Name: Solution Key

Transport II ChBE 3210

Exam 1

Monday, June 8, 2015

Remember, to receive full credit on each problem:

- Write down relevant relationships/equations
- Label variables
- State all assumptions
- Show intermediate steps
- Present solutions clearly with appropriate units

Problem	Possible Points	Score
1	25	
2	25	
3	25	
4	25	
Total		

Problem 1 [5 pts for each part]

A) An experiment compares gas and liquid flow over a flat surface by using water and steam (each at 100°C). If the experiment is set-up such that each scenario have the same hydrodynamic boundary layer thickness (δ), how do their respective thermal boundary layers (δ_t) compare (same thickness or one thicker than the other)? What is the ratio of $\delta_{t\,water}$ to $\delta_{t\,steam}$?

$\frac{\delta}{\delta_t} = Pr^{1/3}$ $\quad \delta = \delta_t Pr^{1/3}$ if $\delta_{water} = \delta_{steam}$ than

$$\delta_{t\,water} Pr_{water}^{1/3} = \delta_{t\,steam} Pr_{steam}^{1/3}$$

$\delta_{t\,water}(1.76)^{1/3} = \delta_{t\,steam}(0.984)^{1/3}$

$\delta_{t\,water} = 0.824\,\delta_{t\,steam}$ Steam thermal layer is thicker.

B) A rectangular enclosure where θ = 0 (bottom surface heated) is characterized by $Nu = 0.069\, Ra_L^{1/3} Pr^{0.074}$. However, when the enclosure is tilted to θ = 180 (top surface heated), $Nu = 1$. Explain what is happening physically that results in $Nu = 1$.

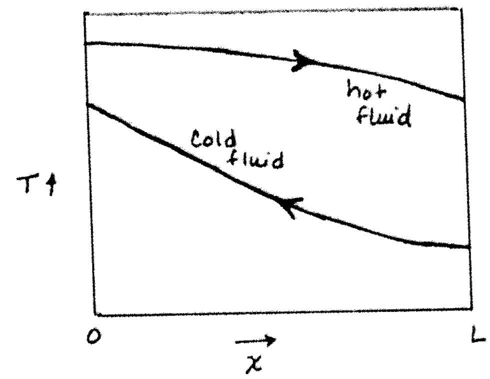
There is no forced convection in an enclosure. Natural convection is a result of density changes ~~resulting from~~ (buoyant forces). When the enclosure is tilted such that the hot surface faces down, natural convection is reduced ($h \approx k/L$). The conductive and convective resistance are equal.

C) Arrange the following in order of lowest excess temperature to highest:

a. Evaporation (no boiling) 1
b. Nucleate Boiling 2
c. Radiation 5
d. Stable Film Boiling 4
e. Unstable Film Boiling 3

a, b, e, d, c

D) The graph on the right shows the fluid temperature profile in a double-pipe heat exchanger, which is operated with equal mass flow rates of water (cp = 4200 J/kg·K) and oil (cp = 1700 J/kg·K). Which is the hot fluid, oil or water?



$\dot{m}_h C_{ph} \Delta T_h = q = \dot{m}_c C_{pc} \Delta T_c$

if $\dot{m}_h = \dot{m}_c$ then $C_{ph} \Delta T_h = C_{pc} \Delta T_c$

Larger C_p value has smaller ΔT

Hot fluid is Water

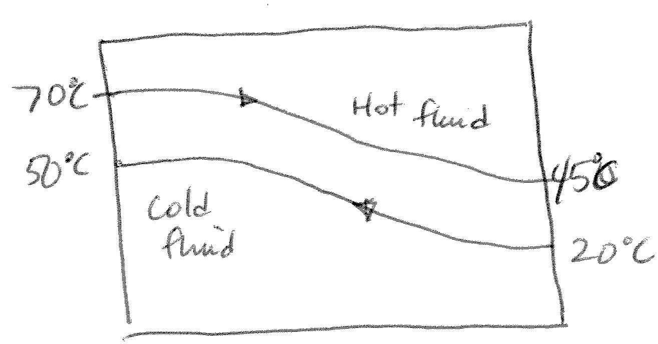
E) In the lab, you find a heat exchanger with an unknown flow arrangement. There are two marked inlets and two marked outlets. You connect one of the inlets to a hot water tap at 70°C and pump cold oil at 20°C into the other inlet. After some time has passed, you measure the outlet temperatures. The water exits at 45°C, and the oil exits at 50°C. Is this a **parallel flow or counter flow** heat exchanger? **Sketch the temperature profile.**

$T_{Hi} = 70°C$

$T_{Ho} = 45°C$

$T_{Ci} = 20°C$

$T_{Co} = 50°C$

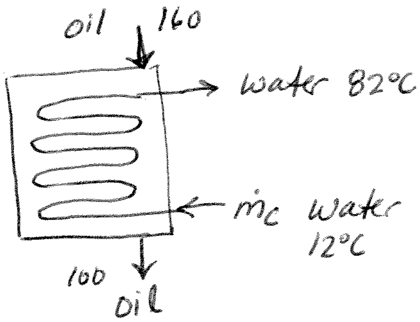


Counter flow because $T_{Co} > T_{Ho}$

Problem 2 [25 pts]

A shell and tube exchanger must be designed to heat 2.5 kg/s of water from 12 to 82°C. The heating is accomplished by passing hot engine oil, which is available at 160°C, through the shell side of the exchanger. The oil is known to provide an average convection coefficient of h_o = 400 W/m²·K on the outside of the tubes. Tubes are thin walled, of a diameter D=25 mm, and make eight (8) passes through the shell. Oil leaves the exchanger at 100°C and has an average heat capacity, cp = 2350 J/kg·K. Assume a clean exchanger with no fouling and that the outside shell is well-insulated.

A) [5 pts] What is the oil mass flow rate?
B) [10 pts] What is the overall heat transfer coefficient, U?
C) [5 pts] What is the correction factor, F?
D) [5 pts] If 10 tubes pass through the heat exchanger, what is the required tube length? Is this sufficient for fully developed flow conditions?

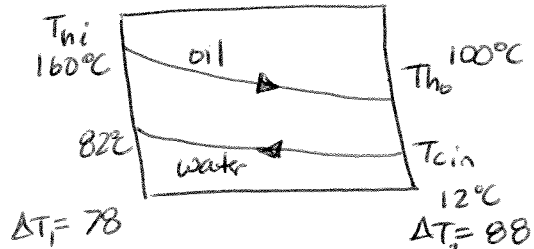


$\dot m_c = 2.5$ kg/s water

$h_o = 400$ W/m²K

D = 25 mm

8 passes



Water

$T_{cin} = 12°C$

$T_{cout} = 82°C$

1pt avg = 47 = 320°K

$C_p = 4180$ J/kg/K

$\mu = 577 \times 10^{-6}$ N·s/m²

$k = 0.640$ W/m·K

$P_r = 3.77$

oil $C_{p\,oil} = 2350$ J/kg K

$T_{hin} = 160$

$T_{hout} = 100$

5 Part A $q = \dot m_c C_{pc} \Delta T_c = \dot m_h C_{ph} \Delta T_h$ 2pt

$$\dot m_h = \left[\frac{2.5\ \text{kg}}{\text{s}} \Big/ \frac{4180\ \text{J}}{\text{kg K}} (82-12)\text{K}\right] \Big/ \left[\frac{2350\ \text{J}}{\text{kg K}} (160-100)\text{K}\right]$$

$$= (7.315 \times 10^5) / (1.41 \times 10^5) = \boxed{5.19\ \text{kg/s}}$$ 2pt

Problem 2

10 Part B Assume No fouling. For thin walled tube $A_i \approx A_o$ (2pt) so $U = \dfrac{1}{(1/h_i + 1/h_o)}$ (2pt)

First determine h_i from Nu_D

If assumed one tube

2pt

$$Re_D = \frac{vD\rho}{\mu} \qquad v\rho \; [=] \; kg/m^2 s = \frac{\text{mass flow rate } kg/s}{\text{pipe area}}$$

$$Re_D = \left[\dot m\left(\frac{4}{\pi D^2}\right)D\right]/\mu = \frac{2.5\ kg}{s}\left|\frac{4}{\pi\ (0.025m)}\right|\frac{m\ s}{577\times10^{-6}\ kg}$$

$Re_D = 220{,}665$ turbulent

2pt

$$Nu_D = 0.023\ Re_D^{0.8}\ Pr^n = 0.023(220{,}665)^{0.8}(3.77)^{0.4} = 736.6$$

$$h_i = \frac{k}{D}Nu_D = \frac{0.64\ W}{m\ K}\left|\frac{736.6}{0.025m}\right. = 18857.8\ W/m^2 K$$

$$U = \frac{1}{(1/h_o + 1/h_i)} = 1/[1/400 + 1/18858] = \boxed{391.7\ W/m^2 K}$$

or 2pt

If assumed ten tubes

$Re_D = 22{,}066.5$ turbulent $Nu_D = 116.7$

$h_i = 2988.8$ $\boxed{U = 352.8\ W/m^2 K}$

5 Part C

$$Y = \frac{82-12}{160-12} \overset{2pt}{=} 0.473 \qquad Z = \frac{160-100}{82-12} \overset{2pt}{=} 0.857$$

$F \overset{1pt}{\approx} \boxed{0.87 \text{ to } 0.88}$ from plot (a)

5 Part D

$q = UA\,\Delta T_{lm} F$ $\quad \Delta T_{lm} \overset{2pt}{=} \dfrac{78-88}{\ln(78/88)} = 82.9°C$

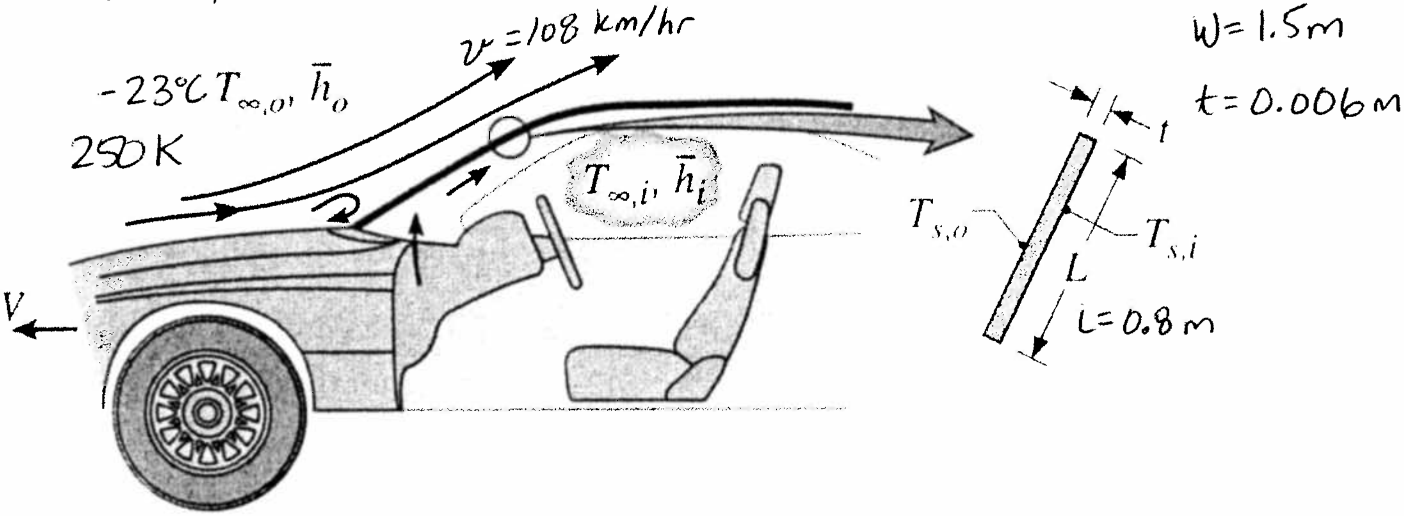
1pt q

Since $A = n_{tubes}\pi D L$ $\quad L = \dfrac{q}{U(n_{tubes}\pi D)F\Delta T_{lm}}$ 2pt for $U = 352.8$ $L = 36.6\ m$

$U = 391.7$ $L = 32.0\ m$

Problem 3 [25 pts]

The defroster of a car functions by discharging warm air on the inner surface of the windshield. To prevent condensation of water vapor on the inner surface, the temperature of the defroster air, $T_{\infty,i}$, and the convective heat transfer coefficient h_i must be large enough to maintain an inside surface temperature $T_{s,i}$ that is at least as high as the dewpoint T_{dp} of the air inside the car.



Consider a rectangular windshield of length L = 0.80 m, width W = 1.5 m and thickness t = 6 mm. The conductive heat transfer coefficient of the glass is k_{glass} = 0.78 W/m·K. The car moves at a velocity v = 108 km/hr in ambient air at $T_{\infty,o}$ = - 23°C.

From laboratory experiments performed on this car model, it is known that the average convective heat transfer coefficient on the *outer surface* of the windshield, h_o is given by the correlation function $Nu_L = 0.03\ Re_L^{0.8}\ Pr^{1/3}$. For this correlation function to apply, the air properties must be taken at bulk temperature. at 250 K

A) [5 pts] Determine the convective heat transfer coefficient on the *outer surface* of the windshield, h_o.

B) [10 pts] Determine the skin friction and drag force on the outside of the windshield.

C) [5 pts] If T_{dp} = 10°C and the defroster air temperature $T_{\infty,i}$ = 50°C , what is the smallest value of h_i for which there will be no condensation on the inner surface of the windshield.

5

D) [5 pts] Based upon the minimum required heat transfer (from part C), what is the temperature of the outside window surface, $T_{s,o}$?

5 Part A

For air at 250K (1pt) $\nu = 1.1315\times10^{-5}\ m^2/s$ $k = 2.2269\times10^{-2}\ W/mK$

$\rho = 1.4133\ kg/m^3$ $Pr = 0.722$

$Nu_L = 0.03\, Re_L^{0.8}\, Pr^{1/3}$ $Re_L = \frac{vL}{\nu} = \underbrace{\frac{108\,km}{hr}\Big|\frac{1000\,m}{km}\Big|\frac{hr}{3600\,s}}_{30\,m/s}\Big|\,0.8\,m\,\Big|\frac{s}{1.1315\times10^{-5}\,m^2}$

1pt $Re = 2.121\times10^{6}$

2pt $\begin{cases} Nu_L = 0.03(2.12\times10^6)^{0.8}(0.722)^{1/3} = 3099 \\ Nu_L = h_o L/k \quad h_o = Nu_L\, k/L = (3099)\left(2.2269\times10^{-2}\frac{W}{mK}\right)\left(\frac{1}{0.8\,m}\right)\end{cases}$

1pt $\boxed{h_o = 86.26\ W/m^2K}$

10 Part B

using Chilton-Colburn $St \cdot Pr^{2/3} = C_f/2$

$St \overset{1pt}{=} Nu/Pr\cdot Re = 3099/(0.722)(2.121\times10^6) = 0.00202$ 1pt

$C_f \overset{2pt}{=} 2\,St\,Pr^{2/3} = 2(0.00202)(0.722)^{2/3} = \boxed{3.257\times10^{-3}}$ 1pt

$F \overset{1pt}{=} \frac{1}{2}C_f\rho v_\infty^2 A = \frac{1}{2}(3.257\times10^{-3})\underbrace{(1.4133\ kg/m^3)}_{1pt}\underbrace{(30^2\ m^2/s^2)}_{1pt}\underbrace{(0.8)(1.5)m^2}_{1pt}$

$\boxed{F = 2.486\ (kg)(m)/s^2} = 2.486\ N$

1pt

5 Part C

Heat transfer through glass to outside ⟺ transfer from inside to glass

$q \overset{2pt}{=} \frac{T_{si} - T_{\infty o}}{\Sigma R} = \frac{T_{si} - T_{\infty o}}{\underbrace{(1/h_oA + t/k_{glass}A)}_{1pt}}$ ⟺ $h_i A(T_{\infty i} - T_{si})$ 1pt

where $T_{si} = T_{dp} = 10°C = 283$

$q = \frac{(283K - 250K)}{\left(\frac{1}{86.26(0.8)(1.5)W/K} + \frac{0.006}{0.78(0.8)(1.5)W/K}\right)} = 2053.4\ W = h_i(0.8)(1.5)(323-283)$

$\boxed{h_i = 42.78\ W/m^2K}$ 1pt

Part D

5

$q = h_o A(T_{so} - T_{\infty o})$ 2pts

$T_{so} = \frac{q}{h_oA} + T_{\infty o} = \frac{2053.4\,W}{86.26\ W/m^2K\,\underbrace{(0.8)(1.5)m^2}_{1pt}} + 25$ 1pt

$\boxed{T_{so} = 269.8K}$ ~~1pt~~

Problem 4 [25 pts]

A homeowner has decided to install an energy efficient "tankless" electric water heater in their house. The design of the water heater essentially consists of a 5 m long, thin, copper tube with 3 cm inner diameter. The outside of the tube is wrapped with electrical resistors, which generate a uniform heat flux through the surface of the tube. The tube and resistors are wrapped in a thick insulation layer, which prevents heat losses to the surroundings and thus maximizes the efficiency of the heater. The water heater is designed so that it can supply a steady flow of hot water to a low-flow shower head: when it operates at maximum power, it can heat a water stream of 10 liter per minute from an inlet bulk temperature of 15°C to an outlet temperature of 65°C.

A) [5 pts] Calculate the electrical power that must be supplied to the "tankless" water heater when it operates at full power.

B) [15 pts] Calculate the temperature of the *inner surface* of the copper tube at the *outlet* of the "tankless" heater.

C) [5 pts] The homeowner is not very happy about the comfort offered by his low-flow shower head and decides to double the water flow rate to 20 liter per minute. What will be the temperature of the water leaving the heater under these conditions? *Again, assume that the water heater is operating at maximum power.*

Part A Heat Transfer inside tubes @ mean $T_b = 40°C = 313K$

Water Properties at 315K $C_p = 4179\ J/kg\,K$ $\rho = \frac{1}{v} = 991\ kg/m^3$

$\mu = 631 \times 10^{-6}\ \frac{Ns}{m^2}$ $Pr = 4.16$ $k = 634 \times 10^{-3}\ W/mK$

$\dot{m} = \rho \dot{V} = (991\ m^3/kg)(0.01\ m^3/min)(1\ min/60sec) = 0.1652\ kg/s$

$q = \dot{m}\, C_p\, \Delta T = 0.1652\frac{kg}{s} / \frac{4179\ J}{kg\,K}(65-15) = \boxed{34.5\ kW}$

Assumes no loss to Surroundings and all heat transferred to water.

property at T_b 1
$\dot{m} = \rho V$ 1
$q = \dot{m}\, C_p\, \Delta T$ 2
final ans 1
$\boxed{5}$

Problem 4

Part B Locally $q/A = h\,\Delta T = h\,(T_{wall} - T_{water})$ 2pt

$$\frac{q}{A} = \frac{34.5\,kW}{\pi D L} = \frac{34.5\,kW}{\pi(0.03)5\,m^2} = 73.24\ kW/m^2$$ 2pt

Need to find h_x at outlet where $T_{water} = 65°C$

5pts

$$Re_D = vD/\nu = vD\rho/\mu \qquad v = \dot{V}/A_{cs} = \frac{0.01\,m^3}{min}\,\Big|\,\frac{min}{60\,sec}\,\Big|\,\frac{4}{\pi(0.03)^2 m^2}$$

$= 0.236$ m/s

$$= \frac{0.236\,m}{s}\,\Big|\,0.03\,m\,\Big|\,\frac{991\,kg}{m^3}\,\Big|\,\frac{m\,s}{631\times10^{-6}\,kg} = \boxed{11{,}119}$$

therefore turbulent ($Re_D > 2\cdot10^4$)

2pt

$$Nu_D = 0.023\,Re_D^{0.8}\,Pr^{n} \qquad n = 0.4 \text{ heated fluid}$$

$$Nu_D = 0.023\,(11119)^{0.8}(4.16)^{0.4} = \boxed{70.18}$$

2pt $\quad Nu_D = \frac{h \cdot D}{k} \qquad h = \frac{Nu_D\,k}{D} = \frac{70.18\,(0.634)\,W}{m\,K}\,\Big|\,\frac{1}{0.03\,m} = \boxed{1483\ W/m^2K}$

Back to $q/A = h\,\Delta T$

$$\Delta T = (q/A)(1/h) = 73.24\times10^3/1483 = 49.4$$

$$T_{wall} = 49.4 + T_{water} = 49.4 + 65 = \boxed{114.4\ °C}$$ 2pt

387.55

$\boxed{15\text{pts}}$

Part C

3pts $\quad q = \dot{m}\,C_p\,\Delta T = 34.5$ kW

C_p stays the same, $\dot{m}$ doubles, so ΔT is halved

$$\Delta T_{new} = 50/2 = 25°$$

$$T_{water\ out} = 15° + 25° = 40\ °C$$ 2pts

$\boxed{5\text{pts}}$

$\boxed{25\text{ total}}$