Engineering **SECOND YEAR**

Part IB Paper 4: Thermofluid Mechanics

THERMODYNAMICS

ISSUED ON

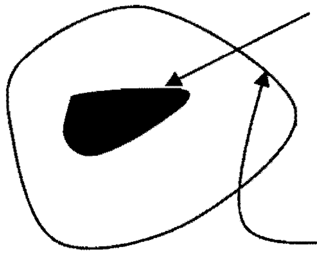
2 2 NOV 2013

Examples Paper 4

Radiative heat transfer

S1. The two walls of a vacuum flask are silvered on the sides facing each other. The emissivity of both surfaces is 0.02, and the temperatures are 100°C and 20°C for the inner and outer walls respectively. Treating the walls as infinite planes, calculate the overall heat transfer rate per unit area, and the irradiation and radiosity of each wall. If a radiation shield of emissivity 0.1 is placed between the walls, what would be the percentage reduction in heat transfer?

Q1. Kirchhoff's identity ($\alpha = \varepsilon$) is a result of absorption and emission behaviour of photons occurring at the quantum scale. However, it can also be "proved" to be true in certain situations using radiative heat transfer arguments.



Consider an evacuated black enclosure, as in the figure, with a grey sample of absorbtivity α inside it. The sample and the enclosure are at thermal equilibrium. By considering an energy balance on the surface of the sample, show that $\alpha = \varepsilon$.

Q2. An electric heater consists of a long rod heating element located along the central axis of a half-cylindrical reflector. The element has diameter 75 mm, emissivity 0.8 and is held at a constant temperature of 980°C. The reflector has diameter 0.5m and its rear surface is insulated. The view factor between the reflector and itself is 0.356. The heater is in a room with ambient temperature 15°C.

Calculate the net radiation heat transfer from the heating element. What is the effect of removing the reflector?

Q3. The view factor given in Q3. might have been estimated by ignoring the presence of the element, as it is rather small relative to the reflector – what value would this give?

Q4. A domestic central heating radiator (the same one already considered in Q8 on example paper 3) hangs a few centimetres from an exterior wall. The radiator is a flat plate 1 m high and 2 m long, with a uniform surface temperature of 60°C. The temperature of the wall behind the radiator is determined by the balance between incident radiation, convection to the room air and conduction through the wall to the outside. The temperature of the room and of the other walls is 20°C, and the outside air temperature is 5°C.

The overall thermal resistance between the inside wall surface and the outside air is 0.4 m^2KW^{-1} and the convection heat transfer coefficient at the inside wall surface is 4.5 $Wm^{-2}K^{-1}$. All surfaces may be considered to be 'black'.

(a) Calculate the radiative heat transfer from each side of the radiator.

(b) Fixing aluminium foil sheet to the wall behind a radiator is sometimes recommended as a way of reducing heat losses. Assess the value of this recommendation by calculating the change in the heat loss rate through the wall behind the radiator. Assume that the foil is a perfect reflector and takes up the temperature of the wall surface on which it is fixed. Is the net heat input to the room increased or decreased? Comment on the result.

Q5. The surface of a work piece is a circular disc which is to be held at 600K in a vacuum for a curing process. The area of the disc is 10 cm^2. The heating is provided by an electrically heated surface of the same diameter as the work piece, placed parallel to and coaxial with the work piece such that the view factor is 0.65. The emissivities of the heater and work piece are 0.8 and 0.2 respectively. The heater and the work piece are each perfectly insulated from behind, and the vessel in which they are placed is large and has surface temperature 300K.

Calculate the temperature of the heater and the electrical power required.

Q6. Estimate the insolation (Wm^{-2}) on the earth's outer atmosphere. How does the total insolation compare with our current energy consumption? *Hint, use wikipedia and treat the sun as a black body.*

Q7. A 1.6 mm diameter thermocouple is being used to monitor the temperature of the exhaust gas of an internal combustion engine. An estimate is required of the magnitude of the error in the reading due to radiation effects. To make this estimate, we will assume that the exhaust gas temperature is 600°C.

(a) Why is it reasonable (for estimation purposes) to assume exhaust gas has the same properties as air and that its properties can be evaluated at a mean temperature of 600°C ? Taking the mass flow as 0.01 kg/s, at a pressure of 1 bar, and the exhaust manifold diameter as 50 mm, estimate the thermocouple surface heat transfer coefficient, assuming that the thermocouple may be thought of as a cylinder in cross flow, where a suitable convective heat transfer correlation is

$$Nu_d \sim 0.9\,\mathrm{Re}_d^{\,0.4}$$

(b) Assuming all surfaces are black, estimate the temperature measured by the thermocouple when the exhaust manifold is at

i) 25°C (representative of the situation when the engine first starts from cold),

and

ii) 500°C (representative of the fully warmed up condition).

(c) What thermocouple diameter would be required to reduce this error to 5°C for case (a i))?

(d) What is the Biot number, and the time constant for each thermocouple? (Assume the thermocouple is made from solid stainless steel, density 8000 kgm^{-3}, specific heat 500 Jkg^{-1}K^{-1}, thermal conductivity 16 Wm^{-1}K^{-1}).

Thermodynamics revision: 1st and 2nd law applied to steady flow device

S2. A gas flows through a single inlet and single exit control volume operating steadily. Heat transfer at a rate $\dot{Q}$ takes place only at a location on the control volume where the temperature is T. For each of the following cases state whether the specific entropy at exit is less, equal or greater than at inlet.

(a) No internal irreversibilities, $\dot{Q}<0$.

(b) Internal irreversibilities, $\dot{Q}>0$.

(c) Internal irreversibilities, $\dot{Q}<0$.

Q8. Review of question Q5 from Part 1A Paper 1, Examples paper 6. The question read 'Q5. Air flows steadily and isothermally at 27°C along a horizontal pipe of constant cross-sectional area 100cm^2. At point A the pressure is 3 bar and the mean velocity is 160m/s. At point B the pressure is 2 bar. Calculate the velocity at point B and find the heat-transfer per kg of air between the two points.'

Review this question and then answer the additional question: assuming the flow is from A to B, calculate the increase in specific entropy due to irreversibility. Suggest a physical cause for the irreversibility, and comment on the validity of the assumption that the flow is from A to B.

Q9. Helium is to be compressed in a steady flow compressor from a pressure of 1 bar and a temperature of 15°C to a pressure of 10 bar. Two ideal processes are proposed:

(a) Adiabatic and reversible.

(b) Isothermal and reversible.

For each of the ideal process above: (i) Sketch a schematic (idealised diagram) of a device which could be used to achieve the process, (ii) mark on the schematic your choice of control volume, (iii) sketch the process on a T-s diagram, and (iv) use the 1st and 2nd laws, where appropriate, to calculate the shaft work required to compress 1kg of helium. Changes in kinetic energy may be neglected.

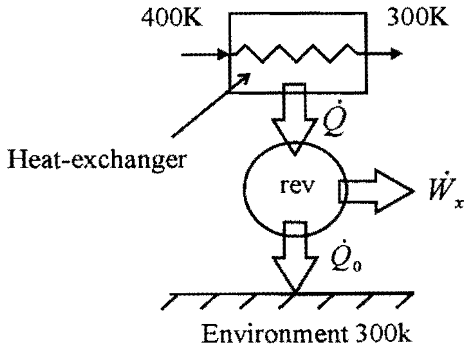
Maximum available power

S3. Name three different mechanisms that can cause irreversible entropy generation. Give a steady flow example for each.

Q10. An industrial process contains a large thermal reservoir at 400K. A steady flow of $1 kgs^{-1}$ of air is taken from the reservoir. A heat flux is extracted from the flow causing its temperature to drop from 400K to 300K, shown in the figure below. The pressure of the flow remains constant. The temperature of the environment is 300K.

(a) Calculate the maximum power potential of the heat flux.

(b) A reversible heat engine is used to extract this maximum power. Calculate the thermal (1^{st} law) efficiency of the engine.



Answers

S1. 6.87 Wm^{-2};

hot wall $J = 761\ Wm^{-2}$, $G = 754\ Wm^{-2}$;

cold wall $J = 754\ Wm^{-2}$, $G = 761\ Wm^{-2}$;

~20 % reduction

1. -
2. 23.8 kWm^{-2}, 10.5% increase
3. The view factor estimate would be too large, by 2%
4. Room side 558.6 W; wall side 333.5 W, loss rate reduced by 117 W
5. 685.9 K, 5.96 W (nb. The power is sensitive to round off error)
6. About 1.3 kW m^{-2} . Total energy consumption is about 0.01% of the total insolation.
7. (a) 290 $Wm^{-2}K^{-1}$

   (b) i) 503°C (97°C error), ii) 563°C (37°C error)

   (c) ~0.01 mm

   (d) For the 1.6 mm TC, Bi = 0.0073, time constant = 5 s, for the 0.01mm TC, 0.001, 1.5 ms
8. 63.1 J/kgK.
9. (a) 2270kJ/kg, (b) 1379kJ/kg.
10. (a) 13.8kW, (b) 13.7%.

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