UNIVERSITY OF BATH

DEPARTMENT OF MECHANICAL ENGINEERING

ME20015

THERMOFLUIDS 3

Monday, 21 January 2008 **16.30 – 18.30**

Candidates should attempt to answer any **THREE** questions.

Candidates may only use University-supplied calculators.

The following are provided:

Thermodynamics Data Sheet
Enthalpy-Entropy Diagram for Steam
Thermodynamic and Transport Properties of Fluids

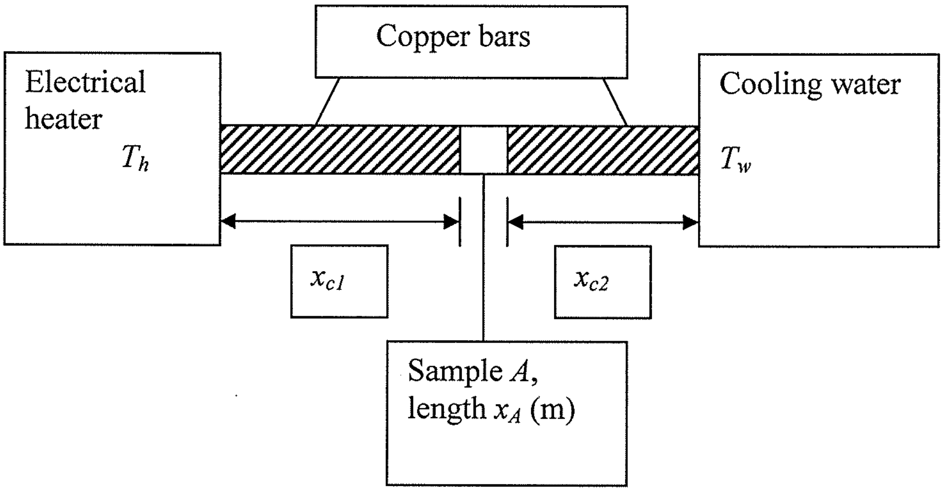
PLEASE FILL IN THE DETAILS ON THE FRONT OF YOUR ANSWER BOOK/COVER AND SIGN IN THE SECTION ON THE RIGHT OF YOUR ANSWER BOOK/COVER, PEEL AWAY ADHESIVE STRIP AND SEAL.

TAKE CARE TO ENTER THE CORRECT CANDIDATE NUMBER AS DETAILED ON YOUR DESK LABEL.

CANDIDATES MUST NOT TURN OVER THE PAGE AND READ THE EXAMINATION PAPER UNTIL THE CHIEF INVIGILATOR GIVES PERMISSION TO DO SO

ME20015 contd...

1. (a) A rig has been constructed as shown in the diagram below to measure the thermal conductivity of a metal sample A by comparing the thermal gradient in the sample to that in copper with a known conductivity k_c. An electrical heater at a constant temperature T_h generates heat which flows through the heated copper bar of length x_{c1} into the sample, of length x_A, which is clamped between the bars, and into a second copper bar of length x_{c2} which is cooled by water at its far end. The design of the rig is such that the cross sectional areas of the bars and sample are constant and the heatflow is 1-dimensional.



(i) Develop an expression which relates the flow of heat from the heater at T_h to the cooling water at T_w in terms of the individual thermal resistances encountered, and sketch the associated thermal resistance network.
Define any terms that you introduce.

[9 marks]

(ii) Sketch a graph of temperature vs axial distance from the heater to the cooling water, through both bars and the sample, and annotate your sketch to explain its important features.

[6 marks]

(iii) If the measured temperature gradient in the metal sample is 0.55 K/m, and that in the copper bars is 4.2 K/m, and k_c = 396 W/mK, calculate the thermal conductivity k_A of the sample.

[4 marks]

(iv) Briefly discuss the overall design of rig with respect to its intended purpose, and by considering unwanted heat transfer effects via convection and radiation, how might the design be improved to produce better results.

[4 marks]

(b) The average Nusselt number over the surface of a sphere in forced convection is approximated by

$$Nu = 0.37\, Re^{0.6}$$

Estimate the heat transfer by convection from a 40 W electric light bulb at 140°C to a 20°C airstream moving at 0.5 m/s. The light bulb can be approximated as a 50mm sphere, and the physical properties for air are given in Table 1.

[10 marks]

2. (a) A domestic heating radiator 0.5 m high by 1m wide has a surface temperature of 50°C in a room of still air at 10°C and 1 atmosphere pressure. Assuming the vertical plate relations for natural convection, (with the characteristic length dimension being the plate height):

$$Nu = 0.51 Ra^{\frac{1}{4}} \quad \text{for } 10^4 < Ra < 10^9$$

$$Nu = 0.1 Ra^{\frac{1}{3}} \quad \text{for } 10^9 < Ra < 10^{13}$$

where the Rayleigh Number $Ra = \dfrac{\rho^2 c_p g \beta \Delta T h^3}{k\mu}$ and properties are evaluated at the film temperature.

g = gravitational acceleration (m/s^2)
ρ = fluid density (kg/m^3)
β = coefficient of volume expansion (1/K)
T_w = wall temperature (K)
T_∞ = temperature of the fluid sufficiently far from surface (K)
h = characteristic length (m)
μ = dynamic viscosity (kg/ms)

(i) Estimate the rate of heat loss from the radiator via natural convection.

[9 marks]

(ii) Assuming grey body behaviour with $\varepsilon = 0.71$, what is the net rate of heat loss from the radiator by thermal radiation?

[5 marks]

(iii) What is the total heat loss from the radiator? Justify, and briefly comment on, your answer.

[3 marks]

Relevant properties for air may be found in Table 1, $g = 9.81\ ms^{-2}$ and the Stefan-Boltzmann constant $\sigma = 5.67 \times 10^{-8}\ W/m^2K^4$.

(b) For a hollow cylinder of length L with negligible axial and angular temperature variation, it can be shown that the steady state temperature T is related to the radius r by the relation

$$\frac{(T - T_1)}{(T_2 - T_1)} = \frac{\ln(r/r_1)}{\ln(r_2/r_1)}$$

Where the surface temperature at inner radius r_1 is T_1 and the surface temperature at outer radius r_2 is T_2.

Show that the heatflux through the cylinder wall can be described by:

$$Q = \frac{2\pi kL(T_1 - T_2)}{\ln(r_2/r_1)}$$

[16 marks]

3. (a) The following data apply to a simple gas turbine.

Pressure ratio	9:1
Compressor isentropic efficiency	85%
Turbine isentropic efficiency	90%
Turbine inlet temperature	1300K

Ambient conditions and thermal properties

Pressure	1 bar
Temperature	15°C

γ air	1.4
Cp air	1.005 kJ/kg K

Assume the working fluid to be air throughout,

(i) Draw a block diagram and temperature-entropy (TS) diagram to represent the unit. [6 marks]

(ii) Calculate the specific work required to drive the compressor, the net specific work output and thermal efficiency of the unit.

[8 marks]

(b) In an attempt to improve the specific work output of the device, a two stage compressor with intercooling is substituted for the original compressor.

(i) Draw a block diagram and TS diagram for the revised unit. [3 marks]

(ii) At what pressure should the intercooler operate to give the largest reduction in compressor work? [2 marks]

(iii) Calculate the specific work required to drive the two stage compressor assuming that the intercooler is able to cool the air entering the second stage of compression down to 288K and that the second stage has the same efficiency as the first. [4 marks]

(iv) Calculate the new net work output and thermal efficiency of the revised unit. [4 marks]

(c) Describe with the aid of a block diagram and TS diagram how you would seek to recover this efficiency loss by harnessing waste heat. [5 marks]

4. A steam plant operates at a condenser pressure of 0.04 bar and a boiler pressure of 50 bar.
   a. Draw a block diagram and TS diagram of the plant [6 marks]
   b. Neglecting feed pump work -
      i. Determine the enthalpy at turbine inlet and exhaust assuming an isentropic efficiency of 90%. [4 marks]
      ii. Calculate the specific heat input, specific work output and thermal efficiency. [3 marks]
      iii. What is the dryness fraction of the steam at turbine exit? [2 marks]

The system is modified to include a superheater capable of raising the temperature of steam entering the turbine to 550°C.

   c. Draw a block diagram and TS diagram of the revised plant [3 marks]
   d. Neglecting feed pump work -
      i. Determine the enthalpy at turbine inlet and exhaust assuming an isentropic efficiency of 90%. [4 marks]
      ii. Calculate the specific heat input, specific work output and thermal efficiency. [3 marks]
      iii. What is the dryness fraction of the steam at turbine exit? [2 marks]

   e. Describe with the aid of a block diagram and TS diagram one method with which you could improve the efficiency of the system by raising the mean temperature at which heat is added. [6 marks]

Table 1: Physical properties of air at atmospheric pressure

Temp (°C)	Dynamic Viscosity (kg/ms)	Thermal Conductivity (W/mK)	Specific Heat Capacity (J/kgK)	Prandtl Number (-)	Density (kg/m^3)
-40	1.519×10^{-5}	0.02102	1002	0.724	1.513
-20	1.624×10^{-5}	0.02258	1002	0.720	1.394
0	1.724×10^{-5}	0.02411	1002	0.717	1.292
20	1.822×10^{-5}	0.02560	1003	0.713	1.204
40	1.916×10^{-5}	0.02707	1003	0.710	1.127
60	2.008×10^{-5}	0.02851	1004	0.707	1.059
80	2.097×10^{-5}	0.02992	1005	0.705	0.999
100	2.183×10^{-5}	0.03131	1007	0.702	0.946
120	2.267×10^{-5}	0.03268	1009	0.700	0.897
140	2.348×10^{-5}	0.03402	1012	0.698	0.854
160	2.428×10^{-5}	0.03535	1014	0.697	0.815
180	2.506×10^{-5}	0.03666	1017	0.696	0.779
200	2.582×10^{-5}	0.03795	1021	0.695	0.746
220	2.656×10^{-5}	0.03922	1025	0.694	0.715
240	2.729×10^{-5}	0.04048	1029	0.693	0.688
260	2.800×10^{-5}	0.04172	1033	0.693	0.662
280	2.870×10^{-5}	0.04295	1037	0.693	0.638
300	2.938×10^{-5}	0.04417	1042	0.693	0.616
320	3.005×10^{-5}	0.04537	1047	0.693	0.595
340	3.071×10^{-5}	0.04656	1052	0.694	0.575
360	3.136×10^{-5}	0.04774	1057	0.694	0.557
380	3.199×10^{-5}	0.04890	1062	0.694	0.540
400	3.262×10^{-5}	0.05006	1066	0.695	0.524
420	3.324×10^{-5}	0.05120	1071	0.695	0.509
440	3.384×10^{-5}	0.05234	1076	0.696	0.495
460	3.444×10^{-5}	0.05347	1081	0.696	0.481
480	3.503×10^{-5}	0.05458	1086	0.697	0.468
500	3.561×10^{-5}	0.05569	1091	0.697	0.456
520	3.618×10^{-5}	0.05679	1096	0.698	0.445
540	3.674×10^{-5}	0.05788	1100	0.698	0.434
560	3.730×10^{-5}	0.05896	1105	0.699	0.423
580	3.785×10^{-5}	0.06003	1109	0.699	0.414
600	3.839×10^{-5}	0.06110	1113	0.700	0.404

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