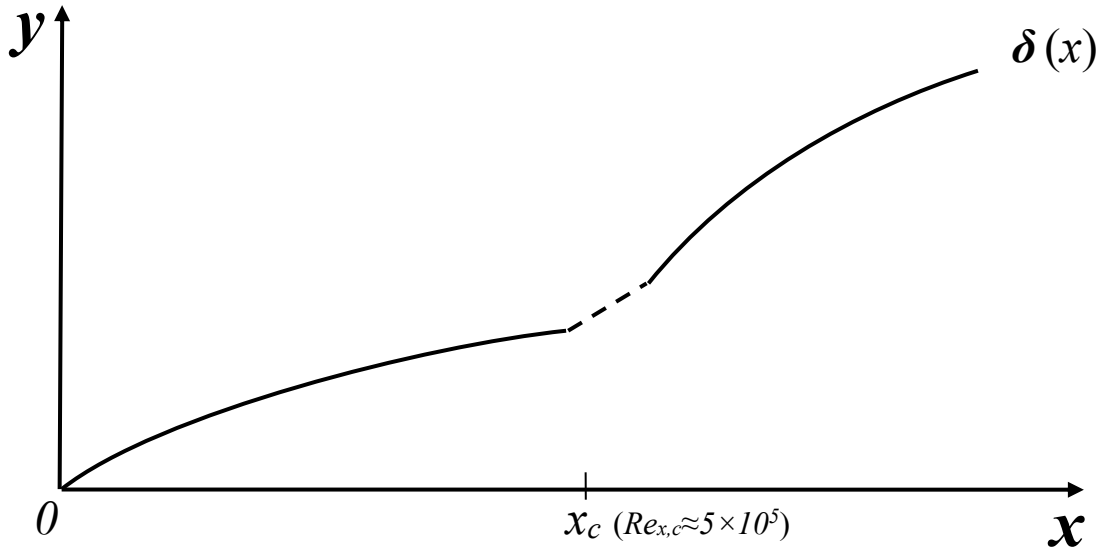


Problem 1 [35 points]

- (a) (9 pts) Consider a cold fluid flowing over a flat plate of uniform surface temperature. The shape of velocity boundary layer (δ) is shown in the figure below. The Prandtl number (Pr) of the fluid is known to be 7. Recall that $Pr = \nu/\alpha$. **Qualitatively sketch the shape of thermal boundary layer (δ_t)** relative to the velocity boundary layer (δ) in the figure below.



Briefly justify your curve in the box below.

Problem 1 – continued

(b) (8 pts) Answer the following questions with True (T) or False (F). There can be multiple correct answers. **Briefly justify your answers.**

(i) *Which of the following is (are) true regarding entry lengths for **laminar** fluid flow inside a circular tube?*

- () The hydrodynamic entry length can be greater than the thermal entry length
- () The hydrodynamic entry length can be equal to the thermal entry length
- () The hydrodynamic entry length can be less than the thermal entry length

Briefly justify your answers in the box below.

(ii) *Which of the following is (are) true regarding Nusselt number for **laminar** fluid flow inside a circular tube?*

- () The average Nusselt number for the entire tube (including entry region) can be greater than the local Nusselt number for fully-developed conditions
- () The average Nusselt number for the entire tube (including entry region) can be equal to the local Nusselt number for fully-developed conditions
- () The average Nusselt number for the entire tube (including entry region) can be less than the local Nusselt number for fully-developed conditions

Briefly justify your answers in the box below.

Problem 1 – continued

(c) (8 pts) Suppose astronomers have found a planet that is likely inhabitable by humans. The temperature, pressure, and composition of the atmosphere on that planet are the same as air on earth but the gravity is 50% less. You can treat people as cylinders and use the correlation $\overline{Nu} = \overline{h}L/k = C Ra_L^{1/4}$, where C is a constant and L is the height of the person.

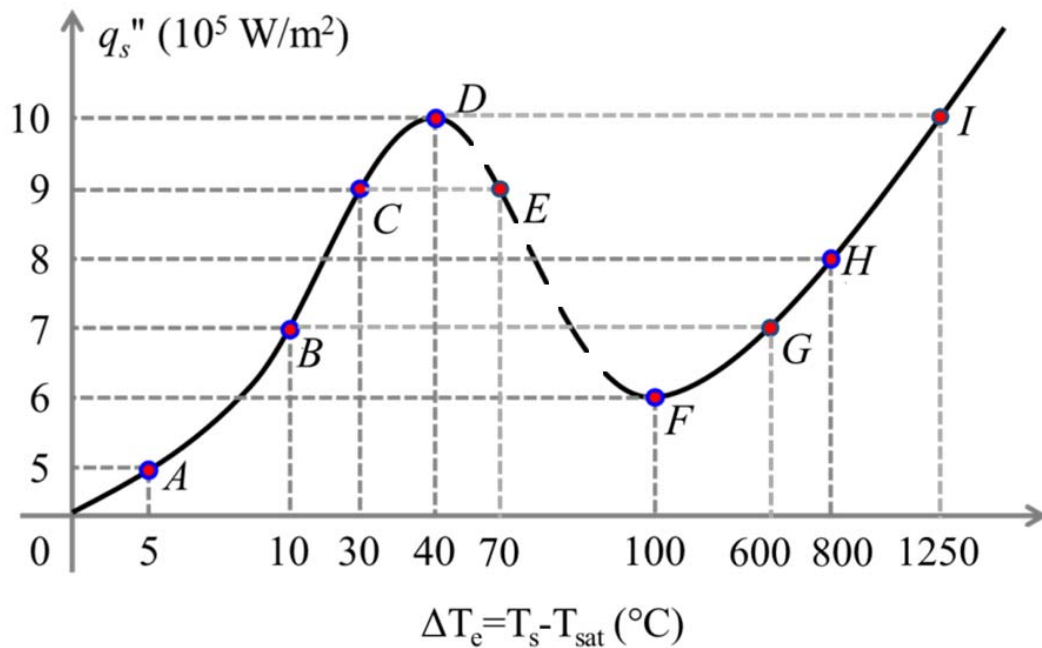
Would people experience different heat transfer due to natural convection? Circle your answer below:

- *Higher* Heat Transfer Rate, i.e., $q_{\text{planet}} > q_{\text{earth}}$
- *Same* Heat Transfer Rate, i.e., $q_{\text{planet}} \approx q_{\text{earth}}$
- *Lower* Heat Transfer Rate, i.e., $q_{\text{planet}} < q_{\text{earth}}$

Briefly justify your answer in the box below.

Problem 1 – continued

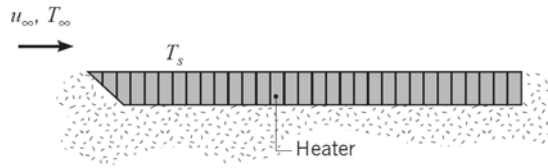
- (d) (10 pts) A thin electrical chip is $1\text{ cm} \times 1\text{ cm}$ in shape and has very small mass. It is cooled by saturated pool boiling of a dielectric fluid with a saturation temperature $T_{\text{sat}} = 80^\circ\text{C}$ under atmospheric pressure. The boiling curve of the fluid is given below. If the chip normally generates 70 W of heat and the fluid is in nucleate boiling regime, the surface temperature of the chip is _____ $^\circ\text{C}$. If the surface temperature of the chip cannot exceed 150°C , the chip power cannot exceed _____ W .



Show your calculations in the box below.

Problem 2 [35 points]

Part I: (20 pts) A flat hot plate is exposed to dry, atmospheric air in parallel flow with $T_\infty = 300$ K and $u_\infty = 10$ m/s. The plate is maintained at a uniform temperature of $T_s = 400$ K by an electrical heating element and is well insulated on the bottom. The plate has length of 0.5 m (along the flow direction) and width of 0.5 m (normal to the plane of the sketch). Thermophysical properties of dry air are listed as below. Assume steady state and neglect radiation.



Properties of Dry Air at Atmosphere Pressure

T(K)	ν (m ² /s)	k (W/mK)	Pr
300	15.89×10^{-6}	0.0263	0.707
350	20.92×10^{-6}	0.0300	0.700
400	26.41×10^{-6}	0.0338	0.690

- (a) _____ Is the flow laminar, turbulent, or mixed? Justify your answer with calculations.
- (b) Which location on the plate has the highest surface heat flux? Briefly justify your answer.
- (c) Calculate the average Nusselt number (\overline{Nu}_L) for the plate.
- (d) Calculate the total required heating power (W) to maintain steady state surface temperature.

Part II: (15 pts) The hot plate is now coated with a liquid layer of volatile species A under the same flow condition and T_s . Note that dry air has 0% relative humidity for species A. Thermophysical properties of species A are listed as below.

Properties of Species A at Atmosphere Pressure

T(K)	h_{fg} (J/kg)	D_{AB} (m ² /s)	Saturated vapor density $\rho_{sat,vapor}$ (kg/m ³)
300	8×10^6	0.5×10^{-6}	0.08
350	9×10^6	1.0×10^{-6}	0.09
400	10×10^6	1.5×10^{-6}	0.10

- (e) Identify a correlation for the average Sherwood number (\overline{Sh}_L) of this problem.
- (f) Calculate the mass loss rate (kg/s) for species A.
- (g) Calculate the total required heating power (W) after coating species A in order to maintain the same steady state surface temperature.

Circle your division: 1 2 3 4

Name _____

Problem 2 – continued

Part I:

Start your answer to part (a) here. [5 pts]

Start your answer to part (b) here. [5 pts]

Start your answer to part (c) here. [5 pts]

Circle your division: 1 2 3 4

Name _____

Problem 2 – continued

Start your answer to part (d) here. [5 pts]

Part II:

Start your answer to part (e) here. [5 pts]

Start your answer to part (f) here. [5 pts]

Circle your division: 1 2 3 4

Name _____

Problem 2 – continued

Start your answer to part (g) here. [5 pts]

Problem 3 [30 points]

Blood is warmed during open-heart surgery using a concentric tube, counter-flow heat exchanger in which water flows through the annular passage while blood flows through the inner tube. The heat exchanger length is $L = 1$ m and the thin-walled inner tube has diameter $D = 50$ mm. Water entering at 60°C with a mass flow rate of 0.1 kg/s is used for heating the blood entering at 28°C with a mass flow rate of 0.1 kg/s. The overall heat transfer coefficient (U) for the heat exchanger is 800 W/($\text{m}^2\cdot\text{K}$). Assume specific heats for water and blood to be $4,200$ J/($\text{kg}\cdot\text{K}$) and $3,500$ J/($\text{kg}\cdot\text{K}$), respectively.

- (a) Calculate the total rate of heat transfer (W) for the heat exchanger.
- (b) Find the outlet temperatures ($^\circ\text{C}$) of water and blood streams.
- (c) Sketch the qualitative variation of the temperature of water and blood along the length of heat exchanger.

List your assumptions below. [2 pts]

Start your answer to part (a) here. [15 pts]

Circle your division: 1 2 3 4

Name _____

Problem 3 – continued

Continue your answer to part (a) here.

Start your answer to part (b) here. [8 pts]

Plot T vs. x in the figure below. [5 pts]

