Homework 1

Homework due Jan 29, 2021 23:14 CST Past due

Due Date

Friday, 1/29 at 11:59 PM ET *(1/30 at 04:59 UTC)*

Directions:

1. Answer each of the homework problems listed below.
2. Click the **Click here to open Gradescope button** below to access Gradescope.
3. Follow the prompts to submit your PDF to the assignment **HW 1**.

   Refer to the *Submitting Assignments With Gradescope* section of this course if you need a reminder of how to submit your assignment in Gradescope.

Homework Information and Guidelines:

1. Each student must turn in their own homework assignment and complete their own calculations, coding, etc. independently.
   - However, we encourage you to use most available resources including other textbooks, information from similar courses online, discussions with class and lab mates, office hours, etc. with the exception of using old solutions to the exact problems to complete the assignment.
   - Cite all your sources including discussions with colleagues and online websites. For example, if you and a friend compare answers or work together on a problem indicate this at the end of the problem. As an example, you might have a list like this at the end of each problem: "Resources used: [1] Fourier, J.B.J., *La Theorie Analytique de la Chaleur*, F. Didot, 1822. [2] Discussion with Joseph Fourier. [3] Wikipedia: Heat Flux, https://en.wikipedia.org/wiki/Heat_flux."
   - If we find papers with identical answers and approaches that do not indicate collaboration in the resource list, this is a violation of the academic honesty policy. Similarly, if your solutions match resources available online, this is a violation of the academic honesty policy.
2. Homework will be collected via Gradescope and is due at 11:59 PM ET. A grace period of 15 minutes is allowed in case of issues during the upload. Beyond that no late homework is accepted.
3. You may submit handwritten solutions or type up your solutions. We encourage you to use computer programs of your choice to solve problems, and some problems will require computational solutions. Recall "sketch" indicates you can draw something by hand, while "plot" indicates you should quantitatively calculate the curves and will likely use a computer program to create the graph. If "sketching" a curve, make sure trends, boundary conditions, etc. are clear.

Problem 1: Identifying Heat Transfer Pathways; Energy Balances

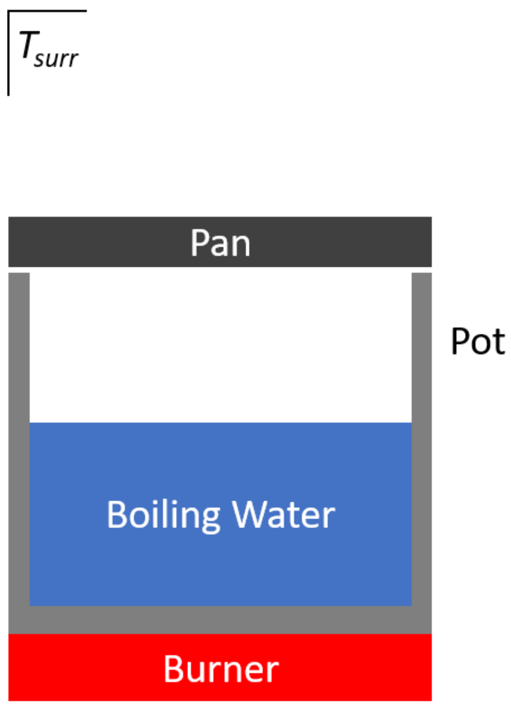
Problem 1, Part 1

Warqa pastry (sometimes referred to as "brick pastry") is an essential Moroccan ingredient, used to make a number of sweet and savory pastries and dishes. Thin sheets of pastry are cooked by "painting" the batter onto a hot pan.

A pot of water is brought to boil with a metal pan placed on top. The top surface of the pan is exposed to ambient conditions (air and walls at T_{surr}). Once the system reaches a steady temperature, thin layers of the batter are painted on the pan surface one at a time, then removed temperature, thin layers of the batter are painted on the pan surface one at a time, then removed and stacked to form the pastry. For now, let's neglect the cooking process and focus on the steady-state temperatures in the system prior to painting the batter.

We'd like to understand the steady state temperature on the top and bottom surface of the pan. To do so, draw a control volume around the pan. Then:

- Draw and label arrows to indicate heat transfer mechanisms to/from the pan.
- Evaluate an energy balance on the pan including the appropriate rate equations for each mechanism of heat transfer. List all assumptions as you analyze the energy balance.
- Find a relation between the surface temperature on the top and bottom surfaces of the pan based on the concept of thermal resistances.
- Identify any additional data (properties, dimensions, etc.) are needed to solve this equation.

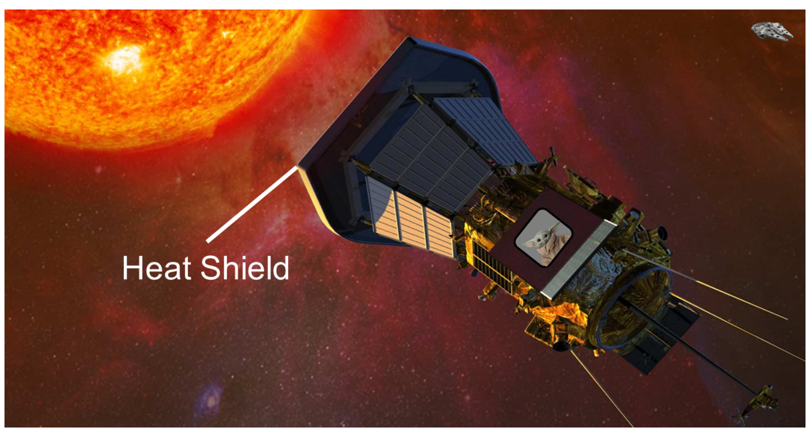


Problem 1, Part 2

NASA's Parker solar probe, which is currently flying to the Sun, is enabled by a collection of some of the best heat transfer technologies. The surface facing the sun is a thermal protection system that needs to maximize the reflection of the sunlight and survive high temperature. For this purpose, the side facing the sun is coated with a special opaque coating with a high reflectivity to sunlight of ρ_s and high emissivity ϵ_c for the radiation emitted in the longer wavelength range corresponding to its operating temperature. Sunlight of intensity G_{Sun} is incident on the heat shield surface. All other surfaces have emissivities of ϵ_o and are exposed to deep space, which you may assume is at $0K$. Assume the solar probe surface is at T_s (spatially uniform).

We'd like to understand the steady state temperature of the solar probe. To do so:

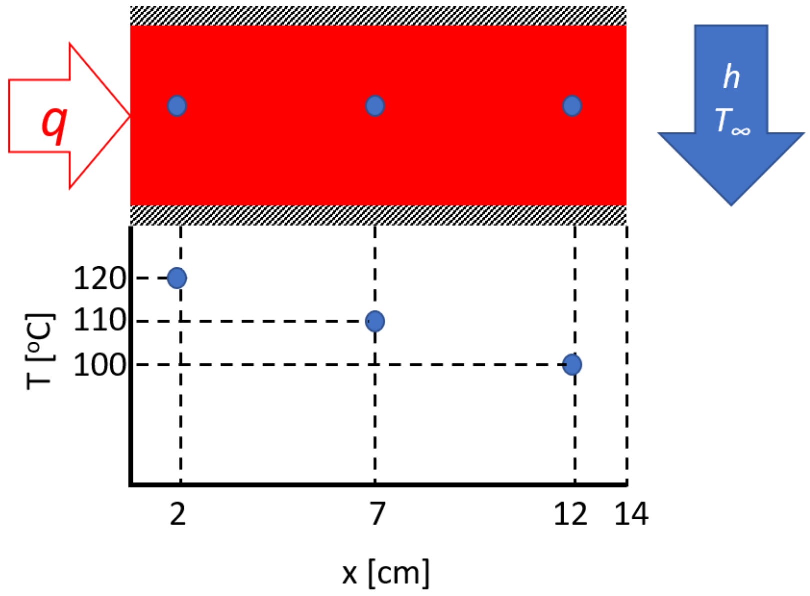
- Draw your control volume.
- Draw and label arrows to indicate heat transfer mechanisms.
- Evaluate an energy balance including the appropriate rate equations for each mechanism of heat transfer. List all assumptions as you analyze the energy balance.
- Identify any additional data (properties, dimensions, etc.) are needed to solve this equation.



Problem 2: Conduction and Convection

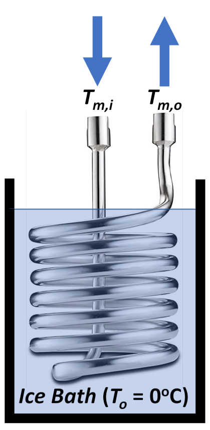
A common way to measure the heat transfer coefficient h involves heating one end of a metal rod and exposing the other end to convection. Multiple thermocouples along the length of the rod quantify the heat flow rate and can be extrapolated to estimate the surface temperature. The cylindrical surface of the rod is well insulated.

Consider the schematic below of one such experiment. The temperature is measured at 3 points along a 1 cm diameter, 14 cm long aluminum rod [$T\,(2cm) = 120^o$C, $T\,(7cm) = 110^o$C, and $T\,(12cm) = 100^o$C]. The right end is exposed to convection with a freestream temperature of 20^o C.



1. Estimate the thermal conductivity of the aluminum. Cite your source.
2. Calculate the heat flow through the aluminum rod in W.
3. Estimate the surface temperature of the rod at $x = 14$ cm.
4. Calculate the heat transfer coefficient h.
5. On one experiment, you forget to include the insulation along the perimeter of the rod, so the perimeter is exposed to convection as well. Sketch the temperature profile along the axis of the rod ($T\,(x)$) for this case in comparison to the given data for the insulated case.

Problem 3: Convection - Internal Flow



Hot water through a coil of tubing submerged in an ice bath. The tubing has an internal diameter of $D = 10$ mm. The fluid enters at temperature $T_{m,i} = 95^o$C and must exit at $T_{m,o} = 5^o$C. Assume the surface of the thin-walled pipe is uniformly at $T_o = 0^o$C and the flow is fully developed. You may assume the section of the tubing outside the bath is well insulated.

1. The fluid properties for pipe flow are evaluated at $\overline{T_m} = \frac{T_{m,i}+T_{m,o}}{2}$. Use saturated water tables to find the thermal conductivity, viscosity, density, and heat capacity of water at $\overline{T_m}$. Cite your source.
2. The cutoff between laminar and turbulent flow for pipes is $Re_D = 2300$. Calculate cutoff mass flow rate between laminar and turbulent flow ($\dot{m}_c$ in kg/s).

Now assume a mass flow rate of 50% the cutoff between laminar and turbulent flow ($\dot{m} = 0.5\dot{m}_c$):

3. Calculate the total energy lost by the hot water as it flows through the pipe (in W). (Do not use h to calculate this value)
4. For fully developed laminar flow, the $Nu_D = \frac{hD}{k_f}$ is a constant. Assuming the ice bath

maintains the surface temperature of the pipe at $T_s = T_o$ uniformly: $Nu_D = 3.66$. Calculate the heat transfer coefficient h.

5. For internal flow with a constant surface temperature, Newton's law of cooling uses the log-mean temperature difference to find the heat transferred from the surface to the fluid: $q = hA\Delta T_{lm}$, where $\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln \frac{\Delta T_1}{\Delta T_2}}$ where $\Delta T_1 = T_s - T_{m,i}$ and $\Delta T_2 = T_s - T_{m,o}$.
   Determine the length of the pipe required to lower the mean temperature of the fluid to 5^oC.
6. At a particular point along the flow, the mean temperature is 50^{o}C, calculate the local heat flux (q'' in W/m^2) from the surface to the fluid at this point along the flow. Note, Newton's law of cooling applies as $q'' = h\left(T_s - T_m\left(x\right)\right)$.

Problem 4: Radiation and Convection

Consider a vertical metal plate (0.5 m height and 0.5 m width) suspended in ambient air at 22^{o}C. The plate has an emissivity of 1 and the surroundings are also at 22^{o}C. Both surfaces of the plate are exposed to both radiation and convection.

Assuming an average surface temperature of 32^{o}C:

1. Estimate the air properties at the film temperature $T_f = \frac{T_s + T_\infty}{2}$.
2. Estimate the convection losses. The $\overline{Nu_L} = \frac{\bar{h}L}{k}$ for free convection depends on the Rayleigh number $\left(Ra_L = \frac{g\beta(T_s - T_\infty)L^3}{\nu\alpha}\right.$, where g is the acceleration due to gravity (9.81 m/s^2) and $\beta = \frac{1}{T_f}$ for an ideal gas$\left.\right)$ as $\overline{Nu_L} = 0.59 Ra_L^{1/4}$. Note: L is the height of the plate.
3. Estimate the radiation heat losses.

Now consider the impact of varying surface temperature. You may continue to use the fluid properties at the film temperature from (1).

4. Calculate and plot the heat losses (convection, radiation, and total) as a function of surface temperature from 25 - 50^{o}C.

Gradescope (External resource) (100.0 points possible)

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Piazza

Post your questions/comments about Homework 1 to the *HW1* discussion forum in Piazza below (optional).

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