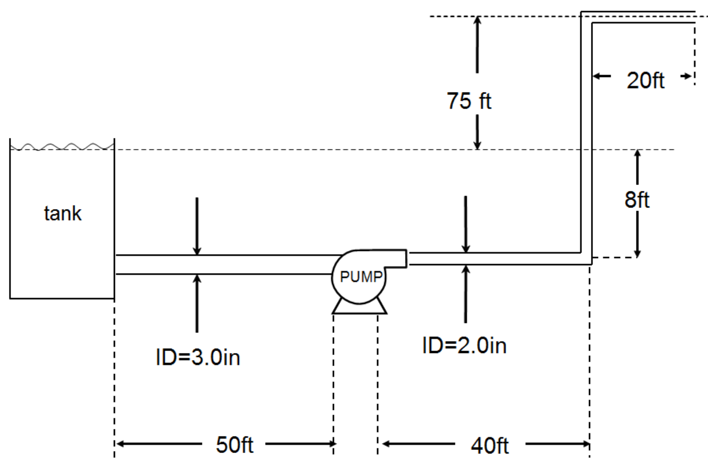
HW2

Michigan Technological University
Chemical Engineering

CM3120 Transport/Unit Ops 2 (rev 2; 2/11/2020)

Unsteady State Heat Transport

1. For the 25^oC water piping system sketched below, what is the pressure at the inlet of the pump? The average fluid velocity at the pump discharge is $1.32\ ft/s$ (turbulent). The friction loss for all the piping and fittings upstream of the pump is $F/g = 2.2\ ft$ head; the friction loss for all the piping and fittings downstream of the pump is $F/g = 2.0\ ft$ head. The tank is open to the atmosphere; the pipe discharges fluid to the atmosphere. Please give your answer in units of $psia\ (lb_f/in^2\ absolute)$. Answer: 17 $psia$.



2. What is the temperature as a function of time at the center of a solid brass sphere subjected to the following treatment: first the sphere is held in a bath and allowed to equilibrate at T_1; subsequently the sphere is submerged into a vigorously stirred bath at constant temperature T_2. Answer: see notes below. Solving the model for this problem is beyond our expectations but you can set it up. Answer: See notes.
3. In a food production line, meat is seared in an apparatus by suddenly sandwiching the refrigerated, uncooked meat between two hot platens, each held to different temperatures (The choice of doing it this way was arrived at through trial-and-error over the years). Model this process so that we can predict the temperature profile in the meat as a function of time and position. We will do the first, simplest model, in which we consider the meat to be long and wide, homogeneous solid. Answer: See notes below.
4. Two parts:
    a. Sketch what you expect the temperature profiles from problem 3 to look like for various times.
    b. Solve for the steady state temperature profile for meat of thickness B and two temperatures T_1 and T_2 with $T_1 > T_2$. Answer: See notes below.

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5. Answer in two sentences. Give an example of the described data correlation (an equation; parts a and b only).
    a. What is the dimensionless quantity that we use to report data correlations for wall force (drag) in laminar and turbulent flow?
    b. What is the dimensionless quantity that we use to report data correlations for convective heat transfer coefficients in laminar and turbulent flow?
    c. What is the dimensionless quantity that helps us keep track of the tradeoff between internal heat flux by conduction and external heat delivered to the boundary by convection?
6. Underground water pipes freeze late in winter in Michigan's Keweenaw Peninsula, especially when the snow has been removed from the ground on top of the pipes. Create a model of the heat transfer effect that the snow has on the overall problem of pipes freezing. If you can solve your model (or find a solution), show me the difference between the time it would take for pipes under plowed area to freeze compared to pipes under 4 feet of snow.
7. A long copper wire (diameter $= 0.635\ cm$) is placed in a rapidly moving stream of air that is at a temperature of 37^oC. Initially the wire is 7^oC, and after 30 seconds the wire is 24^oC. What is your estimate of the heat transfer coefficient between the wire and the air? Answer: $150\ W/m^2K$.
8. A small irregularly shaped stainless steel part (roughly spherical; small enough to fit in your pocket, diameter about one centimeter) is removed from an oven (oven air temperature is $325^oF = 163^oC$) and is dropped into a large, well stirred tank containing an oil at $90^oF = 32^oC$. If the heat transfer coefficient in the oil is $250\ W/m^2K$, what is the temperature of the part after thirty seconds? Answer: $\sim 160^0F = 70^oC$.
9. Long (length$= 1.00m$) cylindrical shafts (physical property data: $k\ =\ 15\ W/mK, \rho\ = 7900\ kg/m^3$, $\hat{C}_p = 477\ J/kgK$) come out of an oven at a uniform temperature of $400°C$. The shaft is then allowed to cool in a forced-convection chamber at $50°C$ with a convection heat transfer coefficient of $120\ W/m^2K$. For some of the shafts we suspect that the temperature is uniform throughout the shaft during cooling, which is easier to analyze, but for some shafts the assumption of uniform internal temperature as a function of time may not be appropriate. What's the largest shaft diameter for which we may appropriately assume that the temperature is uniform throughout the cooling? Answer: $D_{max} = 5.0\ cm$
10. **STRETCH** A long copper wire of diameter D is initially at temperature T_0. Suddenly, electrical current (I, units of $A, amperes$) is sent through the wire. The wire has a resistance per unit length of R_{elec} (units are Ω/m, ohms per meter). The air surrounding the wire is at temperature T_b and is <u>not</u> being force-circulated with a fan or by any mechanical means. Create a model that will predict the temperature of the wire as function of time. Answer: See notes below.
11. Blocks of compacted snow (dimensions 2 meters by 1.2 meters by 0.7 meters) are created to form part of a wintertime festive display (Winter Carnival). The weather has been such that the

blocks are at a uniform temperature of -10.0^oC. If the weather turns unseasonably warm (7.0^oC) what will be the temperature in the middle of the blocks after 12 hours? Physical property data for compacted snow: $k = 0.54\frac{W}{mK}, \rho = 68\frac{kg}{m^3}, \hat{C}_p = 2090\frac{J}{kgK}$. The heat transfer coefficient under the prevailing weather conditions may be estimated to be $12W/m^2K$.
Answer: $-8^oC = 18^oF$

12. **STRETCH** In class we presented the solution for unsteady state heat conduction in a semi-infinite slab and used it to estimate the time for pipes to freeze.

    a. What is the differential equation that is solved for this case? Show how you arrive at this equation starting with the microscopic energy balance
    b. What are the initial condition and the boundary conditions?
    c. We wish to carry out our dimensional analysis techniques on this problem. We need characteristic values for all the variables. What are the characteristic values we have used when nondimensionalizing the microscopic energy balance up to this point (from CM3110 forced convection in a tube)?
    d. Note that we cannot use the characteristic time that we used before. Call your characteristic time t_c and carry out the nondimensionalization. What would be a good choice for t_c for this problem?
    e. Carry out the dimensional analysis to obtain the governing equation in dimensionless form. What are the names of the dimensionless quantities that appear? What are the meanings associated with these quantities?

    Answer: See notes below.

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Notes and **Stretch**:

1. Determining if the MEB is applicable and choosing the two points (point "1" and point "2") are the key steps in any MEB problem (https://youtu.be/e4uEFCtuNic). For more on pumping head see http://pages.mtu.edu/~fmorriso/cm310/pump.pdf. If the absolute pressure at the inlet of the pump falls below the vapor pressure, the pump will cavitate (en.wikipedia.org/wiki/Cavitation). When working with American Engineering Units, you do not need g_c if you remember that a "pound force" (lb_f) is not the same as a "pound mass" (lb_m). These two quantities are related as follows: $32.164\ ft\ lb_m/s^2 = 1.0000\ lb_f$.
2. The PDE-solving (partial differential equation) mathematics required for this problem is beyond our expectations for you, but you should be able to set up the problem and arrive at the appropriate equation to solve and the boundary and initial conditions, written in mathematical form. This is a problem for which the analytical solution may be found, if you can recognize it, in the literature (Carslaw and Jaeger, *Conduction of Heat in Solids*, 2nd edition, p237 (Oxford, 1986). In the lecture notes (lecture 8) we give you the analytical solution for all times t and position $r = 0$ (an infinite sum involving eigenvalues λ_n). Plot the result. How could you use this solution to measure heat transfer coefficient?
3. See TA or instructor or look at Geankoplis 4th edition, problem 5.6-2, p408.
4. Answer part b): $T = \left(\frac{T_2 - T_1}{B}\right)x + T_1$. What is the flux as a function of position? Be careful with sketches. Be sure that as time goes to infinity that your sketch goes to the steady state result.
5. For 5a see pages.mtu.edu/~fmorriso/DataCorrelationForSmoothPipes2013.pdf. See also lecture notes.
6. This one is up to you. I'd love to see your solutions.
7. What is the Biot number for the heating of the wire? What does the value of the Biot number indicate to you?
8. Physical properties of stainless steel are in appendix H. $\mathrm{Bi} = 0.024$. Note that for lumped parameter calculations the characteristic length scale is taken to be volume over surface area. For a sphere this is $R/3$.
9. When is the lumped parameter analysis valid?
10. **STRETCH** Notes/hints. This problem does not use the microscopic energy balance.
    a. The current contributes an energy source term of $I^2 R_{elec} L$, where L is the length of the wire. What are the units of this term?
    b. How does temperature vary within the wire?
    c. To obtain an answer you must carry out a numerical solution (not required)
11. Think of them as semi-infinite solids.
12. Review first dimensional analysis for steady problems (CM3110) and then what we have talked about this semester for unsteady. See also hand notes 2020 lecture 6.