White Paper

Estimating Power Requirements of Etched-Foil Heaters

MINCO

Introduction

Etched-foil heaters have gained significant popularity due to their flexibility, uniform heat distribution, and rapid response times. These heaters consist of a resistive heating element etched onto a thin foil substrate, providing excellent thermal conductivity. Accurate estimation of power requirements is essential for designing the electrical circuitry and ensuring optimal performance of the heating system.

Abstract

When specifying a new etched-foil heater design, the first and often most formidable parameter to determine is heater wattage. How much power is needed to bring a part to temperature in a given time and how much to maintain it there? You can determine your heater needs by experiment or by calculating a theoretical value. The experimental approach gives the best answer, but a wattage estimate should be done before embarking on experiments. This white paper presents some numerical methods for you to use in estimating heater wattage. It is not perfectly accurate, as it is impossible to take into account all the variables acting upon a thermal system. What it does provide is an estimate to serve as a basis for ordering prototypes or starting lab experiments.

Basic Heat Transfer Theory

Two values must be calculated to determine wattage requirements: warm-up and operating heat. Assuming no lost heat, the power required to warm up a block of material is a linear function of the material's mass and specific heat, the degree of temperature rise and the desired warm-up time:

$$P = \frac{mC_p\,(T_f - T_i)}{60000\ t}$$

Where:

P = Heater power (W)

m = Mass of material (g)

C_p = Specific heat of material (J/kg·K) from Table 1

T_f = Final Temperature of material (°C)

T_i = Initial temperature of material (°C)

t = Desired warm-up time (min)

This formula will serve as a shortcut for power estimation if warm-up requirements are the dominant heat demand of the system and losses are small. The figure it gives is a minimum. Add at least 10% for unknown heat losses. For best accuracy, you can estimate heat loss during operation and warm-up. Loss occurs in three forms; conduction, convection, and radiation.

Conduction transfers heat from a warmer object to a cooler one, usually through a solid medium. When speaking of etched-foil heaters, conductive loss generally refers to loss through insulation layers or heat sink mounting hardware. Conduction is a function of the temperature difference between the heater and its surroundings, the distance between hot and cool areas, and the cross-sectional area and conductivity of conductive paths.

Convective loss occurs when the fluid medium surrounding the heater flows in currents and carries heat with it. For purposes of this white paper, the fluid is air. The two types of convection are natural, when heated air rises and creates air currents, and forced, when fans or wind drive air past the heater.

Convective loss depends on the heat sink temperature relative to ambient, the shape and surface area of the heat sink, and the velocity of forced air.

Radiation is heat emitted as infrared energy. Radiant loss varies with temperature difference between the heater and ambient, heater surface area, and the nature of the surfaces radiating and absorbing the heat (emissivity).

Warm-up heat is the heat required to bring the heat sink to temperature in the desired time, plus extra heat to compensate for conductive, radiant, and convective losses during warm-up.

Operating heat equals the sum of steady-state loses and process heat. Process heat represents work done by the heater to thermally process some material, for example, to melt a plastic film placed over the heat sink.

The total minimum heat required for an application is the larger of two values:

1. Warm-up heat, or
2. Operating heat including process requirements.

How to Use this White Paper

To estimate your wattage needs, follow the formulas in the next section "Heater Wattage Estimation Procedure" and reference values listed in Tables 1 and 2. For clarification see the example under "Sample Calculations". Note that Minco has an online thermal calculator that will make your thermal calculations easier than ever before. You can access it via the following link, minco.com/resources/heater-wattage-estimator.

Heater Wattage Estimation Procedure

I. Calculate steady-state heat losses. Include conductive, radiant, and convective losses.

1. **Conduction losses**: Losses due to heat conduction through mounting hardware, insulation, and other material in contact with the heated part. Calculate separately for each conductive path. NOTE: The following calculation is valid for cases where the surface temperature of the material opposite the heater is close to ambient, otherwise the material's surface temperature should be used for T_a.

   Given the following:
   K = Thermal conductivity of material from Table 1 (W/m·K)
   A = Cross-sectional area of material (cm^2)
   T_f = Heat sink temperature (°C)
   T_a = Ambient temperature (°C)
   L = Thickness of insulation = Length of conductive path (mm)
   P_{cd} = Conduction loss (W) = $KA(T_f - T_a)/(10L)$

2. **Radiation Losses:** Losses due to radiant transfer from the heat sink to surroundings. Ignore insulated surfaces.
   Given the following:
   ϵ = Emissivity of heat sink surface from Table 2
   A = Area of exposed surface (cm^2)
   T_{fK} = Final absolute temperature (K=°C+273.15)
   T_{aK} = Ambient absolute temperature (K=°C+273.15)
   P_r = Radiation loss (W) = $\epsilon A(5.6703 \times 10^{-8})(T_{fK}^4 - T_{aK}^4)/10000$

3. **Convection Losses:** Loss to ambient air resulting from natural or forced air movement. Ignore loss with vacuum applications or well insulated surfaces. NOTE: These equations may be invalid for large heaters (longer than 0.5m) or high temperatures (above 250°C). Contact Minco for assistance in these cases.

   a. Determine H (convection coefficient). Use one of two equations for H, depending on whether convection is natural (still air) or forced (fan, wind, etc.). Given the following:
      Natural Convection
      F_C = Configuration factor from Table 3
      $T_{ave} = (T_f + T_a)/2$ (°C)
      L = Characteristic length from Table 3 (cm)
      $H = 1.82\, F_c\, [54.86(T_f - T_a)/L]^{0.25} \exp[-T_{ave}/1611]$ ($W/m^2 \cdot K$)
      Forced Convection
      U = Average air velocity (m/sec)
      L = Length of side parallel to air flow (cm)
      $H = 3.833(U/L)^{0.5}$ ($W/m^2 \cdot K$)
   b. Calculate convection loss. Given the following:
      A = Area of exposed surface (cm^2)
      T_f = Heat sink temperature (°C)

T_a = Ambient temperature (°C)
P_{cv} = Convective loss (W) = $HA(T_f–T_a)/10000$

II. Calculate process heat requirements. If the heater is used for continuous processing (warming, melting, or vaporizing of materials other than the heat sink), calculate power lost to the processed material. For this formula, T_f and T_i are the initial and final temperatures of the processed material. Skip if the heater merely maintains temperature.
For continuous process, substitute the mass flow rate for m/t.
Given the following:

m = Mass of material in each process load (g)
t = Cycle time for each load (s)
Cp = Specific heat of material from Table 1 (J/kg·K)
h = Latent heat of fusion (melting) or vaporization from Table 1 if processed material will change state (J/g)
T_f = Final temperature of material (°C)
T_i = Initial temperature of material (°C)
P_p = Process heat (W) = $(m/t)[(C_p(T_f–T_i)/1000)+h]$

III. Calculate operating heat requirements. The total operating power (after warm-up) is the sum of conductive, radiant, and convective losses plus process power.
$P_o = P_{cd} + P_r + P_{cv} + P_p$

IV. Calculate warm-up requirements. Calculate the power needed to bring the heat sink to temperature in the desired time. Given the following:

m = Mass of material (g)
C_p = Specific heat of material from Table 1 (J/kg·K)
T_f = Final temperature of heat sink (°C)
T_i = Initial temperature of heat sink (°C)
T_a = Ambient temperature (°C)
t = Desired warm-up time (min)
P_{sl} = Steady-state loss (W) = $P_{cd} + P_r + P_{cv}$
H_w = Warm-up coefficient = $P_{si} /(T_f – T_a)$
P_w = Warm-up power (W) = $H_w(T_f–T_i)/(1- \exp(-60000H_w t/(mC_p)) + H_w(T_i – T_a)$
Note: exp (x) = 2.718^x

V. Calculate total heater power. The total power requirement is steady-state power or warm-up power, whichever is larger. Specify actual wattage at least 10% greater than this figure.
P_t = Minimum total power required (W) = Maximum of P_o or P_w
CAUTION: These figures are estimates only. You must operate the heater in your equipment, under actual environmental conditions, to make a final determination of power.

Table 1: Thermal properties of Common Materials

Typical values near room temperature. Contact your material supplier for unlisted materials.

Material	Density (g/cm^3)	Specific heat (J/kg·K)	Thermal conductivity (W/m·K)	Latent heat of fusion or *vaporization (J/g)
ABS	1.217	2090	0.331	
Acetone 100%	0.785	2150	0.166	*523
Acrylic	1.185	1460	0.144	
Aluminum 1100-0	2.71	900	221	393
Aluminum 2024-T4	2.77	875	121	388
Aluminum 6061-T6	2.70	896	167	400
Benzene	0.897	1760	0.15	*395
Beryllium	1.818	217	162	
Brass (70-30)	8.568	418	121	
Brass (80-20)	8.408	380	138	
Butyl Alcohol	0.726	2870		*591
Constantan	8.889	376	21.3	
Copper	8.969	418	394	
Epoxy	1.409	1250	0.346	
Ethyl Alcohol, 95%	0.807	2510	0.187	*861
Fiberglass (Duct Ins.)	0.012		0.0403	
Fiberglass (Spin-Glas)	0.048		0.0375	
Fluoroplastics	2.402	1170	0.245	
Glass	2.643	836	1.04	
Glycerine	1.26	2420	0.284	
Gold	19.315	125	297	
Ice	0.833	2050	2.25	335
Inconel	8.488	460	15	
Iron (Cast)	7.207	544	57.1	
Iron (Wrought)	7.688	502	62.2	
Kerosene	0.809	1970	0.144	*200
Magnesium	1.746	1050	154	
Mercury	13.533	138	8.76	11.6
Mica	2.963	836	0.432	
Molybdenum	10.218	255	141	
Mylar	1.265	1130	0.648	
Nichrome (80-20)	8.296	460	15	
Nickel 200	8.873	460	67.4	
Nylon	1.153	2090	0.245	
Oil, SAE 10W-30	0.89	1800		
Paraffin, Solid	0.9	2880	0.259	147
Paraffin, Melted	0.897	2880	0.242	*163
Platinum	21.445	130	69.2	
Polycarbonate	1.201	1250	0.202	
Polyethylene	0.961	2260	0.504	
Polyimides	1.441	1300	0.98	
Propyl Alcohol	0.804	2380		*687
Silicon	0.232	677	86.5	
Silicone Rubber	1.25	1880	0.216	
Silver	10.49	234	418	
Solder (60/40)	8.648	188	51.2	65.1
Stainless Steel (300)	8.008	502	16.3	
Stainless Steel (430)	7.752	460	21.6	
Steel (Mild Carbon)	7.848	502	65.7	
Sulfuric Acid, 98%	1.837	1460	0.259	*509
Tin, Solid	7.303	234	67.4	
Titanium	4.5	527	19.9	
Transformer Oils	0.902	1760	0.13	
Vegetable Oil	0.921	1800		
Water	0.999	4180	0.588	*2250
Zinc	7.127	397	27.1	

Table 2: Emissivities of Common Materials

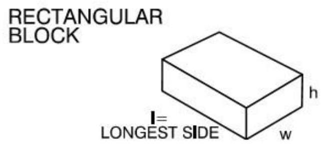
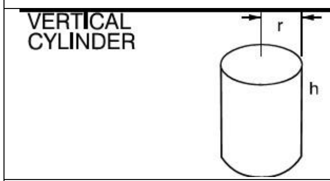
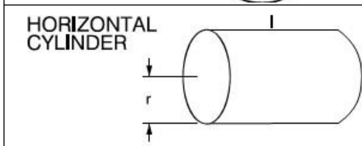
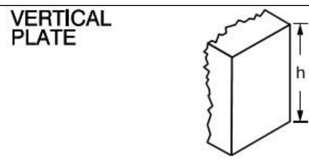
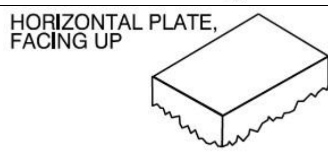
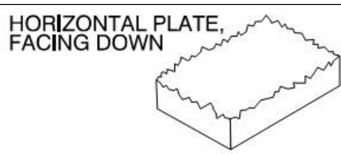
Typical values near room temperature. Contact your material supplier for unlisted materials.

Material	Emissivity
Blackbody	1.0
Aluminum, bright foil	0.07
Aluminum, heavy oxide	0.22
Aluminum, anodized	0.82
Brass, polished	0.04
Brass, heavy oxide	0.60
Copper, polished	0.03
Copper, heavy oxide	0.80
Epoxy	0.95
Glass	0.90
Gold	0.02
Iron, heavy oxide	0.85
Paint (non-metallic)	0.98
Plastics (typical)	0.95
Silicone Rubber	0.95
Silver	0.02
Stainless steel, polished	0.17
Stainless steel, heavy oxide	0.85
Steel (mild), polished	0.10
Steel (mild), heavy oxide	0.85
Zinc	0.25

Disclaimer

There is no warranty regarding the accuracy of information in this white paper. The user is cautioned that the procedures given here only yield estimates, not absolute values. You must make the final determination of the suitability of a heater for your application.

Table 3: Volume, surface area and convection data for common solids

Shape	Volume	Surface area	Characteristic length*	Configuration factor
	V = lwh	A = 2(lw + lh + wh)	L = l·h/(l+h)	0.93
	$V = \pi h r^2$	$A = 2\pi r(r + h)$	L = h	1
	$V = \pi l r^2$	$A = 2\pi r(r + l)$	L = 2r	0.90
		Depends on shape	L = h	1
		Depends on shape	$L = \frac{4 \text{ x Area}}{\text{Perimeter}}$	1.29
		Depends on shape	$L = \frac{4 \text{ x Area}}{\text{Perimeter}}$	0.65

Characteristic length is a factor relating convective heat loss to the shape and orientation of a surface.

Assumptions

This white paper makes the following simplifying assumptions:

- The heat sink, heater, and processed material are at a uniform temperature. This is of course not strictly true. Gradients exist. Outer surfaces are cooler than areas under the heater. But assuming that all temperatures are equal to the setpoint temperature spares us the iterative calculations needed to precisely characterize heat profiles.
- All convection is laminar. The alternative is turbulent convection, a condition occurring with large heaters and high temperatures.
- The convective fluid is air. Different equations are required if the heater is immersed in other media.
- For radiant heat transfer, the surrounding environment is a blackbody at ambient temperature. This is usually a good assumption in large open areas but may not be in a small enclosure.
- Values are conservative. Approximations are chosen to give values higher than the true value, ensuring that heaters will have more than sufficient power for the application.

Sample Calculations

The following is a typical heater application to illustrate the use of the estimation procedure.

For example, we are designing a reflow machine to melt solder on circuit boards. At the core of the machine is a rectangular 6061-T6 aluminum block (Figure 1):

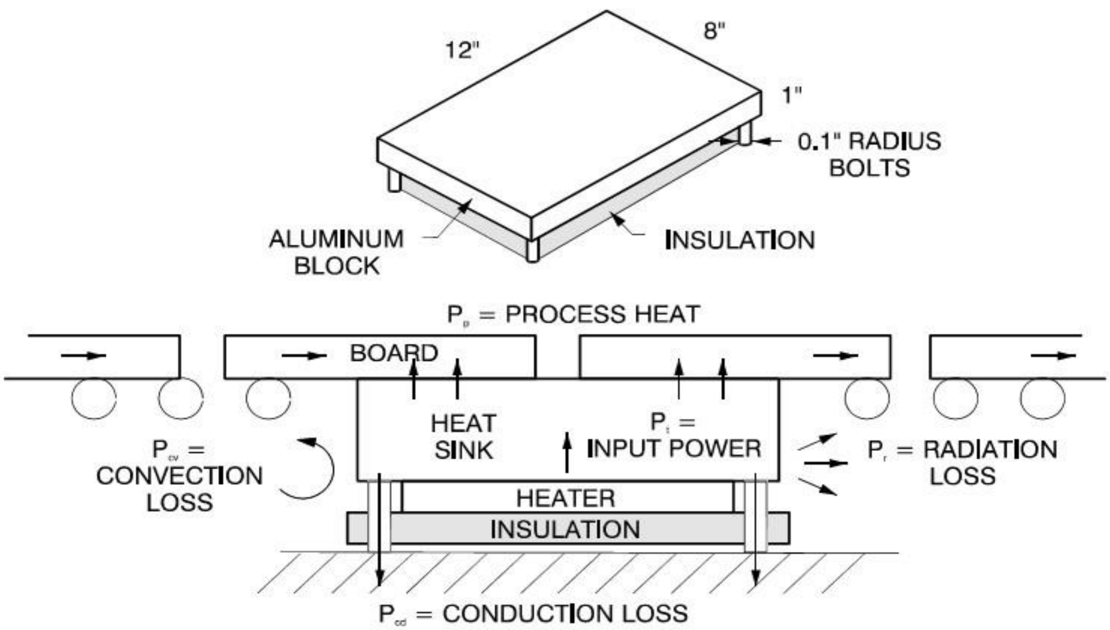


Figure 1

The block is mounted with 1" long steel bolts of 0.1" radius and has 1" of fiberglass insulation beneath it. We want it at an operating temperature of 204.44°C, within five minutes of powering up. The initial temperature is equal to ambient, 21.11°C.

Once in operation, the machine deposits an epoxy-glass circuit board on the block every ten seconds. The dimensions of the board are 6" x 12" x 0.1", and it has 0.01 lb of solder on it to be melted. What is the heat required for warm-up, steady-state maintenance, and processing?

I. Calculate steady state heat losses.

1. **Conduction losses.** We calculate conductive losses through the fiberglass insulation and mounting bolts.

   Cross-sectional area (A):
   Insulation: 8in x 12in x $(2.54\text{cm/in})^2$ = 619.4 cm^2
   Bolts: $4(0.1\text{in})^2 \times \pi \times (2.54\text{cm/in})^2$ = 0.811 cm^2

   Thermal conductivity values (K):
   Insulation: 0.0375 W/m·K
   Bolts: 65.7 W/m·K
   Using the formula in "Heater Wattage Estimation Procedure" section I.1. for the conductive losses, the loss through the insulation is 17 watts and the loss through the bolts is 38 watts. The total conduction loss (P_{cd}) is 55 watts.

2. **Radiation losses**. We will ignore losses from the insulated surface.

The surface area (A) is the top plus the sides =
[(12in x 8in) + 2(12in x 1in) + 2(8in x 1in)] x $(2.54cm/in)^2$ = 877.4 cm^2
Emissivity (∈) is 0.22 from Table 2.

From the formula in section I.2. the radiation loss (P_r) is 49 watts.

3. **Convection losses.** We will ignore convective losses from the insulated underside. The top is a horizontal plate facing up; the sides are vertical plates. Configuration factors (F_c) come from Table 3.

Characteristic length (L):
Top: (4 x 12in x 8in)/[2(12in + 8in)] x (2.54cm/in) = 24.38 cm
Sides: 1in x (2.54cm/in) = 2.54 cm

Area (A):
Top: 12in x 8in x $(2.54cm/in)^2$ = 619.4 cm^2
Sides: [2(12in x 1in) + 2(8in x 1in)] x $(2.54cm/in)^2$ = 258.1 cm^2

From the formula in section I.3. and the configuration factors from Table 3, the natural convection loss from the top of the rectangular block is 113.5 watts and from the sides of the block is 64.5 watts. The total convection loss is (P_{cv}) 178 watts.

II. Process heat requirements. We now calculate the heat needed to bring the board to temperature and melt the solder. The heat required to melt the solder, although negligible, is shown here as an example of calculating a state change.

The time cycle for the process (t) = 10 seconds.
Final temperature of material (T_f) = 204.44°C
Initial temperature of material (T_i) = 21.11°C

The mass of the circuit board is the volume times the density of epoxy from Table 1. (6" x 12" x 0.1") x $(2.54cm/in)^3$ x $(1.41g/cm^3)$ = 166.4g
The specific heat (C_p) of the circuit board = 1250 J/kg·K

The mass of the solder is given as 0.01 lb x (1000g/2.205lb) = 4.54 g
The specific heat of the solder (C_p) = 188 J/kg·K.
Latent heat of fusion (h) = 65.1 J/g

From the formula in section II, the process heat required to heat the board is 3813 watts and the heat required to melt the solder is 45 watts. The total process power (P_p) required is 3858 watts.

III. Calculate operating heat requirements. The total operating power (P_o) required is the sum of the losses (conduction, radiation, and convection) and the process heat requirement. The total operating power is 4140 watts.

IV. Calculate warm-up requirements. The mass of the aluminum heat sink is the volume times the density.

(12in x 8in x 1in) x $(2.54cm/in)^3$ x $(2.71 g/cm^3)$ = 4264g.

From the formulas in section IV, the warm-up coefficient (H_w) is 1.54 and the total warm up power (P_w) is 2480 watts.

V. Calculate total heater power. Total input power (P_t) is the greater of warm-up power (P_w) or operating power (P_o). In this example, the process heat needed to warm the circuit board represents the largest share of the heat requirement. We will add an extra 10% for unknown losses to the operating power (4140 watts) to arrive at the specified heater wattage of 4554 watts.

Dividing the total wattage by the heater area gives a watt density of 4554 W / 96 in^2 = 48.4 W/in^2 (or 7.35 W/cm^2).

Determining Heat Requirements

By Experimentation

Calculations and theory are no substitute for experimentation when designing thermal equipment for optimum performance. Mathematical methods cannot account for all the variables acting upon the system. At some point you will have to mount a heater to your part and power it up to see how it works. If you have used this white paper to estimate power beforehand and have added a sufficient safety factor, your specified wattage should do the job. If not, you will have to redesign.
You can often save money by testing with standard etched-foil heaters before investing in a custom model. The usual procedure is to connect a variable power supply to the heater and gradually increase power until the system performs as desired (or the heater reaches its maximum power rating). A proportional or on-off controller, placed in series with the variable power supply and heater, can simulate real-life control.

Standard heaters come in several resistances. You should specify a resistance low enough to give you the highest wattage you might need at your variable power supply's maximum voltage ($P = V^2/R$).
If you cannot find a standard heater with the correct physical dimensions, contact your supplier. All models with the same nominal voltage, all 28-volt heaters for example, have identical watt densities. If you make a mosaic of these heaters to emulate a larger one and power them in parallel, the watt density will be uniform across all the heaters. Using a 28-volt source gives 5 watts per square inch but heaters can operate at other voltages.

Thermal Simulation

One other technique to estimate power requirements is to perform thermal simulations using computerized techniques such as finite element analysis (FEA) and computational fluid dynamics (CFD). Thermal simulation is commonly employed in the design and optimization of etched-foil heaters to predict and understand their thermal performance. It is useful when simple numerical calculations are not adequate and/or to save on experimental time and costs.

Some of the uses of thermal simulation are to model warm-ups, process loads, control systems, sensor locations; perform sensitivity analysis, map thermal gradients across complex shapes, and determine watt-density zones for profiled heaters.

Achieving Uniform Heat with Dual Element and Profiled Heaters Balancing loads with multiple elements:

What happens if warm-up heat is much greater than steady-state loss (a common situation)? Once the heater reaches setpoint, its excess wattage overpowers the controller and causes temperature spikes.

One solution is to design a heater with two interwoven heating elements. The higher wattage element runs at full power until the controller shuts it off just below the setpoint. The second element, proportionally controlled, maintains setpoint temperature with an ideal duty cycle of 50%. Assuming the warm-up heat requirement is P_w and steady-state loss is P_{sl}, we will specify the warm-up element at (P_w -

$2P_{sl}$) watts and the steady-state element at $2P_{sl}$ watts. This technique also applies when process heat requirements exceed steady-state requirements.

Profiling heater watt-densities:
Our calculations have assumed that all areas of the heater and heat sink are at the same temperature. In reality, large gradients can develop across heat sinks. To obtain uniform temperatures at all points specify a heater with different heat levels in different zones, for example greater watt-densities along the edges to compensate for loss. Contact your supplier for assistance when profiling heaters.

Summary

Determining heater wattage is a crucial step in specifying an etched-foil heater design. In most cases, the best approach is a combination of numerical methods and experimentation. By using the formulas presented in this white paper, you can determine an estimate of your wattage needs. Although they may not be absolutely accurate and cannot account for all the variables that act upon a system, they will provide you with a reasonable starting point from which you can begin your experiments. Thermal simulation can be used in cases where simple numerical or experimental options are not suitable.

Exclusively from Minco – The Heater Wattage Estimator Online Calculator!

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