Figures/easy-pcb-o

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**
- **Forced convection fan driven by bipolar stepper motor with speed control**
- **Type X thermocouple for temperature feedback loop**
- **XXXXX based feedback control**
- **Integrated 120 VAC power supply with surge and short protection**
- **Combined temperature/run time 7–segment display**
- **Convenient pushbutton/menu interface for temperature profile programming**

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 solder 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 predessesors.

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 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

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

Easy–PCB allows hobbyists to produce solder 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 range of capabilities of independent hobbyists.

Figures/control-results.pdf

Faithful Temperature Profile Control

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1 User Interface

2 Plant Design

2.1 Temperature Objectives

2.2 Thermodynamics Theory

The heat required to increase temperature of a unit mass of material by one degree is

$$dQ = mc_p dT \tag{1}$$

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

$$\vec{q} = -k\vec{\nabla}T \tag{2}$$

where k is thermal conductivity with units $\left[\frac{W}{m*K}\right]$.

$$\frac{dQ}{dt} = -k \oint_S \vec{\nabla}T * d\vec{A}$$

where $d\vec{A}$ is a differential area element of a closed surface S.

$$\frac{\delta Q}{\delta t} = -kA\frac{\delta T}{\delta x} \tag{3}$$

$$\frac{dQ}{dt} = hA\Delta T \tag{4}$$

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

2.3 Conceptual 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 responses using PSPICE. Thermodynamics can be modeled in SPICE because temperature is mathematically analogous to voltage (both are potential functions) and heat energy to electric charge.

Starting from the source of heat and moving towards the heat sinks, the first component in a convection oven is a heating element. Most electric heating elements are protected from shorts and moisture by a metal sheath. If the sheath 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 1.

`Figures/sheath-transmission-line.pdf`

Figure 1: One–Dimensional Model of Heating Element Sheath

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

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

And, using Fourier's Law of heat conduction in 1–D, (equation 3) the rate of heat passing through a thin slice is

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

Rewriting these equations to look like current-voltage relationships gives

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

and

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

Values for k, c_p, and ρ of different metals 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 transfered at the end faces.

For sheaths or metal bars where heat is injected at the center of the part and dissipates symmetrically in either direction, the surface area can be doubled so that the transmission line only needs to be integraded in the positive direction.

$$\left\{ \begin{array}{ccc} R_x & \Rightarrow & R_x/2 \\ C_x & \Rightarrow & 2C_x \\ \{x \mid -\frac{w}{2} \leq x \leq \frac{w}{2}\} & \Rightarrow & \{x \mid 0 \leq x \leq \frac{w}{2}\} \end{array} \right. \tag{7}$$

At any moment in time, we can plot the temperature of air as one moves away from the sheath surface. We see there is a certain distance, called the skin depth δ, over which the temperature gradient is nearly dissipaited and the bulk air begins.

PLOT with T0et/alpha and Tbulk on y axis and x on x axis

Forced convection from the fan causes the bulk air, uniform temperature region to be pushed closer to the sheath's surface. If the skin depth can be pushed sufficiently close to the surface, then the time constant shrinks due to the relation $\alpha = \frac{k}{\rho c_p}\delta$. Thus, for sufficiently strong circullation and close skin depth, the time constant becomes small enough that the system is effectively always in steady state, where

$$\frac{dT}{dt} \approx 0$$

From the first law of thermodynamics (conservation of energy), the difference between heat flowing in and out of a thin slice by all mechanisms is equal to the heat stored within that slice, for all t and x.

$$\frac{\delta Q_{\text{cap.}}}{\delta t} * \frac{1}{\delta x} = \frac{\delta Q_{\text{cond.}}}{\delta t} * \frac{1}{\delta x} + \frac{\delta Q_{\text{conv.}}}{\delta t} * \frac{1}{\delta x}$$

Substituting equation 6 for the heat capacity of a thin slice yields:

$$\rho A c_p \frac{\delta T}{\delta t} = \frac{\delta Q_{\text{cond.}}}{\delta t} * \frac{1}{\delta x} + \frac{\delta Q_{\text{conv.}}}{\delta t} * \frac{1}{\delta x}$$

But we have just argued that if the skin depth can be made very close by forced convection, then $\frac{dT}{dt} \to 0$.

$$\frac{\delta Q_{\text{conv.}}}{\delta t} * \frac{1}{\delta x} = -\frac{\delta Q_{\text{cond.}}}{\delta t} * \frac{1}{\delta x}$$

Integrating across x is easy.

$$\frac{dQ_{\text{conv.}}}{dt}(x) = C - \frac{dQ_{\text{cond.}}}{dt}(x)$$

At the surface of the sheath ($X = 0$), heat transfer in the air is 100% conduction because every air molecule at ($X = 0$) is colliding with metal and exchanging energy. Therefore

$$C = \frac{dQ_{\text{cond.}}}{dt}(X = 0)$$

Applying Fourier's Law to the temperature profile found in equation **??** give us equations for the rate of heat tranfer due to conduction, and finally this leads to

$$\dot{Q}_{\text{cond.}}(x) = Q_0 e^{-x/\delta}$$

and

$$\dot{Q}_{\text{conv.}}(x) = Q_0 \left(1 - e^{-x/\delta}\right)$$

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

Material	Linear Region (K–K)	k $\left(\frac{W}{m*K}\right)$	c_p $\left(\frac{kJ}{kg*K}\right)$	ρ (kg/m^3)

where

$$Q_0 = \frac{kAT_0}{\delta} e^{-t/\alpha}$$

Finally, if we absorb $e^{-t/\alpha}$ into T_0 for steady state, then

$$Q_0 = \frac{kA}{\delta} T_0 \tag{8}$$

2.4 Component Selection & SPICE Modeling

2.5 Transfer Model

3 Thermocouple Amplifier Design

3.1 Controller and Power Requirements

4 Motor Driver Design

4.1 Power Requirements

5 Power Circuit Design

6 Controller Design