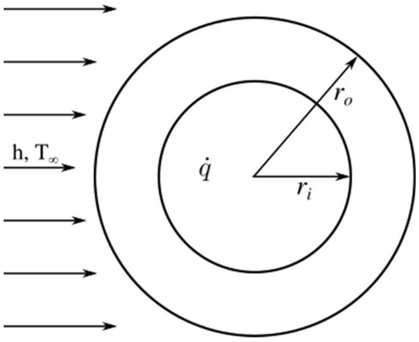
Department of Mechanical Engineering, IIT Bombay
Ph.D. Qualifier Examination in Heat Transfer (Jan 2023)

Time Duration: 3 hours **Max. marks: 100**

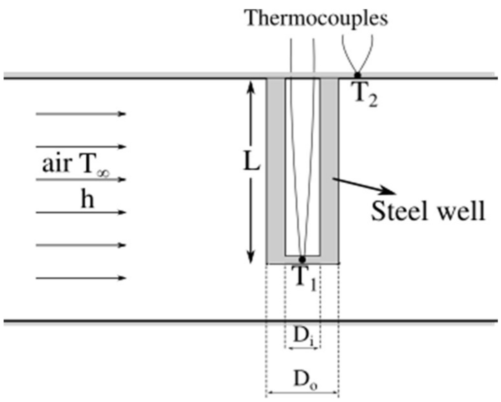
Note:

1. **Minimum passing marks: 40**.
2. All questions are compulsory. This paper consists of 6 questions over 2 pages.
3. The maximum marks per question are given in parenthesis.
4. **Please begin each question on a new page and keep ALL subparts of a question together.** This is important as multiple faculty are involved in grading.
5. Strike out all unwanted work neatly, else, the work that appears first will be taken up for evaluation.
6. This is an open book examination. Only hard copy of the text book **'Fundamentals of Heat and Mass Transfer'** by Incropera, DeWitt, Bergman and Lavine is allowed. **Hand written notes, or any other text are not allowed**.
7. **Make suitable assumptions when needed and clearly state/justify them**.

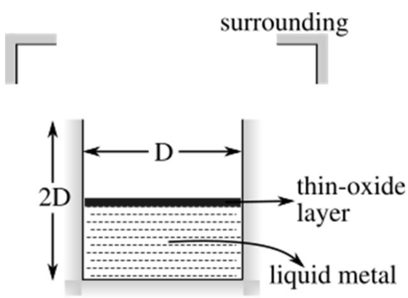
Q1. [**14 points**] Radioactive waste in the form of long solid cylinder of radius r_i is packed in a long, thin-walled cylindrical container of inner radius r_i and outer radius r_o that is made up of material with thermal conductivity k.The waste generates thermal energy non-uniformly as $\dot{q} = \dot{q_0}\left[1 - \left(\frac{r}{r_i}\right)^2\right]$, where $\dot{q_0}$ is a constant volumetric heat generation rate. Steady-state conditions are maintained by submerging the container in a liquid that is at T_∞ and provides a uniform convection coefficient of h across the outer surface of the cylinder. Determine $T(r_i)$, the temperature at radius r_i. Is there a critical value of outer radius, r_0^{cr}, at which $T(r_i)$ is minimum? If yes, find it.



Q2. [**18 Points**] A thermocouple is inserted in a hot air duct to measure the air temperature. The thermocouple (T_1) is soldered to the tip of a steel well of length $L = 0.15\ m$ and inner/outer diameters of D_i, D_o = 5 and 10 mm, respectively. A second thermocouple (T_2) is used to measure the duct wall temperature. The air flow in the duct provides a convective heat transfer coefficient of 50 $\frac{W}{m^2-K}$ on the outer surface of the thermocouple tube, and the two thermocouples register $T_1 = 450\ K$ and $T_2 =$ 375 K. Determine the air temperature T_∞.

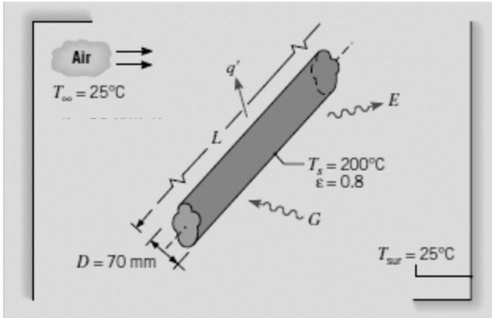


Q3. [**18 Points**] In one of the setups that you have to design for the handling of liquid aluminium metal, your objective is to compute the amount of radiation heat transfer between the top (oxidized solid layer of metal, to be assumed diffuse-gray surface) and the surrounding. For this, you are analysing a cylindrical container with height 2D and diameter D, and perfectly insulated side/bottom walls. The radiation heat transfer between thin solid oxide-layer (emissivity ϵ) and surrounding when the container is half-filled is given by q_{half}. The radiation heat transfer between thin solid oxide-layer and surrounding when the container is completely filled is q_{full}. Calculate $\frac{q_{hal}}{q_{full}}$. The solid oxide layer can be assumed to be at the same temperature in both cases.



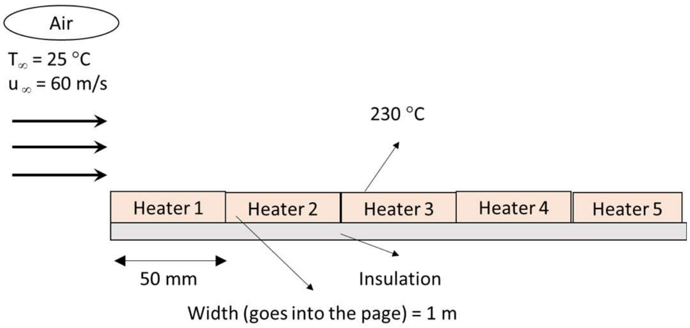
List all assumptions clearly. Please do not introduce any new variables, i.e., your final answer can only be a function of variables provided in the question.

Q4. [**10 Points**] A horizontal uninsulated steam pipe passes through a large room where the air and walls are at 25°C. The outside diameter of the pipe is 70 mm, and its surface temperature and emissivity are 200°C and 0.8, respectively. What are the surface emissive power and irradiation? If the surface is diffuse-gray, what is the heat transfer rate from the surface per unit length of pipe?



Q5. [**20 Points**]

(a) [**12 Points**] A flat plate of width w = 1 m is maintained at a uniform surface temperature, T_s = 230°C, by using independently controlled electrical strip heaters, each of which is 50 mm long. If the atmospheric air at 25°C flows over the plates at a velocity of 60 m/s, what is the electrical power required for the fifth heater? ($\nu = 26.41 \times 10^{-6}$ m²/s, k = 0.0338 W/mK, Pr = 0.69)



(b) [**8 Points**] Consider an engine oil flow entering a pipe at a mass flow rate of 0.5 kg/s. The inlet temperature of the oil is 25°C. The surface of the pipe is maintained at a constant temperature of 100°C. The diameter is 0.025 m, while the length is 10 m. Find the total heat transfer to the oil and the oil outlet temperature. (Engine oil: ρ = 860 kg/m³, C_p = 2076 J/kgK, $\mu = 5.31 \times 10^{-2}$, k = 0.139 W/mK, Pr = 793)

Q6. [**20 Points**]

(a) [**10 Points**] Water flows through a pipe. The diameter of the pipe is D. An insulation is placed on the pipe to reduce the heat loss from the pipe to flowing air. The thickness of the insulation is t. Air flows over the insulation of the pipe at a velocity V. Develop a differential equation that can be used to determine the bulk mean temperature of the water as a function of pipe length in terms of heat transfer coefficients, pipe diameter, insulation thickness, and any others that you may deem necessary. Assume a fully developed flow.

(b) [**10 Points**] Isobutane is condensed by cooling air in the condenser of a power plant. Determine the mass flow rate of air and the overall heat transfer coefficient if the heat exchange area is 24 m². The latent heat, h_{fg}, is 255.7 kJ/kg at 75°C and the specific heat capacity of air is 1005 J/kgK.