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MECHANICAL ENGINEERING
LRESE - Laboratory of Renewable Energy Sciences and Engineering

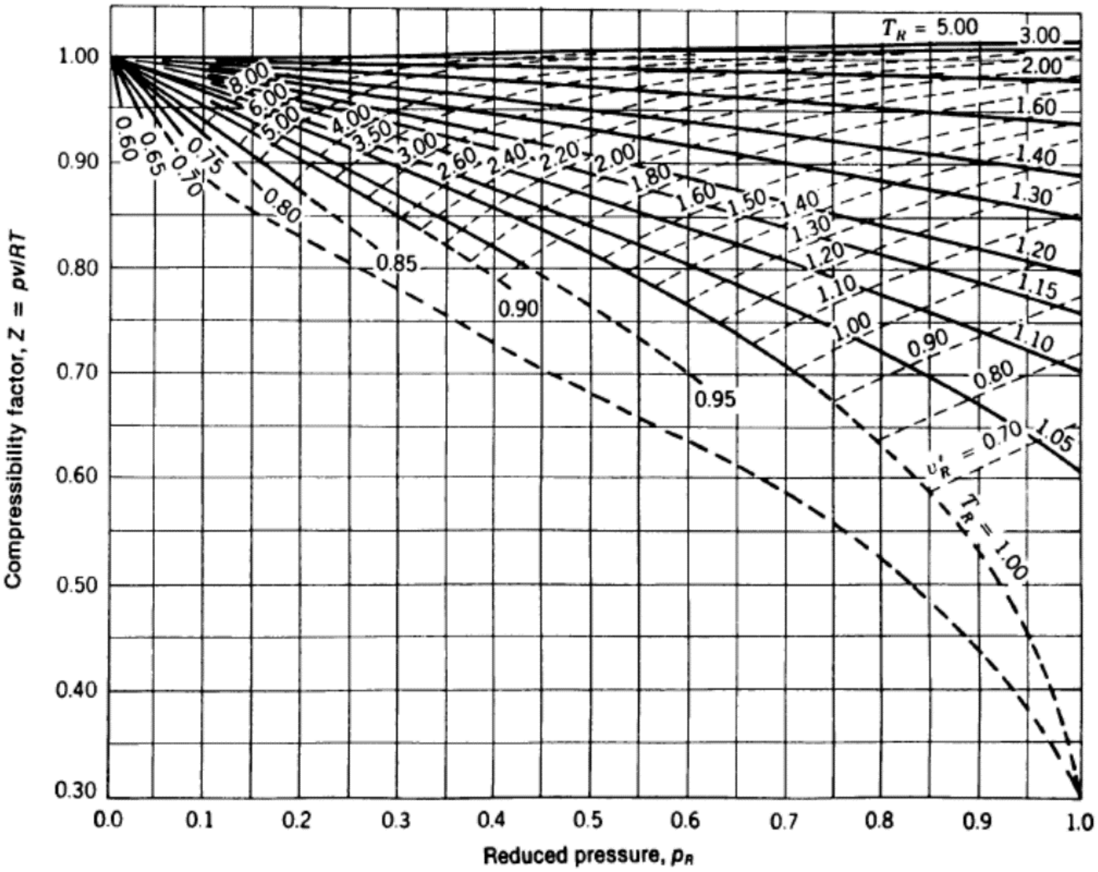
First Name: ________________ Last Name: ________________ Sciper: ________________

Thermodynamics and energetics I: Exam, Part I

Date: January 23, 2024
Duration: part I, 30 minutes
No documents allowed, calculator only. Answers on these sheets only.
Justify your answers with the relevant equations.
7 exercises - Total: [4.3125 points]

Part I, Exercise 1 [1 points]

Carbon dioxide (CO_2) is stored in a tank at 46.2 °C and 66.4 bar. The critical temperature and pressure of CO_2 are $T_C = 31$ °C and $p_C = 73.8$ bar.
Estimate from the chart below the compressibility factor of CO_2 in the tank. Can the gas in this state be accurately described by the ideal gas model? If not, which model would be more accurate?



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Part I, Exercise 2 [0.75 points]

Assume steady state in an adiabatic turbine. Explain if the specific entropy of the fluid increases, decreases or stays constant during:

1. a reversible expansion;
2. an irreversible expansion.

What is the sign of the work transfer rate in the two processes? In which case is the work transfer rate maximum?

Part I, Exercise 3 [0.5 point]

Write the formula of the exergy transfer by heat. In an evaporator of a refrigeration cycle, is the exergy provided to or extracted from the working fluid? Why?

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Part I, Exercise 4 [0.75 points]

Assume a reversible isobaric liquid-vapour phase change of a fluid in a closed system. Derive the relationship between the liquid-vapour specific enthalpy change ($h_\mathrm{g} - h_\mathrm{f}$) and specific entropy change ($s_\mathrm{g} - s_\mathrm{f}$) from the definition of enthalpy ($\mathrm{d}h = \mathrm{d}u + p\mathrm{d}v + v\mathrm{d}p$).

Part I, Exercise 5 [0.375 points]

We consider a vapour compression refrigeration cycle, working with a cold reservoir at 18 °C and ensuring the hot reservoir at 37 °C. The refrigeration capacity is 5 kJ/min and the work input is 1.5 kJ/min.
What is the COP of this cycle?

What is the best possible COP of this cycle?

If the refrigerant is changed (while everything else stayed the same), do you expect the best possible COP would change? Why? What approach would improve the best possible COP?

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Part I, Exercise 6 [0.625 points]
Draw the Ts-diagram of an
ideal vapour compression heat pump cycle:

Indicate three non-idealities that are present in a realistic vapour compression heat pump cycle.

What is a typical working fluid for such a cycle?

Is the COP of a heat pump operating with air as the cold reservoir higher, lower or equal if operated in summer or winter in a climate like Switzerland? Why?

Is the COP in winter higher, lower or equal if the cold reservoir is outside air or ground water? Why?

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Part I, Exercise 7 **[0.3125 points]**
What is the Joule-Thomson coefficient for an ideal gas?

For the real gas hydrogen, measurements were done via an isenthalpic expansion, giving inlet and outlet pressure and temperature of the expansion. How can this data be used to calculate the Joule-Thomson coefficient?

The Joule-Thomson coefficient is negative for hydrogen at these conditions. If you tank a fuel cell car with hydrogen, is the temperature therefore increasing or decreasing when filling the car? What are the implications for the filling process?

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Thermodynamics and energetics I: Exam, Part II

Date: January 23, 2024
Duration: part II, 2 hours 30 minutes
Allowed material: Calculator, personal summary (8 pages A4), and dictionary.
3 exercises - Total: 29.375 points.

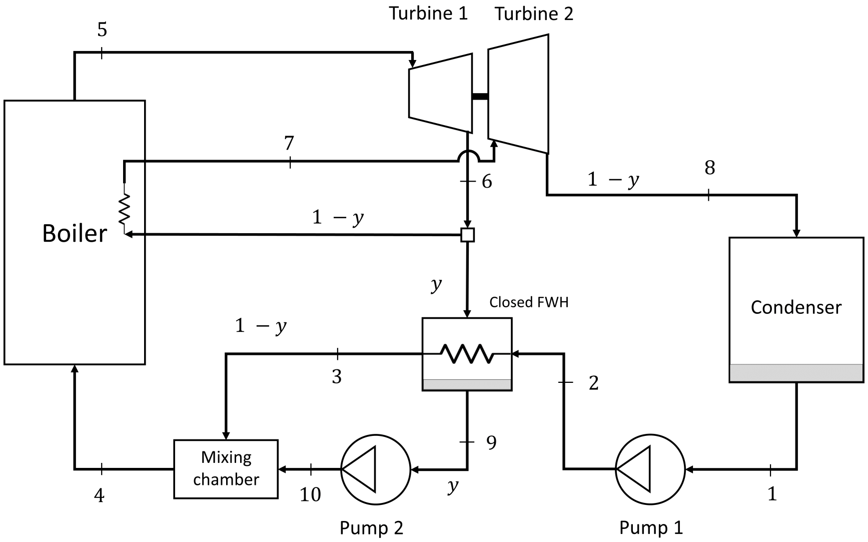
Exercise 1: Regenerative Rankine cycle [13.5 points]

A steam power plant with the layout reported below operates with a regenerative Rankine cycle with one closed feedwater heater (FWH) and reheating.

Steam enters in turbine 1 at 100 bar and 560°C. After the first expansion, the pressure of the fluid is 7 bar. A fraction of the total mass flow rate $y = \dot{m}_9/\dot{m}_{\text{tot}} = 0.15$ goes to the closed FWH and it is then pumped to 100 bar. The other fraction $(1 - y)$ is sent to reheat in the boiler up to 500°C. It then reaches turbine 2, where it expands up to 0.08 bar. After the condenser, the fluid is pumped up to 100 bar, it is heated in the other compartment of the FWH and it is then mixed with the other stream in a mixing chamber. Water leaves the FWH (State 9) and the condenser (State 1) as saturated liquid.

The two pumps of the system are driven by the output of the turbines. A heat transfer rate of 80 MW is provided to the boiler. Adiabatic expansions with isentropic efficiencies $\eta_{s,T1} = 100\%$ and $\eta_{s,T2} = 85\%$ can be assumed in turbines 1 and 2, respectively. Adiabatic compressions with isentropic efficiencies $\eta_{s,P1} = 90\%$ and $\eta_{s,P2} = 100\%$ can be assumed in pumps 1 and 2, respectively.

Assume steady state operation, neglect kinetic and potential energy variations as well as pressure drops in the system. Suppose that liquid water behaves as an incompressible substance with constant specific volume $v = 0.001$ m^3/kg.



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(a) Calculate the specific enthalpy of every state in the cycle. **[6.625 points]**

Feel free to use the following table as a support.

State	p [bar]	T [°C]	x [-]	h [kJ/kg]	s [kJ/(kg K)]
1	0.08				
2s	100				
2	100				
3	100				
4	100				
5	100	560			
6	7.00				
6s	7.00				
7	7.00	500			
8s	0.08				
8	0.08				
9	7.00				
10s	100				
10	100				

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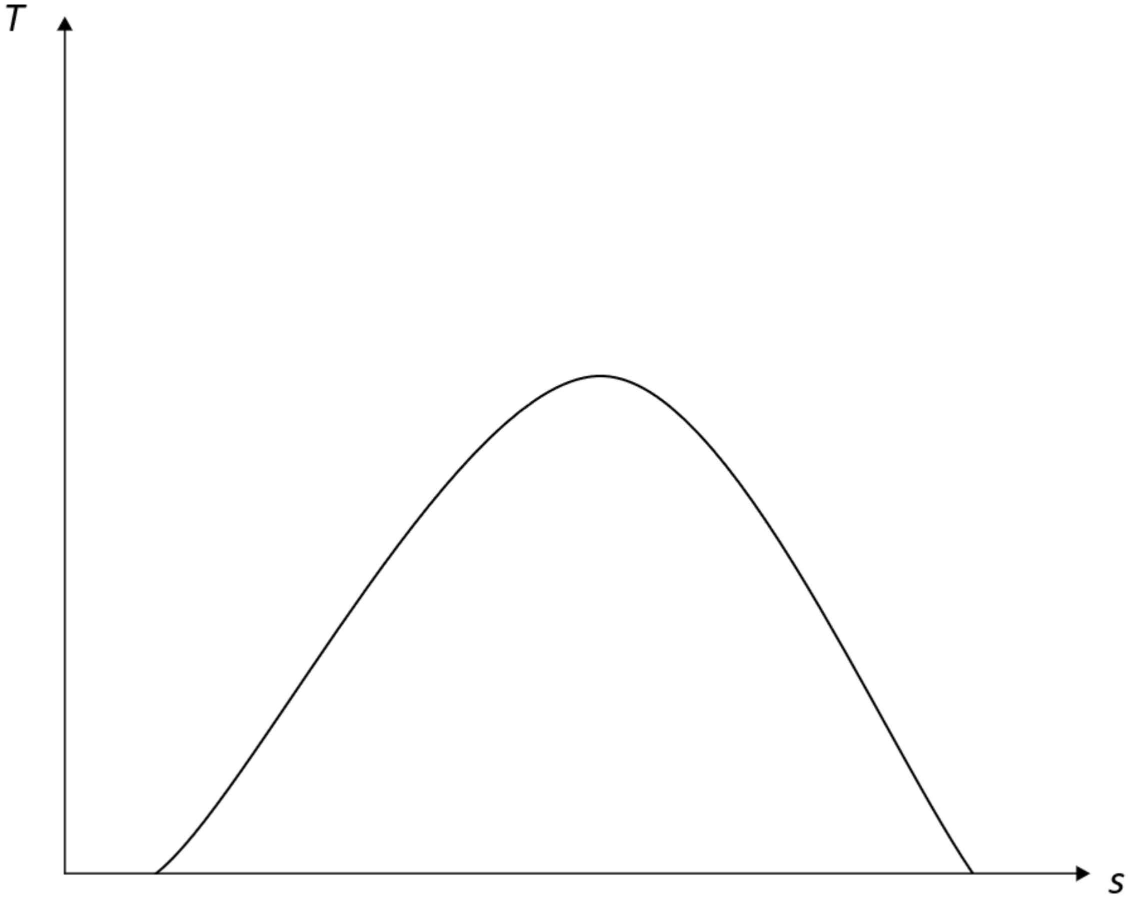
(b) Sketch the qualitative $T - s$ diagram of the cycle. **[3 points]**



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(c) Calculate the total mass flow rate in the system. **[0.625 points]**

(d) Calculate the work transfer rates of the turbines and of the pumps. **[1.75 points]**

(e) Calculate the thermal efficiency of the cycle. **[0.5 points]**

(f) Justify if a higher pressure of the condenser increases, decreases or does not modify the thermal efficiency of the cycle. **[0.5 points]**

(g) In absolute sign, is the exergy transfer by heat larger in the boiler or in the condenser? Why? **[0.5 points]**

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H_2O

TABLE A-3 Properties of Saturated Water (Liquid–Vapor): Pressure Table

		Specific Volume m^3/kg		Internal Energy kJ/kg		Enthalpy kJ/kg			Entropy kJ/kg · K		
Press. bar	Temp. °C	Sat. Liquid $v_f \times 10^3$	Sat. Vapor v_g	Sat. Liquid u_f	Sat. Vapor u_g	Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g	Sat. Liquid s_f	Sat. Vapor s_g	Press. bar
0.04	28.96	1.0040	34.800	121.45	2415.2	121.46	2432.9	2554.4	0.4226	8.4746	0.04
0.06	36.16	1.0064	23.739	151.53	2425.0	151.53	2415.9	2567.4	0.5210	8.3304	0.06
0.08	41.51	1.0084	18.103	173.87	2432.2	173.88	2403.1	2577.0	0.5926	8.2287	0.08
0.10	45.81	1.0102	14.674	191.82	2437.9	191.83	2392.8	2584.7	0.6493	8.1502	0.10
0.20	60.06	1.0172	7.649	251.38	2456.7	251.40	2358.3	2609.7	0.8320	7.9085	0.20
0.30	69.10	1.0223	5.229	289.20	2468.4	289.23	2336.1	2625.3	0.9439	7.7686	0.30
0.40	75.87	1.0265	3.993	317.53	2477.0	317.58	2319.2	2636.8	1.0259	7.6700	0.40
0.50	81.33	1.0300	3.240	340.44	2483.9	340.49	2305.4	2645.9	1.0910	7.5939	0.50
0.60	85.94	1.0331	2.732	359.79	2489.6	359.86	2293.6	2653.5	1.1453	7.5320	0.60
0.70	89.95	1.0360	2.365	376.63	2494.5	376.70	2283.3	2660.0	1.1919	7.4797	0.70
0.80	93.50	1.0380	2.087	391.58	2498.8	391.66	2274.1	2665.8	1.2329	7.4346	0.80
0.90	96.71	1.0410	1.869	405.06	2502.6	405.15	2265.7	2670.9	1.2695	7.3949	0.90
1.00	99.63	1.0432	1.694	417.36	2506.1	417.46	2258.0	2675.5	1.3026	7.3594	1.00
1.50	111.4	1.0528	1.159	466.94	2519.7	467.11	2226.5	2693.6	1.4336	7.2233	1.50
2.00	120.2	1.0605	0.8857	504.49	2529.5	504.70	2201.9	2706.7	1.5301	7.1271	2.00
2.50	127.4	1.0672	0.7187	535.10	2537.2	535.37	2181.5	2716.9	1.6072	7.0527	2.50
3.00	133.6	1.0732	0.6058	561.15	2543.6	561.47	2163.8	2725.3	1.6718	6.9919	3.00
3.50	138.9	1.0786	0.5243	583.95	2546.9	584.33	2148.1	2732.4	1.7275	6.9405	3.50
4.00	143.6	1.0836	0.4625	604.31	2553.6	604.74	2133.8	2738.6	1.7766	6.8959	4.00
4.50	147.9	1.0882	0.4140	622.25	2557.6	623.25	2120.7	2743.9	1.8207	6.8565	4.50
5.00	151.9	1.0926	0.3749	639.68	2561.2	640.23	2108.5	2748.7	1.8607	6.8212	5.00
6.00	158.9	1.1006	0.3157	669.90	2567.4	670.56	2086.3	2756.8	1.9312	6.7600	6.00
7.00	165.0	1.1080	0.2729	696.44	2572.5	697.22	2066.3	2763.5	1.9922	6.7080	7.00
8.00	170.4	1.1148	0.2404	720.22	2576.8	721.11	2048.0	2769.1	2.0462	6.6628	8.00
9.00	175.4	1.1212	0.2150	741.83	2580.5	742.83	2031.1	2773.9	2.0946	6.6226	9.00
10.0	179.9	1.1273	0.1944	761.68	2583.6	762.81	2015.3	2778.1	2.1387	6.5863	10.0
15.0	198.3	1.1539	0.1318	843.16	2594.5	844.84	1947.3	2792.2	2.3150	6.4448	15.0
20.0	212.4	1.1767	0.09963	906.44	2600.3	908.79	1890.7	2799.5	2.4474	6.3409	20.0
25.0	224.0	1.1973	0.07998	959.11	2603.1	962.11	1841.0	2803.1	2.5547	6.2575	25.0
30.0	233.9	1.2165	0.06668	1004.8	2604.1	1008.4	1795.7	2804.2	2.6457	6.1869	30.0
35.0	242.6	1.2347	0.05707	1045.4	2603.7	1049.8	1753.7	2803.4	2.7253	6.1253	35.0
40.0	250.4	1.2522	0.04978	1082.3	2602.3	1087.3	1714.1	2801.4	2.7964	6.0701	40.0
45.0	257.5	1.2692	0.04406	1116.2	2600.1	1121.9	1676.4	2798.3	2.8610	6.0199	45.0
50.0	264.0	1.2859	0.03944	1147.8	2597.1	1154.2	1640.1	2794.3	2.9202	5.9734	50.0
60.0	275.6	1.3187	0.03244	1205.4	2589.7	1213.4	1571.0	2784.3	3.0267	5.8892	60.0
70.0	285.9	1.3513	0.02737	1257.6	2580.5	1267.0	1505.1	2772.1	3.1211	5.8133	70.0
80.0	295.1	1.3842	0.02352	1305.6	2569.8	1316.6	1441.3	2758.0	3.2068	5.7432	80.0
90.0	303.4	1.4178	0.02048	1350.5	2557.8	1363.3	1378.9	2742.1	3.2858	5.6772	90.0
100.	311.1	1.4524	0.01803	1393.0	2544.4	1407.6	1317.1	2724.7	3.3596	5.6141	100.
110.	318.2	1.4886	0.01599	1433.7	2529.8	1450.1	1255.5	2705.6	3.4295	5.5527	110.

TABLE A-4 Properties of Superheated Water Vapor

p = 0.06 bar = 0.006 MPa (T_{sat} = 36.16°C)

T °C	v m^3/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
Sat.	23.739	2425.0	2567.4	8.3304
80	27.132	2487.3	2650.1	8.5804
120	30.219	2544.7	2726.0	8.7840
160	33.302	2602.7	2802.5	8.9693
200	36.383	2661.4	2879.7	9.1398
240	39.462	2721.0	2957.8	9.2982
280	42.540	2781.5	3036.8	9.4464
320	45.618	2843.0	3116.7	9.5859
360	48.696	2905.5	3197.7	9.7180
400	51.774	2969.0	3279.6	9.8435
440	54.851	3033.5	3362.6	9.9633
500	59.467	3132.3	3489.1	10.1336

p = 0.70 bar = 0.07 MPa (T_{sat} = 89.95°C)

T °C	v m^3/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
Sat.	2.365	2494.5	2660.0	7.4797
100	2.434	2509.7	2680.0	7.5341
120	2.571	2539.7	2719.6	7.6375
160	2.841	2599.4	2798.2	7.8279
200	3.108	2659.1	2876.7	8.0012
240	3.374	2719.3	2955.5	8.1611
280	3.640	2780.2	3035.0	8.3162
320	3.905	2842.0	3115.3	8.4504
360	4.170	2904.6	3196.5	8.5828
400	4.434	2968.2	3278.6	8.7086
440	4.698	3032.9	3361.8	8.8286
500	5.095	3131.8	3488.5	8.9991

p = 3.0 bar = 0.30 MPa (T_{sat} = 133.55°C)

T °C	v m^3/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
Sat.	0.606	2543.6	2725.3	6.9919
120				
160	0.651	2587.1	2782.3	7.1276
200	0.716	2650.7	2865.5	7.3115
240	0.781	2713.1	2947.3	7.4774
280	0.844	2775.4	3028.6	7.6299
320	0.907	2838.1	3110.1	7.7722
360	0.969	2901.4	3192.2	7.9061
400	1.032	2965.6	3275.0	8.0330
440	1.094	3030.6	3358.7	8.1538
500	1.187	3130.0	3486.0	8.3251
600	1.341	3300.8	3703.2	8.5892

p = 7.0 bar = 0.70 MPa (T_{sat} = 164.97°C)

T °C	v m^3/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
Sat.	0.2729	2572.5	2763.5	6.7080
180	0.2847	2599.8	2799.1	6.7880
200	0.2999	2634.8	2844.8	6.8865
240	0.3292	2701.8	2932.2	7.0641
280	0.3574	2766.9	3017.1	7.2233
320	0.3852	2831.3	3100.9	7.3697
360	0.4126	2895.8	3184.7	7.5063
400	0.4397	2960.9	3268.7	7.6350
440	0.4667	3026.6	3353.3	7.7571
500	0.5070	3126.8	3481.7	7.9299
600	0.5738	3298.5	3700.2	8.1956
700	0.6403	3476.6	3924.8	8.4391

p = 10.0 bar = 1.0 MPa (T_{sat} = 179.91°C)

T °C	v m^3/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
Sat.	0.1944	2583.6	2778.1	6.5865
200	0.2060	2621.9	2827.9	6.6940
240	0.2275	2692.9	2920.4	6.8817
280	0.2480	2760.2	3008.2	7.0465
320	0.2678	2826.1	3093.9	7.1962
360	0.2873	2891.6	3178.9	7.3349
400	0.3066	2957.3	3263.9	7.4651
440	0.3257	3023.6	3349.3	7.5883
500	0.3541	3124.4	3478.5	7.7622
540	0.3729	3192.6	3565.6	7.8720
600	0.4011	3296.8	3697.9	8.0290
640	0.4198	3367.4	3787.2	8.1290

p = 100 bar = 10.0 MPa (T_{sat} = 311.06°C)

T °C	v m^3/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
Sat.	0.01803	2544.4	2724.7	5.6141
320	0.01925	2588.8	2781.3	5.7103
360	0.02331	2729.1	2962.1	6.0060
400	0.02641	2832.4	3096.5	6.2120
440	0.02911	2922.1	3213.2	6.3805
480	0.03160	3005.4	3321.4	6.5282
520	0.03394	3085.6	3425.1	6.6622
560	0.03619	3164.1	3526.0	6.7864
600	0.03837	3241.7	3625.3	6.9029
640	0.04048	3318.9	3723.7	7.0131
700	0.04358	3434.7	3870.5	7.1687
740	0.04560	3512.1	3968.1	7.2670

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Exercise 2: Air-standard Otto Cycle **[9.5 points]**

At the beginning of the compression process of a cold air-standard Otto cycle, $p_1 = 1$ bar $T_1 = 295$ K, $V_1 = 500$ cm^3. The maximum temperature in the cycle is 2100 K and the compression ratio is 9. Assume the specific heat of air to be $c_p = 1.1$ kJ/(kg K) and its molar mass $M = 29$ g/mol. State 1 can be assumed to be at ambient pressure and temperature.

(a) Plot the qualitative $p - v$ and the $T - s$ diagram of the cycle. **[1 point]**

(b) Calculate the heat addition and the net work of the cycle. **[4.625 points]**

(c) Calculate the mean effective pressure. **[0.5 points]**

(d) Calculate the thermal efficiency. **[0.5 points]**

(e) Calculate the exergy efficiency of the cycle. **[2.25 points]**

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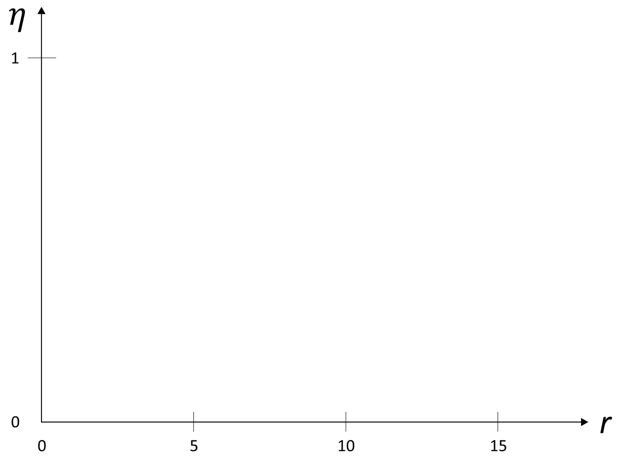
(f) Considering a general cold air-standard Otto cycle, qualitatively plot the thermal efficiency as a function of the compression ratio. **[0.625 points]**



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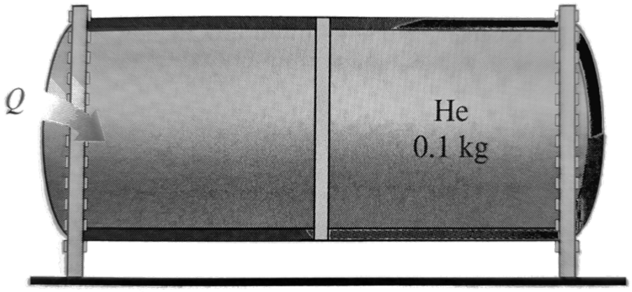
Exercise 3: Entropy generation in two-compartment cylinder [6.375 points]

A horizontal cylinder is separated into two compartments by an adiabatic, frictionless piston. One side contains 0.2 m^3 of nitrogen and the other contains 0.1 kg of helium, both initially at 20 °C and 95 kPa. The sides of the cylinder and the helium are insulated. Now heat is added to the nitrogen side from a reservoir at 500 °C until the pressure of the helium rises to 120 kPa. Assume that kinetic and potential energy changes are negligible and nitrogen and helium are ideal gases with constant specific heats at room temperature, i.e. c_{p,N_2}=1.039 kJ/(kg K), c_{v,N_2}=0.743 kJ/(kg K) and $c_{p,He}$=5.1926 kJ/(kg K), $c_{v,He}$=3.1156 kJ/(kg K). Also, M$_{N_2}$= 0.028 kg/mol and M$_{He}$= 0.004 kg/mol. Assume that the heat transfer occurs at 500 °C.



(a) Determine the final temperature of the helium. [1.75 point]

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(b) Determine the final volume of the nitrogen. **[1.375 point]**

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(c) Determine the heat transfer to the nitrogen. **[2.125 point]**

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(d) Determine the entropy generation during this process. **[1.125 point]**