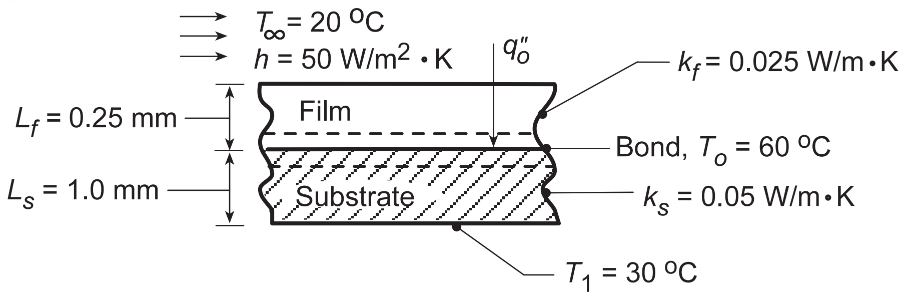
PROBLEM 3.6

KNOWN: Curing of a transparent film by radiant heating with substrate and film surface subjected to known thermal conditions.

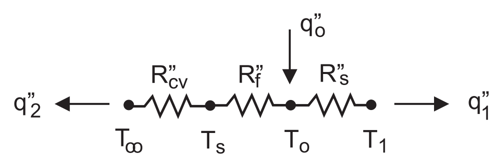
FIND: (a) Thermal circuit for this situation, (b) Radiant heat flux, q''_o (W/m^2), to maintain bond at curing temperature, T_o, (c) Compute and plot q''_o as a function of the film thickness for $0 \le L_f \le 1$ mm, and (d) If the film is not transparent, determine q''_o required to achieve bonding; plot results as a function of L_f.

SCHEMATIC:



ASSUMPTIONS: (1) Steady-state conditions, (2) One-dimensional heat flow, (3) All the radiant heat flux q''_o is absorbed at the bond, (4) Negligible contact resistance.

ANALYSIS: (a) The thermal circuit for this situation is shown at the right. Note that terms are written on a per unit area basis.



(b) Using this circuit and performing an energy balance on the film-substrate interface,

$$q''_o = q''_1 + q''_2 \qquad\qquad q''_o = \frac{T_o - T_\infty}{R''_{cv} + R''_f} + \frac{T_o - T_1}{R''_s}$$

where the thermal resistances are

$$R''_{cv} = 1/h = 1/50\,\text{W/m}^2\cdot\text{K} = 0.020\,\text{m}^2\cdot\text{K/W}$$

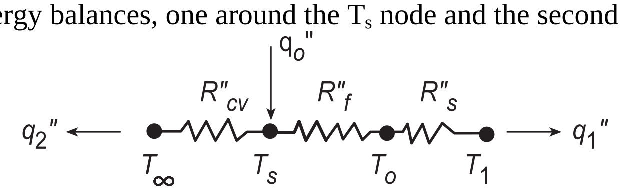
$$R''_f = L_f/k_f = 0.00025\,\text{m}/0.025\,\text{W/m}\cdot\text{K} = 0.010\,\text{m}^2\cdot\text{K/W}$$

$$R''_s = L_s/k_s = 0.001\,\text{m}/0.05\,\text{W/m}\cdot\text{K} = 0.020\,\text{m}^2\cdot\text{K/W}$$

$$q''_o = \frac{(60-20)^\circ\text{C}}{[0.020+0.010]\,\text{m}^2\cdot\text{K/W}} + \frac{(60-30)^\circ\text{C}}{0.020\,\text{m}^2\cdot\text{K/W}} = (1333+1500)\,\text{W/m}^2 = 2833\,\text{W/m}^2 \qquad <$$

(c) For the transparent film, the radiant flux required to achieve bonding as a function of film thickness L_f is shown in the plot below.

(d) If the film is opaque (not transparent), the thermal circuit is shown below. In order to find q''_o, it is necessary to write two energy balances, one around the T_s node and the second about the T_o node.



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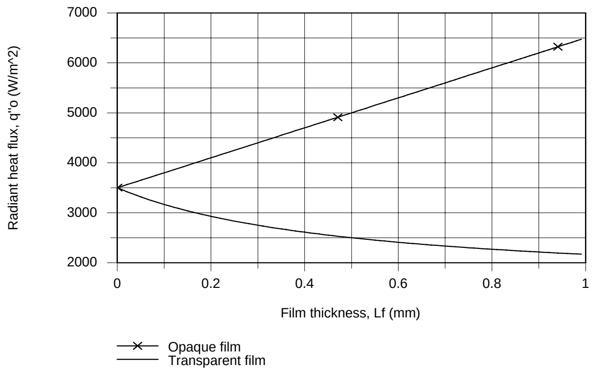
The results of the analysis are plotted below.

Continued...

PROBLEM 3.6 (Cont.)

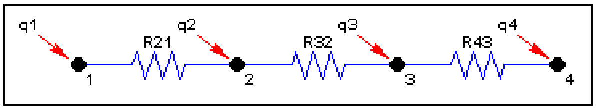


COMMENTS: (1) When the film is transparent, the radiant flux is absorbed on the bond. The flux required decreases with increasing film thickness. Physically, how do you explain this? Why is the relationship not linear?

(2) When the film is opaque, the radiant flux is absorbed on the surface, and the flux required increases with increasing thickness of the film. Physically, how do you explain this? Why is the relationship linear?

(3) The IHT Thermal Resistance Network Model was used to create a model of the film-substrate system and generate the above plot. The Workspace is shown below.

// Thermal Resistance Network Model:
// The Network:

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// Heat rates into node j,qij, through thermal resistance Rij
q21 = (T2 - T1) / R21
q32 = (T3 - T2) / R32
q43 = (T4 - T3) / R43

// Nodal energy balances
q1 + q21 = 0
q2 - q21 + q32 = 0
q3 - q32 + q43 = 0
q4 - q43 = 0

/* Assigned variables list: deselect the qi, Rij and Ti which are unknowns; set qi = 0 for embedded nodal points
at which there is no external source of heat. */
T1 = Tinf           // Ambient air temperature, C
//q1 =              // Heat rate, W; film side
T2 = Ts             // Film surface temperature, C
q2 = 0              // Radiant flux, W/m^2; zero for part (a)
T3 = To             // Bond temperature, C
q3 = qo             // Radiant flux, W/m^2; part (a)
T4 = Tsub           // Substrate temperature, C
//q4 =              // Heat rate, W; substrate side

// Thermal Resistances:
R21 = 1 / ( h * As )          // Convection resistance, K/W
R32 = Lf / (kf * As)          // Conduction resistance, K/W; film
R43 = Ls / (ks * As)// Conduction resistance, K/W; substrate

// Other Assigned Variables:
Tinf = 20           // Ambient air temperature, C
h = 50              // Convection coefficient, W/m^2.K
Lf = 0.00025        // Thickness, m; film
kf = 0.025          // Thermal conductivity, W/m.K; film
To = 60             // Cure temperature, C
Ls = 0.001          // Thickness, m; substrate
ks = 0.05           // Thermal conductivity, W/m.K; substrate
Tsub = 30// Substrate temperature, C
As = 1              // Cross-sectional area, m^2; unit area
```