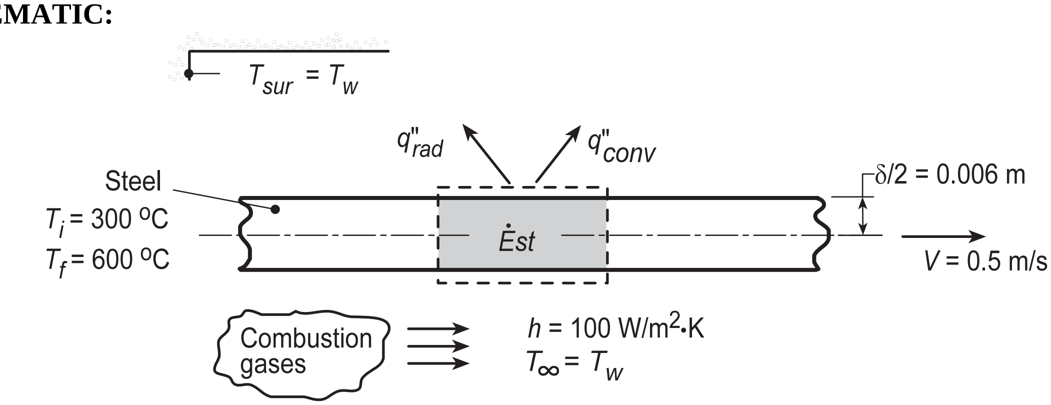
PROBLEM 5.23

KNOWN: Thickness and properties of strip steel heated in an annealing process. Furnace operating conditions.

FIND: (a) Time required to heat the strip from 300 to 600°C. Required furnace length for prescribed strip velocity (V = 0.5 m/s), (b) Effect of wall temperature on strip speed, temperature history, and radiation coefficient.

SCHEMATIC:



ASSUMPTIONS: (1) Constant properties, (2) Negligible temperature gradients in transverse direction across strip, (c) Negligible effect of strip conduction in longitudinal direction.

PROPERTIES: Steel: ρ = 7900 kg/m^3, c_p = 640 J/kg·K, k = 30 W/m·K, ε= 0.7.

ANALYSIS: (a) Considering a fixed (control) mass of the moving strip, its temperature variation with time may be obtained from an energy balance which equates the change in energy storage to heat transfer by convection and radiation. If the surface area associated with one side of the control mass is designated as A_s, $A_{s,c} = A_{s,r} = 2A_s$ and $V = \delta A_s$ in Equation 5.15, which reduces to

$$\rho c \delta \frac{dT}{dt} = -2\left[h\left(T - T_\infty\right) + \varepsilon\sigma\left(T^4 - T_{sur}^4\right)\right]$$

or, introducing the radiation coefficient from Equations 1.8 and 1.9 and integrating,

$$T_f - T_i = -\frac{1}{\rho c\left(\delta/2\right)}\int_o^{t_f}\left[h\left(T - T_\infty\right) + h_r\left(T - T_{sur}\right)\right]dt$$

Using the IHT *Lumped Capacitance Model* to integrate numerically with T_i = 573 K, we find that T_f = 873 K corresponds to

$$t_f \approx 209\text{s}$$ <

in which case, the required furnace length is

$$L = Vt_f \approx 0.5\,\text{m/s} \times 209\,\text{s} \approx 105\,\text{m}$$ <

(b) For T_w = 1123 K and 1273 K, the numerical integration yields $t_f \approx$ 102s and 62s respectively. Hence, for L = 105 m , V = L/t_f yields

$$V\left(T_w = 1123\text{K}\right) = 1.03\,\text{m/s}$$

$$V\left(T_w = 1273\text{K}\right) = 1.69\,\text{m/s}$$ <

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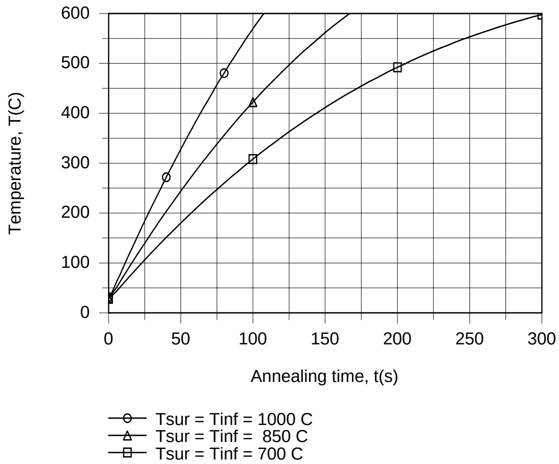
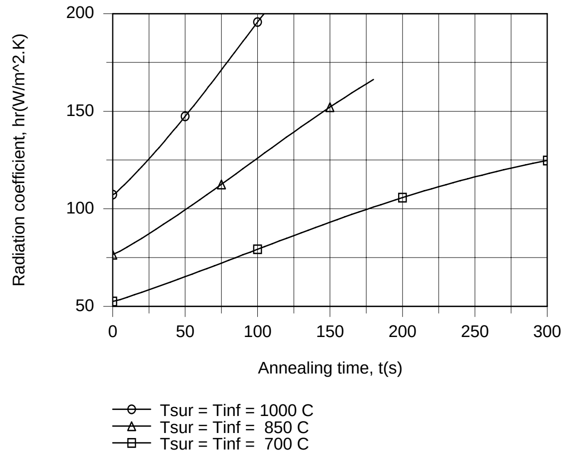
PROBLEM 5.23 (Cont.)

which correspond to increased process rates of 106% and 238%, respectively. Clearly, productivity can be enhanced by increasing the furnace environmental temperature, albeit at the expense of increasing energy utilization and operating costs.

If the annealing process extends from 25°C (298 K) to 600°C (873 K), numerical integration yields the following results for the prescribed furnace temperatures.





As expected, the heating rate and time, respectively, increase and decrease significantly with increasing T_w. Although the radiation heat transfer rate decreases with increasing time, the coefficient h_r increases with t as the strip temperature approaches T_w.

COMMENTS: To check the validity of the lumped capacitance approach, we calculate the Biot number based on a maximum cumulative coefficient of $(h + h_r) \approx 300\ W/m^2 \cdot K$. It follows that $Bi = (h + h_r)(\delta/2)/k = 0.06$ and the assumption is valid.