Design and development of an automated temperature controller for curing ovens

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Declaration

I, Ruaan Morné Schoeman, declare that this project is my own, unaided work. It is being submitted for the requirements for the Magister Technologiae: Engineering: Electrical to the Department: Electronic Engineering at the Vaal University of Technology, Vanderbijlpark. It has not been submitted before for any assessment to any educational institution.

Ruaan Morné Schoeman

Date: 07/12/2011

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Dedication

This dissertation is dedicated to my wife Sharon, daughter Rushane and my parents, Gert and Evy.

Thank you for your love and support.

Abstract

Curing of materials in order to obtain different properties has been a practice for many years. New developments in composite materials increase the need to control certain variables during the curing process. One very significant variable is temperature. Temperature control by itself is an old practice, however when the need for repeatedly controlling the process accurately over long periods of time arises, a system is required that outperforms normal manual control.

One of the aspects within such a system that needs to be considered is the ability to replicate the temperatures within an oven which were originally used for a specific material's curing profile. This means that a curing profile would need to be defined, saved for later and finally be interpreted correctly by the controlling system.

Different control methods were simulated to enable the system to control the temperature which has been defined by literature. This dissertation introduces a variation on the standard control methods and shows improved results.

Switching the oven on and off in order to increase or decrease internal oven temperature seems simple, but can cause switching devices to decrease their operational life span, if not designed carefully. A combination switch was introduced which harnesses the advantages of two very common switching devices to form an improved combination switch.

Software for the personal computer environment, as well as software for the embedded environment were developed and formed a control system that produced acceptable results for temperature control. Accuracies of 98% and more were achieved and found to be acceptable according to standard engineering control practices.

An accurate temperature profile controller was designed, simulated and built in order to control the temperature inside a specific curing oven which, in turn, determined the curing properties of specific materials. The overall results were satisfactory which lead to achieving the objectives outlined in this dissertation.

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Glossary of abbreviations and definitions

A

AC	Alternating current
Armature	The moving iron part of a solenoid or relay

C

Curing	The process of setting or hardening of a material

D

DIAC	A two-terminal AC device that, once gated on by sufficient forward voltage, permits the flow of current until reverse biased
DITI	Digital Infrared Thermal Imaging

G

GUI	Graphical user interface used in the software environment

I

I^2C	Inter-Integrated Circuit is a multi-master serial single-ended computer bus used to attach low-speed peripherals to a motherboard, embedded systems, cell phones, or other electronic devices

M

Microcomputer	A microcontroller including external storage and memory devices

P

Pneumatics	The study of the mechanical properties of air and other gases

R

RTD	Resistance temperature detectors

S

SCR	A current controlled four-layer device for high power and low speed applications electronic devices
Snubber	An auxiliary circuit used to control the rate of rise or fall of the current flowing into a power electronic device
SPI	Serial Peripheral Interface, a full-duplex synchronous serial interface for connecting low-/medium-bandwidth external devices using four wires

T

Thermalset	Having the property of becoming permanently hard and rigid when heated or cured
Thermistors	An electrical resistor whose resistance is greatly reduced by heating, used for measurement and control
Thermography	A technique wherein an infrared camera photographically portrays an object's surface temperature
TRIAC	A power switch that is functionally a pair of converter-grade thyristors connected in anti-parallel
TSVUT	Technology Station of the Vaal University of Technology

Chapter 1 Introduction and overview

1.1 Background

Thermalset is the phase change of a compound into a substantially infusible and insoluble material when it is cured by the application of heat or by chemical means (Swartz, 1984:28). Curing of materials is done at various temperatures in specially designed ovens. A material, such as silica, cures at very high temperatures between 800°C and 1200°C, depending on the materials it is mixed with. The temperature inside an oven affects the properties of the cured material. Thus the curing temperature, which is the temperature at which a cast, moulded or extruded product is subject to during curing (Swartz, 1984:7), is very important and needs to be controlled.

There are a variety of commercial devices available that could be used to monitor the temperature of a curing oven. However, for high temperature measurements, only a few devices can be utilized, depending on the accuracy and temperature ranges required (Dogan, 2002:59). Accurate measurement of temperature is not easy and to obtain accuracies better than 0.5°C requires great care.

Radio thermometry devices measure the radiation emitted by hot objects and is based upon the emissitivity of the object, which is usually not known and additionally may vary with time (Dogan, 2002:69). However, placing sensory devices inside these ovens exposes them to extreme heat environments, resulting in failure of sensors with cumulative exposure, sensory devices can also not be placed inside the curing materials as this would deform the required moulding shape.

The air temperature in an oven could be measured. However, air temperature fluctuations, variations in radiation, nonlinearities in sensor characteristics and sensor drifts need to be kept in mind (CAPGO Pty Ltd, 2010). The following sensory devices, among others, are available for measuring air temperature: thermocouples, resistance temperature detectors (RTD) and monolithic temperature sensors. These sensory devices are designed to function in harsh environmental conditions.

Switching devices are components which are used to switch loads ON and OFF. Switching either direct current (DC) or alternating current (AC) presents its own unique problems. One such problem is heat dissipation in the device itself. Thus, obtaining a suitable device that can switch high currents required by ovens that are controlled by small signal devices (such as microcontrollers) will prove to be challenging in itself.

Sensory devices may be complemented by a microcomputer which is widely used to monitor environmental data and execute decisions based there-on. The term microcomputer is used to describe a system that includes a minimum of a microprocessor, program memory, data memory and input/output functions. Thus, a microcomputer system can be anything from a large computer having hard disks, floppy disks and printers, to a single chip computer (Dogan, 2002:5). For example, microcomputer systems could be implemented in the controlling of various processes, such as maintaining room temperature by activating or deactivating an air conditioning unit.

1.2 Problem statement

Manually controlling the operating temperatures of a curing oven at the Technology Station of the Vaal University of Technology (TSVUT) lacks accuracy and consistency. The curing process is often repeated with materials of the same type, yet the curing results with respect to the material's properties vary. This mainly occurs because the operator has to manually switch the oven's heating element ON or OFF according to personal feeling. Thus, no accurate control technique or constant evaluation parameters are applied to achieve consistency in the repetition of the thermalset or curing process.

1.3 Research methodology

- Temperature range, curing profiles, type of oven and materials to be cured will be obtained through interviews with staff at the TSVUT.
- The best switching technique for high current devices will be identified through a literature search.
- Literature on microcomputers and their communication techniques will be gathered and evaluated to determine what would be needed to control the heating modules.
- Control techniques will be investigated and applied to the embedded environment.
- Data will be collected with respect to the oven's heating characteristics.
- An algorithm will be developed based on the data obtained.
- Simulation of the algorithm in MATLAB will be done.
- A prototype controller will be designed and simulated.
- Results will be evaluated and corrections to the design will be made.

- If simulations of the control technique and communication are satisfactory, then a prototype printed circuit board will be developed.
- The prototype will be then tested with a curing oven.
- Improvements will be made in order to ensure consistency of repeated curing processes.

1.4 Delimitations

- The research will not include the investigation of cooling systems which could assist in the rapid cooling of materials as this will require a large budget.
- The research will not focus on industrial ovens as this research is for a specific need at the TSVUT.
- No alterations or additions can be made to the oven as specified by the TSVUT.

1.5 Importance of research

The research will benefit the TSVUT, as they will be able to produce concurrent samples of a specific curing process. Industry will also benefit from this research, as they will have an entity that could produce consistent results for use in testing phases.

1.6 Overview of the dissertation

This dissertation reports on the development of a curing oven controller which will automatically determine the characteristics of an oven and deduce control parameters to be used in the controlling action.

Chapter 2 presents the equivalent representation of an oven as an electrical circuit. It further describes different temperature sensory equipment currently available in industry. Different switching devices are presented along with various temperature control methods which are used in industrial applications

Chapter 3 introduces the parameters of the oven which are obtained from the simulation model in MATLAB. Other critical components, such as the low loss AC switch, are also presented.

Chapter 4 presents the developed control software along with measurements and tests conducted in order to prove that a curing profile can be replicated.

Chapter 5 contains the conclusions and recommendations obtained from the study.

1.7 Research outputs

This study has already produced the following peer-reviewed research outputs published by IEEE Xplore, the digital database of the Institute of Electrical and Electronic Engineers.

- A conference paper for Optim 2010, entitled “Self-tuning curing oven control” and
- A conference paper for Africon 2011, entitled “Embedded PI-bang-bang curing oven controller”.

1.8 Summary

The accurate curing of materials is an important requirement of the work done by the TSVUT. It is important that the curing process of composite materials be reproduced repeatedly to ensure that the characteristics of the materials are consistent over time. Simulation, collection of data, design and development form an integral part of this research. Cooling systems will not be investigated to keep costs to a minimum in order to produce a control unit that is affordable to the TSVUT as well as to industry.

Chapter 2 Theoretical background

2.1 Introduction

The temperature profile during the curing process of composite materials determines the final characteristics of the cured sample (Bogetti & Gillespie, 1992:626). The problem however, of reproducing the same set of parameters with respect to different temperature settings for specific time periods necessitates the use of a precise controlling device.

The curing of composite materials is normally done in an industrial oven. A heating element of low resistance generates heat which is then transferred to the material or object. This can be seen in figure 1, where heat from the heating element is transferred to the object inside the oven. The heating element is normally a high power device which allows for quick heat generation. The switching of the heating element proves challenging due to the high values of current which flow through it.

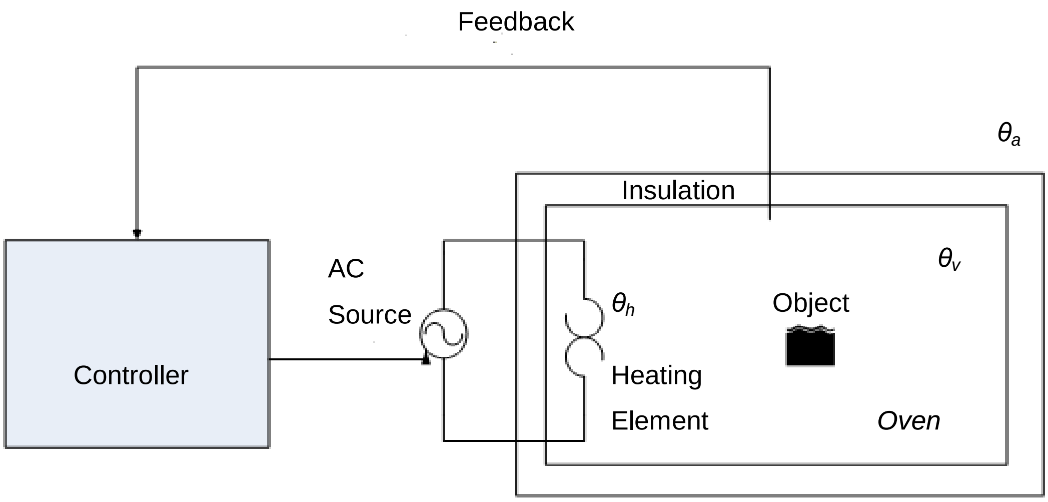


Figure 1 Representation of an electrical oven as a plant (University of EXETER, 2010)

2.2 Oven electrical equivalent model

Heat is the process of energy transfer from one body or system to another due to a difference in temperature (Kesidou & Duit, 1993:85). Thermal energy can be defined as the energy of a body which increases with its temperature. Energy transfer by heat can occur between objects through radiation, conduction and/or convection. Temperature can be used as a measure of the internal energy. Analysis of the heat flow in an oven can either be done by means of thermodynamics or by using an electrical analogy of the heat flow path.

Heat flow can be modelled by an analogy to electrical parameters shown in table 1, where heat flow is represented by current, temperatures are represented by voltages (Schroder & De Doncker, 2000:114-117), heat sources are represented by constant current sources, thermal resistances are represented by resistors and thermal capacitances by capacitors (Birca-Galateanu, 2005).

Table 1 Equivalence between thermal and electrical entities

Thermal quantity	Unit	Electrical quantity	Unit
P – Heat flow, power	W	I – Current flow	A
$\Delta\theta$ – Temperature difference	K	V – Voltage difference	V
R_{th} – Thermal resistance	K/W	R – Electrical resistance	Ω
C_{th} – Thermal mass, capacitance	J/K	C – Electrical capacitance	F
$T_{th} = R_{th} \times C_{th}$ – Thermal RC constant	s	$T = R \times C$ – Electrical RC constant	s

This can be seen in figure 2, where

- R_1 represents the thermal resistance between the heating element and the oven,
- R_2 represents the resistance between the oven and the environment,
- C_1 represents the equivalent capacitance of the oven,
- C_2 represents the equivalent capacitance of the heating element,
- θ_a represents the ambient temperature of the environment,
- W represents the power dissipated in the heating element,
- θ_v represents the oven temperature and
- θ_h represents the heating element temperature.

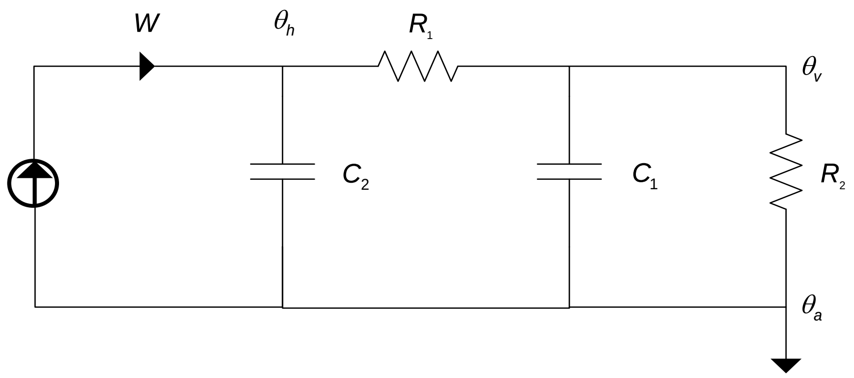


Figure 2 Electrical equivalent of a thermal oven (University of EXETER, 2010)

Capacitor C_2 can be neglected from the equivalent diagram as the capacity of the element to store heat is small in comparison to that of the oven capacity to store heat. Subsequently figure 3 shows a simplified diagram that can be used as the electrical equivalent of a thermal oven with input voltage $v_i(t)$, input current $i(t)$ and output voltage $v_o(t)$.

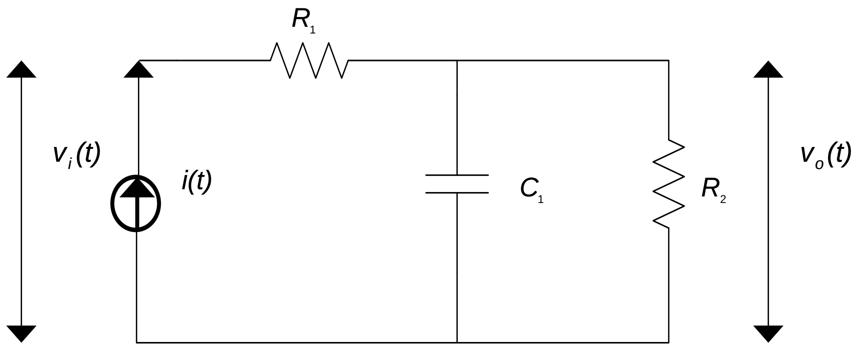


Figure 3 Simplified electrical equivalent of a thermal oven

Finding the transfer function of this circuit is now simplified, which may be done by applying basic electrical principles (see table 2) of current and voltage rules as well as the relationships between voltage, current and impedance (Nise, 2000:52).

Table 2 Voltage and current and current and voltage relationships, summarized (Nise, 2000:52)

Component	Voltage to Current	Current to Voltage	Impedance
Capacitor	$v_c(t) = \frac{1}{C}\int_0^t i_c(t)dt$	$i_c(t) = C\frac{d}{dt}v_c(t)$	$Z_c(s) = \frac{1}{Cs}$
Resistor	$v_r(t) = Ri_r(t)$	$i_r(t) = \frac{v_r(t)}{R}$	$Z_r(s) = R$
Inductor	$v_l(t) = L\frac{d}{dt}i_l(t)$	$i_l(t) = \frac{1}{L}\int_0^t v_l(t)dt$	$Z_l(s) = Ls$

The time domain equation can be found by applying Kirchhoff's voltage law:

$$v_i(t) = R_1 i(t) + v_o(t) \quad \text{… (1)}$$

Where $v_i(t)$ $\equiv$ input voltage in V

$i(t)$ $\equiv$ input current in A

R_1 $\equiv$ thermal resistance between heating element and oven in Ω

$v_o(t)$ $\equiv$ output voltage in V

Using table 2 the current flowing through the capacitor can be written as:

$$i(t) = C_1 \frac{d}{dt} v_o(t) \qquad \text{… (2)}$$

Where $i(t)$ ≡ charge or discharge time in s

$v_o(t)$ ≡ resistance in series in Ω

C_1 ≡ capacitance of the circuit in F

By substituting (2) into (1) results in:

$$v_i(t) = R_1 C_1 \frac{d}{dt} v_o(t) + v_o(t) \qquad \text{… (3)}$$

In Laplace format

$$v_i(s) = [R_1 C_1 s + 1] v_o s \qquad \text{… (4)}$$

The overall transfer function is therefore defined as:

$$\frac{v_o(s)}{v_i(s)} = \frac{1}{R_1 C_1 s + 1} \qquad \text{… (5)}$$

The time constant is often related directly to the circuit *RC* value (the product of the resistance in Ohms and the capacitance in Farads) or to its *L/R* value (the ratio of the inductance in Henrys to its resistance in Ohms)(IEEE EED, 2000:710), which is expressed mathematically as:

$$T = RC \qquad \text{… (6)}$$

Where T ≡ charge or discharge time in s

R ≡ resistance in series in Ω

C ≡ capacitance of the circuit in F

Thus, by substituting equation (6) into equation (5) yields following transfer function:

$$\frac{v_o(s)}{v_i(s)} = \frac{1}{Ts+1} \quad \text{… (7)}$$

$$= \frac{T^{-1}}{s+T^{-1}} \quad \text{… (8)}$$

In order to obtain a transfer function with reference to time requires the application of the inverse Laplace transformations (Nise, 2000:40), as can be seen in table 3

Table 3 Laplace transformations (Boyd, 2009)

Function	Laplace	Function	Laplace	Function	Laplace
1	$\frac{1}{s}$	$\cos at$	$\frac{s}{(s^2+a^2)}$	$\sin at$	$\frac{a}{(s^2+a^2)}$
e^{at}	$\frac{1}{s-a}$	$e^{at}\cos bt$	$\frac{(s-a)}{[(s-a)^2+b^2]}$	$e^{at}\sin bt$	$\frac{b}{[(s-a)^2+b^2]}$
t^n	$\frac{n!}{s(n+1)}$	$uc(t)$	$\frac{e^{-cs}}{s}$	$uct(t)f(t-c)$	$e^{-cs}F(s)$
$t^p, p>-1$	$\frac{G(p+1)}{s(p+1)}$	$t^n e^{at}$	$\frac{n!}{(s-a)(n+1)}$	$e^{ct}f(t)$	$F(c-s)$

Applying the inverse Laplace transform for a unit step function with a magnitude of one, results in the following:

$$v_i(s) = \frac{1}{s} \quad \text{... (9)}$$

$$v_o(s) = v_i(s)\frac{T^{-1}}{s+T^{-1}}$$

$$v_o(s) = s\frac{T^{-1}}{s(s+T^{-1})} \quad \text{… (10)}$$

$$v_o(t) = 1-e^{-\frac{t}{T}} \quad \text{… (11)}$$

Substituting equation (6) into equation (11) yields an equation which represents the output according to electrical terminology:

$$v_o(t) = 1-e^{-\frac{t}{R_1C_1}} \quad \text{… (12)}$$

2.3 Thermal measuring devices

Heat measurements can be made by making use of various different sensory devices. These could include thermistors, RTD's, thermocouples and thermography sensors. However, when temperatures exceed 800°C, few sensory devices have the ability to measure and interpret temperatures correctly.

2.3.1 Thermocouples

Only two devices can be used in the measurement of very high temperatures, namely thermocouples and thermography sensors (OMEGA Engineering, 2005).

A thermocouple (TC) consists of two wires of different conductive material, connected to each other by means of two junctions forming an electrical circuit. If one junction is at temperature θ_{Ref} and the other at θ_{Tip}, then an electromotive force (EMF) is generated in the circuit, which is dependant on the materials and temperatures θ_{Ref} and θ_{Tip}, known as the Seebeck effect (Tong, 2001).

Thomas Johann Seebeck discovered the existence of thermoelectric currents while observing electromagnetic effects associated with bismuth-copper and bismuth-antimony circuits (ASTM Committee E-20 on Temperature Measurement, 1974). The Seebeck effect entails the overall conversion of thermal energy into electrical energy where the Seebeck voltage can be represented as:

$$E = a\left(\theta_{Tip} - \theta_{Ref}\right) \quad \text{… (13)}$$

Where E ≡ electromagnetic force in mV

a ≡ proportionality constant known as the Seebeck coefficient

θ_{Ref} ≡ hot junction temperature in °C

θ_{Tip} ≡ cold junction temperature in °C

Assume that the Seebeck coefficients of two different metallic materials and their lead wires are S_A, S_B, and S_{Lead} respectively. All three Seebeck coefficients are functions of temperature. The output voltage (v_{out}) measured at the gauge seen in figure 4 can be represented as:

$$v_{out} = \int_{Gage}^{Ref} S_{Lead}(\theta)\frac{d\theta}{dx}dx + \int_{Ref}^{Tip} S_A(\theta)\frac{d\theta}{dx}dx + \int_{Ref}^{Gage} S_{Lead}(\theta)\frac{d\theta}{dx}dx + \int_{Tip}^{Ref} S_B(\theta)\frac{d\theta}{dx}dx$$

$$= \int_{\theta_{Ref}}^{\theta_{Tip}} S_A(\theta)d\theta + \int_{\theta_{Tip}}^{\theta_{Ref}} S_B(\theta)d\theta$$

$$= \int_{\theta_{Ref}}^{\theta_{Tip}} [S_A(\theta) - S_B(\theta)]d\theta \qquad \text{… (14)}$$

Where θ_{Ref} ≡ temperature at the reference point in °C

θ_{Tip} ≡ temperature at the probe tip in °C

S_{Lead} ≡ Seebeck coefficients for connecting lead

S_A ≡ Seebeck coefficient, material A

S_B ≡ Seebeck coefficient, material B

v_{out} ≡ electromagnetic force produced by system in mV

According to equation (14) the voltage induced by the temperature and/or material mismatch of the lead wires will cancel, whereas in reality the lead wires will introduce noise into the system. If the Seebeck coefficient functions of the two thermocouple wire materials are pre-calibrated and the reference temperature θ_{Ref} is known, then the temperature at the probe tip becomes the only unknown and can be directly related to the output voltage.

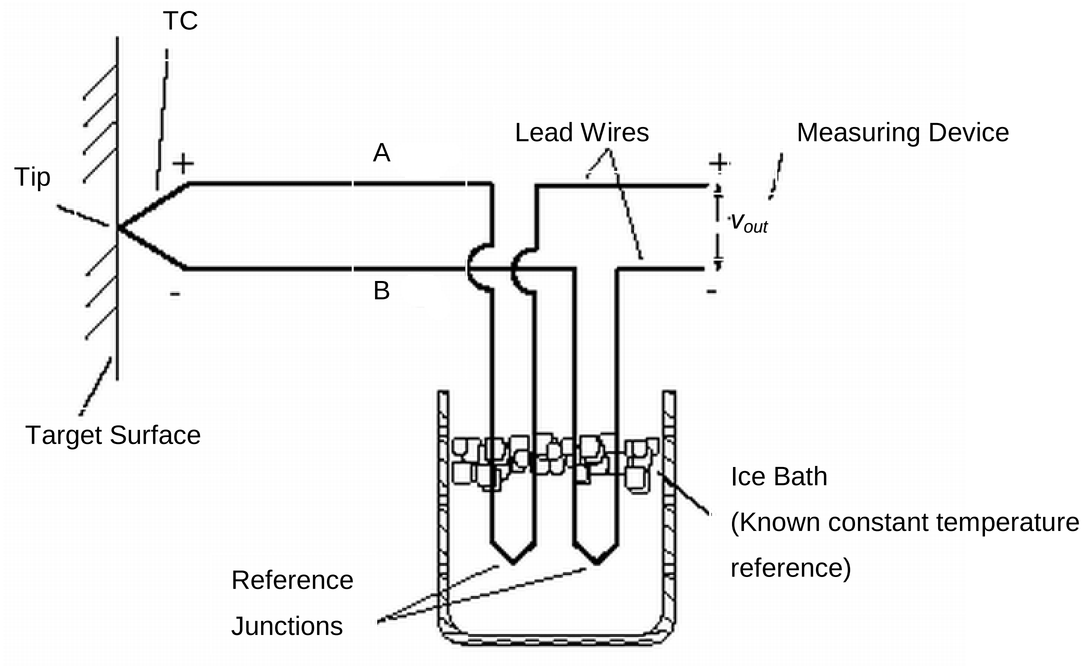


Figure 4 Thermocouple setup (Duff and Towey, 2010)

If the Seebeck coefficients are constant across the targeted temperature range, then the integral in equation (14) can be simplified as seen in equation (15), allowing for the temperature at the probe tip to be calculated as:

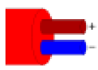
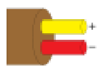
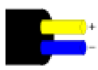
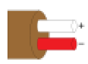
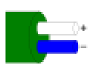
$$V_{out} = (\theta_A - \theta_B)(\theta_{Tip} - \theta_{Ref}) \\ \therefore \theta_{Tip} = \theta_{Ref} + \frac{V_{out}}{\theta_A - \theta_B} \quad \text{… (15)}$$

In practice, manufacturers will provide calibration functions for their products. These functions are usually high order polynomials and are calibrated with respect to a certain reference temperature, normally 0°C or 32°F. Assume that the coefficients of the calibration polynomials are θ_0, θ_1, θ_2, up to θ_n, then the temperature at the probe tip can then be related to the output voltage as shown in equation (16) (Potter, 1997).

$$\theta_{Tip} = \theta_0 + \theta_1 V_{out} + \theta_2 V_{out}^2 + \cdots \theta_n V_{out}^n \quad \text{… (16)}$$

A thermocouple is not an absolute temperature sensor (Bentley, 1984). In other words, a thermocouple requires a reference of known temperature which may be provided by ice water as illustrated by figure 4. While ice water is easy to obtain and has a well known reference, it's not a practical solution out side the laboratory. Thus, common commercialized thermocouples often include another temperature sensor, such as a thermistor, to provide a reference of the ambient temperature.

Table 4 Thermocouple comparison (Efunda, 2010)

Type	Temperature range °C (continuous)	Temperature range °C (short term)	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 1000°C	±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.

According to EN/ANSI standards and most common industrial applications, the thermocouple is often used for temperature measurements between - 40°C and 1800°C (European Solar Thermal Industry Federation., 2007:11). Thermocouples can be classified with respect to their material and their operational temperature (see table 4).

2.3.2 Thermography

Every object radiates heat and emits a certain wavelength which corresponds to the energy it is radiating. Thus thermography can be defined as images produced by infrared cameras showing temperature differences in objects by making use of the infrared spectrum (Dictionary.com, 2010). Thermography had its early origin in 480 BC when Hippocrates experimented with mud which he applied to a human body in order to determine which parts of the body would dry the mud first (Proactive Wellness & Imaging Center, 2011). During the early 1950's, infrared spectrometry was used to monitor the movement of soldiers during night time exercises. Since then, the technology has been made available for commercial use and research within this field has increased rapidly.

Thermography has then been applied to the electrical environment (see figure 5). Fuses emit different heat levels that are represented by different colours. Calibrating these colours (spectrum occupancies) with radiating heat levels enables one to determine the temperature values for different parts of the fuse. The approximate temperature range of thermography is from -20°C to over 2,000°C. This makes it suitable for measuring high temperature values during a curing process.

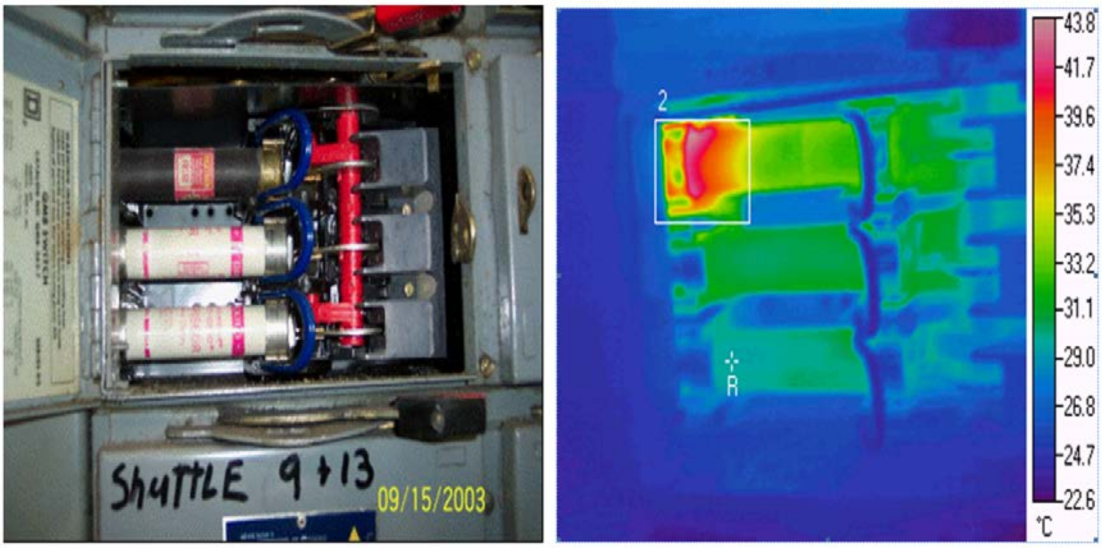


Figure 5 Thermogram of electrical fuses (POWER PLUS ENGINEERING INC, 2003)

2.4 Electrical switching devices

One of the simplest devices found in electrical circuits would be the switch. This device is used to close (complete) or break an electrical circuit, which in turn will allow current either to flow through or not to flow. Switching devices are abundant and come in a variety of different shapes and sizes, yet can be grouped into either mechanical or solid-state devices.

2.4.1 The relay

A device which allows an electrical circuit to control the ON and OFF state without human intervention is a relay (grouped as a mechanical switching device). As can be seen in figure 6, an inductor is used to generate a magnetic field which in turn attracts a contact, thereby closing the circuit and allowing current to flow. This inductor can be energised by other circuits which becomes the controller circuit. Contact bounce is always present during the switching period (Johler, 2000:83-93).

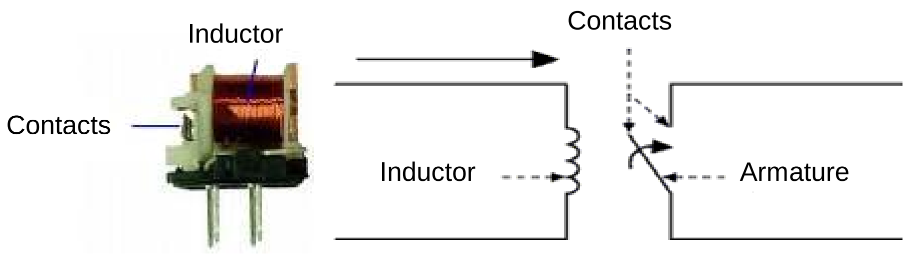


Figure 6 Representation of a relay and its symbol

Contact bounce elates to when contacts strike each other, their momentum and elasticity acts together to cause bounce. This often forms arcing between the contacts, which will in turn lead to contact burn, the process where carbon is deposited onto the contact surfaces of the relay. Repeated carbon deposits increase the resistance between the contacts, thereby limiting the flow of current flow and reducing the performance of the switching device. Several techniques have been developed to reduce carbon deposits during contact bounce.

Some manufacturers allow the contacts to be submerged in oil, thereby reducing the oxygen needed for burning (Buschart & Kuczka, 1992:293-299). Contact bounce also leads to high transients, which could be detrimental to surrounding circuits. Figure 7 illustrates contact bounce which exits during the switch activation and deactivation periods respectively.

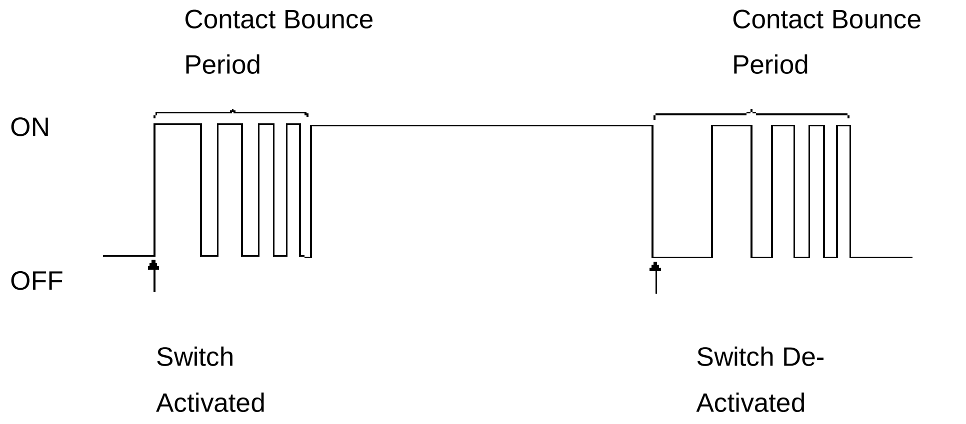


Figure 7 Relay contact bounce during activation and deactivation process (Electronix Express, 2010)

2.4.2 Silicon controlled rectifiers

A silicon controlled rectifier (SCR) can be defined as a four-layer device controlled by current for high power and low speed applications (IEEE EED, 2000:646). SCRs can only be ON or OFF, with no intermediate operating states like transistors. Once latched on, the gate current can be removed and the device will remain on until the anode current becomes negative, or the current through the SCR falls below its holding current. A disadvantage is that a commutation circuit is often needed for forced turn-off (IEEE EED, 2000:646). Figure 8 illustrates the layer composition and ON/OFF states of this device.

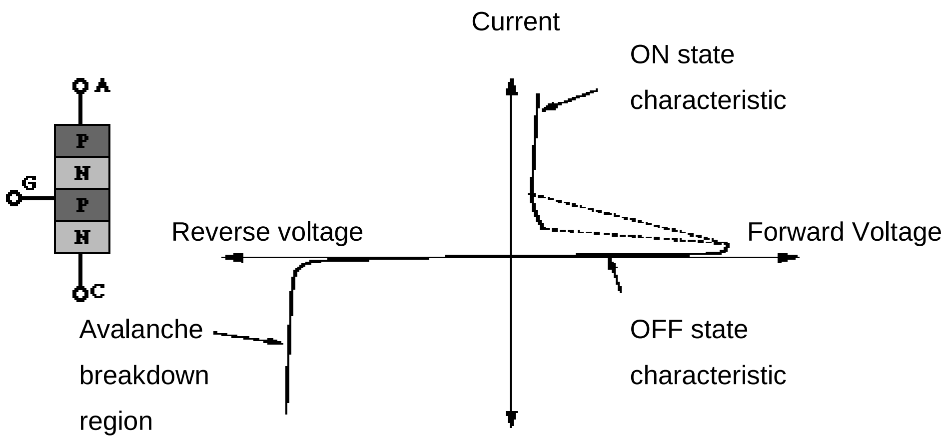


Figure 8 A SCR's characteristic voltage/current curve (American Microsemiconductor Inc., 2010)

A thyristor or SCR is seen as a switch (Taib et al., 1992:568-580). The advantage of this device is that it can operate without involving arcing, thereby negating mechanical wear. The drawback of this device is the internal resistance R_f present between the positive and negative (PN) junctions which will generate heat when current is allowed to flow. Figure 9 illustrates the equivalent circuit for the PN junctions, while figure 10 illustrates the forward resistance, which will generate heat due to current flow.

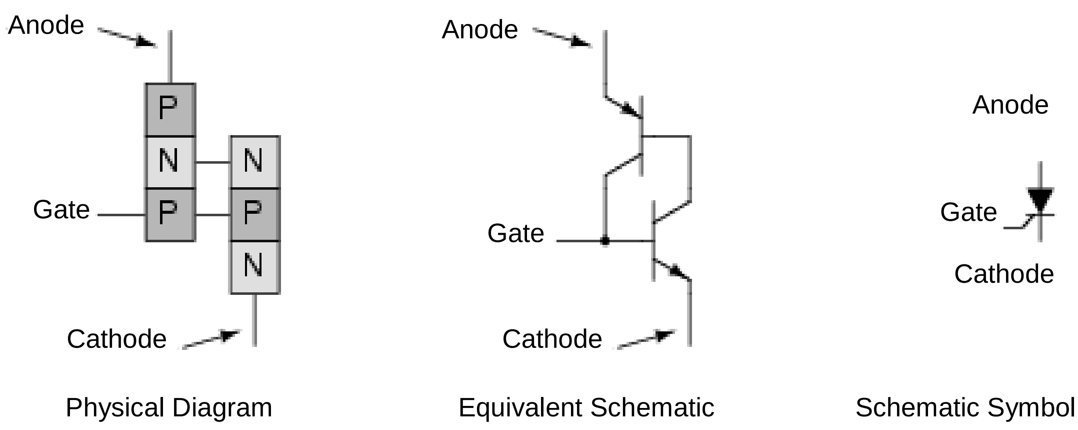


Figure 9 SCR PN layer equivalent circuit

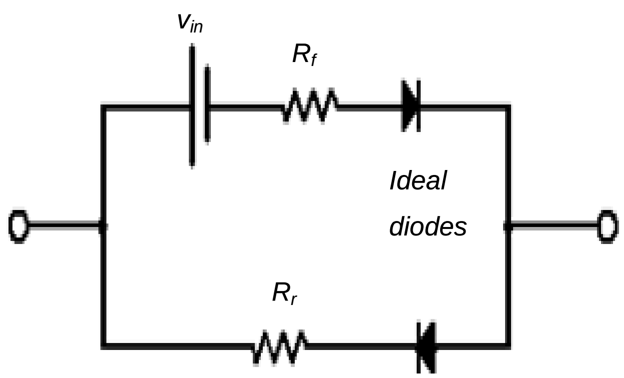


Figure 10 SCR diode equivalent circuit

2.4.3 Triode for alternating currents

A triode for alternating currents (TRIAC) is a component which is equivalent to two SCRs joined in anti-parallel (paralleled but with the polarity reversed) configuration, having their gates connected together. The formal name for a TRIAC is a bidirectional triode thyristor (Gentry et al., 1965). This results in a bidirectional electronic switch that can conduct current in either direction when it is triggered, and thus does not have any polarity. Figure 11 shows the voltage/current curve of the TRIAC and the areas where the device conducts.

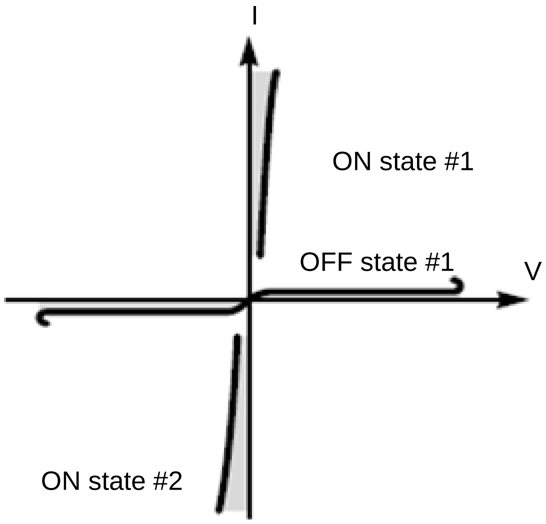


Figure 11 A TRIAC characteristic voltage/current curve (American Microsemiconductor Inc., 2010)

The device can be triggered by either a positive or a negative voltage being applied to its gate electrode. Once triggered, the device continues to conduct until the current through the device drops below a certain threshold value (the holding current), such as at the end of a half-cycle of an alternating current. This makes the TRIAC a very convenient switch for AC circuits, allowing the control of very large currents with milliampere-scale control currents.

TRIACs are able to achieve fast switching speeds with no contact bounce as they area solid-state devices. However, one drawback exists which is the internal resistance, which is present between the PN junctions in the activated state (reverse and forward). Following Ohms law, the internal resistances R_f and R_r will produce heat, which will need to be dissipated when current is flowing. Additional heat dissipation devices, such as heat sinks or cooling fans, are therefore required to keep the device operating correctly.

2.4.4 Snubber circuits

A snubbing circuit can be defined as an auxiliary circuit used to control the current rise and fall rate, flowing into a device or the voltage fall or rise rate across the device during turn-off (IEEE EED, 2000:658). Using a snubber circuit assists in turning-off a device as well as to prevent premature triggering, which may be caused by voltage spikes originating from the mains supply.

The function of the snubber circuit is to protect semiconductor devices by

- limiting device voltages during turn-off transients,
- limiting device currents during turn-on transients,

- limiting the rate-of-rise (d*i*/d*t*) of currents through the semiconductor device at device turn-on,
- limiting the rate-of-rise (d*v*/d*t*) of voltages across the semiconductor device at device turn-off and
- shaping the switching trajectory.

Figure 12 is an example of such a circuit which could be used to protect a SCR against switching transients.

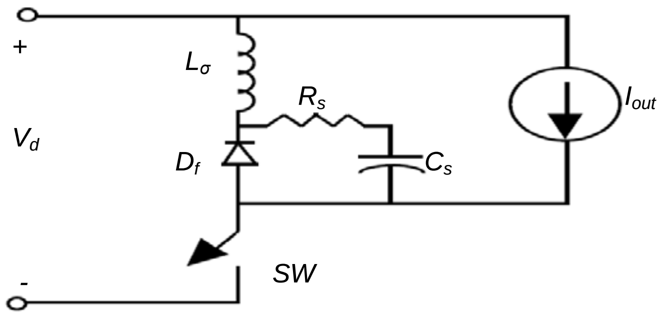


Figure 12 A snubber circuit

A gate resistor or capacitor may be connected between the gate and anode to further prevent false triggering. That, however, increases the required trigger current and / or adds latency (capacitor charging). A DIAC is often used to drive the gates of both TRIACs and SCRs as can be seen in figure 13.

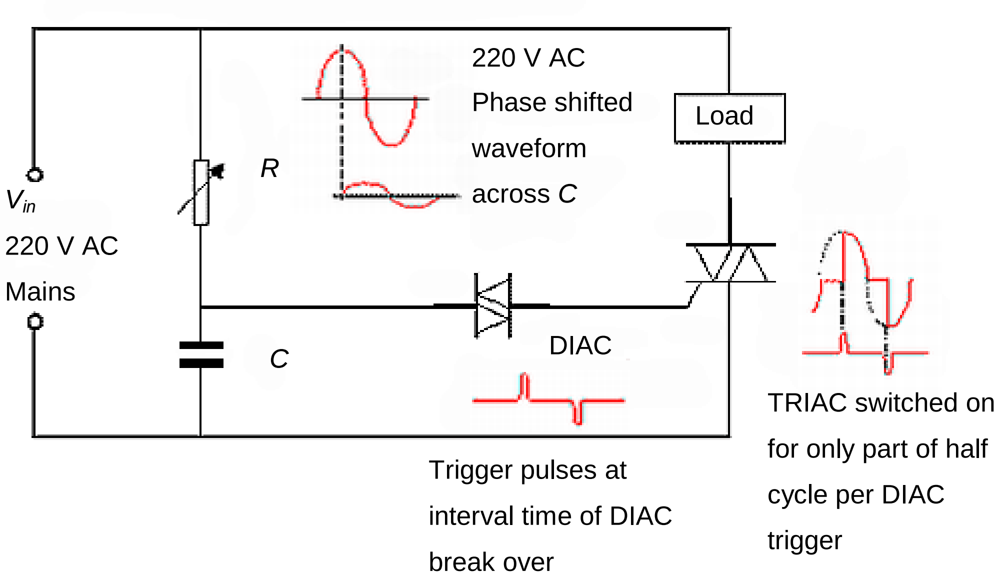


Figure 13 A DIAC used to drive a TRIAC circuit (Coates, 2008)

The DIAC is designed to have a particular break over voltage, which can be in the region of approximately 29 V, when a smaller voltage is applied of either polarity, the device remains in a high resistance state with only a small leakage current flowing. When the break over voltage is achieved of either polarity, the device exhibits a negative resistance which results in its characteristic curve as shown in figure 14.

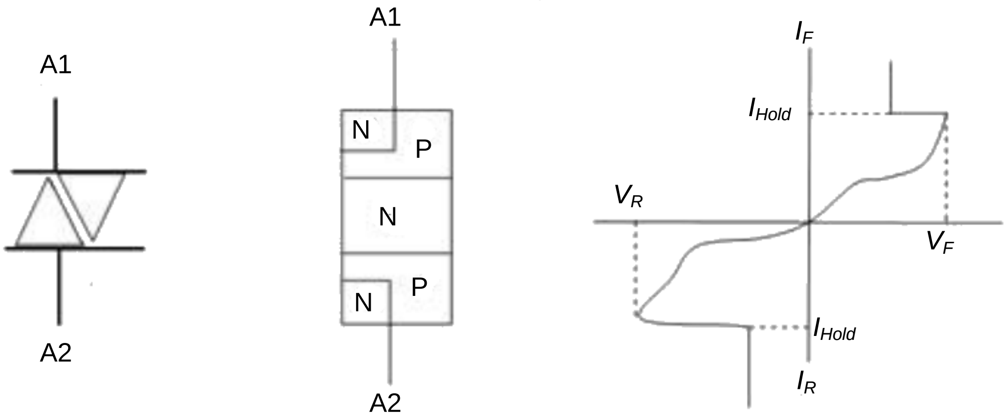


Figure 14 DIAC characteristic curve (Uddin, 2011)

When the voltage across the DIAC exceeds the break-over voltage, an increase in current is observed accompanied by a drop in the voltage across the DIAC. Applying Ohm's law an increase in current through a component should cause an increase in voltage across that component. However, the opposite effect is happening here, exhibiting negative resistance at break-over.

2.5 Control theory

Standard control theory suggests that there are two classic types of control methodologies namely feedforward and feedback control (Cervin et al., 2002:25). The input to a feedback controller is the same as what it is trying to control (the controlled variable is fed back into the controller). A sensory device measures the controlled variable, feeds it back to the controller which in turn adjusts the output. However, feedback control normally results in periods where the controlled variable is not at the desired set-point. This is where feedforward control can be an asset to the control process, as it could avoid the slowness of feedback control. Figure 15 illustrates how the feedback controller can be simplified. Evaluating feedforward control, disturbances are measured and potentially accounted for before they affect the system. A disadvantage of feedforward control lies in the fact that the effect of the disturbances needs to be predicted as accurately as possible, and all disturbances must be measured.

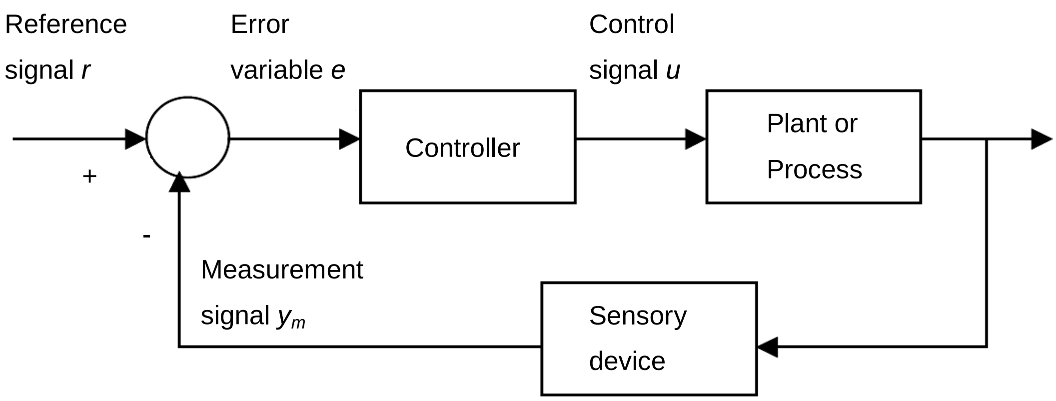


Figure 15 A feedback control system

Achieving the advantages of both these methodologies, combinations of feedback and feedforward control is applied to control processes. Some examples include dead-time compensation and inverse response compensation. Dead-time compensation is used to control devices that take a long time to show any change to a change in input, for example the temperature rise inside an oven when it has been switched on.

Dead-time compensation control uses an element to predict how changes made by the controller will affect the controlled variable in the future. The controlled variable is also measured and used in feedback control. Inverse response compensation involves controlling systems where a change at first affects the measured variable one way, but later affects it in the opposite way.

A variety of applications use feedback control. The benefits of this control method are the possibility of keeping a parameter's value at a fixed level or changing it quickly, despite disturbances that might occur. The basic goal of any controller is to achieve stability in controlling the process (Beardmore, 2006). This means that a controlled system should remain stable within its assigned parameters. The quality of the control can be measured by analysing the accuracy, speed and robustness of a control system.

In feedback control it is desirable to have the output signal follow the reference signal as precisely as possible. If the output signal of the process increases, the measurement signal needs to follow it. This results in the error signal and control signal becoming smaller. This forces the process output signal to decrease, which means that the error signal tends towards zero and the output of the process towards the reference value. Analysing the stability of a control system can be done with frequency response of an open-loop system.

Frequency response of an open-loop system indicates how the system behaves without the feedback loop. The structure of an open-loop system is presented in figure 16.

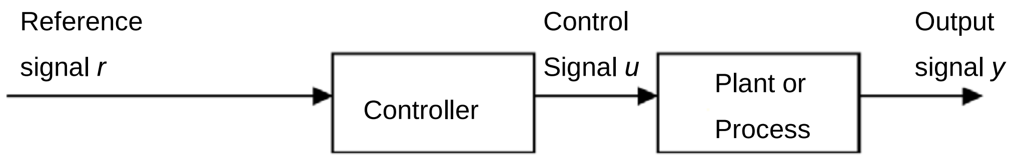


Figure 16 An open-loop control system

Frequency response is a function of ω (frequency) (Tham, 1999). The frequency function gives the gain (amplitude) and phase of a sinusoid signal, which is fed into the system, at every frequency of the output. The frequency response can be calculated from the transfer function of the system by replacing s with $j\omega$ shown in figure 17.

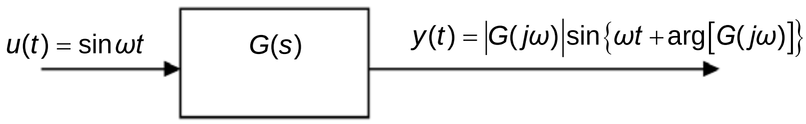


Figure 17 Sinusoidal input and transfer function

Drawbacks of open-loop control are that it requires perfect knowledge of the system and it assumes that there are no disturbances in the system.

2.5.1 Types of controllers

Many previous control valve systems were implemented using mechanical systems or solid state electronics. Pneumatics was often used to transmit information and apply control using pressure. However, most modern industrial control systems now rely on computers as the controller. Obviously it is much easier to implement complex control algorithms on a computer than using a mechanical system.

For feedback controllers there exists a few examples. The most common is a thermostat that just turns the power on if the temperature falls below a certain value and turns the power off if it exceeds a certain value. This is called bang-bang (BB) control (Dogan, 2002). Another simple type of controller is a proportional (P) controller, where, the controller output (control action) is proportional to the error in the measured variable. The error is defined as the difference between the current value (measured) and the desired value (set-point). If the error is large, then the control action is large. This can be represented mathematically by equation 17:

$$c(t) = K_c e(t) + c_s \qquad \dots (17)$$

Where $e(t)$ ≡ error value fed back

K_c ≡ controller's gain value

c_s ≡ steady state control value

It is necessary to maintain the variable at the steady state when there is no error. The gain (K_c) will be positive if an increase in the input variable requires a decrease in the output variable (direct-acting control), and it will be negative if an increase in the input variable requires an increase in the output variable (reverse-acting control). A typical example of a reverse-acting system is controlling the flow of cooling water, if the temperature increases, the flow must be increased to maintain the desired temperature.

Although P-control is simple to understand, it has drawbacks. The biggest problem is that for most systems it will never entirely reduce the error. This is because when the error is zero, the controller only provides the steady state control action so the system will settle back to the original steady state. Having large gains can lead to system instability or can require physical impossibilities, such as infinitely large valves. In systems with high controller gains, instability is mediated primarily through overcompensation (Loannou & Kokotovic, 1984). Subsequently P-control is not capable of making the output equal to the reference and there will be steady-state deviation.

Another example of a controller is a proportional-integral (PI) controller which adds another term to the controller equation (see equation (18)).

$$u(t) = K_c\left(e(t) + \frac{1}{T}\int_0^t e(t)dt\right) \qquad \dots (18)$$

Where T ≡ integration time constant

K_c ≡ controller's gain value

$e(t)$ ≡ error value

If the controller is tuned to be slow and T is large, then the controller first acts such as a P-controller. However as the integration starts to take affect, the steady-state deviation goes slowly to zero. PI-control is therefore a control process where the value of the output signal is based on the error between the target value and the actual (measured) value of the controlled variable, as well as how long that error has existed.

The proportional-integral-derivative (PID) control can be defined as a control scheme whereby the signal that drives the actuator equals the weighted sum of the difference between the time integral of the difference, and time derivative of the difference between the input and the measured actual output (IEEE EED, 2000). Figure 18 shows a commercially available embedded PID-controller.

Figure 18 Industrial PID controller (Nippon Instruments (India) pvt, 2011)

The equation of a PID-controller (equation (19)) has three terms, P, I and D-terms. The derivative term acts as a predictor, because the speed of change of the error signal affects the control signal. The derivative term has a large effect in systems where disturbances are present, because disturbances often occur quickly. This means that fast changes in an error signal might push the process into an unstable state. On the other hand, the derivative term might speed up the controlled system.

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{d}{dt} e(t) \qquad \ldots (19)$$

Where K_p ≡ proportional gain

K_i ≡ integral gain

K_d ≡ derivative gain

$e(t)$ ≡ error

The requirements set for a controller can be contradictory. A controlled close-loop system should be stable and the performance of the controller should be efficient, meaning that the control must be quick and reliable. For example, the better the performance of the controller, the less stable the close-loop system. That is why a compromise has to be made to fulfil all the requirements. The goal is to make the system fast, but not to push it close to the oscillation boundary, where small sudden changes in the system could make the system unstable.

The choosing of the controller's parameters is process sensitive. One need to use different parameters in fast and slow processes. The disturbances also affect the choice of parameters. Techniques used for choosing the parameters used in P, PI, or PID-control, include the step response method or oscillation boundary method, which is based on frequency analysis. The step response method can be used to tune the parameters of a controller, if it is possible to feed a step into an open-loop system (no control or feedback).

If a step of height K_1 (in °C) is fed into the system and the output of the system behaves as in figure 19, then a tangent line can be drawn at the infliction point of the output signal. The height of the output signal is then K_2 (in °C), the delay time is T_1 (in seconds) and the rising time is T_2 (in seconds), which can be calculated using figure 19.

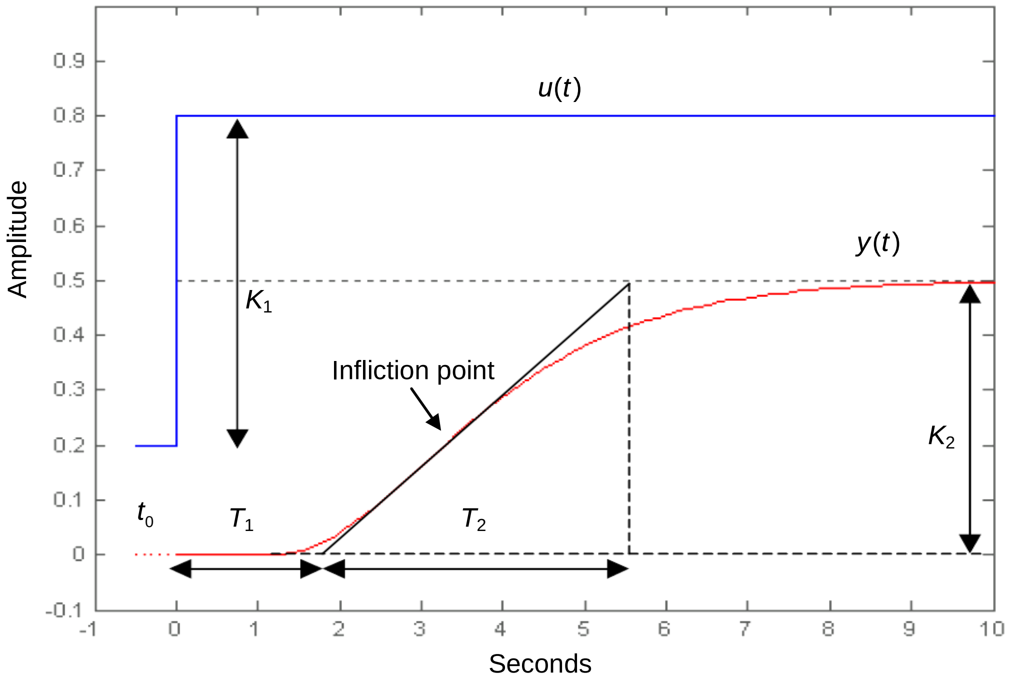


Figure 19 Step response of a system

Once values for K_1, K_2, T_1, and T_2 have been obtained, then the gain, integration time and derivative could be calculated for each controller by either the Ziegler-Nichols or Cohen equation tables. The Ziegler-Nichols method of calculating the parameters for P, PI or PID-controllers is shown in table 5.

Table 5 Controller parameters for a step response method using Ziegler-Nichols (Dogan, 2002)

Controller	Gain K	Integration Time T_1	Derivation Time T_D
P	$\frac{K_1 T_2}{K_2 T_1}$	Not applicable	Not applicable
PI	$0.9\frac{K_1 T_2}{K_2 T_1}$	$3.3T_1$	Not applicable
PID	$1.2\frac{K_1 T_2}{K_2 T_1}$	$2T_1$	$0.5T_1$

2.6 Summary

In this chapter, an equivalent electrical circuit representing the properties of a thermal oven have been presented. Different types of thermal measuring techniques and devices have been discussed and control methods used in industry have been presented.

The next chapter will present characteristic data of the oven, a MATLAB model and algorithm. The progression from an analogue- to digital solution will be discussed and the power switch combination will be shown.

Chapter 3 Simulation and experimental validation

3.1 Introduction

This chapter will introduce data of a curing oven. An analysis of this data will be shown in order to verify the mathematical model in Chapter 2. It will further present the microcontroller logic and design of the combination switch.

3.2 Temperature measuring setup

In order to work towards the model presented in equation (12), measurements with respect to temperatures in and around the oven had to be obtained. Figure 20 presents the temperature measuring setup where five type K-thermocouples were used to obtained temperatures, which were interpreted by a PICOSCOPE data logger (TC-08).

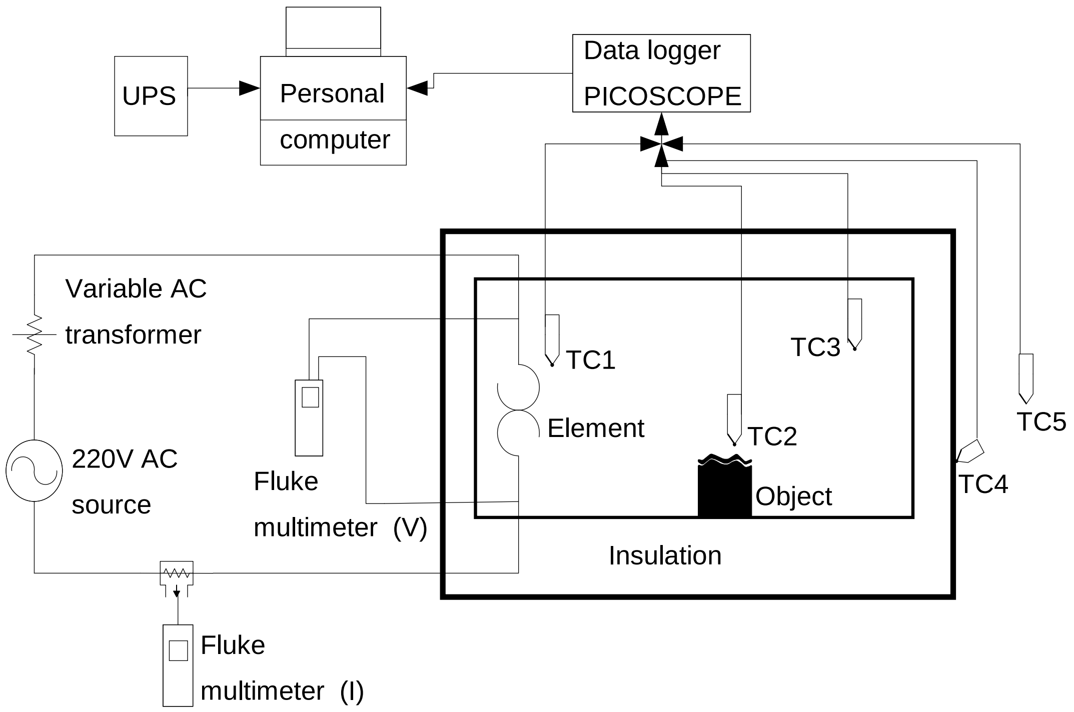


Figure 20 Temperature measuring setup

The PICOSCOPE incorporates Seebeck coefficients for type J and K thermocouples and different coefficients can be used with specific thermocouples on specific channels. Each channel had been setup to interpret type K-thermocouples. All data collected was transferred in real time to a personal computer for analysis and normalization. Thermocouples one to five represent:

- TC1 the ambient temperature,
- TC2 the insulation temperature,
- TC3 the heating element temperature,
- TC4 the oven air temperature and
- TC5 the object temperature.

A multimeter (FLUKE Fl223) was used to obtain readings of the AC voltage source applied to the element. Another multimeter (FLUKE Fl223 with AC current probe FLUKE FC212) was used to obtain readings of AC current drawn by the heating element. A variable AC transformer was used to limit the amount of energy applied to the heating element in order to keep the measurements within range of the test equipment as shown in figure 20.

3.3 Initial oven characteristic data

Using the equipment shown in figure 20, various data points were obtained and processed in graphical form using MATLAB 7.6.0 (see figure 21). The set-point temperature for the experiment was set to 684°C as this was within limits of the thermocouples and other test equipment. In order to analyse the data and obtain an algorithm for the curves, normalization had to be applied (see figure 22). This normalization will also be relevant to later mathematical models used to simulate the controller. Contrasting figure 21 and figure 22, and specifically the object temperature reveals that the heating element does store heat energy, which will be an important factor when designing the controller.

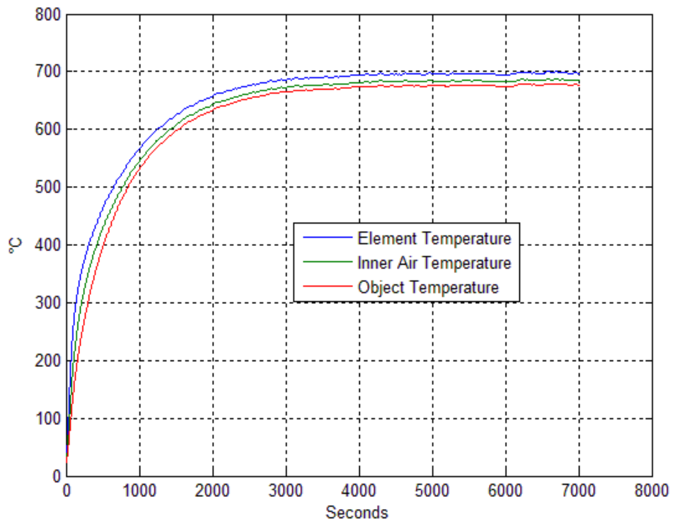


Figure 21 Data obtained for the oven in the ON position

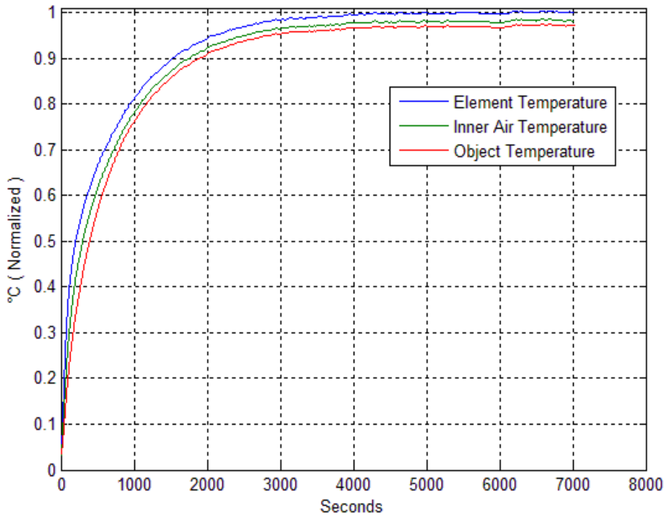


Figure 22 Normalized data obtained for the oven in the ON position

To verify that the shape of the object temperature was not accidental, different shaped objects were placed inside the oven with the experiment repeated. Figure 23 shows different object temperatures measured over a period of 4500 seconds. This proves that the temperature curves follow the same basic shape and that applying curve analysis to this type of graph would be acceptable.

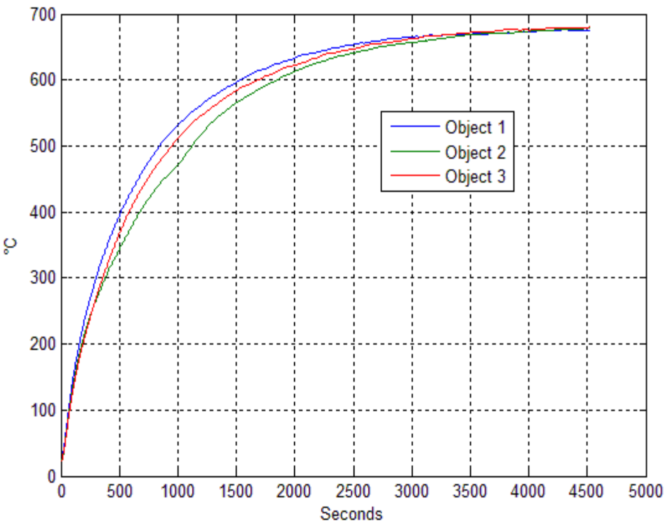


Figure 23 Different objects' temperature curves

Figure 24 shows different object temperatures with corresponding measurements of the oven's air temperature.

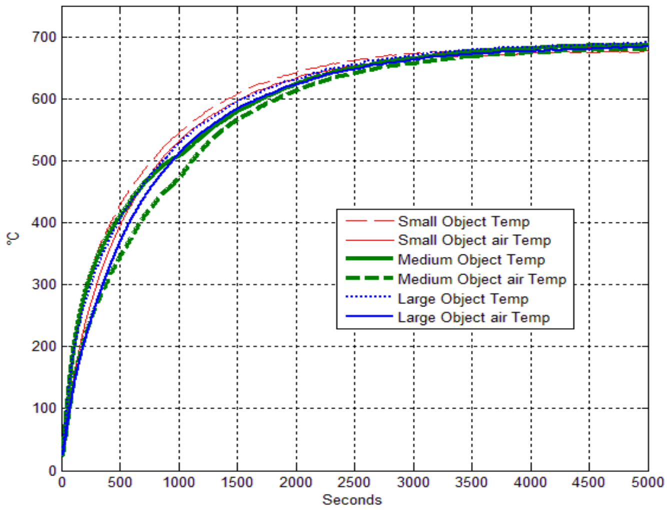


Figure 24 Object temperatures and corresponding oven inner air temperature curves

The readings are those obtained from TC2 and TC3 shown in figure 20. This figure was also used to determine if a relationship exists between air and object temperatures.

Curve analysis is the process, by which the equivalent mathematical model is compared to the data of the experimental model. MATLAB was used to obtain a curve fitted mathematical model (see figure 25).

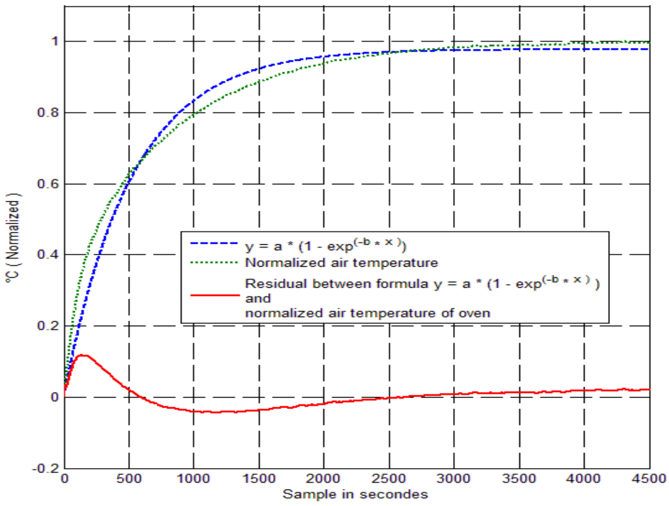


Figure 25 MATLAB curve for data collected, mathematical model fitting and residuals

CURVE EXPERT a software package was used to verify results presented from MATLAB. The fitting software uses either standard mathematical models or models developed by the user. Figure 26 and figure 27 show the analysis done by CURVE EXPERT.

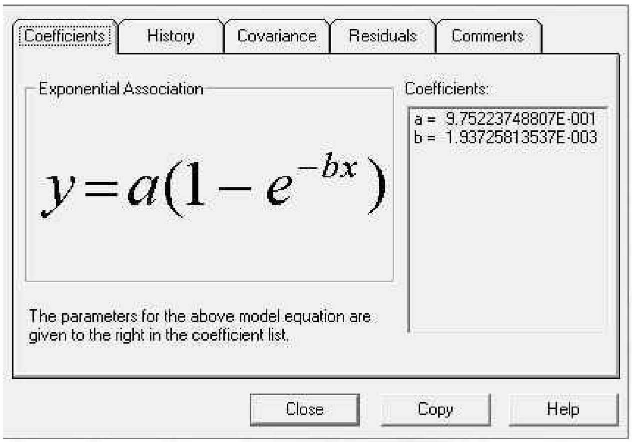


Figure 26 CURVE EXPERT data, mathematical model fitting and residuals

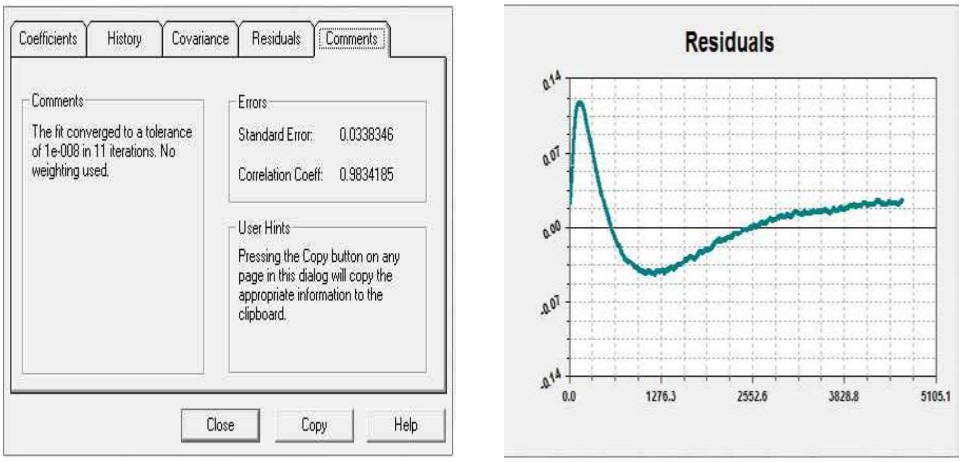


Figure 27 CURVE EXPERT mathematical model coefficients and standard error

The blue line in figure 25 represents the mathematical model fitted to the data curve shown in green. The following mathematical model equation fits the data set with some residual.

$$y = a\left(1 - e^{(-bx)}\right) \quad \ldots (20)$$

Where y ≡ temperature in °C

a ≡ constant as 9.75223

b ≡ constant as 1.93725

x ≡ time in seconds

The residuals from figure 25 and figure 27 are similar and therefore prove that the model used in figure 3 in Chapter 2 to represent the oven in its electrical form is correct. The derived equation (12) and the experimental acquired equation (20) are similar confirming the approach used is correct.

3.4 MATLAB model

The simplified basic model from Chapter 2 has been redrawn in MATLAB. This was done in order to test the fitted curve found as applied to the model for simulation purposes. The model shown in figure 28 was then later developed to include a control system, which could be simulated in MATLAB before applying it to the microcontroller for regulating the temperature of the oven.

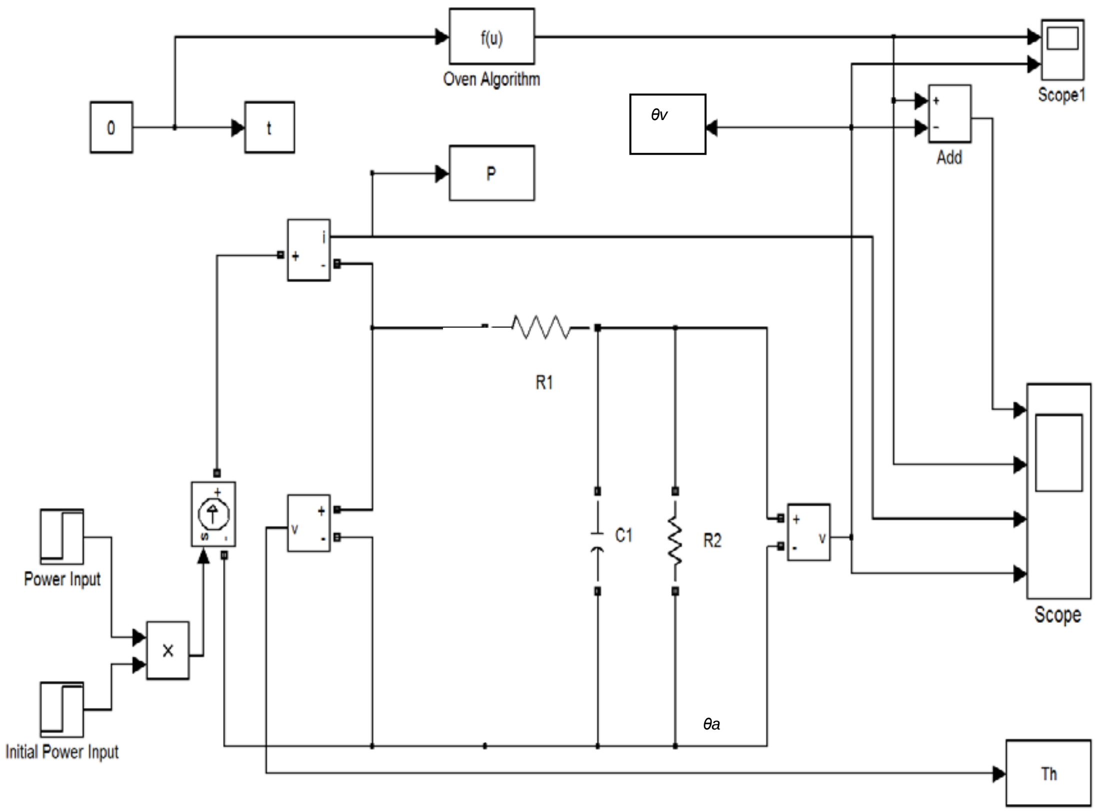


Figure 28 MATLAB representation of the simplified electrical oven model

3.4.1 Control of air temperature using Bang-Bang, PI and PID control

Using the Ziegler-Nichols criterion, the parameters of the controller can be calculated from the measurements taken. The parameters of the controller are presented in table 5.

MATLAB was used to implement a control method to the model as shown in figure 29. Using the Ziegler-Nichols step response technique, control parameters of the oven plant were determined and simulated in MATLAB for the PI control method. The PI control method was chosen because of its smaller over-shoot when nearing the set-point. The simulation setup used in MATLAB is shown in figure 29.

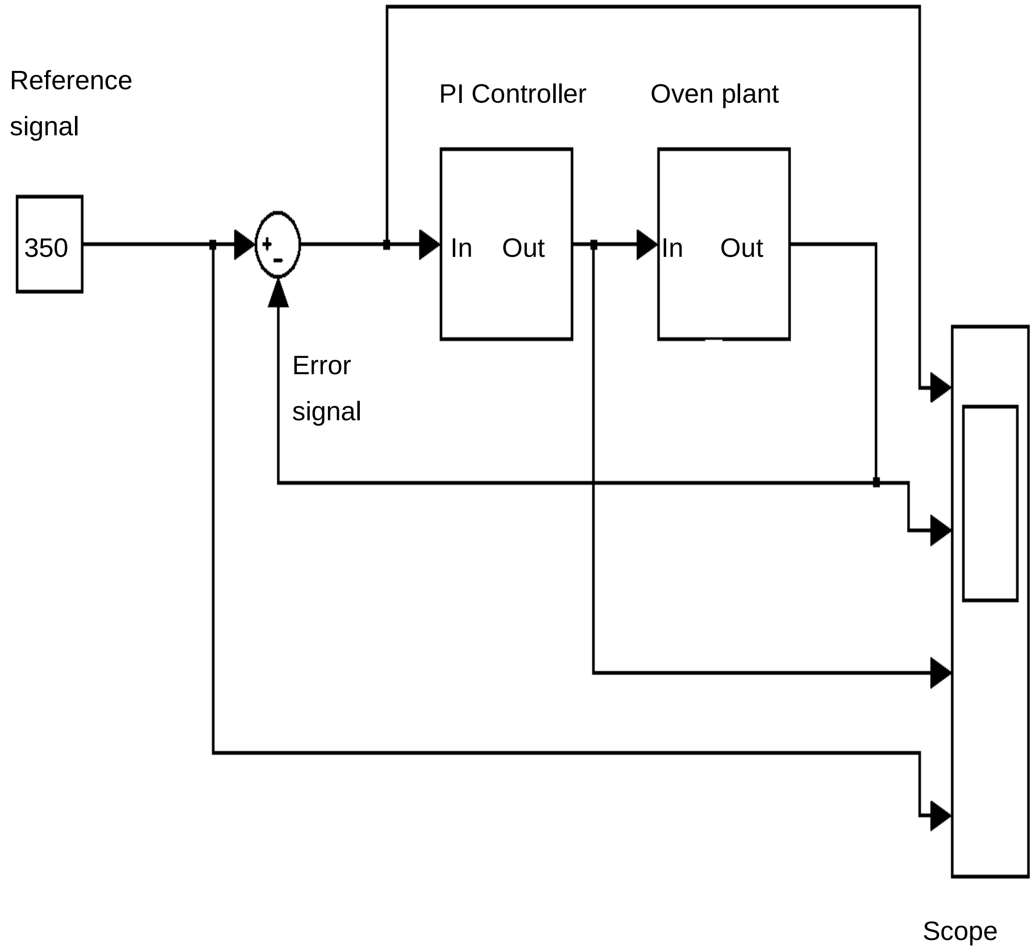


Figure 29 MATLAB model of the simplified oven model and controller

3.4.2 Stability analysis of the analogue solution

Using MATLAB's SISO tools, a stability analysis was done using a step response method (see figure 30). As a result of a step input, the Open-Loop Bode and Root Locus results (see figure 31), a conclusion can be drawn that the control parameters for K_p *and* K_i (determined using table 5), for this specific model are within range and that the control loop is stable.

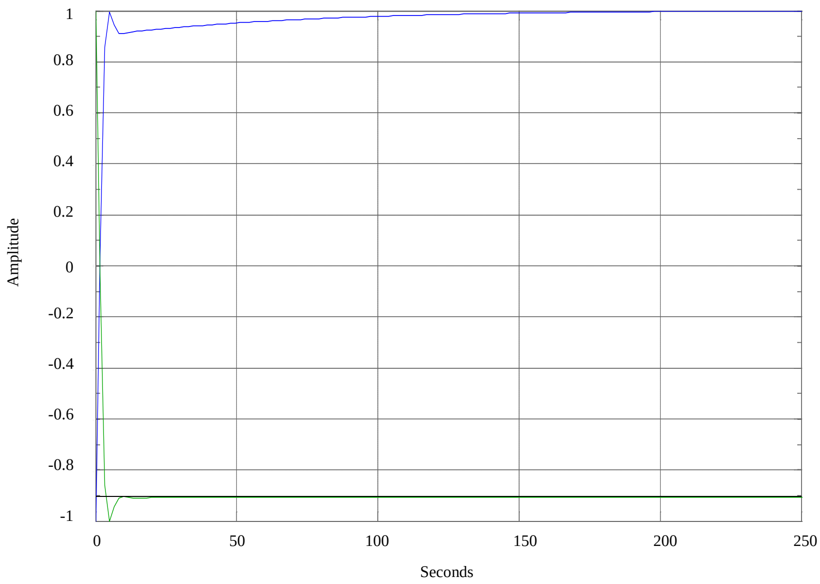


Figure 30 Step response analysis graph

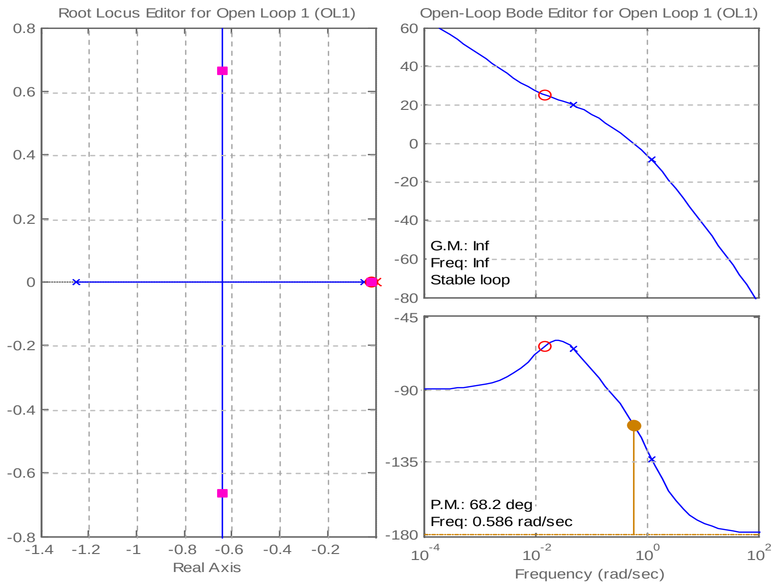


Figure 31 MATLAB SISO tools stability analysis graph

3.5 Progression from analogue to digital solution

According to Schoeman (2011), it is suggested that each control technique (BB, PI and PID) has its own individual advantages and disadvantages. The BB technique has a very fast rise time, but once the set-point is reached the variant between the switch on and switch off temperatures is high. The PI control technique has a very stable and small variant when the set-point is reached, but its rise time towards the set-point is slow.

PID is an improvement on PI in respect that the rise time toward the set-point is much faster, but not as fast as BB (Schoeman, 2011). It also has a characteristic of over-shoot when the set-point is reached and the settling time is therefore increased when compared to PI control. This can be seen in figure 32, which was obtained using simulation models in PROTEUS VIRTUAL SYSTEM MODELLING (PVSM) 7.2. Different control methods were applied via embedded software programs using a microcontroller circuit (see figure 33).

PVSM 7.2 combines mixed mode SPICE circuit simulation, animated components and microprocessor models to facilitate co-simulation of complete microcontroller based designs (Labcenter Elctronics, 2010). It is possible to develop and test such designs before a physical prototype is constructed. At the heart of PVSM is ProSPICE. This is an established product that combines a SPICE3f5 analogue simulator kernel with a fast event-driven digital simulator to provide seamless mixed-mode simulation (Labcenter Elctronics, 2010). The use of a SPICE3f5 kernel allows for the use of the numerous manufacturer-supplied SPICE models, around 6000 of these are included with the package. PVSM 7.2 includes a number of virtual instruments including an oscilloscope, logic analyser, function generator, pattern generator, counter timer and virtual terminal as well as simple voltmeters and ammeters. In addition, dedicated Master/Slave/Monitor mode protocol analysers are provided for SPI and I^2C communications.

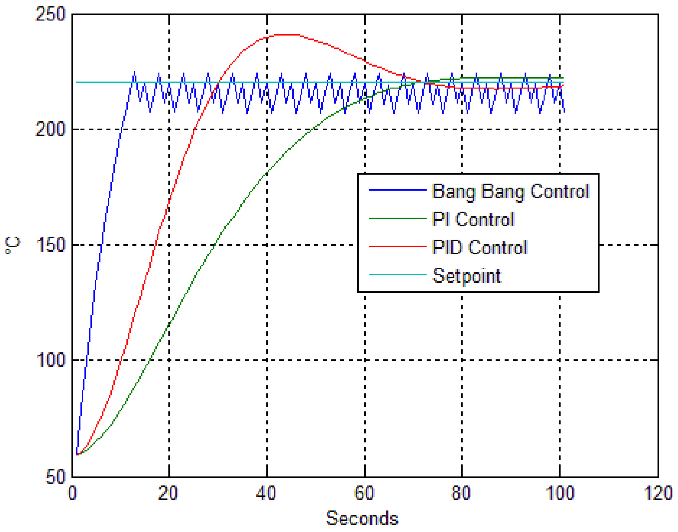


Figure 32 Control methods' step response graphs (Schoeman, 2011)

The parameters used (K_1, K_2, T_1, T_2) in the microcontroller software were determined using Ziegler-Nichols' method shown in table 5. In order to overcome the disadvantages of PI and BB control, it was decided to apply a combination control where the controller would initially use BB control to achieve a faster rise time towards the set-point and then switch over to PI control at 90% of the setpoint value.

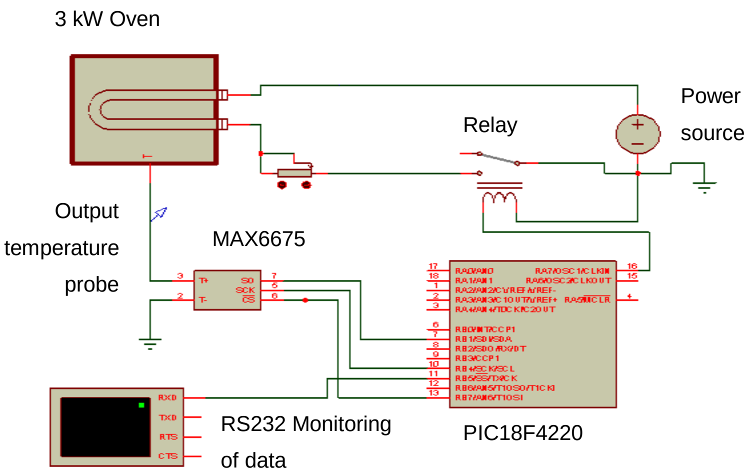


Figure 33 Proteus circuit used for simulation of control methods

Initial simulations showed very little improvement. However, once the PI parameters where updated during the BB control phase, the application of using two control methods showed a faster rise time as well as a faster settling time in comparison to only using PI control. Figure 34 shows the simulated graphs of the combination method with updated and non-updated PI parameters during the BB control phase.

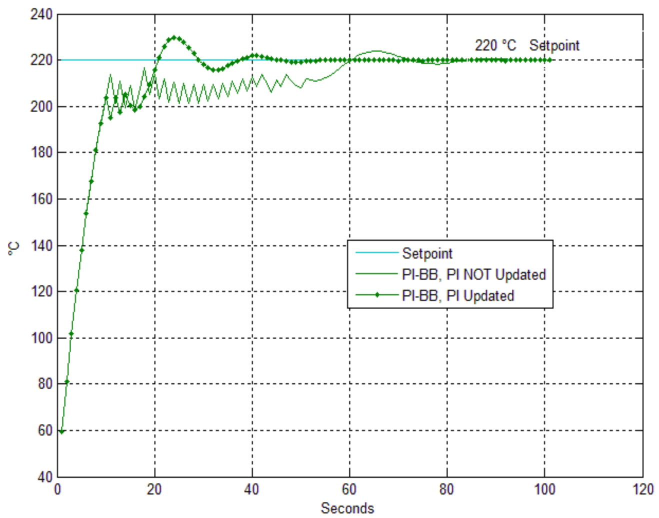


Figure 34 Proteus simulation of PI-BB control methods

3.5.1 Microcontroller program flow chart

According to Damij (2007) a flowchart is a good technique to represent the logical flow of a process that a program needs to follow. The microcontroller program was written in CCS C, a software package that uses the structure of C, but is optimised for microcontrollers. The program was developed for a PIC18F4220. Annexure B shows the program which was written in CCS C for a PIC microcontroller that follows the flowchart shown in figure 35.

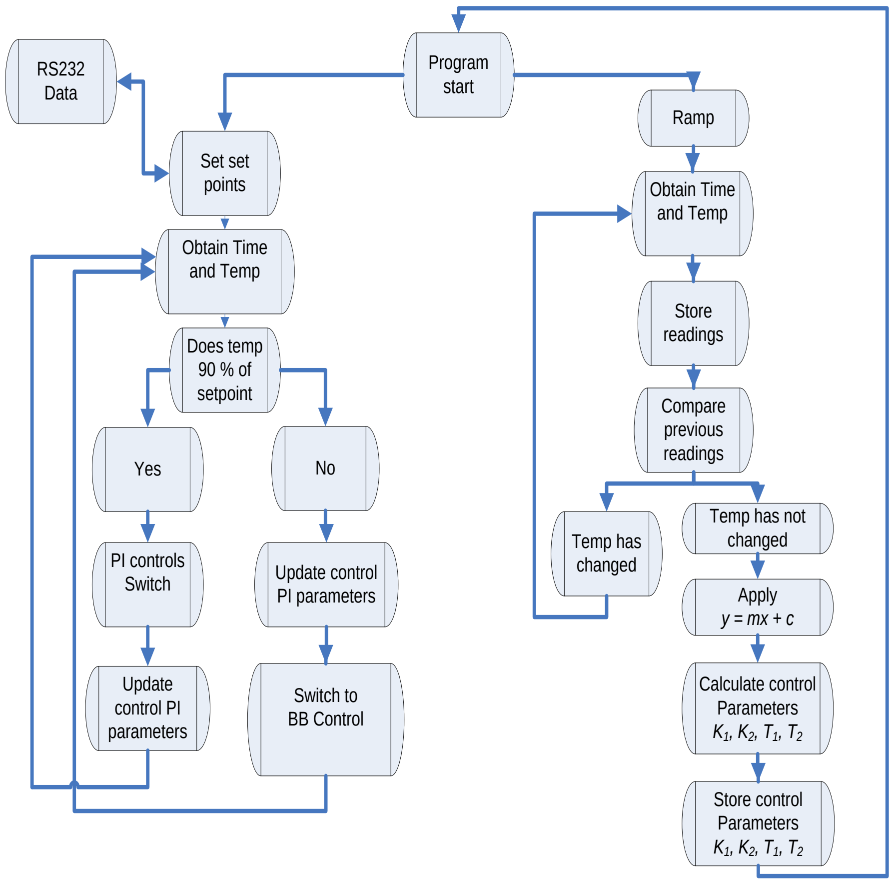


Figure 35 A flowchart outlining the functions of the CCS C software program

3.6 Design of a combination switch

As mentioned in Chapter 2, to counteract the disadvantages of a relay and of a TRIAC, a combination switch is used. Figure 36 shows this combination which encompasses a relay and a TRIAC to form a complete switching device.

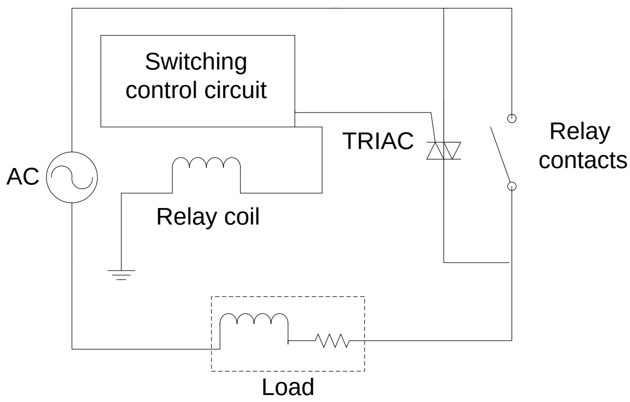


Figure 36 Combination switch

The switching control circuit is very important, as it will activate the two devices in such a way that only the advantages of each device are realized. The timing of the switching actions will be controlled by the microcontroller shown in figure 33.

3.6.1 Switch simulation data

The simulation of the combination switch was initially done using MATLAB Simulink. Figure 37 shows the design where two SCRs form the circuit of a TRIAC device. The control circuit will need to switch the relay and the TRIAC on simultaneously. The TRIAC is a solid-state device which will switch on faster, as the relay's coil must first be energised before enough magnetic energy is available to engage the contacts.

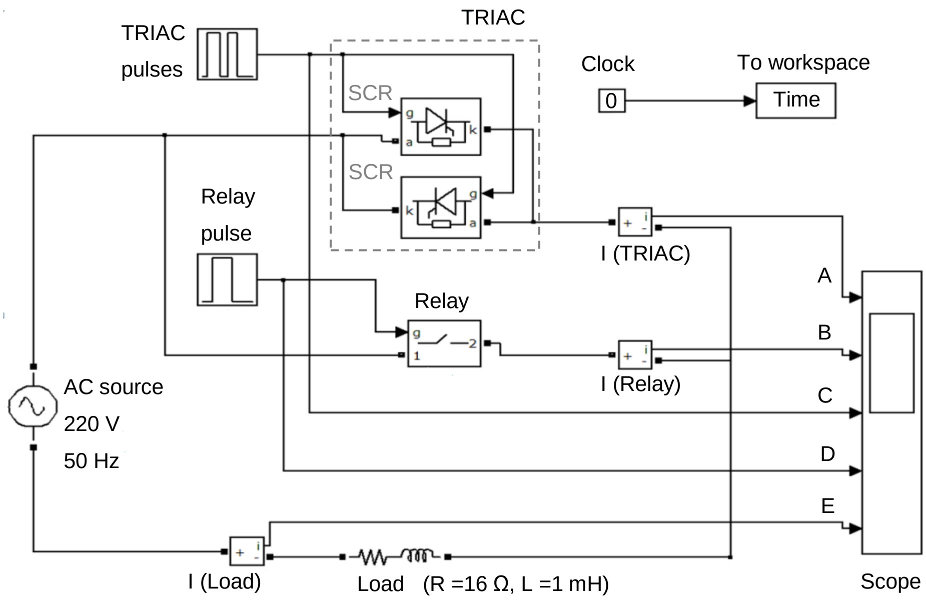


Figure 37 Simulation model of combination switch

This means that the load current will first flow through the TRIAC, thereby reducing the arcing of the relay contacts during switch on. As the relay is energised, contact bounce will still occur but with minimal arcing, as the load current flows through the TRIAC. Figure 38 show the results of the MATLAB simulation where current is seen to shift from the TRIAC to the relay during switch on. However, the load current remains constant during the switch on period.

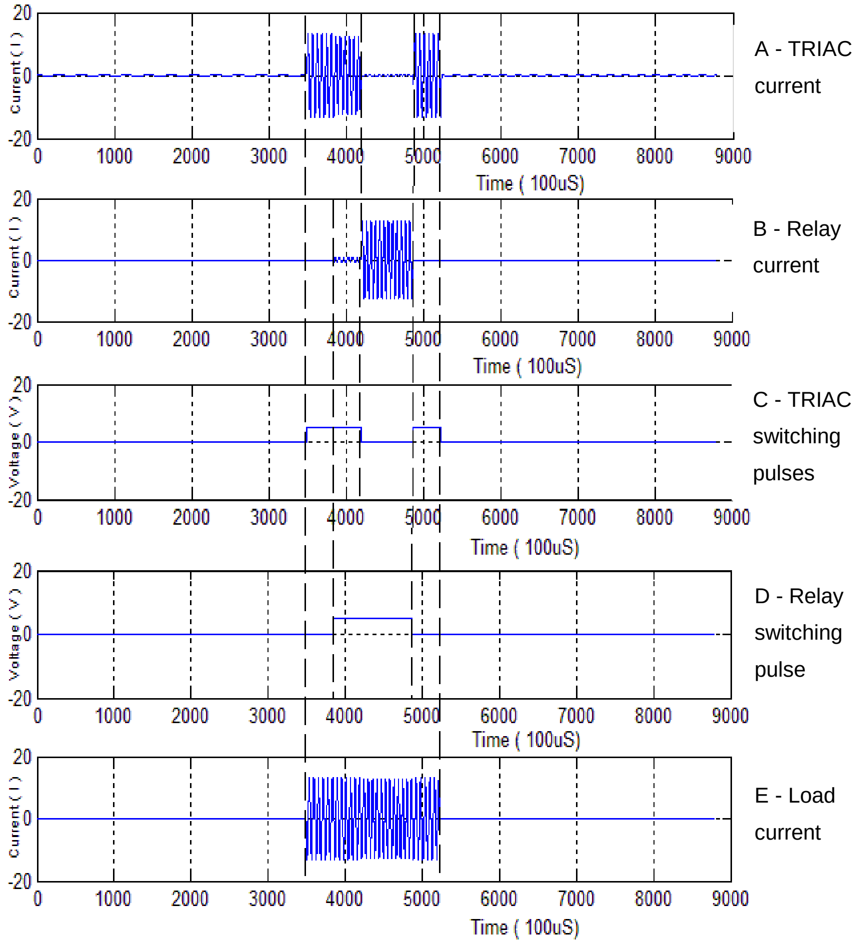


Figure 38 MATLAB simulated results of switching currents in relay, TRIAC and load

3.6.2 Switch practical results

The current through the TRIAC and relay was measured using an oscilloscope and two Fluke FC212 current probes, one measuring the relay contact current and the other the TRIAC current. Figure 39 shows when the contacts of the relay close (the resistance between them is less than that of the TRIAC's internal resistance R_f and R_r), current is transferred from the TRIAC to the relay contacts. As the contacts open the resistance between them increases so that it becomes more than that of the TRIAC, which causes current to flow through the TRIAC. This occurs even during contact bounce, which is due to the mechanical forces between the relay contact plates. This transfer of current will continue until the contact bounce process settles, which was measured to be around 3 ms in this particular case.

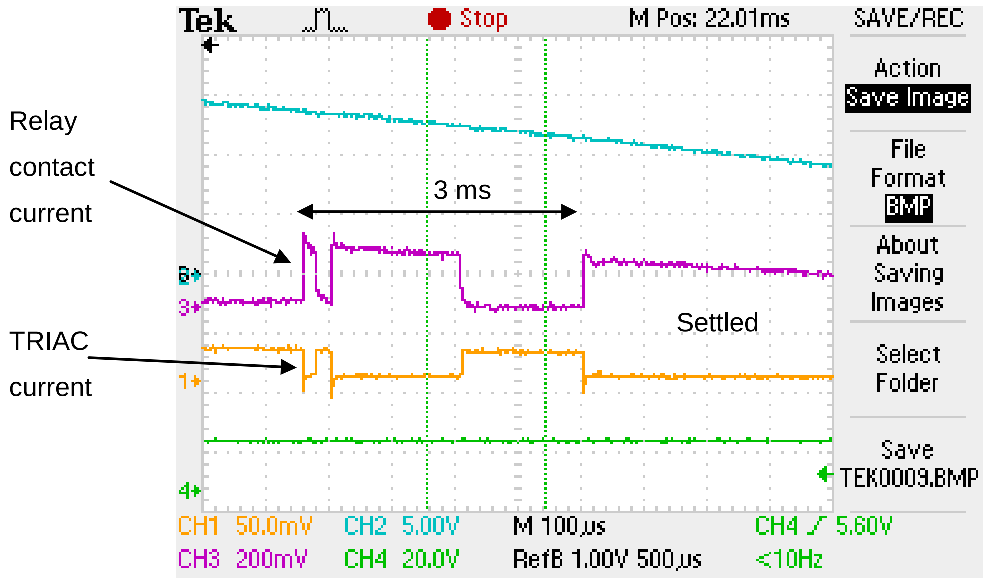


Figure 39 Measured current transfers between relay and TRIAC

Figure 40 indicates the relay switching settling time. The settling time will differ from relay to relay, due to different coils and voltages used by various manufacturers.

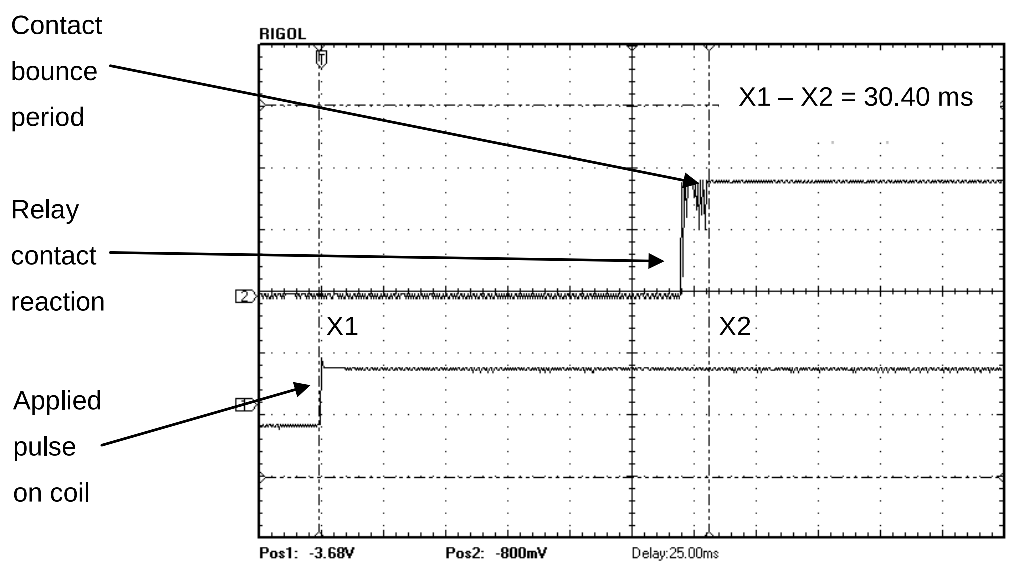


Figure 40 Relay settling duration

3.7 Summary

This chapter presented the analog system, oven characteristic curves, mathematical algorithm in the electrical environment, and a digital controller. The simulation and practical results of a combination switch in order to prolong longevity were also shown. The next chapter describes the controller and software which were developed to control the oven for a preset curing profile, along with relevant results.

Chapter 4 Experimental results

4.1 Introduction

This chapter will present the practical setup used to obtain results, the software interface developed for use in the curing profile control and the hardware prototypes that were developed. Results will be evaluated and experiments repeated to determine stability of control parameters during curing profile runs.

4.2 Practical setup and curing control results

A practical setup in the laboratory was done using a PIC3 development board, a PIC18F4220, switching board, sensor board, a 3 kW oven and developed software as mentioned in the previous chapter. Figure 41 shows the configuration of the setup used to obtain the results.

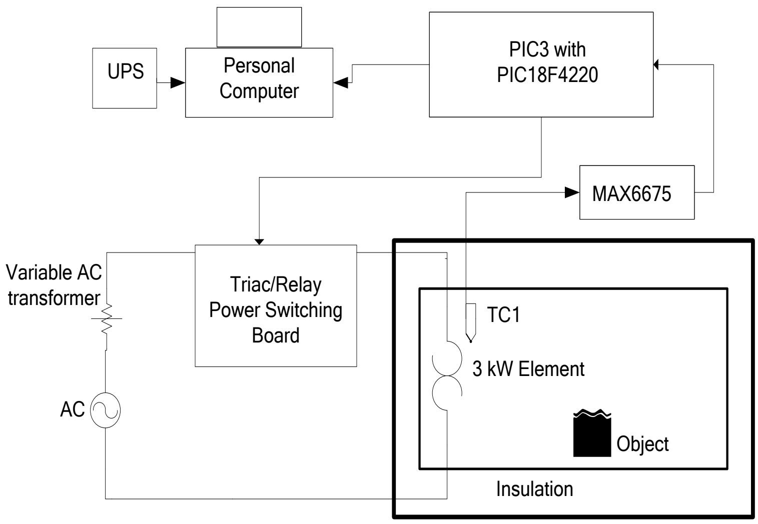


Figure 41 Practical setup of a 3 kW oven and switching board

A graphical user interface (GUI) was developed in Microsoft Visual Basic 6 (annexure A), which allows the user to enter and save a desired curing profile. This is vital in order to ensure that the same curing profile could be applied at a later stage to the same type of material. Figure 42 and figure 43 shows the capability of the developed software that allow the creating and storing facility of a specific curing profile.

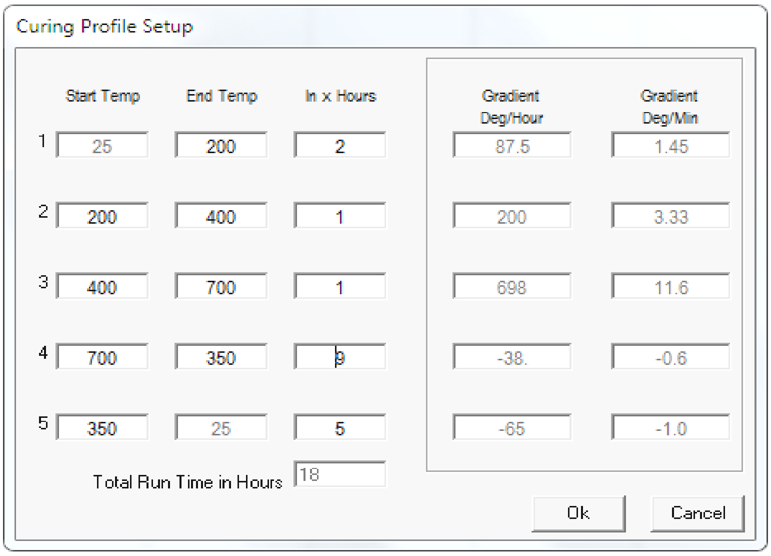


Figure 42 Curing profile creation capabilities of developed software

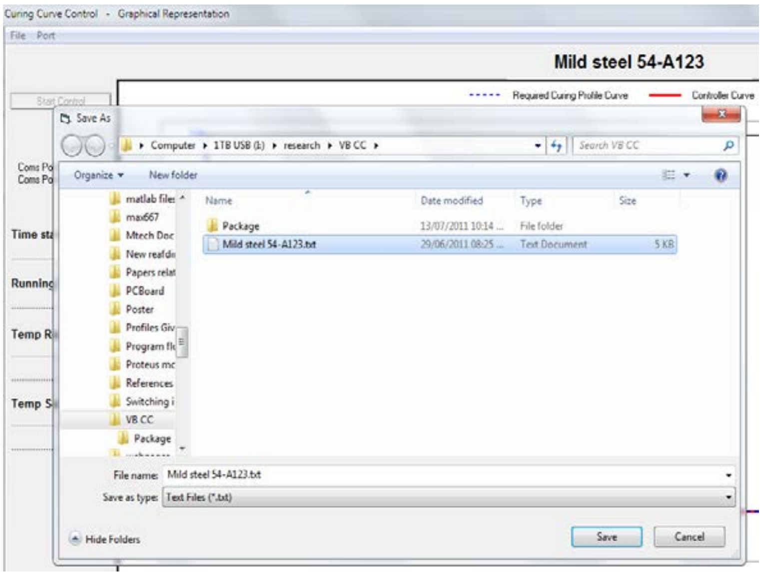


Figure 43 Curing profile saving capabilities of developed software

The blue dotted line in figure 44 represents the curing profile entered into the personal computer and acts as a visual representation of the curing profile required by the operator. The oven is initially set to full on. During this process, the PIC18F4220 microcontroller determines the control parameters as discussed using the Ziegler-Nichols method. Once this is done, the oven is ready to start the controlling process based on the predefined curing profile as in figure 44.

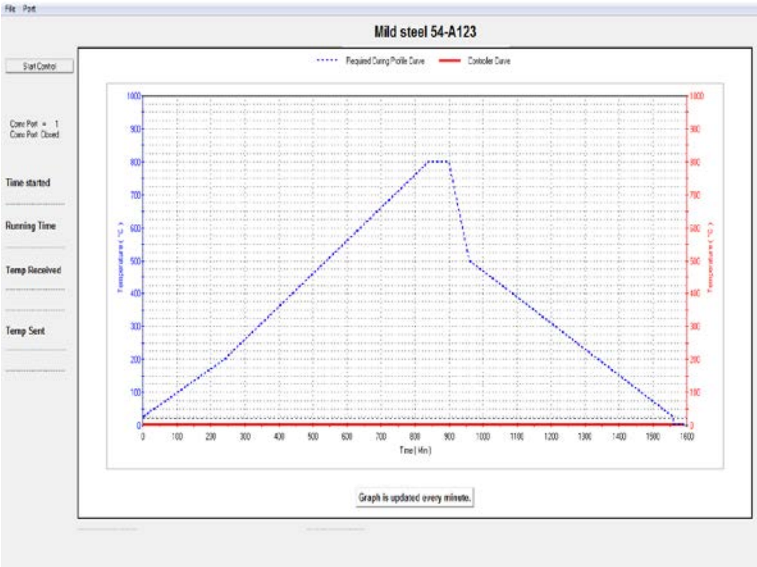


Figure 44 Curing profile saved in developed software

The time lapsed graph shown in figure 44, is updated every minute. The microcontroller updates the control parameters, taking an average of one hundred temperature readings, and determines the error with respect to the previous control parameters. This error is fed back into the control loop, ten times a minute, meaning that the control process has six seconds to read the temperature, average the readings, determine the new control parameters and apply it to the combination switch device.

4.3 Hardware

The software on the personal computer is used to provide a new set-point every minute that co-insides with the curing profile curve. It further visually shows the progress of the control process that is being applied to the oven with respect to the curing profile. The MAX6675 (annexure E) integrated circuit was used to convert the temperature readings from the thermocouple into a digital format to be used by the microcontroller. It has an accuracy of 0.5°C and a temperature range of -100°C to 2200°C. This device incorporates a coldjuction reference which is factory calibrated during the manufacturing process, thereby reducing the need for additional procedures and equipment during setup. Figure 45 shows the MAX6675 mounted on a prototype board for easy use with a common bread board.

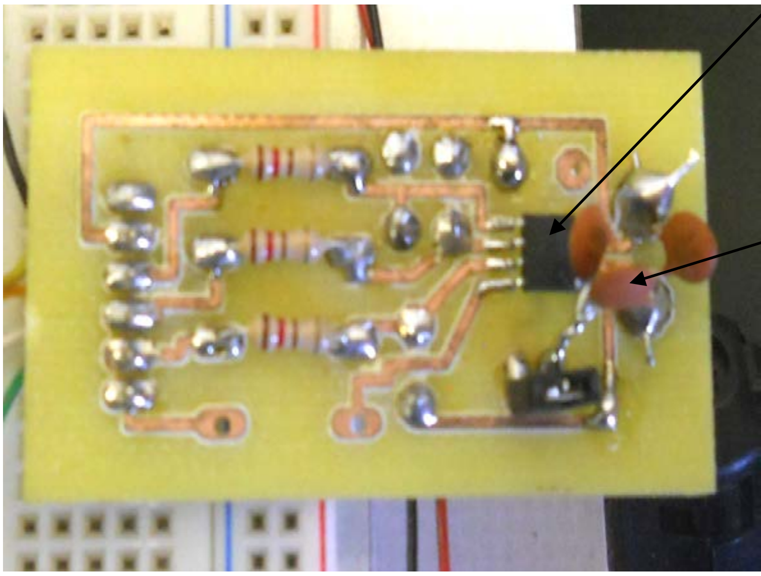


Figure 45 MAX6675 integrated circuit mounted on the prototype board

Data is sent via an I^2C bus to the microcontroller and interpreted as a digital word. This is used to update the control parameters as mentioned earlier. The switching board can now be activated. Both TRIAC and relay are energised, but because of the time taken to fully energise the coil of the relay, a delay is experienced between these two devices. This is ideal as the TRIAC will conduct the current first, and then the relay when the contacts come to rest. The switching board is shown in figure 46. Connections to the oven's heating element are visible and the live wire is either closed or opened by either device.

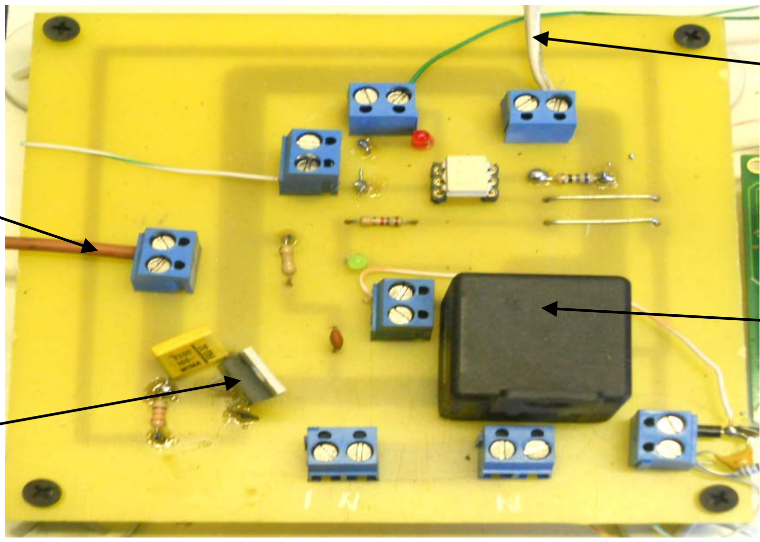


Figure 46 Combination power switch on the prototype board

Visual indications, in the form of two light emitting diodes (leds) are provided to show which device is activated. Combination switch activation was set to six seconds, in order to obtain the correct number of readings per minute as the processing time and communication between the temperature sensor and microcontroller is lengthy. Adapting the ON/OFF time of the switch in this way helped to achieve balance between activation time and delays due to processing.

Figure 47 shows a liquid crystal display (LCD) which is used to display the current set-point received from the personal computer and the average temperature measured during the processing time.

Figure 47 Operator information display unit

Figure 48 indicates the prototype controller (including microcontroller and a RS232 integrated circuit) which is used for communicating with the personal computer. The reason for using the RS232 communication protocol was due to the fact that it is included in the microcontroller, the PIC18F4220. This helps to reduce costs and minimize the total number of components required.

The control circuit uses a DC supply, but needs to switch an AC circuit. Therefore it was decided to isolate these two supply circuits. This was done by using an optocoupler driver (MOC3040 - see annexure F) which activated the TRIAC device. The relay provides its own isolation between the two circuits, as DC is applied to the coil, and AC to the relay contacts.

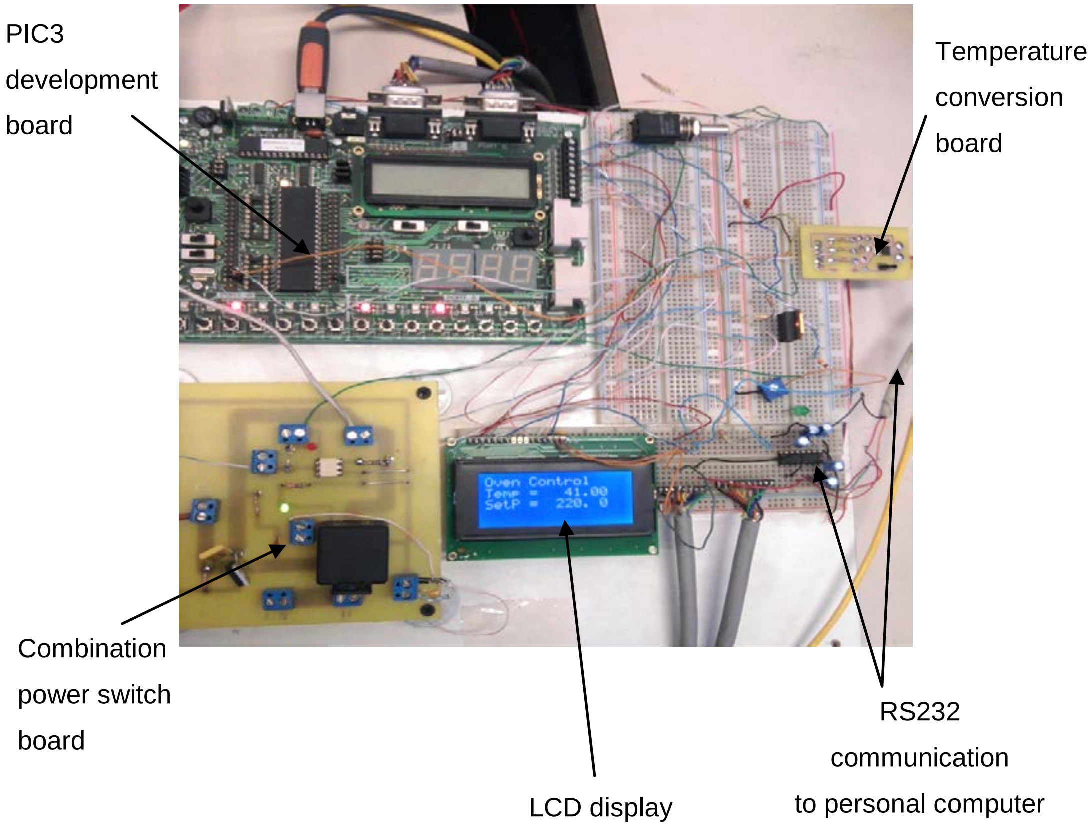


Figure 48 Prototype control unit with combination power switch

Calibration of the system was done using an infrared thermometer (LUTRON TM-2000). The thermometer uses an infrared beam to measure the amount of energy radiated by an object in order to determine its temperature. Figure 49 shows the infrared thermometer being used to measure the temperature of the thermocouple tip.

Figure 49 Infrared thermometer with laser target indicator, pointed at the thermocouple tip

Once calibration was complete the control parameters were automatically determined by the controller. A curing profile from the TSVUT was loaded in order to determine if the controller could follow it. Figure 50 shows the results of this process. A second curing profile was used to verify that the controller was following the loaded profile, as shown in figure 51.

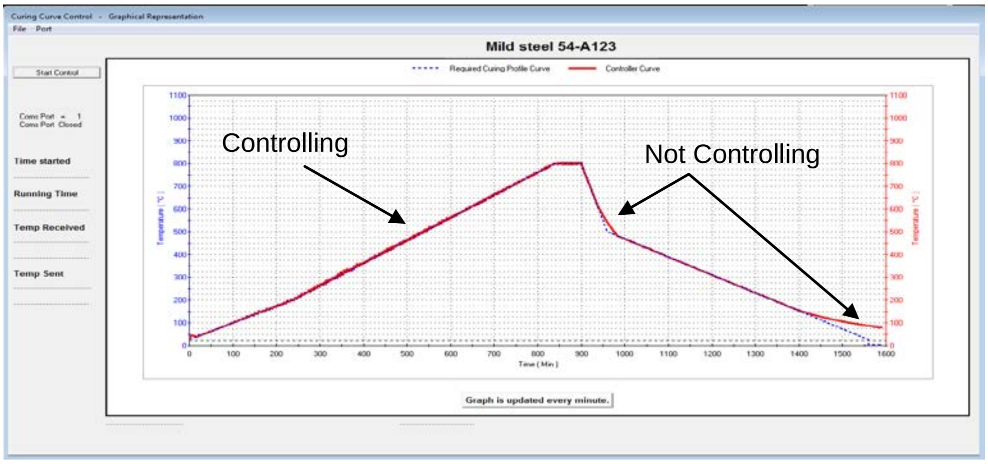


Figure 50 Predefined curing profile control results

From figure 50 and figure 51 it can be seen that the curing oven could not be controlled during certain times of the cooling process. This was found due to the fact that the rate of required cooling was outside the limits of the ovens normal cooling characteristics. The requested cooling profile was much faster than the natural cooling of the oven, and thus the controller could not follow it. As no additional changes to the oven were allowed, it was deemed acceptable. A second run was completed in order to determine the validity of the results (see figure 52).

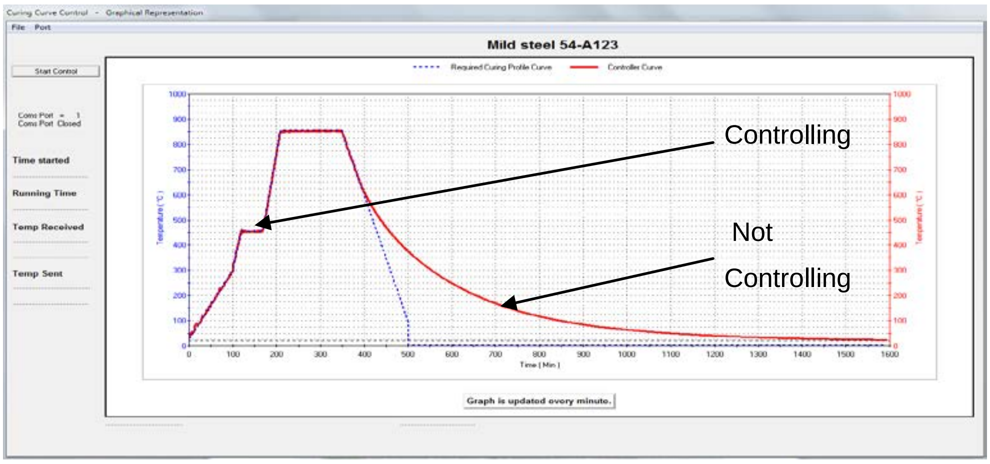


Figure 51 The second curing profile control results

The second run proved successful with a slight difference in the starting area of the profile, after which the controller effectively controlled the temperature as defined by the curing profile. Analysing a section of figure 52 using MATLAB indicates that there is still some over-shoot and under-shoot, as suggested by the simulated results.

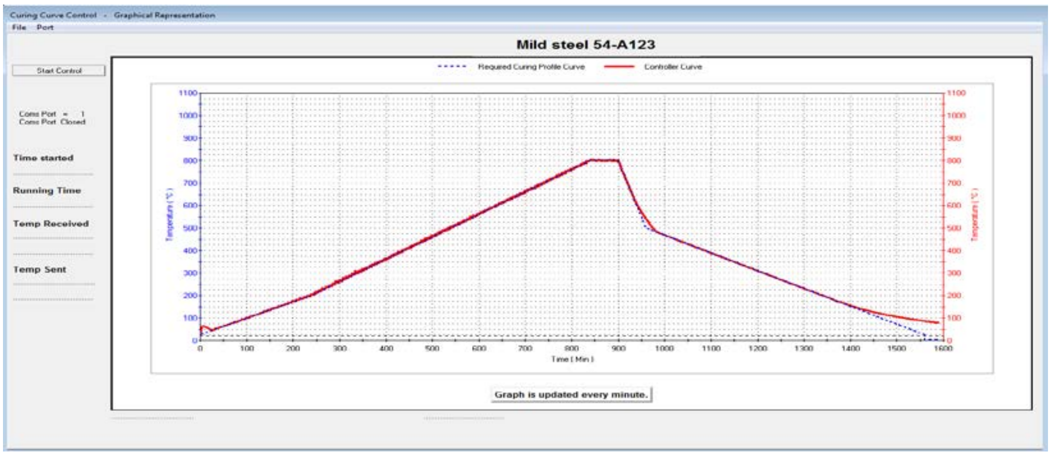


Figure 52 Predefined curing profile validity results

The over-shoot was found to be less than 5% over the duration of the curing profile. This was found to be valid for both curing profiles, including the second confirmation run of the initial curing profile. Figure 53 shows a sample of the maximum over- and under-shoot of an area during the curing profile.

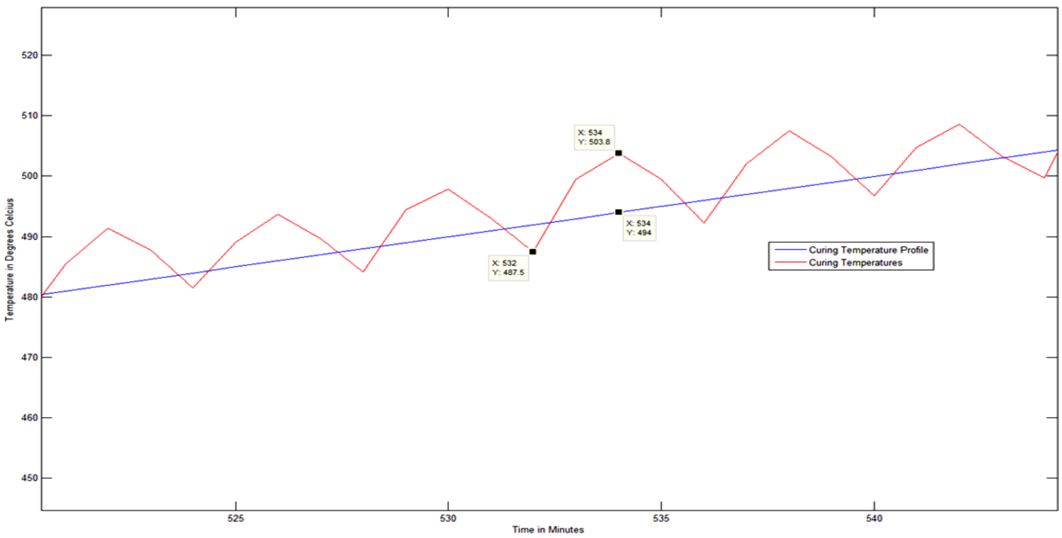


Figure 53 Over-shoot and under-shoot visualisation using MATLAB

The over-shoot was measured after 534 minutes and was found to be 503.8°C at the 494°C set-point. Using the previous reading at 532 minutes of 487.5°C an over-shoot and under-shoot percentage can be calculated with equation (21) and equation (22).

$$\%Err = \frac{T_{measured} - T_{setpoint}}{T_{setpoint}} \text{ x } 100 \qquad \text{… (21)}$$

$$\%Err = \frac{503.8°C - 494°C}{494°C} \text{ x } 100$$

$$\%Err = 1.98\%$$

A 1.98% over-shoot exits.

$$\%Err = \frac{T_{measured} - T_{setpoint}}{T_{setpoint}} \text{ x } 100 \qquad \text{… (22)}$$

$$\%Err = \frac{494°C - 487.5°C}{494°C} \text{ x } 100$$

$$\%Err = 1.31\%$$

A 1.31% under-shoot exists.

4.4 Summary

This chapter considered the hardware and software design of the controller. It showed results of the controlling process after calibration was completed. The controlling process was repeated using different profiles in order to establish consistency and validity. The error obtained for under- and over-shoots were shown.

Chapter 5 presents some conclusions and discusses a few recommendations that have come to light.

Chapter 5 Conclusions and recommendations

5.1 Concluding comments

This chapter presents the conclusions reached with regard to the design and development of an automated temperature controller for curing ovens. The initial objectives will be compared to the outcomes of the project. Recommendations for future research will then be highlighted.

5.2 Conclusions attained from the study

The theoretical study revealed that the most suitable sensor available for measuring high temperatures is a type K-thermocouple. Cold compensation was needed in order to provide the correct reference for calculations of temperature and the MAX6675 was therefore chosen due to its accuracy, cost effectiveness and availability. It has the added benefit of being able to convert analogue temperature voltages into a digital form for processing by the microcontroller. The thermal conversion had to be calibrated and an infrared thermometer (LUTRON TM2000) was used to achieve this. Due to high inrush currents during switching, the MAX6675 was initially found to be unstable. A filtering device on the input of the MAX6675 was subsequently included, which allowed the sensor to provide stable readings in digital format to the microcontroller for processing.

The design and development of the prototype controller was accomplished by using a PIC18F4220 microcontroller. The controller software was written using CCS C, a C programming language used for PIC microcontrollers. A PIC3 development board (see figure 48) was used to embed the software code in the PIC18F4220. The code is provided in annexure B.

The switching unit proved successful in harnessing the advantages of a TRIAC and a relay by reducing heat, noise and contact burn. However, if a faster control is required, then other switching devices need be considered, as the relay has a delayed activation time.

5.3 Recommendations

The use of RTD’s as sensory devices for low temperature applications (below 600°C), can be investigated in order to provide a simple interface to the microcontroller, thereby eliminating the need for the MAX6675 device. This could reduce the cost of the overall development.

Different switching methods with respect to the technique used to drive the combination switch can be re-evaluated, in order to find another technique that will help to reduce transients during higher switching speeds.

Placing the sensory device inside the oven at different positions could help to ensure a better temperature representation of the heat inside the oven. This could lead to an enhanced representation of the object's temperature inside the oven.

5.4 Other applications

The designed controller could also be used for:

- Determining and controlling temperatures in fuel cells; and
- Geyser control in solar geyser systems.

The combination switch could be used in power electronic applications, such as lighting and pump control.

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Annexure A Visual Basic 6 curing profile control program

```
Public dincnt As Integer
Public doutcnt As Integer
Public tmrcnt As Integer
Public tmrcnt1 As Integer
Public tmrcoms As Integer
Public Maxcnt As Integer
Private Sub Command1_Click()
Dim a As Integer
Exit Sub
If lblCommport.Caption < "1" Then
frmSplash.lblInfo.Caption = "Select Comm Port First ... "
frmSplash.Show
DoEvents
aa = Timer
bb = aa + 3
Do While aa < bb
DoEvents
aa = Timer
Loop
frmSplash.Hide
DoEvents
Exit Sub
End If
DoEvents
frmSplash.lblInfo.Caption = "Loading Curing Profile ... "
frmSplash.Show
DoEvents
DoEvents
Dim t As Double
Dim inc As Double
Maxcnt = 0
ghCurve.Visible = False
a = 0: inc = 1: t = 0
t = 25                                  ' Room Temperature
a = 1560 * 1.02                         ' Total number of minutes
ghCurve.ChartArea.Axes.Item(1).DataMax.Value = a
ghCurve.ChartArea.Axes.Item(1).DataMax = a
a = 0
For a = 1 To 1560                       ' Intervals in minutes
If a = 1 Then inc = 0.729
If a = 241 Then inc = 1
If a = 841 Then inc = 0
If a = 901 Then inc = -5
If a = 961 Then inc = -0.792
```

```
t = t + inc
ghCurve.ChartGroups(1).Data.Y(1, a) = t          ' Curing Plot
ghCurve.ChartGroups(2).Data.Y(1, a) = 2          ' Incoming Plot
If t > Maxcnt Then Maxcnt = t
Next a
ghCurve.ChartArea.Axes.Item(3).DataMax = Maxcnt + (Maxcnt * 0.05)
ghCurve.ChartArea.Axes.Item(2).DataMax = Maxcnt + (Maxcnt * 0.05)
ghCurve.Refresh
ghCurve.Visible = True
DoEvents
frmSplash.Hide
DoEvents
If lblCommport.Caption > "0" Then Command2.Enabled = True
End Sub
Private Sub Command2_Click()
If UCase(Command2.Caption) = "START CONTROL" Then
Command1.Enabled = False
Command2.Caption = "Stop Control"
MSComm1.CommPort = lblCommport.Caption
MSComm1.PortOpen = True
Label3.Caption = "..................": Label4.Caption = "..................": Label7.Caption = "..................": Label8.Caption =
"..................": Label9.Caption = ".................."
Label10.Caption = "..................": Label14.Caption = ".................."
Label2.Caption = "Coms Port   Open "
dincnt = 0
doutcnt = 0
tmrcnt = 0: tmrcnt1 = 0
stra = "25.00001"
Label3.Caption = stra
Label9.Caption = 1
MSComm1.Output = Trim(stra) & vbCr
tmrplot.Enabled = True
tmrComms.Enabled = True
tmrcoms = 0
Label14.Caption = Now
tmrplot_Timer
DoEvents
Exit Sub
End If
If UCase(Command2.Caption) = "STOP CONTROL" Then
Command1.Enabled = True
Command2.Caption = "Start Control"
stra = "02.00000"
DoEvents
Label3.Caption = "..................": Label4.Caption = "..................": Label7.Caption = "..................": Label8.Caption =
"..................": Label9.Caption = ".................."
Label10.Caption = ".................."
```

```
DoEvents
tmrComms.Enabled = False
tmrplot.Enabled = False
MSComm1.Output = Trim(stra) & vbCr
MSComm1.PortOpen = False
Label2.Caption = "Coms Port  Closed"
dincnt = 1
doutcnt = 0
tmrcnt = 0: tmrcnt1 = 0
tmrcoms = 0
DoEvents
Exit Sub
End If
End Sub
Private Sub set-pointcomms()
End Sub
Private Sub Label16_Click()
End Sub
Private Sub mnuExit_Click(Index As Integer)
End
End Sub
Private Sub mnuLoad_Click()
CommonDialog1.Filter = "All Files (*.*)|*.*|Text Files (*.txt)|*.txt|Batch Files (*.bat)|*.bat"    ' Specify default filter.
CommonDialog1.FilterIndex = 2    ' Display the Open dialog box.
CommonDialog1.ShowOpen   ' get a free file number
FileName = CommonDialog1.FileName
file1 = FreeFile    'open the file
If FileName = "" Then Exit Sub
DoEvents
frmSplash.lblInfo.Caption = "Loading Curing Profile ... "
frmSplash.Show
DoEvents
DoEvents
Maxcnt = 0
ghCurve.Visible = False
Open CommonDialog1.FileName For Input As file1    ' Add some text to the file
Input #file1, Profilename
lblProfileName.Caption = Profilename
Input #file1, tempmax1
ghCurve.ChartArea.Axes.Item(3).DataMax = tempmax1
Input #file1, tempmax2
ghCurve.ChartArea.Axes.Item(2).DataMax = tempmax2
Input #file1, minmax
ghCurve.ChartArea.Axes.Item(1).DataMax = minmax
Loopin:
Input #file1, i, cp, mcp
If i = "" Or i = " " Then GoTo loopout
```

```
ghCurve.ChartGroups(1).Data.Y(1, i) = Val(cp)
ghCurve.ChartGroups(2).Data.Y(1, i) = Val(mcp)
If Val(i) = Val(minmax) Then GoTo loopout
GoTo Loopin
loopout:
Close #file1
ghCurve.Refresh
ghCurve.Visible = True
DoEvents
frmSplash.Hide
DoEvents
If lblCommport.Caption > "0" Then Command2.Enabled = True
CommonDialog1.FileName = ""
FileName = ""
End Sub
Private Sub mnuNew_Click(Index As Integer)
frmCPsetup.Show
End Sub
Private Sub mnuPort_Click()
frmPort.Show
End Sub
Private Sub mnuPrint_Click()
Dim PrintDc As Long
Dim Y As Long
Dim iHeight As Long
Dim iWidth As Long
Dim iMargin As Long
Dim iSpace As Long
Dim qInfo As String
Dim qInfo1 As String
Dim qResult As Integer
'Make sure the user really wants to print the charts
qInfo = "Is it ok to print to the following printer?"
qInfo1 = Printer.DeviceName
qInfo = qInfo + Chr$(13) + """" + qInfo1 + """"
qResult = MsgBox(qInfo, 4, "OK To Print?")
If qResult = 7 Then
Exit Sub
End If
Printer.Print "                    "
Printer.Print "Curing Profile Name : " & lblProfileName.Caption     'Print header
Printer.Print "                    "
Printer.Print "                    "
Printer.Print "Date Started          : " & Label14.Caption
Printer.Print "Run Period            : " & Label11.Caption
Printer.Print "                    "
Printer.Print "Printed on            : " & Now
```

```
Printer.Print "                        "
Y = Printer.CurrentY + 10                  'Set position for line
Printer.Line (0, Y)-(Printer.ScaleWidth, Y) 'Draw a line across the page
iMargin = 1000 / Printer.TwipsPerPixelY + 400
iHeight = Printer.Height / Printer.TwipsPerPixelY - (iMargin * 2)
iWidth = Printer.Width / Printer.TwipsPerPixelX - iMargin
iSpace = 100 / Printer.TwipsPerPixelX
Result = ghCurve.DrawToDC(Printer.hDC, oc2dFormatEnhMetafile, oc2dScaleToFit, 0, Margin, iWidth, iHeight)
Printer.EndDoc
End Sub
Private Sub mnuReset_Click()
Dim a As Integer
DoEvents
frmSplash.lblInfo.Caption = "Resetting Measured Curing Profile ... "
frmSplash.Show
DoEvents
DoEvents
Maxcnt = 0
ghCurve.Visible = False
For a = 1 To Val(ghCurve.ChartArea.Axes.Item(1).DataMax.Value)
ghCurve.ChartGroups(2).Data.Y(1, a) = 2          ' Incoming Plot
Next a
ghCurve.Refresh
ghCurve.Visible = True
DoEvents
frmSplash.Hide
DoEvents
If lblCommport.Caption > "0" Then Command2.Enabled = True
End Sub
Private Sub mnuSave_Click(Index As Integer)
' Set filters.
CommonDialog1.Filter = "All Files (*.*)|*.*|Text Files (*.txt)|*.txt|Batch Files (*.bat)|*.bat"    ' Specify default filter.
CommonDialog1.FilterIndex = 2    ' Display the Open dialog box.
CommonDialog1.ShowSave ' get a free file number
FileName = CommonDialog1.FileName
file1 = FreeFile    'open the file
If FileName = "" Then Exit Sub
Open CommonDialog1.FileName For Output As file1    ' Add some text to the file
Print #file1, lblProfileName.Caption
Print #file1, (Val(ghCurve.ChartArea.Axes.Item(3).DataMax) * 1.05)
Print #file1, (Val(ghCurve.ChartArea.Axes.Item(2).DataMax) * 1.05)
Print #file1, Val(ghCurve.ChartArea.Axes.Item(1).DataMax.Value)
For i = 1 To Val(ghCurve.ChartArea.Axes.Item(1).DataMax)
If i = 1561 Then
a = a
End If
If Val(ghCurve.ChartGroups(1).Data.Y(1, i)) < 2 Then ghCurve.ChartGroups(1).Data.Y(1, i) = 2
```

```
If Val(ghCurve.ChartGroups(2).Data.Y(1, i)) < 2 Then ghCurve.ChartGroups(2).Data.Y(1, i) = 2
If Val(ghCurve.ChartGroups(2).Data.Y(1, i)) = 1E+308 Then ghCurve.ChartGroups(2).Data.Y(1, i) = 2
Print #file1, i & vbTab & "," & ghCurve.ChartGroups(1).Data.Y(1, i) & vbTab & "," &
ghCurve.ChartGroups(2).Data.Y(1, i)
Next i
Close #file1
ghCurve.Refresh
ghCurve.Visible = True
DoEvents
DoEvents
CommonDialog1.FileName = ""
FileName = ""
End Sub
Private Sub MSComm1_oncomm()
Dim str As String
Dim stra As String
Dim bufin
Dim bufins
Select Case Me.MSComm1.CommEvent
Case comEvReceive
' This is used when data is received
stra = MSComm1.Input
Label4.Caption = stra
dincnt = dincnt + 1
Label8.Caption = dincnt
tmrcoms = 0
DoEvents
If dinct = 10000 Then dicnt = 2
MSComm1.InBufferCount = 0
End Select
End Sub
Private Sub tmrComms_Timer()
tmrcoms = tmrcoms + 1
TimetoAdd = TimeValue(Now) - TimeValue(Label14.Caption)
Label11.Caption = Format(TimetoAdd, "hh:mm:ss ")
If tmrcoms = 57 Then
tmrComms.Enabled = False
tmrplot.Enabled = False
Command2_Click
frmSplash.lblInfo.Caption = "Comms Lost...... ... "
frmSplash.Show
DoEvents
aa = Timer
bb = aa + 2
Do While aa < bb
DoEvents   ' Yield to other processes.
aa = Timer
```

```
Loop
frmSplash.Hide
Label3.Caption = "..................": Label4.Caption = "..................": Label7.Caption = "..................": Label8.Caption =
"..................": Label9.Caption = ".................."
Label10.Caption = ".................."
DoEvents
DoEvents
Command2.SetFocus
End If
DoEvents
End Sub
Private Sub tmrplot_Timer()
Dim str, stra
TimetoAdd = TimeValue(Now) - TimeValue(Label14.Caption)
Label11.Caption = Format(TimetoAdd, "hh:mm:ss ")
stra = Label4.Caption
Label10.Caption = Val(Label10.Caption) + 1
For i = 1 To 10
If Mid(stra, i, 1) = "," Then GoTo hop1
Next i
hop1:
str = Val(Mid(stra, 1, i - 1))
Label7.Caption = str
If Val(str) > 2 And Val(str) < 1101 Then
ghCurve.ChartGroups(2).Data.Y(1, Val(Label10.Caption)) = str
ghCurve.Refresh
DoEvents
End If
If Val(Label10.Caption) < 2 Then
If Val(Label7.Caption) < (Val(Label3.Caption) - 0.5) Then
Label10.Caption = Val(Label10.Caption) - 1
tmrcnt = 0
'GoTo jj
End If
End If
tmrcnt = tmrcnt + 1
jj:
If tmrcnt = 1 Then
If tmrcnt1 = 0 Then
str = Mid((ghCurve.ChartGroups(1).Data.Y(1, 1)), 1, 8)
str = Round(str, 2)
For u = 1 To Len(str)
rr = Mid(str, u, 1)
If rr = "." Then GoTo hop11
Next u
str = Val(str) + 0.00001
str = Val(str)
```

```
hop11:
stra = "00000001"
Mid(stra, 1, Len(str)) = str
Label3.Caption = stra
Label9.Caption = doutcnt
If Command2.Caption = "STOP CONTROL" Then
MSComm1.Output = Trim(stra) & vbCr
If Val(Label3.Caption) > Val(Label7.Caption) - 0.5 Then
Else
dincnt = 1: doutcnt = 1
Exit Sub
End If
End If
tmrcnt1 = 111
End If
End If
If tmrcnt = 1 Then
doutcnt = doutcnt + 1
If Command2.Enabled = True Then
If doutcnt + 1 > 9363 Then doutcnt = doutcnt - 10
str = Mid((ghCurve.ChartGroups(1).Data.Y(1, doutcnt)), 1, 8)
str = Round(str, 2)
For u = 1 To Len(str)
rr = Mid(str, u, 1)
If rr = "." Then GoTo hop12
Next u
 str = Val(str) + 0.00001
 str = Val(str)
hop12:
stra = "00000001"
Mid(stra, 1, Len(str)) = str
Label3.Caption = stra
Label9.Caption = doutcnt
MSComm1.Output = (stra) & vbCr
tmrcnt = 0: tmrcnt1 = 111
End If
End If
DoEvents
End Sub
```

Annexure B PIC18F4220 CCS C program

```
#include "main.h"
#include <stdlib.h>
#include <float.h>
#include "flex_lcd.c"
#include "max6675.c"
#include "PIparameterCalc.c"

char Received[9];
char msg[8];
int16 count,cnt1,cnt2,cnt3,dd;
float D,Td,T1,K,T,Kp,Ti,a,b,c;
float value1,value,mult,set-point,rkt,ekt,pkt,pktp,ukt,qkt,max,min,pkt_1,ekt_1;
#int_rda
void handle_data(void)
{
gets(received);
set-point=atof(received);
if (set-point<1)
{
//set-point=0;
}
else
{
rkt=set-point;
}
}
void main_on()
{
output_high(PIN_a1);
delay_ms(1);
output_high(PIN_a2);
delay_ms(30);
output_low(PIN_a1);
delay_ms(1);
}
Void main_off()
{
output_high(PIN_a1);
delay_ms(1);
output_low(PIN_a2);
delay_ms(30);
output_low(PIN_a1);
delay_ms(1);
}
void main()
{
```

```
 WDT_ON;
   setup_wdt(WDT_2304MS);
setup_adc_ports(NO_ANALOGS|VSS_VDD);
setup_adc(ADC_OFF|ADC_TAD_MUL_0);
setup_psp(PSP_DISABLED);
setup_spi(SPI_SS_DISABLED);
setup_wdt(WDT_OFF);
setup_timer_0(RTCC_INTERNAL|RTCC_DIV_16|RTCC_8_bit);
setup_timer_1(T1_DISABLED);
setup_timer_2(T2_DISABLED,0,1);
setup_timer_3(T3_DISABLED|T3_DIV_BY_1);
setup_comparator(NC_NC_NC_NC);
setup_vref(FALSE);
enable_interrupts(INT_RDA);
enable_interrupts(GLOBAL);
setup_oscillator(OSC_8MHZ|OSC_TIMER1|OSC_31250|OSC_PLL_OFF);
cnt1=0;cnt2=0;cnt3=0;
lcd_init();
lcd_putc("\fGood day\n");
delay_ms(950);
lcd_putc("\fOven Control\n");
delay_ms(950);
lcd_gotoxy(1,2);
lcd_putc("Temp =       C");
T1=2400000;
T=5000;                                   //Sample time in milisecondes
Td=1000;
K=680;
Kp=(0.9*T1)/(K*Td);
Ti=3.3*Td;
//D=0.5*Td;
a=Kp;
b=Kp*(T/Ti);
//c=(Kp*D)/T;
max=1000-60-49;              //maximum on time of heater in milisecondes, 60
milisecondes for the ON/OFF of the switch and 80 milliseconds for the comms
min=1;                                    //minimum off time of heater in milisecondes
                                           // define set-point in Degrees C
set-point=2.00;
rkt=set-point;
pkt_1=0.0;
ekt_1=1.0;
count=0;
value=0;
dd=0;
do
{
```

```
hop1:
value1=0; cnt3=0;value=0;mult=0.49995;
restart_wdt();
for (cnt3=1;cnt3<=7;++cnt3)
{
value=do_everything();
value=value-49;
value1=value1+value;
}
value=value1/7;
if ((value>-1)    & (value<119))   { mult=0.5060;}    // 0  Deg to 60  Deg
if ((value>120)  & (value<262))   { mult=0.4998;}    // 60.25 Deg to 130 Deg
if ((value>263)  & (value<4003))   { mult=0.5029;}   // 130.25 Deg to 190 Deg
value=value*mult;
value=value+10.00;
sprintf(msg,"%8.2f",value);
                                                      // calculate error
   ekt=rkt-value;
                                                     // calculate i term
   pkt=(b*ekt)+pkt_1;
                                                     // calculate p term
   pktp=(a*ekt);
                                                     // calculate d term
    //qkt=c*(ekt-ekt_1);
                                                     // calculate pid output
   ukt=pkt+pktp; //+qkt;
                                                     // check min and max limits
   if (ukt>=max)
   {
   pkt=pkt_1;
   ukt=max;
   }
   else if (ukt<=min)
  {
  pkt=pkt_1;
  ukt=min;
  }
  //      LCD OUTPUT
 lcd_gotoxy(8,2);lcd_putc(msg[1]);msg[1]="";lcd_gotoxy(9,2);lcd_putc(msg[2]);msg[2]="";
 lcd_gotoxy(10,2);lcd_putc(msg[3]);msg[3]="";lcd_gotoxy(11,2);lcd_putc(msg[4]);msg[4]="";
 lcd_gotoxy(12,2);lcd_putc(msg[5]);msg[5]="";lcd_gotoxy(13,2);lcd_putc(msg[6]);msg[6]="";
 lcd_gotoxy(14,2);lcd_putc(msg[7]);msg[7]="";
 sprintf(msg,"%8.2f",set-point);
 lcd_gotoxy(17,1);lcd_putc("SetP =          C");
 lcd_gotoxy(24,1);lcd_putc(msg[1]);msg[1]="";lcd_gotoxy(25,1);lcd_putc(msg[2]);msg[2]="";
 lcd_gotoxy(26,1);lcd_putc(msg[3]);msg[3]="";lcd_gotoxy(27,1);lcd_putc(msg[4]);msg[4]="";
 lcd_gotoxy(28,1);lcd_putc(msg[5]);msg[5]="";lcd_gotoxy(29,1);lcd_putc(msg[6]);msg[6]="";
```

```
 lcd_gotoxy(30,1);lcd_putc(msg[7]);msg[7]="";
  //      LCD OUTPUT
 //      RS232   OUTPUT
printf("%08.2f",value);printf(" , ");
//printf("%08.2f",value1);printf(" , ");
printf("%09.2f",ekt);printf(" , ");
printf("%09.2f",pkt);printf(" , ");
printf("%09.0f",pktp);printf(" , ");
printf("%09.0f",qkt);printf(" , ");
printf("%09.0f",ukt);printf(" , ");
printf("%09.0f",(max-ukt));printf(":");
//printf(" \r\n");
//      RS232   OUTPUT
                                        // send control for heater switching
if (value<(rkt-3))
{
main_on();
cnt1=0;
delay_ms(1000);
cnt1=0;
main_off();
delay_ms(1);
cnt1=0;
}
if (value>(rkt+2))
{
main_off();
cnt1=0;
}
if (rkt<3)
{
output_low(PIN_a1);
output_low(PIN_a2);
cnt1=0;
}
if (ukt<1)
{
cnt1=0;
main_off();
goto hop2;
}
main_on();
cnt1=0;
delay_ms((int16)ukt);
cnt1=0;
main_off();
ay_ms((int16)max-(int16)ukt);
```

```
cnt1=0;
hop2:
                                        //save variables for use in next loop
pkt_1=pkt;
ekt_1=ekt;
output_low(PIN_a1);
output_low(PIN_a2);
value=0;
} while (dd==0); //While end
}
```

Include Files used by the controller

<main.h>

<stdlib.h>

<float.h>

<flex_lcd.c>

<max6675.c>

<PIparameterCalc.c>

Annexure C Turnitin originality report

Turnitin Originality Report

m12 by Ruaan Schoeman

From m12 (mtech)

Processed on 20-Nov-2011 3:39 AM PST
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http://www.control.hut.fi/Kurssit/AS-0.2230/tyo11/Instructions.pdf

paper text:

The temperature profile during the curing process of composite materials determines the final characteristics of the cured sample. The problem however of reproducing the same set of parameters with respect to different temperature settings for specific time periods makes for a control device to be present. Curing composite materials is normally done in an industrial oven. A heating element of low resistance generates heat which is then transferred to the material or object. This can be seen in figure 1 below, where heat from the heating element is transferred to the object inside the oven. Figure 1 Representation of electrical oven as a plant 2.2 Oven electrical equivalent model Heat is the process of energy transfer from one body or system to another due to a difference in temperature .Thermal energy can be defined as the energy of a body which increases with its temperature. Energy transfer by heat can occur between objects by radiation, conduction and/or convection (Kesidou and Duit 1993). Temperature can be used as a measure of the internal energy. Analysis of the heat flow in the oven can either be done by means of thermodynamics or by using and electrical analogy of the heat flow path. Heat flow can be modelled by an analogy to an electrical circuit seen in table 1, where heat flow is represented by current, temperatures are represented by voltages, heat sources are represented by constant current sources, thermal resistances are represented by resistors and thermal capacitances by capacitors . Table 1 Equivalence between thermal and electrical entities Thermal quantity Unit Electrical quantity Unit P, Heat flow, power W I, Current flow A Δθ, Temperature difference K V, Voltage V Rth, Thermal resistance K/W R, Electrical resistance Ω Cth, Thermal mass, capacitance J/K C, Electrical Capacitance F τth=Rth*Cth, Thermal RC constant s T = R*C, Electrical RC constant s This can be seen in figure 2 were R1 represents the thermal resistance between the heating element and the oven, R2 represents the resistance between the oven and the environment, C1 represents the heat capacity of the element, C2 represents the heat capacity of the oven, θa represents the ambient temperature of the environment, W represents the power dissipated in the heating elements, θv the oven temperature and θh represents the heating element temperature. The capacitor C1 can be neglected from the equivalent diagram as the capacity of the element to store heat is very little in comparison to that of the oven capacity to store heat. Figure 2 Electrical equivalent of thermal oven Therefore figure 3 shows the diagram that can be used as the electrical equivalent of a thermal oven with input voltage vi(t) input current i(t) and output voltage vo(t). Figure 3 Electrical equivalent of thermal oven, simplified Finding the transfer function of this circuit now becomes simplified, by applying basic electrical principals of current and voltage rules as well as the relationships between voltage, current and impedance as can be seen in table 2. Table 2 Voltage and current and current and voltage relationships, summarized The time domain equation can be found by applying Kirchhoff's voltage law: (1) Now by using table two the current flowing through the capacitor can be written (2) By substituting (2) in (1) all terms in

Annexure D NRF Nexus title search report

12/5/11 Research Projects: Guided Search Screen

>> Research Projects >> NRF Funded Research >> Forthcoming Conferences >> Professional Associations

National Research Foundation NRF

Nexus Database System | Advanced Search | Professional Search | Main Menu |

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Basic Search

Example: e business; small enterprises; shop; vendor

Title words/phrases — Title index

or

Authors — Author index

or

Institutions — Institution index

or

Titles, subjects, abstracts: Design and development of an automated temperature controller for curing o — Basic index

Limit your search

Years from 1900 *2000*   Years to 2011 *2006*

Your search did not retrieve any hits. Try using synonyms or browsing the index for suitable terms.

Hit Count: 0

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Annexure E MAX6675 datasheet

19-2235; Rev 1; 3/02

MAXIM

Cold-Junction-Compensated K-Thermocouple-to-Digital Converter (0°C to +1024°C)

MAX6675

General Description

The MAX6675 performs cold-junction compensation and digitizes the signal from a type-K thermocouple. The data is output in a 12-bit resolution, SPI™-compatible, read-only format.

This converter resolves temperatures to 0.25°C, allows readings as high as +1024°C, and exhibits thermocouple accuracy of 8LSBs for temperatures ranging from 0°C to +700°C.

The MAX6675 is available in a small, 8-pin SO package.

Applications

Industrial

Appliances

HVAC

Automotive

SPI is a trademark of Motorola, Inc.

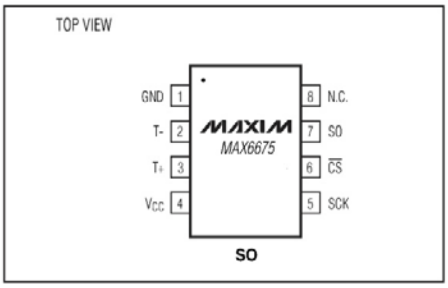
Features

- ♦ Direct Digital Conversion of Type -K Thermocouple Output
- ♦ Cold-Junction Compensation
- ♦ Simple SPI-Compatible Serial Interface
- ♦ 12-Bit, 0.25°C Resolution
- ♦ Open Thermocouple Detection

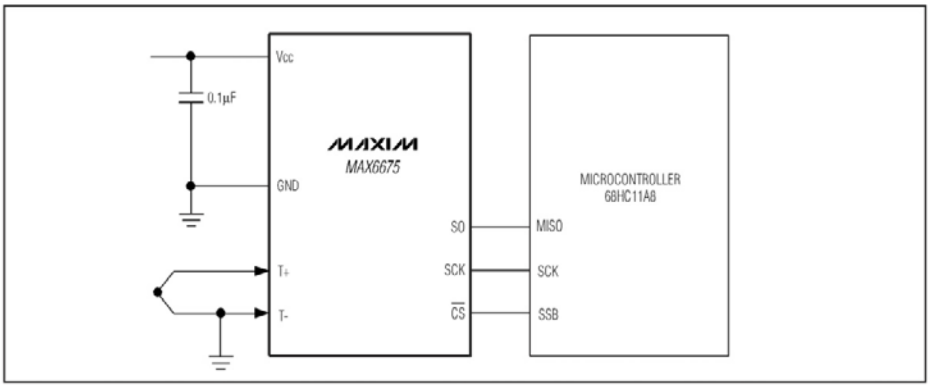
Ordering Information

PART	TEMP RANGE	PIN-PACKAGE
MAX6675ISA	-20°C to +85°C	8 SO

Pin Configuration



Typical Application Circuit



For pricing, delivery, and ordering information, please contact Maxim/Dallas Direct! at 1-888-629-4642, or visit Maxim's website at www.maxim-ic.com.

Cold-Junction-Compensated K-Thermocouple-to-Digital Converter (0°C to +1024°C)

ABSOLUTE MAXIMUM RATINGS

Supply Voltage (V_{CC} to GND) .... -0.3V to +6V
SO, SCK, $\overline{CS}$, T-, T+ to GND .... -0.3V to V_{CC} + 0.3V
SO Current 50mA
ESD Protection (Human Body Model) .... ±2000V
Continuous Power Dissipation (T_A = +70°C)
  8-Pin SO (derate 5.88mW/°C above +70°C) 471mW
Operating Temperature Range .... -20°C to +85°C
Storage Temperature Range .... -65°C to +150°C
Junction Temperature .... +150°C
SO Package
  Vapor Phase (60s) .... +215°C
  Infrared (15s) .... +220°C
Lead Temperature (soldering, 10s) .... +300°C

Stresses beyond those listed under "Absolute Maximum Ratings" may cause permanent damage to the device. These are stress ratings only, and functional operation of the device at these or any other conditions beyond those indicated in the operational sections of the specifications is not implied. Exposure to absolute maximum rating conditions for extended periods may affect device reliability.

ELECTRICAL CHARACTERISTICS

(V_{CC} = +3.0V to +5.5V, T_A = -20°C to +85°C, unless otherwise noted. Typical values specified at +25°C.) (Note 1)

PARAMETER	SYMBOL	CONDITIONS		MIN	TYP	MAX	UNITS
Temperature Error		$T_{THERMOCOUPLE}$ = +700°C, T_A = +25°C (Note 2)	V_{CC} = +3.3V	-5		+5	LSB
			V_{CC} = +5V	-6		+6	
		$T_{THERMOCOUPLE}$ = 0°C to +700°C, T_A = +25°C (Note 2)	V_{CC} = +3.3V	-8		+8	
			V_{CC} = +5V	-9		+9	
		$T_{THERMOCOUPLE}$ = +700°C to +1000°C, T_A = +25°C (Note 2)	V_{CC} = +3.3V	-17		+17	
			V_{CC} = +5V	-19		+19	
Thermocouple Conversion Constant					10.25		µV/LSB
Cold-Junction Compensation Error		T_A = -20°C to +85°C (Note 2)	V_{CC} = +3.3V	-3.0		+3.0	°C
			V_{CC} = +5V	-3.0		+3.0	
Resolution					0.25		°C
Thermocouple Input Impedance					60		kΩ
Supply Voltage	V_{CC}			3.0		5.5	V
Supply Current	I_{CC}				0.7	1.5	mA
Power-On Reset Threshold		V_{CC} rising		1	2	2.5	V
Power-On Reset Hysteresis					50		mV
Conversion Time		(Note 2)			0.17	0.22	s
SERIAL INTERFACE							
Input Low Voltage	V_{IL}					0.3 x V_{CC}	V
Input High Voltage	V_{IH}			0.7 x V_{CC}			V
Input Leakage Current	I_{LEAK}	V_{IN} = GND or V_{CC}				±5	µA
Input Capacitance	C_{IN}				5		pF

ELECTRICAL CHARACTERISTICS (continued)

(V_{CC} = +3.0V to +5.5V, T_A = -20°C to +85°C, unless otherwise noted. Typical values specified at +25°C.) (Note 1)

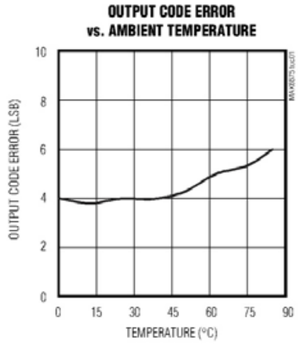
PARAMETER	SYMBOL	CONDITIONS	MIN	TYP	MAX	UNITS
Output High Voltage	V_{OH}	I_{SOURCE} = 1.6mA	V_{CC} - 0.4			V
Output Low Voltage	V_{OL}	I_{SINK} = 1.6mA			0.4	V
TIMING						
Serial Clock Frequency	f_{SCL}				4.3	MHz
SCK Pulse High Width	t_{CH}		100			ns
SCK Pulse Low Width	t_{CL}		100			ns
CSB Fall to SCK Rise	t_{CSS}	C_L = 10pF	100			ns
CSB Fall to Output Enable	t_{DV}	C_L = 10pF			100	ns
CSB Rise to Output Disable	t_{TR}	C_L = 10pF			100	ns
SCK Fall to Output Data Valid	t_{DO}	C_L = 10pF			100	ns

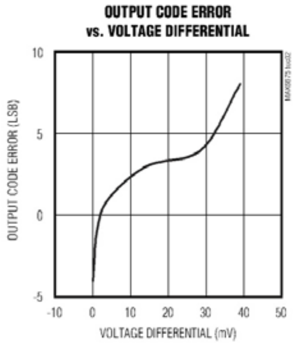
Note 1: All specifications are 100% tested at T_A = +25°C. Specification limits over temperature (T_A = T_{MIN} to T_{MAX}) are guaranteed by design and characterization, not production tested.

Note 2: Guaranteed by design. Not production tested.

Typical Operating Characteristics

(V_{CC} = +3.3V, T_A = +25°C, unless otherwise noted.)





Cold-Junction-Compensated K-Thermocouple-to-Digital Converter (0°C to +1024°C)

Pin Description

PIN	NAME	FUNCTION
1	GND	Ground
2	T-	Alumel Lead of Type-K Thermocouple. Should be connected to ground externally.
3	T+	Chromel Lead of Type-K Thermocouple
4	V_{CC}	Positive Supply. Bypass with a 0.1µF capacitor to GND.
5	SCK	Serial Clock Input
6	$\overline{CS}$	Chip Select. Set $\overline{CS}$ low to enable the serial interface.
7	SO	Serial Data Output
8	N.C.	No Connection

Detailed Description

The MAX6675 is a sophisticated thermocouple-to-digital converter with a built-in 12-bit analog-to-digital converter (ADC). The MAX6675 also contains cold-junction compensation sensing and correction, a digital controller, an SPI-compatible interface, and associated control logic.

The MAX6675 is designed to work in conjunction with an external microcontroller (µC) or other intelligence in thermostatic, process-control, or monitoring applications.

Temperature Conversion

The MAX6675 includes signal-conditioning hardware to convert the thermocouple's signal into a voltage compatible with the input channels of the ADC. The T+ and T- inputs connect to internal circuitry that reduces the introduction of noise errors from the thermocouple wires.

Before converting the thermoelectric voltages into equivalent temperature values, it is necessary to compensate for the difference between the thermocouple cold-junction side (MAX6675 ambient temperature) and a 0°C virtual reference. For a type-K thermocouple, the voltage changes by 41µV/°C, which approximates the thermocouple characteristic with the following linear equation:

$$V_{OUT} = (41\mu V / °C) \times (T_R - T_{AMB})$$

Where:

V_{OUT} is the thermocouple output voltage (µV).

T_R is the temperature of the remote thermocouple junction (°C).

T_{AMB} is the ambient temperature (°C).

Cold-Junction Compensation

The function of the thermocouple is to sense a difference in temperature between two ends of the thermocouple wires. The thermocouple's hot junction can be read from 0°C to +1023.75°C. The cold end (ambient temperature of the board on which the MAX6675 is mounted) can only range from -20°C to +85°C. While the temperature at the cold end fluctuates, the MAX6675 continues to accurately sense the temperature difference at the opposite end.

The MAX6675 senses and corrects for the changes in the ambient temperature with cold-junction compensation. The device converts the ambient temperature reading into a voltage using a temperature-sensing diode. To make the actual thermocouple temperature measurement, the MAX6675 measures the voltage from the thermocouple's output and from the sensing diode. The device's internal circuitry passes the diode's voltage (sensing ambient temperature) and thermocouple voltage (sensing remote temperature minus ambient temperature) to the conversion function stored in the ADC to calculate the thermocouple's hot-junction temperature.

Optimal performance from the MAX6675 is achieved when the thermocouple cold junction and the MAX6675 are at the same temperature. Avoid placing heat-generating devices or components near the MAX6675 because this may produce cold-junction-related errors.

Digitization

The ADC adds the cold-junction diode measurement with the amplified thermocouple voltage and reads out the 12-bit result onto the SO pin. A sequence of all zeros means the thermocouple reading is 0°C. A sequence of all ones means the thermocouple reading is +1023.75°C.

Applications Information

Serial Interface

The *Typical Application Circuit* shows the MAX6675 interfaced with a microcontroller. In this example, the MAX6675 processes the reading from the thermocouple and transmits the data through a serial interface. Force $\overline{CS}$ low and apply a clock signal at SCK to read the results at SO. Forcing $\overline{CS}$ low immediately stops any conversion process. Initiate a new conversion process by forcing $\overline{CS}$ high.

Force $\overline{CS}$ low to output the first bit on the SO pin. A complete serial interface read requires 16 clock cycles. Read the 16 output bits on the falling edge of the clock. The first bit, D15, is a dummy sign bit and is always zero. Bits D14–D3 contain the converted temperature in the order of MSB to LSB. Bit D2 is normally low and goes high when the thermocouple input is open. D1 is low to provide a device ID for the MAX6675 and bit D0 is three-state.

Figure 1a is the serial interface protocol and Figure 1b shows the serial interface timing. Figure 2 is the SO output.

Open Thermocouple

Bit D2 is normally low and goes high if the thermocouple input is open. In order to allow the operation of the open thermocouple detector, T- must be grounded. Make the ground connection as close to the GND pin as possible.

Noise Considerations

The accuracy of the MAX6675 is susceptible to power-supply coupled noise. The effects of power-supply noise can be minimized by placing a 0.1µF ceramic bypass capacitor close to the supply pin of the device.

Thermal Considerations

Self-heating degrades the temperature measurement accuracy of the MAX6675 in some applications. The magnitude of the temperature errors depends on the thermal conductivity of the MAX6675 package, the mounting technique, and the effects of airflow. Use a large ground plane to improve the temperature measurement accuracy of the MAX6675.

The accuracy of a thermocouple system can also be improved by following these precautions:

- Use the largest wire possible that does not shunt heat away from the measurement area.
- If small wire is required, use it only in the region of the measurement and use extension wire for the region with no temperature gradient.
- Avoid mechanical stress and vibration, which could strain the wires.
- When using long thermocouple wires, use a twisted-pair extension wire.
- Avoid steep temperature gradients.
- Try to use the thermocouple wire well within its temperature rating.
- Use the proper sheathing material in hostile environments to protect the thermocouple wire.
- Use extension wire only at low temperatures and only in regions of small gradients.
- Keep an event log and a continuous record of thermocouple resistance.

Reducing Effects of Pick-Up Noise

The input amplifier (A1) is a low-noise amplifier designed to enable high-precision input sensing. Keep the thermocouple and connecting wires away from electrical noise sources.

Chip Information

TRANSISTOR COUNT: 6720

PROCESS: BiCMOS

Cold-Junction-Compensated K-Thermocouple-to-Digital Converter (0°C to +1024°C)

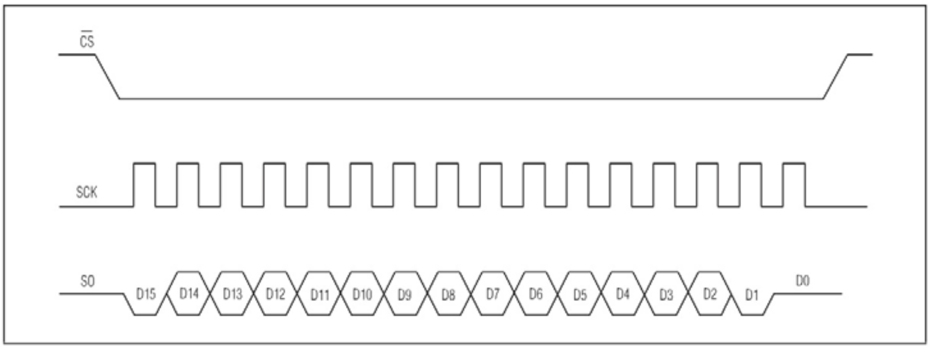


Figure 1a. Serial Interface Protocol

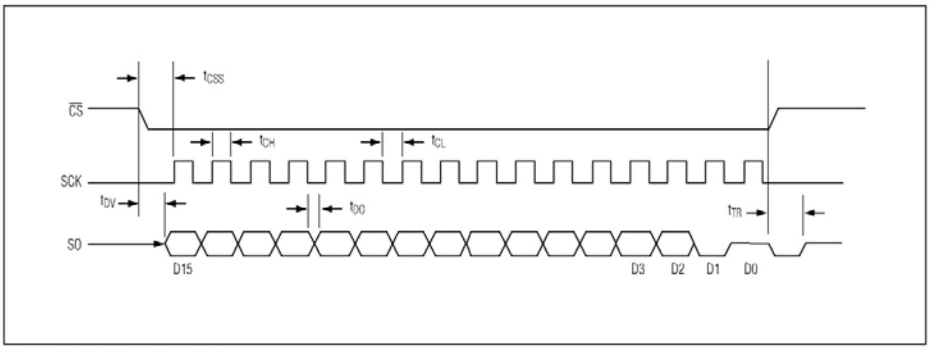
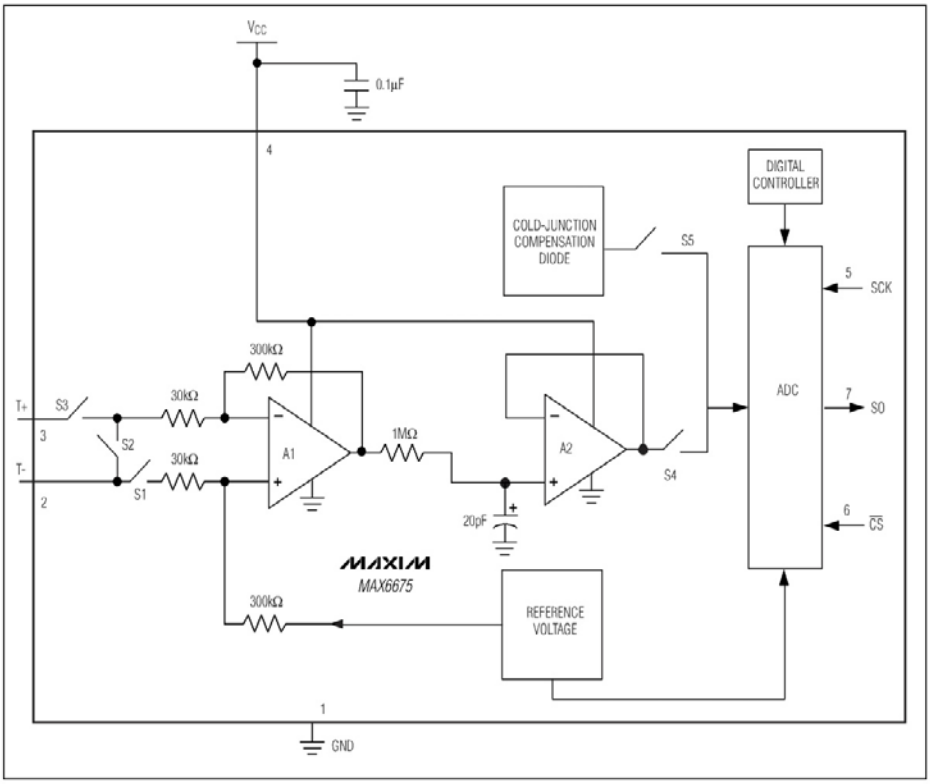


Figure 1b. Serial Interface Timing

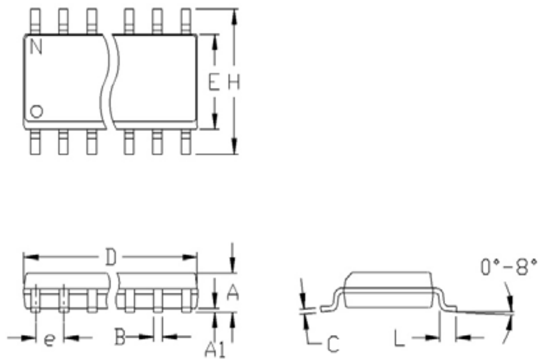
BIT	DUMMY SIGN BIT	12-BIT TEMPERATURE READING											THERMOCOUPLE INPUT	DEVICE ID	STATE
Bit	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
	0	MSB										LSB		0	Three-state

Figure 2. SO Output

Block Diagram



Package Information



	INCHES		MILLIMETERS	
	MIN	MAX	MIN	MAX
A	0.053	0.069	1.35	1.75
A1	0.004	0.010	0.10	0.25
B	0.014	0.019	0.35	0.49
C	0.007	0.010	0.19	0.25
e	0.050		1.27	
E	0.150	0.157	3.80	4.00
H	0.228	0.244	5.80	6.20
h	0.010	0.020	0.25	0.50
L	0.016	0.050	0.40	1.27

	INCHES		MILLIMETERS			
	MIN	MAX	MIN	MAX	N	MS012
D	0.189	0.197	4.80	5.00	8	A
D	0.337	0.344	8.55	8.75	14	B
D	0.386	0.394	9.80	10.00	16	C

NOTES:
1. D&E DO NOT INCLUDE MOLD FLASH
2. MOLD FLASH OR PROTRUSIONS NOT TO EXCEED .15mm (.006")
3. LEADS TO BE COPLANAR WITHIN .102mm (.004")
4. CONTROLLING DIMENSION: MILLIMETER
5. MEETS JEDEC MS012-XX AS SHOWN IN ABOVE TABLE
6. N = NUMBER OF PINS

MAXIM — PROPRIETARY INFORMATION | TITLE: PACKAGE FAMILY OUTLINE: SOIC .150" | 1/1 | DOCUMENT CONTROL NUMBER: 21-0041 | REV: A

Maxim cannot assume responsibility for use of any circuitry other than circuitry entirely embodied in a Maxim product. No circuit patent licenses are implied. Maxim reserves the right to change the circuitry and specifications without notice at any time.

Annexure F MOC3040 datasheet

MOTOROLA
Semiconductors
Boîte postale 1029 - 31023 Toulouse CEDEX - FRANCE

MOC3040
MOC3041

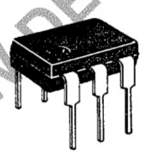
OPTO COUPLER / ISOLATOR
ZERO CROSSING TRIAC DRIVER
400 VOLTS

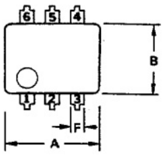
ZERO VOLTAGE CROSSING OPTICALLY ISOLATED TRIAC DRIVER

This device consists of a gallium arsenide infrared emitting diode optically coupled to a monolithic silicon detector performing the function of a Zero Voltage Crossing bilateral triac driver.

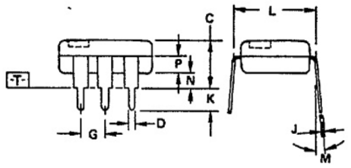
They are designed for use with a triac in the interface of logic systems to equipment powered from 220 Vac lines, such as solid-state relays, industrial controls, motors, solenoids and consumer appliances, etc.

- Simplifies Logic Control of 220 Vac Power
- Zero Voltage Crossing
- High Breakdown Voltage: V_{DRM} = 400 V Min
- High Isolation Voltage: V_{ISO} = 7500 V Min
- Small, Economical, 6-Pin DIP Package
- Same Pin Configuration as MOC3020/3021
- UL Recognized, File No. E54915
- dv/dt of 100 V/µs Typ





NOTES:
1. DIMENSIONS A AND B ARE DATUMS.
2. -T- IS SEATING PLANE.
3. POSITIONAL TOLERANCES FOR LEADS: ⌖ Ø 0.13 (0.005) Ⓜ T A Ⓜ B Ⓜ
4. DIMENSION L TO CENTER OF LEADS WHEN FORMED PARALLEL.
5. DIMENSIONING AND TOLERANCING PER ANSI Y14.5, 1973.

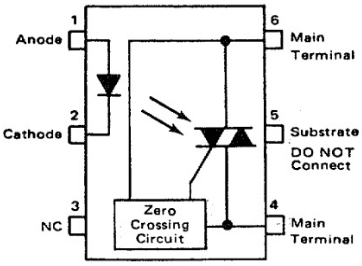


DIM	MILLIMETERS MIN	MILLIMETERS MAX	INCHES MIN	INCHES MAX
A	8.13	8.89	0.320	0.350
B	6.10	6.60	0.240	0.260
C	2.92	5.08	0.115	0.200
D	0.41	0.51	0.016	0.020
F	1.02	1.78	0.040	0.070
G	2.54 BSC		0.100 BSC	
J	0.20	0.30	0.008	0.012
K	2.54	3.81	0.100	0.150
L	7.62 BSC		0.300 BSC	
M	0°	15°	0°	15°
N	0.38	2.54	0.015	0.100
P	1.27	2.03	0.050	0.080

STYLE 6:
PIN
1. ANODE
2. CATHODE
3. NC
4. MAIN TERMINAL
5. SUBSTRATE
6. MAIN TERMINAL

CASE 730A-01

COUPLER SCHEMATIC

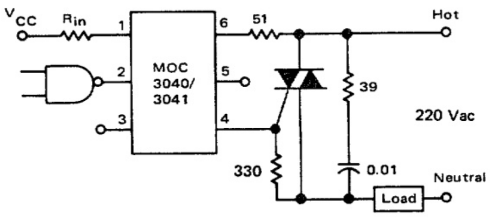


MAXIMUM RATINGS (T_A = 25°C unless otherwise noted)

Rating	Symbol	Value	Unit
INFRARED EMITTING DIODE MAXIMUM RATINGS			
Reverse Voltage	V_R	6.0	Volts
Forward Current – Continuous	I_F	50	mA
Total Power Dissipation @ T_A = 25°C Negligible Power in Output Driver Derate above 25°C	P_D	120 1.33	mW mW/°C
OUTPUT DRIVER MAXIMUM RATINGS			
Off-State Output Terminal Voltage	V_{DRM}	400	Volts
On-State RMS Current T_A = 25°C (Full Cycle, 50 to 60 Hz) T_A = 70°C	$I_{T(RMS)}$	100 50	mA mA
Peak Nonrepetitive Surge Current (PW = 10 ms)	I_{TSM}	1.2	A
Total Power Dissipation @ T_A = 25°C Derate above 25°C	P_D	300 4.0	mW mW/°C
TOTAL DEVICE MAXIMUM RATINGS			
Isolation Surge Voltage (1) (Peak ac Voltage, 60 Hz, 5 Second Duration)	V_{ISO}	7500	Vac
Total Power Dissipation @ T_A = 25°C Derate above 25°C	P_D	330 4.4	mW mW/°C
Junction Temperature Range	T_J	-40 to +100	°C
Ambient Operating Temperature Range	T_A	-40 to +70	°C
Storage Temperature Range	T_{stg}	-40 to +150	°C
Soldering Temperature (10 s)	–	260	°C

(1) Isolation surge voltage, V_{ISO}, is an internal device dielectric breakdown rating.

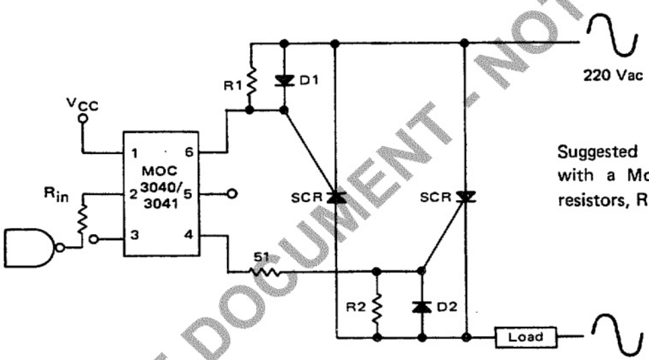
FIGURE 3 — HOT-LINE SWITCHING APPLICATION CIRCUIT



Typical circuit for use when hot line switching is required. In this circuit the "hot" side of the line is switched and the load connected to the cold or neutral side. The load may be connected to either the neutral or hot line.

R_{in} is calculated so that I_F is equal to the rated I_{FT} of the part, 15 mA for the MOC3041 or 30 mA for the MOC3040. The 39 ohm resistor and 0.01 μF capacitor are for snubbing of the triac and may or may not be necessary depending upon the particular triac and load used.

FIGURE 4 — INVERSE-PARALLEL SCR DRIVER CIRCUIT



Suggested method of firing two, back-to-back SCR's, with a Motorola triac driver. Diodes can be 1N4001; resistors, R1 and R2, are optional 330 ohms.

ELECTRICAL CHARACTERISTICS (T_A = 25°C unless otherwise noted)

Characteristic	Symbol	Min	Typ	Max	Unit
LED CHARACTERISTICS					
Reverse Leakage Current (V_R = 6.0 V)	I_R	–	0.05	100	μA
Forward Voltage (I_F = 30 mA)	V_F	–	1.3	1.5	Volts
DETECTOR CHARACTERISTICS (I_F = 0 unless otherwise noted)					
Peak Blocking Current, Either Direction (Rated V_{DRM}, Note 1)	I_{DRM1}	–	2.0	100	nA
Peak On-State Voltage, Either Direction (I_{TM} = 100 mA Peak)	V_{TM}	–	1.8	3.0	Volts
Critical Rate of Rise of Off-State Voltage	dv/dt	–	100	–	V/μs
COUPLED CHARACTERISTICS					
LED Trigger Current, Current Required to Latch Output (Main Terminal Voltage = 3.0 V, Note 2) MOC3040	I_{FT}	–	–	30	mA
MOC3041		–	–	15	
Holding Current, Either Direction	I_H	–	200	–	μA
ZERO CROSSING CHARACTERISTICS					
Inhibit Voltage (I_F = Rated I_{FT}, MT1-MT2 Voltage above which device will not trigger.)	V_{IH}	–	15	40	Volts
Leakage in Inhibited State (I_F = Rated I_{FT}, Rated V_{DRM}, Off State)	I_{DRM2}	–	100	300	μA

Note 1. Test voltage must be applied within dv/dt rating.
2. All devices are guaranteed to trigger at an I_F value less than or equal to max I_{FT}. Therefore, recommended operating I_F lies between max I_{FT} (30 mA for MOC3040, 15 mA for MOC3041) and absolute max I_F (50 mA).

TYPICAL ELECTRICAL CHARACTERISTICS

FIGURE 1 – ON-STATE CHARACTERISTICS

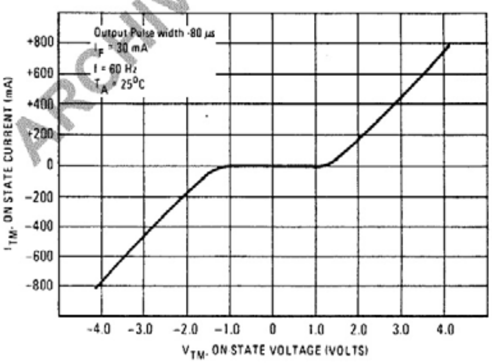
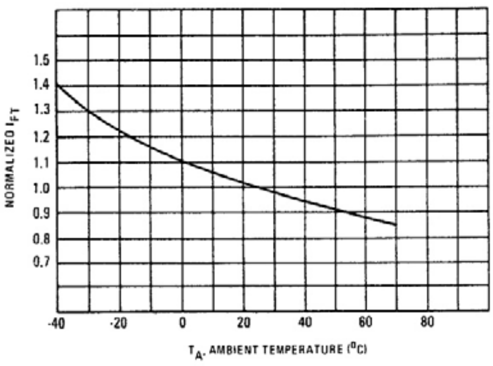


FIGURE 2 – TRIGGER CURRENT versus TEMPERATURE



Annexure G Type K-thermocouple datasheet

MAXIMUM TEMPERATURE RANGE

Thermocouple Grade
– 328 to 2282°F
– 200 to 1250°C

Extension Grade
32 to 392°F
0 to 200°C

LIMITS OF ERROR
(whichever is greater)
Standard: 2.2°C or 0.75% Above 0°C
2.2°C or 2.0% Below 0°C
Special: 1.1°C or 0.4%

COMMENTS, BARE WIRE ENVIRONMENT:
Clean Oxidizing and Inert; Limited Use in Vacuum or Reducing; Wide Temperature Range; Most Popular Calibration

TEMPERATURE IN DEGREES °F
REFERENCE JUNCTION AT 32°F

Thermocouple Grade

Nickel-Chromium
vs.
Nickel-Aluminum

Extension Grade

Revised Thermocouple Reference Tables

TYPE K

Reference Tables
N.I.S.T.
Monograph 175
Revised to
ITS-90

Z

Thermoelectric Voltage in Millivolts

°F	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	°F
-450							-6.458	-6.457	-6.457	-6.456	-6.456	-450
-440	-6.456	-6.455	-6.454	-6.454	-6.453	-6.452	-6.451	-6.450	-6.449	-6.448	-6.446	-440
-430	-6.446	-6.445	-6.444	-6.443	-6.441	-6.440	-6.438	-6.436	-6.435	-6.433	-6.431	-430
-420	-6.431	-6.429	-6.427	-6.425	-6.423	-6.421	-6.419	-6.416	-6.414	-6.411	-6.409	-420
-410	-6.409	-6.406	-6.404	-6.401	-6.398	-6.395	-6.392	-6.389	-6.386	-6.383	-6.380	-410
-400	-6.380	-6.377	-6.373	-6.370	-6.366	-6.363	-6.359	-6.355	-6.352	-6.348	-6.344	-400
-390	-6.344	-6.340	-6.336	-6.332	-6.328	-6.323	-6.319	-6.315	-6.310	-6.306	-6.301	-390
-380	-6.301	-6.296	-6.292	-6.287	-6.282	-6.277	-6.272	-6.267	-6.262	-6.257	-6.251	-380
-370	-6.251	-6.246	-6.241	-6.235	-6.230	-6.224	-6.218	-6.213	-6.207	-6.201	-6.195	-370
-360	-6.195	-6.189	-6.183	-6.177	-6.171	-6.165	-6.158	-6.152	-6.146	-6.139	-6.133	-360
-350	-6.133	-6.126	-6.119	-6.113	-6.106	-6.099	-6.092	-6.085	-6.078	-6.071	-6.064	-350
-340	-6.064	-6.057	-6.049	-6.042	-6.035	-6.027	-6.020	-6.012	-6.004	-5.997	-5.989	-340
-330	-5.989	-5.981	-5.973	-5.965	-5.957	-5.949	-5.941	-5.933	-5.925	-5.917	-5.908	-330
-320	-5.908	-5.900	-5.891	-5.883	-5.874	-5.866	-5.857	-5.848	-5.840	-5.831	-5.822	-320
-310	-5.822	-5.813	-5.804	-5.795	-5.786	-5.776	-5.767	-5.758	-5.749	-5.739	-5.730	-310
-300	-5.730	-5.720	-5.711	-5.701	-5.691	-5.682	-5.672	-5.662	-5.652	-5.642	-5.632	-300
-290	-5.632	-5.622	-5.612	-5.602	-5.592	-5.581	-5.571	-5.561	-5.550	-5.540	-5.529	-290
-280	-5.529	-5.519	-5.508	-5.497	-5.487	-5.476	-5.465	-5.454	-5.443	-5.432	-5.421	-280
-270	-5.421	-5.410	-5.399	-5.388	-5.377	-5.365	-5.354	-5.343	-5.331	-5.320	-5.308	-270
-260	-5.308	-5.296	-5.285	-5.273	-5.261	-5.250	-5.238	-5.226	-5.214	-5.202	-5.190	-260
-250	-5.190	-5.178	-5.166	-5.153	-5.141	-5.129	-5.117	-5.104	-5.092	-5.079	-5.067	-250
-240	-5.067	-5.054	-5.042	-5.029	-5.016	-5.003	-4.991	-4.978	-4.965	-4.952	-4.939	-240
-230	-4.939	-4.926	-4.913	-4.900	-4.886	-4.873	-4.860	-4.847	-4.833	-4.820	-4.806	-230
-220	-4.806	-4.793	-4.779	-4.766	-4.752	-4.738	-4.724	-4.711	-4.697	-4.683	-4.669	-220
-210	-4.669	-4.655	-4.641	-4.627	-4.613	-4.599	-4.584	-4.570	-4.556	-4.542	-4.527	-210
-200	-4.527	-4.513	-4.498	-4.484	-4.469	-4.455	-4.440	-4.425	-4.411	-4.396	-4.381	-200
-190	-4.381	-4.366	-4.351	-4.336	-4.321	-4.306	-4.291	-4.276	-4.261	-4.246	-4.231	-190
-180	-4.231	-4.215	-4.200	-4.185	-4.169	-4.154	-4.138	-4.123	-4.107	-4.091	-4.076	-180
-170	-4.076	-4.060	-4.044	-4.029	-4.013	-3.997	-3.981	-3.965	-3.949	-3.933	-3.917	-170
-160	-3.917	-3.901	-3.885	-3.869	-3.852	-3.836	-3.820	-3.803	-3.787	-3.771	-3.754	-160
-150	-3.754	-3.738	-3.721	-3.705	-3.688	-3.671	-3.655	-3.638	-3.621	-3.604	-3.587	-150
-140	-3.587	-3.571	-3.554	-3.537	-3.520	-3.503	-3.486	-3.468	-3.451	-3.434	-3.417	-140
-130	-3.417	-3.400	-3.382	-3.365	-3.348	-3.330	-3.313	-3.295	-3.278	-3.260	-3.243	-130
-120	-3.243	-3.225	-3.207	-3.190	-3.172	-3.154	-3.136	-3.119	-3.101	-3.083	-3.065	-120
-110	-3.065	-3.047	-3.029	-3.011	-2.993	-2.975	-2.957	-2.938	-2.920	-2.902	-2.884	-110
-100	-2.884	-2.865	-2.847	-2.829	-2.810	-2.792	-2.773	-2.755	-2.736	-2.718	-2.699	-100
-90	-2.699	-2.680	-2.662	-2.643	-2.624	-2.605	-2.587	-2.568	-2.549	-2.530	-2.511	-90
-80	-2.511	-2.492	-2.473	-2.454	-2.435	-2.416	-2.397	-2.378	-2.359	-2.339	-2.320	-80
-70	-2.320	-2.301	-2.282	-2.262	-2.243	-2.223	-2.204	-2.185	-2.165	-2.146	-2.126	-70
-60	-2.126	-2.106	-2.087	-2.067	-2.048	-2.028	-2.008	-1.988	-1.969	-1.949	-1.929	-60
-50	-1.929	-1.909	-1.889	-1.869	-1.850	-1.830	-1.810	-1.790	-1.770	-1.749	-1.729	-50
-40	-1.729	-1.709	-1.689	-1.669	-1.649	-1.628	-1.608	-1.588	-1.568	-1.547	-1.527	-40
-30	-1.527	-1.507	-1.486	-1.466	-1.445	-1.425	-1.404	-1.384	-1.363	-1.343	-1.322	-30
-20	-1.322	-1.301	-1.281	-1.260	-1.239	-1.218	-1.198	-1.177	-1.156	-1.135	-1.114	-20
-10	-1.114	-1.094	-1.073	-1.052	-1.031	-1.010	-0.989	-0.968	-0.947	-0.926	-0.905	-10
0	-0.905	-0.883	-0.862	-0.841	-0.820	-0.799	-0.778	-0.756	-0.735	-0.714	-0.692	0

°F	0	1	2	3	4	5	6	7	8	9	10	°F
0	-0.692	-0.671	-0.650	-0.628	-0.607	-0.586	-0.564	-0.543	-0.521	-0.500	-0.478	0
10	-0.478	-0.457	-0.435	-0.413	-0.392	-0.370	-0.349	-0.327	-0.305	-0.284	-0.262	10
20	-0.262	-0.240	-0.218	-0.197	-0.175	-0.153	-0.131	-0.109	-0.088	-0.066	-0.044	20
30	-0.044	-0.022	0.000	0.022	0.044	0.066	0.088	0.110	0.132	0.154	0.176	30
40	0.176	0.198	0.220	0.242	0.264	0.286	0.308	0.330	0.353	0.375	0.397	40
50	0.397	0.419	0.441	0.463	0.486	0.508	0.530	0.552	0.575	0.597	0.619	50
60	0.619	0.642	0.664	0.686	0.709	0.731	0.753	0.776	0.798	0.821	0.843	60
70	0.843	0.865	0.888	0.910	0.933	0.955	0.978	1.000	1.023	1.045	1.068	70
80	1.068	1.090	1.113	1.136	1.158	1.181	1.203	1.226	1.249	1.271	1.294	80
90	1.294	1.316	1.339	1.362	1.384	1.407	1.430	1.453	1.475	1.498	1.521	90
°F	0	1	2	3	4	5	6	7	8	9	10	°F

°F	0	1	2	3	4	5	6	7	8	9	10	°F
100	1.521	1.543	1.566	1.589	1.612	1.635	1.657	1.680	1.703	1.726	1.749	100
110	1.749	1.771	1.794	1.817	1.840	1.863	1.886	1.909	1.931	1.954	1.977	110
120	1.977	2.000	2.023	2.046	2.069	2.092	2.115	2.138	2.161	2.184	2.207	120
130	2.207	2.230	2.253	2.276	2.298	2.321	2.344	2.367	2.390	2.413	2.436	130
140	2.436	2.459	2.483	2.506	2.529	2.552	2.575	2.598	2.621	2.644	2.667	140
150	2.667	2.690	2.713	2.736	2.759	2.782	2.805	2.828	2.851	2.874	2.897	150
160	2.897	2.920	2.944	2.967	2.990	3.013	3.036	3.059	3.082	3.105	3.128	160
170	3.128	3.151	3.174	3.197	3.220	3.244	3.267	3.290	3.313	3.336	3.359	170
180	3.359	3.382	3.405	3.428	3.451	3.474	3.497	3.520	3.544	3.567	3.590	180
190	3.590	3.613	3.636	3.659	3.682	3.705	3.728	3.751	3.774	3.797	3.820	190
200	3.820	3.843	3.866	3.889	3.912	3.935	3.958	3.981	4.004	4.027	4.050	200
210	4.050	4.073	4.096	4.119	4.142	4.165	4.188	4.211	4.234	4.257	4.280	210
220	4.280	4.303	4.326	4.349	4.372	4.395	4.417	4.440	4.463	4.486	4.509	220
230	4.509	4.532	4.555	4.578	4.601	4.623	4.646	4.669	4.692	4.715	4.738	230
240	4.738	4.760	4.783	4.806	4.829	4.852	4.874	4.897	4.920	4.943	4.965	240
250	4.965	4.988	5.011	5.034	5.056	5.079	5.102	5.124	5.147	5.170	5.192	250
260	5.192	5.215	5.238	5.260	5.283	5.306	5.328	5.351	5.374	5.396	5.419	260
270	5.419	5.441	5.464	5.487	5.509	5.532	5.554	5.577	5.599	5.622	5.644	270
280	5.644	5.667	5.690	5.712	5.735	5.757	5.779	5.802	5.824	5.847	5.869	280
290	5.869	5.892	5.914	5.937	5.959	5.982	6.004	6.026	6.049	6.071	6.094	290
300	6.094	6.116	6.138	6.161	6.183	6.205	6.228	6.250	6.272	6.295	6.317	300
310	6.317	6.339	6.362	6.384	6.406	6.429	6.451	6.473	6.496	6.518	6.540	310
320	6.540	6.562	6.585	6.607	6.629	6.652	6.674	6.696	6.718	6.741	6.763	320
330	6.763	6.785	6.807	6.829	6.852	6.874	6.896	6.918	6.941	6.963	6.985	330
340	6.985	7.007	7.029	7.052	7.074	7.096	7.118	7.140	7.163	7.185	7.207	340
350	7.207	7.229	7.251	7.273	7.296	7.318	7.340	7.362	7.384	7.407	7.429	350
360	7.429	7.451	7.473	7.495	7.517	7.540	7.562	7.584	7.606	7.628	7.650	360
370	7.650	7.673	7.695	7.717	7.739	7.761	7.783	7.806	7.828	7.850	7.872	370
380	7.872	7.894	7.917	7.939	7.961	7.983	8.005	8.027	8.050	8.072	8.094	380
390	8.094	8.116	8.138	8.161	8.183	8.205	8.227	8.250	8.272	8.294	8.316	390
400	8.316	8.338	8.361	8.383	8.405	8.427	8.450	8.472	8.494	8.516	8.539	400
410	8.539	8.561	8.583	8.605	8.628	8.650	8.672	8.694	8.717	8.739	8.761	410
420	8.761	8.784	8.806	8.828	8.851	8.873	8.895	8.918	8.940	8.962	8.985	420
430	8.985	9.007	9.029	9.052	9.074	9.096	9.119	9.141	9.163	9.186	9.208	430
440	9.208	9.231	9.253	9.275	9.298	9.320	9.343	9.365	9.388	9.410	9.432	440
450	9.432	9.455	9.477	9.500	9.522	9.545	9.567	9.590	9.612	9.635	9.657	450
460	9.657	9.680	9.702	9.725	9.747	9.770	9.792	9.815	9.837	9.860	9.882	460
470	9.882	9.905	9.927	9.950	9.973	9.995	10.018	10.040	10.063	10.086	10.108	470
480	10.108	10.131	10.153	10.176	10.199	10.221	10.244	10.267	10.289	10.312	10.334	480
490	10.334	10.357	10.380	10.402	10.425	10.448	10.471	10.493	10.516	10.539	10.561	490
500	10.561	10.584	10.607	10.629	10.652	10.675	10.698	10.720	10.743	10.766	10.789	500
510	10.789	10.811	10.834	10.857	10.880	10.903	10.926	10.948	10.971	10.994	11.017	510
520	11.017	11.039	11.062	11.085	11.108	11.131	11.154	11.176	11.199	11.222	11.245	520
530	11.245	11.268	11.291	11.313	11.336	11.359	11.382	11.405	11.428	11.451	11.474	530
540	11.474	11.497	11.519	11.542	11.565	11.588	11.611	11.634	11.657	11.680	11.703	540
550	11.703	11.726	11.749	11.772	11.795	11.818	11.841	11.864	11.887	11.910	11.933	550
560	11.933	11.956	11.978	12.001	12.024	12.047	12.070	12.093	12.116	12.140	12.163	560
570	12.163	12.186	12.209	12.232	12.255	12.278	12.301	12.324	12.347	12.370	12.393	570
580	12.393	12.416	12.439	12.462	12.485	12.508	12.531	12.554	12.577	12.600	12.624	580
590	12.624	12.647	12.670	12.693	12.716	12.739	12.762	12.785	12.808	12.831	12.855	590
600	12.855	12.878	12.901	12.924	12.947	12.970	12.993	13.016	13.040	13.063	13.086	600
610	13.086	13.109	13.132	13.155	13.179	13.202	13.225	13.248	13.271	13.294	13.318	610
620	13.318	13.341	13.364	13.387	13.410	13.433	13.457	13.480	13.503	13.526	13.549	620
630	13.549	13.573	13.596	13.619	13.642	13.665	13.689	13.712	13.735	13.758	13.782	630
640	13.782	13.805	13.828	13.851	13.874	13.898	13.921	13.944	13.967	13.991	14.014	640
650	14.014	14.037	14.060	14.084	14.107	14.130	14.154	14.177	14.200	14.223	14.247	650
660	14.247	14.270	14.293	14.316	14.340	14.363	14.386	14.410	14.433	14.456	14.479	660
670	14.479	14.503	14.526	14.549	14.573	14.596	14.619	14.643	14.666	14.689	14.713	670
680	14.713	14.736	14.759	14.783	14.806	14.829	14.853	14.876	14.899	14.923	14.946	680
690	14.946	14.969	14.993	15.016	15.039	15.063	15.086	15.109	15.133	15.156	15.179	690
°F	0	1	2	3	4	5	6	7	8	9	10	°F

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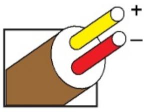
Revised Thermocouple Reference Tables

TYPE K

Reference Tables N.I.S.T. Monograph 175 Revised to ITS-90



Thermocouple Grade

Nickel-Chromium vs. Nickel-Aluminum

Extension Grade

MAXIMUM TEMPERATURE RANGE

Thermocouple Grade
– 328 to 2282°F
– 200 to 1250°C

Extension Grade
32 to 392°F
0 to 200°C

LIMITS OF ERROR
(whichever is greater)
Standard: 2.2°C or 0.75% Above 0°C
2.2°C or 2.0% Below 0°C
Special: 1.1°C or 0.4%

COMMENTS, BARE WIRE ENVIRONMENT:
Clean Oxidizing and Inert; Limited Use in Vacuum or Reducing; Wide Temperature Range; Most Popular Calibration

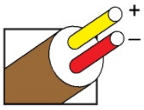
TEMPERATURE IN DEGREES °F
REFERENCE JUNCTION AT 32°F

Thermoelectric Voltage in Millivolts

°F	0	1	2	3	4	5	6	7	8	9	10	°F
700	15.179	15.203	15.226	15.250	15.273	15.296	15.320	15.343	15.366	15.390	15.413	700
710	15.413	15.437	15.460	15.483	15.507	15.530	15.554	15.577	15.600	15.624	15.647	710
720	15.647	15.671	15.694	15.717	15.741	15.764	15.788	15.811	15.834	15.858	15.881	720
730	15.881	15.905	15.928	15.952	15.975	15.998	16.022	16.045	16.069	16.092	16.116	730
740	16.116	16.139	16.163	16.186	16.209	16.233	16.256	16.280	16.303	16.327	16.350	740
750	16.350	16.374	16.397	16.421	16.444	16.468	16.491	16.514	16.538	16.561	16.585	750
760	16.585	16.608	16.632	16.655	16.679	16.702	16.726	16.749	16.773	16.796	16.820	760
770	16.820	16.843	16.867	16.890	16.914	16.937	16.961	16.984	17.008	17.031	17.055	770
780	17.055	17.078	17.102	17.125	17.149	17.173	17.196	17.220	17.243	17.267	17.290	780
790	17.290	17.314	17.337	17.361	17.384	17.408	17.431	17.455	17.478	17.502	17.526	790
800	17.526	17.549	17.573	17.596	17.620	17.643	17.667	17.690	17.714	17.738	17.761	800
810	17.761	17.785	17.808	17.832	17.855	17.879	17.902	17.926	17.950	17.973	17.997	810
820	17.997	18.020	18.044	18.068	18.091	18.115	18.138	18.162	18.185	18.209	18.233	820
830	18.233	18.256	18.280	18.303	18.327	18.351	18.374	18.398	18.421	18.445	18.469	830
840	18.469	18.492	18.516	18.539	18.563	18.587	18.610	18.634	18.657	18.681	18.705	840
850	18.705	18.728	18.752	18.776	18.799	18.823	18.846	18.870	18.894	18.917	18.941	850
860	18.941	18.965	18.988	19.012	19.035	19.059	19.083	19.106	19.130	19.154	19.177	860
870	19.177	19.201	19.224	19.248	19.272	19.295	19.319	19.343	19.366	19.390	19.414	870
880	19.414	19.437	19.461	19.485	19.508	19.532	19.556	19.579	19.603	19.626	19.650	880
890	19.650	19.674	19.697	19.721	19.745	19.768	19.792	19.816	19.839	19.863	19.887	890
900	19.887	19.910	19.934	19.958	19.981	20.005	20.029	20.052	20.076	20.100	20.123	900
910	20.123	20.147	20.171	20.194	20.218	20.242	20.265	20.289	20.313	20.336	20.360	910
920	20.360	20.384	20.407	20.431	20.455	20.479	20.502	20.526	20.550	20.573	20.597	920
930	20.597	20.621	20.644	20.668	20.692	20.715	20.739	20.763	20.786	20.810	20.834	930
940	20.834	20.857	20.881	20.905	20.929	20.952	20.976	21.000	21.023	21.047	21.071	940
950	21.071	21.094	21.118	21.142	21.165	21.189	21.213	21.236	21.260	21.284	21.308	950
960	21.308	21.331	21.355	21.379	21.402	21.426	21.450	21.473	21.497	21.521	21.544	960
970	21.544	21.568	21.592	21.616	21.639	21.663	21.687	21.710	21.734	21.758	21.781	970
980	21.781	21.805	21.829	21.852	21.876	21.900	21.924	21.947	21.971	21.995	22.018	980
990	22.018	22.042	22.066	22.089	22.113	22.137	22.160	22.184	22.208	22.232	22.255	990
1000	22.255	22.279	22.303	22.326	22.350	22.374	22.397	22.421	22.445	22.468	22.492	1000
1010	22.492	22.516	22.540	22.563	22.587	22.611	22.634	22.658	22.682	22.705	22.729	1010
1020	22.729	22.753	22.776	22.800	22.824	22.847	22.871	22.895	22.919	22.942	22.966	1020
1030	22.966	22.990	23.013	23.037	23.061	23.084	23.108	23.132	23.155	23.179	23.203	1030
1040	23.203	23.226	23.250	23.274	23.297	23.321	23.345	23.368	23.392	23.416	23.439	1040
1050	23.439	23.463	23.487	23.510	23.534	23.558	23.581	23.605	23.629	23.652	23.676	1050
1060	23.676	23.700	23.723	23.747	23.771	23.794	23.818	23.842	23.865	23.889	23.913	1060
1070	23.913	23.936	23.960	23.984	24.007	24.031	24.055	24.078	24.102	24.126	24.149	1070
1080	24.149	24.173	24.197	24.220	24.244	24.267	24.291	24.315	24.338	24.362	24.386	1080
1090	24.386	24.409	24.433	24.457	24.480	24.504	24.527	24.551	24.575	24.598	24.622	1090
1100	24.622	24.646	24.669	24.693	24.717	24.740	24.764	24.787	24.811	24.835	24.858	1100
1110	24.858	24.882	24.905	24.929	24.953	24.976	25.000	25.024	25.047	25.071	25.094	1110
1120	25.094	25.118	25.142	25.165	25.189	25.212	25.236	25.260	25.283	25.307	25.330	1120
1130	25.330	25.354	25.377	25.401	25.425	25.448	25.472	25.495	25.519	25.543	25.566	1130
1140	25.566	25.590	25.613	25.637	25.660	25.684	25.708	25.731	25.755	25.778	25.802	1140
1150	25.802	25.825	25.849	25.873	25.896	25.920	25.943	25.967	25.990	26.014	26.037	1150
1160	26.037	26.061	26.084	26.108	26.132	26.155	26.179	26.202	26.226	26.249	26.273	1160
1170	26.273	26.296	26.320	26.343	26.367	26.390	26.414	26.437	26.461	26.484	26.508	1170
1180	26.508	26.532	26.555	26.579	26.602	26.626	26.649	26.673	26.696	26.720	26.743	1180
1190	26.743	26.767	26.790	26.814	26.837	26.861	26.884	26.907	26.931	26.954	26.978	1190
1200	26.978	27.001	27.025	27.048	27.072	27.095	27.119	27.142	27.166	27.189	27.213	1200
1210	27.213	27.236	27.259	27.283	27.306	27.330	27.353	27.377	27.400	27.424	27.447	1210
1220	27.447	27.471	27.494	27.517	27.541	27.564	27.588	27.611	27.635	27.658	27.681	1220
1230	27.681	27.705	27.728	27.752	27.775	27.798	27.822	27.845	27.869	27.892	27.915	1230
1240	27.915	27.939	27.962	27.986	28.009	28.032	28.056	28.079	28.103	28.126	28.149	1240
1250	28.149	28.173	28.196	28.219	28.243	28.266	28.289	28.313	28.336	28.360	28.383	1250
1260	28.383	28.406	28.430	28.453	28.476	28.500	28.523	28.546	28.570	28.593	28.616	1260
1270	28.616	28.640	28.663	28.686	28.710	28.733	28.756	28.780	28.803	28.826	28.849	1270
1280	28.849	28.873	28.896	28.919	28.943	28.966	28.989	29.013	29.036	29.059	29.082	1280
1290	29.082	29.106	29.129	29.152	29.176	29.199	29.222	29.245	29.269	29.292	29.315	1290
°F	0	1	2	3	4	5	6	7	8	9	10	°F

°F	0	1	2	3	4	5	6	7	8	9	10	°F
1300	29.315	29.338	29.362	29.385	29.408	29.431	29.455	29.478	29.501	29.524	29.548	1300
1310	29.548	29.571	29.594	29.617	29.640	29.664	29.687	29.710	29.733	29.757	29.780	1310
1320	29.780	29.803	29.826	29.849	29.873	29.896	29.919	29.942	29.965	29.989	30.012	1320
1330	30.012	30.035	30.058	30.081	30.104	30.128	30.151	30.174	30.197	30.220	30.243	1330
1340	30.243	30.267	30.290	30.313	30.336	30.359	30.382	30.405	30.429	30.452	30.475	1340
1350	30.475	30.498	30.521	30.544	30.567	30.590	30.613	30.637	30.660	30.683	30.706	1350
1360	30.706	30.729	30.752	30.775	30.798	30.821	30.844	30.868	30.891	30.914	30.937	1360
1370	30.937	30.960	30.983	31.006	31.029	31.052	31.075	31.098	31.121	31.144	31.167	1370
1380	31.167	31.190	31.213	31.236	31.260	31.283	31.306	31.329	31.352	31.375	31.398	1380
1390	31.398	31.421	31.444	31.467	31.490	31.513	31.536	31.559	31.582	31.605	31.628	1390
1400	31.628	31.651	31.674	31.697	31.720	31.743	31.766	31.789	31.812	31.834	31.857	1400
1410	31.857	31.880	31.903	31.926	31.949	31.972	31.995	32.018	32.041	32.064	32.087	1410
1420	32.087	32.110	32.133	32.156	32.179	32.202	32.224	32.247	32.270	32.293	32.316	1420
1430	32.316	32.339	32.362	32.385	32.408	32.431	32.453	32.476	32.499	32.522	32.545	1430
1440	32.545	32.568	32.591	32.614	32.636	32.659	32.682	32.705	32.728	32.751	32.774	1440
1450	32.774	32.796	32.819	32.842	32.865	32.888	32.911	32.933	32.956	32.979	33.002	1450
1460	33.002	33.025	33.047	33.070	33.093	33.116	33.139	33.161	33.184	33.207	33.230	1460
1470	33.230	33.253	33.275	33.298	33.321	33.344	33.366	33.389	33.412	33.435	33.458	1470
1480	33.458	33.480	33.503	33.526	33.548	33.571	33.594	33.617	33.639	33.662	33.685	1480
1490	33.685	33.708	33.730	33.753	33.776	33.798	33.821	33.844	33.867	33.889	33.912	1490
1500	33.912	33.935	33.957	33.980	34.003	34.025	34.048	34.071	34.093	34.116	34.139	1500
1510	34.139	34.161	34.184	34.207	34.229	34.252	34.275	34.297	34.320	34.343	34.365	1510
1520	34.365	34.388	34.410	34.433	34.456	34.478	34.501	34.524	34.546	34.569	34.591	1520
1530	34.591	34.614	34.637	34.659	34.682	34.704	34.727	34.750	34.772	34.795	34.817	1530
1540	34.817	34.840	34.862	34.885	34.908	34.930	34.953	34.975	34.998	35.020	35.043	1540
1550	35.043	35.065	35.088	35.110	35.133	35.156	35.178	35.201	35.223	35.246	35.268	1550
1560	35.268	35.291	35.313	35.336	35.358	35.381	35.403	35.426	35.448	35.471	35.493	1560
1570	35.493	35.516	35.538	35.560	35.583	35.605	35.628	35.650	35.673	35.695	35.718	1570
1580	35.718	35.740	35.763	35.785	35.807	35.830	35.852	35.875	35.897	35.920	35.942	1580
1590	35.942	35.964	35.987	36.009	36.032	36.054	36.076	36.099	36.121	36.144	36.166	1590
1600	36.166	36.188	36.211	36.233	36.256	36.278	36.300	36.323	36.345	36.367	36.390	1600
1610	36.390	36.412	36.434	36.457	36.479	36.501	36.524	36.546	36.568	36.591	36.613	1610
1620	36.613	36.635	36.658	36.680	36.702	36.725	36.747	36.769	36.792	36.814	36.836	1620
1630	36.836	36.859	36.881	36.903	36.925	36.948	36.970	36.992	37.014	37.037	37.059	1630
1640	37.059	37.081	37.104	37.126	37.148	37.170	37.193	37.215	37.237	37.259	37.281	1640
1650	37.281	37.304	37.326	37.348	37.370	37.393	37.415	37.437	37.459	37.481	37.504	1650
1660	37.504	37.526	37.548	37.570	37.592	37.615	37.637	37.659	37.681	37.703	37.725	1660
1670	37.725	37.748	37.770	37.792	37.814	37.836	37.858	37.881	37.903	37.925	37.947	1670
1680	37.947	37.969	37.991	38.013	38.036	38.058	38.080	38.102	38.124	38.146	38.168	1680
1690	38.168	38.190	38.212	38.235	38.257	38.279	38.301	38.323	38.345	38.367	38.389	1690
1700	38.389	38.411	38.433	38.455	38.477	38.499	38.522	38.544	38.566	38.588	38.610	1700
1710	38.610	38.632	38.654	38.676	38.698	38.720	38.742	38.764	38.786	38.808	38.830	1710
1720	38.830	38.852	38.874	38.896	38.918	38.940	38.962	38.984	39.006	39.028	39.050	1720
1730	39.050	39.072	39.094	39.116	39.138	39.160	39.182	39.204	39.226	39.248	39.270	1730
1740	39.270	39.292	39.314	39.335	39.357	39.379	39.401	39.423	39.445	39.467	39.489	1740
1750	39.489	39.511	39.533	39.555	39.577	39.599	39.620	39.642	39.664	39.686	39.708	1750
1760	39.708	39.730	39.752	39.774	39.796	39.817	39.839	39.861	39.883	39.905	39.927	1760
1770	39.927	39.949	39.970	39.992	40.014	40.036	40.058	40.080	40.101	40.123	40.145	1770
1780	40.145	40.167	40.189	40.211	40.232	40.254	40.276	40.298	40.320	40.341	40.363	1780
1790	40.363	40.385	40.407	40.429	40.450	40.472	40.494	40.516	40.537	40.559	40.581	1790
1800	40.581	40.603	40.624	40.646	40.668	40.690	40.711	40.733	40.755	40.777	40.798	1800
1810	40.798	40.820	40.842	40.864	40.885	40.907	40.929	40.950	40.972	40.994	41.015	1810
1820	41.015	41.037	41.059	41.081	41.102	41.124	41.146	41.167	41.189	41.211	41.232	1820
1830	41.232	41.254	41.276	41.297	41.319	41.341	41.362	41.384	41.405	41.427	41.449	1830
1840	41.449	41.470	41.492	41.514	41.535	41.557	41.578	41.600	41.622	41.643	41.665	1840
1850	41.665	41.686	41.708	41.730	41.751	41.773	41.794	41.816	41.838	41.859	41.881	1850
1860	41.881	41.902	41.924	41.945	41.967	41.988	42.010	42.032	42.053	42.075	42.096	1860
1870	42.096	42.118	42.139	42.161	42.182	42.204	42.225	42.247	42.268	42.290	42.311	1870
1880	42.311	42.333	42.354	42.376	42.397	42.419	42.440	42.462	42.483	42.505	42.526	1880
1890	42.526	42.548	42.569	42.591	42.612	42.633	42.655	42.676	42.698	42.719	42.741	1890
°F	0	1	2	3	4	5	6	7	8	9	10	°F

MAXIMUM TEMPERATURE RANGE
Thermocouple Grade
– 328 to 2282°F
– 200 to 1250°C
Extension Grade
32 to 392°F
0 to 200°C
LIMITS OF ERROR
(whichever is greater)
Standard: 2.2°C or 0.75% Above 0°C
2.2°C or 2.0% Below 0°C
Special: 1.1°C or 0.4%
COMMENTS, BARE WIRE ENVIRONMENT:
Clean Oxidizing and Inert; Limited Use in Vacuum or Reducing; Wide Temperature Range; Most Popular Calibration
TEMPERATURE IN DEGREES °F
REFERENCE JUNCTION AT 32°F



Thermocouple Grade

Nickel-Chromium vs. Nickel-Aluminum

Extension Grade

Revised Thermocouple Reference Tables

TYPE K

Reference Tables N.I.S.T. Monograph 175 Revised to ITS-90

Z

Thermoelectric Voltage in Millivolts

°F	0	1	2	3	4	5	6	7	8	9	10	°F
1900	42.741	42.762	42.783	42.805	42.826	42.848	42.869	42.891	42.912	42.933	42.955	1900
1910	42.955	42.976	42.998	43.019	43.040	43.062	43.083	43.104	43.126	43.147	43.169	1910
1920	43.169	43.190	43.211	43.233	43.254	43.275	43.297	43.318	43.339	43.361	43.382	1920
1930	43.382	43.403	43.425	43.446	43.467	43.489	43.510	43.531	43.552	43.574	43.595	1930
1940	43.595	43.616	43.638	43.659	43.680	43.701	43.723	43.744	43.765	43.787	43.808	1940
1950	43.808	43.829	43.850	43.872	43.893	43.914	43.935	43.957	43.978	43.999	44.020	1950
1960	44.020	44.041	44.063	44.084	44.105	44.126	44.147	44.169	44.190	44.211	44.232	1960
1970	44.232	44.253	44.275	44.296	44.317	44.338	44.359	44.380	44.402	44.423	44.444	1970
1980	44.444	44.465	44.486	44.507	44.528	44.550	44.571	44.592	44.613	44.634	44.655	1980
1990	44.655	44.676	44.697	44.719	44.740	44.761	44.782	44.803	44.824	44.845	44.866	1990
2000	44.866	44.887	44.908	44.929	44.950	44.971	44.992	45.014	45.035	45.056	45.077	2000
2010	45.077	45.098	45.119	45.140	45.161	45.182	45.203	45.224	45.245	45.266	45.287	2010
2020	45.287	45.308	45.329	45.350	45.371	45.392	45.413	45.434	45.455	45.476	45.497	2020
2030	45.497	45.518	45.539	45.560	45.580	45.601	45.622	45.643	45.664	45.685	45.706	2030
2040	45.706	45.727	45.748	45.769	45.790	45.811	45.832	45.852	45.873	45.894	45.915	2040
2050	45.915	45.936	45.957	45.978	45.999	46.019	46.040	46.061	46.082	46.103	46.124	2050
2060	46.124	46.145	46.165	46.186	46.207	46.228	46.249	46.269	46.290	46.311	46.332	2060
2070	46.332	46.353	46.373	46.394	46.415	46.436	46.457	46.477	46.498	46.519	46.540	2070
2080	46.540	46.560	46.581	46.602	46.623	46.643	46.664	46.685	46.706	46.726	46.747	2080
2090	46.747	46.768	46.789	46.809	46.830	46.851	46.871	46.892	46.913	46.933	46.954	2090
2100	46.954	46.975	46.995	47.016	47.037	47.057	47.078	47.099	47.119	47.140	47.161	2100
2110	47.161	47.181	47.202	47.223	47.243	47.264	47.284	47.305	47.326	47.346	47.367	2110
2120	47.367	47.387	47.408	47.429	47.449	47.470	47.490	47.511	47.531	47.552	47.573	2120
2130	47.573	47.593	47.614	47.634	47.655	47.675	47.696	47.716	47.737	47.757	47.778	2130
2140	47.778	47.798	47.819	47.839	47.860	47.880	47.901	47.921	47.942	47.962	47.983	2140
2150	47.983	48.003	48.024	48.044	48.065	48.085	48.105	48.126	48.146	48.167	48.187	2150
2160	48.187	48.208	48.228	48.248	48.269	48.289	48.310	48.330	48.350	48.371	48.391	2160
2170	48.391	48.411	48.432	48.452	48.473	48.493	48.513	48.534	48.554	48.574	48.595	2170
2180	48.595	48.615	48.635	48.656	48.676	48.696	48.717	48.737	48.757	48.777	48.798	2180
2190	48.798	48.818	48.838	48.859	48.879	48.899	48.919	48.940	48.960	48.980	49.000	2190
2200	49.000	49.021	49.041	49.061	49.081	49.101	49.122	49.142	49.162	49.182	49.202	2200
2210	49.202	49.223	49.243	49.263	49.283	49.303	49.323	49.344	49.364	49.384	49.404	2210
2220	49.404	49.424	49.444	49.465	49.485	49.505	49.525	49.545	49.565	49.585	49.605	2220
2230	49.605	49.625	49.645	49.666	49.686	49.706	49.726	49.746	49.766	49.786	49.806	2230
2240	49.806	49.826	49.846	49.866	49.886	49.906	49.926	49.946	49.966	49.986	50.006	2240
°F	0	1	2	3	4	5	6	7	8	9	10	°F

°F	0	1	2	3	4	5	6	7	8	9	10	°F
2250	50.006	50.026	50.046	50.066	50.086	50.106	50.126	50.146	50.166	50.186	50.206	2250
2260	50.206	50.226	50.246	50.266	50.286	50.306	50.326	50.346	50.366	50.385	50.405	2260
2270	50.405	50.425	50.445	50.465	50.485	50.505	50.525	50.545	50.564	50.584	50.604	2270
2280	50.604	50.624	50.644	50.664	50.684	50.703	50.723	50.743	50.763	50.783	50.802	2280
2290	50.802	50.822	50.842	50.862	50.882	50.901	50.921	50.941	50.961	50.981	51.000	2290
2300	51.000	51.020	51.040	51.060	51.079	51.099	51.119	51.139	51.158	51.178	51.198	2300
2310	51.198	51.217	51.237	51.257	51.276	51.296	51.316	51.336	51.355	51.375	51.395	2310
2320	51.395	51.414	51.434	51.453	51.473	51.493	51.512	51.532	51.552	51.571	51.591	2320
2330	51.591	51.611	51.630	51.650	51.669	51.689	51.708	51.728	51.748	51.767	51.787	2330
2340	51.787	51.806	51.826	51.845	51.865	51.885	51.904	51.924	51.943	51.963	51.982	2340
2350	51.982	52.002	52.021	52.041	52.060	52.080	52.099	52.119	52.138	52.158	52.177	2350
2360	52.177	52.197	52.216	52.235	52.255	52.274	52.294	52.313	52.333	52.352	52.371	2360
2370	52.371	52.391	52.410	52.430	52.449	52.468	52.488	52.507	52.527	52.546	52.565	2370
2380	52.565	52.585	52.604	52.623	52.643	52.662	52.681	52.701	52.720	52.739	52.759	2380
239052.759		52.778	52.797	52.817	52.836	52.855	52.875	52.894	52.913	52.932	52.952	2390
2400	52.952	52.971	52.990	53.010	53.029	53.048	53.067	53.087	53.106	53.125	53.144	2400
2410	53.144	53.163	53.183	53.202	53.221	53.240	53.260	53.279	53.298	53.317	53.336	2410
2420	53.336	53.355	53.375	53.394	53.413	53.432	53.451	53.470	53.490	53.509	53.528	2420
2430	53.528	53.547	53.566	53.585	53.604	53.623	53.643	53.662	53.681	53.700	53.719	2430
2440	53.719	53.738	53.757	53.776	53.795	53.814	53.833	53.852	53.871	53.890	53.910	2440
2450	53.910	53.929	53.948	53.967	53.986	54.005	54.024	54.043	54.062	54.081	54.100	2450
2460	54.100	54.119	54.138	54.157	54.176	54.195	54.214	54.233	54.252	54.271	54.289	2460
2470	54.289	54.308	54.327	54.346	54.365	54.384	54.403	54.422	54.441	54.460	54.479	2470
2480	54.479	54.498	54.517	54.536	54.554	54.573	54.592	54.611	54.630	54.649	54.668	2480
2490	54.668	54.687	54.705	54.724	54.743	54.762	54.781	54.800	54.819	54.837	54.856	2490
2500	54.856	54.875	54.894									2500
°F	0	1	2	3	4	5	6	7	8	9	10	°F