

Easy-PCB Solder Reflow Oven

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Features

- Insulated aluminum frame with XxYxZ interior chamber
- XXX Watt heating element with solid state relay control
- 120 VAC power supply with surge and short protection
- Forced convection fan driven by bipolar stepper motor with speed control
- Type X thermocouple for temperature feedback loop
- PIC18F14K50 based control
- Convenient 7-segment display and pushbutton user interface

heat absorbtion seen in infrared radiation based systems. Furthermore, *Easy-PCB* was designed from the ground up for soldering, so the heating elements and oven frame were optimized alongside the temperature controller for a typical solder reflow profile.

Figures/control-system.pdf

Introduction

Easy-PCB is a small, desktop convection oven for DIY reflow soldering at home.

As integrated circuits continue to become smaller and faster, many μ Controllers, FPGAs, and other ICs are no longer available in DIP form for breadboard prototyping or iron soldering. Similar to the shift away from PC parallel ports in the early 2000s, the shift away from DIPs means modern electronics hobbyists need more complicated equipment than their predecessors.

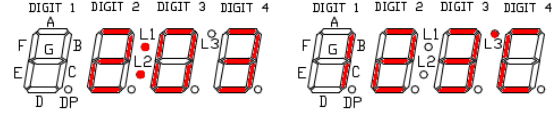
Currently, commercial solder reflow stations are available for soldering fine pitch, SMD, and BGA componenets. More recently, several hackers have created open source designs for inexpensive reflow ovens, using converted kitchen toaster ovens.

Easy-PCB is better because it is a convection oven; controlled air flow prevents parts from being blown out of position and convection heating obviates the uneven

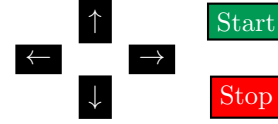
The *Easy-PCB* Control System: not just a controller bolted onto a disjoint oven.

Easy-PCB allows hobbyists to produce reflow temperature profiles with a high degree of accuracy and repeatability. Alongside freely available PCB design programs like Eagle and low-quantity fabrication services like OSH Park, *Easy-PCB* makes modern integrated components, such as digital CMOS cameras, within the design space of hobbyists and hackers.

Figures/control-results.pdf



The red 'stop' button can be pressed at anytime to quit the current process or reset the microcontroller.



Pushbutton Interface

Set point programming with the 4 nav keys is used to enter a time-temperature profile. Use the 'left' and 'right' keys to move between set points and the 'up' and 'down' keys to edit each set point value.

Faithful Temperature Profile Control

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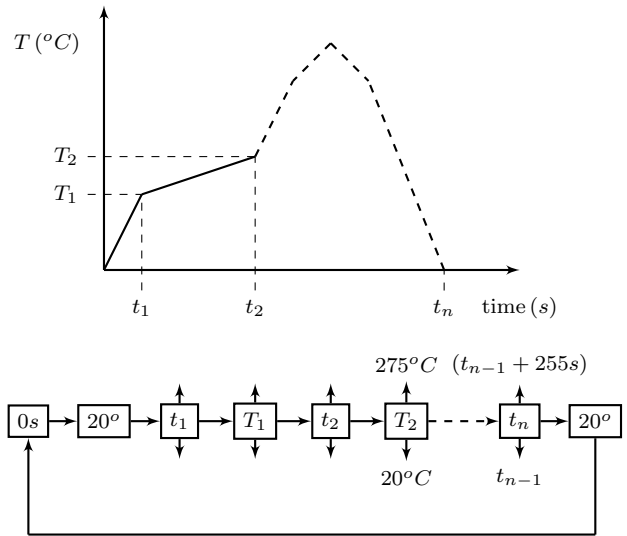
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1 User Interface

Easy-PCB presents temperature and time information on a four digit LED display. After pressing the green 'start' button, the current temperature and process runtime are alternately displayed every second.



Set Point Programming

A total of 128 set points can be entered. The first set point is always (0s, 20°C), and the process will terminate at the next occurrence of 20°C in a point. Temperatures can take any value in the range $20^{\circ}\text{C} < T < 275^{\circ}\text{C} = 527^{\circ}\text{F}$. The time between two points must be between $0 \leq t < 255$ seconds.

2 Plant Design

2.1 Temperature Objectives

A typical solder reflow profile is shown in figure 1. The optimal shape and peak temperature depend on the components and, more significantly, on the use of

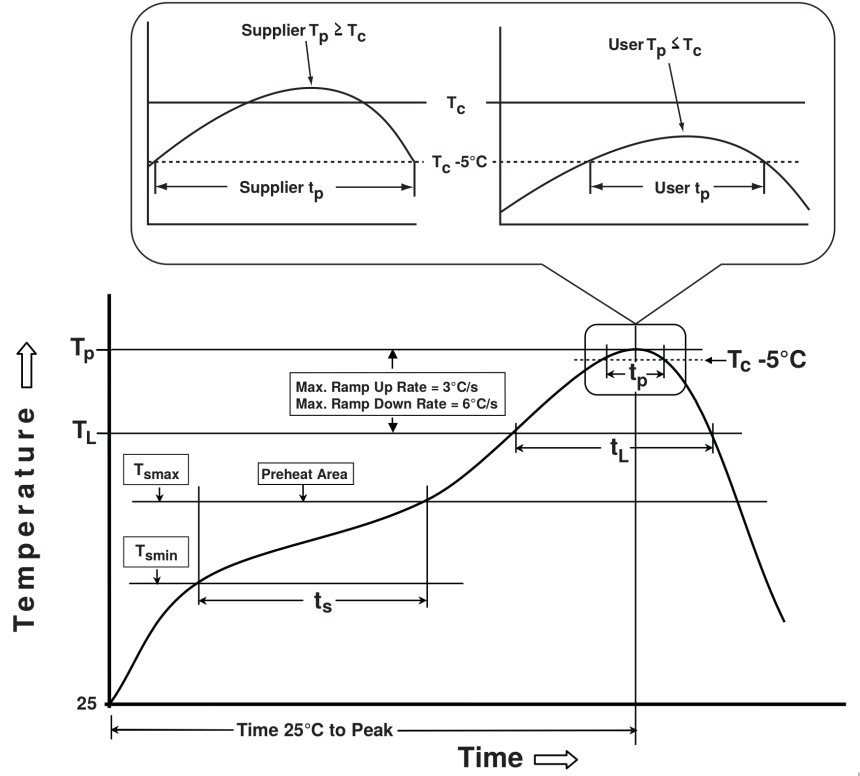


Figure 1: Standard Solder Reflow Profile, per IPC/JEDEC STD-1-020D.1

lead solder.

$$T_p \approx T_c = \begin{cases} 220 - 235^\circ\text{C} & \text{Lead solder} \\ 245 - 260^\circ\text{C} & \text{Pb-free} \end{cases}$$

$$t_p = \begin{cases} 20\text{s} & \text{Lead solder} \\ 30\text{s} & \text{Pb-free} \end{cases}$$

Easy-PCB was designed from the ground up for faithfully producing these reflow profiles. This design process for the thermodynamic system is detailed below.

2.2 Thermodynamics Theory

Heat is everyone's least favorite form of energy because it tends to dissipate everywhere and is difficult to transform into useful work. Nevertheless, it is a form of energy so it is measured in joules.

$$Q := \text{Heat [Joules]}$$

From a microscopic view, heat is the kinetic energy of gas molecules or the vibrational energy of bonds in solids. In both cases, summed over every molecule, every bond, and every vibrational mode in the system.

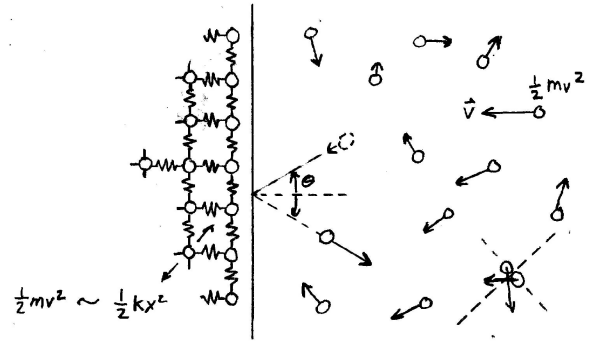


Figure 2: Heat Energy on a Molecular Scale

Temperature is a potential field that measures an objects tendency to give up or absorb heat. On average, heat always flows from regions of hotter temperature to lower temperature. Temperature is usually measured in Kelvin or Celsius, which are related by

$$T_{\text{Celsius}} = T_{\text{Kelvin}} + 273.16.$$

Another way to think of temperature is a measure of heat density that also incorporates the types of bonds (or lack thereof) in which heat energy is stored.

For example, a glacier contains more heat than a pot of boiling water, but has a much lower heat density.

The relationship between temperature and heat stored in an object is given by

$$dQ = mc_p dT, \quad (1)$$

where c_p is the specific heat of the material with units $\left[\frac{kJ}{kg \cdot K} \right]$.

So heat flows spontaneously to reduce temperature gradients, but how does heat flow and at what rate? There are three mechanisms of heat transfer: *conduction*, *convection*, and *radiation*.

Conduction of heat is caused by molecular interactions, such as the push-pull of nearby atomic bonds in solids or elastic collisions between molecules of air.

The empirical relation for conduction is Fourier's Law, which says the rate of heat transfer due to conduction is proportional to both the difference in temperature and the media:

$$\vec{q} = k \vec{\nabla} T$$

where \vec{q} is the rate of heat transfer per unit surface area and k is the thermal conductivity of the medium with units $\left[\frac{W}{m \cdot K} \right]$.

In integral form, Fourier's Law is

$$\frac{\delta Q}{\delta t} = k \oint_S \vec{\nabla} T \cdot d\vec{A}.$$

And, in the one dimensional case,

$$\frac{\delta Q}{\delta t} = -kA \frac{\delta T}{\delta x}. \quad (2)$$

Convection is the second mechanism of heat transfer, involving the bulk movement of particles driven by diffusion.

Every air molecule is moving in a random direction with random kinetic energy, but a region of air with higher average kinetic energy (temperature) will see more molecules leaving than entering on average, because those leaving are moving faster than those entering.

Note that in convection, no molecules gain or lose energy; molecules of different energy simply trade places.

If a fan is used to apply work to a gas, the rate of convection increases and then Newton's Law of Cooling can predict the rate of convection in gas near a solid surface of different temperature.

$$\frac{dQ}{dt} = hA\Delta T \quad (3)$$

where h is the heat transfer coefficient with units $\left[\frac{W}{m^2 \cdot K} \right]$.

Radiation, the third mechanism of heat transfer, is more familiar to electrical engineers. In any material, electrons have discrete amounts of energy based on the wave patterns that can exist for the atomic geometry. When an electron spontaneously falls to a less energetic pattern, that energy is emitted as a photon of light.

The classic, physics-history example is black body radiation, when a metal is heated to high temperature and glows. A more modern example is the LED.

The empirical relation for radiation is the Stefan-Boltzmann Law, which says that the total energy radiated, over all wavelengths and per unit surface area, is proportional to the fourth power of the body's temperature.

$$j^* = \sigma T^4 \quad (4)$$

where σ is a proportionality constant derived from other constants of nature.

Mechanisms & Media Usually one mechanism of heat transfer is dominant in a particular medium, so much so that we can ignore the other two. Typically this means conduction in solids, convection in fluids or gas, and radiation in space. However, sometimes the picture is more complicated including two cases in an oven:

1. At the boundary of metal and air, where conduction and convection are both significant.
2. In a thermocouple loop, where thermal diffusion (convection) of electrons is useful despite conduction still being dominant.

2.3 Thermodynamic Design

Most microwaves draw between 600 and 1200 Watts of power. An IR toaster oven may draw 1500 Watts into its lamps. How much power does *Easy-PCB* need to produce the required temperature profiles?

Our approach for answering this question is to browse available parts on McMaster.com, imagine how they would be assembled into an oven, and then model their thermodynamic response using SPICE.

A first conceptual design of *Easy-PCB* is shown in figure 3.

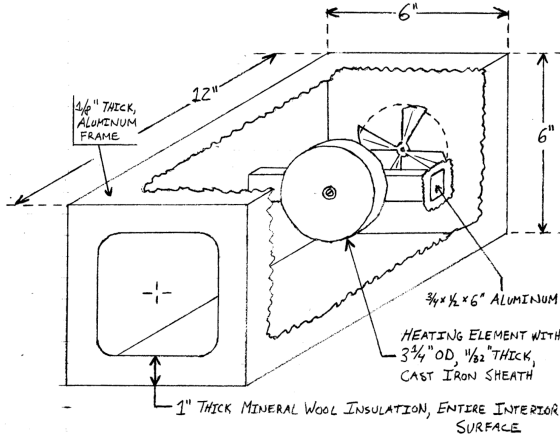


Figure 3: Concept for Thermodynamic System

Conduction through Metals & Insulation

In the concept, the oven chamber is isolated from the outside with walls of mineral wool insulation and aluminum. If the wall is relatively thin compared to the square root of its surface area, then its heat transfer can be modeled as a 1-D transmission line, like shown in figure 4.

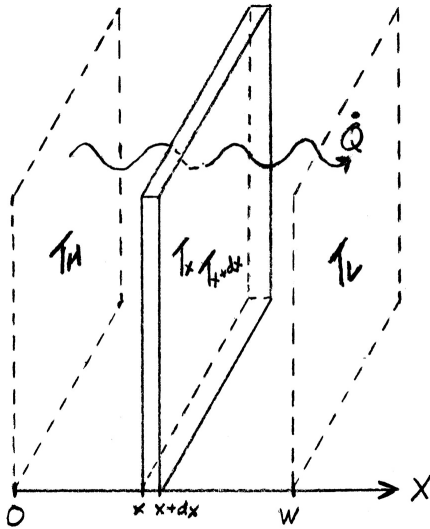


Figure 4: Heat Conduction in 1-D

Assuming conduction is the dominant mechanism of heat transfer and using Fourier's Law in 1-D, (equation 2) the rate of heat passing through a thin slice is

$$\frac{\delta Q}{\delta t} = -kA \frac{\delta T}{\delta x}$$

And, from equation 1, the heat capacity of a thin slice of the metal sheath is

$$dQ = (\rho A dx) c_p dT$$

Rewriting these equations to look like current-voltage relationships gives

$$\delta T = R_x \frac{\delta Q}{\delta t}, \quad R_x = \frac{\delta x}{kA} \quad (5)$$

and

$$\frac{\delta Q}{\delta t} = C_x \frac{\delta T}{\delta t}, \quad C_x = \rho A c_p * \delta x \quad (6)$$

Values for thermal conductivity k , specific heat capacity c_p , and density ρ of different materials are listed in table 1.

Long metal bars and rods can also be modeled with equations 5 and 6 if the heat loss along the length of the bar is assumed to be negligible compared to heat transferred at the end faces.

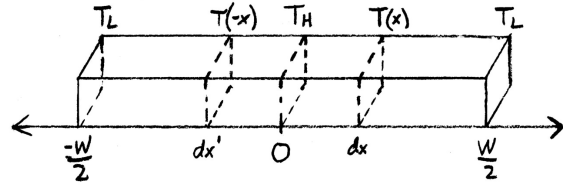


Figure 5: 1-D Conduction in Both Directions

For metal components where heat is injected at the center of the part and dissipates symmetrically in either direction, such as the support bar shown in figure 5 or the metal sheath encasing the heating element, the surface area can be doubled so that the transmission line only needs to be integrated in the positive direction.

$$\left\{ \begin{array}{lll} A_x & \Rightarrow & 2A_x \\ R_x & \Rightarrow & R_x/2 \\ C_x & \Rightarrow & 2C_x \\ \{x | -\frac{w}{2} \leq x \leq \frac{w}{2}\} & \Rightarrow & \{x | 0 \leq x \leq \frac{w}{2}\} \end{array} \right. \quad (7)$$

Conductivity of Metal-Air Interface

In the bulk volume of air, convection is the dominant form of heat transfer and collisions are relatively rare. However, where the air meets a solid surface, the net convection must go to zero because there can be no net movement of air molecules into the solid. Furthermore, every air molecule that reaches the surface experiences a collision so there is 100% conduction at the surface.

For some distance away from the surface, there is a larger than normal chance of head-on collisions and slower rates of diffusion due to the nearby wall. In

Table 1: Thermal Conductivity, Specific Heat, and Density of Selected Materials

Material	Linear Range ($^{\circ}C$)	k ($\frac{W}{m \cdot K}$)	c_p ($\frac{kJ}{kg \cdot K}$)	ρ (kg/m^3)
Type 6061 Aluminum	25	167	0.896	2700
Type 304 Stainless Steel	0–100	16.2	0.5	8000
Cast Iron	25	55.0	0.46	6800–7800
1.0 K-factor Insulation	-	0.1442	-	-
0.23 K-factor Insulation	-	0.0332	-	-
Nichrome NiCr C Alloy	-	0.450	0.135	8244

this region, both conduction and convection may be significant. To analyze this transition region, we will start at the surface where there is 100% conduction because that is the mechanism we have equations for.

From the first law of thermodynamics, the rate of heat being stored in a differential volume is equal to the rate of heat entering less the rate of heat leaving the volume element.

$$\frac{\delta Q_{\text{stored}}}{\delta t} = \frac{\delta Q_{\text{in}}}{\delta t} - \frac{\delta Q_{\text{out}}}{\delta t}$$

Looking back at figure 4, the differential volume element is a plane, so

$$\frac{\delta Q_{\text{stored}}}{\delta t} = \frac{\delta Q_x}{\delta t} - \frac{\delta Q_{x+\delta x}}{\delta t}.$$

Substituting in equation 1 for stored heat capacity and equation 2 for conduction through the element yields a transport equation.

$$mc_p \frac{\delta T}{\delta t} = kA \frac{\delta T}{\delta x} \quad (8)$$

This cannot be solved analytically unless space and time are independent. Sorry Albert.

$$T(x, t) = T_x(x) * T_t(t) \quad (9)$$

Applying the chain rule to equation 8

$$mc_p \frac{\delta T_t(t)}{\delta t} T_x(x) = kA \frac{\delta T_x(x)}{\delta x} T_t(t)$$

and separating variables gives

$$mc_p \frac{\delta T_t(t)}{\delta t} * \frac{1}{T_t(t)} = kA \frac{\delta T_x(x)}{\delta x} * \frac{1}{T_x(x)}.$$

The only way for the equality to be true for all space and time is if both sides are equal to a common constant.

$$\alpha = mc_p \frac{\delta T_t(t)}{\delta t} * \frac{1}{T_t(t)}$$

$$\alpha = kA \frac{\delta T_x(x)}{\delta x} * \frac{1}{T_x(x)}$$

Each of these can be solved by separation of variables.

$$\frac{\alpha}{kA} \delta x = \frac{\delta T_x(x)}{T_x(x)}$$

$$\frac{\alpha}{kA} \int \delta x = \int \frac{1}{T_x(x)} * \delta T_x(x)$$

$$\frac{\alpha x}{kA} = \ln(T_x(x)) + \beta_1$$

$$T_x(x) = \beta_1' e^{\alpha x / kA}$$

Similarly for time,

$$T_t(t) = \beta_2' e^{\alpha t / mc_p}.$$

Recombining the independent components gives

$$\Delta T(x, t) = \beta_1' \beta_2' e^{\alpha x / kA + \alpha t / mc_p}$$

The boundary conditions are that at $t = 0$ and $x = 0$, the temperature difference is the initial temperature difference, and at $t \rightarrow \infty$ and $x \rightarrow \infty$, the temperature difference dissipates to zero.

$$\Delta T(x, t) = \Delta T_0 e^{-\alpha x / kA - \alpha t / mc_p}$$

Now, for the sake of physical intuition we can write

$$\Delta T(x, t) = \Delta T_0 e^{-(x/\delta + t/\tau)}, \quad (10)$$

where δ is a ‘skin depth’ over which the spacial gradient decays to $1/e$ its initial value and τ is a time constant related to the skin depth by

$$\tau = \frac{mc_p}{kA} \delta. \quad (11)$$

Make some arguments and plot the temperature and heat transfer curves. Assume steady state and somehow that active cooling makes it all valid.

Applying Fourier’s law to the temperature profile found in equation 10, gives us the rate of heat transfer in the air due to conduction.

$$\frac{dQ}{dt} = -kA \frac{dT}{dx} = \frac{kA}{\delta} \Delta T_0 e^{-(x/\delta + t/\tau)}$$

Table 2: Typical Convective Heat Transfer Coefficients

Fluid	Conv.	$h_c \left[\frac{W}{m^2 \cdot K} \right]$
Gases, & dry vapors	free	0.5 – 1000
	forced	10 – 1000
Water & liquids	free	50 – 3000
	forced	50 – 10000
Boiling Water	-	3 – 100
Condensing H_2O Vapor	-	5 – 100

Table 3: Thermal Properties of Air

$T [^\circ C]$	$\rho \left[\frac{kg}{m^3} \right]$	$c_p \left[\frac{kJ}{kg \cdot K} \right]$	$k \left[\frac{W}{m \cdot K} \right]$
20	1.205	1.005	0.0257
40	1.127	1.005	0.0271
60	1.067	1.009	0.0285
80	1.000	1.009	0.0299
100	0.946	1.009	0.0314
120	0.898	1.013	0.0328
140	0.854	1.013	0.0343
160	0.815	1.017	0.0358
180	0.779	1.022	0.0372
200	0.746	1.026	0.0386
250	0.675	1.034	0.0421
300	0.616	1.047	0.0454

Again assuming steady state, the rate of heat transfer at any distance from the wall is equal to the rate of conduction at the wall.

$$\frac{dQ}{dt} = \frac{kA}{\delta} \Delta T_0 = h_c A \Delta T_0 \quad (12)$$

This is the information we were after and, ironically, it turns out this is Newton’s Law of Cooling (equation 3) where $h_c = k/\delta$. Since we do not have any way of predicting the skin depth except by experimentation, some common values for the convective heat transfer coefficient h_c are listed in table 2.

Equation 12 can be rewritten to look like Ohm’s law for SPICE analysis.

$$\Delta T = R_c \frac{dQ}{dt}, \quad R_c = \frac{1}{h_c A} = \frac{\delta}{kA} \quad (13)$$

Heat Capacity of Chamber Air

The heat capacity of the air in the chamber cannot be analyzed with constant coefficient assumptions.

$$dQ = m(T) c_p(T) dT \quad (14)$$

From table 3, we can see that the specific heat of air does not vary much over the temperature range of the oven; less than 0.3% from $c_{p(20^\circ C)}$ over the range

20 – 300°C. However, the density and mass of air in the chamber may change significantly.

Assuming that the air in the chamber behaves like an ideal gas and is made up of the normal percentages of N_2 , O_2 , CO_2 , etc., then mass and temperature are related by

$$PV = \frac{m}{M} RT \Rightarrow m(T) = \frac{MPV}{R} T$$

where the ideal gas constant is

$$R = 5.00745 \left[\frac{\text{atm} \cdot \text{in}^3}{\text{mol} \cdot K} \right]$$

and the molar mass of air is

$$M = 28.97 \left[\frac{g}{\text{mol}} \right]$$

For the first oven concept in figure 3, the volume of the chamber is fixed in natural units of in^3 and there are likely small leaks that let the chamber pressure equilibrate to atmospheric pressure 1 atm.

Substituting $m(T)$ into equation 14, converting from absolute Kelvin scale to Celsius, and manipulating to look like a current–voltage relationship results in

$$\frac{dQ}{dt} = C_c(T) \frac{dT}{dt} \quad (15)$$

where

$$C_c(T) = \frac{c_{p(20^\circ C)} MPV}{R(T + 273.16^\circ C)}. \quad (16)$$

Equivalently,

$$C_c(T) = \frac{(5.8143 \left[\frac{J}{\text{in}^3} \right]) * V}{T + 273.16^\circ C}.$$

2.4 Component Selection & SPICE Modeling

Unfortunately, SPICE does not have a primitive circuit element for a variable capacitor. In order to simulate the heat capacity of an ideal gas, we must build a subcircuit that behaves according to

$$i_c = C(v_c) \frac{dv_c}{dt},$$

or, alternatively,

$$\int i_c dt = \int C(v_c) dv_c. \quad (17)$$

The interface of the SPICE circuit will be a dependent source where either v_c is dependent on i_c or vice versa.

The left side of equation 17 is an integrator, which can be implemented with a buffer and a capacitor. For

the SPICE circuit shown in figure 6, the integrated current is proportional to the voltage of the ‘int’ node.

$$\int i_c dt = C_{int} * v_{int}$$

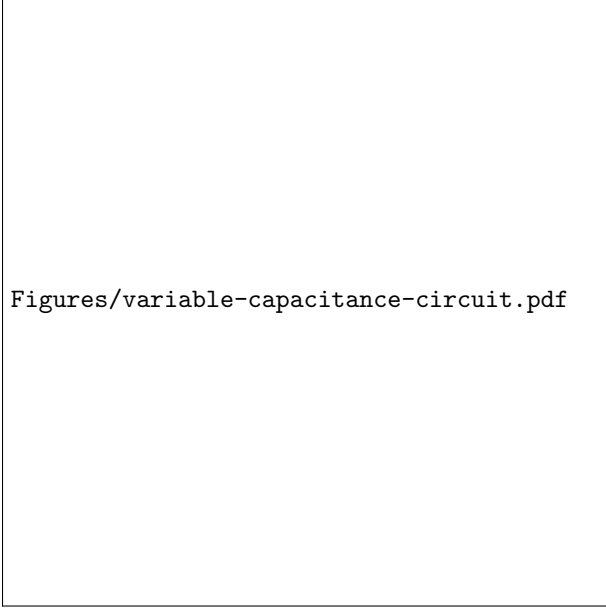


Figure 6: Voltage Variable Capacitor in SPICE

For the right side of equation 17, it can be solved for the variable heat capacitance of an ideal gas found in equation 16.

$$\begin{aligned} \int C(v_c) dv_c &= \frac{c_p MPV}{R} \int \frac{dv_c}{v_c + 273.16} \\ &= \frac{c_p MPV}{R} \ln(v_c + 273.16) + A \end{aligned}$$

Recombining the left and right halves gives

$$C_{int} v_{int} = \frac{c_p MPV}{R} \ln(v_c + 273.16) + A,$$

which can be solved to find a nonlinear expression for a dependent source v_c .

Solving...

$$\frac{RC_{int}}{c_p MPV} * v_{int} = \ln(v_c + 273.16) + A$$

$$v_c = A' e^{v_{int}/B} - 273.16$$

Finally, applying boundary conditions $v_c(0) = 0$ and $v_{int}(0) = 0$ gives

$$v_c = 273.16 \left(e^{v_{int}/B} - 1 \right) \quad (18)$$

where constant B is

$$\begin{aligned} B &= \frac{c_p MP}{R} * V * C_{int} \\ &= \left(5.8413 \left[\frac{J}{in^3} \right] \right) * V * C_{int} \end{aligned} \quad (19)$$

and V is the constant volume of air.

Table 4: Nichrome Wire Properties (NiCr C)

Composition	59.2%Ni	16%Cr	23.5%Fe	1.3%Si
Resistivity (ρ)	$675 * \pi$	$\left[\frac{\Omega \cdot \text{mil}^2}{ft} \right]$		
Melting Pt.	1350	$[^{\circ}C]$		
Temp. $[^{\circ}C]$	20	93	204	315
% ρ Increase	0	1.7	3.5	5.2

2.5 Transfer Model

3 Temperature Feedback Design

The Seebeck voltage is the electromotive force that develops in a conductive loop made of two different metal alloys. It is described by

$$E_S = \int_{T_R}^T \alpha_{A,B} dT, \quad (20)$$

where T and T_R are the temperatures of the hot and cold junctions and $\alpha_{A,B}$ is the Seebeck coefficient between materials A and B .

A type-K thermocouple was selected because they are readily available and resist oxidation at temperatures up to $1260^{\circ}C$. From the ‘Manual on the use of Thermocouples in Temperature Measurement’ (STP 470A), the nominal Seebeck coefficients for type-K thermocouples is

$$\alpha_{KP,KN} = \begin{cases} 0^{\circ}C & 39.4 \mu V/^{\circ}C \\ 200^{\circ}C & 40.0 \mu V/^{\circ}C \\ 400^{\circ}C & 42.3 \mu V/^{\circ}C \end{cases} . \quad (21)$$

The positive wire KP is one of the following alloys: Chromel, Tophel, T-1, or ThermoKanthal KP. The negative wire KN is Alumel, Nial, T-2, or ThermoKanthal KN.

The thermoelectric potential in a K loop is very small; for a temperature difference of $T - T_R = 500^{\circ}C$, the voltage developed is only on the order of $E_S = 20 mV$. Consequently, the signal needs to be amplified before it can be read by an ADC. The op amp circuit shown in figure 7 can be used.

Five volt μ controllers usually have ADC ranges of 0–3.3 V. To scale 20 mV to 3.3 V and 0 V to 0 V, the feedback resistors should be

$$\frac{V_{ADC(max)}}{V_{K(max)}} = \frac{R_2}{R_1} \quad (22)$$

$$\frac{3.3 mV}{20 mV} = 165$$

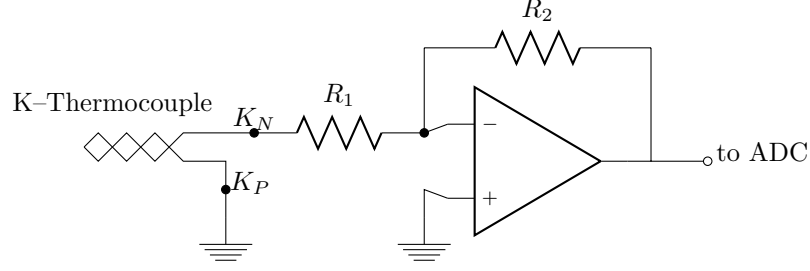


Figure 7: Thermocouple Amplifier

3.1 Controller and Power Requirements

4 Motor Driver Design

4.1 Power Requirements

5 Power Circuit Design

5.1 PCB Trace Width

The minimum width and clearance for high current, high voltage traces on a PCB can be calculated using

$$I = 0.048[A] * \left(\frac{\Delta T}{[^{\circ}C]} \right)^{0.44} * \left(\frac{A}{[mil^2]} \right)^{0.725} \quad (23)$$

and

$$\text{Clearance} = 0.023[in] + \frac{0.0002[in]}{[V]} * V_{\text{peak}} \quad (24)$$

from the design standard for PCB trace width ANSI/IPC-2221. Note that equation 23 is only for exterior traces.

For 10 A, 120 VAC power with a maximum temperature rise of 10°C and standard copper thickness 1 oz = 1.4 mil, the minimum trace width is 0.278 in and minimum clearance is 0.057 in.

6 Controller Design