

ChE 306: HEAT TRANSFER
 FALL 2010 EXAM I
 (35 POINTS)
 WEDNESDAY, SEPTEMBER 15, 2010

CLOSED BOOK / CLOSED NOTES / CLOSED HOMEWORK / NO CALCULATORS

1. (6 pts) MULTIPLE CHOICE

For the equation: $\Delta U = m c_p \Delta T + m h_{fg}$

D What does the first term ($m c_p \Delta T$) represent?
 (A) conductive heat transfer (B) heat transfer by convection (C) radiative heat transfer
 (D) sensible internal energy change (E) latent (phase change) internal energy change
 (F) internal energy change by chemical reaction

E What does the second term ($m h_{fg}$) represent?
 (A) conductive heat transfer (B) heat transfer by convection (C) radiative heat transfer
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2. (8 pts) Fourier's law for heat transfer by conduction is: $q = -k A \nabla T$

Define each of the variables and list the SI units for each variable: q , k , A , & ∇T

q = heat transfer rate (W)

k = thermal conductivity (W/m-k)

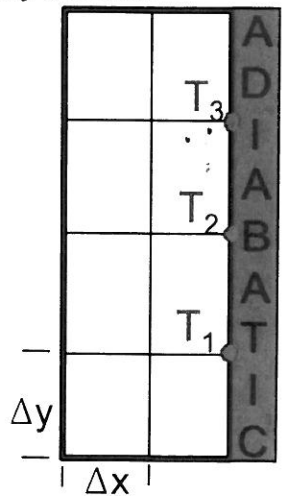
A = surface area (m²)

∇T = temperature gradient (K/m or °C/m)

3. (4 pts) For the diagram at the right for a 2D material with thermal conductivity k and no energy generation, what is the steady state heat transfer rate (q) by conduction from node 1 to node 2 along an adiabatic surface?

Leave your answer in terms of: T_1 , T_2 , T_3 , Δx , Δy , Δz and k .

$$q = -k (\Delta z) \left(\frac{\Delta x}{z} \right) \frac{(T_2 - T_1)}{\Delta y}$$



4. (5 pts) For the same 2-D material in #3, which of the following will **IMPROVE** the accuracy of the 2-D temperature profile generated by finite divided differences? (you may need to mark more than 1)

- $\Delta x \rightarrow 0$ $\Delta y \rightarrow 0$, $\Delta z \rightarrow 0$ $\Delta x = \Delta y$
 $\Delta x \rightarrow \infty$ $\Delta y \rightarrow \infty$, $\Delta z \rightarrow \infty$ $\Delta t \rightarrow 0$

Δz DIRECTION UNSTEADY STATE
 UNIMPORTANT for 2-D HX
 makes it easier to solve, but (CONTINUED ON BACK)
 not necessarily more accurate.

5 (2 pts). MULTIPLE CHOICE:

- C Which of the following materials has the **highest** thermal conductivity, k ?
 (A) pyrex glass (B) rubber (C) copper (D) air (E) wood

6. (4 pts) MULTIPLE CHOICE

Answer the following based on Newton's Law of Convective Cooling, which can be written as:

$$q'' = h (T_s - T_\infty)$$

- D What are the English units for q'' ?
 (A) W (B) Btu/h (C) Btu (D) Btu/h-ft² (E) Btu/°F (F) W/m²-K (G) J/kg

- C What is T_∞ ?
 (A) the surface temperature of a solid
 (B) the temperature of solid surfaces surrounding an object
 (C) the temperature of a fluid far away from a surface
 (D) the temperature of a fluid immediately next to a surface
 (E) the temperature of the surface at time = ∞

7. (4 pts) For 1-D unsteady state heat transfer with heat generated in the solid material, what term(s) of the heat diffusion (energy balance) equation can be ignored (i.e. = 0)?

$$d/dx (k (dT/dx)) + d/dy (k (dT/dy)) + d/dz (k (dT/dz)) + q = m c_p dT/dt$$

D

D

8. (2 pts) TRUE/FALSE

- F Convective heat transfer occurs between a surface and the surroundings regardless of the medium (fluid) and is normally only important if the surface temperature is very high.

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FALL 2010 EXAM 1

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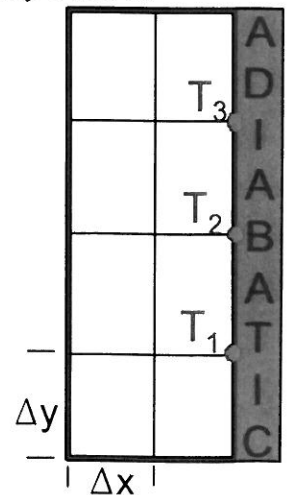
Define each of the variables and list the SI units for each variable: q , k , A , & ∇T

q		W
k	See	W/m-k
A	other	m ²
∇T	Version	K/m or °C/m

3. (4 pts) For the diagram at the right for a 2D material with thermal conductivity k and no energy generation, what is the steady state heat transfer rate (q) by conduction from node 2 to node 3 along an adiabatic surface ?

Leave your answer in terms of: T_1 , T_2 , T_3 , Δx , Δy , Δz and k .

$$q = -k (\Delta z) \left(\frac{\Delta y}{2} \right) \frac{(T_3 - T_2)}{\Delta y}$$



4. (5 pts) For the same 2-D material in #3, which of the following will IMPROVE the accuracy of the 2-D temperature profile generated by finite divided differences? (you may need to mark more than 1)

- $\Delta x \rightarrow \infty$ $\Delta y \rightarrow \infty$, $\Delta z \rightarrow \infty$ $\Delta t \rightarrow 0$
 $\Delta x \rightarrow 0$ $\Delta y \rightarrow 0$, $\Delta z \rightarrow 0$ $\Delta x = \Delta y$

(CONTINUED ON BACK)

5 (2 pts). MULTIPLE CHOICE:

- D Which of the following materials has the **highest** thermal conductivity, k ?
 (A) wood (B) pyrex glass (C) rubber (D) copper (E) air

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7. (6 pts) MULTIPLE CHOICE

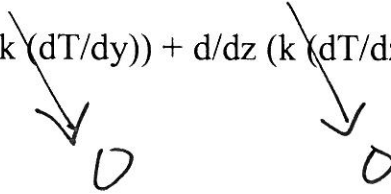
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$$d/dx (k (dT/dx)) + d/dy (k (dT/dy)) + d/dz (k (dT/dz)) + \dot{q} = m c_p dT/dt$$



Soun

NAME

ChE 306: HEAT TRANSFER

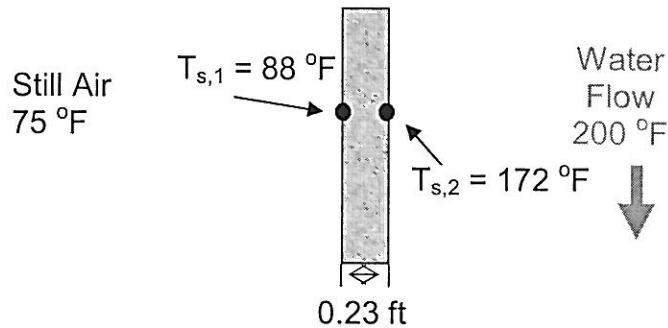
FALL 2010 EXAM 1

(65 points)

WEDNESDAY, SEPTEMBER 15, 2010

OPEN BOOK / OPEN NOTES / OPEN HOMEWORK / CALCULATORS ALLOWED

1 (10 pts). The heat flux through the material below is $-56 \text{ Btu/ft}^2\text{-h}$. Heat transfer is 1-dimensional, the material has constant k , and there is no energy generation within it. What is its **thermal conductivity**? The material has dimensions of 12 ft high by 20 feet deep (into the paper) and a thickness of 0.23 ft (as marked).



$$q'' = -k \frac{dT}{dx} = -k \frac{\Delta T}{\Delta x}$$

$$k = \frac{-q'' \cdot \Delta x}{\Delta T}$$

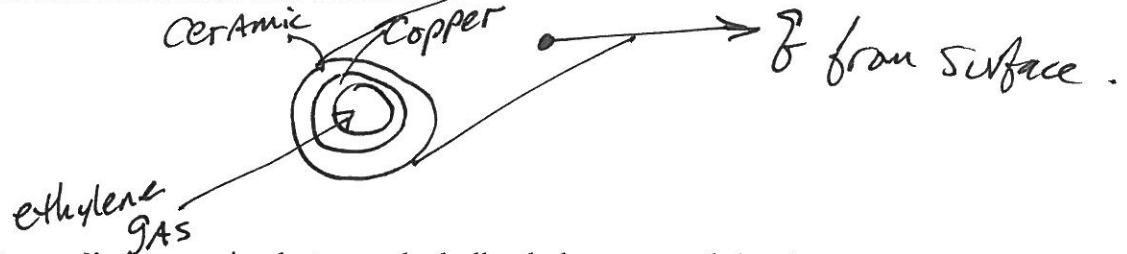
$$= \frac{-(-56 \frac{\text{Btu}}{\text{ft}^2\text{-h}})(0.23 \text{ ft})}{172 - 88 \text{ } ^\circ\text{F}}$$

$$k = 0.15 \text{ Btu/h-ft-}^\circ\text{F}$$

2 (~~28~~²⁷ pts). Ethylene gas at 340 °C flows through a 70-m long cylindrical copper pipe coated with a layer of ceramic. The outer surface is exposed to air at 30 °C and surroundings also at 30 °C (i.e., radiation must be considered). The copper pipe has 3 cm inner diameter, 4 cm outer diameter. The ceramic insulating layer is 0.2 cm thick.

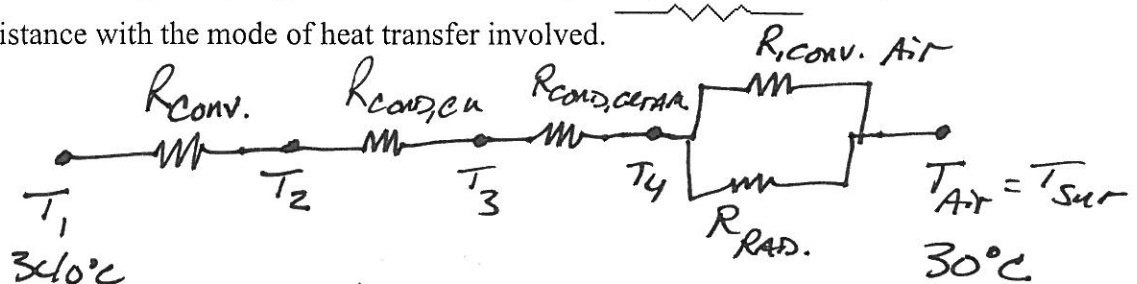
MATERIAL PROPERTIES	Density (kg/m ³)	Heat Capacity (J/kg-K)	Thermal Conductivity (W/m-K)	Emissivity (no units)
Copper	8932	406	387	0.46
Ceramic	2600	808	3.48	0.81

- 5 A. Draw a sketch of the problem, indicating the arrangement of materials. Draw an arrow on the diagram to indicate the direction of heat transfer.



- 5 B. Draw a resistance diagram going between the bulk ethylene gas and the air temperature.

Label each resistance with the mode of heat transfer involved.



- 8 C. What is the thermal resistance due to the ceramic layer (in K/W)?

$$R_{\text{ceram}} = \frac{\ln \left(\frac{r_2}{r_1} \right)}{2\pi L k} = \frac{\ln \left(\frac{2+0.2}{2} \right)}{2\pi (70\text{m})(3.48 \text{ W/m-k})}$$

$$= 6.23 \times 10^{-5} \text{ K/W}$$

- 9 D. If the surface temperature of the ceramic exposed to the air is 97 °C, what is the rate of heat loss due to RADIATION only (in W)?

$$q_{\text{RAD}} = \epsilon \sigma A (T_s^4 - T_{\text{sur}}^4)$$

$$= (0.81) (5.67 \cdot 10^{-8} \text{ W/m}^2\text{-K}^4) (70\text{m} \pi (0.04\text{m})) (370^4 - 303^4)$$

$$= \underline{4580 \text{ W}}$$

3 (28 pts). A 3-inch titanium sphere at 0 °F is placed into a hot oil bath at 200 °F.*

DATA	Titanium sphere	Oil bath
Density (lb_m/ft^3)	281	66.6
Heat Capacity ($\text{Btu}/\text{lb}_m\text{-}^\circ\text{F}$)	0.125	0.000652
Thermal Conductivity ($\text{Btu}/\text{h}\text{-ft}\text{-}^\circ\text{F}$)	12.7	0.151
Convective Heat Transfer Coefficient ($\text{Btu}/\text{h}\text{-ft}^2\text{-}^\circ\text{F}$)	N/A	3.80
Mass (lb_m)	-0.0851	73.9

A (10). Can lumped capacitance be used to evaluate $T(t)$?

*LISTED wrong. 2.23 lb_m.
L_c = r/3 = 0.5 in.*

$$Bi = \frac{h L_c}{k_s} = \frac{(3.80 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F})(0.5 \text{ in}/12 \text{ in/ft})}{12.7 \text{ Btu/h}\cdot\text{ft}\cdot^\circ\text{F}}$$

$$= 0.012 < 0.1 \quad \underline{\text{yes}}$$

B (12). Regardless of your answer to (A), assume that lumped capacitance is valid and determine the temperature of the sphere 10 minutes after it is placed in the bath.

$$\frac{\theta}{\theta_i} = \frac{T - T_\infty}{T_i - T_\infty} = \exp\left(-\frac{h A t}{m c_p}\right) = \exp\left(-\frac{h A t}{\rho V c_p}\right)$$

*If you used
M. = 0.851*

$$\frac{\theta}{\theta_i} = \exp(-11.7)$$

$$= 8 \times 10^{-6}$$

$$T = 200^\circ\text{F}$$

$$(199.99999)$$

$$= \exp\left(-\frac{(3.8) 4\pi \left(\frac{1.5}{12}\right)^2 \cdot \left(\frac{10}{60} \text{ h}\right)}{(281 \text{ lb}_m/\text{ft}^3) \left(\frac{4}{3}\pi \left(\frac{1.5}{12}\right)^3\right) (0.125)}\right)$$

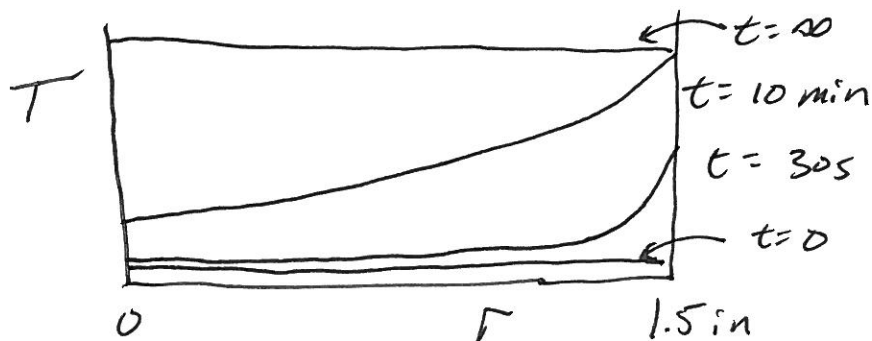
$$= \exp(-0.43)$$

$$= 0.65$$

$$T = 0.65(0 - 200^\circ\text{F}) + 200^\circ\text{F} = \underline{70.2^\circ\text{F}}$$

C (6). Regardless of your answer to (A), assume that $Bi > 1$ and lumped capacitance cannot be used.

Draw a qualitative temperature profile sketch of T vs. radius (starting at $r = 0$) showing the temperature profile $T(r)$ at 0 s, 30 s, 10 minutes, and $t = \infty$.



* Note: The volume of a sphere is $\frac{4}{3}\pi r^3$; its surface area is $4\pi r^2$.