CBE 30356 Transport II
Problem Set 8
Due via Gradescope, 11:55 PM 3/20/23

1). Last year the CBE department worked on a project with HB Fuller to investigate ways of accelerating their glue fabrication process. One proposed candidate for the time limiting step was the rate of heating/mixing/melting in a very large vessel. This 6 ft diameter vessel is filled with plastic glue precursor which must be melted and blended. Heating is primarily accomplished by a hot oil heating system wrapping the vessel with about 300 ft of 3 inch ID half-round pipe welded to the side. So:

a. Calculate the hydraulic diameter of the half-round pipe.

b. The oil has a density of 0.831 g/cm^3 and kinematic viscosity of 0.53 cs at the operating inlet temperature (417°F). The flow rate is reported to be 114 GPM. Based on this, calculate the fluid velocity, the residence time in the pipe, and the Reynolds number.

c. The heat transfer fluid is Therminol 59, which at these temperatures has a heat capacity of Cp = 2.3 kJ/kg°K and conductivity k = 0.103 W/m°K. Using this, calculate the Prandtl number.

d. Using the Dittus-Boelter correlation, calculate the Nusselt number and the heat transfer coefficient.

e. The oil is reported to have an exit temperature of 405°F. Based on this, what is the energy transfer from the fluid to the vessel? The heater for the oil has a rating of 200kW. How does the energy loss of the oil compare to the maximum heating rate?

f. Based on the energy exchange with the vessel and the pipe area (the 3 inch x 300 ft part welded to the vessel), calculate the temperature of the vessel wall in contact with the oil (e.g., the $T_w - T_b$ temperature difference).

g. The vessel is 3/8" thick SS 304 steel. Calculate the heat transfer coefficient for the steel wall. How does the heat transfer coefficient of the steel compare to that of the oil pipe?

h. The contents of the vessel being heated are at approximately 300°F during the time the oil temperatures were being measured. Based on this, estimate the internal heat transfer coefficient.

i. We can model the heat transfer inside the vessel as heat transfer through a stagnant film (an effective film thickness). If the conductivity of the goo on the inside is 0.2 W/m°K, what would be the thickness of this layer?

j. Based on all this, what's controlling the heat transfer in this system?

2). Evaporation of a drop. Consider a drop of water floating in zero g on the ISS (e.g., no convection!). We are interested in determining how long a drop would float around before evaporating. For your calculations we shall assume that the air is maintained at 27°C at 1 atm pressure and a relative humidity of 50% (e.g., the fraction of saturation at that temperature). (Note that both these values are a little high, but are still in the nominal range according to the ISS website). At this temperature the water vapor pressure is only 0.0352 atm, so it is small – but I'd still like for you to use the finite mole fraction correction.

a. Develop the expression for the molar flux from the surface of a drop of radius R for an infinite medium (e.g., R_2>>R, a bit simpler than was done in class).

b. If we assume that the temperature is uniform everywhere, and the diffusivity of water vapor in air is 0.242 cm^2/s at this temperature, calculate the rate of change in radius for a 1mm diameter drop. Don't forget to convert from moles to mass!

3). Continuing with this problem, we recognize that the evaporation leads to cooling at the drop surface. This, in turn, decreases the equilibrium concentration at the surface as well, which suppresses the evaporation rate (there's a feedback mechanism). So:

a. If the latent heat of vaporization is L and the thermal conductivity of air is k, determine how the temperature at the surface of the drop depends on the molar flux expression. You can use the pure conduction result we derived earlier in the semester as the convection from evaporation is very small.

b. The heat of vaporization of water is $24.4\text{x}10^5$ J/kg at room temperature (it's higher the further away you get from the boiling point) and the thermal conductivity of air is 0.026 W/m°K. Based on the molar flux you calculated in question 2, what is the temperature at the surface of the drop (hint: it's way off…)?

c. Now we include the effect of temperature on x_{A1}, the equilibrium concentration at the surface of the drop. The vapor pressure of water (in kPa) is well approximated by the Buck Equation (e.g., https://en.wikipedia.org/wiki/Vapour_pressure_of_water). Using this, determine the instantaneous rate of evaporation of our 1mm diameter drop. Note that this will need to be done iteratively (or via root finding) as the flux goes down as the temperature goes down, leading to a smaller temperature change.

4). As time goes on, the drop radius gets smaller and smaller. Eventually the drop evaporates entirely! We want to determine the evaporation time.

a. Using the results of problem 2 (e.g., ignoring temperature effects), determine the evaporation time of our 1mm diameter drop. This can be done analytically, as you should have a simple expression for the rate of change in R as a function of R.

b. Now take the results of problem 3 and include the effect of temperature on evaporation rate. How does your value compare to that in part a?