Name: ______________________________

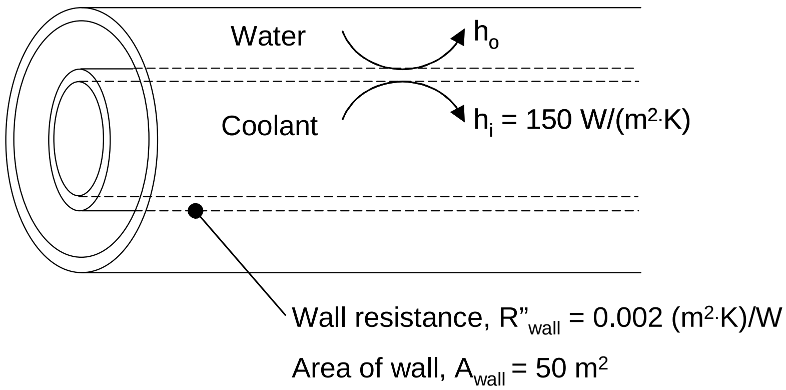
**ME 315: Heat and Mass Transfer**
**Spring 2008**
**EXAM 3**
**Thursday, 17 April 2008**
**7:00 to 8:00 PM**

**Instructions:** This is an open-book exam. You may refer to your course textbook, your class notes and your graded homework assignments. Show all work clearly for maximum credit. **CIRCLE ALL ANSWERS**.

| Problem | Score |
|---|---|
| 1 | / 20 |
| 2 | / 22 |
| 3 | / 18 |
| Total | / 60 |

Name: ______________________________

1. (20 points) A concentric tube heat exchanger is used to cool water at a mass flow rate of 1 kg/s from 80 °C to 40 °C. The coolant enters at 0 °C and exits at 50 °C. The specific heat for water and coolant are $c_{p,water}$ = 4200 J/(kg·K) and $c_{p,cool}$ = 1500 J/(kg·K), respectively. The surface area of the thin-walled tube separating the water and coolant is 50 $m^2$.




   a. (2 points) In order to achieve the desired inlet and outlet temperatures, which concentric tube heat exchanger configuration must be used? Circle the correct configuration below.

      Parallel Flow          Counter Flow

   b. (4 points) Find the rate of heat transferred from the water to the coolant.
   c. (4 points) What must the mass flow rate of the coolant be in order to remove the desired heat from the water?
   d. (4 points) What is the effectiveness of the heat exchanger?
   e. (6 points) If the heat transfer coefficient on the coolant side is $h_i$ = 150 W/($m^2$·K) and the thin wall between the water and coolant has a resistance of $R''_{wall}$ = 0.002 ($m^2$·K)/W, then what is the heat transfer coefficient on the water side ($h_o$)?

Water | Refrigerant

$T_{hi} := (80 + 273)K$ | $T_{ci} := (0 + 273)K$

coolant (refrigerant) cooling the water
water>refrig

$T_{ho} := (40 + 273)K$ | $T_{co} := (50 + 273)K$

$A_{wall} := 50m^2$

$c_{ph} := 4200 \frac{J}{kg \cdot K}$ | $c_{pc} := 1500 \frac{J}{kg \cdot K}$

$R_{wall} := 0.002 \frac{m^2 \cdot K}{W}$

$m_{h.dot} := 1 \frac{kg}{s}$ | $h_i := 150 \frac{W}{m^2 \cdot K}$

b )

$C_h := m_{h.dot} \cdot c_{ph}$ $\qquad C_h = 4.2 \times 10^3 \frac{W}{K}$

$q := C_h \cdot (T_{hi} - T_{ho})$ $\qquad q = 1.68 \times 10^5 W$

c )

$C_c := \frac{q}{T_{co} - T_{ci}}$ $\qquad C_c = 3.36 \times 10^3 \frac{W}{K}$

$m_{c.dot} := \frac{C_c}{c_{pc}}$ $\qquad m_{c.dot} = 2.24 \frac{kg}{s}$

d )

Therefore,

$C_{min} := C_c$

$q_{max} := C_{min} \cdot (T_{hi} - T_{ci})$

$\varepsilon := \frac{q}{q_{max}}$ $\qquad \varepsilon = 0.625$

Note that epsilon could also be found using the epsilon - NTU method if they solve for U to get NTU and then use equation 11.29b or Figure 11.11 but this is much more involved since they know q and q_max.

e )

$\Delta T_1 := T_{hi} - T_{co}$

$\Delta T_2 := T_{ho} - T_{ci}$

$\Delta T_{lm} := \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)}$ $\qquad \Delta T_{lm} = 34.761 K$

$$U := \frac{q}{A_{wall} \cdot \Delta T_{lm}} \qquad U = 96.661 \frac{W}{m^2 \cdot K}$$

$$U_{overall} := \left(\frac{1}{h_i} + R_{wall} + \frac{1}{h_o}\right)^{-1}$$

$$h_o := \left(\frac{1}{U} - \frac{1}{h_i} - R_{wall}\right)^{-1} \qquad h_o = 595.682 \frac{W}{m^2 \cdot K}$$

Name: ________________________________

2. (22 points) Consider one side of a flat, mechanically polished, stainless steel surface that is in contact with a fluid and has a square area of 0.01 $m^2$ (10 cm on a side). In each of the following two scenarios, **indicate the dominant heat transfer mode(s)** (such as conduction, convection, radiation, etc.) and **determine the input power [W]** required to maintain its surface at 390 K at atmospheric pressure in the following two scenarios:

   a. (11 points) Surface oriented vertically in quiescent air at 300 K.

   Air properties at an appropriate temperature:

$$\nu_{air} = 20.9x10^{-6}\left[\frac{m^2}{s}\right] \qquad k_{air} = 0.03\left[\frac{W}{m\cdot K}\right]$$

$$\mu_{air} = 208.2x10^{-7}\left[\frac{kg}{m\cdot s}\right] \qquad \alpha_{air} = 29.9x10^{-6}\left[\frac{m^2}{s}\right]$$

$$c_{p,air} = 1009\left[\frac{J}{kg\cdot K}\right] \qquad \Pr_{air} = 0.7$$

$$\rho_{air} = 0.995\left[\frac{kg}{m^3}\right]$$

   b. (11 points) Surface oriented horizontally in quiescent water at 300 K

   Saturated water properties (for liquid and vapor) at an appropriate temperature:

$$\mu_l = 279x10^{-6}\left[\frac{kg}{m\cdot s}\right] \qquad \mu_v = 12x10^{-6}\left[\frac{kg}{m\cdot s}\right] \qquad h_{fg} = 2257\left[\frac{kJ}{kg}\right]$$

$$c_{p,l} = 4217\left[\frac{J}{kg\cdot K}\right] \qquad c_{p,v} = 2029\left[\frac{J}{kg\cdot K}\right] \qquad \sigma_{surf,tension} = 0.059\left[\frac{kg}{s^2}\right]$$

$$\rho_l = 957.8\left[\frac{kg}{m^3}\right] \qquad \rho_v = 0.596\left[\frac{kg}{m^3}\right]$$

$$k_l = 0.68\left[\frac{W}{m\cdot K}\right] \qquad k_v = 0.025\left[\frac{W}{m\cdot K}\right]$$

$$\Pr_l = 1.76 \qquad \Pr_v = 0.984$$

a ) Given

$T_s := 390K$

$T_{inf} := 300K$

$T_f := \frac{T_s + T_{inf}}{2}$

$T_f = 345\,K$

$w := 10cm$

$L := 10cm$

$A := w \cdot L$

$A = 0.01\,m^2$

$\sigma := 5.67 \cdot 10^{-8} \frac{W}{m^2 \cdot K^4}$

Air at Tf ~ 350 K

$\nu_{air} := 20.9 \cdot 10^{-6} \frac{m^2}{s}$

$\mu_{air} := 208.2 \cdot 10^{-7} \frac{kg}{m \cdot s}$

$c_{p.air} := 1009 \frac{J}{kg \cdot K}$

$\rho_{air} := 0.995 \frac{kg}{m^3}$

$k_{air} := 0.03 \frac{W}{m \cdot K}$

$\alpha_{air} := 29.9 \cdot 10^{-6} \frac{m^2}{s}$

$Pr_{air} := 0.7$

for an ideal gas: $\beta := \frac{1}{T_f}$

$Ra_L := \frac{g \cdot \beta \cdot (T_s - T_{inf}) \cdot L^3}{\nu_{air} \cdot \alpha_{air}}$ $\quad Ra_L = 4.094 \times 10^6$ $\quad$ Therefore the flow is laminar.

Any of the following 3 relations could be used to evaluate the q_free convection

Using 9.24

$C := 0.59$ $\quad n := \frac{1}{4}$ $\quad Nu_{Lavg1} := C \cdot Ra_L^{\,n}$ $\quad Nu_{Lavg1} = 26.539$ $\quad h_1 := \frac{k_{air} \cdot Nu_{Lavg1}}{L}$

$h_1 = 7.962 \frac{W}{m^2 \cdot K}$

Using 9.26

$$Nu_{Lavg2} := \left[ 0.825 + \frac{0.387 \cdot Ra_L^{\frac{1}{6}}}{\left[ 1 + \left( \frac{0.492}{Pr_{air}} \right)^{\frac{9}{16}} \right]^{\frac{8}{27}}} \right]^2$$

$Nu_{Lavg2} = 24.245$ $\quad h_2 := \frac{k_{air} \cdot Nu_{Lavg2}}{L}$

$h_2 = 7.273 \frac{W}{m^2 \cdot K}$

Using 9.27

$$Nu_{Lavg3} := 0.68 + \frac{0.67 \cdot Ra_L^{\frac{1}{4}}}{\left[1 + \left(\frac{0.492}{Pr_{air}}\right)^{\frac{9}{16}}\right]^{\frac{4}{9}}}$$

$Nu_{Lavg3} = 23.775$

$$h_3 := \frac{k_{air} \cdot Nu_{Lavg3}}{L}$$

$$h_3 = 7.132 \frac{W}{m^2 \cdot K}$$

For stainless steel the emissivity can be found from Table A.11 in the appendix

$\varepsilon := 0.17$

Radiation needs to be included since the plate is at a high temperature and can emit to the surroundings. Assume the surrounding temperature is the same as the T_inf.

$$q_1 := h_1 \cdot A \cdot (T_s - T_{inf}) + \varepsilon \cdot A \cdot \sigma \cdot \left(T_s^4 - T_{inf}^4\right)$$

$q_1 = 8.615\,W$

$$q_2 := h_2 \cdot A \cdot (T_s - T_{inf}) + \varepsilon \cdot A \cdot \sigma \cdot \left(T_s^4 - T_{inf}^4\right)$$

$q_2 = 7.995\,W$

$$q_3 := h_3 \cdot A \cdot (T_s - T_{inf}) + \varepsilon \cdot A \cdot \sigma \cdot \left(T_s^4 - T_{inf}^4\right)$$

$q_3 = 7.868\,W$

$$q_{rad} := \varepsilon \cdot A \cdot \sigma \cdot \left(T_s^4 - T_{inf}^4\right)$$

$q_{rad} = 1.449\,W$

b ) Water at T = 373 K

$\mu_l := 279 \cdot 10^{-6} \frac{kg}{m \cdot s}$ $\mu_v := 12 \cdot 10^{-6} \frac{kg}{m \cdot s}$ $h_{fg} := 2257000 \frac{J}{kg}$

$c_{p.l} := 4217 \frac{J}{kg \cdot K}$ $c_{p.v} := 2029 \frac{J}{kg \cdot K}$ $\sigma_{st} := 0.059 \frac{kg}{s^2}$

$\rho_l := 957.8 \frac{kg}{m^3}$ $\rho_v := 0.596 \frac{kg}{m^3}$

$k_l := 0.68 \frac{W}{m \cdot K}$ $k_v := 0.025 \frac{W}{m \cdot K}$

$Pr_l := 1.76$ $Pr_v := 0.984$

$T_{sat} := 373K$

$\Delta T_e := T_s - T_{sat}$ $\Delta T_e = 17\,K$

Since the surface temperature would cause an excess temperature that is in the nucleate boiling range for water at atmospheric pressure (5 < Te < 30), we have nucleate boiling occuring.

Using Rohsenow's correlation, 10.5 and constants from Table 10.1

$C_{sf} := 0.0132$ $\quad$ $n := 1.0$

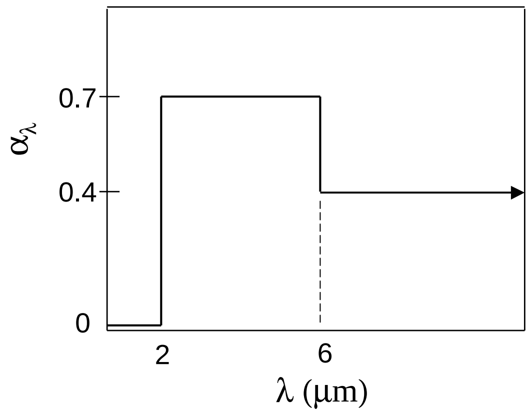
$$q_{boiling} := A \cdot \mu_l \cdot h_{fg} \cdot \left[\frac{g \cdot (\rho_l - \rho_v)}{\sigma_{st}}\right]^{\frac{1}{2}} \cdot \left(\frac{c_{p.l} \cdot \Delta T_e}{C_{sf} \cdot h_{fg} \cdot {Pr_l}^{n}}\right)^{3}$$

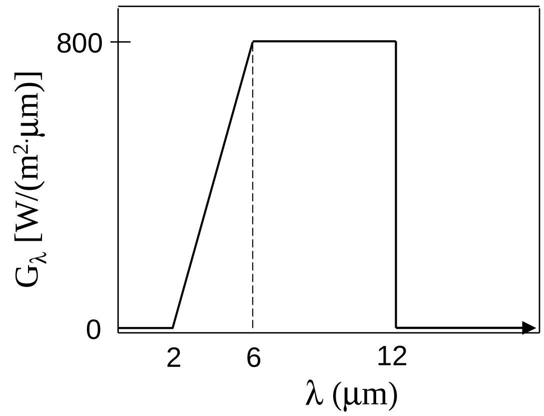
$q_{boiling} = 6.419 \times 10^{3}\,W$

In this case, radiation can be neglected since q_rad << q_boiling

Name: ______________________________

3. (18 points) An opaque, diffuse surface has a spectral, hemispherical absorptivity and spectral irradiation as shown in the two figures below.




a. (6 points) Using the spectral absorptivity ($\alpha_\lambda$) and the given irradiation values over the spectral range ($G_\lambda$), calculate the total, hemispherical absorptivity of the surface.
b. (6 points) What is the total, hemispherical emissivity of the surface when the surface is at a temperature of 1000 K?
c. (2 points) Is the surface gray? Explain.
d. (4 points) If the surface is initially at 1000 K as above, show whether the surface temperature will increase or decrease after being exposed to the irradiation (neglecting conduction and convection).

Given

$\alpha_{\lambda1} := 0.7$ $\lambda_1 := 2$ $T_s := 1000K$

$\alpha_{\lambda2} := 0.4$ $\lambda_2 := 6$ $\sigma := 5.67 \cdot 10^{-8} \frac{W}{m^2 \cdot K^4}$

$\lambda_3 := 12$

a )

$$G_{2\_6} := \frac{800}{2} \frac{W}{m^2}$$

$$G_{6\_12} := 800 \frac{W}{m^2}$$

$$G_{abs} := \alpha_{\lambda1} \cdot G_{2\_6} \cdot (\lambda_2 - \lambda_1) + \alpha_{\lambda2} \cdot G_{6\_12} \cdot (\lambda_3 - \lambda_2) \qquad G_{abs} = 3.04 \times 10^3 \frac{W}{m^2}$$

$$G := G_{2\_6} \cdot (\lambda_2 - \lambda_1) + G_{6\_12} \cdot (\lambda_3 - \lambda_2) \qquad G = 6.4 \times 10^3 \frac{W}{m^2}$$

$$\alpha := \frac{G_{abs}}{G} \qquad \alpha = 0.475$$

b )

Since the surface is diffuse: $\varepsilon_\lambda := \alpha_\lambda$

$$\lambda T_{1.rad} := \lambda_1 \cdot T_s \qquad \lambda T_{1.rad} = 2 \times 10^3 K \qquad F_{1.rad} := 0.066728$$

$$\lambda T_{2.rad} := \lambda_2 \cdot T_s \qquad \lambda T_{2.rad} = 6 \times 10^3 K \qquad F_{2.rad} := 0.737818$$

$$\varepsilon := \alpha_{\lambda1} \cdot (F_{2.rad} - F_{1.rad}) + \alpha_{\lambda2} \cdot (1 - F_{2.rad}) \qquad \varepsilon = 0.575$$

c )

The surface is not gray since the total hemispherical emissivity does not equal the total hemispherical absorptivity.

d )

$$q_{rad} := \varepsilon \cdot \sigma \cdot T_s^4 \qquad q_{rad} = 3.258 \times 10^4 \frac{W}{m^2}$$

$$q_{net} := G_{abs} - q_{rad} \qquad q_{net} = -2.954 \times 10^4 \frac{W}{m^2}$$

Therefore, the surface temperature will decrease since q_rad > G_abs