T.R.
YUZUNCU YIL UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES
DEPARTMENT OF MECHANICAL ENGINEERING

TEMPERATURE CONTROL OF A SYSTEM WITH SMALL VOLUME IN HEATING AND COOLING PROCESS

MASTER THESIS

PREPARED BY: Sulaiman Abdullah MOHAMMED
SUPERVISOR: Asst. Prof. Dr. Atilla BAYRAM

VAN-2017

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ACCEPTANCE and APPROVAL PAGE

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THESIS STATEMENT

All information contained in the thesis which was obtained in the framework of ethical conduct and academic rules In addition all types of information that does not belong to me have been named appropriately in the thesis prepared by the thesis writing rules.

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ABSTRACT

TEMPERATURE CONTROL OF A SYSTEM WİTH SMALL VOLUME IN HEATING AND COOLING PROCESS

MOHAMMED, Sulaiman Abdullah
M. Sc. Thesis, Mechanical Engineering Department
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Temperature control of systems has become an important subject in many areas, especially, in industrial operations at wide range of operating temperature. Another important field of the temperature control is the identification of mechanic characteristics of materials. This study consists of a design of temperature controlled heating and cooling system. This system, which allows operations over wider temperature ranges, will be used in a tension-compression testing machine. The heating side of the system involves basically an isolated metal box, dry resistance, voltage regulator, thermocouple, air fun, relay, amplifier, microcontroller and computer. The temperature inside the box is controlled by a feedback control. This feedback control system measures the temperature via a K-type thermocouple and uses a PID controller to compensate the errors.

The cooling process is very important for cooling the electric and electronic devices, industrial process, food production process, pharmaceutical industry and scientific laboratory. If you work on the cryogenic processes, the best method for quite lower temperatures is to use liquid nitrogen. For this system, in addition to the heating part devices, the cooling system involves an electronic valve, DC motor driver and a liquid nitrogen tank. In this side, a proportional control is used to control the temperature in accordance with the valve characteristics.

The Arduino board is used as microcontroller because it is simple, cheaper, and easy to program. All communications between the computer and the setup are made via the Arduino card. For real time implementations, the programs written on MATLAB software have shown a great success for both the communication and the control.

In this experimental study, based on the requirement, the heating and cooling processes are performed separately or sometimes both at the same time. At first, the user uploads the desired temperature profile to the computer via a program written in MATLAB. By running the program, the temperature control system starts to work. The temperature of the inside of the isolated box is measured continuously with a type-K

thermocouple. This temperature measured by the thermocouple is converted to an analog signal at a voltage of microvolt level. This analog signal is boosted to a millivolt level via MAX31855 amplifier plugged into Arduino. At the same time, this amplifier converts the analog signal to the digital one. This signal is transferred via USB to a program written in MATLAB environment compatible with Arduino and converted a temperature in degrees Celsius. The program also includes PID, P, and on / off controllers as software, and tries to minimize the temperature error between measurement and reference using one of them according to the process. For this aim, the output modified on the controller is transmitted with USB to Arduino again. If heating of the system is required, Arduino adjusts the temperature by changing the load of AC voltage on the heater by sending 0 to 5V DC signal to the power regulator. The cooling process is performed by adjusting the amount of liquid nitrogen by Arduino sending +5, 0 or –5 V constant DC voltage to the electric valve via the motor driver for a calculated time. In some cases, cooling and heating processes can occur simultaneously to supply the desired temperature reference.

In this study, the temperature of the isolated box can be held easily between $+400\ ^{0}\mathrm{C}$ and $-100\ ^{0}\mathrm{C}$. Implementing some experiments, the user defined different reference temperature profiles are achieved on the test machine and are compared with that of the mathematical modeling of the cooling and heating system. It is seen that the errors are acceptable level.

Keywords:

Arduino, Control system, Cooling and heating, Temperature control.

ÖZET

KÜÇÜK HACİMLİ BİR SİSTEMİN YÜKSEK VE DÜŞÜK DEĞERLERDE ISITILMASI VE SOĞUTULMASINDA SICAKLIK KONTROLÜ

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Sıcaklık kontrol sistemleri birçok alanda özellikle geniş çalışma sıcaklığı aralıklarındaki endüstriyel işlemlerde oldukça önemli bir konu olmuştur. Sıcaklık kontrolünün diğer önemli bir kullanım alanı ise malzemelerin mekanik karakteristiklerinin tanımlanmasında kullanılmasıdır. Bu çalışma sıcaklık kontrollü bir ısıtma ve soğutma sisteminin tasarımını içermektedir. Çok geniş sıcaklık aralıklarında çalışmaya izin veren bu sistem bir çekme-basma test cihazı üzerinde kullanılacaktır. Sistemin ısıtma tarafı temel olarak yalıtılmış metal hazne, kuru rezistans, güç ayarlayıcı, ısıl çift, hava fanı, röle, yükselteç, mikro kontrolcü ve bilgisayardan oluşmaktadır. Haznenin içinin sıcaklığı bir geri besleme kontrolü ile kontrol edilmektedir. Bu geri besleme kontrol sistemi sıcaklığı bir K-tipi ısıl çift ile ölmekte olup hataları telafi etmek için PID kontrolcü kullanmaktadır.

Soğutma işlemi elektrik-elektronik cihazların soğutulmasında, endüstriyel süreçlerde, gıda üretim süreçlerinde, ilaç endüstrisinde ve bilimsel laboratuarlarda oldukça önemli bir işlemdir. Eğer kriyojenik süreçler üzerine çalışıyorsanız çok düşük sıcaklıklar için en iyi metot sıvı azot kullanmak olacaktır. Bu sistem için ısıtma kısmındaki cihazlara ek olarak soğutma sistemi elektronik valf, DC motor sürücüsü ve sıvı azot tankını da içermektedir. Bu kısımda sıcaklık kontrolü valf karakteristiğine uygun olarak oransal kontrol işlemi ile yapılmaktadır.

Bu sitemde basit, ucuz ve programlanması kolay olduğu için mikro kontrolcü olarak Arduino elektronik kartı kullanılmıştır. Bilgisayar ve deney düzeneği arasındaki tüm haberleşmeler bu kart aracılığı ile gerçekleştirilmiştir. Gerçek zamanlı uygulamalar için MATLAB yazılım paket programı üzerinde yazılan programlar hem haberleşmede hem de kontrolde büyük bir başarı göstermiştir.

Bu deneysel çalışmada, ihtiyaca göre ısıtma ve soğutma işlemleri ayrı ayrı, bazen de her ikisi aynı anda gerçekleşebilmektedir. Önce, kullanıcı istenilen sıcaklık profilini MATLAB programı aracılığı ile bilgisayara yüklemektedir. Programın çalıştırılmasıyla sıcaklık kontrol sistemi çalışmaya başlar. Yalıtılmış haznenin içinin sıcaklığı K-tipi bir ısıl çift ile sürekli olarak ölçülmektedir. Isıl çift ile ölçülen sıcaklık mikro volt seviyesinde bir analog sinyaldir. Bu sinyal Arduino'ya takılan MAX31855 yükselticisi ile mili volt seviyesine yükseltilmektedir. Aynı zamanda bu yükseltici analog sinyali dijitale de çevirmektedir. Arduino'ya aktarılan bu sinyal USB aracılığı ile Arduino ile uyumlu çalışan MATLAB ortamında yazılan bir programa santigrat derece cinsinden sıcaklık olarak aktarılmaktadır. Bu program aynı zamanda yazılım olarak PID, P ve On/Off kontrolcüleri ihtiva edip işlemin türüne göre bunlardan birini kullanarak ölçüm ve referans arasındaki sıcaklık hatasını en aza indirmeye çalışmaktadır. Bu amaç için kontrolcüde düzeltilmiş çıkış yine USB aracılığı ile Arduino'ya iletilmektedir. İşlemin türüne göre eğer ısıtma işlemi gerekiyorsa Arduino 0-5V arası DC sinyali güç ayarlayıcıya göndererek ısıtıcı üzerindeki AC voltajın yükünü değiştirerek sıcaklığı ayarlamaktadır. Eğer soğutma işlemine ihtiyaç duyuluyorsa Arduino elektrik valfına motor sürücüsü aracılığı ile hesaplanan bir zaman için +5, 0 veya –5 V sabit DC voltajı göndererek sıvı azotun miktarını ayarlayarak soğutma işlemini yapılmaktadır. Bazı durumlarda soğutma ve ısıtma işlemi aynı anda gerçekleşebilmektedir.

Bu çalışmada, yalıtılmış haznenin sıcaklığı $+400\ ^{0}C$ ila $-100\ ^{0}C$ arasında kolay bir şekilde tutulabilmiştir. Bazı deneysel çalışmaların uygulanmasıyla, kullanıcı tanımlı değişik sıcaklık profilleri başarılı bir şekilde test cihazı üzerinde gerçekleştirilmiş ve sonuçlar ısıtma ve soğutma sisteminin matematiksel modelinden elde edilen sonuçlar ile karşılaştırılmıştır. Oluşan hataların kabul edilebilir bir seviyede oldukları görülmüştür.

Anahtar kelimeler: Arduino, Isıtma ve soğutma, Kontrol sistemi, Sıcaklık kontrolü.

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Sulaiman Abdullah MOHAMMED

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SYMBOLS AND ABBREVIATIONS

Some symbols and abbreviations used in this study are presented below, along with descriptions**.**

Symbols	**Description**
A	Area [m^2]
L	Length [m]
V	Volume [m^3]
R	Thermal resistance [K/W].
T	Temperature [°C or Kelvin].
C	Thermal capacity [J/ (kg K)].
h	Heat transfer coefficient [W/ (m^2 K)].
k	Thermal conductivity [W/ (m K)].
$\dot{Q}$	Heat flow [W].
W	Power [W].
$\dot{m}$	Mass flow rate [kg/s].
ρ	Density [kg/m^3].
ϕ	Humid air relative humidity [%].
h	Latent heat of evaporation LN2 [J/kg].
C_p	Specific heat capacities at constant pressure [kJ/kg K].
C_v	Specific heat capacities at constant Volume [kJ/kg K].
K	Ration of specific heats$\frac{CP}{CV}$.
U	Overall heat transfer coefficient (W/(m2•K))
m	Mass. kg
T_1 **&** T_2	Temperature. °C
dh	Latent heat of evaporation of nitrogen [J/kg].
K	Process gain Process gain
τ	Dead time constant (sec).
t	Process time

Abbreviations	Explanation
MPC	Model Predictive Controller
PLC	Programmable Logic Controller.
PL	Personal computer.
SERS	Surface enhanced Raman spectroscopy.
PHE	Plate heat exchanger.
ISE	Integral square error.
GPIO	General Purpose Input Output Pins.
USB	Universal Serial Bus.
ITAE	Integral time-weighted absolute error.
LabVIEW	Laboratory Virtual InstruNomenclature.
USEP	United states environmental protection.
TCP	Transmission Control Protocol.
DFB	Distributed Feedback Laser.
FOPDT	First-Order plus Dead time.
TCP	Transmission Control Protocol
DFB	Distributed Feedback Laser.
SISO	Single input and single output.
MIMO	Multiple inputs and multiple outputs.
P	Proportional controller.
PI	Proportional–integral controller.
PD	Proportion derivative controller.
PID	proportional–integral–derivative controller
SSR	Solid State Relays.
TC	Thermocouple.
RTD	Resistance temperature detectors.
EMF	Electromotive force.
LCD	Liquid Crystal Display.
ANSI	American National Standards Institute.
CJC	cold-junction compensation
NIST	National Institute of standards and Technology.

PWM	Pulse width modulation.
EMF	Electromagnetic force.
PWM	Pulse width modulation.
EEPROM	Electrically Erasable Programmable Read only Memory.
SRAM	Static random-access memory
CFC	Chlorofluorocarbon halo methane (R-12) Freon-12, used as a refrigerant and aerosol spray propellant.
ESO	European southern observatory.
AGATA	Advanced Gamma Tracking Array.
IDE	Integrated development environment.
SPI	Serial Peripheral Interface.
FTDI	Future Technology Devices International.

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APPENDIX **Pages**

1. INTRODUCTION

Nowadays, the control system is a significant requirement in all features in the life of human beings. That is especially true for industrial areas; in operations which embrace the precise and complex procedure frequently in a short time that human is unable to perform it correctly and accurately. Therefore, control systems have become very important. By controlling the temperature, some properties of the materials can be modified by heating treatment according to the requirements and the operational environment for these substances. These properties consist of mechanical properties, electrical, thermal, chemical and physical properties. Generally, properties of the material vary from one to another, and they are changed by the influence of the temperature (Acuña, 2008). The importance of monitoring or temperature control is to improve the mechanical properties depending on the working circumstances of materials or devices. Besides heating, the cooling process is also essential in the manufacturing process. For instance, the electric and electronic devices, domestic services, food production process, industrial process, pharmaceutical industry and scientific laboratory are required to use the cooling systems to be maintained necessitated temperature. Electrical fan, cooling by water and air, refrigeration cycle using ammonia (R12), cooling with liquefied gases are the some cooling methods. Cooling to very low temperatures (cryogen process), liquefied gases such as liquefied carbon dioxide, nitrogen, neon, helium are utilized for cooling down purposes.

A successful heat treating is obtained by a decent control of heating and cooling process of a material to achieve certain mechanical properties such as hardness, strength, flexibility and the reduction of residual stresses. Many heat treating processes require accurate temperature control over the heating cycle. This process is applied extensively in metals production and in the tempering and annealing of glass and ceramics products. Sometime materials are exposed to extremely high temperatures (exceeding 400°C) during the industrial processes. On the other hand, the temperature in some areas drops to around –70°C. In these circumstances, the metal or other materials are subjected to tensile stress and compression during operation. The required properties are acquired by heating to specific temperatures and re-cooled in different approaches and at different speeds for particular properties. For instance, the heat treatment process is conducted by

heating the materials to specific temperature according to the each material and keeping it at the temperature for a brief period of time and then cooling it down by coolant. In addition every.

Heating treatment processes are similar in heating stages, however, are varied in the cooling process. Nevertheless, it cannot be performed without precise heating and cooling control systems.

This study consists of a design of temperature controlled heating and cooling system. This system, which allows operations over wider temperature ranges, will be used in a tension-compression testing machine. The heating side of the system involves basically an isolated metal box, dry resistance, voltage regulator, thermocouple, air fun, relay, amplifier, microcontroller and computer. The temperature inside the box is controlled by a feedback control. This feedback control system measures the temperature via a K-type thermocouple and uses a PID controller to compensate the errors. The cooling process is very important for cooling the electric and electronic devices, industrial process, food production process, pharmaceutical industry and scientific laboratory. If you work on the cryogenic processes, the best method for quite lower temperatures is to use liquid nitrogen. For this system, in addition to the heating part devices, the cooling system involves an electronic valve, DC motor driver and a liquid nitrogen tank. In this part, a proportional control is used to control the temperature in accordance with the valve characteristics. In this study, liquid nitrogen was utilized for cooling down process as it is very effective coolant, cheap and easily obtainable. It has the ability to cool down a vast number of material because its boiling temperature is very low (–196 °C).

The general purpose of the controller selection is to compare the actual temperature (instantaneous temperature) with its set point (reference temperature) and produce an output signed to maintain the temperature of the system in this set point range. The whole system should be analyzed in order to choose the proper controller. When selecting a controller, the following items should be taken in to consideration.

- The type of input sensor: for example RTD sensor (resistance temperature detector) thermocouple T/c, card, and temperature range.
- Placement of sensor: contacted sensor and noncontact sensor.
- Control algorithm requirement: for instance on/off, proportional, auto tune PID, fuzzy logic and etc.

- Type of output hardware: such as (electromechanical relay), SSR (Solid State Relay) and analog output signal, regulated power.
- Additional outputs or system requirements: like display required of temperature and/or set point, cooling outputs, alarms, limit, computer communication, etc.

The thesis investigates temperature control in heating and cooling of a small volume system which is utilized to indicate the variation of material properties at different temperatures. This dissertation has been grouped in two sections of studies:

1-The temperature control in heating system until 400°C by electric heater.

The heating process is controlled by microcontroller Arduino Mega 2560 and by MATLAB software code and PID controller. In this experimental project, the devices were designed as small cubic box which is precisely insulated. It was assumed that the system is homogeneous; the heat transfer is stable and occurs only in one direction.

In this system, the heat source is a dry resistance. This resistance is 2.5 kW and the isolated cubic box's inner temperature is adjusted by regulating the voltage on dry resistance. The resistance power can be regulated between 0-2.5 kW. Here the voltage adjustment is done by using 0-5 V DC input. The ELCON Power Regulator produces the desired AC voltage between %0 - %100 (0-220V) according the DC supply by DC source (ARDUINO). The AC Voltage is controlled by Arduino with the output PWM signal that is between 0 – 5V DC. Here the Arduino is used as a microcontroller. Because of using feedback temperature control, the inside isolated box's temperature is measured as an output. The temperature measuring is done by thermocouple type-K which worked in range of –180 °C to +1380 °C produces analog signal at microvolt level. However, Arduino can read the signal at 4.8 millivolts level minimum. For this reason the signal has to be amplified before Arduino's input. Therefore, an amplifier which is called MAX31855 is needed. The measurements are transmitted to a computer with USB connection. With a user coded software the controller produces the necessary input and transmits the signal through serial ports from ARDUINO. The input signal is received as DC Volt to the ELCON regulator and the regulator supplies the control of temperature to obtain the desired temperature profile.

2-The temperature control in cooling system by liquid nitrogen until -100°C.

In addition to the devices used in the heating part, a DC motor shield, the electric valve and liquid nitrogen tank are added to the system for cooling. With a user coded software, the controller produces the necessary input and transmits the signal through serial ports from ARDUINO. The input signal as a DC voltage is transmitted to the electric valve and the DC motor controls the takes the quantity of liquid nitrogen to obtain the desired temperature profile. In the meanwhile, when the rapid temperature rise is needed and an air fan with 100W is used to increase the temperature by pumping the air at environment temperature into the box. Sometimes the natural heating cannot produce enough heat transfer for the desired temperature profile. The air fan is controlled by Arduino as on-off.

The Arduino board is used as microcontroller because it is simple, cheaper, and easy to program. All communications between the computer and the setup are made via the Arduino card. For real time implementations, the programs written on MATLAB software have shown a great success for both the communication and the control.

In this study, the temperature of the isolated box can be held easily between $+400\ ^{0}\mathrm{C}$ and $-100\ ^{0}\mathrm{C}$. Implementing some experiments, the user defined different reference temperature profiles are achieved on the test machine and are compared with that of the mathematical modeling of the cooling and heating system. It is seen that the errors are acceptable level.

1.1. Motivation of the Studies

Time saving, decreasing the product cost and improving product quality are some motivations of this system. The development of control system requires the understanding of the device and learning new technology like Arduino microcontroller. The urgent studies also require for finding the most precise control systems to obtain the required specifications with high accuracy and at the lowest cost.

1.2. Studies Objective

Control systems are an imperative part of industrial processes which do not necessitate human operator during operation. An automatic control system has an important role in easing the burden of everyday life. The main objective of this work is

to create a thermal system to control heating and cooling process which consists of some electrical and electronic devices. This system is used for a tension-compression testing machine in the different type of temperature profiles.

Other aims of this research:

1. Designing the temperature control system for an experimental setup which is going to identify the features of materials at very high temperatures or at very low temperatures. This setup is utilized to examine a tension and compression of materials.

2. Design an economic insolated system to inspect the temperature control system

3. Benefited from the liquid nitrogen for cooling in industrial process.

4. Design an isolating system in order to save the energy in heating and cooling process.

5. Test which type of controller is suitable for these systems.

6. Utilize the new technology for temperature control system to optimize the industrial process.

7. Benefit from the new controller device and modern control system.

1.3. Study Structure

- Chapter one including general introduction which involves a background about temperature control system, motivate of research and study objectives, project structure.
- Chapter two comprises of the literature review of the main concept or device which used in this field such as heat transfer, heat losses, control system, temperature measurement, heat source, cooling control system, heating control system, controller types and method of control system.
- Chapter three consists of method and material including all devices used in the setup, analogue diagram of the setup, calculation for heating process, calculation for cooling process, heating and cooling (thermal system) modeling.
- Chapter four comprises experimental and theoretical results, in heating, cooling, combined processes, types of controller.
- Chapter five involves conclusion, discussion and future works.

2. LITERATURE REVIEW

There are numerous investigations in literature, about the controlling temperature of heating and cooling systems by various approaches. The systems of temperature control are highly significant in every manufacturing procedure to optimize the characteristic of the substance via temperature handling. This review is comprised of in several sections containing heat transfer approach, measurement of temperature, heat source, cryogens systems, control systems, modeling of heating and cooling systems and controller type.

2.1. Heat Transfer Process.

Bovo, (2014) investigated the heat transfer principles in inner burning engines from stand point modeling. Actually, there is a diverse difference between the two concepts. The quantity of internal energy and measurements of the amount of energy motivated by the molecules of a material demonstrates temperature. Also temperature indicates the level of hotness, which is utilized for estimating the heat transfer direction. Conversely, heat is energy that transfers. In nature, heat streams to low temperature body from higher temperature body. Furthermore, Lienhard (2013), also examined heat transfer principles. The heat movement because of the variation in the temperatures is called heat transfer. For heat transfer, there are three models. Where the variation in temperatures in more than two bodies brings about heat transfer that happens in the following approaches.

1- Conduction: it is the process heat transmission between the atoms and molecules of substance.

2- Convection: it happens as a liquid streams surrounding a subject.

3- Radiation: it is the process of heat transfer via radiation of electromagnetic which develops because of the temperature of the body. This method does not require a substance.

Mihir (2015), examined the analytical of heat transfer. This examination reported that temperature is connected with the movement of molecules which are rotational movement within a material, being directly associated with the molecules kinetic energy

as vibration. In addition, Reddy and et.al (2010), studied the finite element approach in fluid dynamics and heat transfer. This study declared that the phase alteration is not existed and no work has been done on the system. The alteration in temperature, the system′s mass and the specific heat are the most important factors that affect the heat transfer. Li and et.al (2015), examined an experimental study on the characteristics of heat and mass transfer for a heat exchanger of desiccant-coated fin-tube. In this study, the relation between heat and mass transfer was also examined.

2.2 Temperature Measurement

An apparatus which can measure and sense the physical properties of the environment such as pressure, humidity, light, and temperature, resistance to touch, luminance, weight, and size is called sensors. They convert an analog signal to electric signal. These sensors also convert energy from one type to another one in temperature control system. Utilizing various principles, there are several approaches for measuring temperature. Nowadays, for controlling the temperature system, temperature sensors are frequently combined into the same chip as memory circuits, microprocessors and other integral circuit.

The author studies thermocouple temperature measurements for twin jet thermal mixing (Peters, 2011). There are many devices which convert energy from one form to another one, for example, mechanical or thermal form to another form such as electric form. Thermocouples (TC) convert thermal energy to electrical energy. These devices are commonly used to make temperature measurements. A simple description of thermocouple is two wires made of different metals connected in the end then generates an electrical voltage in microvolt measured across the two ends. There are many methods to measure the temperature using different principles. Generally there are four common types given as follows.

- Thermo resistive (RTDs and thermistors).
- Mechanical (liquid-in-glass thermometers, bimetallic strips, etc.).
- Radiative (infrared and optical pyrometers).
- Thermo junctive (thermocouples).

Schoeman (2012), investigated the design and development of an automated temperature controller for curing ovens. In this study, heat measurements can be made by making use of various different sensory devices. When the temperatures exceed 800°C, few sensory devices have the ability to measure and take temperatures correctly. Some of them are;

- A thermoelectric device converts thermal energy to electrical energy.
- Resistance temperature detector (RTDs) a temperature alteration results in the electrical resistance of a substance to alter.
- Radiative (infrared and visual pyrometers). The temperature can change radiative properties of an object. Therefore, radiative properties are recorded for inferring the temperature of the object.

Masilamani (2008), inspected production, design, and classification of a platform of micro machined heat converter for thermoelectric energy production. According to factors maximum operating temperature range and faster response time are important for selection of the thermocouples. As a result, in the fabrication of K-type thermocouples around 10 % chromium and 90% nickel are utilized. Ruiz (2012), studied the temperature control of a scientific device. The thermocouples are based on the Seebeck effect. In the Seeback effect, a voltage difference between the two junctions is generated by temperature difference between two junctions of two different electrical conductors or semiconductors. The Seebeck effect entails the overall of thermal energy into electrical energy where the Seebeck voltage can be represented as:

$$E = a\left(\theta_{Tip} - \theta_{Ref}\right)$$

Where:

E ≡ electromagnetic force in micro Volte

a ≡ proportionality constant known as the Seebeck coefficient

θ_{Tip} ≡ temperature in cold junction, °C

θ_{Ref} ≡ temperature in hot junction, °C

2.3. Control System

Ogata (1970), expressed the major basics of control systems such as feedback control, processes of systems, block diagrams, types of control system (MIMO, SISO) transfer function, disturbances. In addition, he stated that modeling (mathematical) of the plant is the initial stage in the design of any control system. The authors studied the feedback systems and demonstrated that a system behavior altered with over time, frequently in reaction to dynamic force or an external stimulation (Aström and Murray, 2010). The circumstances where two or more dynamical systems are connected are termed the feedback. According to that every single system impacts the others. Therefore, their dynamics are coupled strongly. As the first system impacts the second one and the second system influences the first one, which leads to circular argument, plain causal reasoning regarding a feedback system is complicated. In general, types of the system are separated into two main categorize:

- Closed Loop (one or more feedback loop are available between the output and the input).
- Open loop (the control action of the input is not affected by the output) (referred to as non-feedback system)

2.4. Heat Source

Turunen ([2006), studied the electrical floor heating systems in China-Shenyang. The heater is simpler and the way of transforming the electricity to the heat in the resistance is very simple. In the electrical heating method, the current is passed through a wire or other high resistance material forming a heating element. The heat proportional to $Q = I^2 R$ loss produced in the heating element is delivered to the charge by one or more of the modes of transfer of heat i.e. conduction, convection and radiation. Here, *Q*, the mount of electrical energy change into the heat, *I*, current flows through an electrical conductor with resistance *R*. If the heat is transferred by conduction, the resistor must be in contact with the charge. An enclosure known as heating chamber is required for heat transfer by radiation and convection for the charge. Haye (2013) studied industrial

solutions for inductive heating of steels. It was explained that the principle of heating process by electromagnetic induction and used these methods for melting metal in the heat treatment process. The company of Fairchild Semiconductor (2000), examined heating system induction topology for manufacturing reason. Resistance heating is used in many applications as a general type of electric process heating. The relation between the voltage and current is based on Joule's effective.

The followings are some kinds of electric heating.

- Resistance heating (dry electric heating)
- Heating by conduction
- Heating by infrared radiation
- Heating by electric arc
- Induction heating (Infrared Radiation Heating)
- Laser heating
- Plasma heating

2.5. Cooling Temperature Control System by Liquid Nitrogen

Temperature control of cooling system is very important in industrial process, manufacturing, scientific laboratories, especially in cryogenic processes. There are a few researcher studying temperature control systems by liquid nitrogen such as (Dhananchezian, and et al. 2009). This study investigated experimentally cryogenic cooling by liquid nitrogen in the process of the orthogonal machining as indicated in Figure 2.1. According to the results of the experiments, based on the cutting velocity and feed proportion (cutting parameters) and work material, the nitrogen liquid decreases the cutting temperature around 19-40%. These studies stated that the cutting force was enhanced to a maximum of 15% and 10% by using the cryogenic cooling. Compared to dry machining, the chip thickness was reduced approximately up to 25% via cryogenic machining with liquid nitrogen jet. Cryogenic machining alleviated the cutting angle up to 30%.

Figure 2.1. The setup of cooling cutting machine.

A large infrared instrument was designed for pre-cooling by liquid nitrogen at ESO (European southern observatory) (Lizon, 2010). So as to save the infrared instrument in safety state, liquid nitrogen is the optimum liquefied gases to cool the large infrared systems. Damian and et. al. (2010), presented the fuzzy controller for liquid nitrogen cryogenic freezer which utilized the liquid nitrogen and another liquefied gases in the cryogenic process. Figure 2.2 describes this system regarded as the “novel revolution” in the food production.

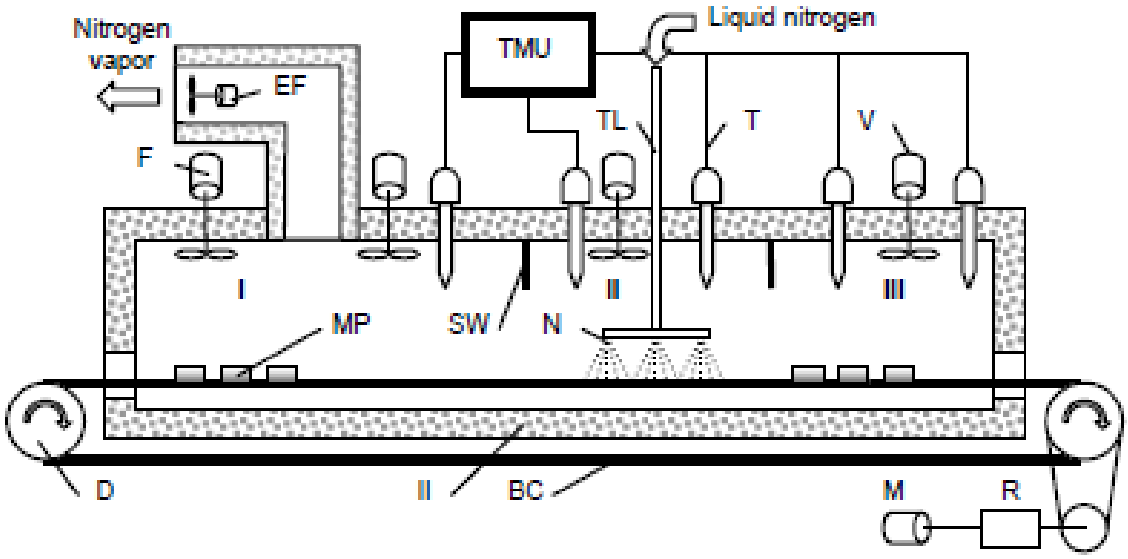


Figure 2.2. Fuzzy controller for liquid nitrogen cryogenic freezer.

Tai, (2008) investigated two-phase flow and phase-change of cryogenic heat transfer in microgravity. The cryogenic fluids have wide application in the industry. For example, in the aerospace industry, they are utilized as liquid fuel like liquid oxygen and hydrogen and also as a coolant like liquid nitrogen and helium in medical applications. . In some special cases, for example, cryogenic fluids are used in spacecraft's not only at low temperatures but also under low gravity. Kumar, (2014) designed and improved a cryocooler depended upon a plant of liquid nitrogen. The cold head of the cryocooler with small size gives an advantage because of cooling. It can be assembled on top of a Dewar. This allows the size of the entire dimension of liquefier installation to be reduced. This characteristic made the system preferred in many places in which the less amount of liquid nitrogen is enough.

In order to make the astronomical instrument mechanically stability on a nanometer level, Haug (2013) investigated the liquid nitrogen cooled cryostat. In cryogen process for the gravity, the study employed liquid nitrogen. This is a novel instrument to precisely narrow-angle interferometric imaging and infrared astrometry. Jial and et.al (2015) inspected temperature control cooling system depended on subsection control using simulation program. The main aim of this system is to supply the discharge temperature within desired range while trying to keep the output temperature at the admissible level. For controlling the outlet temperature of the compressor and the

temperature discharge of system respectively, a two-level subsection control approaches is designed. Furthermore, the target value of temperature discharge of the system is separated to three sections. Each section provides the various value of the temperature outlet compressor. The control of the system for these aims is accomplished more easily and decreases the cost-compensation of the systems by using this approach. The outcomes of the simulation demonstrated that while compressor output temperature controlled in design value, the system temperature discharge is regulated effortlessly to the given target value. In the meantime, throughout the entire processes, the temperature control valve (TCV), ram air valve (RAV) were under normal conditions.

Ariffin and et.al (2006) designed the temperature controlled fan for home application by adjusting the temperature of the room via a thermostat which measured the temperature. The fan speed is regulated according to the set point which indicated instantaneously by user and thermostat reading. When the differences between these two points are large, the fan speed becomes faster and if there's no difference between these two values, the fan is stopped.

2.6. Heating Temperature Control System

In the industrial process and heat treatment, the temperature control is vital. Several researchers presented various approaches such as (Schoeman, 2012). The study covered the design and development of automatic temperature controller for curing ovens. The type-K thermocouple was applied to measure the temperature with microcontroller PIC18F4220 to design and develop an automated temperature controller for curing ovens as shown in Figure2.3.

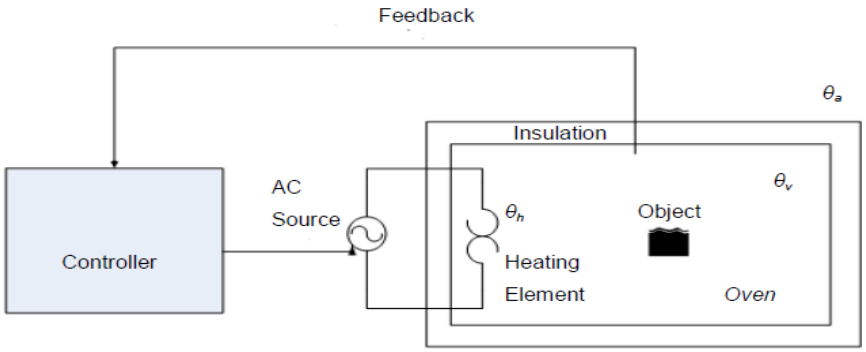


Figure 2.3 an automated temperature controller for curing ovens.

Appelblad (2014, developed a temperature controlling cell for Raman spectroscopy for detecting in situ gases utilizing an Arduino Uno microcontroller with proportional-integral (PI) control action. The temperature of a surface amplified by Raman spectroscopy (SERS) substrate can be normalized by the controlled cell within -15 to +110 °C and the temperature is kept fixed over long times at ±0.22 °C of the set point temperature. This system can be used for cooling or heating according to the set point. Jaafar, (2013) presented a study on automatic room temperature control based on the difference between inside and outside room temperature. It was observed that the compressor speed has a great role in achieving the reference set point. To control the room temperature, the controller was designed based on adaptive fuzzy. The researcher indicated that the controller was not only capable of tracking the input reference and but also the output response of the system in terms of tracking performance was achieved by the adaptive fuzzy control. The system was designed and tested in SIMULINK by MATLAB program to obtain a mathematical model for the air conditioning system and helped to reduce the high cost of electricity. In another research, Latha and et.al (2013)] studied on millienium3 PLC based temperature control using LM35. The researcher used LM35 for measuring the temperature and PLC as a controller. The system received the temperature via the LM35 and after that compared it with the set point that was specified by the user. The controller runs either a fan or heat source according to the difference between the instantaneously temperature and set point. Besides, Mazlee (2009) presented the control system involving an AC air heater, LCD (liquid-crystal display) and temperature sensor. There were three circles, two of them were for administering the fan speed and the other one was for operating the AC heater. The purpose of the work was automatically controlling the temperature value inside the room. Firstly, when the temperature ranged between 0ºC and 15ºC, the air heater operated for heating the room. Secondly, if the temperature ranged between 16ºC and 25ºC, this system did not operate as the temperature was comfortable. Thirdly, the fan operated in the level 1 for decreasing the temperature when the temperature was between 26 to 40 ºC. Finally, the fan operated rapidly to decrease the temperature when the temperature was higher than 40ºC.

2.7. Types of Controller

There are many methods to control systems such as two way ON/OFF, fuzzy logic, P, PI, PD, PID and PLC. Each method is used for a specific process in accordance with the matching the industrial process requirements that are high precision and the speed of response. For instance, in this study, PID controller was applied because of its extraordinary effectiveness and simplicity of implementation. Ding and Li (2008) studied the programmable logic controller (PLC) which is an industrial control computer. The system has good stability, high reliability, and broad application prospect and is also feasible for the economy. Li and Lei (2011) investigated a temperature monitoring system used in industry and how to measure the temperature. The results were compared between look-up table and formula approach. The comparison and analysis revealed that the look-up table approach alleviated the algorithm errors for both nonlinear and linear factors. The system is lower cost and has higher reliability.

In the study of Gore and Mobeen (2015), ARM processor with Ethernet controller W5100 makes the internet connection in the simpler way for embedded systems. W5100 Ethernet controller is embedded to a Hardwired TCP/IP. This design basically consists of SPI communication module. It is employed for monitoring some industrial physical parameters such as pressure, temperature, humidity and gas can be monitored by this system. The different sensors receive data and can function as a network utilizing LAN to SPI communication. Higher data transmission rates and no hired telecommunication lines were achieved by using LAN. Kumar and Rameshkumar (2013) used virtual instrumentation, LabVIEW on a PC to control and monitor the temperature. Via Ethernet port, the simulator obtained the information from the microcontroller. A PC monitor and the LCD in microcontroller can display all data. Furthermore, by accessing the web page via web browser, the user was able to monitor the temperature reading acquired from the workplace and to control the temperature with a PC.

For any system, the dynamic behavior has to be derived for designing and controlling the cooling or heating processes. Various identification procedures are recommended in the area of temperature control modeling to define the parameters of the system. Srisertpol and Phungphimai (2010), demonstrated the model reference adaptive control method with PI controller for the electromagnetic oven process. The results of the

research presents that PI controller adjusts for efficiency of the plant response to track model reference. The research outcomes indicated that PI controller regulated for the plant effectiveness reacted to follow reference model. Lute and Dolf (1995), presented a predictive control system. The designed system is based on model estimation and able to keep the indoor temperature of the experimental cell in the demanded limits during almost the time. The researchers compared the proposed LPC system with conventional on/off and PI control systems within the same type of temperature limits. It shows the LPC system saves about 10% in terms of energy consumption annually. This advantageous result stems from the possible firmer control at required limits, no overshot and oscillations happened give. In addition, this achieves a comfortable indoor condition since less than hours of overheating occurred exceed the desired temperature limits. Generally the heating systems are modeled as first degree delayed time.

The main methods like PID, neural network, fuzzy-logic are presented for heating or cooling temperature control systems. Due to its efficiency and simplicity, PID controller is most widely used. A novel kind of fuzzy self-tuning PID controller by simulation was discoursed by (Jiang and Xuchu, 2012). The outcomes displayed that a better performance was accomplished via the proposed controller by improving the temperature control precision. Furthermore, in comparison to the conventional PID, this controller had higher performance, which was feasible and sensible for the temperature system, in accordance to the outcomes of the simulation.

The MATLAB –SIMULINK temperature control of the oven was presented for the desired temperature changes (Bolat, 2007). A PIC microcontroller through RS-232 provides the communication between the oven and the computer. Ziegler-Nichols, P, PI, relay tuning and ISTE disturbance criterion for PI methods are used to adjust the temperature of the oven. These methods are simulated first and implemented by using MATLAB-SIMULINK through the microcontroller PIC based card. PI controller with a relay produces the better response among the entire controllers for both experiments and simulations. For high efficient temperature control systems, a microcontroller and a feedback controller are necessary. In this way, the desired temperature profiles can be acquired. As a new trend, the cheaper, easier to use and simpler coded microcontroller, Arduino is started to get used frequently in many studies, especially, low ambient temperature control. Many researchers have focused on the control process via Arduino

like (Krishnamurthi, and et. al., 2015). In this study, Arduino was utilized to measure real time climate conditions such as humidity and temperature. In addition, Ayuba, Yusuf [2016] devised a system of temperature control via Arduino in a factory. The cooling unit was activated automatically as ON when the temperature reading by the sensor which interfaces with the Arduino was higher than the desired temperature of the factory. This provided a possibility to adjust the cooling speed unit. The LABVIEW program used in this system had an ability to regulate controls manually and responding in real time to pass the next step further. A graphical temperature chart was used on the PC to run, store and display the outcomes. Mishra and Pinaki (2013), also designed a temperature controllers implementing LabVIEW. This controller is based on ON/OFF temperature measurement and used LABVIEW to control the temperature and make sure that the temperature does not exceed a certain set point.

Bisoyi (2013) applied an ON/OFF controller to control the temperature online. Basically, this controller generates ON or OFF outputs without any interval state. When the temperature only diverges from the set point, the ON/OFF controller generates an output. To control a heater, the output is OFF when the temperature exceeds the set point, and ON when the temperature is below the set point. Generally, where a precise control is not necessitated, ON/OFF controller can be applied efficiently. It is highly inexpensive type of controlling system. It is not recommended in the applications faced to instability in system variables.

Mishra, Manish [2013] used ATMEGA32 circuit microcontroller and LM35 sensor to control the temperature any system. The systems temperature was displayed on a liquid crystal display (LCD) within –55°C to +150°C. The preset value saved by the user in the microcontroller was compared to this temperature. To produce a large collector and emitter current, a small current entering the base of the transistor was amplified. Chachan (2014), utilized DHT11 that is a basic, super-low-expenses digital humidity and temperature sensor in designing a smart humidity and temperature observing system. In this system, Arduino board operated a digital signal on the data pin. Abdul (2011) attempted to cope with the overheating issue in industry by applying PID temperature controller. The researcher has used PIC16F876A as a microcontroller. The experimental outcomes displayed that PID controller is the best choice to minimize the power consumption rather than typical ON/OFF controller.

Many approaches like empirical tuning like Ziegler–Nichols method, trial-and-error tuning, optimization, and prediction method, analytical tuning and auto-tuning with identification of the plant model can calibrate the parameters of a PID controller. (Sakallah, 2009; Afraa and Al-Tae, 2011) demonstrated a comparison of temperature control in the process of heat exchanger. The tuning of control parameter was analyzed in this study. Two methods were suggested for determining the parameters of PI and PID controllers such as Nichols (Bode diagram) and Ziegler- Cohen-Coon (process reaction curve). These applied were to find the better values of integral time (τ_I), derivative time (τ_D) and proportional gain (K_c). Accurate outcomes were attained by utilizing artificial neural network over PI, PID and classical fuzzy logic controller. The study stated that in compared to PI, PID, classical fuzzy logic and artificial neural network controller, the PID fuzzy controller had superior controlling outcomes of temperature. Salam and Islam (2013) designed a control system for the temperature of water in heat pump. The authors combined both PID and MPC (Model Predictive Control) controller. These controllers employ to obtain the model to expect the future behavior of the system and also an optimal control of the system with these controllers is achieved by changing the constraints.

Time delay should be taken into consideration through all system modeling because it can aggravate its performance and also make a thermal control system unstable. Díaz and et. al. (2004), investigated the impacts of delay in the long ducts thermal systems. The impression of thermal inertia, closed loops and branching were discussed on the behavior of some ducted systems. Alkhalaf (2015), modified the time delay for improving performance control system. The author presented a mathematical method to ameliorate its performance owing to the sampling time and the delay time. So as to improve the performance of the control system, two main points were considered in the efficiency of the presented method. For estimating the performance of system, the minimum delay time has to be analyzed. The performance gets closer that of the continuous system as the sampling time approaches to zero. On another control approach, Xue-dong (2013), used the improved PLC technology in designing a temperature control system. The study combined PID and PLC based on the technology of temperature control. This supported PLC ladder figure programming language for programming, therefore recognizing the temperature control automatically. Also, the study indicated that this system enhanced the stability, fast-response, reliability, precise control, providing

with realistic meaning to the industrial control. .Jiang and Xuchu (2012) utilized a novel type of self-tuning fuzzy PID controller. The results of this study indicated that this controller accomplished higher precision on temperature control and superior performance in compared to typical PID. In accordance to the outcomes of the simulation, the presented system is more feasible and reasonable for the temperature control system.

3. MATERIAL AND METHOD

In this chapter, we will explain all the components used to design the whole system, detail all the specifications, technologies and any particularities about each device. There are many equipment and electronic components that will be used during the development of temperature controller. The research is done experimentally about temperature control system in heating and cooling. This study is based on a process of experimental to get the data and results through two processes.

1- Heating process by electric heater until 400°C where oven temperature is manipulated by Arduino Mega 2560 with a type-K thermocouple.

2- Cooling process by liquid nitrogen, usually used in cryogen process. We can obtain very low temperatures up to –196°C. When liquid nitrogen is converted from a liquid state to gas state by absorbing heat, this leads to a very low temperature.

The results are recorded in both heating and cooling processes and carried out through simulations within the MATLAB software program to get the best results.

3.1. Devices and Materials

In this thesis, many devices are used to supply the requirements for heating and cooling process. These devices and materials and also their properties are given in Table1.

Table 1. Devices and materials with their properties.

Device or material name	**The properties**
Insulating box	Outer dimension: 0.4 m x 0.4 m x 0.4 m, and inner dimension: 0.25 m x 0.25 m x 0.25 m with three layers
Insulation Materials (rock wool)	Thickness: 7 cm
Thermocouple	Type-K, working in the range – 180°C to1300°C with accuracy +/– 1.5
Electric resistance.	Dry
Power regulator	0-220 VAC with 0-5.6 V DC control
Microcontroller	Arduino Mega 2560
Amplifier	Adafruit Max31855
Liquid nitrogen electric valve	Solenoid valve with 12 V DC
DC motor shield	5-12 V and 0.6 A (4 DC + 2 Step)
Air pump (fan)	200Watt
Relay	On-Off, 5V DC
Liquid nitrogen tube (Dewar)	50L, 1.5 bar
Insulate pipe	cupper
Computer	

The diagram defining the whole system used in a tension-compression testing machine is shown in Figure 3.1.

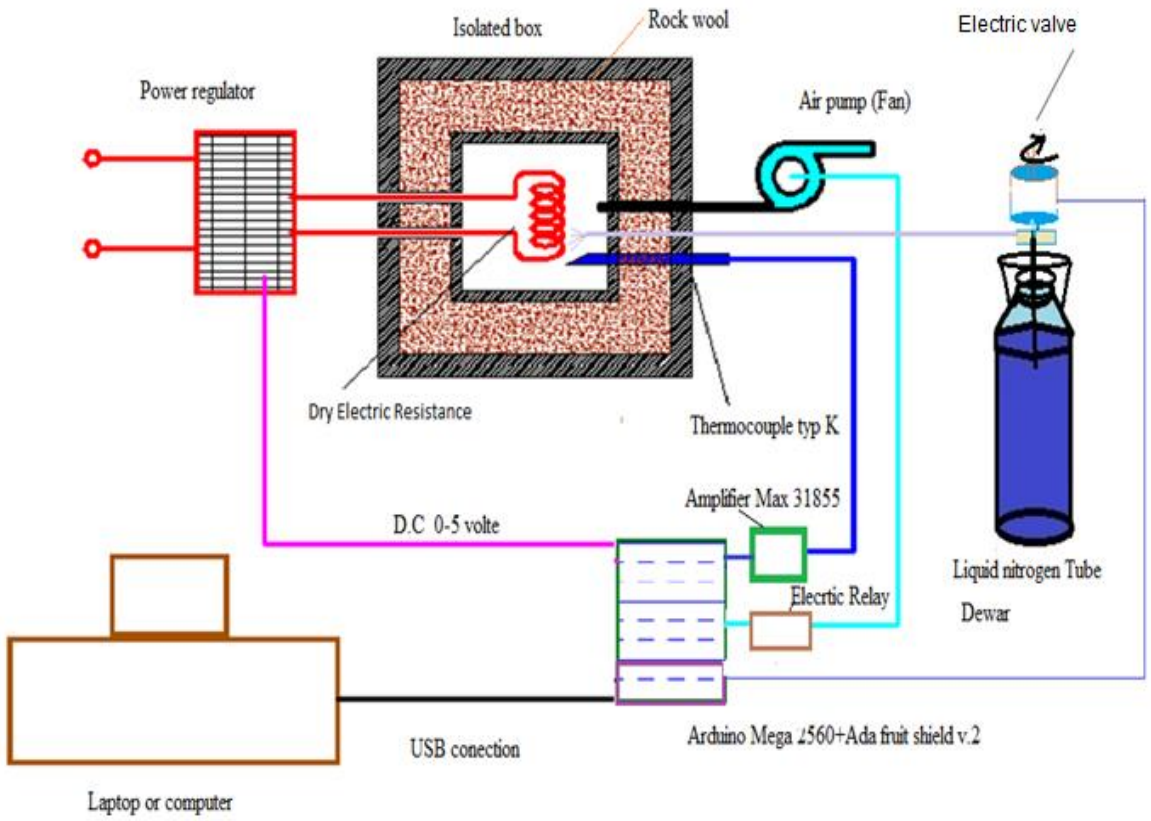


Figure 3.1. The setup including of cooling and heating system.

In Figure 3.2, the picture of the experimental setup is given. All the devices and materials used in this system are explained in details in the next chapters.

Figure 3.2. The picture of the experimental setup.

3.1.1. Isolated box

The box is in cubic shape because it's easy for transportation, isolating and for calculation the heat losses. The outer dimension is (0.4 m x 0.4 m x 0.4 m) and inner dimension (0.25 m x 0.25 m x 0.25 m). These dimensions are suitable in order to decrease the heat loss in heating and cooling and also it is suitable for testing the tension and compression of material. The isolated box has three layers. The first one is made of steel plate with its thickness of 3mm and the second layer is an isolating material of rock wool with its thickness of 7 cm and the last layer is also steel plate with 2mm thickness. We assume the box isolated is homogenous in heat transfer .The main objective of this work is to create a thermal system to control heating and cooling processes. The dimensions and shape of the box are given in Figure 3.3 and Figure 3.4.

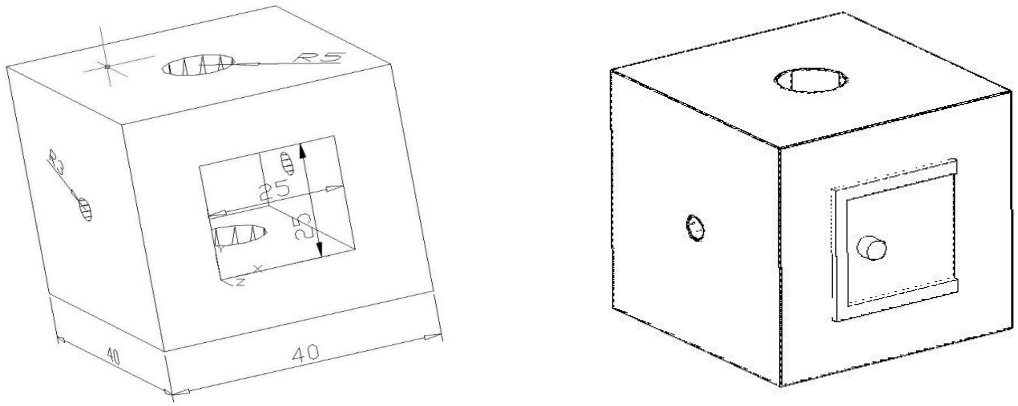


Figure 3.3. The views and dimensions of the isolated box.

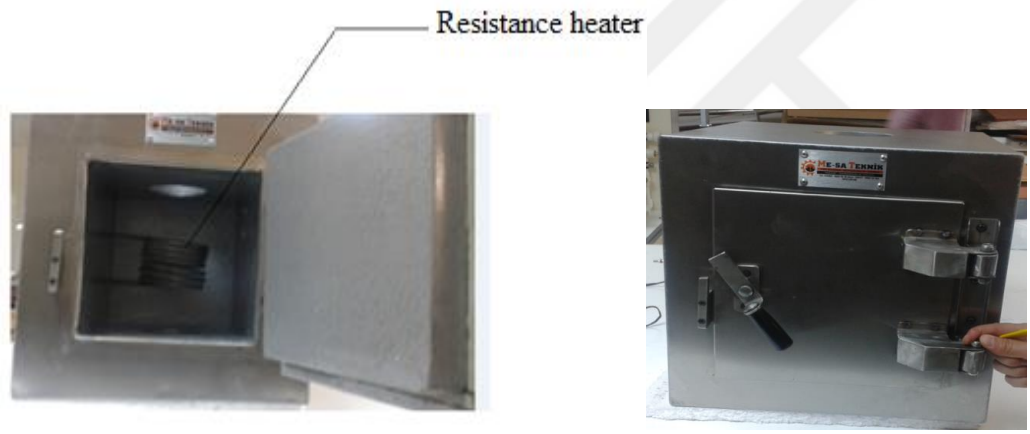


Figure 3.4. The pictures of the isolated cubic box.

In our system we have some general assumptions given as follows.

1-Steady state heat transfer that means the temperature inside the isolated box does not change with time, but varies by location.

2- Heat transfer is obtained in one direction (X- direction) means that the heat is not transmitted in the second (Y- direction) and the third dimension (Z- direction) of the box walls such as the case of large panels and long pipes.

3- The heat transfer coefficient is stable. Thermal conductivity is reasonable as the value of a few plants change with temperature change.

4- There is no emerging energy inside the walls.

5- Heat transfer inside and outside the box occurs only by natural convection.

These assumptions will be the basis of our experimental work during the study. General heat transfer equation,

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}+\frac{\dot{q}}{k}=\frac{1}{\alpha}\cdot\frac{\partial T}{\partial t} \tag{3.1}$$

The heat transfer equation in one dimension: $\frac{\partial^2 T}{\partial y^2}=0$, $\frac{\partial^2 T}{\partial z^2}=0$

Steady state equation: $\frac{\partial T}{\partial t}=0$

No heat generation inside the walls: $\frac{\dot{q}}{k}=0$

Finally, after the assumptions explained above, the heat transfer equation takes the form of that in Eqn (2).

$$\frac{d}{dx}\left(k\cdot\frac{dT}{dx}\right)=0 \tag{3.2}$$

The equation is 2nd order so that the integration will result in 2 constants of integration. To evaluate these constants, two boundary conditions will be required for each coordinate direction. The boundary conditions are given in Figure 3.5.

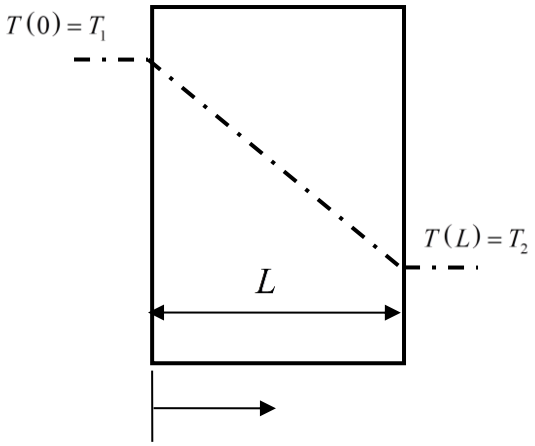


Figure 3.5. The boundary conditions for the heat transfer equation.

Finally, the above differential equation for the homogeneous box walls in one dimensional geometry between two endpoints gives the heat flow rate at constant temperature as follows.

$$\dot{q}_x = -K\,A\,\frac{T_2 - T_1}{L} \tag{3.3}$$

This equation is known as Fourier Law of Heat Condition. Where $\dot{q}_x$ is heat transfer rate in the direction of x, K is the thermal conductivity, A is the area of heat transfer, L is the length of the box walls and T_1, T_2 are inner and outer temperature.

Heat transfer through the insulated box is homogeneous and in one dimensions. The materials used for the manufacturing of thermally insulated box are steel plates and isolating material. These can bear the force and pressure at high and lower temperatures. The heat transfer takes place through multiple wall layers. The thermal resistance increase with the number of layers. If each layer has different resistance which is dependent on the thickness and coefficient material, the heat transfer should be modified. This modification for the isolated box is made according to Figure 3.6.

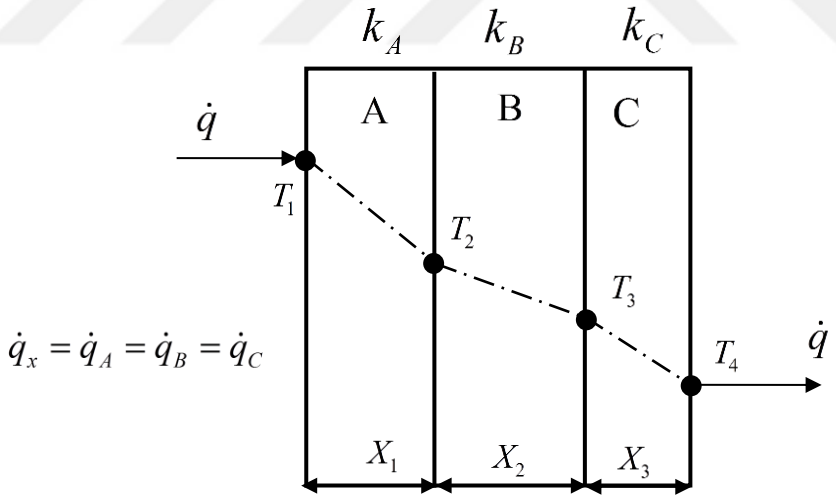


Figure 3.6. The multilayer wall.

$$\dot{q}_{\mathrm{A}} = K_{\mathrm{A}} A \frac{(T_1 - T_2)}{X_1} = \dot{q}_B = K_{\mathrm{B}} A \frac{(T_2 - T_3)}{X_2} = \dot{q}_C = K_{\mathrm{C}} A \frac{(T_3 - T_4)}{X_3} \tag{3.4}$$

After some simplifications, the equations is

$$\frac{\dot{q}}{A} = \frac{T_1 - T_4}{\frac{X_1}{K_A} + \frac{X_2}{K_B} + \frac{X_3}{K_C}} \tag{3.5}$$

Generally, the denominator of "Eq. 3.5" is called thermal resistance (*R*). Thermal resistance (*R*) is the resistance of a particular means or system to the flow of heat through its boundaries and is based on geometry and thermal properties of the means such as thermal conductivity.

$$\frac{1}{U} = \frac{1}{h} + \frac{\Delta X}{K} \tag{3.6}$$

The overall heat transfer coefficient *U* is a measure of the overall ability of a series of conductive and convective barriers to transfer the heat rate. For calculating the total heat transfer, the equations below can be used for the sake of the simplicity.

$$\dot{q} = U\ A\ \Delta T = U\ A\ (T_1 - T_4) \tag{3.7}$$

3.1. 2. Isolate material

Thermal insulation is a process which delays or minimizes the loss or gain of heat or power based on the performance of the following tasks:

1. Conserve the energy by reducing the heat loss or gain.

2. Control surface temperature to keep individuals and comfort temperature.

3. Avoid or reduce damage to equipment from exposure to fires or atmospheric corrosion.

4. Prevent the flow of steam or water condensation on cold surfaces.

5. Facilitate temperature control process in industrial process.

6. Increase operating heating, cooling, ventilation and plumbing efficiency, and steam systems in commercial and industrial facilities.

7. Reducing emissions of pollutants in the environments

8. Making mechanical systems operate in accordance with the conditions specified standards and quality required during the stages of production.

Thermal properties are the most important consideration when selecting any insulation materials according to the some properties. These are temperature range, thermal conductivity, heat, emissivity, thermal resistance and thermal transmittance.

There are many types of insulating materials. Generally, thermal insulation material is divided into four sections.

1. Animal origin insulating materials: such as animal wool, however insulation is limited.

2. Insulating materials such as glass wool, rock wool and one of the best thermal insulating materials.

3. Materials and industrial insulation: include rubber and plastic foam, and the last one is the most common,

4. Insulating materials of plant origin: include fiber or cellulosic materials such as sugar cane, cotton and others. Insulation materials can be burnt at different temperature which depends on the insulation materials types:

Glass wool: 230 - 260 ° C

Rock wool: 700 - 850 °

Ceramic fiber: 1200 °

Rook wool is a form of natural organic fiber material which is assembled as a result of exposing the molten basalt rock it is also called mineral wool or mineral fiber, a fiber made from man-made from natural or synthetic minerals. Rock wool is used for high efficiency in thermal insulation applications, acoustic insulation and prevents the spread of fire. The thermal conductivity factor is very low and it has high ability to absorb sound waves and heat. We chose the rock wool for isolating the cubic box because it’s not burnt in the range of 0 – 400 °C and the thermal conductivity is very low 0.04 (W/m K) and also it is very chip. This isolating material with its thickness of 7cm is used between two steel plates and also is used to cover around the pipe of the liquid nitrogen (Fonteno, 1990).

3.1.3. Temperature measurement

Temperature sensors are used in many applications for different types of industries including heating, ventilation and air conditioning (HVAC), medicine, food processing, and robotics generally. Temperature sensing is one of the most sensitive properties or parameters for industries. Sensors perceive physical phenomena and convert these to the compatible electrical signs that are relatively easy to measure. Sensors that cannot generate an electrical signal naturally are integrated with electronics device to yield the measurable sign. Generally, there are two types of temperature measurement.

3.1.3.1. Non-contact temperature measurement

Every form of matter with above absolute zero temperature emits infrared radiation according to its temperature (Afraa and Al-Tae, 2011). It explains the launch of radiant energy from the heat source in the form of energy emitted in the infrared part of the electromagnetic spectrum. This method is usually used to control the solids and fluids which are reflective, however, are not effective with gases resulting from natural transparency. In addition to its speed and lack of interference, the primary advantages of noncontact thermometry are the capability of measuring in high temperature ranges up to 3000°C. It is kept in mind that only the surface temperature can be measured. A picture of non-contact temperature sensor is given in Figure 3.7.

Figure 3.7. Non-contact temperature sensor.

3.1.3.2. Contact temperature measurement.

Temperature sensing needs directly physical contact with the means or object to being perceived. The temperature of gases, liquids or solids can be monitored by using these devices. Basically, temperature can be measured via this type of sensors at very wide temperature range. The other type of sensors typically takes the measurement by having contact with the measured matter. Precaution is very important to prevent the sensor from damaging by the matter for a safety. The advantage of using temperature sensors communication is that it produces s a more precise result compared to the temperature sensors being non-contact. This type of sensors is shown in Figure 3.8.

Figure 3.8. Contact temperature sensor.

The device of temperature measurement contacts with the objects or space to measure its temperature. We can find these types in every aspect of our lives, whether at home or at work. There are many types of contact temperature sensor as the following.

1. Thermocouples (TCs)
2. Thermistors
3. Resistance Thermometers (RTDs PRTs, SPRTs)
4. Liquid in Glass Thermometers (LIGs)
5. Filled System Thermometers (Filled)
6. Bimetallic Thermometers (Bimetals)
7. Semiconductor Temperature Sensors (Semi, ICs)
8. Labels, Crayons, Paints, Tabs (Phase Change Devices)
9. Other Temperature Sensors

3.1.3.3 Thermocouples

Thermocouple is commonly devices used for temperature measurement It converts the thermal energy to electric energy. Basically, thermocouple involves two pieces of distinct metals with their ends joined together (by twisting, soldering or welding) (Schoeman, 2012). When heat is applied to the linkup, a voltage, in the range of mille-volt (microvolt), is generated. Because of this, thermocouple is known as self-powered devices. Commercial thermocouples are cheaper, exchangeable, and have standard connectors shown in Figure 3.9.

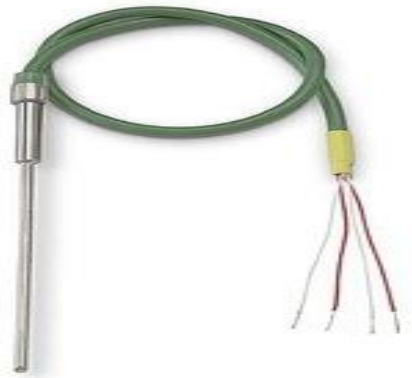


Figure 3.9. A thermocouple.

Figure 3.10 shows a completed thermocouple circuit. The voltage at each joint point depends on the junction temperature. If the temperature T1 is greater than T2, then the voltage at the junction-1 is greater than the voltage at the junction-2. In the circuit described below, the current circuit shown on the galvanometer depends on the relative magnitudes of the voltages at two junctions. For temperature measurement by thermocouple, one end of the thermocouple should be placed in the contact with the material or space called (hot or measurement joint) and the other end has to be kept at fixed temperature called cold joint.

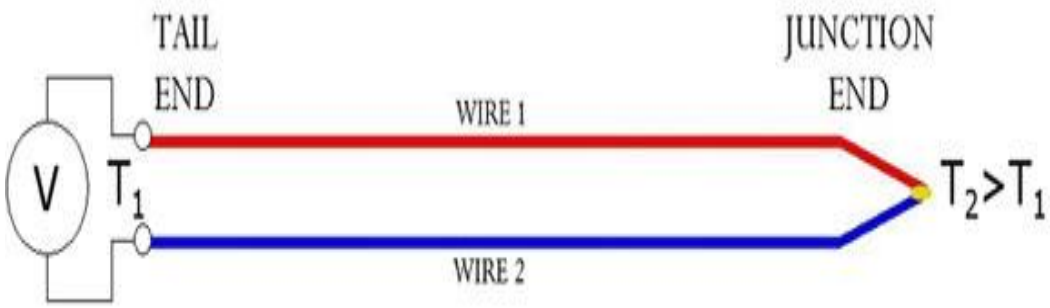


Figure 3.10. Thermocouple circuit.

A tip point on the thermocouple kept at fixed temperature is called cold or reference junction. There is a relationship between total circuit voltages (emf). This emf at the junctions is:

$$Circuit\ emf\ = Measurement\ emf\ - Reference\ emf$$

If the reference emf and circuit emf are specified, the measurement emf can be carried out and the relative temperature is identified. So as to convert this emf generated by a thermocouple to the standard 4-20 mA signal, a temperature transmitter is required.

Thermocouples are very robust and can function over a wide range of temperature. A thermocouple is created whenever two distinct metals touch each other and the contact point generate a small open-circuit voltage as a function of temperature. This thermoelectric voltage is known as the Seebeck voltage discovered by Thomas Seebeck in 1821.

$$DV = S \times DT$$

In this equation, DV represents the change in voltage, S responsible for the Seebeck coefficient, and finally DT is used for the change in temperatures varying with temperature.

There are many types of thermocouples. We chose the type-K thermocouple which is worked in the temperature range from −180°C to +1300°C with tolerance ±1.5°C between −40°C and 375°C, ±0.004°C between 375°C and 1000°C.

Only two devices can be used in the measurement of very high temperatures, namely thermocouples and thermograph sensors. Thermocouples can be classified with

respect to their material and their operational temperature. In Appendix 1.the different types of thermocouples and their properties are given.

When a metal exposed to temperature gradient, its electrons move faster. Since the thermocouple composed of two different metals, the speed of electrons is different in each metal which are connected with each other at the junction. Then, the electrons interfere with each other. This causes to increase the electrons in one metal and to lack the electrons in the other metal. Also, this leads to create at the end each metal two different current. The flow of electrons or flow the electric current which called thermal current. Depending on the metal type and temperature gradient, the difference between these two current is measured by microvolt. This voltage is referred to an EMF (electro-motive force). In Figure 3.11, the graphic shows the change of EMF with temperature for some kinds of thermocouples.

For K-type thermocouple, the NIST polynomials provide precisely a temperature conversion with error less than 0.06^{o}C. The voltage/temperature relationship is define by tables and equations published by NIST (National Institute of Standards and Technology). NIST declared two types of polynomials. The first one generates voltage as a function of temperature, and the second one gives temperature as a function of voltage. Both of these formulas are described here for converting a thermocouple temperature. In these tables and equations, reference junction end must be kept at a temperature of 0 ^{o}C. It is possible to avoid having a 0 ^{o}C reference junction. The measure of the thermocouple can be calculated by using both the forward and inverse NIST polynomials if the temperature of the reference junction is precisely specified. The voltage on a thermocouple is generated across the thermocouple and leads to it proportional to the difference in temperature from one end of the thermocouple wire to the other. It is well known that the voltage is formed in the wire, not on the thermocouple junction. A temperature gradient exists ever in the wire pair.

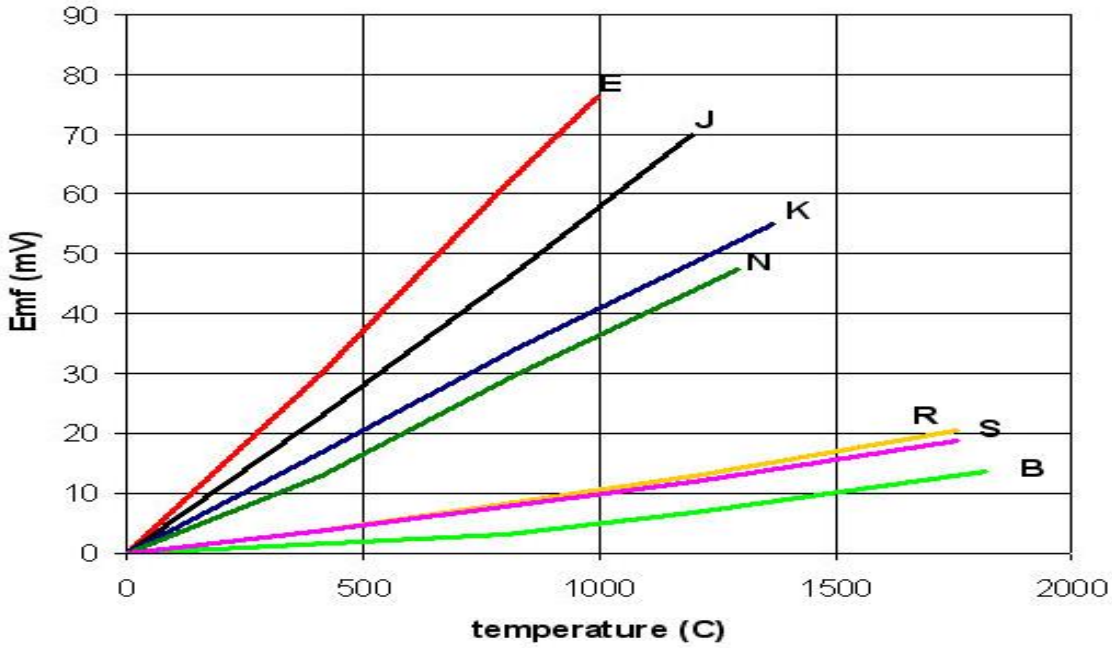


Figure 3.11. EMF voltage vs. temperature relationship for some kinds of thermocouples.

Another temperature measurement type is resistance temperature detector (RTD). The temperature change leads to the electrical resistance of a material to vary. Owing to the wide range of temperature, precision, stability and well standardization for manufacturers, platinum is commonly used material for thermocouples. RTDs shown in Figure 3.12 are considered by a linear positive change in resistance with respect to the temperature.

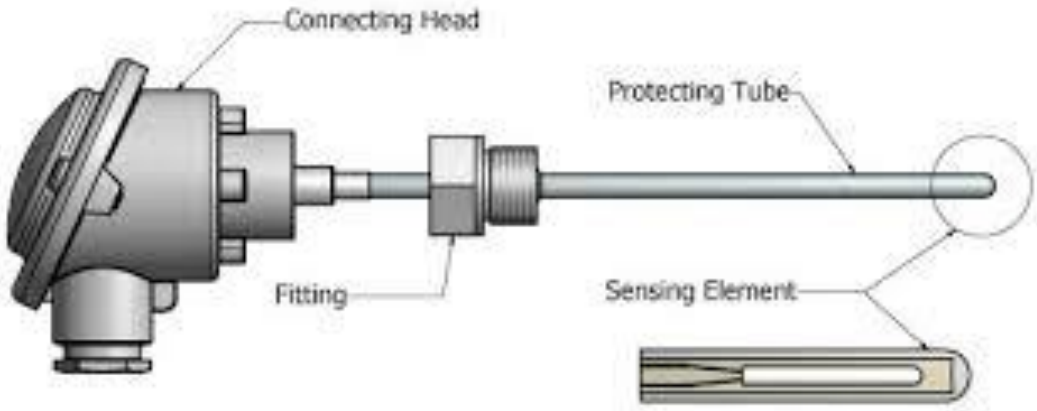


Figure 3.12. Resistance temperature detector, RTD.

3.1.4. Electric heating source

For any process converting electric energy to heat energy, there are many methods for heating process by electricity. Some common methods are explained in the next sections.

3.1.4.1. Electric resistance

Electrical energy is changed to heat via the electrical resistance, for this aim, electric heater is an electrical appliance converting the electric current to heat energy. Common applications of heating by electric involve heating of space, culinary, heating water and various industrial processes. The principle of heating by electric is based on an electric current passing through the resistor and then transforming the electrical energy into heat energy. Most modern electric heating equipment use nichrome wire as the active component, heating element Produced energy in the heating element is transmitted by one or more heat transfer method such as conduction, convection and radiation.

In this study, an electric resistance shown in Figure 3.13 is used a heater duo to its simplicity, easy to use and control. This heater consists of a resistive element covered with steel sheet. It can produce sufficient heat by adjusting the voltage applied at two poles between 0 - 220 AC Volt. The maximum power of the heater is 2.5kW.

Figure 3.13. Electric heater.

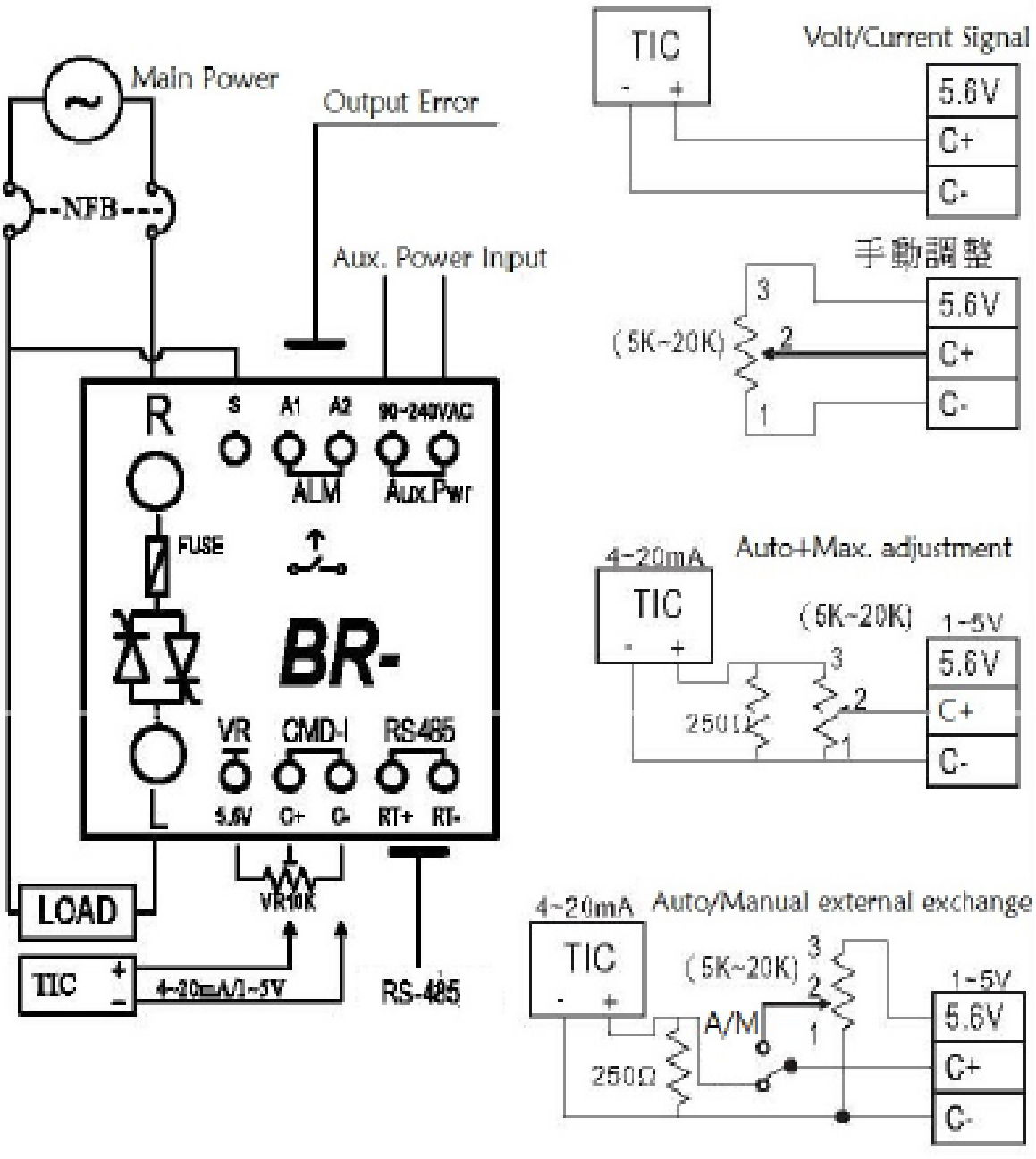
3.1.4.2. Induction electric heating.

Inductively heating (or agitation) which is a magnetic method does not rely on the generation of heat transmitted through the air to the body to be heated. However, this method depends on the body itself, which generates heat and therefore supplies to reduce the loss of energy. The advantage of this method is to provide precisely the exact degree of the metal temperature, and the time of heating is very low. This method is used extensively in various industrial applications such as metal smelting and welded.

3.1.5. Power regulator

Power regulator is an electronic device making the user to manipulate the status of an electrical circuit through the opening or closing a circuit using voltage or current. It supplies a required voltage to a heater or any devices in the range of 0-220 AC volt. Power regulator generates this variable voltage by adjusting the input DC volt or a potentiometer. In this experimental setup, ELCON power regulator shown in Figure 3.14 is used to control the voltage of the heater. For this regulator, the control DC voltage is supplied with Arduino microcontroller. In fact, as seen from Figure 3.15, the power regulator can control the output voltage with 0-5.6 DC volt for 0-220 AC volt. However, Arduino can generate 0-5 DC volt, and it causes the heater works with 97% of the maximum power. This power regulator is very effective to control the temperature of the system. Also, it has a very simple electric connection assembly and can be used simply by applying the user manual given in Appendix2.

Figure 3.14. ELCON type power regulator.



Terminal / Item	R, L		Signal Terminal
	30A	60A	
Diameter	5.5	14	AWG16~20
Y Terminal	5.5~5	14~6	

Figure 3.15. ELCON wiring diagram (ELCON manual).

3.1.6. Microcontroller (Arduino)

Smith (2011), presented a study on the development of an electronic board based on Arduino. It involves a physical Arduino Programmable circuit board often referred to as microcontroller and also a part of software, or IDE (Integrated Development Environment) that runs on your computer, is used to write and upload the computer code to the physical board. This modern electronic device can communicate with the surrounding environment through a number of sensors for example photocell sensor, temperature sensor ,humidity sensor , and can affect the surroundings through the controlling many electric device such as DC motor, an electronic device diode light (LED). Arduino has a small microcontroller board with a USB plug to connect to the computer and a number of connection sockets that can be wired up to external electronics devices or sensors, such as motors, relays, light sensors etc.

The main part of Arduino is the micro-controller which is a small computer on a single integrated circuit containing a processor core, memory, and programmable input/output peripherals. The primary part is that a micro-controller which consists of the processor (which all computers have), memory and some input/output pins often called GPIO (General Purpose Input Output Pins). Arduino is simpler, cheaper, easier to program and open-source project. With Arduino, software/hardware is extremely accessible and it is very flexible to be customized and extended. It presents a variety of digital and analog inputs such as SPI (serial interface) and digital PWM outputs.

Arduino is connected to computer or laptop via one of USB cable, micro USB, or FTDI breakout and communicates using standard serial protocol, also can run in standalone mode. Arduino is supported by a growing online community (library), lots of source code is already available and many examples from other users can shared and posted.

There are many types of Arduino with different characteristics. The common differences between the modules are the number of inputs and outputs, the type of microcontroller process, speed and the capacity of the flash memory

In this research, we selected Arduino Mega 2560 shown in Figure 3.16. Mega 2560 is a microcontroller board based on the AT Mega 2560 with 54 digital Input / Output

pins and 16 Input / Output analog pins. It is recommended for more spaces such as control, 3D projects, robotic applications and many electronic hobbies. Some technical features of this board is give in Table 2.

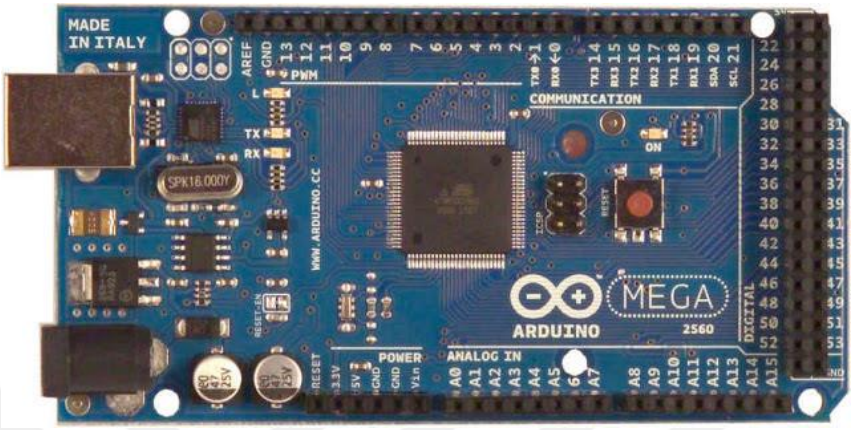


Figure 3.16. Arduino Mega 2560.

Table 2. The technical features of Arduino Mega 2560

Microcontroller	ATmega2560
Operating Voltage	5V
Input Voltage (recommended)	7-12V
Input Voltage (limit)	6-20V
Digital I/O Pins	54 (of which 15 provide PWM output)
Analog Input Pins	16
DC Current per I/O Pin	20 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	256 KB of which 8 KB used by boot loader
SRAM	8 KB
EEPROM	4 KB
Clock Speed	Hz

3.1.7 Amplifier

Amplifier is an electronic device used to increase input voltage to the microcontroller or computer. Signal of the sensor outputs with generally micro volt level is too weak to measure on the computer or any measurement device. The signal level should be increased up to at least micro volt. For this aim, the electronic measurement systems involve an amplifier to obtain the suitable signals. In this thesis, the thermocouple generates the voltage for the temperature at micro volt level. However, Arduino cannot read the signal less than 4.8 mill volt. For this reason, the signal has to be amplified before Arduino's input. Therefore, an amplifier called MAX31855 shown in Figure 3.17 is used to amplify the thermocouple signal for precise temperature. This amplifier is a production of ADAFRUIT Company and is designed to measure the temperature from any thermocouple.

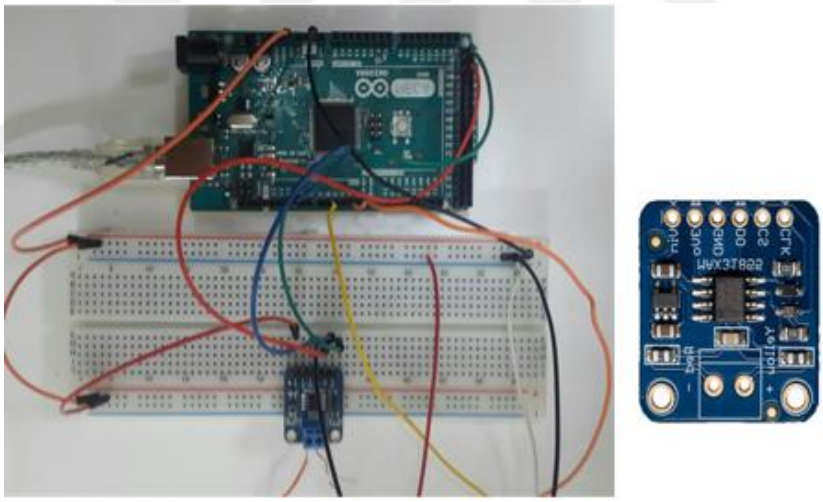


Figure 3.17. Arduino with MAX31855 amplifier.

A great attention should be paid when the measurement is performed since any very weak or magnetic area signal as a disturbance can affect the measurement.

3.1.8. Electronic valve (SUN YEH)

Electronic valve is a device that controls or regulates the flow of a fluid (liquids, gases) by opening, closing, or partially hampering various passage way. For controlling the quantity of liquid nitrogen to injection inside the box, the quarter-turn actuators are

designed for the operation of valves which require a swivel stroke of 90°. In this study, an electronic valve from SUN YEH Company is used as shown in Figure 3.18. It has an electric quarter-turn actuator which offers a range of 35 N.m to run by 12 DC volts. This valve performs the entire opening or closing process in 12 second. It consists of a three main part DC motor, gear box and return valve. This valve generally works at the ambient temperature of –30 - +65 ^{o}C. However, in this experimental study, liquid nitrogen is used to cool the system. The temperature drops a fairly low value, for example, –100 ^{o}C. Therefore, to save the valve, a ball valve is assembled to the electronic valve via a shaft connected with the output of the DC motor. The DC motor with gear box produce rotary motion and this motion is converted to a linear motion in a straight line to adjust the ball valve opening.

Figure 3.18. Electronic valvetype, SUN YEH.

In order to control the liquid nitrogen flow, the control input is applied to the different input pins (pin-3 for the opening and pin-4 for the closing). The electronic circuit belonging to the valve is given in Figure 3.18. The opening and closing of the valve is considered as two separate operations. For this reason, a motor driver with two digital inputs is used to control the valve situation depicted in Appendix 3.

3.1.9. DC motor driver (ADAFRUIT DC motor shield)

Motor shield is a driver module for motors that allows the user to make a connection between motors and microcontroller. This module can drive any inductive loads such as relays, solenoids, DC and stepping motors and also the direction and speed

can be defined easily. Arduino cannot supply more than +5 DC volts. However, in this study, the cooling valve needs a constant voltage of 12 volts. To adjust the opening and closing of the electronic valve by Arduino, a motor driver should be used for the required voltage. For this aim, Adafruit motor shield with version-2 shown in Figure 3.19 is very suitable to drive the 12 volt DC motors via Arduino with 5 DC volts.

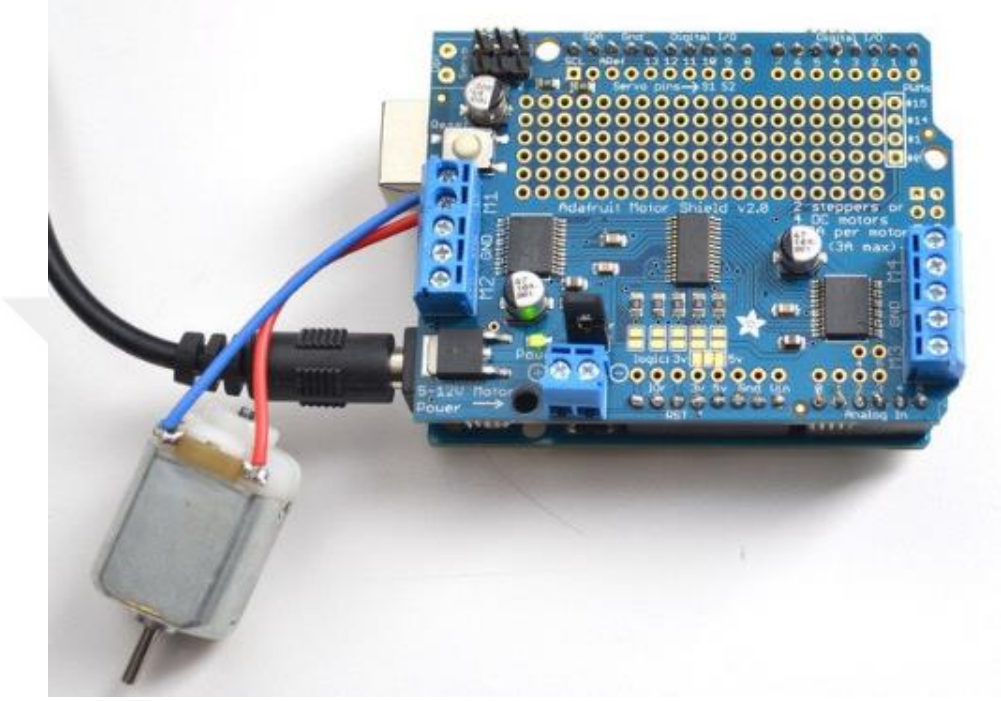


Figure 3.19. ADAFRUIT DC motor shield with version-2.

3.1.10. Liquid nitrogen tube (Dewar)

Cooling by liquid nitrogen and another liquefied gases are very effective method for very low temperature called cryogen process. Liquefied gases are stored in special tube called Dewar. Dewar is cryogenic cylinder tube used to accumulate liquid cryogens such as liquid nitrogen, helium, oxygen, etc. It usually consists of a cylinder surrounded by a vacuum which insulates the cylinder from the atmosphere or environment. The picture of a liquid nitrogen tube is given in Figure 3.20. The most confident material to construct liquefied gas tubes is usually stainless steel (SS 304) because of its higher strength and low thermal conductivity. For experimental and commercial purposes, this material is excellent choice for manufacturing Dewar's due to its strength and availability. However, Dewar's are fabricated generally from epoxy- fiberglass and aluminum. Liquid

nitrogen Dewar consists of multi-layered insulation covering the ship cryogen to decrease the heat load of radiation coming from the jacket vacuum at ambient temperature.

Figure 3.20. Liquid nitrogen tube (Dewar).

Nitrogen is a chemical element represented by symbol of N. It's classified within the non-metals, at the atmosphere conditions of pressure and temperature; it's colorless and tasteless, odorless. The gas form is diatomic N2. The nitrogen is basic element in the environment which consists of about 78% of the Earth's atmosphere, and thus is more pure in terms of the abundance of chemical elements. Some properties of nitrogen is given in Table3.

The liquid nitrogen is produced by liquefying the nitrogen element acquired commercially by fractional distillation of natural air. For the nitrogen, the expansion from liquid to gas states is 1:694. Therefore, the liquid nitrogen fills a volume with its gas phase in a very shorter time when boils.

Table 3. Some properties of nitrogen (Çengel and Michael, 1994)

Boiling point at 1 atm	–195.8°C
Freezing Point at 1 atm	–210.0°C
Critical temperature	–146.9°C
Critical pressure	33.5 atm
Density, at liquid	808.5 kg/m^3
Density, at gas, 20°C, 1 atm	1.16 kg/m^3
Latent heat of vaporization	199.1 kJ/kg

3.1.11. Air pump.

For cooling or heating the system in the heated or cooled phases respectively, an air fan with 100W is used as an intermediate controller element. Figure 3.21 shows the picture of this fun. For the heating process, when the rapid temperature drop is needed, the air at environment temperature is pumped into the isolated box via this fun. Sometimes, the natural cooling cannot produce enough heat transfer for the desired temperature profile in cooling process. The air at environment temperature is pumped when the temperature inside the isolated box to raise the temperature faster. The air fun run with 220V AC voltage and is controlled by Arduino as on/off. For this aim, Arduino supplies an electric relay with 5V DC digital output for ON position and 0V DC digital output for OFF position.

Figure 3.21. Air pump (Fan).

3.1.12. Electric relay

Relay is an electrical switch that makes an electrical connection between application points with respect to a control signal. The operating principle of a relay is dependent on an electromagnet mechanically or a semiconductor without moving part to actuate a switch. The electromechanical relays and solid-stare relays are the most generally and widely used type of relay. The purpose of electric relay is to control AC voltage (high voltage) by DC voltage (low voltage). In this study, to control the fan, the fan voltage of 220V AC is switched by the relay actuated with Arduino's 5V DC digital output. The simple diagram and picture of the relay are shown in Figure 3.22.

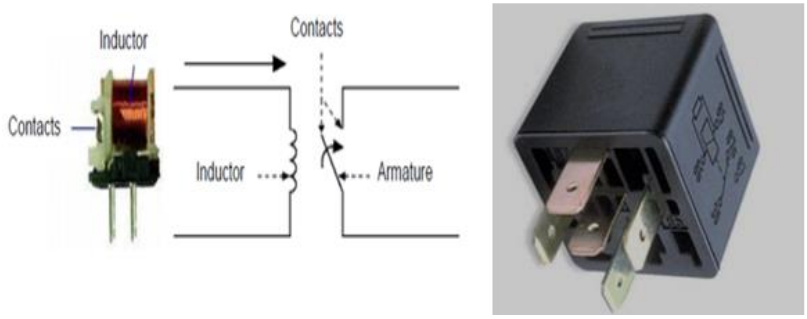


Figure 3.22. Electric Relay.

3.1.13. Computer

The connection between the computer and Arduino is made by USB which is a serial communication interface. In the computer, all manipulations to control the system are implemented via a program written with MATLAB software. This program involves many special MATLAB commands related to Arduino to recognize the driver, amplifier and microcontroller. The controller is run in the computer software and also the user defined reference temperature profile is loaded to the computer over this software. The temperature measure via thermocouple can be recorded and displayed over the computer on the MATLAB environment. In the experiment, a laptop with the CPU is AMD A8-3550MX APU and 8.00GB RAM is used.

3.2. Analogue diagram of the setup

In this experimental study, based on the requirement, the heating and cooling processes are performed separately or sometimes both at the same time. The flow chart of this experimental setup is depicted in Figure 3.23.

At first, the user uploads the desired temperature profile to the computer via a program written in MATLAB. By running the program, the temperature control system starts to Work. The temperature of the inside of the isolated box is measured continuously with a type-K thermocouple. This temperature measured by the thermocouple is converted to an analog signal at a voltage of microvolt level. This analog signal is boosted to a millivolt level via MAX31855 amplifier plugged into Arduino. At the same time, this

amplifier converts the analog signal to the digital one. This signal is transferred via USB to a program written in MATLAB environment compatible with Arduino and converted a temperature in degrees Celsius. The program also includes PID, P, and ON /OFF controllers as software, and tries to minimize the temperature error between measurement and reference using one of them according to the process. For this aim, the output modified on the controller is transmitted with USB to Arduino again. If heating of the system is required, Arduino adjusts the temperature by changing the load of AC voltage on the heater by sending 0 to 5V DC signal to the power regulator. The cooling process is performed by adjusting the amount of liquid nitrogen by Arduino sending +5, 0 or –5 V constant DC voltage to the electric valve via the motor driver for a calculated time. In some cases, cooling and heating processes can occur simultaneously to supply the desired temperature reference.

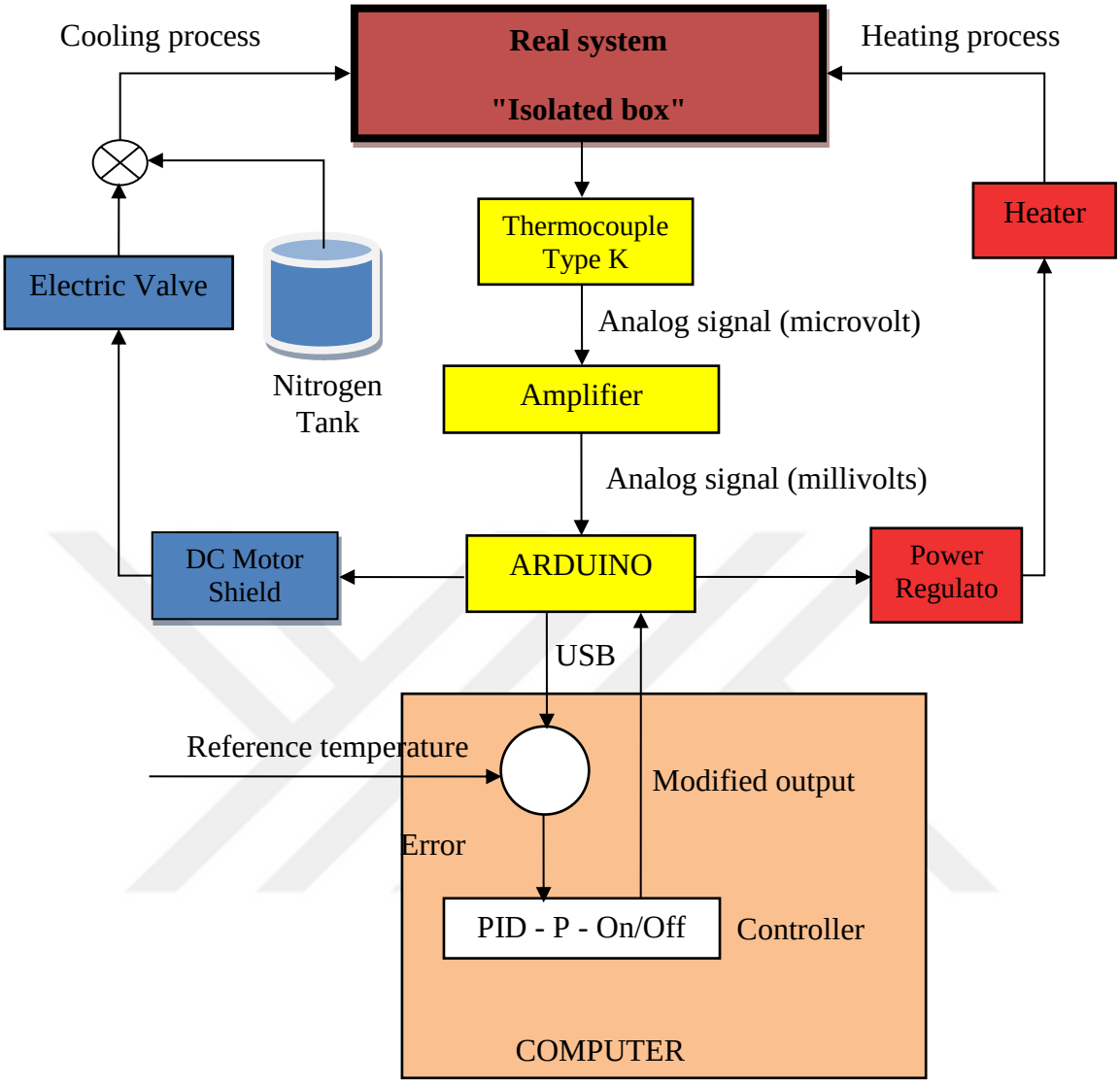


Figure 3.23. Flow chart of the experimental setup.

3.3. Calculations

3.3.1 The calculation heat loss

In this research, we selected the cubic box with the outer dimensions of (40cmx40cmx40cm) and the inner dimensions of (25cmx25cmx25cm) based on in a tension-compression testing machine. This box must be smaller in order to reduce the heat capacity and loss since the capacity and loss are proportional to the size of the box. The insulated box wall consists of three layers. The outer layers are made of iron with

thickness of 3 mm, the intermediate layers are rock wool isolated material with thickness of 7 cm and, finally, the inner layers are also iron with thickness of 2 mm. For isolated material, rock wool is used because its burning temperature is higher (700 ^{o}C) with a good thermal conductivity. The thermal parameters of the material used in the box are given in Table 4. The calculations are given according the calculations are given according to the Figure 3.24. and the related equations, "Eqns 3.4-3.7" as follows.

Table 4. The thermal parameters of the material (Anonymous, 2016)

Thermal conductivity of cast iron at 400 °C	$K_1 = 60$ W/mK
Thermal conductivity of rook wool	$K_2 = 0.045$ W/mK
Thermal conductivity of cast iron at 20 °C	$K_3 = 80$ W/mK
Heat transfer coefficient of air on cast iron surface at 400 °C	$h = 5.7$ W/m^{2}K
Heat transfer coefficient of air on cast iron surface at 400 °C	$h = 5.7$ W/m^{2}K
Box dimensions: X_1 , X_2, X_3	2mm, 7cm, 3mm
Critical temperatures: T_{in} , T_{out}	400 °C, 20 °C

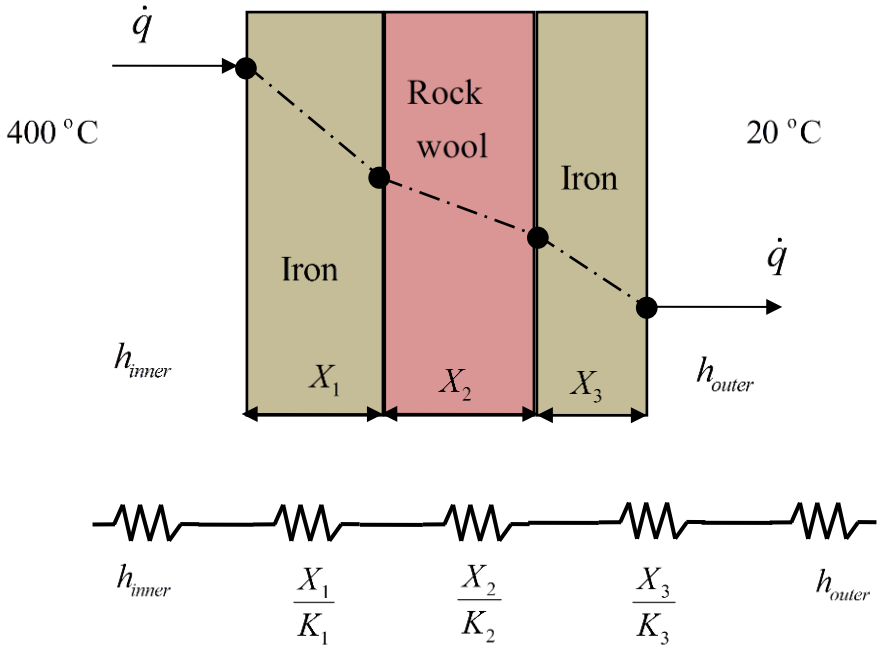


Figure 3.24. Thermal resistance in serial connecting.

The heat convection of the system is given as follows.

$$\dot{Q} = A\ U\ \Delta T \qquad (3.8)$$

Where A is the inside area of the one surface of the box, U is overall heat transfer coefficients and $\Delta T = T_{in} - T_{out}$ is the temperature difference between the inner and outer of the box.

$$R = \frac{1}{h_{in}} + \frac{X_1}{K_1} + \frac{X_2}{K_2} + \frac{X_3}{K_3} + \frac{1}{h_{out}} = \frac{1}{5.7} + \frac{0.002}{60} + \frac{0.07}{0.045} + \frac{0.003}{80} + \frac{1}{5.7} = 0.3509 \ ,$$

$$U = \frac{1}{R} = 2.8498$$

$$\dot{Q} = (0.25 \times 0.25)(2.8498)(400 - 20) = 67.6827 \ \text{Watt}$$

For six surfaces of the box, the total heat requirement;

$$Q_{total} = 6 \times Q = 402.0962 \quad \text{Watt}$$

This value is the minimum power of the heater. Considering the other losses, higher temperature than 400 °C and faster time heating process, the heater power is chosen 2.5 kW.

3.3.2. Cooling process by liquid nitrogen

Considering the working temperature conditions between than 20 °C and then -100 °C, the mass of the air in the box can be calculated at the average temperature,

$$T_{ave} = \frac{20 + (-100)}{2} = -40 \ ^{\circ}C$$

The density of the air at this average temperature is $\rho_{air} = 1.514 \ \text{kg/m}^3$ (Çengel,2002).

$$m_{air} = (0.25 \times 0.25 \times 0.25)(1.514) = 0.094625 \ [\text{kg}]$$

Gas constants at – 40 °C are $C_p = 1.002$ and $C_v = \frac{C_p}{1.4} = 0.7152$ (Çengel, 2002).

Where C_p is the specific heat for a constant pressure and C_v is the specific heat for a constant volume. The heat capacity for the cooling process is given as follows.

$$\dot{Q}_{air} = m_{air}\, C_v\, \Delta T \qquad (3.9)$$

$$Q_{air} = 0.094625 \times 0.715714 \times (20 - (-100)) = 8.127 \text{ Watt}$$

The heat losses through the box in cooling process can be calculated related to the previous case for the heat transfer.

$\Delta T = 20 - (-100) = 120$

$\dot{Q}_{cool} = A\ U\ \Delta T = 0.0625 \times 2.8498 \times 120 = 21.3735$ Watt

The loss heat for the cooling is

$$\dot{Q}_{loss} = \dot{Q} \times 6 = 128.24 \text{ Watt}$$

The total heat requirement is

$$Q_{total} = Q_{loss} + Q_{air} = 128.24 + 8.127 = 136.367 \text{ Watt}$$

The quantity of liquid nitrogen can be calculated based on the decreasing the temperature of air to –100°C. The latent heat is defined as follows when liquid nitrogen is converted from liquid to evaporated case.

$$\dot{Q}_{latent} = \dot{m} \times \left(h_{liquid} - h_{evaporeted}\right) = \dot{m} \times dh$$

dh = 199.73 Joule/gram (Anonymous, 2016).

$$\dot{m} = \frac{Q_{latent}}{dh} = \frac{136.376}{199.73} = 0.6828 \quad [\text{gram/s}]$$

3.4. Mathematical Modeling of the System

Generally the thermal systems are modeled as first order systems. In Laplace domain, the transfer function between the reference temperature input and the measured temperature at the inside of the box is given as follows.

$$G(s) = \frac{1}{1 + \tau_2 s} \qquad (3.1$$

Time-delay usually cannot be avoided in many mechanical and electrical systems, and the presence of the time delay in analogue or digital systems imposes strict limitations on the efficiency of these systems and holds analysis and design process (Sakallah, 1999). Therefore, the change in temperature does not occur immediately during the process of heating or cooling, however, delay time is represented by the formula $e^{-s\tau_1}$. Time delay for thermal systems is rather large compared to especially mechanical and electrical ones. This delay stems from generally the heated system capacity, heater type, thermocouple and controller. In addition, non-zero initial temperature should be considered in the modeling. Thus, the general form become as follows.

$$G(s) = T_0 + \frac{K}{1+\tau_2 s} e^{-s\tau_1} \tag{3.11}$$

T_0 : Initial temperature
K : Static gain ($K > 0$ for heating systems and $K < 0$ for cooling systems)
τ_1 : Apparent time delay
τ_2 : Apparent time constant

The experimental system gives the temperature outputs for a step response. For this recorded data set, the parameters can be calculated according to the graphical calculation of process curve method as follows. The details about these calculations can be found in (Zareh, 2009).

$$\left.\begin{array}{l} \tau_1 = 66 \text{ seconds} \\ \tau_2 = 117 \text{ seconds} \end{array}\right\} \quad \begin{array}{l} \tau_1 + \tau_2 = t_2 \\ \tau_1 + \dfrac{\tau_2}{3} = t_1 \end{array} \tag{3.12}$$

$K = 420 - 30 = 390\ ^{o}\text{C}$

With these parameter values calculated, the transfer function of the heating system is given in "Eq. 3.13". The theoretical and the experimental data have been shown in Figure 3.25.

$$G(s) = 30.0 + \frac{390}{1+117s} e^{-66s} \tag{3.13}$$

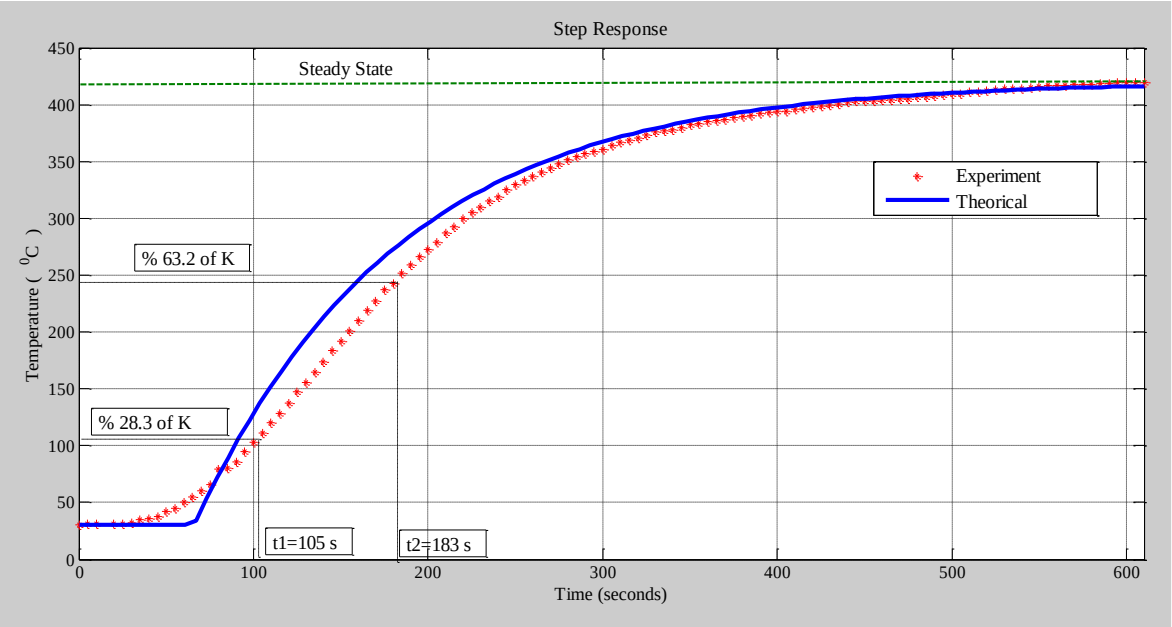


Figure 3.25. The Theoretical and experimental data of the heating part.

So as to model the cooling side of the system, the same procedure can be applied with the same assumptions. The only difference is the use of temperatures below zero.

$$K = -120 - 24.75 = -144.75\ ^{o}\mathrm{C}$$

$$\left.\begin{aligned} \tau_1 + \tau_2 &= t_2 \\ \tau_1 + \frac{\tau_2}{3} &= t_1 \end{aligned}\right\} \qquad \begin{aligned} \tau_1 &= 2 \text{ seconds} \\ \tau_2 &= 129 \text{ seconds} \end{aligned}$$

$$G(s) = 24.75 + \frac{-144.75}{1+129s} e^{-2s} \tag{3.14}$$

For the cooling part, the experimental and theoretical results are indicated in Figure 3.26 with the related time constants. Unlike the heating section, the delay time of the cooling process is very little because the liquid nitrogen is applied directly onto the system and the thermocouple can sense the temperature changes immediately. The speed of the system depends on the response time of the thermocouple. The K-type thermocouple used in this study is very sensitive to the temperature changes. However, in the heating system, the heater warms up first itself and then increases the temperature of system. This causes the larger time delay for the heating process.

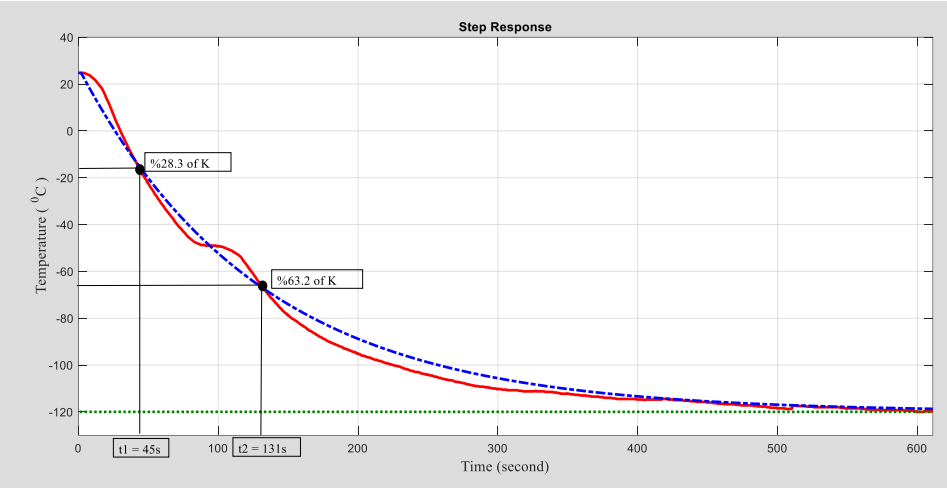


Figure 3.26. The Theoretical and experimental data of the cooling part.

3.5. Design of Controllers

The first criterion to select the type of controller is that the controller should be very simple to implement in the processes and easily adapted to the system by adjusting its parameters. For this aim, PID (Proportional + Integral + Derivative) controller is more effective and used in many types of control applications. The general equation for PID controller is given as follows.

$$u(t) = K_p e(t) + K_i \int e(t)\,dt + K_d \frac{de(t)}{dt} \qquad (3.15)$$

A PID controller continuously calculates an error value e(t) as a difference between desired set point and measured value and applies a correction based on PID terms. In this study, the error consists of the difference between the reference temperature defined by the user and the real temperature measured via thermocouple. The modified input can be adjusted by changing the coefficient of PID controller. There are many methods to calculate these coefficients for example, Ziegler-Nichols Method. However, for the sake of the simplicity, in this study, trial and error method was preferred to choose the coefficient of the controller.

In this heating and cooling system, three different processes were used to accomplish the experiment. These are heating process by using a heater controlled with power regulator, cooling process by using liquid nitrogen and air fun for low-speed

heating and cooling according to the system requirement. For these different processes, three different control types are used in the complete system.

In heating system, PID control is the better choice to control the temperature profile. The power regulator can work at any range of DC voltage between 0 and 5 V. Therefore, the modified input can be affected by three terms of PID.

The lower temperature can be obtained by regulating the flow of liquid nitrogen via an electronic valve. This valve is a solenoid valve and starts to open with 12V DC constant voltage and stops at that position when the applied voltage is stopped. Also, the closing process takes place in the same way, but, reverse direction with –12V. It takes seven seconds for the valve to be fully opened or fully closed. The nitrogen flow can be adjusted by applying ±12V for a certain period of time. This timing is set to be proportional to the temperature error. In specified error limits, P (proportional) controller is used to keep the temperature at the desired values. Out of these error limits, the valve tends to fully open or completely close.

The other temperature control device is the air fun pushing the air in the environment into the isolated box. It can be used not only to cool the system but also to heat the system. Because of this, it is an auxiliary device to control the temperature of the system. The control operation of the air fun depends on the sign of the temperature error. In the heating process, when the real temperature becomes larger than the desired value, the air fun is activated via a relay until the error sign changes whereas in the cooling process, the procedure works a reverse direction. The meaning of such a work is known as ON-OFF control. The control signals are supplied with a relay actuated 5V DC voltage via Arduino.

3.6. Computer Program

In fact, it can be said that the computer program is the foremost component of the experimental setup. As software, the computer program involves the controllers, interfaces and graphical parts. All temperature data are received, manipulated and transmitted via this program. Because of its efficiency, easier to program, many drivers of auxiliary devices involved, many researchers prefer to use MATLAB package program for control applications.

In this study, the software running the system and connecting the experimental setup to the computer was written in MATLAB. Arduino hardware is at first established to MATLAB. MAX31855 amplifier, motor drivers are also introduced to the computer program and their input and output configurations are constituted for the pin number of Arduino. Then, the variables, constants used in the control program are assigned. The reference temperature is loaded from an external file. The temperature control of the system starts within a loop that lasts 1.0 second for each cycle. The temperature data is received via the thermocouple in every loop as an analog DC voltage at a level of microvolt. However, this information is converted to a digital data with the amplifier. This digital data is operated on the program and converted to the temperature value by using a formulation. The error between the measured and reference temperatures is calculated. After that, the control starts. To control the temperature, some different scenarios are created in the program written in MATLAB. These scenarios vary depending on the temperature error and the direction of the temperature change, i.e. the slope of the reference curve. For example, the heating part of the system only works if the measured temperature is greater than 60°C.and the slope is greater than zero or if the temperature is greater than 60°C. And the slope is equal to zero, the input is step and the temperature is tried to keep constant via heating. In another scenario, the cooling part and air fun works together if the temperature is less than 175°C.and the slope is less zero or in order to keep the temperature at–100°C., also, the cooling part and air fun run together. Two functions for the heating and cooling are written separately in the program. In the meanwhile, according to the sign of the error, the command to open and close the relay for the air fan has been created. PID parameters are individually defined for step or ramp input in the heating function. In the control program, the measured temperature and DC actuated voltage of the power regulator are saved in every loop. These temperature values during the operation are shown graphically by the program. The whole control program written in MATLAB is given in Appendix 4.

4. RESULTS

The experimental work will be implemented under three titles to examine the system behavior in detail. These involves only heating, only cooling and combined work.

4.1. The Results of the Heating System

Briefly, in this part, the heat source is a dry resistance with a power of 2.5 kW. The inner temperature of the isolated box is adjusted by regulating the voltage on the dry resistance. The resistance power can be regulated between 0-2.5 kW. The voltage adjustment is done by using 0-5 V DC input generated via Arduino. In this feedback temperature control system, the inner temperature is measured as an output a thermocouple type-K. In the meanwhile, when the rapid temperature drop is needed, an air fan with 100W is used to decrease the temperature by pumping the air at environment temperature into the box. Sometimes the natural cooling cannot produce enough heat transfer for the desired temperature profile.

At first, the heating system was tested for the different power by adjusting the power regulator loads between 0% and 100% of the full load. For this aim, the heater is actuated with 0.5 V, 1.0 V, 2.0 V, 3.0 V and 5.0 V DC inputs from Arduino. Each power stage can be supplied by applying 20%, 50%, 75%, 90% and 100% of full power respectively. The outcomes can be seen in Figure 4.1. Due to the characteristics of the power regulator, the output AC voltage to the heater is not proportional to DC input voltages. From the figures, the response time for all the loads reaching the steady state of the desired temperature are approximately 1000 s. The delay time is the same for all possibilities. This is an expected result corresponding a thermal system characteristics which is a larger setting and delay time.

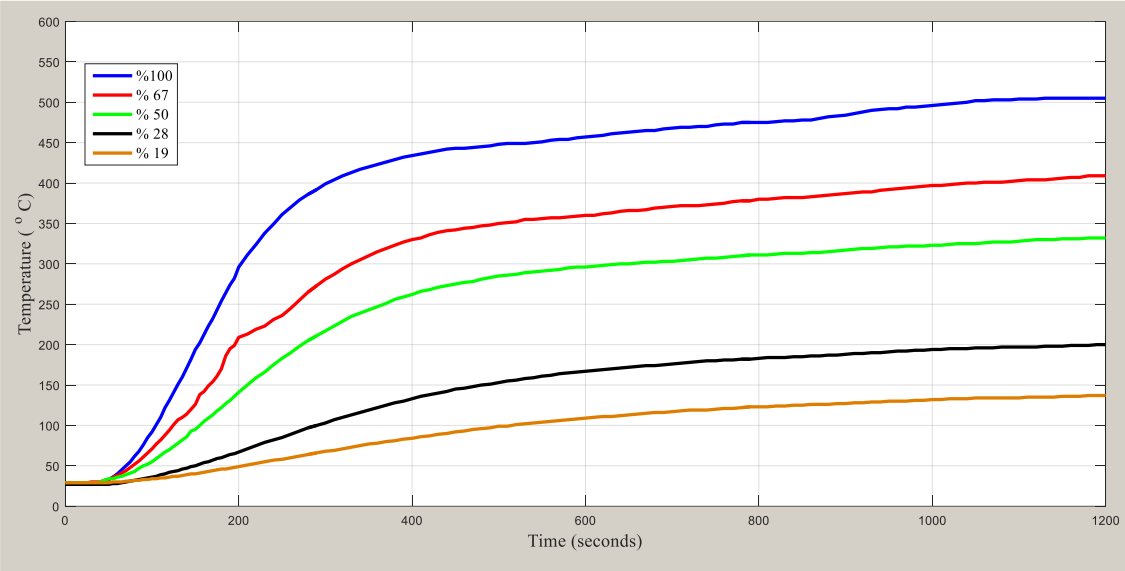


Figure 4.1. The temperature of the heating system for different constant DC input voltages.

So as to identify the behavior of the system, some step and ramp inputs are tested with the different PID coefficients. A two-level step input is given to the heating system with the different PID gains to select the better response. When a proportional gain is used alone, the system gives a responds with very oscillatory and also does not reach the reference input. Therefore, the derivative and integral gains must be assigned to the controller. Especially, the integral gain does not only compensate the offset error and also decreases the raising time. The results are shown in Figure 4.2 with the different possibilities. For this step input, the better choice seems to be $K_p = 130$, $K_i = 0.04$ and $K_d = 30$. In the figure, the theoretical response is a bit different from the experimental ones because it was modeled at the different environment and also the different input temperatures. The larger delay time for the theoretical model is due to this reason. However, the result indicated that the real and theoretical results are highly compatible with each other.

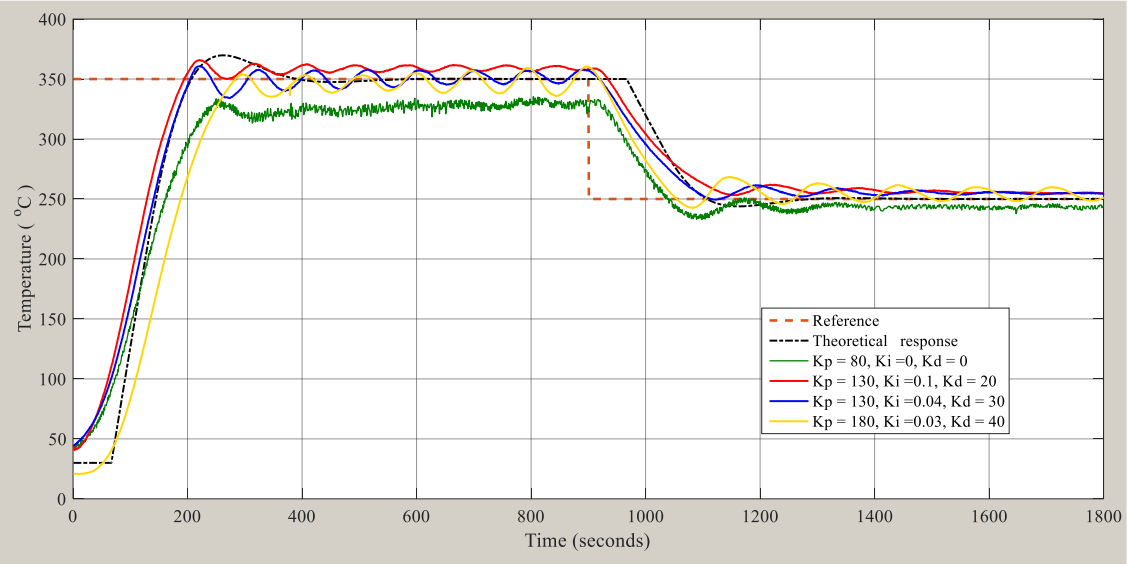


Figure 4.2. The temperature change of the heating system with the different PID coefficients for a two-level step input.

In another experiment, the heating system was subject to a two-level ramp input as shown in Figure 4.3. The temperature increases to +400°C in 500 seconds and then decreases to +250°C in 400 seconds. In fact, this is a reference tracking experiment. The better tracking response was supplied with the coefficients of $K_p = 144$, $K_i = 0.7$ and $K_d = 110$. Like the step responses, the proportional gain used alone could not reach the desired top temperature value and also could not follow the temperature reference in an acceptable way. From this figure, the integral action has a very important role to improve the system behavior. Compared to the reference input, there appeared a time delay because it is known that this thermal system has naturally a time delay. In this experiment, the cooling process from higher temperatures happened by itself.

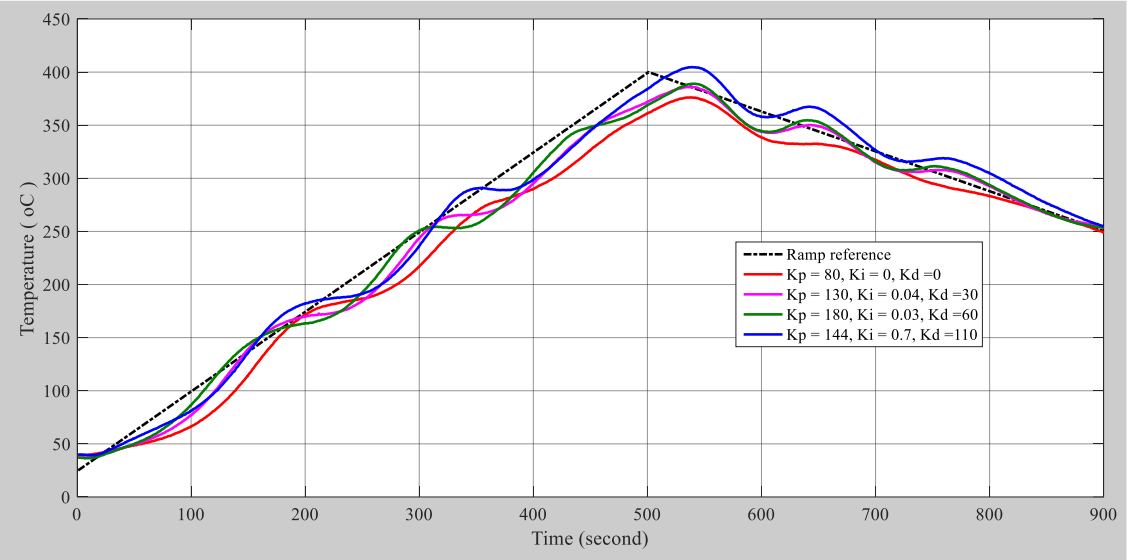


Figure 4.3. The temperature change of the heating system with the different PID coefficients for a two-level ramp input.

For the experiment related to only the heating part, the coefficients of the PID controller are changed according to the output responses. In the experiments, the reference temperature profile consists of some ramp and step inputs. After some successive increasing and decreasing ramp inputs, the temperature of the inside of the box were kept at 200°C, 350°C and 250°C respectively as shown in Figure 4.4. As shown from the figures, all possibilities of the controller gains can give the reasonable temperature profiles.

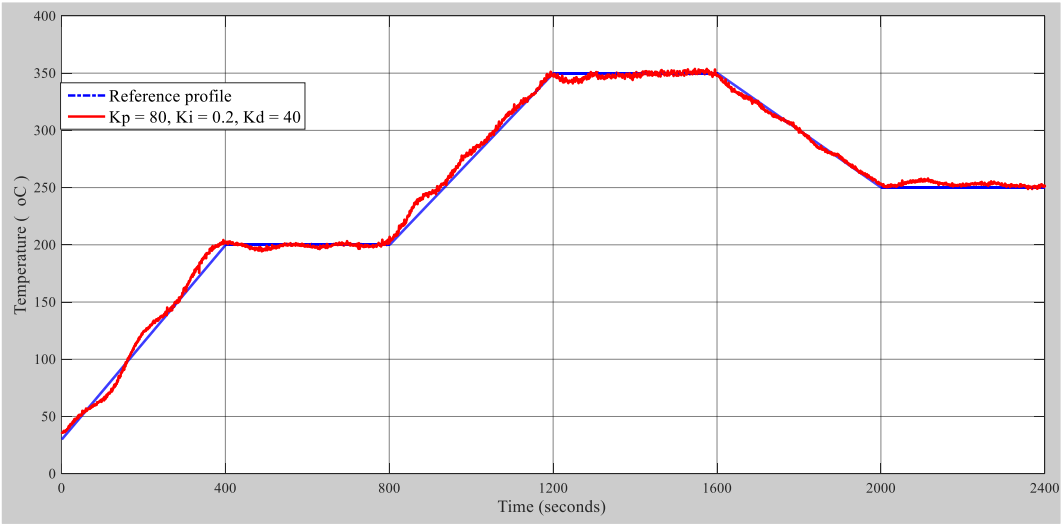


Figure 4.4. The temperature change of the heating system for a combined temperature profile.

The proportional gain with higher values gives oscillatory outputs. However, there is no offset on the outputs. The better results are obtained for the parameters of $K_p = 80$, $K_i = 0.2$ and $K_d = 40$. The error between the reference and real temperature for this parameter set is given in Figure 4.5. Meanwhile, the DC voltage changes of the power regulator corresponding to these parameters are shown in Figure 4.6. Increasing the values of these parameters, especially, K_p and K_i, makes the system very oscillatory and even unstable. In this experiment, the heated system decreases its temperature itself by natural cooling. In fact, the temperature with higher values can be decreased by using the air fun which drives the air with the environment temperature into the heated box. The preferred coefficients result in approximately the error of $\pm 10\ ^{o}\mathrm{C}$. In these figures, there are some oscillations on the output temperatures because the measurement device which is thermocouples is very sensitive to the noises and gives the very low voltage of millivolt level. Any change of the voltage with the noise can be result in very high voltage input for the input of Arduino via the MAX31855 amplifier. Also, there appeared a little time delay.

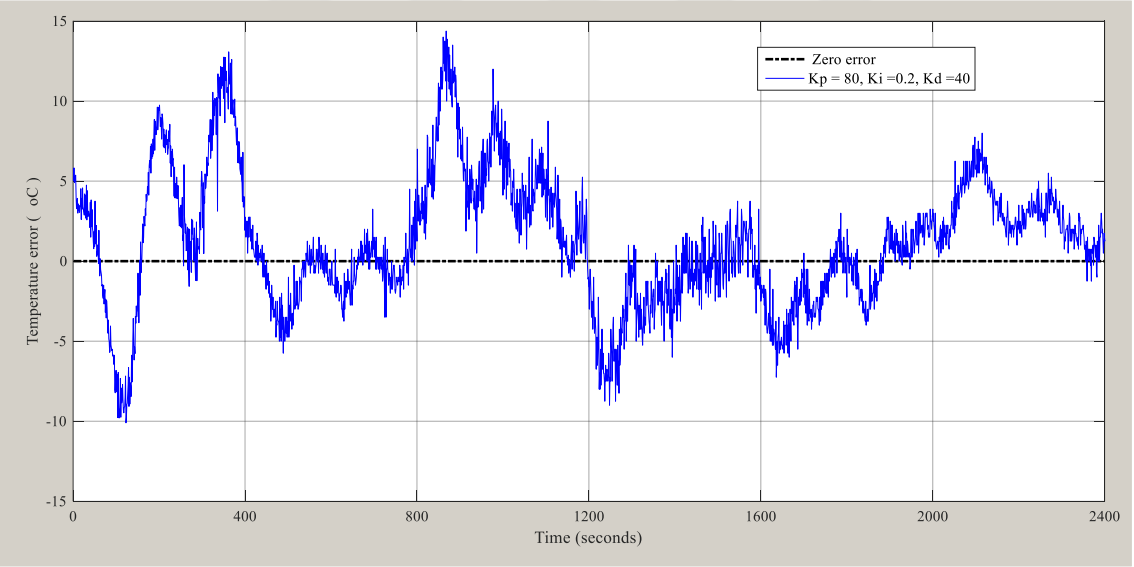


Figure 4.5. The temperature error of the heating system for the different PID coefficients.

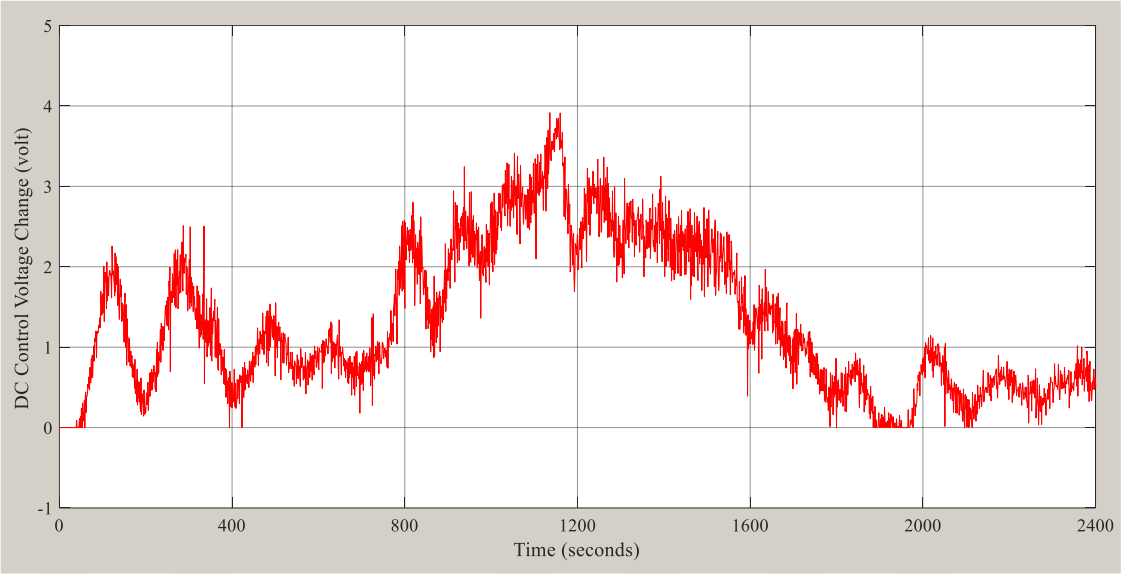


Figure 4.6. The input DC control voltage for the power regulator.

4.2. The Results of the Cooling System

In the cooling processes, the motor shield actuates the electric valve to control the quantity of liquid nitrogen. The liquid nitrogen is injected inside the box by opening or closing the rotating valve. The temperature is measured by thermocouple through the amplifier. Then, the MATLAB software plotted the related curves of cooling experiment. The system gives the temperature outputs to very low level according to the user references which are the step and the combination of step and ramp responses.

The first experiment of the cooling control is carried out by loading the temperature reference which is a step function with –80 °C. Some temperature results are shown in Figure 4.7. In these experiments, the control system tries to keep the temperature at –80° C it for a period of time. The control algorithm exploits the valve according to the instantaneous error between the real and reference temperatures and a given error band.

$$error = (\text{Real temperature}) - (\text{Reference temperature})$$

Opening or closing of the valve to adjust the liquid nitrogen depends on the calculated error. When the error value are very large, the electric valve completely opens while the electric valve completely closes when the error value very large with negative

sign. However, the valve is actuated for the fine tuning of the nitrogen according to the error band. This means that the electric valve opens partially. The outcomes are shown in Figure 4.7 for the error bands at different intervals. There is a slight difference in the results because the initial temperatures of the experiment are different and the experiments are done at the different air pressure of the nitrogen tank. In this experiment, the air fan for heating was not used. Instead, the warming of the system happens naturally on its own. In the experiments, the system receives data from the thermocouple every 1 second. Full opening or closing of the valve takes 12 seconds. For larger absolute errors, the valve opens or closes 1 second for each cycle. However, in the case of smaller errors, an opening or closing duration less than 1 second is assigned proportional to the errors within the error band.

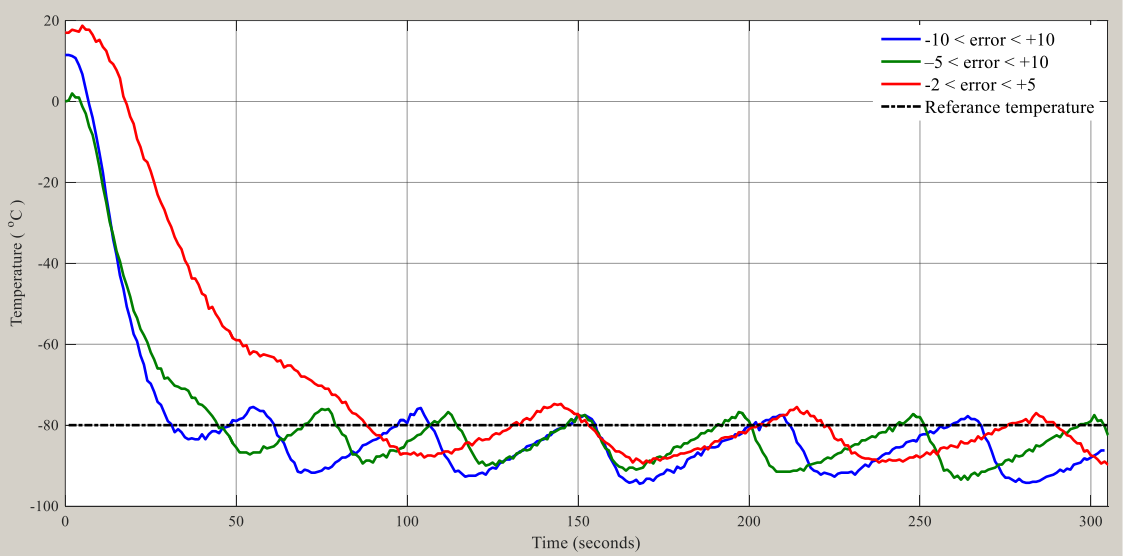


Figure 4.7. The temperature changes of the cooling stage for the step input.

The natural cooling or heating alone cannot usually enough. Therefore, an electric fun is used to pump the air at room temperature into the isolated box. This is a simple device and helps to control the temperature very much. The second experiment on cooling was performed for the combined temperature references. These references consist of some step and ramp inputs. The results of such an experiment have been given in Figure 4.8 for the different profiles. In this figure, the first experiment represented by a blue line is better than the second experiment represented by a green line. The difference stems from using the air fun. In the first experiment, the air fun was used to control the

temperature as an additional controller. Thus, the amplitude of the overshoots is alleviated substantially. In both cases, the system has yielded acceptable outcomes.

In the cooling side of the system, the air fun is controlled by On-Off while the control of the electric valve is supplied with P controller. The opening or closing duration of the valve is adjusted proportional to the temperature error.

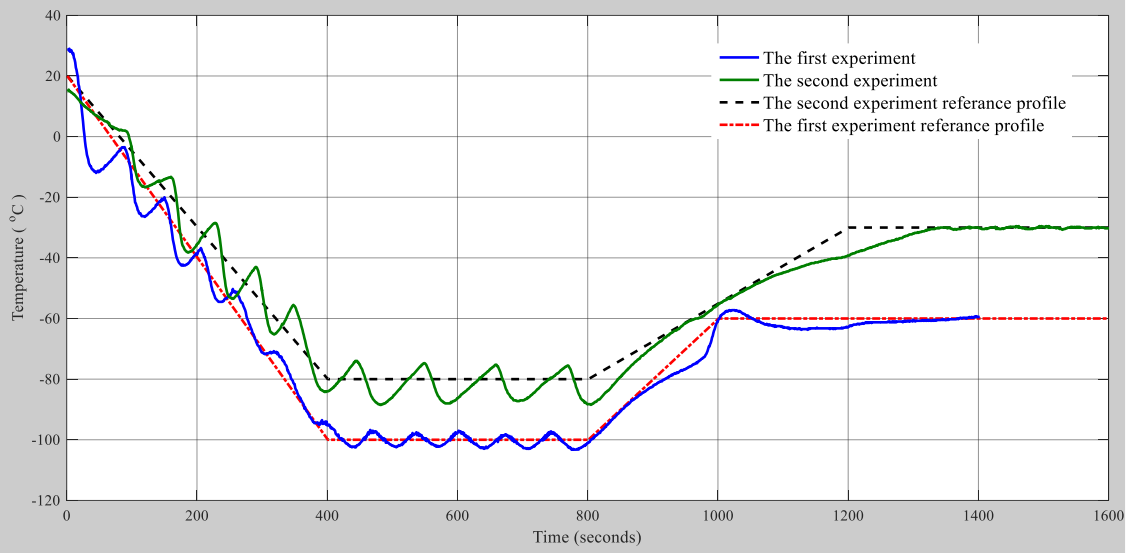


Figure 4.8. The temperature changes of the cooling stage for the different type of reference inputs.

4.3. Results of the Combined System

This part involves both heating and cooling processes. As seen from Figure 4.9, the reference temperature profile consists of some ramp and step inputs for different applied times. The temperature can increase up to +300°C and also decrease until –100°C and keep them for a while.. This combined profile is chosen for the standard tension and compression testing of the material. For example, the first test started with the environment temperature of 20°C and finished the temperature of –50°C during 2200 seconds. The second test followed the same profile but it returned to the starting point, which took a full temperature cycle. From the figure, another difference is that the second experiment cannot reach the desired temperature since the experiments were performed at different air pressure of nitrogen tank. The air pressure in the first experiment was 1.0

bar while it is 0.5 bars in the second one. Also, these two experiments were done at the dissimilar environment conditions. The reason can be seen from Figure 4.10 which is the DC actuated voltage of the power regulator.

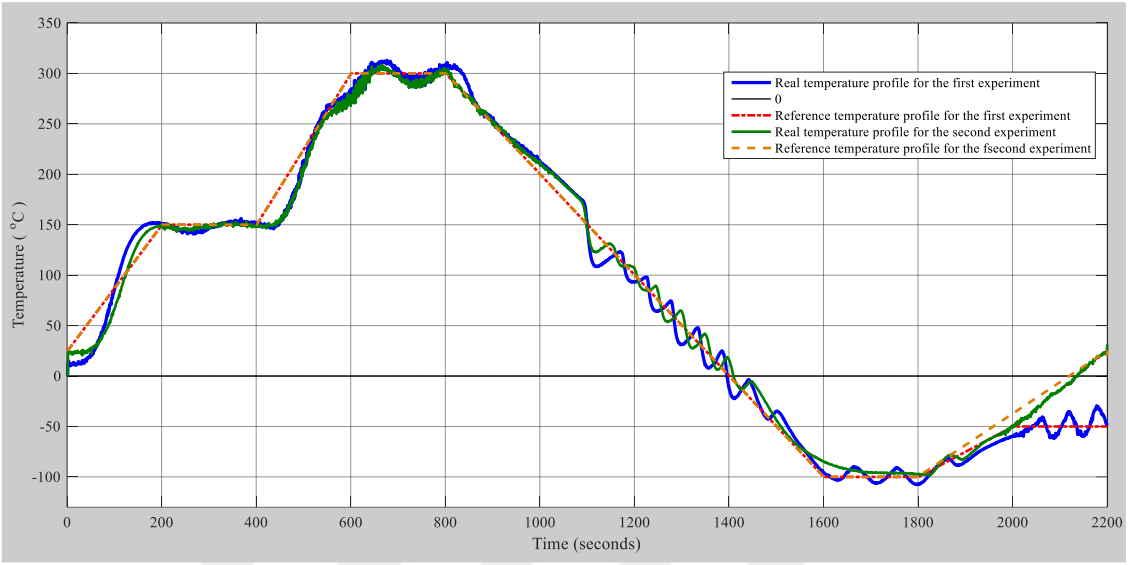


Figure 4.9. The temperature changes of the combined stage for the different type of reference inputs.

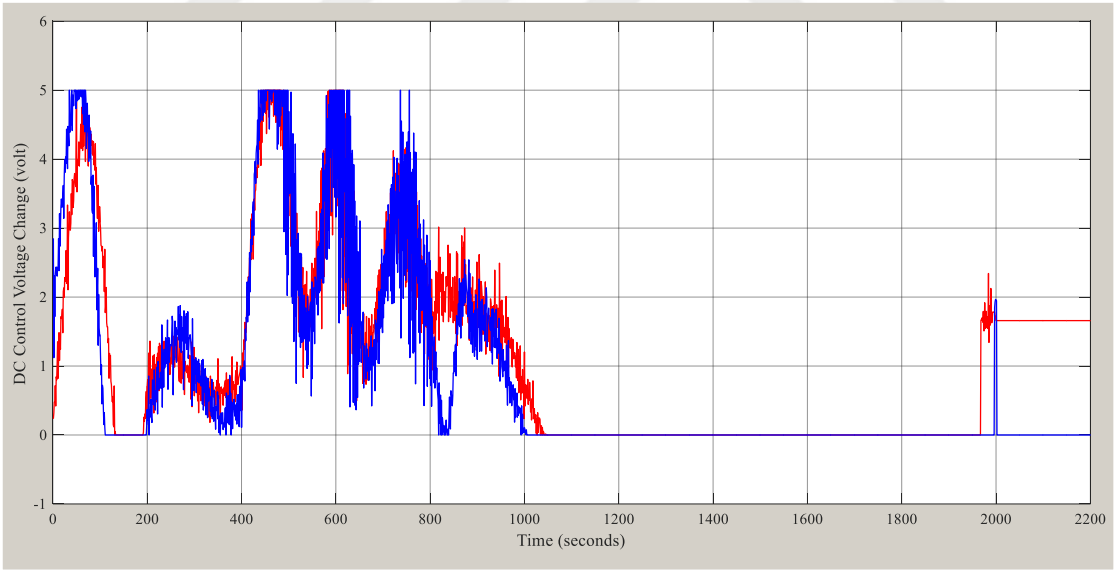


Figure 4.10. The DC control voltage change for the power regulator for the combined stage temperature profile.

5. DISCUSSION and CONCLUSIONS

The main objective of this work is to create a thermal system to control the heating and cooling processes which consist of some electrical and electronic devices. This system is used for a tension-compression testing machine. Thus, the physical properties of the materials can be investigated at very high and low temperatures with different profiles. This system involves basically an isolated metal box, dry resistance, voltage regulator, electric valve, nitrogen tank, thermocouple, air fan, relay, amplifier, motor driver, microcontroller and computer. For real time implementations, a control program was written on MATLAB software. This program enables to test the behavior of materials in different temperature profiles such as combination of step and ramp inputs.

The temperature control of a heating-cooling system can be necessary for many industrial fields such as food production, manufacturing and metal industries. Besides, the control at the wide temperature ranges is very important in the scientific fields. This design of such a system which is very simple and very low cost will be preferred especially in lower temperatures. These features are one of the remarkable superiority of the control setup. Another important subject is that Arduino microcontroller was used in this study. Compared to the other control apparatus, it is very cheap, easily available and easily controllable in any environment. In addition, measuring physical data and transmitting them to a computer happen quite simply and effectively. The experimental setup demonstrates that the performance of the heating and cooling processes is promising. Also, the experimental outcomes can be fitted to that of the theoretical model pretty well. In this study, the temperature can be measured quickly and successfully by thermocouple type K and the data can be easily transmitted and processed on the computer via Arduino and amplifier MAX31855. However, there was a noise arising from an external magnetic field or the leakage current of the heater. Although the noise on the thermocouple did not create a significant problem, it should be taken into account for the data processing because thermocouples are very sensitive to noise and the amplifier can strengthen this noise. For this aim, the thermocouple was isolated from the disturbing environment. Then, the internal metal walls of the isolated box stores the heat energy and thus it behaves as a disturbance. In addition to these, the coefficients of PID

controller should be adjusted adaptively for fine tuning of the temperature. Nevertheless, conceivably accurate outcomes were obtained in spite of these drawbacks.

The system designed in this study can increase the temperature up to +500 °C and decrease the temperature up to –120°C. It can be seen from the figures, the step, ramp and combined temperature references given could be followed with small and acceptable errors. The power regulator used in the control has given a quite effective performance. The valve used for cooling satisfied the expectations. If a valve such as servovalve adjusting the amount of nitrogen flow relative to the error was used in the cooling system, much more accurate outputs could be obtained. However, the price of such a valve is much higher than that of the valve used in this study.

The control program written in MATLAB has shown a great success in introducing the hardware to the computer, in easily programming and correcting errors.

The air fan in the setup is used as an auxiliary controller. The air fan supplies the result to be more accurate and also ensures that the temperature distribution inside the isolated box is more homogeneous.

The designed system in this study provided the following contributions.

- This system is quite simpler and cheaper compared to its equivalent products such as a system controlled by PLC.
- It is easily controlled and has higher performance relative to its price.
- It works with small and acceptable errors.

In the future work related to this study, there are some suggestions to improve the system. At first, PID coefficients used in the experiments were chosen by trial and error. These coefficients can be defined by some methods used in literature such as Ziegler-Nichols, neural network, response surface etc. Then, instead of PID controller, sliding mode controller, fuzzy-logic controller are more current methods and can provide more precise results. Also, a flow control system similar to servovalve can be used in this setup to supply liquid nitrogen proportional to temperature error. Finally, the controlling system can be designed via Arduino microcontroller using Wi-Fi for remote control with smart phone.

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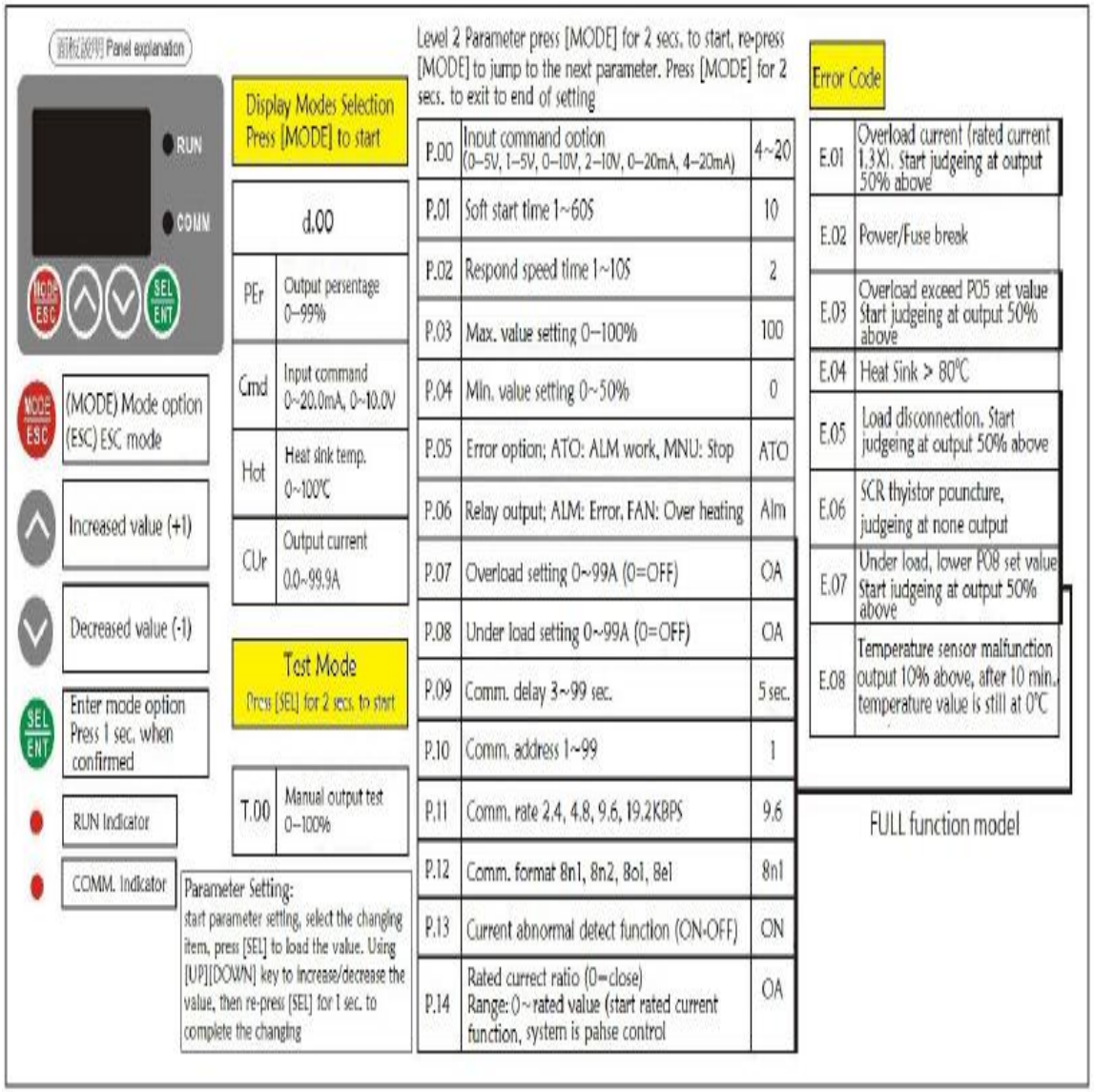
APPENDIX INDEX

Appendix 1. Thermocouple comparison (Schoeman, 2012)

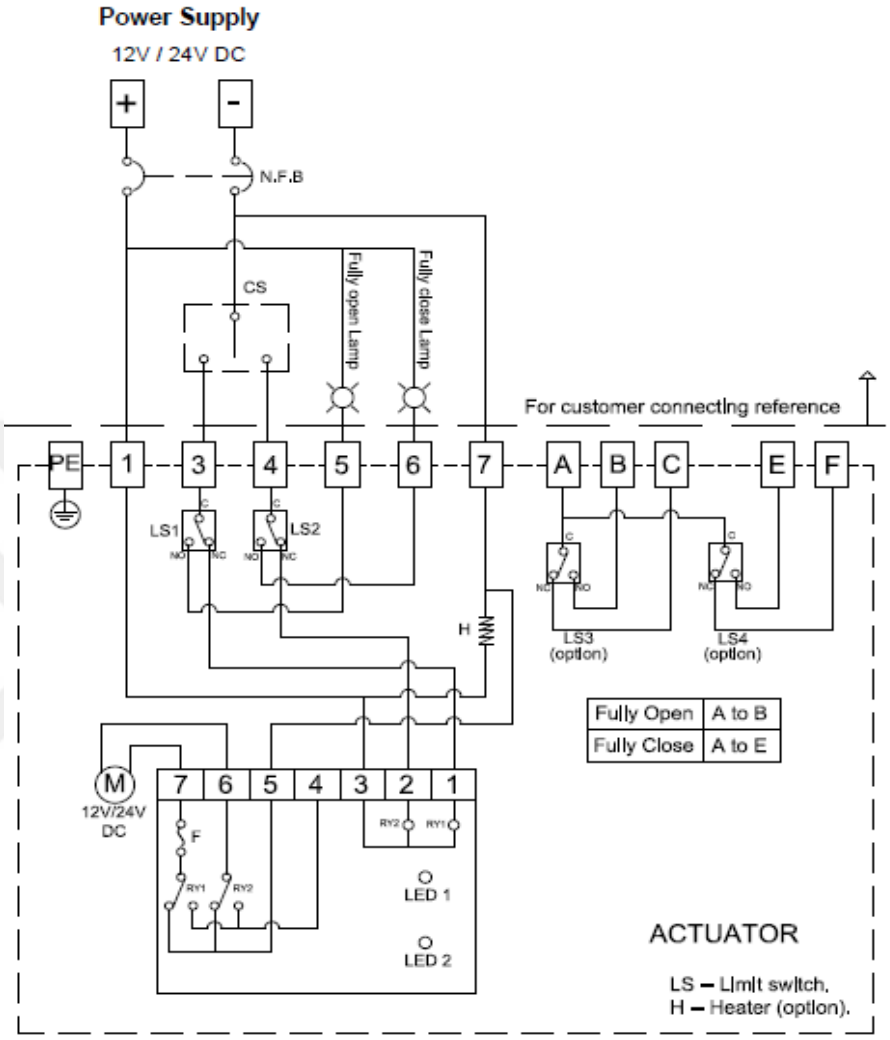
Type	Temperature range	Temperature range °C	Tolerance class one (°C)	Tolerance class two (°C)	BS Colour code	ANSI Colour code
K	0°C to +1100°C	−180°C to +1300°C	±1.5°C between −40°C and 375°C ±0.004°C ×T between 375°C and	±2.5°C between −40 °C and 333°C ±0.0075°C ×T between 333°C and 1200°C		
J	0°C to +700°C	−180°C to +800 °C	±1.5°C between −40°C and 375°C ±0.004°C ×T between 375 °C and 750°C	±2.5°C between −40°C and 333°C ±0.0075°C ×T between 333°C and 750°C		
R	0°C to +1600°C	−50°C to +1700°C	±1.0°C between 0°C and 1100°C ±[1°C + 0.003°C ×(T − 1100°C)] between 1100 °C and 1600°C	±1.5°C between 0°C and 600°C ±0.0025°C ×T between 600°C and 1600°C		Not defined.

Appendix 2. Power regulator operation & display functions (ELCON power regulator manual)

Operation & Display Function (BRD & BRA)



Appendix 3. Electronic valve circuit of SUN YEH



NOTE:

1. "+" connects to #1, "–" connects to #7.
2. "–" connects to #3 for "OPEN", "–" connects to #4 for "CLOSE".
3. Using less than 3A current for "A, B, C, E, F".
4. Using battery to supply power for DC units.

Appendix 4: MATLAB software codes for heating and cooling control system.

```
%%%%%%%%%%  THE  TEMPERATURE  CONTROL  OF  HEATING  AND  COOLING  SYSTEM
%%%%%%%%%%

% THERMOCOUPLE and MOTOR COMMUNICATION

a                                                                    =
arduino('COM5','Mega2560','Libraries',{'SPI','Adafruit/MotorShieldV2'}
);
dev = spidev(a,'D10'); %Chip select pin D10, MISO ICSP-1(D50), SCK  ICSP-
3 %(D52), MOSI(not used)

t=0;
Sicaklik=0;
zaman=0;

% ARDUINO CONFIGURATION
configurePin(a,'D3','DigitalOutput');
configurePin(a,'D5','DigitalOutput');

% ASSIGN VARIABLES

% Valve variables
shield = addon(a, 'Adafruit\MotorShieldV2');
addrs = scanI2CBus(a,0);
dcm1 = dcmotor(shield,1,'Speed',0);
dcm2=dcmotor(shield,2,'Speed',0);
start(dcm1);
start(dcm2);

% Error and PID variables
double santigrat;
double IHata;
IHata=0;
ilkhata=0;
ITop=0;
double Hata;
tps=1; % pause time

load CombTRef; % Load the temperature reference from the existing file

k=1;

% THE CALCULATION LOOPS FOR THE ASSIGNED TIME and PLOT THE FIGURES

for i=1:1800;

dataIn = [1 1]; % to receive two pieces of information, two pieces of
%information are sent.
dataOut = writeRead(dev,dataIn,'uint16'); % uint16, the required largest
%integer number for using the function.
veripaketi=uint32(dataOut(1)); % combine two pieces information for a
32-bit %integer number.
veripaketi=bitshift(veripaketi,16); %data(1) and shifted to uint32.
```

```
z = bitor(veripaketi,uint32(dataOut(2))); %data(2) and using bitor()
command, %shifted to uint32.
z = dec2bin(z,32); %create 32 - bit binary number.
santigrat=bin2dec(z(2:14))*0.25; % from MAX31855 datasheet, 1 Celsius
%corresponds to 18-31 bit. This numbers are arranged reversely in MATLAB.

% Multiplied by 0.25 since the datasheet says the LSB is 0.25°C.
% Check the ADAFRUIT MAX31855 library for an in-depth look at processing
these bits.


%COOLING TEMPERATURE MODIFICATION
if (santigrat>1900)
    santigrat=santigrat-2048;
end

Sicaklik = [Sicaklik, santigrat];
t=t+1;
zaman = [zaman, t];

plot(zaman,Sicaklik);
drawnow;
grid on;
hold on;

%%%% THIS PART SHOWS WHICH MODUL RUNS %%%%%%%%%%
 T1=CombTRef(i);
    T2=CombTRef(i+1);
    mt=T2-T1;
    TG=santigrat;
ReferansNoktasi=CombTRef(i);
Hata=(ReferansNoktasi-santigrat);

% Different scenarios for temperature control

    if (TG>60 && mt>0)
        %%%% heat the system  %%%%%%%%
        [controlPwm,ITop]=heating(Hata,IHata,ilkhata);
        writePWMVoltage(a,'D3',controlPwm);
        tps=1;
        ST=1
    end
        %%%%%%%%%%%%%%%

        if (TG>60 && mt==0)
        %%%% heat the system and keep the temperature consant  %%%%%%%%
        [controlPwm,ITop]=heating(Hata,IHata,ilkhata);
        writePWMVoltage(a,'D3',controlPwm);
         tps=1;
         ST=2
         %%%%%%%%%%%%%%%

        end

        if (TG>175 && mt<0)
```

```
          %%%% coolig the system via a fun and heat the system %%%%

         [controlPwm,ITop]=heating(Hata,IHata,ilkhata);
         writePWMVoltage(a,'D3',controlPwm);

          tps=1;
          ST=3
          %%%%%%%%%%%%%%%
         end

           if (TG<60 && TG>0 && mt>0)
               %%%% Bu heat the system  %%%%%%%%

        [controlPwm,ITop]=heating(Hata,IHata,ilkhata);
         writePWMVoltage(a,'D3',controlPwm);
         tps=1;
         ST=4
         %%%%%%%%%%%%%%%
           end

           if (TG>0 && TG<175 && mt<0)
               %%%% cool the system and control the temperature by the
fun %%%%

               tps=cooling(Hata,dcm2,dcm1);
                pause(tps);

                 if (Hata>0)
                      writeDigitalPin(a,'D5',1);
                     else
                        writeDigitalPin(a,'D5',0);
                end

             ST=5
         %%%%%%%%%%%%%%%
           end

          if (TG<-60 && TG>-200 && mt<0)
        %%%%  only cooling is active %%%%%%%%

         tps=cooling(Hata,dcm2,dcm1);
         controlPwm=0;
                ST=6
          end
          %%%%%%%%%%

          if (TG<-60 && TG>-200 && mt==0)
              %%%% only cooling is active %%%%%%%%

        tps=cooling(Hata,dcm2,dcm1);
        controlPwm=0;
        ST=7

         %%%%%%%%%%%%%%%
          end
```

```
        if (TG<-60 && TG>-200 && mt>0)
            %%%% cool the system and control the temperature by the fun
%%%%%%

        tps=cooling(Hata,dcm2,dcm1);
        controlPwm=0;

             if (Hata>0)
            writeDigitalPin(a,'D5',1);
             else
          writeDigitalPin(a,'D5',0);
             end
               ST=8
             %%%%%%%%%%%%%%%
        end

    if (TG>-60 && TG<0 && mt>0)
      %%%% cooling and heating work together to control the temperature
%%%%%

       if Hata>0
             [controlPwm,ITop]=heating(Hata,IHata,ilkhata);
        writePWMVoltage(a,'D3',controlPwm);
        tps=1;
       else
        tps=cooling(Hata,dcm2,dcm1);

       end
       ST=9
    end
       %%%%%%%%%%%%%%%

         if (TG<0 && TG>-60 && mt<0)
            %%%% cool the system and control the temperature by the fun
%%%%%%

        tps=cooling(Hata,dcm2,dcm1);

             if (Hata>0)
            writeDigitalPin(a,'D5',1);
             else
          writeDigitalPin(a,'D5',0);
             end

            ST=10
         end
              %%%%%%%%%%%%%%%
             if (TG<0 && TG>-60 && mt==0)
            %%%% cool the system and control the temperature by the fun
%%%%%

       tps=cooling(Hata,dcm2,dcm1);
       controlPwm=0;
              if (Hata>0)
            writeDigitalPin(a,'D5',1);
             else
          writeDigitalPin(a,'D5',0);
```

```
            end
        ST=11

         %%%%%%%%%%%%%%%
               end

               if (TG<60 && TG>0 && mt==0)
               %%%% only heating works  %%%%%%%%

        [controlPwm,ITop]=heating(Hata,IHata,ilkhata);
         writePWMVoltage(a,'D3',controlPwm);
         tps=1;
         ST=12
         %%%%%%%%%%%%%%%
              end


         if (TG<300 && TG>100 && mt<0)
             if Hata>0
             writeDigitalPin(a,'D5',0);
             else
         writeDigitalPin(a,'D5',1);
             end
         end


%%%%%%%%%%%% END OF CONTROL   %%%%%%%%%%%%%%%%
Voltaj(k)=controlPwm;  % save the DC control voltage of the power
regulator

IHata=ITop;
ilkhata=Hata;
pause(tps);% wait a while for getting new data from the thermocouple

k=k+1;
end



% THE FUNCTION TO CONTROL THE HEATER

function [F,ITop]=heating(Hata,IHata,ilkhata)

% PID parameters
double kP;
double kI;
double kD;

if abs(Hata)>20 % PID parameters for step inputs

      kP=40;
      kI=0;
      kD=0;
 else             % PID parameters for ramp inputs

   kP=80;
```

```
   kI=0.4;
   kD=60;
end
%
double P;
double I;
double D;
double PID;
%

double sonislem;
sonislem=0;

double SonSicaklik;
double deltaZaman;

deltaZaman=1;

P=Hata*kP; % P, proportional term


ITop=IHata+Hata*deltaZaman; % I, integral term
I=ITop*kI;

D =((Hata-ilkhata)*kD)./deltaZaman; % D, derivative term

 PID=P+I+D; % Total error


% Outputs
double controlPwm;
controlPwm=((PID/3200)*5);

 if controlPwm>=5;
    controlPwm=5;
 end
 if controlPwm<0;
    controlPwm=0;
 end

F=controlPwm;
end

% THE FUNCTION TO CONTROL THE COOLING SIDE

function dtps=cooling(hata,dcm2,dcm1)

if hata>0
    ts=1;

elseif (hata>-7 || hata<2) % Error band

    ts=(abs(hata)/10)*0.5;

else
    ts=1;
```

```
end

if (hata<0) % Open the valve
    stop(dcm2);
    dcm1.Speed=1;
    start(dcm1);
    pause(ts);
    stop(dcm1);
else
    stop(dcm1); % Close the valve
    dcm2.Speed=1;
    start(dcm2);
    pause(ts);
end
tp=1;
dtps=tp-ts;
```

Appendix 5. EXTENDED TURKISH SUMMERY (TÜRKÇE)

1. ÖZET

Genel olarak malzemeler çok farklı kullanım alanlarına sahiptir ve bu alanlarına göre de çalışma koşulları çok geniş bir yelpazede değişiklik gösterir. Bilindiği üzere malzemeler farklı sıcaklıklar altında farklı mekanik, elektriksel, kimyasal ve termal karakteristiklere sahiptir. Bu durumda tasarımın yapılacağı konsept dahilinde kullanılacak malzemelerin doğru bir şekilde seçilmesi için karakteristiğinin değişiklik şartlarda tanımlanması yüksek önem arz etmektedir. Sıcaklık kontrol sistemleri birçok alanda özellikle geniş çalışma sıcaklığı aralıklarındaki endüstriyel işlemlerde oldukça önemli bir konu olmuştur. Sıcaklık kontrolünün diğer önemli bir kullanım alanı ise malzemelerin mekanik karakteristiklerinin tanımlanmasında kullanılmasıdır.

Bu çalışma sıcaklık kontrollü bir ısıtma ve soğutma sisteminin tasarımını içermektedir. Çok geniş sıcaklık aralıklarında çalışmaya izin veren bu sistem, bir çekme-basma test cihazı üzerinde kullanılacaktır. Sistemin ısıtma tarafı temel olarak yalıtılmış metal hazne, kuru rezistans, güç ayarlayıcı, ısıl çift, hava fanı, röle, yükselteç, mikro kontrolcü ve bilgisayardan oluşmaktadır. Haznenin içinin sıcaklığı bir geri besleme kontrolü ile kontrol edilmektedir. Bu geri besleme kontrol sistemi sıcaklığı bir K-tipi ısıl çift ile ölmekte olup hataları telafi etmek için PID kontrolcü kullanmaktadır. Soğutma işlemi elektrik-elektronik cihazların soğutulmasında, endüstriyel süreçlerde, gıda üretim süreçlerinde, ilaç endüstrisinde ve bilimsel laboratuarlarda oldukça önemli bir işlemdir. Eğer kriyojenik süreçler üzerine çalışıyorsanız çok düşük sıcaklıklar için en iyi metot sıvı azot kullanmak olacaktır. Bu sistem için ısıtma kısmındaki cihazlara ek olarak soğutma sistemi elektronik valf, DC motor sürücüsü ve sıvı azot tankını da içermektedir. Bu kısımda sıcaklık kontrolü valf karakteristiğine uygun olarak oransal kontrol işlemi ile yapılmaktadır.

Bu deneysel çalışmada, ihtiyaca göre ısıtma ve soğutma işlemleri ayrı ayrı, bazen de her ikisi aynı anda gerçekleşebilmektedir. Önce, kullanıcı istenilen sıcaklık profilini MATLAB programı aracılığı ile bilgisayara yüklemektedir. Programın çalıştırılmasıyla sıcaklık kontrol sistemi çalışmaya başlar. Yalıtılmış haznenin içinin sıcaklığı K-tipi bir ısıl çift ile sürekli olarak ölçülmektedir.

Bu çalışmada, yalıtılmış haznenin sıcaklığı +400 ºC ila –100 °C arasında kolay bir şekilde tutulabilmiştir. Bazı deneysel çalışmaların uygulanmasıyla, kullanıcı tanımlı değişik sıcaklık profilleri başarılı bir şekilde test cihazı üzerinde gerçekleştirilmiş ve sonuçlar ısıtma ve soğutma sisteminin matematiksel modelinden elde edilen sonuçlar ile karşılaştırılmıştır. Oluşan hataların kabul edilebilir bir seviyede oldukları görülmüştür.

2. MATERYAL VE YÖNTEM

Bu çalışma teorik ve deneysel olmak üzere iki kısımdan oluşmaktadır. Teorik kısımda hem ısıtma hem de soğutma kısımlarının matematiksel modelleri oluşturulmuştur. Bu modeller birinci dereceden diferansiyel denklemler olup aynı zamanda zaman gecikmesinde sahiptirler. Bu modellerin parametrelerinin değerlerini bulmak için adım girişe karşılık gerçek sıcaklık değerleri ölçülüp kaydedilmiştir. Ölçümler ile elde edilen grafik üzerinden değerler okunarak ilgili modelleme parametreleri hesaplanmıştır.

Bu çalışmanın uygulama kısmı için bir düzenek tasarlanmıştır. Bu düzenek temel olarak yalıtılmış metal hazne, kuru rezistans, güç ayarlayıcı, ısıl çift, hava fanı, röle, yükselteç, mikro kontrolcü, elektrik valfi, motor sürücüsü, sıvı azot tankı (Dewar) ve bilgisayardan oluşmaktadır. Bu sitemde basit, ucuz ve programlanması kolay olduğu için mikro kontrolcü olarak Arduino elektronik kartı kullanılmıştır. Bilgisayar ve deney düzeneği arasındaki tüm haberleşmeler bu kart aracılığı ile gerçekleştirilmiştir. Gerçek zamanlı uygulamalar için MATLAB yazılım paket programı üzerinde yazılan programlar hem haberleşmede hem de kontrolde büyük bir başarı göstermiştir.

Bu deneysel çalışmada, ihtiyaca göre ısıtma ve soğutma işlemleri ayrı ayrı, bazen de her ikisi aynı anda gerçekleşebilmektedir. Önce, kullanıcı istenilen sıcaklık profilini MATLAB programı aracılığı ile bilgisayara yüklemektedir. Programın çalıştırılmasıyla sıcaklık kontrol sistemi çalışmaya başlar. Yalıtılmış haznenin içinin sıcaklığı K-tipi bir ısıl çift ile sürekli olarak ölçülmektedir. Isıl çift ile ölçülen sıcaklık mikro volt seviyesinde bir analog sinyaldir. Bu sinyal Arduino'ya takılan MAX31855 yükselticisi ile mili volt seviyesine yükseltilmektedir. Aynı zamanda bu yükseltici analog sinyali dijitale de çevirmektedir. Arduino'ya aktarılan bu sinyal USB aracılığı ile Arduino ile uyumlu

çalışan MATLAB ortamında yazılan bir programa santigrat derece cinsinden sıcaklık olarak aktarılmaktadır. Bu program aynı zamanda yazılım olarak PID, P ve On/Off kontrolcüleri ihtiva edip işlemin türüne göre bunlardan birini kullanarak ölçüm ve referans arasındaki sıcaklık hatasını en aza indirmeye çalışmaktadır. Bu amaç için kontrolcüde düzeltilmiş çıkış yine USB aracılığı ile Arduino'ya iletilmektedir. İşlemin türüne göre eğer ısıtma işlemi gerekiyorsa Arduino 0-5V arası DC sinyali güç ayarlayıcıya göndererek ısıtıcı üzerindeki AC voltajın yükünü değiştirerek sıcaklığı ayarlamaktadır. Eğer soğutma işlemine ihtiyaç duyuluyorsa Arduino elektrik valfına motor sürücüsü aracılığı ile hesaplanan bir zaman için +5, 0 veya –5 V sabit DC voltajı göndererek sıvı azotun miktarını ayarlayarak soğutma işlemini yapılmaktadır. Bazı durumlarda soğutma ve ısıtma işlemi aynı anda gerçekleşebilmektedir. Isıtma işleminde sıcaklık AC voltaja göre değişmekte olup sistem üzerinde bu işi yapacak olan ELKON marka bir güç ayarlayıcı kullanılmıştır. Bu cihazın kullanılması sistemin ısıtma sürekli kontrolünü etkin bir şekilde gerçekleşmesini sağlamıştır. Soğutma kısmında kullanılan elektronik valf verilen 12 V DC voltajın işaretine göre 12 saniyede ya tümüyle açılmakta yada tümüyle kapanmaktadır. Bu valfı kontrole uygun hale getirmek için MATLAB ta yazılan kontrol programında hataya göre açılma ve kapanma süreleri hesaplanarak işlem gerçekleştirilmiştir.

Deney aşamasında PID kontrolcünün katsayıları verilen değişik sıcaklık girişlerine karşılık deneme-yanılma yoluyla tespit edilmiştir. Bu arada sistemin çok yüksek sıcaklık değerlerinden daha düşük değerlere doğru soğutulması veya çok düşük negatif değerlerden daha yüksek değerlere ısıtılması için bir hava vantilatörü kullanılmıştır.

Sistemin performansını test etmek için yine MATLAB'ta yazılan program ile çizdirilen grafiklerden faydalanılmıştır. Bu çalışmanın uygulama kısmının tasarlanıp üretilmesi Yüzüncü Yıl Üniversitesi Bilimsel Araştırma Projeleri Koordinasyon Birimi 2015-FBE-YL305 Numaralı projesi ile gerçekleştirilmiştir. Aynı zamanda Türkiye Bilimsel Araştırma ve Geliştirme Kurumu (TÜBİTAK)-215M808 nolu proje dahilinde de bazı deney malzemelerinin alımında destek alınmıştır.

3. SONUÇ

Bu çalışmanın temel amacı bazı elektrik elektronik cihazları kullanarak bir ısıl sistemin ısıtma ve soğutma proseslerinin sıcaklık kontrollerinin yapılması olmuştur. Bu sistem bir çekme-basma deney cihazı için tasarlanmıştır. Böylece bir malzemenin oldukça yüksek ve düşük ve değişik sıcaklık profillerindeki fiziksel özellikleri incelenebilecektir. Bu sistemin gerçek zamanlı uygulamaları MATLAB üzerinde yazılan bir program ile gerçekleştirilmiştir. Bu program malzemelerin davranışlarını adım, rampa gibi girişlerin bir bileşimi olan değişik sıcaklık profillerinde test edilmesine olanak sağlamıştır. Elde edilen sonuçlar göz önüne alındığında basit ve düşük maliyetli böyle bir sistemin birçok çalışma alanında özelliklede çok düşük sıcaklıklardaki çalışmalarda tercih edilebileceği düşünülmektedir. Diğer önemli bir konu Arduino mikrokontrolcünün bu çalışmada kullanılmış olmasıdır. Diğer kontrolcüler ile kıyaslandığında bu kontrolcü oldukça ucuz, kolay elde edilebilir ve herhangi bir ortamda kolayca programlanabilirdir. Üstelik fizikisel verilerin ölçülüp bilgisayara iletilmesi Arduino ile basit ve etkin şekilde gerçekleşmiştir.

Bu çalışmanın deneysel kısmının sonuçları göstermiştir ki sistemin ısıtma ve soğutma işlemlerinin performansı umut verici olup sonuçlar teorik çalışmalardaki sonuçlarla da oldukça iyi bir şekilde uyum göstermektedir. Tasarlanan sistem ile sıcaklık bir K-tipi ısıl çifti aracılığı ile çabuk ve başarılı bir şekilde ölçülüp Arduino ve MAX31855 yükselticisi sayesinde bilgisayara iletilip işlenebilmiştir. Fakat harici manyetik alan veya ısıtıcının kaçak akımından kaynaklanan bir gürültüye deneyler sırasında sonuçlar üzerinde rastlanmıştır. Böyle bir gürültü sonuçlar üzerinde bir problem oluşturmasa da verilerin işlenmesinde dikkate alınmalıdır. Çünkü ısıl çiftler oldukça hassas cihazlar olup bu gürültüler yükselteçler üzerinde güçlenebilirler. Sistem için diğer olumsuz durum ise yalıtılmış metal kutunun ısı enerjisini biriktirmesi ve bu durumun bir bozucu gibi davranış göstermesidir. Bunlara ek olarak PID kontrolcü katsayıları sıcaklığın hassas ayarlanmasında uyarlamalı olarak seçilebilirlerdi. Yinede bu olumsuzluklara rağmen makul sayılabilecek doğrulukta sonuçlar elde edilmiştir.

Isıtma soğutma sistemi sıcaklığı +500°C'ye kadar çıkarabilmekte ve –120°C'ye düşürebilmektedir. İlgili grafiklerden de görülebildiği gibi adım, rampa ve birleşik sıcaklık referansları küçük ve kabul edilebilir hatalar ile takip edilebilmiştir. Bu çalışmada

güç ayarlayıcı sistemin ısıtma kısmının kontrolde oldukça iyi bir performans sergilemiştir. Soğutmada kullanılan valf beklentileri karşılamıştır. Servovalf gibi hata ile orantılı bir azot akışını ayarlayan bir valf kulanınsa idi daha doğru çıkışlar elde edilebilirdi. Fakat böyle bir valfın fiyatı kullanılan valf ile karşılaştırıldığında oldukça yüksektir. Bu çalışmanın en önemli unsurlarında biri de MATLAB'ta yazılan kontrol programıdır. Bu program donanımların bilgisayara tanıtılmasında, kolay programlamada ve hataların düzeltilmesinde büyük bir başarı göstermiştir. Deney setinde kullanılan hava vantilatörü yardımcı kontrolcü olarak kullanılıp sonuçların daha doğru olmasını sağlamış ve yalıtılmış metal kutu içindeki sıcaklık dağılımının homojen olmasını temin etmiştir.

Bu çalışmada tasarlanan sistem aşağıdaki katkıları sağlamıştır.

- Bu sistem PLC gibi eş değer bir kontrolcü ile karşılaştırıldığında oldukça basit ve ucuz bir sistem olmuştur.
- Bu sistem maliyeti ile karşılaştırıldığında yüksek performansa sahip olup kolayca kontrol edilebilmektedir.
- Sistem çok küçük ve kabul edilebilir hatalar ile çalışmaktadır.

Gelecekte bu tasarım geliştirilmesi ile ilgili olarak yapılabilecek başka çalışmalar da mevcuttur. Öncelikli olarak deneme yanılma ile seçilen PID katsayıları Ziegler-Nichols, sinir ağı, cevap yüzeyi gibi değişik metotlar kullanılarak bulunabilirler. Bunun yanında, daha hassas sonuçlar üretmek için PID kontrolcü yerine, kayan kip kontrolcü, fuzzy-logic gibi daha güncel kontrolcüler kullanılabilir. Bunlara ek olarak servovalfa benzer sıcaklık hatası ile orantılı azot akışı sağlayacak akış kontrol sistemleri kullanılabilir. Son olarak, kontrol sistemi akıllı telefon ile Arduino'yu kullanarak uzaktan kumanda ile kontrol edilmek için tasarlanabilir.

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