

The University of Nottingham

DEPARTMENT OF Mechanical, Material and Manufacturing Engineering

A LEVEL 3 MODULE, MMME3081 SEMESTER 2021-2022

ThermoFluids 3

Time allowed 2 hours plus 30 minutes upload period

Open-book take-home examination

Answer ALL questions

You must submit a single pdf document, produced in accordance with the guidelines provided on take-home examinations, that contains all of the work that you wish to have marked for this open-book examination. Your submission file should be named in the format '[Student ID]_[Module Code].pdf'.

Write your student ID number at the top of each page of your answers.

This work must be carried out and submitted as described on the Moodle page for this module. All work must be submitted via Moodle by the submission deadline.

Work submitted after the deadline will not be accepted without a valid EC.

No academic enquiries will be answered by staff and no amendments to papers will be issued during the examination. If you believe there is a misprint, note it in your submission but answer the question as written.

Contact your Module Teams Channel or SS-AssessEng-UPE@exmail.nottingham.ac.uk for support as indicated in your training.

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Part 1. Complete all questions

1. A vessel contains 2 kmol of hydrogen and 3 kmol of carbon monoxide at a temperature of 1600K and pressure of 1 bar. Calculate the molar enthalpy and specific enthalpy of the gas mixture, including enthalpy of formation in the answer.

Use data from the tables given below

[7 marks]

\bar{h}	\bar{u}	\bar{s}°	\bar{g}°	T	\bar{h}	\bar{u}	\bar{s}°	\bar{g}°	
[kJ/kmol]	[kJ/kmol]	[kJ/kmol K]	[kJ/kmol]	[K]	[kJ/kmol]	[kJ/kmol]	[kJ/kmol K]	[kJ/kmol]	
Hydrogen (H ₂)				$\bar{m} = 2.016 \frac{\text{kg}}{\text{kmol}}$	Carbon Monoxide (CO)				$\bar{m} = 28.0105 \frac{\text{kg}}{\text{kmol}}$
-8468	-8468	0	-8468	0	-8699	-8669	0	-8669	
-5293	-6124	102.04	-15496	100	-5770	-6601	165.74	-22344	
-2770	-4433	119.33	-26635	200	-2858	-4521	185.92	-40041	
0	-2479	130.57	-38931	298.15	0	-2479	197.54	-58898	
54	-2440	130.75	-39172	300	54	-2440	197.72	-59263	
2958	-368	139.11	-52684	400	2975	-351	206.12	-79475	
8812	3823	150.97	-81769	600	8941	3953	218.20	-121980	
14703	8051	159.44	-112850	800	15175	8524	227.16	-166550	
20686	12371	166.11	-145430	1000	21686	13371	234.42	-212740	
26794	16817	171.68	-179220	1200	28426	18449	240.56	-260250	
33062	21422	176.51	-214050	1400	35338	23698	245.89	-308910	
39522	26219	180.82	-249790	1600	42384	29081	250.59	-358560	
46150	31184	184.72	-286350	1800	49522	34556	254.80	-409110	
52932	36303	188.30	-323660	2000	56739	40110	258.60	-460460	
59860	41569	191.60	-361650	2200	64019	45728	262.06	-512520	
66915	46960	194.67	-400290	2400	71346	51391	265.25	-565260	
74090	52473	197.54	-439510	2600	78714	57096	268.20	-618610	
81370	58090	200.23	-479280	2800	86115	62835	270.94	-672530	
88743	63799	202.78	-519590	3000	93542	68598	273.51	-726980	
96199	69592	205.18	-560390	3200	101000	74391	275.91	-781930	
103740	75469	207.47	-601650	3400	108480	80210	278.18	-837340	
111360	81430	209.65	-643370	3600	115980	86044	280.32	-893190	
119060	87469	211.73	-685510	3800	123490	91900	282.36	-949460	
126850	93589	213.73	-728060	4000	131030	97769	284.29	-1006120	

	\bar{m}	$\Delta \bar{h}_{10}^\circ$
	[kg/kmol]	[kJ/kmol]
C (graphite)	12.011	0
C (diamond)	12.011	1900
C (gas)	12.011	714990
CH ₄ (gas)	16.043	-74870
C ₂ H ₄ (gas)	28.054	52470
CO (gas)	28.0105	-110530
CO ₂ (gas)	44.010	-393520
H (gas)	1.008	217990
H ₂ (gas)	2.016	0
OH (gas)	17.005	39710
H ₂ O (liq)	18.0155	-285820
H ₂ O (vap)	18.0155	-241830
N (gas)	14.0065	472650
N ₂ (gas)	28.013	0
NO (gas)	30.006	90290
O (gas)	15.9995	249170
O ₂ (gas)	31.999	0

2. Explain the impact that the isentropic efficiency of less than 100% in the compressor and turbine of a gas turbine have on the performance compared to that of an ideal air cycle gas turbine. Draw a diagram to explain your answer. (Write no more than 150 words)

[6 marks]

3. A pressure vessel is used to store hydrogen for an automotive vehicle. Initially the pressure is 50 bar and temperature is 20°C. It is then filled from a reservoir at a constant pressure of 350 bar at temperature of 20°C until the final pressure in the vessel is 350 bar. Explain the advantages of precooling the hydrogen before it is fed into the vessel. (Write no more than 150 words) [7 marks]

4. Hot exhaust gases from an industrial furnace are used to generate steam in a heat recovery boiler. The steam is used to generate electricity in a steam turbine generator and the exhaust steam is condensed in a heat exchanger to transfer heat at 50°C to an industrial process. The heat recovery system is shown in Figure Q4, where the temperature and pressure of the steam and hot exhaust gases are shown.

The mass flow rate of the hot exhaust gases is $(15 + X)$ kg/s, where X is the last digit of your Student ID number (e.g. if your Student ID ends with the number 5, exhaust gas mass flow rate is 20 kg/s).

The mechanical to electrical efficiency of the generator is 90%.

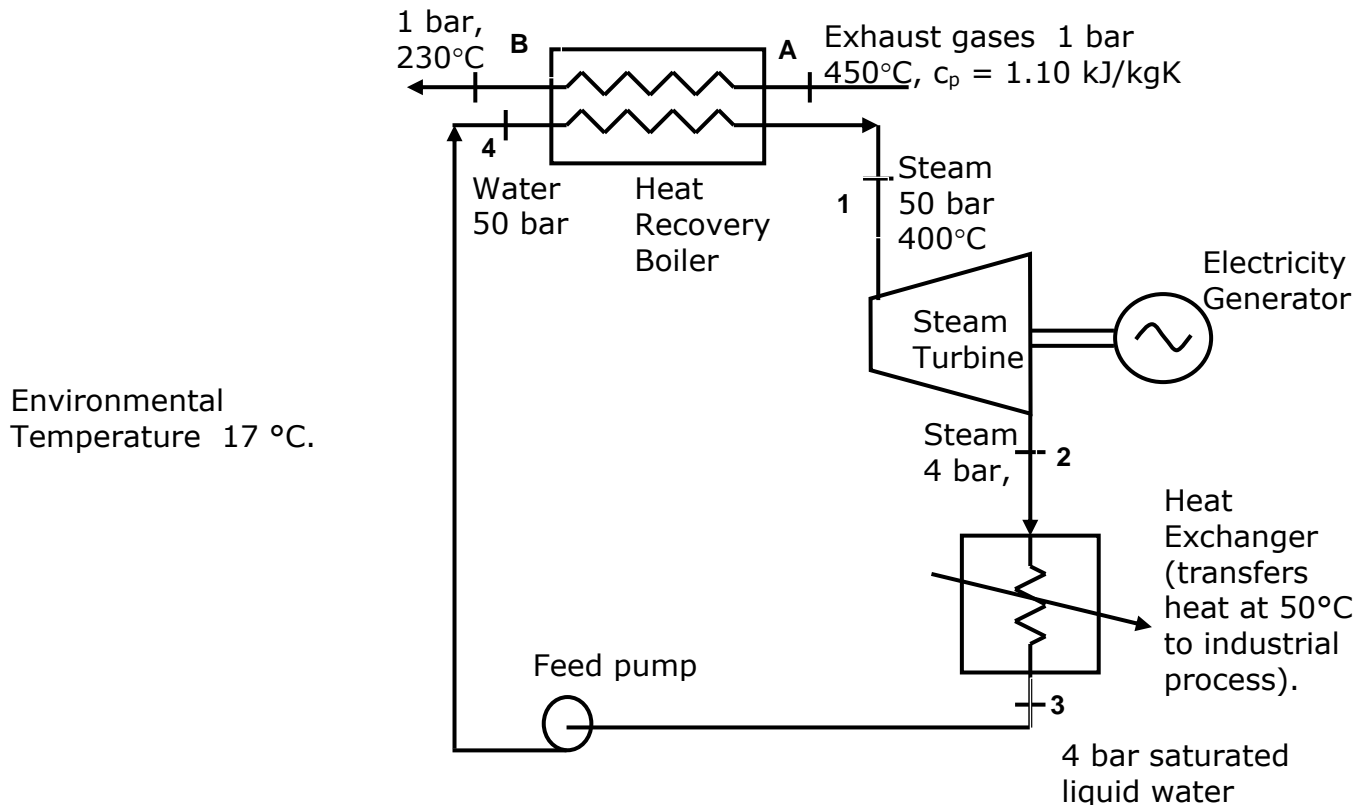


Figure Q4.

The conditions in the steam cycle, enthalpy and entropy at each point in the cycle are shown in the table below. Point 2' assumes an isentropic expansion of the inlet steam to the turbine.

Location	Steam Condition	Temperature [°C]	Pressure [bar]	Enthalpy [kJ/kg]	Entropy [kJ/kgK]
1	S/H steam	400	50	3196	6.646
2'	Wet steam	143.6	4	?	?
2	Wet steam	143.6	4	2718	6.847
3	Water	143.6	4	605	1.776
4	Water	143.6	50	605	1.776

- a) Calculate:
- i) The Mass flow rate of steam from the heat recovery boiler.
 - ii) The electricity output from the steam turbine generator.
 - iii) The rate of heat transfer from the heat exchanger to the industrial process
 - iv) The isentropic efficiency of the steam turbine. [12 marks]
- b) Calculate
- i) The rate of exergy decrease in the exhaust gases as they pass through the heat recovery boiler.
 - ii) The rate of thermal exergy transfer to the industrial process
 - iii) The rate of irreversibility in the heat recovery boiler, steam turbine generator and heat exchanger.
 - iv) The rational efficiency of the heat recovery system. [12 marks]
- c) Comment critically on the performance of the heat recovery system and explain how its performance could be increased. (Write no more than 150 words) [6 marks]

Additional information

All pressures are given as absolute pressure.
Ignore the feed pump work in all calculations.

The environmental temperature is 17°C at which temperature the specific enthalpy and specific entropy of water is 71.3 kJ/kg and 0.253 kJ/kgK respectively.

You may use the enthalpy entropy chart provided on Moodle to determine the enthalpy and entropy of the steam at Point 2', or the extract of the steam tables provided or other data source. State your data source in your answer.

A Formula Sheet is also available on Moodle.

State any assumptions that you make.

Part 2: Complete all questions

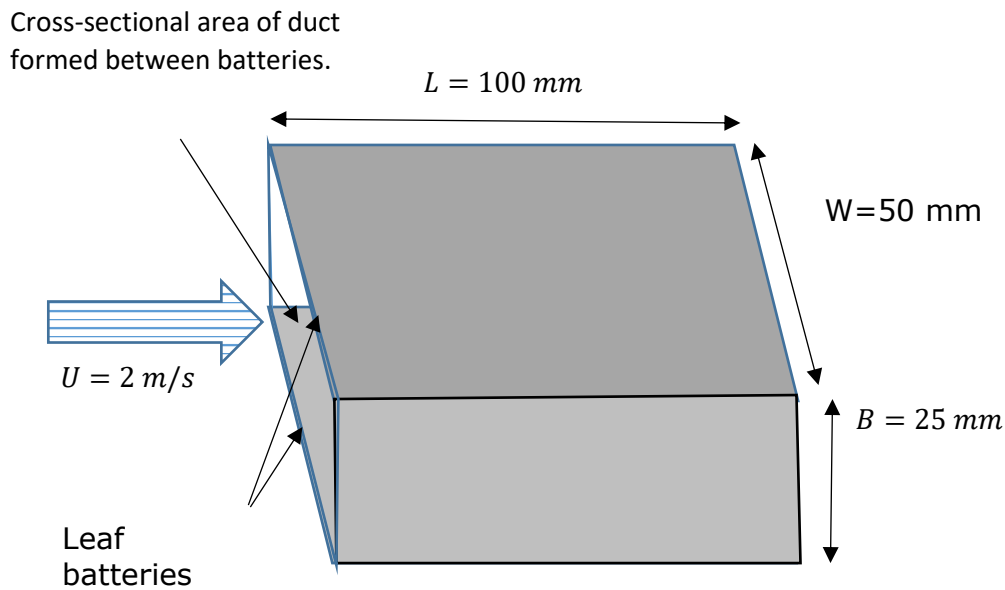


Figure Q5

5. To cool two leaf batteries, air is blown between them. The length of the batteries in the flow-wise direction is 100 mm, the distance between them is 25 mm and the width of them is 50 mm. Assume that the area of this unit is bounded to form a duct with a hydraulic diameter $D = 4A_c/P$ (A_c is cross-sectional area, and P is the perimeter of the duct formed by this unit). The surface of the batteries needs to be kept below 37°C when being charged. In this condition, they jointly generate 1 W of heat from both leaf batteries towards the inside of the duct. If the air flowing over the batteries is at 17°C and the air flows at a speed of 1 m/s, the actual heat loss can be calculated from either.

$$Nu_D = 0.023 Re_D^{\frac{4}{5}} Pr^n, n = 0.4 \text{ for heating, } n = 0.3 \text{ for cooling, } 0.7 \leq Pr \leq 166, Re_D \geq 4000,$$

$$\text{or } Nu_D = 3.39, Re_D < 4000$$

Assuming that the heat of the batteries is just below the critical temperature, follow the below procedure to determine which of the above correlations should you use, and is the flow speed enough to keep the system cool.

- Which correlation is valid for this Reynolds number of flow. [5 marks]
- Estimate the heat transfer coefficient in the duct [3 marks]
- By considering only the surfaces of the leaf batteries facing into the duct only, estimate the heat loss from the leaf batteries by convection only. [2 marks]
- Explain the meaning of this answer if the system needs to be maintained at the critical temperature and determine the final temperature that the system might reach with this heat transfer coefficient. [4 marks]
- Using diagrams and using technical language in less than 400 words explain how the boundary layers near the entrance to the duct can affect the optimal heat transfer from the system if the batteries are very long. [5 marks]

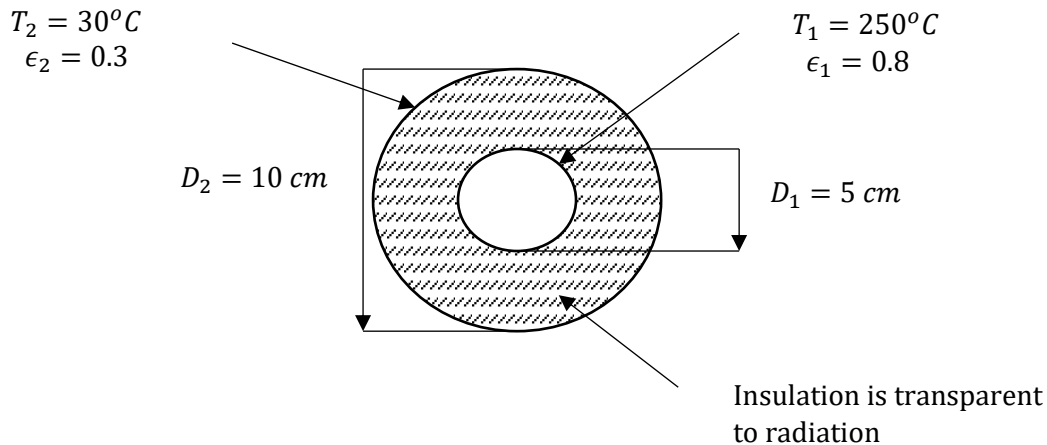


Figure Q6

6. The figure shows two concentric metal pipes. The inner one carries steam at $250^\circ C$, and the outer one is there to protect against high pressure rupturing of the inner pipe. Between the pipes is insulation which reduces conduction to almost negligible amounts. Assuming that the insulation is transparent to thermal radiation at these wavelengths, and using the parameters in the diagram, please answer the following questions.

- What are the four view factors in this situation assuming the unit length of pipe is so long that end effects are negligible. [4 marks]
- Draw a labelled resistance network showing the potentials and resistances needed to solve this problem. [7 marks]
- Calculate the heat loss per unit meter of this pipe. [7 marks]
- If the insulation became more opaque, what would be the effect on the overall heat transfer. [4 marks]

7. A very long, 1 cm diameter copper rod ($k = 377\text{ W/mK}$) is exposed to the environment at $T_a = T_{ID}^\circ C$. The base of the rod is maintained at $T_b = 150^\circ C$. The heat transfer coefficient between the rod and the surrounding air is $h = 11\text{ W/m}^2 K$. Using Fin theory, determine the heat transfer rate from the rod to the surrounding air. [9 marks]

$$T_{ID} = 20 + (\text{last digit of your student ID})$$

e.g. if your student ID is 12345678, then you would use $T_a = 20 + 8 = 28^\circ C$

1. $H = H_{f_0} + \Delta H$

For hydrogen $H_{f_0} = 0$ as it is an element, and $\Delta H = 39522$ kJ/kmol at 1600 K.
For Carbon monoxide $H_{f_0} = -110530$ kJ/kmol, and $\Delta H = 42384$ at 1600 K

[3 marks]

So molar enthalpy of mixture is $2(0 + 39533) + 3(-110530 + 42384)$
 $= -125372$ kmol. [2 marks]

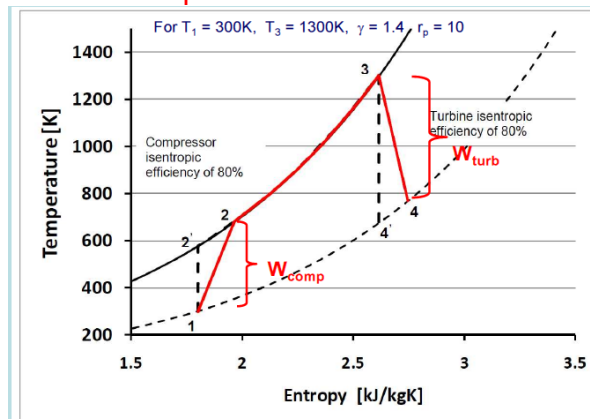
There are 5 kmols of gas in total so molar enthalpy is $-125372/5 = -25074$
kJ/kmol [1 mark]

The mass of the mixture is $2 \times 2 + 3 \times 28 = 88$ kg.

So specific enthalpy of the mixture is $-125372/88 = -1425$ kJ/kg [1 marks]

2. The effects of isentropic efficiency of less than 100% on the compressor and turbine are as follows:

- Increase work input to the compressor (but slight reduction in heat input needed in combustion chamber)
- Decrease in work output from the turbine.
- Both of these changes in work result in a loss in net work output from the gas turbine, which will result in a significant reduction in thermal efficiency.
- As the air flow through the gas turbine will not change there is also a significant reduction in specific work output. [4 marks]



[2 marks]

3. As the hydrogen enters the vessel the temperature of the gas inside the vessel will increase and the final temperature will be significantly above the initial temperature. [2 marks]

This will result in the density being lower than at 20°C and so the mass of gas in the vessel is less than it would be. So it is advantageous to precool the gas to maximise the mass that can be stored. [2 marks]

Additionally, as the gas increases in temperature as the vessel is filled, the temperature may be above the service temperature of some of the materials used. So precooling helps to prevent thermal damage to the vessel. [3 marks]

4. The solution is provided for a student with an ID ending in 5.

a) i) Mass flow rate of exhaust gas is $15 + 5 = 20$ kg/s.

From energy balance on heat recovery boiler.

$$\dot{m}c_p(T_A - T_B) = \dot{m}_{st}(h_1 - h_4)$$

$$\dot{m}_{st} = 20 \times 1.1 \times (450 - 230)/(3196 - 605) = 1.868 \text{ kg/s}$$

Steam mass flow rate is 1.868 kg/s [3 marks]

ii) The output from the steam turbine is $\dot{m}_{st}(h_1 - h_2) = 1.868 \times (3196 - 2718)$

Power from steam turbine is 892.9 kW

Electricity output from generator is $0.9 \times 892.9 = 0.80 \text{ MW}$ [3 marks]

iii) Rate of heat transfer in heat exchanger is $\dot{m}_{st}(h_2 - h_3)$

Rate of heat transfer is $1.868 \times (2718 - 605) = 3947 \text{ kW}$ (3.9 MW) [3 marks]

iv) Isentropic efficiency of steam turbine is given by $(h_1 - h_2)/(h_1 - h_{2'})$

Enthalpy of steam at 2' is found from tables/chart = 2634 kJ/kg

Entropy of steam at 2' is same as 1 as process is isentropic.

Isentropic efficiency = $(3196 - 2718)/(3196 - 2634) = 0.85$ (85%)
[3 marks]

b) i) Exergy of a gas is given by: $\dot{m} \left(c_p(T_1 - T_0) - T_0 \left(c_p \ln \left(\frac{T_1}{T_0} \right) - R \ln \left(\frac{p_1}{p_0} \right) \right) \right)$

Environmental temperature T_0 is $17^\circ\text{C} = 290 \text{ K}$

So exergy of exhaust gas at A is $20 \times (1.1 \times (450 - 17) - 290(1.1 \times \ln((450+273)/290)))$
= 3698 kW

Exergy of exhaust gas at B is $20 \times (1.1 \times (230 - 17) - 290(1.1 \times \ln((230+273)/290)))$
= 1172 kW

So **reduction in exergy in exhaust gases** is $3698 - 1172 = 2526 \text{ kW}$ (2.53 MW)
[3 marks]

ii) Rate of thermal exergy transfer to the process is given by $\dot{Q} \left(\frac{T_1 - T_0}{T_1} \right)$

Rate of thermal exergy transfer to process is $3974 (50 - 17)/(290) = 452 \text{ kW}$
[3 marks]

iii) Flow exergy in a flow of steam is given by: $\dot{m}((h_1 - h_0) - T_0(s_1 - s_0))$

Flow exergy of steam in cycle is:

Point 1 2374 kW
Point 2 1372 kW
Point 3 172 kW
Point 4 172 kW

Irreversibility in heat recovery boiler = $2526 - (2374 - 172) = 324 \text{ kW}$
Irreversibility in steam turbine generators = $(2374 - 1372) - 893 = 109 \text{ kW}$
Irreversibility in heat exchanger = $(1372 - 172) - 452 = 748 \text{ kW}$
[3 marks]

iv) The rational efficiency of the steam heat recovery system is:
Electricity generated + thermal exergy to process/reduction in exergy of exhaust gases.

$$\text{Rational Efficiency} = (0.8 + 0.45)/2.53 = 49.4\%$$

[3 marks]

c) The exergy analysis shows that the greatest irreversibility in the system is in the heat exchanger. This is because there is a large temperature difference between the steam temperature (144 °C) and the temperature at which heat is required for the industrial process (50°C). [2 marks]

So the steam pressure at the turbine exhaust could be lower, this would reduce the irreversibility in the heat exchanger and improve the system by:

Increasing the output from the turbine generator.

Reducing the temperature of the boiler feedwater which could decrease the hot gas exhaust temperature at outlet from the heat recovery boiler, resulting in more heat recovery and the potential for more electricity to be generated.

But it is likely that a larger heat exchanger would be needed as the temperature difference across it would be lower. [2 marks]

The performance could also be increased by operating the steam cycle at a higher temperature and pressure to reduce the irreversibility in the boiler. [1 mark]

The output from the turbine generator could also be increased by increasing the efficiency of the turbine and generator. [1 mark]

5. a) To determine correlation we need Reynolds number.

$$U = 1 \text{ ms}^{-1}, D = \frac{4A}{P} = \frac{4(0.025 \times 0.05)}{2(0.05 + 0.025)} = 0.033 \text{ m. [1]}$$

$$\text{Film temperature is } T = \frac{17+37}{2} = 27^\circ\text{C} = 300 \text{ K [1]}$$

$$\text{At 300 K, the kinematic viscosity for the air is: } \nu = 1.568E - 5 \text{ m}^2\text{s}^{-2} \text{ [1]}$$

$$\text{So } Re = \frac{UD}{\nu} = \frac{(1)(0.033)}{1.568E-5} = 2126 \text{ [1]}$$

This is smaller than 4000 so use [1]

$$Nu_D = 3.39, Re_D < 4000$$

b) To get the heat transfer coefficient we also need the thermal conductivity of the air at the film temperature.

$$k = 0.02624 \text{ W/mK [1]}$$

$$Nu_D = 3.39 = h \frac{D}{k} \rightarrow h = 3.39 \frac{k}{D} = \frac{3.39(0.0333)}{0.02624} = 4.3064 \text{ W/m}^2\text{K [2 marks]}$$

c) Surface area of leaf batteries is: [1]

$$A_s = (0.1 \times 0.05) \times 2 = 0.01 \text{ m}^2$$

The heat loss by convection at critical temperature is: [2]

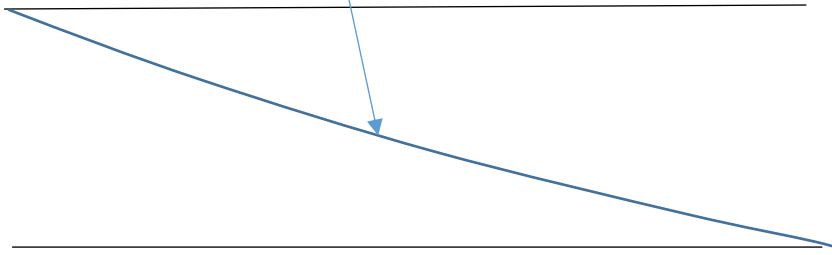
$$\dot{q} = hA(37 - 17) = 0.8613 \text{ W}$$

d) Not enough energy will be removed. This means that the batteries will increase in temperature until the correct heat flow is achieved. [2] This happens at [2]

$$\dot{q} = 1 \text{ W} = hA(T_f - T_a) \rightarrow T_f = T_a + \frac{1}{hA} = 40.22^\circ\text{C}$$

e)

Boundary layer grows. If it hits opposite wall, it will decrease the heat transfer past that point



In entrance flow, the heat being lost from the wall extends to the outside of the boundary layer. If the duct is long, then the boundary layers can reach the far side. At this point the air in contact with the opposing wall is hotter, so the temperature difference is smaller. Through Newtons law of cooling, decreasing the temperature difference, decreases the heat loss from that point on. [5 marks]

6. a) First set up equations

$$F_{11} + F_{12} = 1 \quad (1)$$

$$F_{21} + F_{22} = 1 \quad (2)$$

$$A_1 F_{12} = A_2 F_{21} \quad (3)$$

Then state known values

Inner area per unit length $A_1 = \pi 0.05 = 0.157 \text{ m}$

Outer area per unit length $A_2 = \pi 0.1 = 0.314 \text{ m}$

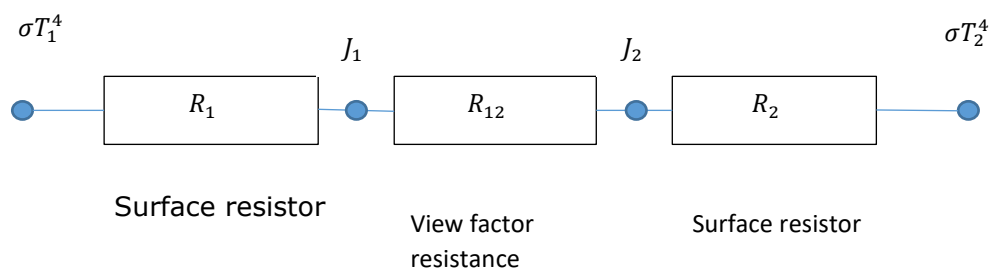
Surface 1 cannot see itself so $F_{11} = 0$

So (1) $\rightarrow F_{12} = 1$

(3) $\rightarrow F_{21} = \frac{A_1}{A_2} F_{12} \rightarrow F_{21} = 0.5$

(2) $\rightarrow F_{22} = 1 - F_{21} = 0.5$

So values are: $F_{11} = 0, F_{12} = 1, F_{21} = 0.5, F_{22} = 0.5$ [4 marks]



b) [7 marks] for correct labelling

c)

$$\dot{q} = \frac{\sigma T_1^4 - \sigma T_2^4}{R_1 + R_{12} + R_2}$$

$$R_1 = \frac{1 - \epsilon_1}{\epsilon_1 A_1} = \frac{1 - 0.8}{0.8(0.158)} = 1.59 \text{ m}^{-2}$$

$$R_2 = \frac{1 - \epsilon_2}{\epsilon_2 A_2} = \frac{1 - 0.3}{0.3(0.314)} = 7.43 \text{ m}^{-2}$$

$$R_{12} = \frac{1}{F_{12} A_1} = \frac{1}{0.157} = 6.36 \text{ m}^{-2}$$

$$\sigma T_1^4 = 5.67E - 8 (523)^4 = 4242 \text{ W/m}^2$$

$$\sigma T_2^4 = 5.67E - 8 (303)^4 = 478 \text{ W/m}^2$$

$$\dot{q} = \frac{4242 - 478}{1.59 + 6.36 + 7.43} = 245 \text{ W}$$

[7 marks]

- d) If the insulation became opaque, less would transmit through the material. Instead the radiation would interact with the insulation and heat it up close to the inner pipe. This would have the effect of decreasing the heat loss. [4 marks]

7. In a long fin, the heat through the root is $\dot{q} = \frac{kA d\theta}{dx}$

We also know $\theta = \theta_0 e^{-mx}$

Differentiate this leads to $\frac{d\theta}{dx} = -m \theta_0 e^{-mx}$ [2]

So $\dot{q} = -kA m \theta_0 e^{-mx}$ which at $x=0$ is $\dot{q} = -kA m \theta_0$. [2]

-ve sign is because θ_0 is -ve. Can cancel by switching temperature order.

Need fin shape parameter.

$$m = \sqrt{\frac{hP}{kA}} = \sqrt{\frac{11(0.0314)}{377(7.85E - 5)}} = 3.41 \text{ m}^{-1} \text{ [3]}$$

$$\dot{q} = 377(7.854E - 5)(150 - 25) = 12.6 \text{ W [2]}$$