Electric Heaters

Power Calculations

Calculations for Required Heat Energy

When performing your own calculations, refer to the Reference Data section (begins on page 127) for values of materials covered by these equations.

The total heat energy (kWH or Btu) required to satisfy the system needs will be either of the two values shown below depending on which calculated result is larger.

A. Heat Required for Start-Up

B. Heat Required to Maintain the Desired Temperature

The power required (kW) will be the heat energy value (kWH) divided by the required start-up or working cycle time. The kW rating of the heater will be the greater of these values plus a safety factor.

The calculation of start-up and operating requirements consist of several distinct parts that are best handled separately. However, a short method can also be used for a quick estimate of heat energy required. Both methods are defined and then evaluated using the following formulas and methods:

Short Method

Start-up watts = A + C + ⅔L + Safety Factor

Operating watts = B + D + L + Safety Factor

Safety Factor is normally 10 percent to 35 percent based on application.

A = Watts required to raise the temperature of material and equipment to the operating point, within the time desired

B = Watts required to raise temperature of the material during the working cycle

Equation for A and B (Absorbed watts-raising temperature)

$$\frac{\text{Weight of material (lbs)} \cdot \begin{array}{c}\text{Specific heat}\\ \text{of material}\\ \text{(Btu/lb} \cdot {}^\circ\text{F)}\end{array} \cdot \text{temperature rise (}^\circ\text{F)}}{\text{Start-up or cycle time (hrs)} \cdot 3.412}$$

C = Watts required to melt or vaporize material during start-up period

D = Watts required to melt or vaporize material during working cycle

Equation for C and D (Absorbed watts-melting or vaporizing)

$$\frac{\text{Weight of material (lbs)} \cdot \text{heat of fusion or vaporization (Btu/lb)}}{\text{Start-up or cycle time (hrs)} \cdot 3.412}$$

L = Watts lost from surfaces by:

- Conduction-use equation below
- Radiation-use heat loss curves
- Convection-use heat loss curves

Equation for L (Lost conducted watts)

$$\frac{\begin{array}{c}\text{Thermal conductivity}\\ \text{of material or insulation}\\ (\text{Btu} \cdot \text{in./ft}^2 \cdot {}^\circ\text{F} \cdot \text{hr})\end{array} \quad \begin{array}{c}\text{Surface area}\\ (\text{ft}^2)\end{array} \quad \begin{array}{c}\text{Temp. differential}\\ \text{to ambient}\\ ({}^\circ\text{F})\end{array}}{\text{Thickness of material or insulation (in.)} \cdot 3.412}$$

Application Guide

Electric Heaters

Power Calculations—Conduction and Convection Heating

Equation 1—Absorbed Energy, Heat Required to Raise the Temperature of a Material

Because substances all heat differently, different amounts of heat are required in making a temperature change. The specific heat capacity of a substance is the quantity of heat needed to raise the temperature of a unit quantity of the substance by one degree. Calling the amount of heat added Q, which will cause a change in temperature ΔT to a weight of substance W, at a specific heat of material C_p, then $Q = w \cdot C_p \cdot \Delta T$.

Since all calculations are in watts, an additional conversion of 3.412 Btu = 1 Wh is introduced yielding:

Equation 1

$$Q_A \text{ or } Q_B = \frac{w \cdot C_p \cdot \Delta T}{3.412}$$

Q_A = Heat Required to Raise Temperature of Materials During Heat-Up (Wh)

Q_B = Heat Required to Raise Temperature of Materials Processed in Working Cycle (Wh)

w = Weight of Material (lb)

C_p = Specific Heat of Material (Btu/lb • °F)

ΔT = Temperature Rise of Material ($T_{Final} - T_{Initial}$)(°F)

This equation should be applied to all materials absorbing heat in the application. Heated media, work being processed, vessels, racks, belts, and ventilation air should be included.

Example: How much heat energy is needed to change the temperature of 50 lbs of copper from 10°F to 70°F?

$$Q = w \cdot C_p \cdot \Delta T$$

$$= \frac{(50 \text{ lbs}) \cdot (0.10 \text{ Btu/lb} \cdot {}^\circ\text{F}) \cdot (60^\circ\text{F})}{3.412} = 88 \text{ (Wh)}$$

Equation 2—Heat Required to Melt or Vaporize a Material

In considering adding heat to a substance, it is also necessary to anticipate changes in state that might occur during this heating such as melting and vaporizing. The heat needed to melt a material is known as the **latent heat of fusion** and represented by H_f. Another state change is involved in vaporization and condensation. The **latent heat of vaporization** H_v of the substance is the energy required to change a substance from a liquid to a vapor. This same amount of energy is released as the vapor condenses back to a liquid.

Equation 2

$$Q_C \text{ or } Q_D = \frac{w \cdot H_f}{3.412} \quad \text{OR} \quad \frac{w \cdot H_v}{3.412}$$

Q_C = Heat Required to Melt/Vaporize Materials During Heat-Up (Wh)

Q_D = Heat Required to Melt/Vaporize Materials Processed in Working Cycle (Wh)

w = Weight of Material (lb)

H_f = Latent Heat of Fusion (Btu/lb)

H_v = Latent Heat of Vaporization (Btu/lb)

Example: How much energy is required to melt 50 lbs of lead?

$$Q = w \cdot H_f$$

$$= \frac{(50 \text{ lbs}) \cdot (9.8 \text{ Btu/lb})}{3.412 \text{ Btu/(Wh)}} = 144 \text{ (Wh)}$$

Changing state (melting and vaporizing) is a constant temperature process. The C_p value (from Equation 1) of a material also changes with a change in state. Separate calculations are thus required using Equation 1 for the material below and above the phase change temperature.

Electric Heaters

Power Calculations

Continued

Conduction Heat Losses

Heat transfer by conduction is the contact exchange of heat from one body at a higher temperature to another body at a lower temperature, or between portions of the same body at different temperatures.

Equation 3A—Heat Required to Replace Conduction Losses

$$Q_{L1} = \frac{k \cdot A \cdot \Delta T \cdot t_e}{3.412 \cdot L}$$

Q_{L1} = Conduction Heat Losses (Wh)

k = Thermal Conductivity (Btu • in./ft^2 • °F • hour)

A = Heat Transfer Surface Area (ft^2)

L = Thickness of Material (in.)

ΔT = Temperature Difference Across Material (T_2-T_1) °F

t_e = Exposure Time (hr)

This expression can be used to calculate losses through insulated walls of containers or other plane surfaces **where the temperature of both surfaces can be determined or estimated**. Tabulated values of thermal conductivity are included in the Reference Data section (begins on page 134).

Convection Heat Losses

Convection is a special case of conduction. Convection is defined as the transfer of heat from a high temperature region in a gas or liquid as a result of movement of the masses of the fluid. The Reference Data section (page 127) includes graphs and charts showing natural and forced convection losses under various conditions.

Equation 3B—Convection Losses

$$Q_{L2} = A \cdot F_{SL} \cdot C_F$$

Q_{L2} = Convection Heat Losses (Wh)

A = Surface Area (in^2)

F_{SL} = Vertical Surface Convection Loss Factor (W/in^2) Evaluated at Surface Temperature (See Ref. 9, page 26)

C_F = Surface Orientation Factor

Heated surface faces up horizontally = 1.29

Vertical = 1.00

Heated surface faces down horizontally = 0.63

Radiation Heat Losses

For the purposes of this section, graphs are used to estimate radiation losses. Charts in the Reference Data section (page 127) give emissivity values for various materials.
Radiation losses are **not** dependent on orientation of the surface.
Emissivity is used to adjust for a material's ability to radiate heat energy.

Equation 3C—Radiation Losses

$$Q_{L3} = A \cdot F_{SL} \cdot e$$

Q_{L3} = Radiation Heat Losses (Wh)

A = Surface Area (in^2)

F_{SL} = Blackbody Radiation Loss Factor at Surface Temperature (W/in^2)

e = Emissivity Correction Factor of Material Surface

Example:

Using Reference 139, page 155, we find that a blackbody radiator (perfect radiator) at 500°F, has heat losses of 2.5 W/in^2.
Polished aluminum, in contrast, (e = 0.09) only has heat losses of 0.22 W/in^2 at the same temperature (2.5 W/in^2 • 0.09 = 0.22 W/in^2).

Electric Heaters

Power Calculations

Continued

Combined Convection and Radiation Heat Losses

Some curves in Reference 139 (page 155) combine both radiation and convection losses. This saves you from having to use both Equations 3B and 3C. If only the convection component is required, then the radiation component must be determined separately and subtracted from the combined curve.

Equation 3D—Combined Convection and Radiation Heat Losses

$$Q_{L4} = A \cdot F_{SL}$$

Q_{L4} = Surface Heat Losses Combined Convection and Radiation (Wh)
A = Surface Area (in^2)
F_{SL} = Combined Surface Loss Factor at Surface Temperature (W/in^2)

This equation assumes a constant surface temperature.

Total Heat Losses

The total conduction, convection and radiation heat losses are summed together to allow for all losses in the power equations. Depending on the application, heat losses may make up only a small fraction of total power required... or it may be the largest portion of the total. Therefore, **do not** ignore heat losses unless previous experience tells you it's alright to do.

Equation 3E—Total Losses

$Q_L = Q_{L1} + Q_{L2} + Q_{L3}$ If convection and radiation losses are calculated separately. (Surfaces are not uniformly insulated and losses must be calculated separately.)

OR

$Q_L = Q_{L1} + Q_{L4}$ If combined radiation and convection curves are used. (Pipes, ducts, uniformly insulated bodies.)

Equations 4 and 5 Start-Up and Operating Power Required

Both of these equations estimate required energy and convert it to power. Since power (watts) specifies an energy rate, we can use power to select electric heater requirements. Both the start-up power and the operating power must be analyzed before heater selection can take place.

Equation 4—Start-Up Power (Watts)

$$P_s = \left[\frac{Q_A + Q_C}{t_s} + \frac{2}{3}(Q_L)\right] \cdot (1 + \text{S.F.})$$

Q_A = Heat Absorbed by Materials During Heat-Up (Wh)
Q_C = Latent Heat Absorbed During Heat-Up (Wh)
Q_L = Conduction, Convection, Radiation Losses (Wh)
S.F. = Safety Factor
t_s = Start-Up (Heat-Up) Time Required (hr)

During start-up of a system the losses are zero, and rise to 100 percent at process temperature. A good approximation of actual losses is obtained when heat losses (Q_L) are multiplied by ⅔ .

Equation 5—Operating Power (Watts)

$$P_o = \left[\frac{Q_B + Q_D}{t_c} + (Q_L)\right] \cdot (1 + \text{S.F.})$$

Q_B = Heat Absorbed by Processed Materials in Working Cycle (Wh)
Q_D = Latent Heat Absorbed by Materials Heated in Working Cycle (Wh)
Q_L = Conduction, Convection, Radiation Losses (Wh)
S.F. = Safety Factor
t_c = Cycle Time Required (hr)

Electric Heaters

Power Calculations—Radiant Heating

When the primary mode of heat transfer is radiation, we add a step after Equation 5.

Equation 6 is used to calculate the net radiant heat transfer between two bodies. We use this to calculate either the radiant heater temperature required or (if we know the heater temperature, but not the power required) the maximum power which can be transfered to the load.

Equation 6—Radiation Heat Transfer Between Infinite Size Parallel Surfaces

$$\frac{P_R}{A} = \frac{S\ (T_1^4 - T_2^4)\left(\frac{1}{e_f}\right)\ F}{(144\ \text{in}^2/\text{ft}^2)\ \ (3.412\ \text{Btu/Wh})}$$

P_R = Power Absorbed by the Load (watts) - from Equation 4 or 5
A = Area of Heater (in^2) - known or assumed
S = Stephan Boltzman Constant
= $0.1714 \cdot 10^{-8}$ (Btu/Hr. Sq. Ft. °R^4)
T_1(°R) = Emitter Temperature (°F + 460)
T_2(°R) = Load Temperature (°F + 460)
e_f = Emissivity Correction Factor - see below
F = Shape Factor (0 to 1.0) - from Reference 139, page 155

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e_S = Heater Emissivity (from Material Emissivity Tables)
e_L = Load Emissivity (from Material Emissivity Tables)
D_S = Heater Diameter
D_L = Load Diameter

Emissivity Correction Factor (e_f)

$$e_f = \frac{1}{e_S} + \frac{1}{e_L} - 1$$

Plane Surfaces

$$e_f = \frac{1}{e_S} + \frac{D_S}{D_L}\left(\frac{1}{e_L} - 1\right)$$

Concentric Cylinders
Inner Radiating Outward

$$e_f = \frac{1}{e_S} + \left(\frac{D_S}{D_L} \cdot \frac{1}{e_L}\right) - 1$$

Concentric Cylinders
Outer Radiating Inward

Power Evaluation

After calculating the start-up and operating power requirements, a comparison must be made and various options evaluated.

Shown in Reference 1 are the start-up and operating watts displayed in a graphic format to help you see how power requirements add up.

With this graphic aid in mind, the following evaluations are possible:

- Compare start-up watts to operating watts.
- Evaluate effects of lengthening start-up time such that start-up watts equals operating watts (use timer to start system before shift).

Comparison of Start-Up and Operating Power Requirements

Ref. 1