

THE UNIVERSITY OF NOTTINGHAM

DEPARTMENT OF MECHANICAL, MATERIAL AND MANUFACTURING ENGINEERING

A LEVEL 3 MODULE, SPRING SEMESTER 2021-2022

**THERMOFLUIDS 3**

Time allowed TWO hours plus 30 minutes upload period

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***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]\_[MMME3081].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-Assess-Eng@exmail.nottingham.ac.uk](mailto:SS-Assess-Eng@exmail.nottingham.ac.uk) for support as indicated in your training.*

***Plagiarism, false authorship and collusion are serious academic offences*** as defined in the University's Academic Misconduct Policy and will be dealt with in accordance with the University's Academic Misconduct Procedures. By agreeing that you have completed the academic misconduct training accessible through the Moodle page you declare that work submitted is your own, that you understand the meaning of academic misconduct and that you have not engaged in it in the production of this work.

**ADDITIONAL MATERIAL:      Steam Tables, Formula Sheet**

### 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]

$\bar{h}$ [kJ/kmol]	$\bar{u}$ [kJ/kmol]	$\bar{s}^\circ$ [kJ/kmol K]	$\bar{g}^\circ$ [kJ/kmol]	$T$ [K]	$\bar{h}$ [kJ/kmol]	$\bar{u}$ [kJ/kmol]	$\bar{s}^\circ$ [kJ/kmol K]	$\bar{g}^\circ$ [kJ/kmol]
Hydrogen (H <sub>2</sub> )					Carbon Monoxide (CO)			
$\bar{m} = 2.016 \frac{\text{kg}}{\text{kmol}}$					$\bar{m} = 28.0105 \frac{\text{kg}}{\text{kmol}}$			
-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	-38231	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

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

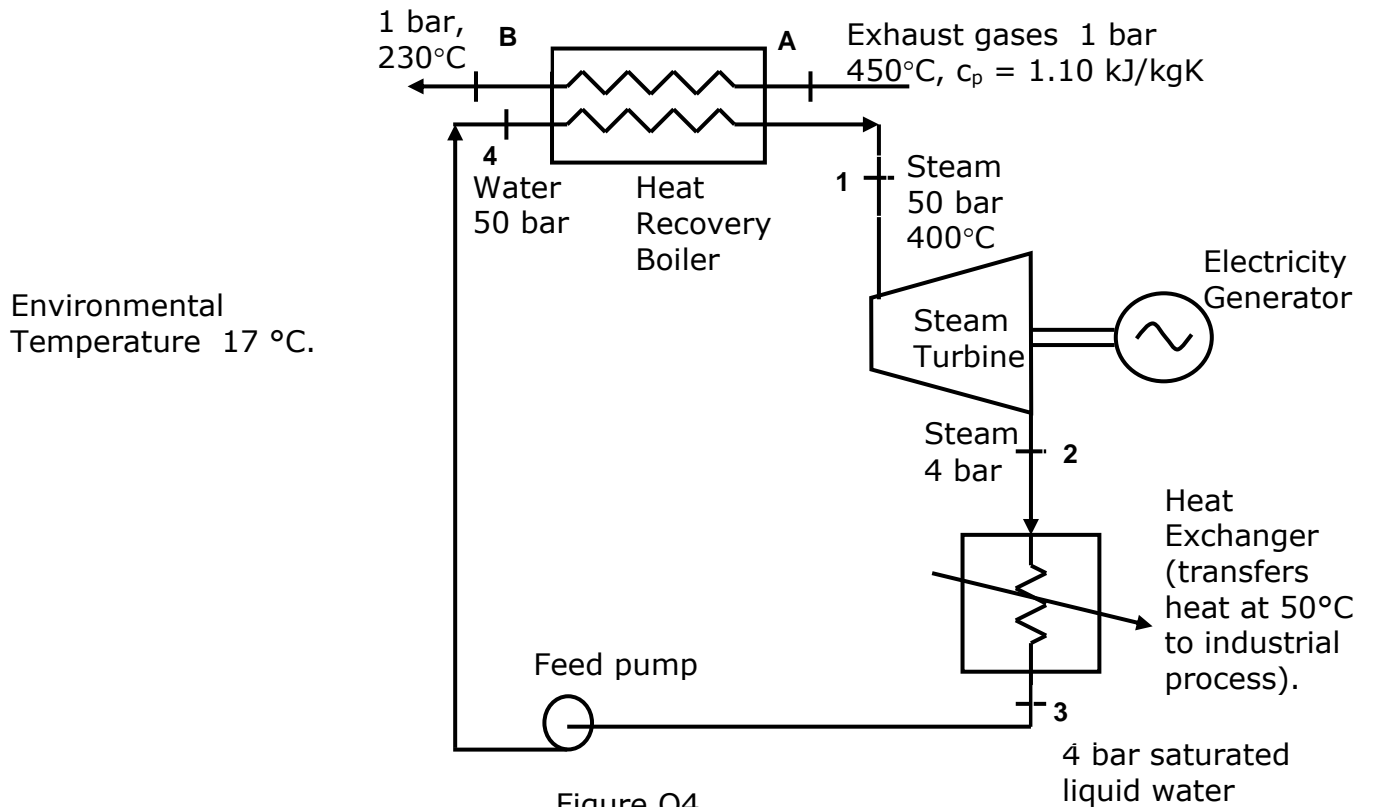
2. Explain the impact that the isentropic efficiency of less than 100% in the compressor and turbine of a gas turbine have on the performance compared to that of an ideal air cycle gas turbine. Draw a diagram to explain your answer. (Write no more than 150 words)

[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%.



*Continued on next page*

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

Cross-sectional area of duct formed between batteries.

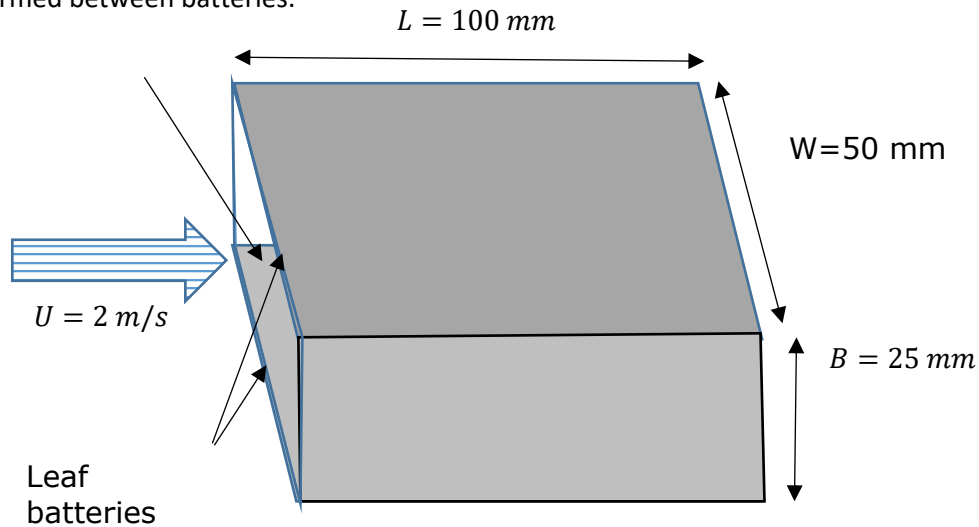


Figure Q5

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  $37^\circ\text{C}$  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  $17^\circ\text{C}$  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]

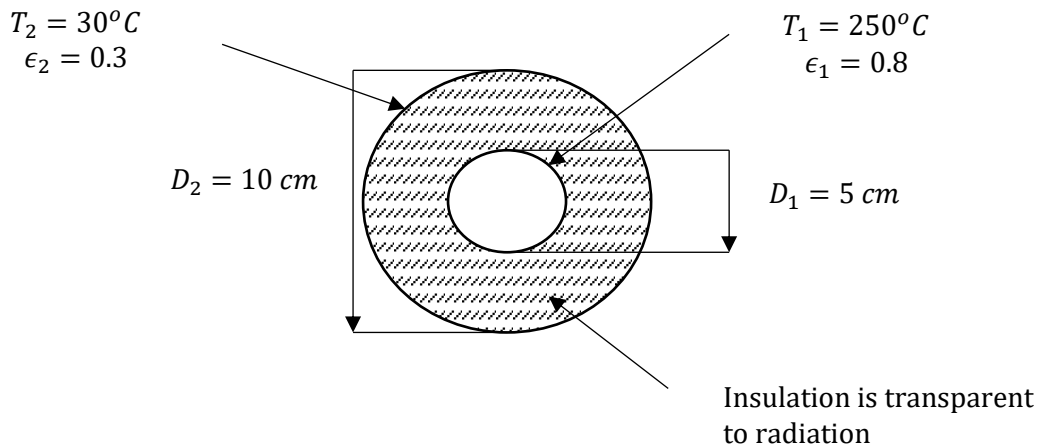


Figure Q6

6. The figure shows two concentric metal pipes. The inner one carries steam at  $250^\circ\text{C}$ , 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 metre 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  $T_a = T_{ID}^\circ\text{C}$ . The base of the rod is maintained at  $T_b = 150^\circ\text{C}$ . The heat transfer coefficient between the rod and the surrounding air is  $h = 11 \text{ W/m}^2\text{K}$ . 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  $T_a = 20 + 8 = 28^\circ\text{C}$

END