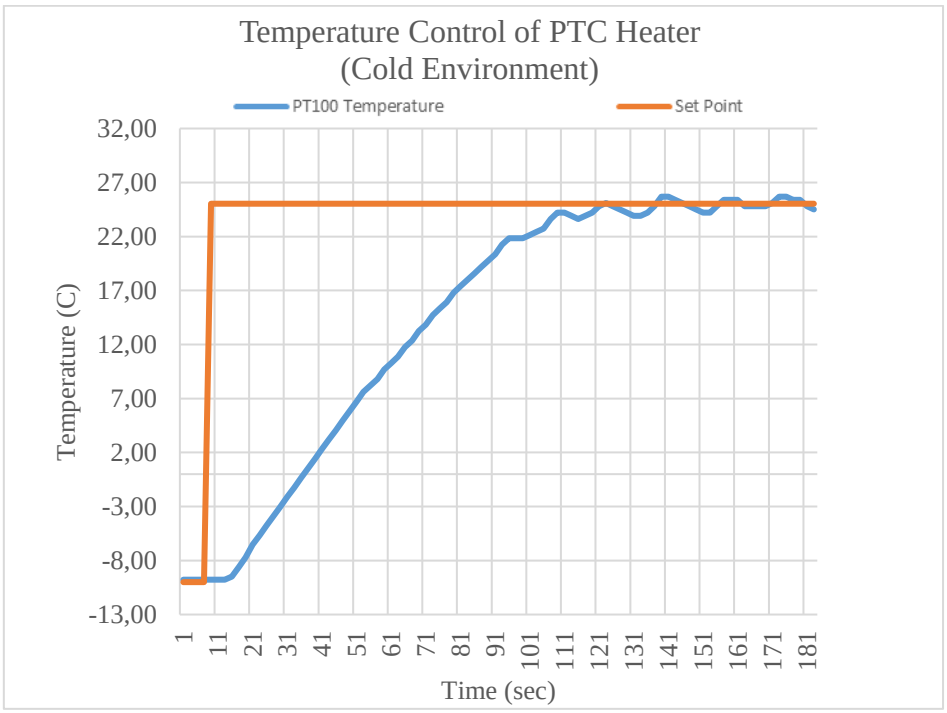


Figure 79: Temperature control of PTC heater (using TMCS) vs time (sec)
Gain P=1, I=0.3, D=0.01 Set point = 25ºC

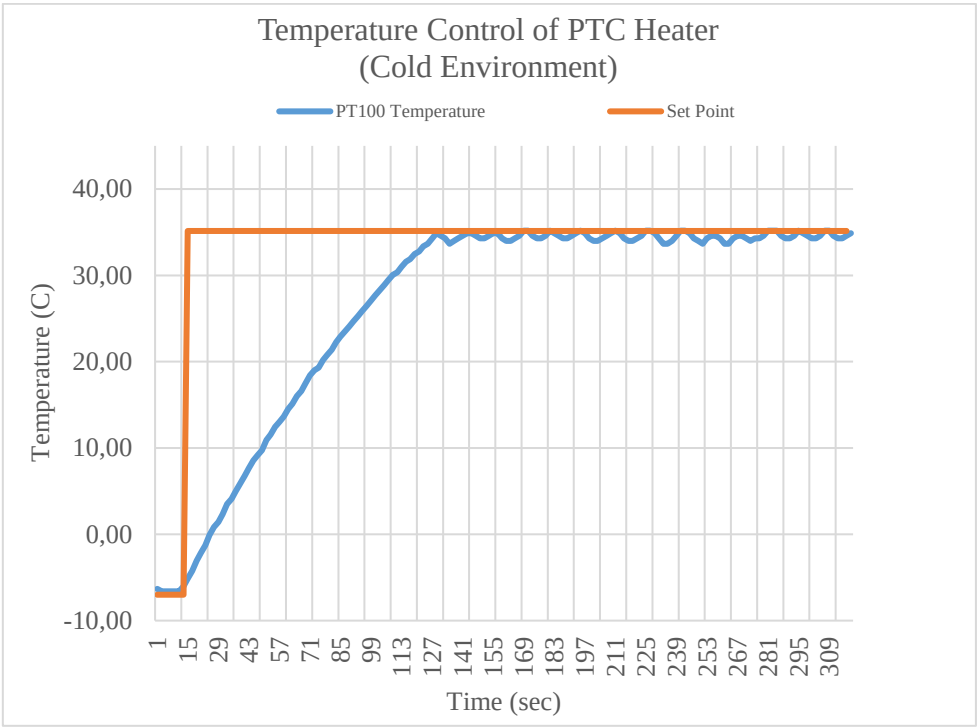


Figure 80: Temperature control of PTC heater (using TMCS) vs time (sec)
Gain P=5, I=0.15, D=0 Set point = 35ºC

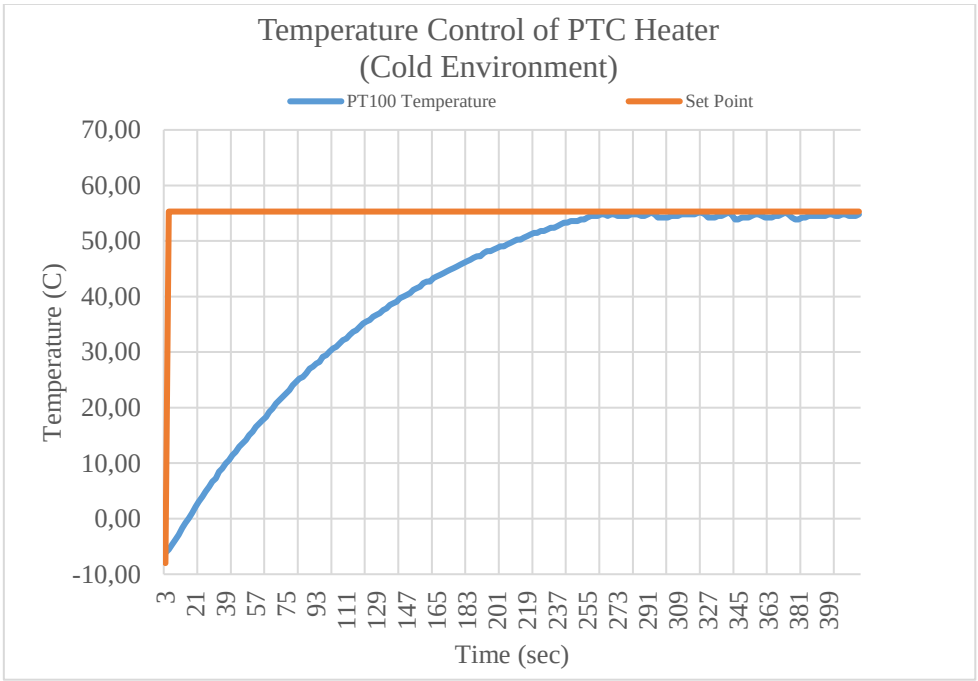


Figure 81: Temperature control of PTC heater (using TMCS) vs time (sec)
Gain P=5, I=0.15, D=0 Set point = 55ºC

4.3.3. Comparison of TMCS with corresponding IR readings of PTC heater

Section 4.2.1 and Section 4.2.2 shows the optimization of TMCS at room and cold environment conditions. Once the system is optimized, IR thermography (IRT) was done for comparison. The results shows that the infrared temperature readings of the resistive heater corresponds with its TMCS readings. Figure 82 and Figure 83 show the comparison at room temperature at 35ºC and 55ºC. Figure 84 and Figure 85 show the comparison in cold environment condition at 35ºC and 55ºC. It is observed that both temperature readings are close enough. A temperature offset of ±0.5ºC (approximately) was observed between the IR and TMCS (pt100) temperature readings.

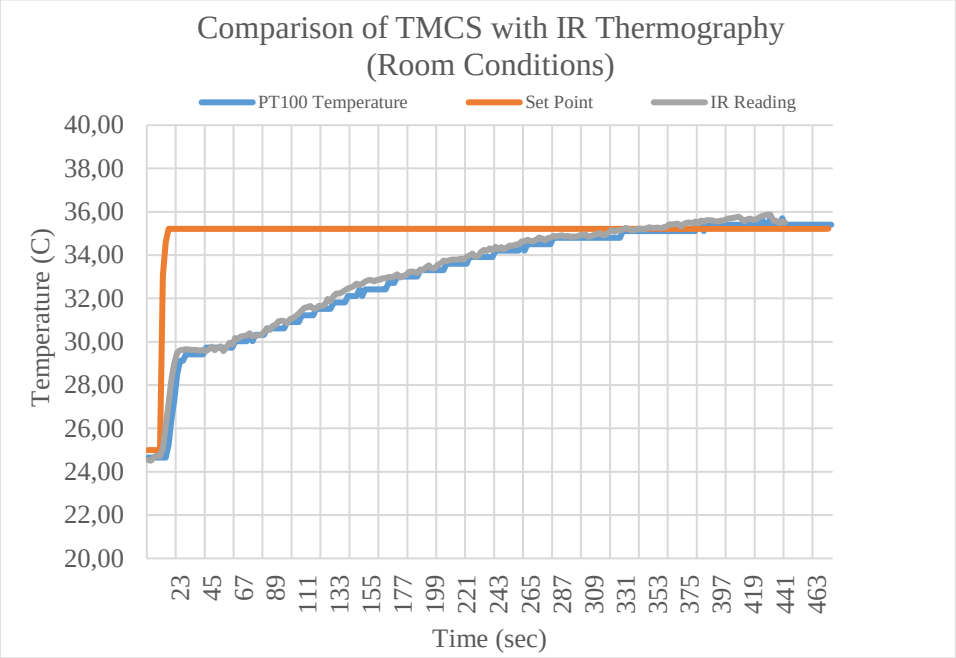


Figure 82: Comparison of TMCS with IR thermography
Gain P=1, I=2, D=0 Set point = 35ºC

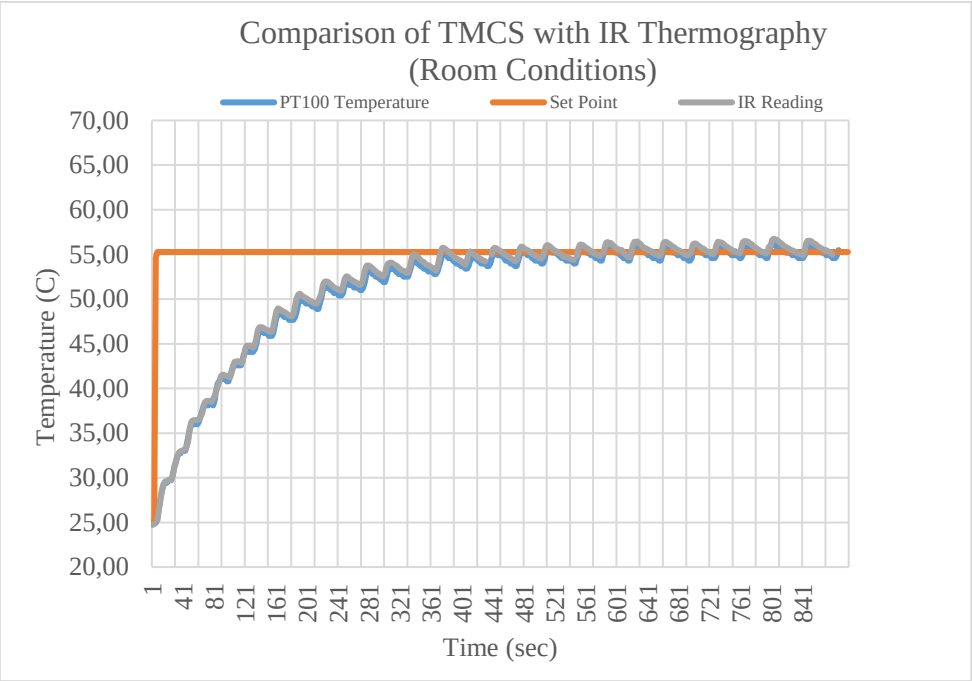


Figure 83: Comparison of TMCS with IR thermography
Gain P=1, I=2, D=0 Set point = 55ºC

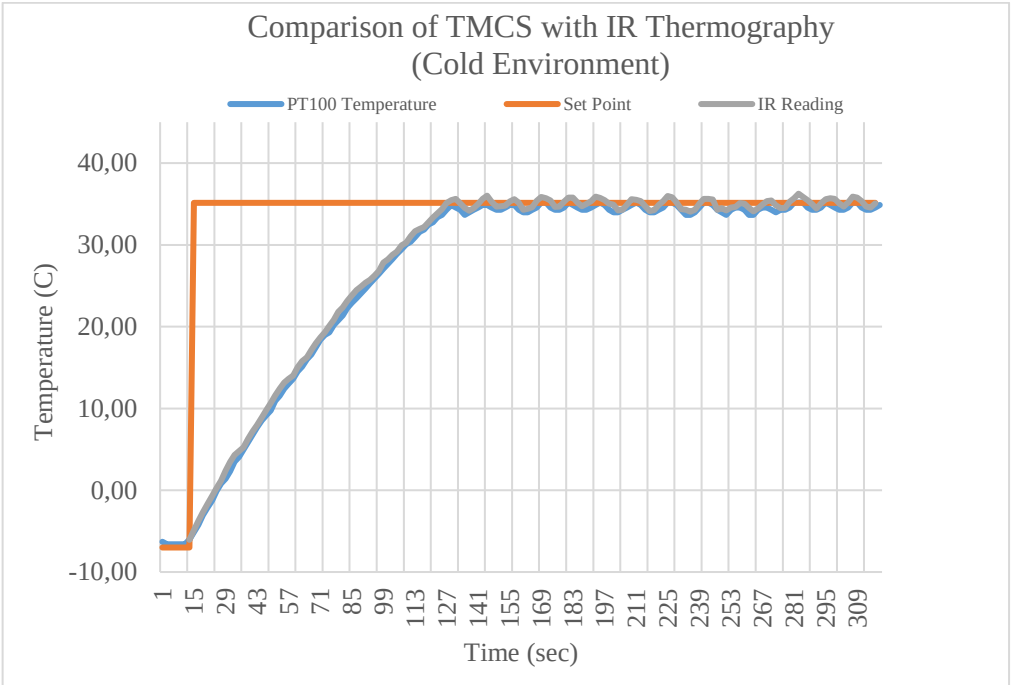


Figure 84: Comparison of TMCS with IR thermography
Gain P=5, I=0.15, D=0 Set point = 35ºC

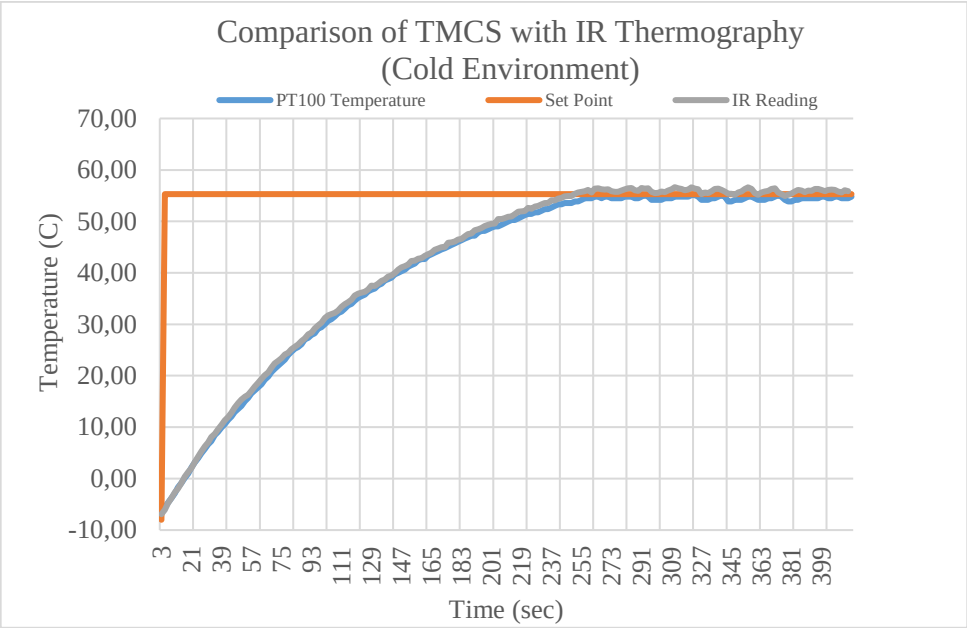


Figure 85: Comparison of TMCS with IR thermography
Gain P=5, I=0.15, D=0 Set point = 55°C

4.4. MATLAB® Simulation Results of PTC Heater

4.4.1. Comparison of simulated vs experimental results at room conditions

The model of PTC heater described in Section 3.6.3 (Figure 58) was simulated at room conditions. It can be observed form Figure 86 that the temperature of the PTC heater rises from 24°C. The temperature of the heater continues to rise until it reaches its maximum point i.e. 100°C.

Figure 86 shows that the temperature of simulated PTC heater reaches 100°C within 650 seconds (approximately). This response corresponds to the experimental results of PTC heater obtained at room temperature as shown in Figure 64. In Figure 64 temperature reaches 100°C within 680 seconds (approximately).

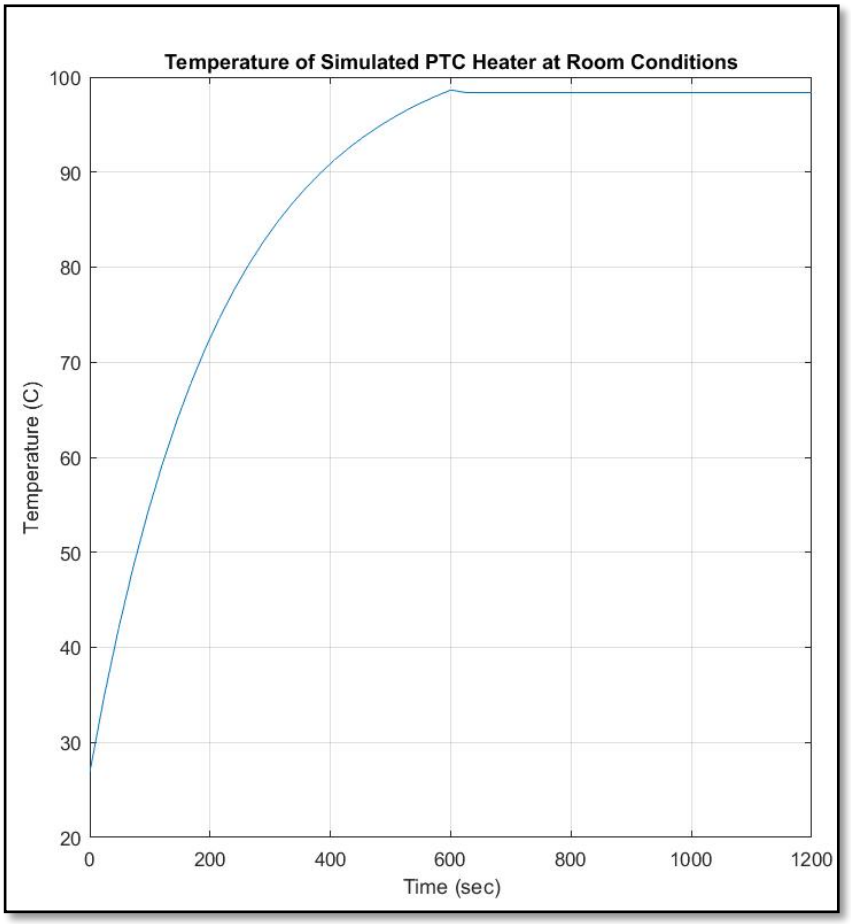


Figure 86: Temperature of PTC heater at room conditions (simulation results)

4.4.2. Comparison of simulated vs experimental results in cold conditions

The model of PTC heater described in Section 3.6.4 (Figure 59) was simulated in cold environmental conditions. It can be observed form Figure 87 that the temperature of the simulated PTC heater rises from -10^{o}C.The temperature of the heater continues to rise until it reaches at 65^{o}C. The temperature is maintained at 65^{o}C. The temperature does not rise further due to the cold environment.

The simulated temperature vs time response corresponds to the experimental result of PTC heater obtained in cold environmental conditions. The simulated result shown in Figure 87 can be compared with the experimental results shown in Figure 65.

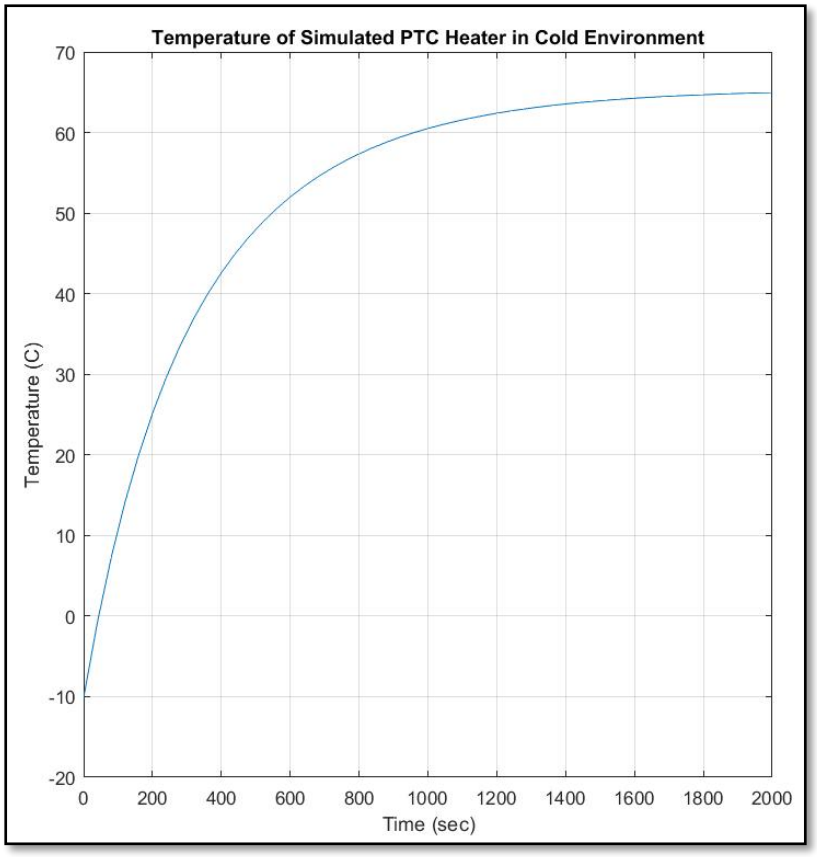


Figure 87: Temperature of PTC heater in cold environment (simulation results)

4.5. Limitations

1. It is observed that steady state error of TMCS is more in cold environment condition as compared to room conditions. The cold atmosphere might be the contributing factor. It can also be due to the localized conditions inside the cold environment chamber. This chamber is installed with a cooling fan to blow cool air from top to bottom. The irregular gusts of cool air can cause forced convection on the surface of the resistive heater. This can cause a sudden temperature drop in the resistive heater. This can introduce a small delayed response of PID controller (of TMCS). Hence, the steady state error could become more in the cold environment chamber. The steady state error can be improved if the thermal mass of the heating element is increased considerably. This testing was not inside the scope of the study.

2. Further when the IR and TMCS temperature readings of resistive heater were compared. A temperature offset of ±0.5^{o}C (approximately) was observed between the IR and TMCS (pt100) temperature readings. It can be caused due to two reasons. First, IR plot can vary from TMCS resistive heater plot (measured by pt100) due to change in emissivity with temperature. It means that emissivity of the coating material on resistive heater can slightly vary as the temperature rises. This can influence the temperature reading obtained from IR

camera. Secondly, the excitation current of pt100 needs to be entered correctly in the TMCS software. A slight fluctuation in excitation current (in mA) can affect the temperature by ±0.2^{o}C observed by pt100.

Chapter 5

5. Conclusion

This work presents a comprehensive analysis of smart heating devices at room conditions and cold environment conditions. Their application is broad ranging from modern day industrial appliances to the emerging smart wearables. Two temperature measurement methods were used in this analysis. A contact based measurement (using a RTD i.e. pt100) and a non-contact based measurement (IR thermography using T1030Sc FLIR® IR camera). To implement the methodology, a prototype of temperature measurement and control system (TMCS) is developed. It is based on PID control system where pt100 is providing temperature feedback. The surface temperatures of the PTC heater are recorded using TMCS and compared with the infrared temperature readings. In this study, a laboratory scale prototype of heating control system is implemented. Inclusion of IRT provides an added advantage to validate this control system. The experiments are performed at room conditions and the cold environment conditions. The results from contact and non-contact measurements correspond with one another. The experimental results shows a typical control system response. The steady state error of ±0.3^{o}C at room conditions was observed using TMCS prototype. However, the steady state error inside cold environment was found more as compared to room environment. The steady state error of ±0.6^{o}C was observed in cold environmental chamber. The TMCS temperature readings were compared with infrared thermography (IRT). The comparison of temperature measurements acquired from TMCS and IRT correspond with each other with an error of ±0.5^{o}C (approximately). A PTC heater's model was simulated in this study. The simulation results of resistive heater correlates with the experimental results.

The learning outcomes from this work is thermal analysis of PTC heaters and peltier device. It contains the design and implementation of a temperature measurement and control system. Furthermore, it includes the fundamental understanding of smart heating devices, implementing a laboratory scale prototype, understanding of IR Thermographic principles, operations of an industrial IR camera, hands on experience in engineering software tools such as LabView®, MATLAB®, FLIR® Research IR and Altium® Designer.

5.1. Future Work

This work focused on the understanding of thermal analysis of smart heating devices. These heating devices are widely used in the industry. There are many possible applications of such devices. The future applications includes electronic appliances with controlled heating and smart heating wearables. Self-heating smart jackets are recently manufactured that involve resistive heating [18]. Moreover, wearable resistive heaters can potentially be used in medical

field for thermal therapy [19]. Performance analysis of such heating devices can be helpful in the product development.

A laboratory scale prototype is successfully tested namely temperature measurement and control system (TMCS). This prototype can be further developed and tested in industrial applications.

The PID control system implemented in the TMCS can be improved by introducing an additional feedback of IR temperature. This could assist to improve the PID control response and reduce the steady state error.

Finally, the results from this thesis are intended to be published in a journal article.

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