Heat Transfer
23CGA006

Semester 2 2023/24 | In-Person Exam paper

This examination is to take place in-person at a central University venue under exam conditions. The standard length of time for this paper is **2 hours**.

You will not be able to leave the exam hall for the first 30 or final 15 minutes of your exam. Your invigilator will collect your exam paper when you have finished.

<u>Help during the exam</u>

Invigilators are not able to answer queries about the content of your exam paper. Instead, please make a note of your query in your answer script to be considered during the marking process.

If you feel unwell, please raise your hand so that an invigilator can assist you.

You may use a calculator for this exam. It must comply with the University's Calculator Policy for In-Person exams, in particular that it must not be able to transmit or receive information (e.g. mobile devices and smart watches are **not** allowed).

Attempt **THREE** questions in total. Each question carries 25 marks.

Candidates should show full working for all calculations and derivations.

A formula sheet is provided at the end of this exam paper.

1. A spherical tank made of 2 cm thick stainless steel is used to store iced water at 0°C at atmospheric pressure. The tank is located in a room with a temperature of 22°C. The walls of the room are also at 22°C. The outer surface of the tank is black and heat transfer between the outer surface of the tank and the surroundings is by natural convection and radiation.

   (a) Provide the problem statement; sketch a labelled diagram of this problem and list relevant information on it; draw the thermal resistance network of this heat transfer problem. [3 marks]

   (b) Determine the individual and total thermal resistances for this heat transfer problem. [13 marks]

   (c) Determine the rate of heat transfer to the iced water in the tank. [4 marks]

   (d) Determine the amount of ice at 0°C that melts during a 24 h period. [2 marks]

   (e) State any assumption(s) made. [3 marks]

<u>Data:</u>

Internal diameter of the tank: 3 m

Thermal conductivity of stainless steel: 15 W m^{-1} K^{-1}

Convection coefficient at the inner surface of the tank: 80 W m^{-2} K^{-1}

Convection coefficient at the outer surface of the tank: 10 W m^{-2} K^{-1}

The heat of fusion of water at atmospheric pressure: 333.7 kJ kg^{-1}

The emissivity of the outer surface of the tank: 1.0

<u>Equations:</u>

$$h_{rad} = \varepsilon\sigma\left(T_s^2 + T_\infty^2\right)\left(T_s + T_\infty\right)$$

where the symbols have their usual meanings.

2. Hot air enters an uninsulated square duct that passes through the attic of a house. The air enters at atmospheric pressure at 80°C at a rate of 0.15 $m^3 s^{-1}$. The duct has a length of 8 m, a cross section of 0.2 m x 0.2 m, and is observed to be nearly isothermal at 60°C.

(a) Provide the problem statement; draw a sketch of the system and indicate relevant information. List the property values from Table Q2 needed for this problem. [5 marks]

(b) Determine the Reynolds number and thermal entry length of this problem. [5 marks]

(c) Determine the exit temperature of the air. [8 marks]

(d) Determine the rate of heat loss from the duct to the attic space. [4 marks]

(e) State any assumption(s) made. [3 marks]

Equations:

For turbulent flow, the entry length is approximately: $L_h \approx L_t \approx 10D$

For fully developed turbulent flow in the entire duct:

$$T_e = T_s - (T_s - T_i)\exp(-hA_s/\dot{m}C_p)\ ; \qquad \Delta T_{\ln} = \frac{T_i - T_e}{\ln\frac{T_s - T_e}{T_s - T_i}}$$

where the symbols have their usual meanings.

Data: **Table Q2.**

Properties of air at 1 atm pressure

Temp. T, °C	Density ρ, kg/m^3	Specific Heat C_p, J/kg · K	Thermal Conductivity k, W/m · K	Thermal Diffusivity α, m²/s	Dynamic Viscosity μ, $kg/m \cdot s$	Kinematic Viscosity ν, m^2/s	Prandtl Number Pr
15	1.225	1007	0.02476	2.009×10^{-5}	1.802×10^{-5}	1.470×10^{-5}	0.7323
20	1.204	1007	0.02514	2.074×10^{-5}	1.825×10^{-5}	1.516×10^{-5}	0.7309
25	1.184	1007	0.02551	2.141×10^{-5}	1.849×10^{-5}	1.562×10^{-5}	0.7296
30	1.164	1007	0.02588	2.208×10^{-5}	1.872×10^{-5}	1.608×10^{-5}	0.7282
35	1.145	1007	0.02625	2.277×10^{-5}	1.895×10^{-5}	1.655×10^{-5}	0.7268
40	1.127	1007	0.02662	2.346×10^{-5}	1.918×10^{-5}	1.702×10^{-5}	0.7255
45	1.109	1007	0.02699	2.416×10^{-5}	1.941×10^{-5}	1.750×10^{-5}	0.7241
50	1.092	1007	0.02735	2.487×10^{-5}	1.963×10^{-5}	1.798×10^{-5}	0.7228
60	1.059	1007	0.02808	2.632×10^{-5}	2.008×10^{-5}	1.896×10^{-5}	0.7202
70	1.028	1007	0.02881	2.780×10^{-5}	2.052×10^{-5}	1.995×10^{-5}	0.7177
80	0.9994	1008	0.02953	2.931×10^{-5}	2.096×10^{-5}	2.097×10^{-5}	0.7154
90	0.9718	1008	0.03024	3.086×10^{-5}	2.139×10^{-5}	2.201×10^{-5}	0.7132
100	0.9458	1009	0.03095	3.243×10^{-5}	2.181×10^{-5}	2.306×10^{-5}	0.7111

3. Three different design configurations for an oil-water heat exchanger are being considered: (i) double pipe co-current flow, (ii) double pipe counter-current flow, and (iii) shell-and-tube with one shell pass and 2-tube passes (oil on the shell side). The heat exchanger will be used to heat water (c_p = 4180 J kg^{-1} K^{-1}) from 30°C to 90°C by oil (c_p = 2200 J kg^{-1} K^{-1}), entering the exchanger at 160°C. The mass flow rates of oil and water are 6.75 kg s^{-1} and 2.25 kg s^{-1}, respectively. An overall heat transfer coefficient of 1850 W m^{-2} K^{-1} applies for all three configurations.

(a) State all assumptions made to solve the problem. [3 marks]

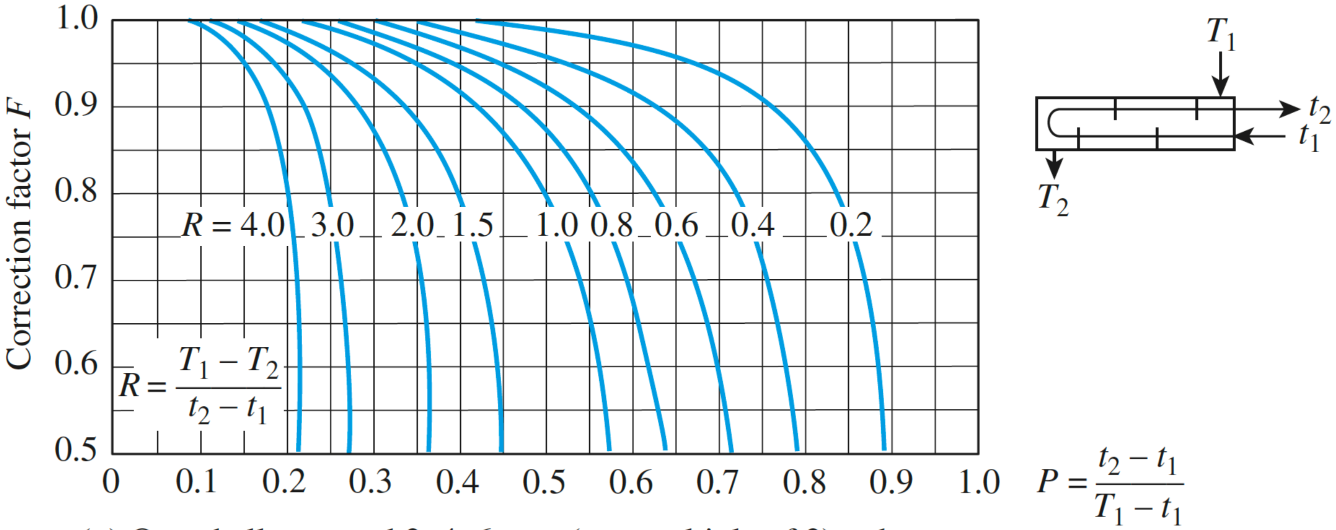
(b) Determine the temperature of the oil leaving each heat exchanger. [2 marks]

(c) Calculate the log mean temperature difference for each heat exchanger configuration. [6 marks]

(d) Determine the heat transfer surface area required for each heat exchanger configuration. [6 marks]

(e) If the double-pipe co-current heat exchanger is subjected to a fouling resistance of 2×10^{-4} m^2 K W^{-1}, calculate the new oil flow rate required to guarantee the same heat duty (i.e., to heat water from 30°C to 90°C flowing at 2.25 kg s^{-1}). [8 marks]

<u>Data:</u>



(a) One-shell pass and 2, 4, 6, etc. (any multiple of 2), tube passes

Figure Q3. Correction factor (F) chart for counter-flow, multi-pass heat exchangers. T and t represent shell- and tube-side temperatures, respectively.

4. (a) Show that the net radiation heat transfer between two infinitely long grey, opaque, diffuse concentric cylinders of surface emissivities, ε_1 and ε_1, maintained at uniform temperatures, T_1 and T_2 can be represented by

$$\dot{Q}_{12} = \frac{\sigma A_1 (T_1^4 - T_2^4)}{\frac{1}{\varepsilon_1} + \frac{1 - \varepsilon_2}{\varepsilon_2}\left(\frac{r_1}{r_2}\right)^2}$$

where the symbols have their usual meanings. Include the thermal resistance network diagram of the system as part of your answer. [8 marks]

(b) Liquid nitrogen is stored in a thin-walled, cylindrical container of 0.8 m diameter and 2.4 m length, which is enclosed within a second, thin-walled, cylindrical container of the same length and 1.6 m diameter. The opaque, diffuse, grey container surfaces have emissivities of 0.02 and 0.05, for the inner and outer containers, respectively, which are separated by an evacuated space. The outer container's surface is at 6°C and the inner container's surface is at -196°C.

If the latent heat of vaporisation of nitrogen is 199 kJ kg^{-1}, determine the rate of loss of mass of liquid nitrogen due to evaporation. [4 marks]

(c) A thin radiation shield of same length as the container and 1.0 m diameter with different surface emissivities of $\varepsilon_{3,1}$ = 0.03 and $\varepsilon_{3,2}$ = 0.06 is inserted midway between the inner and outer container surfaces.

(i) Draw the thermal resistance network diagram of the system. [2 marks]

(ii) Determine the new rate of mass loss of liquid nitrogen due to evaporation. [6 marks]

(iii) Calculate the percentage reduction in the rate of loss of mass of liquid nitrogen due to the shield. [2 marks]

(iv) State all assumptions made to solve the problem. [3 marks]

END OF PAPER

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