2010 Heat Transfer Midterm Exam (Including Solutions)

ASSUMPTIONS:

- STEADY-STATE
- 1D RADIAL H-T WITHIN CABLE
- $L \gg r_o$
- CONSTANT h OVER CABLE SURFACE
- RADIATION H-T IS NEGLIGIBLE
- THERMAL CONDUCTIVITY OF COPPER AND POLYETHYLENE ARE CONSTANT
- NO CONTACT RESISTANCE BETWEEN COPPER AND POLYETHYLENE

SOLUTION:

FIRST, LET'S DETERMINE THE AMOUNT OF HEAT GENERATION WITHIN THE CABLE DUE TO CURRENT FLOW.

THE CURRENT WITHIN THE CABLE CAN BE FOUND FROM:

$$I = \frac{P_{ELECT}}{\Delta V_{ACTUATOR}} = \frac{100 \times 10^3 \, W}{200 \text{ VOLTS}} = 500 \text{ Amps}$$

KNOWING THE CURRENT, WE CAN EXPRESS THE HEAT GENERATED WITHIN THE CABLE AS:

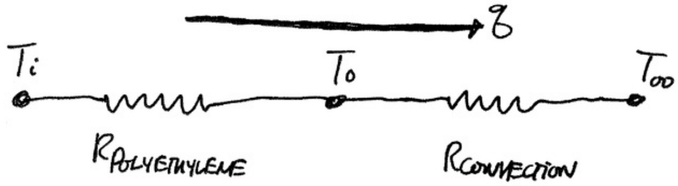
$$S_{GEN} = \frac{R_{ELECT}}{\pi r_i^2} \times I^2 \times L$$

THE LATTER CORRESPONDS TO THE HEAT GENERATED WITHIN THE ENTIRE CABLE.

THEN, AT STEADY STATE, THE HEAT TRANSFER RATE OUT OF THE CABLE MUST BE EQUAL TO S_{GEN}:

$$\boxed{q = S_{GEN} = \frac{R_{ELECT}}{\pi r_i^2} \times I^2 \times L} \qquad \mathrm{I}$$

THEN, USE THE RESISTANCE ANALOGY:



USING THE CONDUCTION SHAPE FACTOR TABLE,

$$R_{POLYETHYLENE} = \frac{\ln(r_o/r_i)}{k_{POLYETHYLENE} \times 2\pi L}$$

ALSO RECALL THAT:

$$R_{CONVECTION} = \frac{1}{h\, 2\pi r_o L}$$

THEN, WE CAN RELATE q TO T_i:

$$\boxed{q = -\frac{\Delta T}{\Sigma R} = \frac{T_i - T_\infty}{\dfrac{\ln(r_o/r_i)}{k_{POLYETHYLENE} \times 2\pi L} + \dfrac{1}{h\, 2\pi r_o L}}} \qquad \mathrm{II}$$

EQUATE I AND II:

$$\frac{R_{ELECT} I^2 L}{\pi r_i^2} = \frac{2\pi L (T_i - T_\infty)}{\frac{\ln(r_o/r_i)}{k_{POLYETHYLENE}} + \frac{1}{h r_o}}$$

REWRITE AS:

$$r_i^2 = \left(\frac{\ln(r_o/r_i)}{k_{POLYETHYLENE}} + \frac{1}{h r_o} \right) \frac{R_{ELECT} I^2}{2\pi^2 (T_i - T_\infty)}$$

EXPRESS r_o AS $r_i + 0.005m$:

$$\boxed{r_i = \left[\left(\frac{\ln((r_i + 0.005m)/r_i)}{k_{POLYETHYLENE}} + \frac{1}{h(r_i + 0.005m)} \right) \frac{R_{ELECT} I^2}{2\pi^2 (T_i - T_\infty)} \right]^{1/2}} \quad \text{III}$$

TO ENSURE THAT THE TEMPERATURE WITHIN THE INSULATOR DOES NOT APPROACH ITS MELTING POINT BY LESS THAN 40°C, IT IS NECESSARY TO SET

$T_i = 80°C$

$h = 7 \ W/m^2 °C$

THEN ALL TERMS WITHIN EQ. III ARE KNOWN EXCEPT FOR r_i.

THEN DETERMINE r_i THROUGH PICARD ITERATIONS BY FIRST REWRITING EQ. III AS:

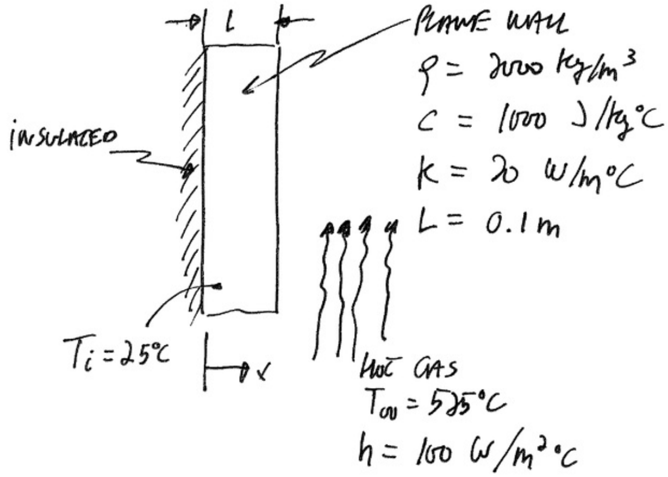
$$r_i^{n+1} = \left[\left(\frac{\ln\left((r_i^n + 0.005\,m)/r_i^n \right)}{0.5\ W/m°C} + \frac{1}{7\ W/m^2°C \times (r_i^n + 0.005\,m)} \right) \times 2.503 \times 10^{-6}\ \frac{Wm}{°C} \right]^{1/2}$$

n	r_i^n (m)	r_i^{n+1} (m)
1	0.005	0.0063
2	0.0063	0.0059
3	0.0059	0.0060
4	0.006	0.006

THEN, IT FOLLOWS THAT THE OPTIMAL RADIUS OF THE COPPER CABLE (RESULTING IN MINIMAL WEIGHT WHILE MAINTAINING THE POLYETHYLENE COATING TO A SAFE TEMPERATURE) IS OF:

$$\boxed{r_i = 0.006\ m}$$ (A)

#3 CONSIDER A PLANE WALL TO BE USED AS A THERMAL STORAGE UNIT:



WANTED:

- time t AT WHICH THE WALL HAS ACHIEVED 80% OF ITS MAXIMUM POSSIBLE ENERGY STORAGE
- FOR TIME t CALCULATED IN FIRST PART, FIND MAX. TEMP. IN WALL.

ASSUMPTIONS:

- CONSTANT ρ, c, k WITHIN WALL
- 1D HEAT TRANSFER WITHIN WALL
- CONSTANT h AND T_∞ OVER EXPOSED SURFACE
- NO RADIATION

SOLUTION:

FIRST, CALCULATE BIOT NUMBER:

$$Bi = \frac{hL}{k} = \frac{100 \ W/m^2°C \times 0.1m}{20 \ W/m°C} = 0.5$$

BECAUSE $Bi > 0.1$, CANNOT USE L.C.A. RESORT TO HEISLER CHARTS. THEN, CALCULATE Q/Q_0:

$$\frac{Q}{Q_0} = \frac{\rho Vc\,(T_i - \bar{T})}{\rho Vc\,(T_i - T_\infty)} = \frac{T_i - \bar{T}}{T_i - T_\infty}$$

WHEN WALL ACHIEVES 80% OF ITS MAXIMUM POSSIBLE ENERGY STORAGE; $\bar{T}$ WILL BE EQUAL TO:

$$\bar{T} = 0.80 \times (T_\infty - T_i) + T_i = 0.8\,T_\infty + 0.2\,T_i$$

SUBSTITUTE LATTER IN FORMER:

$$\frac{Q}{Q_0} = \frac{T_i - 0.8\,T_\infty - 0.2\,T_i}{T_i - T_\infty} = 0.8 \times \frac{(T_i - T_\infty)}{T_i - T_\infty} = 0.8$$

NOW, KNOWING $Q/Q_0 = 0.8$ AND $Bi = 0.5$, USE HEISLER CHART "INTERNAL ENERGY CHANGE AS A FUNCTION OF TIME FOR A PLANE WALL...." AND FIND $Bi^2 Fo$:

$$Bi^2 Fo = 1.0$$

THEN FROM $Bi^2 Fo = 1$, FIND t:

$$Bi^2 Fo = \frac{h^2 \alpha t}{k^2} = \frac{h^2 \cancel{k} t}{\rho c k^{\cancel{2}}} = \frac{h^2 t}{\rho c k}$$

ISOLATE t:

$$t = \frac{\rho c k (Bi^2 Fo)}{h^2} = \frac{2000\ kg/m^3 \times 1000\ J/kg°C \times 20\ W/m°C \times 1.0}{(100\ W/m^2°C)^2}$$

$$\boxed{t = 4000\ s}$$ (14)

NOW, AT $t = 4000\ s$, FIND MAX. TEMPERATURE IN WALL, T_{MAX}. NOTE THAT T_{MAX} IS LOCATED AT $x = L$, BECAUSE THIS IS THE CLOSEST POINT TO THE HOT ~~gas~~ GAS HEATING THE WALL. FIRST, FIND FOURIER #:

$$Fo = \frac{\alpha t}{L^2} = \frac{k t}{\rho c L^2} = \frac{20\ W/m°C \times 4000 s}{2000\ kg/m^3 \times 1000\ J/kg°C \times (0.1 m)^2}$$

$$Fo = 4.0$$

THEN FIND T_{MAX} AS FOLLOWS:

$$\frac{T_{MAX} - T_\infty}{T_i - T_\infty} = \underbrace{\frac{T_o - T_\infty}{T_i - T_\infty}}_{\substack{\text{USE CHART} \\ \text{"MIDPLANE TEMP."} \\ \text{WITH } Fo = 4.0 \\ \text{AND } Bi^{-1} = 2.0}} \times \underbrace{\frac{T_{MAX} - T_\infty}{T_o - T_\infty}}_{\substack{\text{USE CHART "TEMP. DIST."} \\ \text{WITH } x/L = 1.0,\ Fo = 4.0 \\ \text{AND } Bi^{-1} = 2.0}}$$

THIS YIELDS

$$\frac{T_{MAX} - T_\infty}{T_i - T_\infty} = 0.2 \times 0.8 = 0.16$$

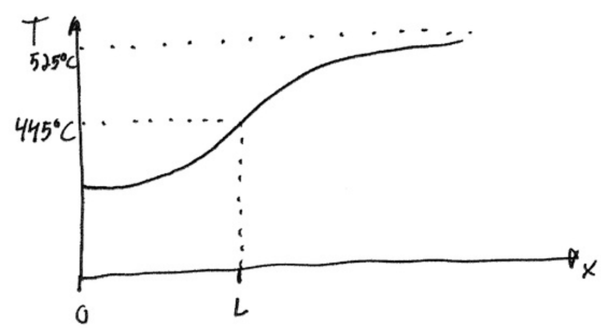
THEN ISOLATE T_{MAX}:

$$T_{MAX} = 0.16 \times (T_i - T_\infty) + T_\infty$$

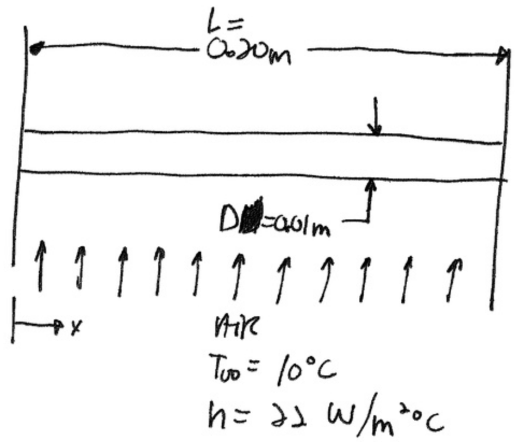
$$T_{MAX} = 0.16 \times (25°C - 525°C) + 525°C$$

$$\boxed{T_{MAX} = 445\ °C}\ (A)$$

NOTE: THIS IS A HEATING PROBLEM, NOT A COOLING PROBLEM. THE TEMPERATURE DISTRIBUTION AT $t = 4000\ s$ IS HENCE AS FOLLOWS:



#4 CONSIDER HEAT TRANSFER IN A FIN JOINING TWO WALLS AT 110°C:



WANTED:

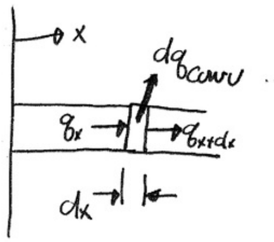
- FOR NO CONTACT RESISTANCE AT ROD SURFACE, $T = 60°C$ AT $x = 0.10m$. FIND k.
- KNOWING k, FIND CONTACT CONDUCTANCE IF $T = 70°C$ AT $x = 0.10\ m$.

ASSUMPTIONS:

- 1D HEAT CONDUCTION ALONG x
- CONSTANT k, ρ, c WITHIN ROD
- CONSTANT h AND T_∞ ACTING ON ROD SURFACE.
- NO CONTACT RESISTANCE BETWEEN ROD AND WALLS
- RADIATION IS NEGLIGIBLE.
- STEADY-STATE

SOLUTION:

FIRST, WORK OUT AN ANALYTICAL EXPRESSION YIELDING T AS A FUNCTION OF x:



AT STEADY STATE, THE INTEGRAL FORM OF THE HEAT EQUATION YIELDS:

$$q_x = q_{x+dx} + dq_{conv}$$

WITH:

$$q_x = -k \frac{dT}{dx} \frac{\pi D^2}{4}$$

$$q_{x+dx} = -k \frac{dT}{dx} \frac{\pi D^2}{4} - \frac{d}{dx}\left(\frac{k\pi D^2}{4} \frac{dT}{dx}\right) dx + \ldots$$

SUBSTITUTE LATTER IN HEAT EQUATION:

$$\cancel{-\frac{\pi D^2 k}{4} \frac{dT}{dx}} - dq_{conv} = \cancel{-\frac{k\pi D^2}{4} \frac{dT}{dx}} - \frac{d}{dx}\left(\frac{k\pi D^2}{4} \frac{dT}{dx}\right) dx$$

FOR CONSTANT k, THIS YIELDS:

$$dq_{conv} = +\frac{k\pi D^2}{4}\frac{d^2T}{dx^2}dx$$

NOW USE RESISTANCE ANALOGY TO EXPRESS dq_{conv}:

$$dq_{conv} = \frac{-\Delta T}{\Sigma R} = \frac{-(T_\infty - T)}{\frac{1}{h\pi D dx} + \frac{1}{h_c \pi D dx}}$$

WITH h_c THE CONTACT CONDUCTANCE. REARRANGE:

$$dq_{conv} = \frac{(T - T_\infty)\pi D dx}{\frac{1}{h} + \frac{1}{h_c}}$$

SUBSTITUTE IN HEAT EQUATION:

$$\frac{\cancel{\pi}\cancel{D}\cancel{dx}\,(T - T_\infty)}{\frac{1}{h} + \frac{1}{h_c}} = +\frac{k\cancel{\pi}D^{\cancel{2}}}{4}\frac{d^2T}{dx^2}\cancel{dx}$$

OR

$$T - T_\infty = +\left(\frac{1}{h} + \frac{1}{h_c}\right)\frac{kD}{4}\;\frac{d^2T}{dx^2}$$

NOW DEFINE

$$\theta \equiv T - T_\infty$$

$$m^2 \equiv \frac{4}{kD\left(\frac{1}{h} + \frac{1}{h_c}\right)}$$

THEN THE HEAT EQ. BECOMES:

$$\frac{d^2\theta}{dx^2} = \theta m^2$$

FIND SOLUTION USING H-T TABLES:

$$\boxed{\theta = A \sinh(mx) + B \cosh(mx)}$$

APPLY B.C.s TO FIND A AND B; AT $x=0$, $T = T_w$; THIS YIELDS:

$$\boxed{T_w - T_\infty = B}$$

ALSO, DUE TO SYMMETRY, AT $x = L/2$, $d\theta/dx = 0$:

$$\left.\frac{d\theta}{dx}\right|_{x=L/2} = 0 = Am \cosh\left(\frac{mL}{2}\right) + Bm \sinh\left(\frac{mL}{2}\right)$$

ISOLATE A:

$$\boxed{A = -B \tanh\left(\frac{mL}{2}\right)}$$