Fundamentals of Heat and Mass Transfer

Chapter 1

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Second Law of Thermodynamics (1 of 5)

- The first law of thermodynamics specifies the relationship among different forms of energy when there is a transformation.
- It does not tell us anything about whether a transformation takes place or not.
- The second law completes this lack in the first law. It identifies the processes which are possible and that which are impossible.

Second Law of Thermodynamics (2 of 5)

There are two statements of the second law of thermodynamics which are stated as follows:

(1) The First Statement: There is no device that can transform all the heat input into useful work. That is to say, there is no device that has 100 percent efficiency. Thus, part of the supplied heat, as an input, is lost to a heat sink.

(2) The Second Statement: There is no device that can by itself move heat from a low temperature reservoir to a high temperature reservoir.

Second Law of Thermodynamics (3 of 5)

- The first law of thermodynamics specifies the relationship among If there is a device that does that kind of work it must be run by an outside power.

- **The example of the first statement is internal combustion engine**

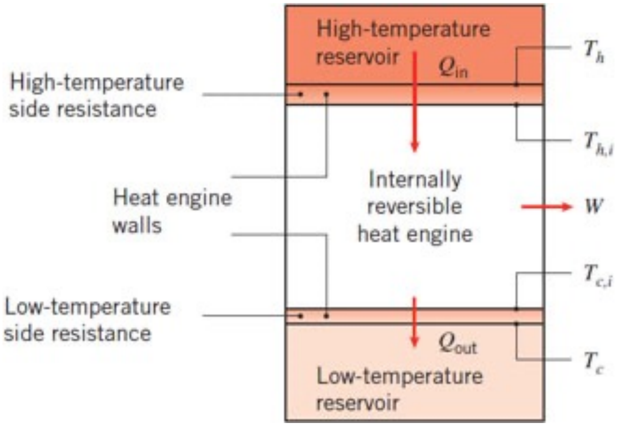
- **The example of the second statement is the refrigeration cycle.** In such a cycle, heat is removed from the evaporator, which is at low temperature, and it is thrown into the ambient surrounding through the condenser, which is at a higher temperature. Outside power must be supplied to the compressor, which makes this heat transfer possible.

Second Law of Thermodynamics (4 of 5)

For a reversible heat engine neglecting heat transfer effects between the heat engine and large reservoirs, the Carnot efficiency is

$$\eta_C = \frac{W}{Q_{\text{in}}} = 1 - \frac{Q_{\text{out}}}{Q_{\text{in}}} = 1 - \frac{T_c}{T_h} \qquad (1.15, 1.16)$$

where T_c and T_h are the absolute temperatures of large cold and hot reservoirs, respectively. For an internally reversible heat engine with heat transfer to and from the large reservoirs properly accounted for, the modified Carnot efficiency is



$$\eta_m = \frac{W}{Q_{\text{in}}} = 1 - \frac{Q_{\text{out}}}{Q_{\text{in}}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{T_{c,i}}{T_{h,i}} \qquad (1.17)$$

where $T_{c,i} > T_c$ and $T_h > T_{h,i}$ are the absolute temperatures seen by the internally reversible heat engine. Note that q_{out} and q_{in} are heat transfer rates (J/s or W).

Internally reversible heat engine exchanging heat with high- and low-temperature reservoirs through thermal resistances.

Second Law of Thermodynamics (5 of 5)

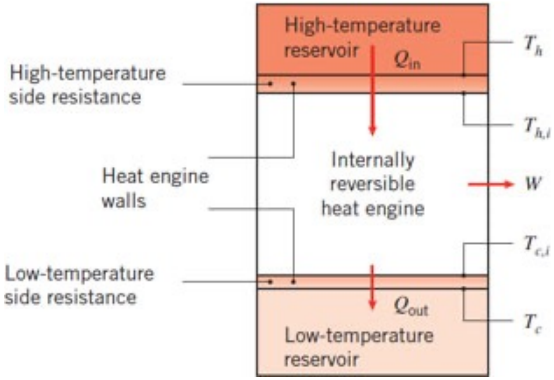
- Heat transfer resistances associated with, for example, walls separating the internally reversible heat engine from the hot and cold reservoirs relate the heat transfer rates to temperature differences:

$$(T_h - T_{h,i}) = q_{in} R_{t,h} \qquad (T_{c,i} - T_c) = q_{out} R_{t,c} \qquad (1.18\text{ a, b})$$

In reality, heat transfer resistances (K/W) must be non-zero since according to the rate equations, for any temperature difference only a finite amount of heat may be transferred.

The modified Carnot efficiency may ultimately be expressed as

$$\eta_m = 1 - \frac{T_c}{T_h - q_{in} R_{tot}} \text{ where } R_{tot} = R_{t,h} + R_{t,c} \qquad (1.21)$$



From Equation 1.21,

- $\eta_m = \eta_c$ only if R_{tot} could be made infinitely small
- For realistic situations ($R_{tot} \neq 0$), $\eta_m < \eta_c$
- Good heat transfer engineering is a key to improve the efficiency of heat engines.

EXAMPLE 1.7

In a large steam power plant, the combustion of coal provides a heat rate of qin = 2500 MW at a flame temperature of T_h = 1000 K.

Heat is rejected from the plant to a river flowing at T_c = 300 K.

Heat is transferred from the combustion products to the exterior of large tubes in the boiler by way of radiation and convection, through the boiler tubes by conduction, and then from the interior tube surface to the working fluid (water) by convection.

On the cold side, heat is extracted from the power plant by condensation of steam on the exterior condenser tube surfaces, through the condenser tube walls by conduction, and from the interior of the condenser tubes to the river water by convection.

Hot and cold side thermal resistances account for the combined effects of conduction, convection, and radiation and, under design conditions, they are $R_{t,h}$ = 8 × 10−8 K/W and $R_{t,c}$ = 2 × 10−8 K/W, respectively.

EXAMPLE 1.7

1. Determine the efficiency and power output of the power plant, accounting for heat transfer effects to and from the cold and hot reservoirs.

Treat the power plant as an internally reversible heat engine.

2. Over time, coal slag will accumulate on the combustion side of the boiler tubes. This fouling process increases the hot side resistance to $R_{t,h} = 9 \times 10{-}8$ K/W. Concurrently, biological matter can accumulate on the river water side of the condenser tubes, increasing the cold side resistance to $R_{t,c} = 2.2 \times 10{-}8$ K/W. Find the efficiency and power output of the plant under fouled conditions.

SOLUTION

Known: Source and sink temperatures and heat input rate for an internally reversible heat engine. Thermal resistances separating heat engine from source and sink under clean and fouled conditions.

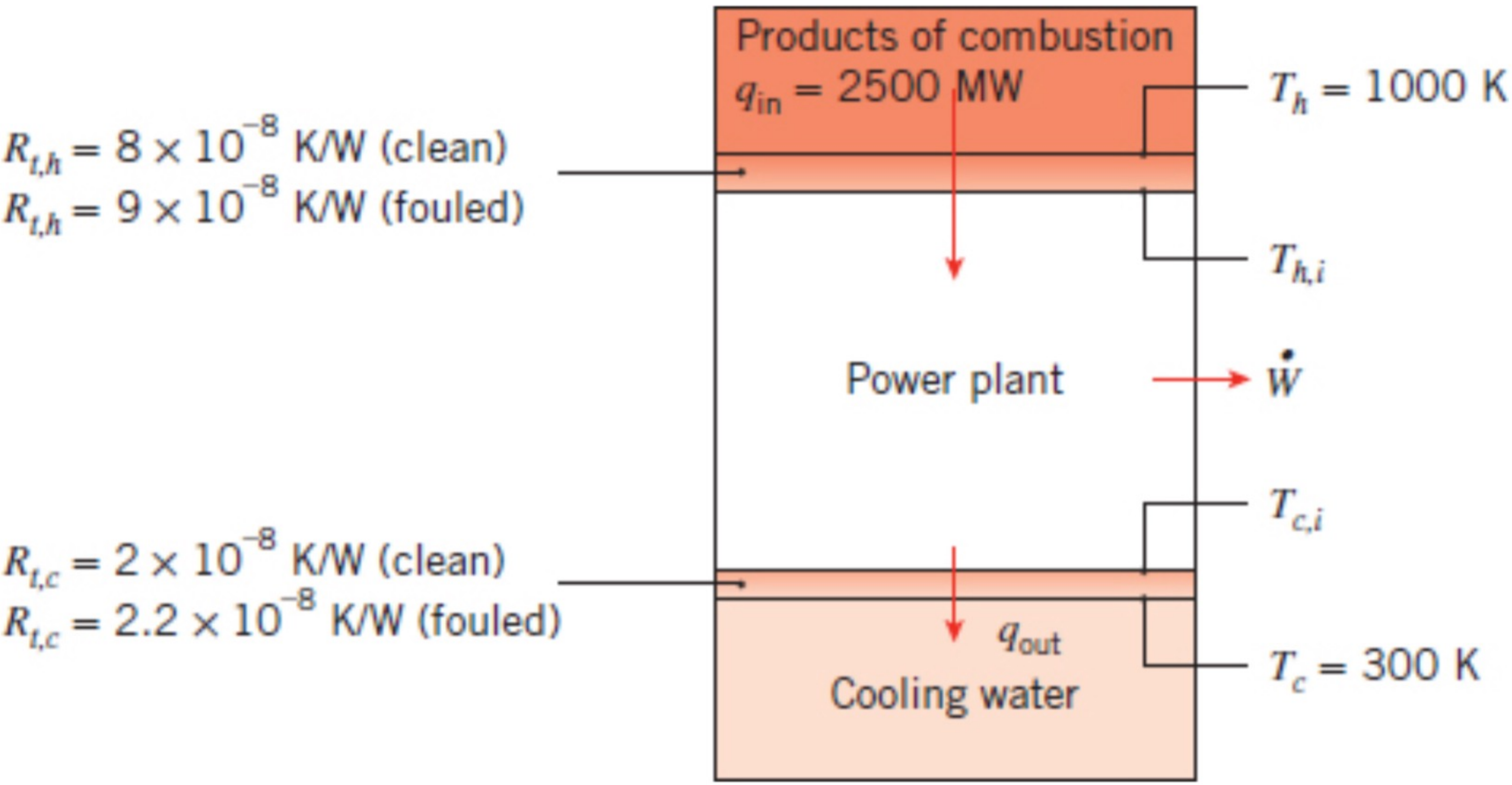
Find:

1. Efficiency and power output for clean conditions.

2. Efficiency and power output under fouled conditions.

EXAMPLE 1.7

Schematic:



EXAMPLE 1.7

Assumptions:

1. Steady-state conditions.

2. Power plant behaves as an internally reversible heat engine, so its efficiency is the modified efficiency.

Analysis:

1. The modified efficiency of the internally reversible power plant, considering realistic heat transfer effects on the hot and cold sides of the power plant:

EXAMPLE 1.7

$$\eta_m = 1 - \frac{T_c}{T_h - q_{in} R_{tot}}$$

where, for clean conditions

$$R_{tot} = R_{t,h} + R_{t,c} = 8 \times 10^{-8}\ \text{K/W} + 2 \times 10^{-8}\ \text{K/W} = 1.0 \times 10^{-7}\ \text{K/W}$$

Thus

$$\eta_m = 1 - \frac{T_c}{T_h - q_{in} R_{tot}} = 1 - \frac{300\ \text{K}}{1000\ \text{K} - 2500 \times 10^6\ \text{W} \times 1.0 \times 10^{-7}\ \text{K/W}} = 0.60 = 60\,\%$$

The power output is given by

$$\dot{W} = q_{in}\,\eta_m = 2500\ \text{MW} \times 0.60 = 1500\ \text{MW}$$

2. Under fouled conditions, the preceding calculations are repeated to find

$$\eta_m = 0.583 = 58.3\,\% \ \text{and}\ \dot{W} = 1460\ \text{MW}$$

EXAMPLE 1.7

Comments:

1. The actual efficiency and power output of a power plant operating between these temperatures would be much less than the foregoing values, since there would be other irreversibilities internal to the power plant. Even if these irreversibilities were considered in a more comprehensive analysis, fouling effects would still reduce the plant efficiency and power output.

2. The Carnot efficiency is $\eta_c = 1 - T_c/T_h = 1 - 300\ \text{K}/1000\ \text{K} = 70\%$. The corresponding power output would be . Thus, if the effect of irreversible heat transfer from and to the hot and cold reservoirs, respectively, were neglected, the power output of the plant would be significantly overpredicted.

3. Fouling reduces the power output of the plant by $\Delta P = 40$ MW. If the plant owner sells the electricity at a price of \$0.08/kW · h, the daily lost revenue associated with operating the fouled plant would be
   $C = 40{,}000\ \text{kW} \times \$0.08/\text{kW} \cdot \text{h} \times 24\ \text{h/day} = \$76{,}800/\text{day}$.

Units and Dimensions

Dimension		Unit
Length (L)	→	foot (ft)
Mass (m)	→	pound mass (lb_m)
Time (t)	→	second (s)
Temperature (T)	→	degree Fahrenheit (°F)

Quantity and Symbol	Unit and Symbol
Length (L)	meter (m)
Mass (m)	kilogram (kg)
Amount of substance	mole (mol)
Time (t)	second (s)
Electric current (I)	ampere (A)
Thermodynamic temperature (T)	kelvin (K)
Plane angle[a] (θ)	radian (rad)
Solid angle[a] (ω)	steradian (sr)

Units and Dimensions

Quantity	Name and Symbol	Formula	Expression in SI Base Units
Force	newton (N)	$m \cdot kg/s^2$	$m \cdot kg/s^2$
Pressure and stress	pascal (Pa)	N/m^2	$kg/m \cdot s^2$
Energy	joule (J)	$N \cdot m$	$m^2 \cdot kg/s^2$
Power	watt (W)	J/s	$m^2 \cdot kg/s^3$

Units and Dimensions

Prefix	Abbreviation	Multiplier
femto	f	10^{-15}
pico	p	10^{-12}
nano	n	10^{-9}
micro	μ	10^{-6}
milli	m	10^{-3}
centi	c	10^{-2}
hecto	h	10^{2}
kilo	k	10^{3}
mega	M	10^{6}
giga	G	10^{9}
tera	T	10^{12}
peta	P	10^{15}
exa	E	10^{18}

Analysis of Heat Transfer Problems: Methodology

A major objective of this text is to prepare you to solve engineering problems that involve heat transfer processes.

To this end, numerous problems are provided at the end of each chapter.

Working on these problems, you will gain a deeper appreciation for the fundamentals of the subject, and you will gain confidence in your ability to apply these fundamentals to the solution of engineering problems.

Analysis of Heat Transfer Problems: Methodology

In solving problems, we advocate the use of a systematic procedure characterized by a prescribed format.

We consistently employ this procedure in our examples, and we require our students to use it in their problem solutions.

It consists of the following steps:

1. Known: After carefully reading the problem, state briefly and concisely what is known about the problem. Do not repeat the problem statement.

2. Find: State briefly and concisely what must be found.

Analysis of Heat Transfer Problems: Methodology

7. Comments: Discuss your results. Such a discussion may include a summary of key conclusions, a critique of the original assumptions, and an inference of trends obtained by performing additional what-if and parameter sensitivity calculations.

The importance of following steps 1 through 4 should not be underestimated. They provide a useful guide to thinking about a problem before effecting its solution. In step 7, we hope you will take the initiative to gain additional insights by performing calculations that may be computer based. The software accompanying this text provides a suitable tool for effecting such calculations.

EXAMPLE 1.8

The coating on a plate is cured by exposure to an infrared lamp providing a uniform irradiation of 2000 W/m2. It absorbs 80% of the infrared irradiation and has an emissivity of 0.50. It is also exposed to an airflow and large surroundings for which temperatures are 20°C and 30°C, respectively.

1. If the convection coefficient between the plate and the ambient air is 15 W/m2 · K, what is the cure temperature of the plate?

2. The final characteristics of the coating, including wear and durability, are known to depend on the temperature at which curing occurs.

   An airflow system is able to control the air velocity, and hence the convection coefficient, on the cured surface, but the process engineer needs to know how the temperature depends on the convection coefficient. Provide the desired information by computing and plotting the surface temperature as a function of h for $2 \le h \le 100$ W/m2 · K. What value of h would provide a cure temperature of 50°C?

EXAMPLE 1.8

SOLUTION

Known: Coating with prescribed radiation properties is cured by irradiation from an infrared lamp. Heat transfer from the coating is by convection to ambient air and radiation exchange with the surroundings.

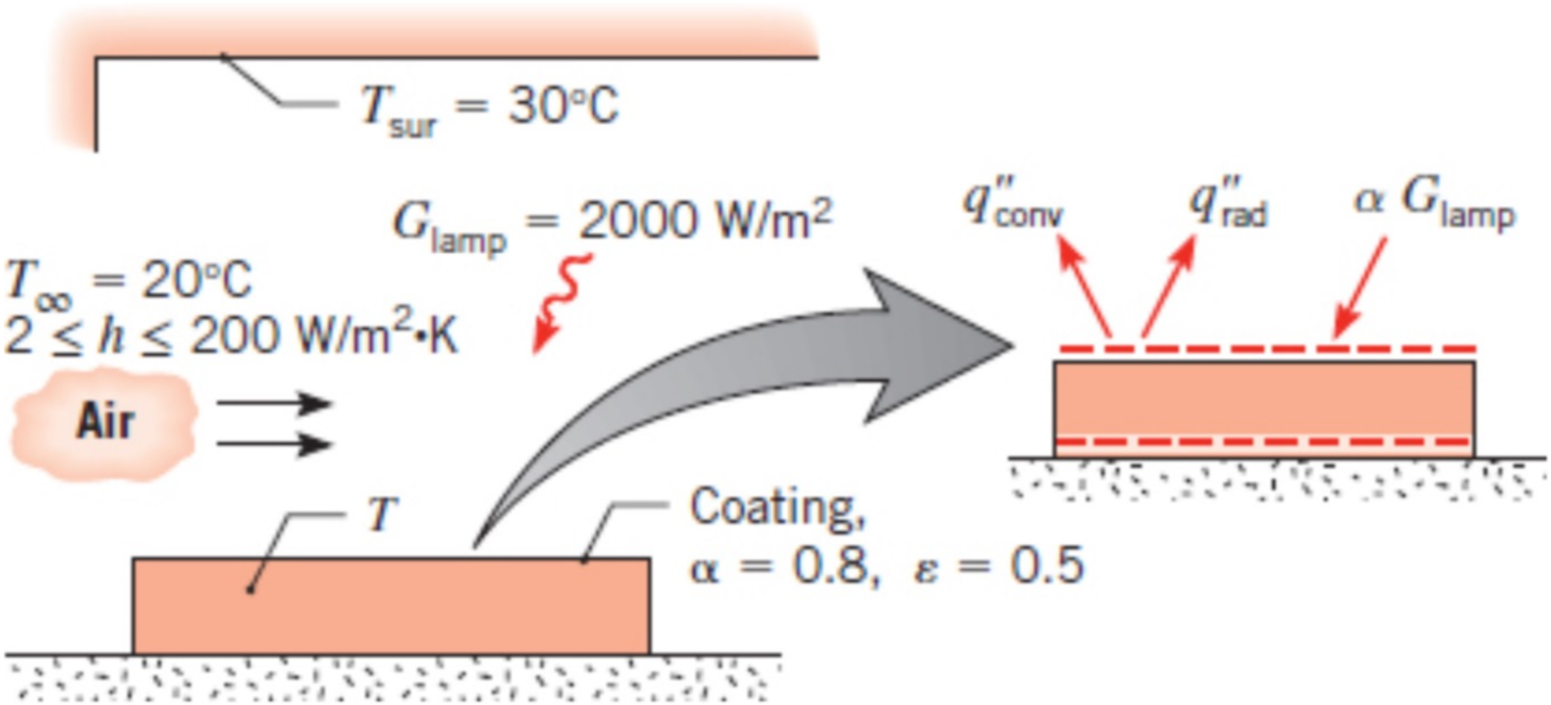
Find:

1. Cure temperature for $h = 15\ W/m^2 \cdot K$.

2. Effect of airflow on the cure temperature for $2 \leq h \leq 100$ W/m2 · K. Value of h for which the cure temperature is 50°C.

EXAMPLE 1.8

Schematic:



EXAMPLE 1.8

Assumptions:

1. Steady-state conditions.
2. Negligible heat loss from back surface of plate.
3. Plate is small object in large surroundings, and coating has an absorptivity of $\alpha_{sur} = \varepsilon = 0.5$ with respect to irradiation from the surroundings.

Analysis:

1. Since the process corresponds to steady-state conditions and there is no heat transfer at the back surface, the plate must be isothermal ($T_s = T$).

   Hence the desired temperature may be determined by placing a control surface about the exposed surface and applying Equation 1.13 or by placing the control surface about the entire plate and applying Equation 1.12c. Adopting the latter approach and recognizing that there is no energy generation , Equation 1.12c reduces to:

EXAMPLE 1.8

$$\dot{E}_{in} - \dot{E}_{out} = 0$$

where for steady-state conditions. With energy inflow due to absorption of the lamp irradiation by the coating and outflow due to convection and net radiation transfer to the surroundings, it follows that

$$(\alpha G)_{lamp} - q''_{conv} - q''_{rad} = 0$$

$$(\alpha G)_{lamp} - h(T - T_\infty) - \varepsilon\sigma(T^4 - T^4_{sur}) = 0$$

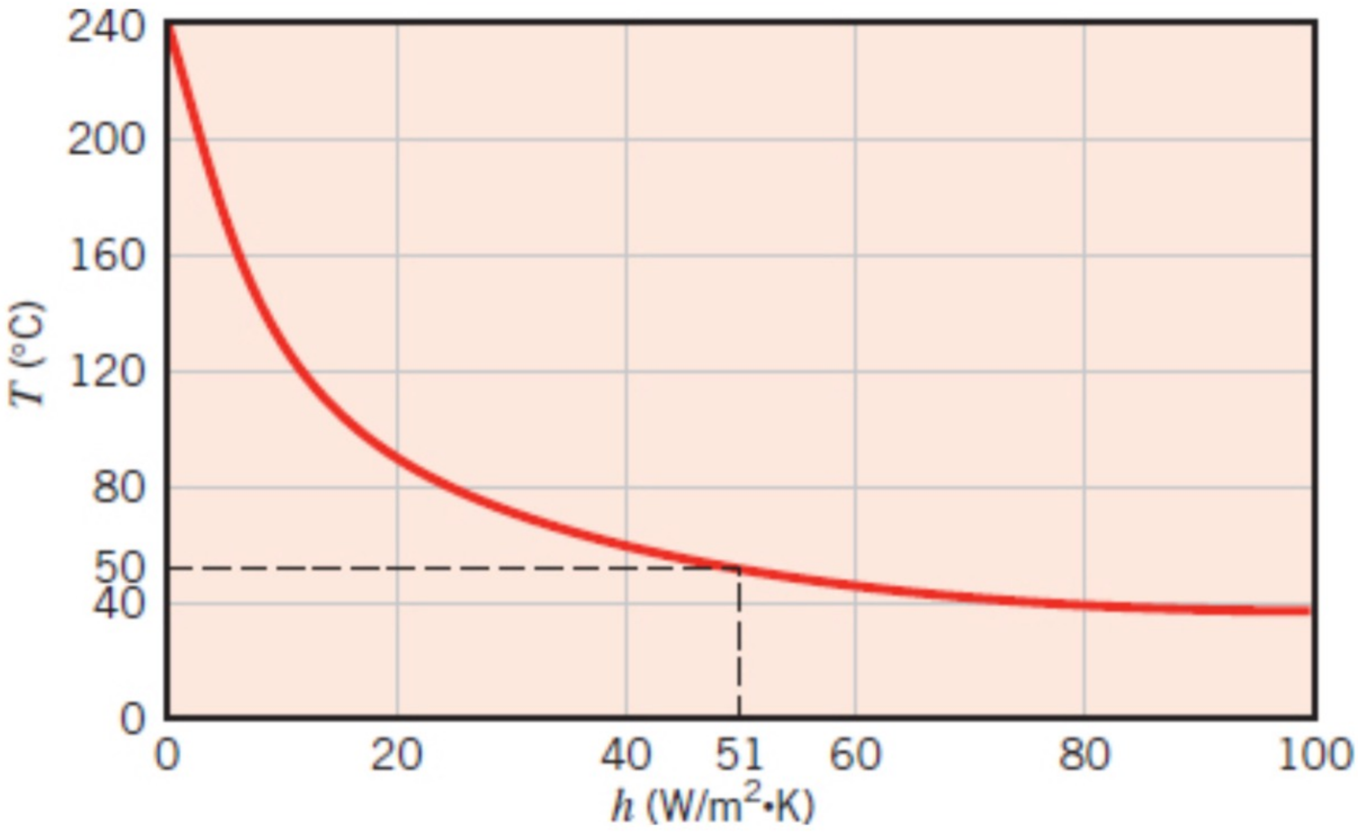
$$0.8 \times 2000\ \mathrm{W/m^2} - 15\ \mathrm{W/m^2 \cdot K}(T - 293)\mathrm{K} - 0.5 \times 5.67 \times 10^{-8}\ \mathrm{W/m^2 \cdot K^4}(T^4 - 303^4)\mathrm{K}^4 = 0$$

and solving by trial-and-error, we obtain:

$$T = 377\ \mathrm{K} = 104°\mathrm{C}$$

EXAMPLE 1.8

2. Solving the foregoing energy balance for selected values of h in the prescribed range and plotting the results, we obtain



EXAMPLE 1.8

If a cure temperature of 50°C is desired, the airflow must provide a convection coefficient of

$$h(T=50°C)=51.0\ W/m^2\cdot K$$

Comments:

1. The coating (plate) temperature may be reduced by decreasing T_∞ and T_{sur}, as well as by increasing the air velocity and hence the convection coefficient.
2. The relative contributions of convection and radiation to heat transfer from the plate vary greatly with h. For h = 2 $W/m^2 \cdot K$, T = 204°C and radiation dominates . Conversely, for h = 200 $W/m^2 \cdot K$, T = 28°C and convection dominates . In fact, for this condition the plate temperature is slightly less than that of the surroundings and net radiation exchange is to the plate.