UNIVERSITY OF RUHUNA

Faculty of Engineering

End-Semester 4 Examination in Engineering: December 2022

Module Number: MN 4201 **Module Name: Applied Thermodynamics**

[Three Hours]

[Answer **Five Questions** only, each question carries **20** marks]

Instructions:

1. Required steam tables are provided.
2. Ideal gas properties of air are provided in Table 1.
3. One dimensional isentropic compressible flow data is provided in Table 2.
4. Start your answers to each question on a fresh page.

Q1 (a) What are the four processes of the ideal Otto cycle? Show the processes of the Otto cycle on a P-v and T-s diagram.

[4 Marks]

(b) An ideal Otto cycle has a compression ratio of 9. At the beginning of the compression process, air is at 100 kPa and 32°C, and 900 kJ/kg of heat is transferred to air during the constant-volume heat-addition process. Taking into account the variation of specific heats with temperature, determine the following,

(Note: Gas Constant R = 0.287 kJ/kgK)

i. The pressure and the temperature at the end of the heat-addition process

[4 Marks]

ii. The net work output

[4 Marks]

iii. The thermal efficiency

[4 Marks]

iv. The mean effective pressure (MEP).

[4 Marks]

Q2 (a) How does the ideal Diesel cycle differ from the ideal Otto cycle?

[4 Marks]

(b) Briefly explain the cutoff ratio? How does it affect the thermal efficiency of a Diesel cycle.

[4 Marks]

(c) An ideal diesel engine has a compression ratio of 20 and uses air as the working fluid. The state of air at the beginning of the compression process is 95 kPa and 20°C. Assume constant specific heats for air at room temperature.

Given that:

1. The following equation is valid for an isentropic process occurring between two states 1 and 2. The symbols T and v denote temperature (K) and specific volume (m^3/kg) respectively,

$$(T_2/T_1)=(v_1/v_2)^{(k-1)}$$

2. Cp = 1.005 kJ/kgK, Cv=0.718 kJ/kgK, k=1.4, R=0.287 kJ/kgK

If the maximum temperature in the cycle is not to exceed 2200 K, Calculate

i. the thermal efficiency

[6 Marks]

ii. the mean effective pressure (MEP).

[6 Marks]

Q3 (a) An ideal reheat Rankine cycle with water as the working fluid operates the boiler at 15,000 kPa, the reheater is at 2000 kPa, and the condenser is at 100 kPa. The temperature is 450°C at the entrance of the high-pressure and low-pressure turbines. The mass flow rate through the cycle is 1.74 kg/s. Determine the following,

i. Power used by the pumps

[3.0 Marks]

ii. Power produced by the cycle

[3.0 Marks]

iii. Rate of heat transfer in the reheater

[4.0 Marks]

iv. Thermal efficiency of the system

[4.0 Marks]

(b) State three (03) methods of increasing the thermal efficiency of a simple ideal Rankine Cycle. Provide a brief explanation for each of the stated methods.

[6.0 Marks]

Q4 (a) A stationary gas-turbine power plant operates on a simple ideal Brayton cycle with air as the working fluid. The air enters the compressor at 95 kPa and 290 K and the turbine at 760 kPa and 1100 K. Heat is transferred to air at a rate of 35,000 kJ/s. Assume variable specific heats and calculate the power delivered by this plant.

[8.0 Marks]

(b) Explain the term "back work ratio".

[4.0 Marks]

(c) Explain how the inefficiencies of the turbine and the compressor affect the following,

i. Back work ratio

[4.0 Marks]

ii. Thermal efficiency of a gas turbine engine

[4.0 Marks]

Q5 (a) Explain the terms "stagnation enthalpy" and "dynamic temperature".

[4.0 Marks]

(b) Can a shock wave develop in the converging section of a converging–diverging nozzle? Explain your answer.

[4.0 Marks]

(c) A converging nozzle has an exit area of $0.001 m^2$. Air enters the nozzle with negligible velocity at a pressure of 1.0 MPa and a temperature of 360 K. Assume that air behaves as an ideal gas and the process is isentropic.

Note: $k=1.4$, $R=0.287$ kJ/kgK

i. Calculate the critical pressure and critical temperature.

[3.0 Marks]

ii. Calculate the exit velocity if a back pressure of 500 kPa is applied at the exit of the converging nozzle.

[3.0 Marks]

iii. Calculate the mass flow rate through the converging nozzle.

[6.0 Marks]

Q6 (a) Ethane gas (C_2H_6) at 25°C is burned in a steady-flow combustion chamber at a rate of 5 kg/h with the stoichiometric amount of air, which is preheated to 500 K before entering the combustion chamber. An analysis of the combustion gases reveals that all the hydrogen in the fuel burns to H_2O but only 95 percent of the carbon burns to CO_2, the remaining 5 percent forms CO. The products leave the combustion chamber at 800 K.

Note: Molar mass of C_2H_6 is 30 kg/kmol. Enthalpy values are given in Table 3.

i. Write the theoretical combustion equation.

[3.0 Marks]

ii. Write the actual combustion equation.

[3.0 Marks]

iii. Calculate the rate of heat transfer from the combustion chamber.

[6.0 Marks]

(b) Explain the following,

i. Air to fuel ratio

[2.0 Marks]

ii. Equivalence ratio

[2.0 Marks]

(c) Provide a brief explanation of adiabatic flame temperature. Clearly state the factors affecting the adiabatic flame temperature and the conditions required to achieve the maximum adiabatic flame temperature.

[4.0 Marks]

Ideal-gas properties of air

T K	h kJ/kg	P_r	u kJ/kg	v_r	s° kJ/kg·K	T K	h kJ/kg	P_r	u kJ/kg	v_r	s° kJ/kg·K
200	199.97	0.3363	142.56	1707.0	1.29559	580	586.04	14.38	419.55	115.7	2.37348
210	209.97	0.3987	149.69	1512.0	1.34444	590	596.52	15.31	427.15	110.6	2.39140
220	219.97	0.4690	156.82	1346.0	1.39105	600	607.02	16.28	434.78	105.8	2.40902
230	230.02	0.5477	164.00	1205.0	1.43557	610	617.53	17.30	442.42	101.2	2.42644
240	240.02	0.6355	171.13	1084.0	1.47824	620	628.07	18.36	450.09	96.92	2.44356
250	250.05	0.7329	178.28	979.0	1.51917	630	638.63	19.84	457.78	92.84	2.46048
260	260.09	0.8405	185.45	887.8	1.55848	640	649.22	20.64	465.50	88.99	2.47716
270	270.11	0.9590	192.60	808.0	1.59634	650	659.84	21.86	473.25	85.34	2.49364
280	280.13	1.0889	199.75	738.0	1.63279	660	670.47	23.13	481.01	81.89	2.50985
285	285.14	1.1584	203.33	706.1	1.65055	670	681.14	24.46	488.81	78.61	2.52589
290	290.16	1.2311	206.91	676.1	1.66802	680	691.82	25.85	496.62	75.50	2.54175
295	295.17	1.3068	210.49	647.9	1.68515	690	702.52	27.29	504.45	72.56	2.55731
298	298.18	1.3543	212.64	631.9	1.69528	700	713.27	28.80	512.33	69.76	2.57277
300	300.19	1.3860	214.07	621.2	1.70203	710	724.04	30.38	520.23	67.07	2.58810
305	305.22	1.4686	217.67	596.0	1.71865	720	734.82	32.02	528.14	64.53	2.60319
310	310.24	1.5546	221.25	572.3	1.73498	730	745.62	33.72	536.07	62.13	2.61803
315	315.27	1.6442	224.85	549.8	1.75106	740	756.44	35.50	544.02	59.82	2.63280
320	320.29	1.7375	228.42	528.6	1.76690	750	767.29	37.35	551.99	57.63	2.64737
325	325.31	1.8345	232.02	508.4	1.78249	760	778.18	39.27	560.01	55.54	2.66176
330	330.34	1.9352	235.61	489.4	1.79783	780	800.03	43.35	576.12	51.64	2.69013
340	340.42	2.149	242.82	454.1	1.82790	800	821.95	47.75	592.30	48.08	2.71787
350	350.49	2.379	250.02	422.2	1.85708	820	843.98	52.59	608.59	44.84	2.74504
360	360.58	2.626	257.24	393.4	1.88543	840	866.08	57.60	624.95	41.85	2.77170
370	370.67	2.892	264.46	367.2	1.91313	860	888.27	63.09	641.40	39.12	2.79783
380	380.77	3.176	271.69	343.4	1.94001	880	910.56	68.98	657.95	36.61	2.82344
390	390.88	3.481	278.93	321.5	1.96633	900	932.93	75.29	674.58	34.31	2.84856
400	400.98	3.806	286.16	301.6	1.99194	920	955.38	82.05	691.28	32.18	2.87324
410	411.12	4.153	293.43	283.3	2.01699	940	977.92	89.28	708.08	30.22	2.89748
420	421.26	4.522	300.69	266.6	2.04142	960	1000.55	97.00	725.02	28.40	2.92128
430	431.43	4.915	307.99	251.1	2.06533	980	1023.25	105.2	741.98	26.73	2.94468
440	441.61	5.332	315.30	236.8	2.08870	1000	1046.04	114.0	758.94	25.17	2.96770
450	451.80	5.775	322.62	223.6	2.11161	1020	1068.89	123.4	776.10	23.72	2.99034
460	462.02	6.245	329.97	211.4	2.13407	1040	1091.85	133.3	793.36	23.29	3.01260
470	472.24	6.742	337.32	200.1	2.15604	1060	1114.86	143.9	810.62	21.14	3.03449
480	482.49	7.268	344.70	189.5	2.17760	1080	1137.89	155.2	827.88	19.98	3.05608
490	492.74	7.824	352.08	179.7	2.19876	1100	1161.07	167.1	845.33	18.896	3.07732
500	503.02	8.411	359.49	170.6	2.21952	1120	1184.28	179.7	862.79	17.886	3.09825
510	513.32	9.031	366.92	162.1	2.23993	1140	1207.57	193.1	880.35	16.946	3.11883
520	523.63	9.684	374.36	154.1	2.25997	1160	1230.92	207.2	897.91	16.064	3.13916
530	533.98	10.37	381.84	146.7	2.27967	1180	1254.34	222.2	915.57	15.241	3.15916
540	544.35	11.10	389.34	139.7	2.29906	1200	1277.79	238.0	933.33	14.470	3.17888
550	554.74	11.86	396.86	133.1	2.31809	1220	1301.31	254.7	951.09	13.747	3.19834
560	565.17	12.66	404.42	127.0	2.33685	1240	1324.93	272.3	968.95	13.069	3.21751
570	575.59	13.50	411.97	121.2	2.35531						
1260	1348.55	290.8	986.90	12.435	3.23638	1600	1757.57	791.2	1298.30	5.804	3.52364
1280	1372.24	310.4	1004.76	11.835	3.25510	1620	1782.00	834.1	1316.96	5.574	3.53879
1300	1395.97	330.9	1022.82	11.275	3.27345	1640	1806.46	878.9	1335.72	5.355	3.55381
1320	1419.76	352.5	1040.88	10.747	3.29160	1660	1830.96	925.6	1354.48	5.147	3.56867
1340	1443.60	375.3	1058.94	10.247	3.30959	1680	1855.50	974.2	1373.24	4.949	3.58335
1360	1467.49	399.1	1077.10	9.780	3.32724	1700	1880.1	1025	1392.7	4.761	3.5979
1380	1491.44	424.2	1095.26	9.337	3.34474	1750	1941.6	1161	1439.8	4.328	3.6336
1400	1515.42	450.5	1113.52	8.919	3.36200	1800	2003.3	1310	1487.2	3.994	3.6684
1420	1539.44	478.0	1131.77	8.526	3.37901	1850	2065.3	1475	1534.9	3.601	3.7023
1440	1563.51	506.9	1150.13	8.153	3.39586	1900	2127.4	1655	1582.6	3.295	3.7354
1460	1587.63	537.1	1168.49	7.801	3.41247	1950	2189.7	1852	1630.6	3.022	3.7677
1480	1611.79	568.8	1186.95	7.468	3.42892	2000	2252.1	2068	1678.7	2.776	3.7994
1500	1635.97	601.9	1205.41	7.152	3.44516	2050	2314.6	2303	1726.8	2.555	3.8303
1520	1660.23	636.5	1223.87	6.854	3.46120	2100	2377.7	2559	1775.3	2.356	3.8605
1540	1684.51	672.8	1242.43	6.569	3.47712	2150	2440.3	2837	1823.8	2.175	3.8901
1560	1708.82	710.5	1260.99	6.301	3.49276	2200	2503.2	3138	1872.4	2.012	3.9191
1580	1733.17	750.0	1279.65	6.046	3.50829	2250	2566.4	3464	1921.3	1.864	3.9474

Table 1 – Ideal Gas Properties of Air

One-dimensional isentropic compressible-flow functions for an ideal gas with $k = 1.4$

Ma	Ma*	A/A*	P/P_0	ρ/ρ_0	T/T_0
0	0	∞	1.0000	1.0000	1.0000
0.1	0.1094	5.8218	0.9930	0.9950	0.9980
0.2	0.2182	2.9635	0.9725	0.9803	0.9921
0.3	0.3257	2.0351	0.9395	0.9564	0.9823
0.4	0.4313	1.5901	0.8956	0.9243	0.9690
0.5	0.5345	1.3398	0.8430	0.8852	0.9524
0.6	0.6348	1.1882	0.7840	0.8405	0.9328
0.7	0.7318	1.0944	0.7209	0.7916	0.9107
0.8	0.8251	1.0382	0.6560	0.7400	0.8865
0.9	0.9146	1.0089	0.5913	0.6870	0.8606
1.0	1.0000	1.0000	0.5283	0.6339	0.8333
1.2	1.1583	1.0304	0.4124	0.5311	0.7764
1.4	1.2999	1.1149	0.3142	0.4374	0.7184
1.6	1.4254	1.2502	0.2353	0.3557	0.6614
1.8	1.5360	1.4390	0.1740	0.2868	0.6068
2.0	1.6330	1.6875	0.1278	0.2300	0.5556
2.2	1.7179	2.0050	0.0935	0.1841	0.5081
2.4	1.7922	2.4031	0.0684	0.1472	0.4647
2.6	1.8571	2.8960	0.0501	0.1179	0.4252
2.8	1.9140	3.5001	0.0368	0.0946	0.3894
3.0	1.9640	4.2346	0.0272	0.0760	0.3571
5.0	2.2361	25.000	0.0019	0.0113	0.1667
∞	2.2495	∞	0	0	0

Table 2 – One dimensional isentropic compressible flow functions for an ideal gas with k=1.4 for Question 5

Substance	$\bar{h}^o_f$ kJ/kmol	$\bar{h}_{500K}$ kJ/kmol	$\bar{h}_{298K}$ kJ/kmol	$\bar{h}_{800K}$ kJ/kmol
$C_2H_{6(g)}$	-84,680	-	-	-
O_2	0	14,770	8,682	24,523
N_2	0	14,581	8,669	23,714
H_2O	-241,820	-	9,904	27,896
CO	-110,530	-	8,669	23,844
CO_2	-393,520	-	9,364	32,179

Table 3 – Enthalpy values for Question 6