1.	/20
2.	/20
3.	/20
4.	/20
5.	/20

Name: SOLUTION

Final Exam

CM3110 Spring
Thursday 29 April 2021

Rules:

- Closed book, closed notes.
- Two-page 8.5" by 11" study sheet allowed, double sided; you may use a calculator; you may not search the internet or receive help from anyone.
- Please text clarification questions to Dr. Morrison 906-487-9703. I will respond if I am able.
- All work submitted for the exam must be your own.
- Do not discuss the contents of the exam with anyone before 11:59pm Thursday, 29 April 2021.
- *Please copy the following Honors Pledge onto the first page of your exam submission and sign and date your agreement to it.*

Honor Pledge:

On my honor, I agree to abide by the rules stated on the exam sheet.

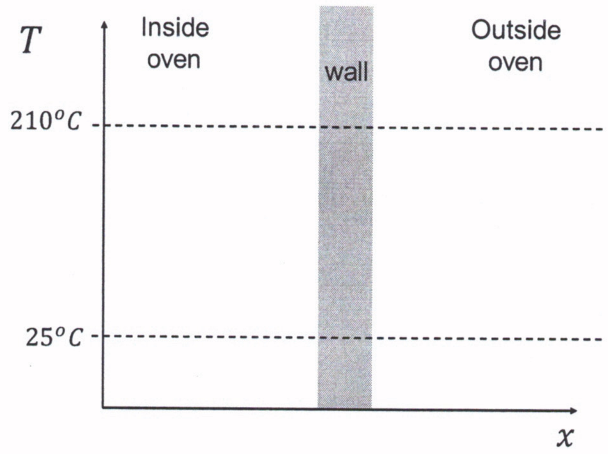
Signature ______________________________

Date ____________________

Exam Instructions:

i. You may work on the exam for up to three hours and 30 minutes (210 minutes).
ii. Please submit your exam work promptly after the time for working has passed.
iii. Please be neat. Only neat answers will be granted partial credit. Please use a dark pencil or pen so that your work is readable once scanned.
iv. Significant figures always count.
v. Please box your final answers.
vi. Submit your work as a single PDF file; put your name on every page. (Genius Scan is a free app that can create a PDF from photos taken by your phone)
vii. Submit your exam study sheet as a separate PDF file; put your name on the first page (at a minimum)

1. (20 points) A reaction taking place in an oven keeps the air temperature inside the oven at 210^oC. The wall of the oven is steel and is $0.5in$ thick. A few feet away from the oven, the air in the room that holds the oven is 25^oC. On the axes below, sketch the most likely temperature profile in all three regions (inside the oven, in the wall, outside the oven). Please be precise in your sketch.

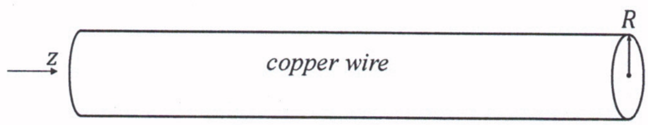


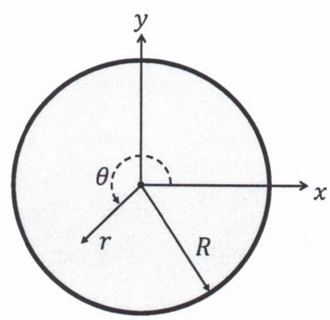
2. (20 points) A 1-2 shell and tube heat exchanger uses a hot oil stream (shell side, inlet temperature= 81.0^oC; outlet temperature= 64.1^oC; oil heat capacity $6.345\ kJ/kg\ K$) to heat up a cold water stream (tube-side, inlet temperature 43.5^oC; outlet temperature 54.75^oC). What is the correct mean temperature difference (also called the *driving force for heat transfer*) in the heat exchanger (in units of ^oC)?

3. (20 points) What is the pressure drop in $200.0\ meters$ of smooth horizontal copper tubing of inner diameter $1.5\ cm = 0.015\ m$? Water at 25^oC is flowing steadily at $1.31 \times 10^1\ m/s$ average velocity. Please give your answer in kPa.

4. (20 points) For the heat-transfer question below, please provide (1) the simplified governing equation (the microscopic energy balance) and (2) the appropriate boundary conditions. You do not need to solve the equations.

What is the steady state temperature profile in a long, solid copper wire (thermal conductivity k, heat capacity $\hat{C}_p$, radius R) if heat is generated uniformly in the wire by the flow of electric current? The heat is generated throughout the wire at a rate of S_o W/m^3, and the wire is in a room with bulk air temperature of T_b. You may assume that the heat transfer coefficient from the wire to the room is h and that the room temperature is cooler than the wire wall temperature, which is unknown.





5. (20 points) A horizontal pipe (Schedule 40, outer diameter 2.375 in; inner diameter 2.067 in; steel) connects two tanks in a pilot plant. The hot oil flowing in the tube heats the pipe to an outside surface temperature of 116^oC. A fan blows on the pipe, sending a steady flow of 15^oC air (1.0 atm) across the tube at 12 m/s. What is the heat loss (kW/m^2) from the pipe?

Final Exam
CM3110 (Morrison)
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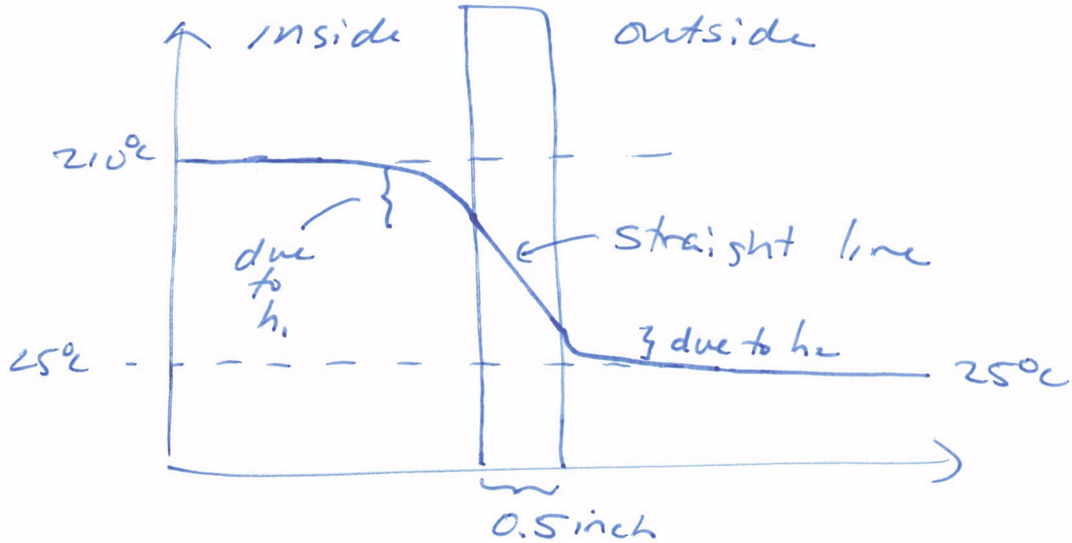
(1)



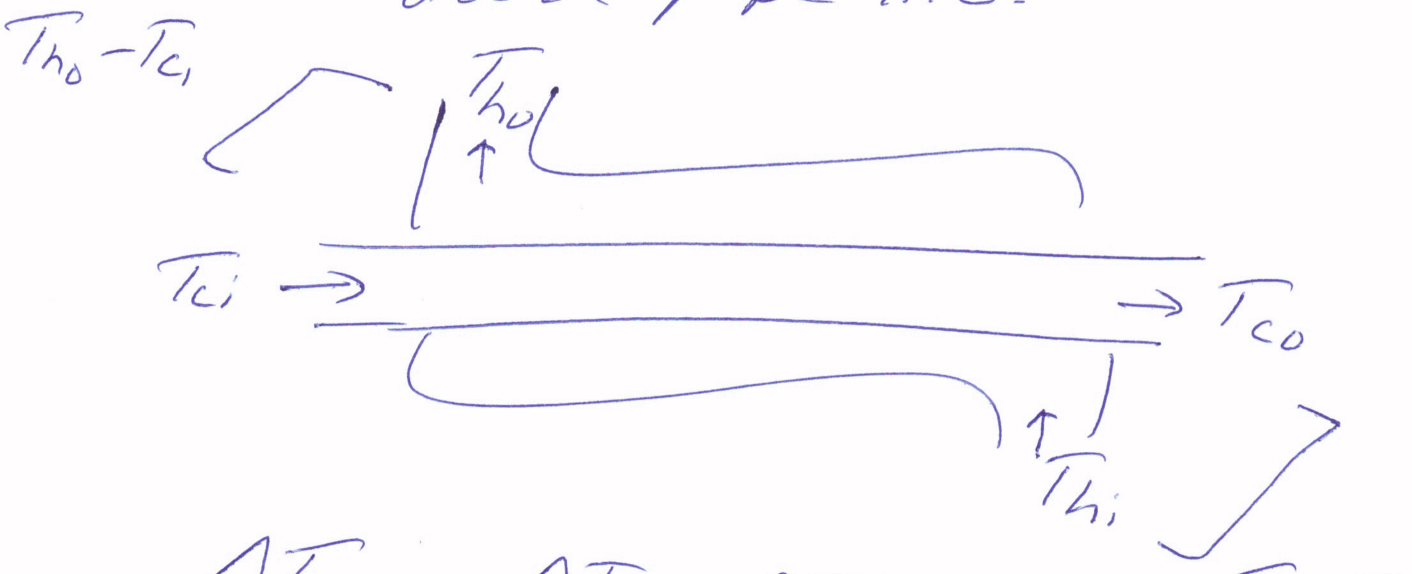
Addendum to Final Exam Soln
29 April 2021 F. MORRISON

1-2 Shell + Tube heat exchanger

$$\Delta T_{df} = \Delta T_{lm} F_T$$

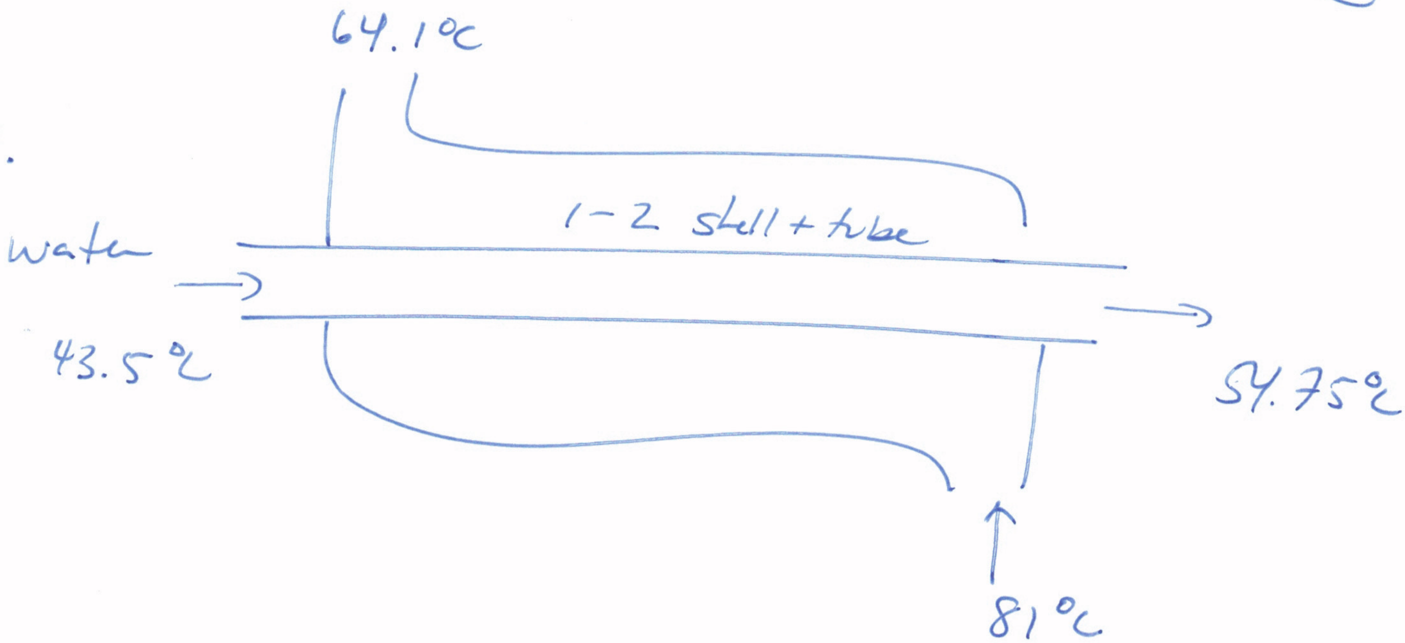
ΔT_{lm}: written as if it's a counter current double pipe H.E.

F_T: from charts



$$\Delta T_{lm} = \frac{\Delta T_{left} - \Delta T_{right}}{\ln \dfrac{\Delta T_{left}}{\Delta T_{right}}}$$

2.



$\hat{C}_p = 6.345 \frac{kJ}{kg\,K}$

$\Delta T_{\text{driving force}} = ?$

$$\Delta T = \Delta T_{lm} F_T$$

$$\Delta T_{lm} = \frac{\Delta T_{left} - \Delta T_{right}}{\ln \frac{\Delta T_{left}}{\Delta T_{right}}}$$

$$= \frac{20.6 - 26.25}{\ln \frac{20.6}{26.25}} = \boxed{23.31\ °C}$$

To obtain F_T use Fig 4.9-4c

$$Z = \frac{T_{hi} - T_{ho}}{T_{co} - T_{ci}} = \frac{81 - 64.1}{54.75 - 43.5}$$

$$\boxed{Z = 1.5}$$

$$Y = \frac{T_{co} - T_{ci}}{T_{hi} - T_{ci}} = \frac{54.75 - 43.5}{81 - 43.5}$$

$$\boxed{Y = 0.3}$$

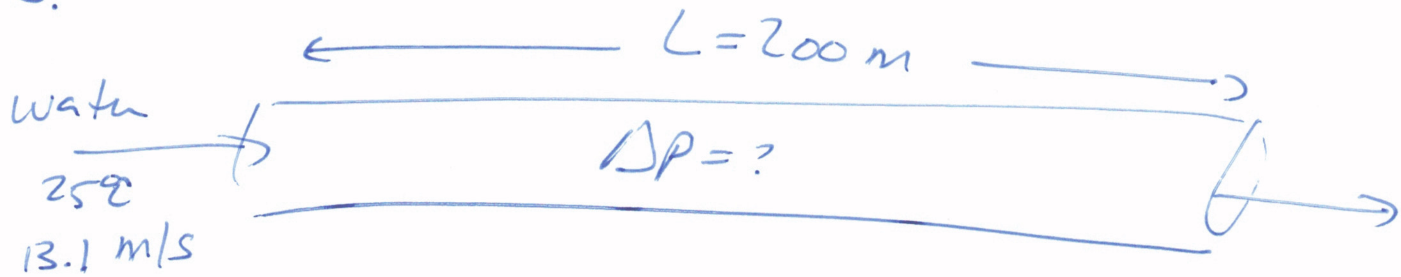
Reading graph $F_T = 0.93$

$$\Delta T_{df} = \Delta T_{lm} F_T = (23.31)(0.93)$$

$$\boxed{\Delta T_{df} = 22\,°C}$$

//

3.



$D = 0.015\, m$

$$Re = \frac{\rho \langle V \rangle D}{\mu}$$

$$= \frac{(997.03\ \frac{kg}{m^3})(13.1\ \frac{m}{s})(0.015\ m)}{8.937 \times 10^{-4}\ \frac{kg}{m\,s}}$$

$$= 2.192194 \times 10^{5} \Rightarrow \text{TURBULENT}$$

$$= 219{,}000$$

To obtain ΔP need f from a data correlation. Use simplified.

$$f = \frac{1.02}{4} (\log Re)^{-2.5}$$

$$f = 3.86819 \times 10^{-3}$$

Pipe flow:

$$f = \frac{\Delta P D}{2 L \rho \langle v \rangle^2}$$

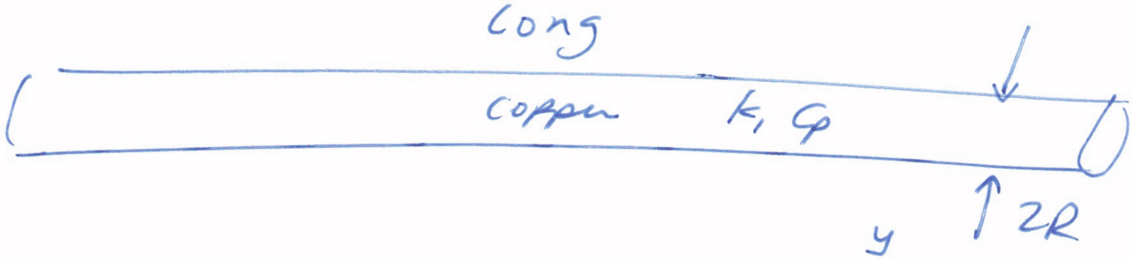
$$\Delta P = \frac{2 f L \rho \langle v \rangle^2}{D}$$

$$= \frac{(2)(3.86819 \times 10^{-3})(200\,m)(997.03\,\frac{kg}{m^3})(13.1\,\frac{m}{s})^2}{0.015\,m}$$

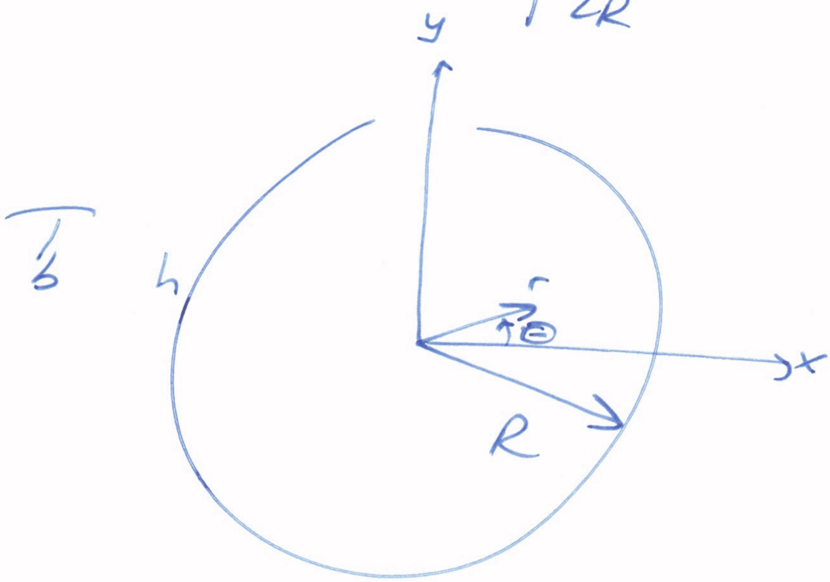
$$= 1.765 \times 10^7 \quad \frac{kg\,m}{s^2}\,m^2 \quad \frac{N\,s^2}{kg\,m} \quad \frac{Pa}{N/m^2}$$

$$\boxed{\Delta P = 18{,}000\ kPa}$$

4.



$T(r) = ?$



electric current

$S_0 \ \frac{W}{m^3}$

$T_b < T_{wire}$

see next page:

$$0 = \frac{k}{r}\frac{d}{dr}\left(r\frac{dT}{dr}\right) + S_e$$

BC: $r = 0 \quad \frac{dT}{dr} = 0$ (symmetry)

$r = R \quad -k\frac{dT}{dr} = \underbrace{h(T - T_b)}_{\text{Newton's Law of cooling}}$

The **Equation of Energy** for systems with **constant k**

Microscopic energy balance, constant thermal conductivity; Gibbs notation

$$\rho \hat{C}_p \left(\frac{\partial T}{\partial t} + \underline{v} \cdot \nabla T \right) = k \nabla^2 T + S_e$$

Microscopic energy balance, constant thermal conductivity; Cartesian coordinates

$$\rho \hat{C}_p \left(\frac{\partial T}{\partial t} + v_x \frac{\partial T}{\partial x} + v_y \frac{\partial T}{\partial y} + v_z \frac{\partial T}{\partial z} \right) = k \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + S_e$$

$v = 0$

Microscopic energy balance, constant thermal conductivity; cylindrical coordinates

$$\rho \hat{C}_p \left(\frac{\partial T}{\partial t} + v_r \frac{\partial T}{\partial r} + \frac{v_\theta}{r} \frac{\partial T}{\partial \theta} + v_z \frac{\partial T}{\partial z} \right) = k \left(\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 T}{\partial \theta^2} + \frac{\partial^2 T}{\partial z^2} \right) + S_e$$

Steady — θ Symmetry — Long — yes elec current

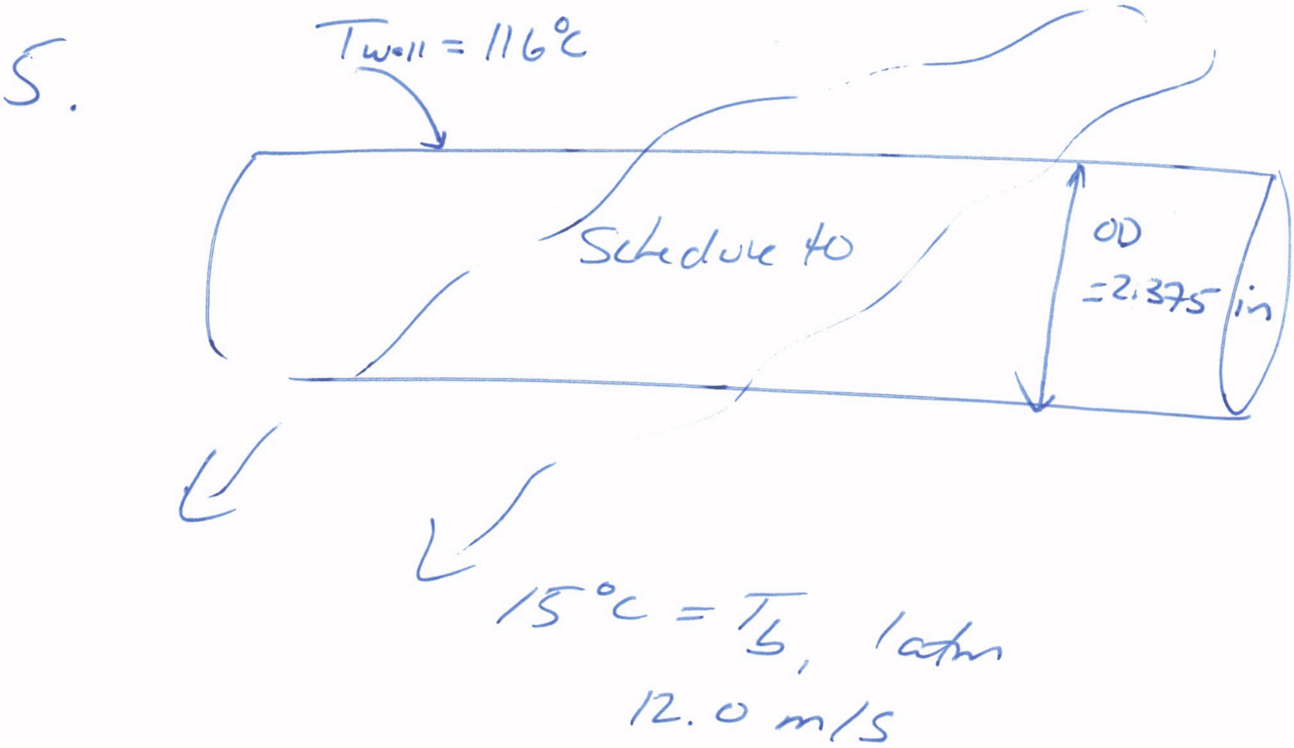
Microscopic energy balance, constant thermal conductivity; spherical coordinates

$$\rho \hat{C}_p \left(\frac{\partial T}{\partial t} + v_r \frac{\partial T}{\partial r} + \frac{v_\theta}{r} \frac{\partial T}{\partial \theta} + \frac{v_\phi}{r \sin\theta} \frac{\partial T}{\partial \phi} \right)$$
$$= k \left(\frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{\partial T}{\partial r} \right) + \frac{1}{r^2 \sin\theta} \frac{\partial}{\partial \theta} \left(\sin\theta \frac{\partial T}{\partial \theta} \right) + \frac{1}{r^2 \sin^2\theta} \frac{\partial^2 T}{\partial \phi^2} \right) + S_e$$

$$0 = k \frac{1}{r} \frac{d}{dr} \left(r \frac{dT}{dr} \right) + S_e$$

Reference: F. A. Morrison, "Web Appendix to *An Introduction to Fluid Mechanics*," Cambridge University Press, New York, 2013 (*pages.mtu.edu/~fmorriso/cm310/IFMWebAppendixDMicroEBalanceMorrison.pdf*). This worksheet is on the web at *pages.mtu.edu/~fmorriso/cm310/energy.pdf*.

5.



What is $\frac{q_r}{A}$?

Forced convection around horizontal pipe

$$\frac{q_r}{A} = h\left(T_{wall} - T_b\right)$$

↑ h from data correlation

$$Nu = \frac{hD}{k} = C Re^m Pr^{\frac{1}{3}}$$

all material properties at the film temperature

$$T_f = \frac{T_w + T_b}{2} = \frac{116 + 15}{2} = \boxed{65.5^\circ C}$$

From A.3-3 (Table) T = 65.6 °C (close enough)

$Pr = 0.702$

$k = 0.02925 \frac{W}{mK}$

$\rho = 1.043 \frac{kg}{m^3}$

$\mu = 2.03 \times 10^{-5} \frac{kg}{ms}$

$$Re = \frac{\rho V D}{\mu} = \frac{\left(1.043 \frac{kg}{m^3}\right)\left(12.0 \frac{m}{s}\right)\left(\frac{2.375}{39.37} m\right)}{\left(2.03 \times 10^{-5} \frac{kg}{ms}\right)}$$

$$\boxed{Re = 37{,}193.6}$$

$Re = 37194 \Rightarrow m = 0.618$

$C = 0.193$

$$Nu = c Re^m Pr^{\frac{1}{3}}$$

$$= (0.193)(37193.6)^{0.618}(0.702)^{\frac{1}{3}}$$

$$Nu = 114.52 = \frac{h\left(\frac{2.375}{39.37}\,m\right)}{\left(0.02925\,\frac{W}{mK}\right)}$$

$$\boxed{h = 55.528\,\frac{W}{m^2K}}$$

$$\frac{q}{A} = h\,(T_w - T_b)$$

$$= 55.528\,(116 - 15)\,\cancel{K}\,\frac{W}{m^2\cancel{K}}$$

$$\frac{q}{A} = 5608\,\frac{W}{m^2}$$

$$\boxed{\frac{q}{A} = 5600\,\frac{W}{m^2}}$$

if we neglect radiation

Radiation

$$h_{rad} = \frac{\overset{0.79\ (steel)}{\varepsilon}\,\sigma\left(T_s^4 - T_b^4\right)}{T_s - T_b}$$

$$= \frac{(0.79)\left(5.676\times10^{-8}\ \frac{W}{m^2 K^4}\right)\left(389.16^4 - 288.16^4\right) K^4}{(116-15)\ K}$$

$$= 7.122\ \frac{W}{m^2 K}$$ pretty big

$$h = h_{fluid} + h_{rad} = (55.528 + 7.122)$$

$$= 62.65\ \frac{W}{m^2 K}$$

$$\frac{q}{A} = \left(62.65\ \frac{W}{m^2 K}\right)(101\ K)$$

$$= 6328\ \frac{W}{m^2}$$

$$= \boxed{6300\ \frac{W}{m^2}}$$

11% higher w/ radiation considered. //