The University of Nottingham

DEPARTMENT OF MECHANICAL, MATERIALS AND MANUFACTURING ENGINEERING

A LEVEL 3 MODULE, SPRING SEMESTER 2018-2019

THERMOFLUIDS 3

Time allowed TWO Hours

Candidates may complete the front cover of their answer book and sign their desk card but must NOT write anything else until the start of the examination period is announced

Answer ALL questions from Section A and ONE question from Section B

Only silent, self contained calculators with a Single-Line Display or Dual-Line Display are permitted in this examination.

Dictionaries are not allowed with one exception. Those whose first language is not English may use a standard translation dictionary to translate between that language and English provided that neither language is the subject of this examination. Subject specific translation dictionaries are not permitted.

No electronic devices capable of storing and retrieving text, including electronic dictionaries, may be used.

DO NOT turn examination paper over until instructed to do so

In this examination candidates are required to answer ALL questions in Section A and ONE of the TWO questions in Section B. If a candidate answers more than the required number of questions, both questions will be marked and the highest mark will be used in the final examination mark.

ADDITIONAL MATERIAL: Thermodynamic Properties of Fluids & other data (in S.I Units)
Formula sheet

INFORMATION FOR INVIGILATORS:

Question papers should be collected in at the end of the exam – do not allow candidates to take copies from the exam room.

Section A

Answer ALL questions in this section

1. A poker is placed into a fire in a room which is at 28 °C. The cylindrical shaped poker is 600 mm long and has a diameter of 10 mm. 100 mm of the poker is inserted into the fire and the material of the poker below that point is at a constant temperature of 600 °C. Assuming that the poker acts as a fin, and using the values given below, estimate the maximum distance from the cold end of the poker that you could safely hold the poker if you are comfortable with holding metal at 40 °C.

   Assumptions: Assume that the poker is a long fin with temperature difference at location x ($\theta(x)$) given by:

   $$\theta(x) = \theta_0 \, e^{-mx}, \text{where } m = \sqrt{\frac{hP}{kA}}$$

   Properties:
   Heat transfer coefficient of convection around the poker $h = 20 \text{ W/m}^2\text{K}$
   Thermal conductivity of poker: $k_{poker} = 52 \text{ W/mK}$ [6]

2. (a) State the definition of the fin effectiveness and the fin efficiency relative to the heat loss from an ideal fin, the heat loss without the fin, and the real heat loss through the fin and comment on the expected ranges of the two values. [4]

   (b) Explain clearly the definition of an ideal fin. [2]

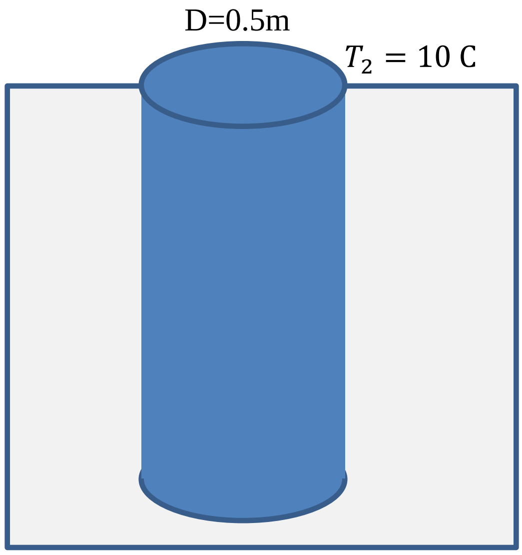
3. A 1.5 metre drum that has a diameter of 0.5 m is buried to its lid in the garden. It is filled with water and a heater inserted that maintains the temperature at 60 °C. The lid is a good insulator so that no heat is lost through the lid, but the walls are in contact with soil and heat can be lost in that direction. The soil has a thermal conductivity of $k = 1.2 \text{ W/mK}$.

   Using the information in fig. Q3, estimate the power of the heater needed to maintain the temperature at 60 °C inside the drum. [4]

For heat flow from a vertical isothermal cylinder of length L buried in a semi-infinite medium (L>>D),

$$S = \frac{2\pi L}{ln\left(\frac{4L}{D}\right)}$$

Fig Q3



4. A radiator can be assumed to be a hot plate mounted vertically. If the surface of the radiator is at a hotter temperature T_s than the surrounding air (at T_∞), then natural convection will form over the surface of the radiator. Draw two clearly labelled sketches that show the expected temperature profile and velocity profile over the surface respectively if the Prandtl number ($Pr = \nu/\mu$) is of the order of 1. Highlight all important features of the velocity and thermal boundary layers and compare the thicknesses of these boundary layers and explain their meaning. Assume that the boundary layer is laminar and developing from the base of the radiator. [7]

5. Wien's Law states that the maximum wavelength of radiation is related to the temperature by: $\lambda_{\max} T = 2898\ \mu\text{mK}$. Infrared radiation is at longer wavelengths than ultra-violet radiation. With the aid of diagrams, explain why a star that has a surface temperature of 3000 K looks red while a star that has a temperature of 10000 K is blue in tint. Assume that stars emit as black bodies. [4]

6. (a) Fig. Q6 shows the diffuse reflection of sunlight from surface 1 to surface 2. In the figure (A) the view factor from Area A_1 to Area A_2 is $F_{1-2} = 0.15$. Using the reciprocity relationship, calculate the view factor from Area A_2 to Area A_1? [1]

(b) In figure (B) the flat surface of area A_1 is replaced by a concave surface with the same width as the flat plate, but larger surface area due to the curvature. How does this affect the view factor of diffuse reflection from the new surface A_1 to surface A_2? [2]

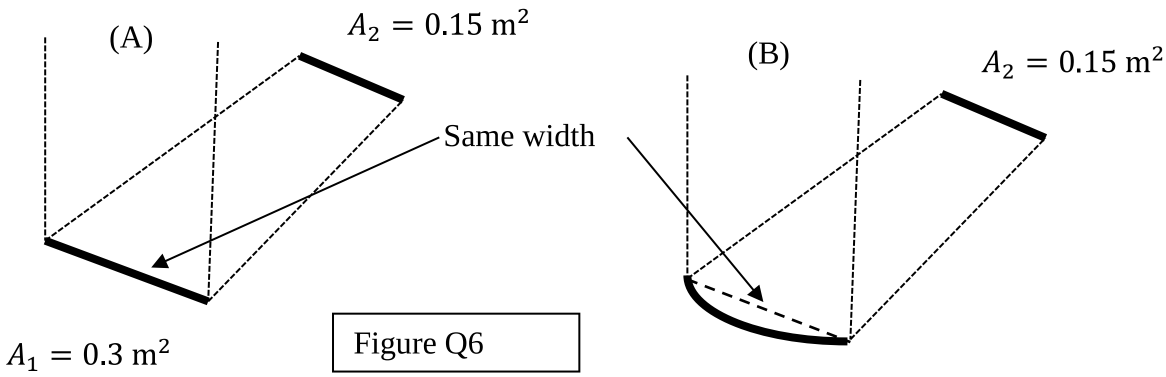


Figure Q6

7. The overall forced convection across a flat plat can be shown to give the following relationship between the Nusselt number, Reynolds number and Prandtl number of:

$$\overline{Nu}_L = 0.644 Pr^{\frac{1}{3}} Re_L^{\frac{1}{2}} \quad for\ Pr \geq 0.5$$

Using your knowledge of the analogy between heat transfer and mass transfer, rewrite this relationship in terms of the overall Sherwood number, the Schmidt number and the Reynolds number to represent the mass transfer from a flat plate. [2]

8. Calculate the molar Gibbs function of carbon dioxide at a temperature of 1200 K and a pressure of 5 bar, in which the enthalpy is expressed in terms of enthalpy of formation. [5]

9. In a steam cycle what is the difference between a closed and an open feedheater? [2]

10. An evacuated vessel is filled with steam from a pipeline in which there is dry saturated steam at a pressure of 15 bar. When the vessel is filled to a pressure of 15 bar what is the temperature in the vessel? [4]

11. What is the advantage of using exhaust gas recuperation in a gas turbine? Why is exhaust gas recuperation less effective at high pressure ratios? Use a diagram to illustrate your answer if you wish. [7]

12. An electric fan heater consumes 2 kW of electricity. Air enters the fan heater at a temperature of 18 °C and leaves at a temperature of 55 °C. If the environmental temperature is 7 °C, calculate the rational efficiency of the fan heater. Assume a specific heat capacity for air at constant pressure of 1.0 kJ/kgK. [6]

    Briefly state how the electricity could be used to provide heating more efficiently. [1]

13. Compressor blades and turbine blades in axial flow machines have particular structural characteristics determined by their function and the nature of the flow through them. Sketch the outline shape of a typical compressor blade and a typical turbine blade, highlighting their characteristics, and briefly explain their need. [6]

14. Sketch the velocity triangles for the stator and rotor of a 50% reaction turbine stage and explain the meaning of reaction with regard to the sketch. [3]

15. Describe with the aid of a sketch how velocity changes across an oblique shock. Explain the meaning of Prandtl-Meyer flow and the situations where it is likely to occur. [4]

Section B

Answer ONE from this section

16. (a) The first stage of a gas turbine has an inlet stagnation temperature of 1900 K. The rotor blades can be considered to have a mean radius of 0.25 m, with a blade height of 0.01 m, and the shaft speed is 18,000 rpm. The reaction is 50%, the flow coefficient is 0.9 and the stage loading coefficient is 1.8. Given the gas has γ=1.33, R=287 J/kgK, and the nozzle efficiency is 97%.

i) Using the information you have been given on the formula sheet develop an expression for the absolute velocity entering and leaving the rotor blade and hence calculate the relative and absolute flow angles [6]

ii) Calculate the absolute velocity of the gas at nozzle exit [5]

iii) Given that the static pressure at nozzle exit is 24.4 bar, calculate the mass flow rate. [3]

(b) Two blades in a turbine cascade are illustrated in Figure Q16. The melting point of steel is about 1780 K. For safety this could be restricted to 1700 K. If combustion gases are increased from 1700 K to 1900 K, then the Carnot efficiency of a gas turbine will increase from 82.35% to 84.2%. This is a significant increase and could decrease the carbon footprint of energy generation. However if we are to make this increase, we need to cool the blades otherwise the steel would melt and catastrophically fail. Following the procedure below, estimate the heat that would need to be removed from the turbine blade to safely obtain this increase.

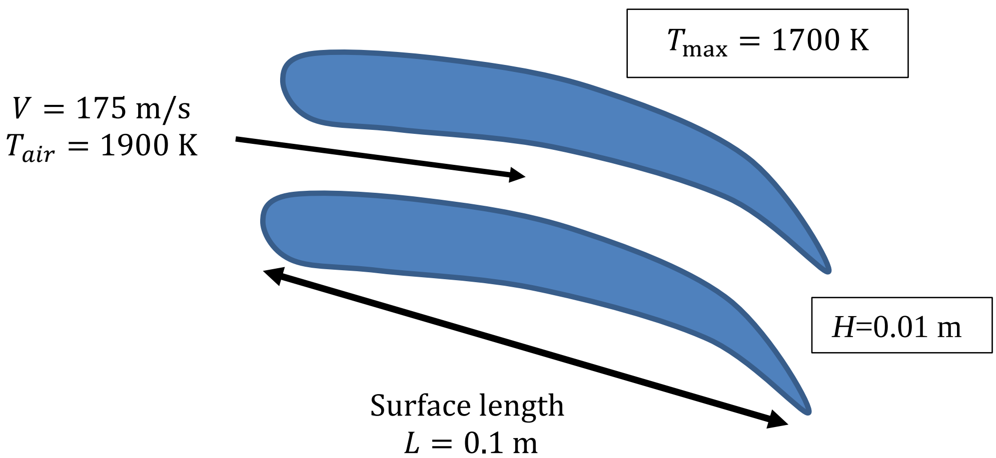


Figure Q16

Assume that the empirical correlation for the heat flow to both of the aerofoils will be $Nu_L = 0.023 Re^{0.8}\, Pr^n$, where *n* is 0.4 for heating and 0.3 for cooling the fluid.

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i) What is the Reynolds number ($Re = VL/v$) of the flow between the blades? [2]

ii) Using this value of Reynolds number, estimate the heat transfer coefficient for one of the surfaces of the turbine blade. [10]

iii) By making the assumption that the heat transfer coefficient is the same on both sides of one blade, estimate the heat ($\dot{Q}''$) that will need to be removed from a unit length of the blade to maintain it at 1700 K if the temperature of the gas is increased to 1900 K [4]

17. Exhaust gases leave an industrial furnace at a temperature of 440 °C, with a mass flow rate of 14.5 kg/s. Assume the specific heat capacity of the gases is 1.05 kJ/kgK. The hot gases pass through a heat recovery boiler at a constant pressure of 1 bar to produce steam and generate power in a steam turbine generator. The steam cycle is as shown in the Figure Q17. The steam leaves the boiler at a pressure of 40 bar and temperature of 400 °C. The steam turbine has an isentropic efficiency of 84% and the condenser pressure is 0.1 bar (absolute). The generator has an efficiency of 93%.

(a) If the pinch temperature difference in the heat recovery boiler is 13 °C, calculate the electricity power output from the generator and the thermal efficiency of the steam cycle. [15]

(b) Calculate the rate of irreversibility in the heat recovery boiler, steam turbine generator and condenser. [10]

(c) Discuss how the electricity power output could be increased? [5]

The environmental temperature is 7 °C.
Assume that water is a liquid at this temperature and that the specific gas constant for

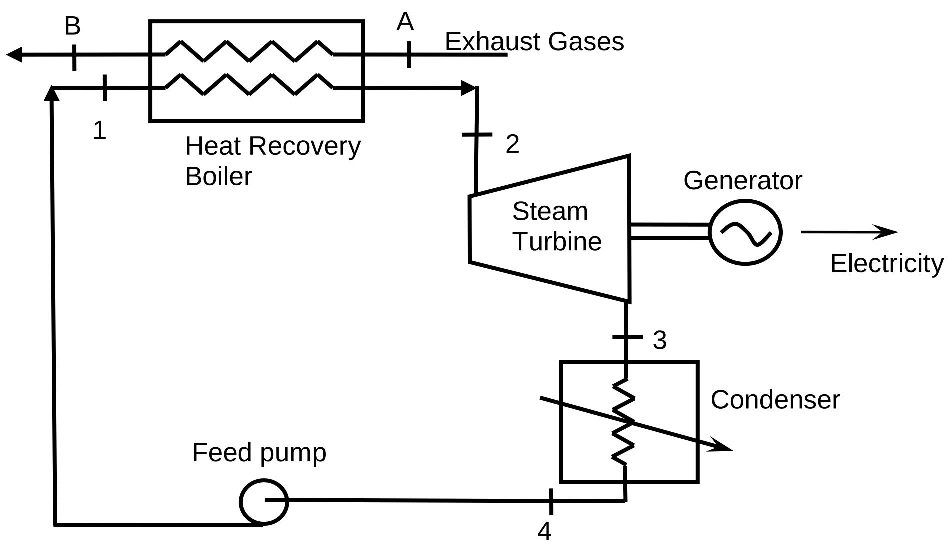

Figure Q17

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