Aalto University
School of Engineering

COE-C2007 Themodynamics, 2021

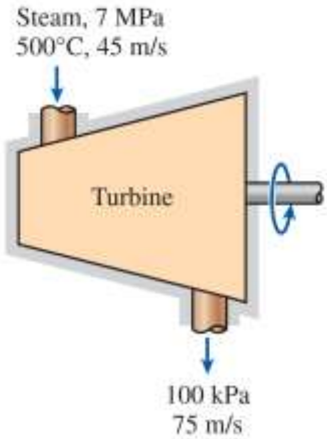
Learning Exercise 3

The exercise is to be completed independently (do not copy paste from other students) and returned as a single pdf report with appropriate use of pictures and charts, as well as presentation of used equations in possible calculations. Name the uploaded pdf-file so that it tells the course, learning exercise number and your name, like Thermodynamics_LE3_Lastname.pdf

No single question/problem is compulsory, but a minimum of 50 % of points is required in order to pass the exercise. Include also your name and student number on the first page of the report. A proper length of an answer per question would be maximum 1 page. The time for answering this exercise is estimated not to exceed 8 hours, provided that you have attended lectures.

Return DL of LE3: Friday February 4, 2022, 23:55, in MyCourses.

1. Steam enters an adiabatic turbine steadily at 7 MPa, 500°C, and 45 m/s and leaves at 100 kPa and 75 m/s. If the power output of the turbine is 5 MW and the isentropic efficiency is 77 percent, determine (a) the mass flow rate of steam through the turbine, (b) the temperature at the turbine exit, and (c) the rate of entropy generation during this process.? **(20 Points)**



A steam turbine for which the power output and the isentropic efficiency are given is considered. The mass flow rate of the steam, the temperature of the steam at the turbine exit, and the entropy generation are to be determined.

Assumptions:

1. Steady operating conditions exist.
2. Potential energy and kinetic energy changes are negligible.

Analysis

(a) The properties of the steam at the inlet of the turbine and the enthalpy at the exit for the isentropic case are can be found inTable A-6

TABLE A–6

Superheated water *(Continued)*

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg·K	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg·K	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg·K
	P = 4.0 MPa (250.35°C)				P = 4.5 MPa (257.44°C)				P = 5.0 MPa (263.94°C)			
Sat.	0.04978	2601.7	2800.8	6.0696	0.04406	2599.7	2798.0	6.0198	0.03945	2597.0	2794.2	5.9737
275	0.05461	2668.9	2887.3	6.2312	0.04733	2651.4	2864.4	6.1429	0.04144	2632.3	2839.5	6.0571
300	0.05887	2726.2	2961.7	6.3639	0.05138	2713.0	2944.2	6.2854	0.04535	2699.0	2925.7	6.2111
350	0.06647	2827.4	3093.3	6.5843	0.05842	2818.6	3081.5	6.5153	0.05197	2809.5	3069.3	6.4516
400	0.07343	2920.8	3214.5	6.7714	0.06477	2914.2	3205.7	6.7071	0.05784	2907.5	3196.7	6.6483
450	0.08004	3011.0	3331.2	6.9386	0.07076	3005.8	3324.2	6.8770	0.06332	3000.6	3317.2	6.8210
500	0.08644	3100.3	3446.0	7.0922	0.07652	3096.0	3440.4	7.0323	0.06858	3091.8	3434.7	6.9781
600	0.09886	3279.4	3674.9	7.3706	0.08766	3276.4	3670.9	7.3127	0.07870	3273.3	3666.9	7.2605
700	0.11098	3462.4	3906.3	7.6214	0.09850	3460.0	3903.3	7.5647	0.08852	3457.7	3900.3	7.5136
800	0.12292	3650.6	4142.3	7.8523	0.10916	3648.8	4140.0	7.7962	0.09816	3646.9	4137.7	7.7458
900	0.13476	3844.8	4383.9	8.0675	0.11972	3843.3	4382.1	8.0118	0.10769	3841.8	4380.2	7.9619
1000	0.14653	4045.1	4631.2	8.2698	0.13020	4043.9	4629.8	8.2144	0.11715	4042.6	4628.3	8.1648
1100	0.15824	4251.4	4884.4	8.4612	0.14064	4250.4	4883.2	8.4060	0.12655	4249.3	4882.1	8.3566
1200	0.16992	4463.5	5143.2	8.6430	0.15103	4462.6	5142.2	8.5880	0.13592	4461.6	5141.3	8.5388
1300	0.18157	4680.9	5407.2	8.8164	0.16140	4680.1	5406.5	8.7616	0.14527	4679.3	5405.7	8.7124
	P = 6.0 MPa (275.59°C)				P = 7.0 MPa (285.83°C)				P = 8.0 MPa (295.01°C)			
Sat.	0.03245	2589.9	2784.6	5.8902	0.027378	2581.0	2772.6	5.8148	0.023525	2570.5	2758.7	5.7450
300	0.03619	2668.4	2885.6	6.0703	0.029492	2633.5	2839.9	5.9337	0.024279	2592.3	2786.5	5.7937
350	0.04225	2790.4	3043.9	6.3357	0.035262	2770.1	3016.9	6.2305	0.029975	2748.3	2988.1	6.1321
400	0.04742	2893.7	3178.3	6.5432	0.039958	2879.5	3159.2	6.4502	0.034344	2864.6	3139.4	6.3658
450	0.05217	2989.9	3302.9	6.7219	0.044187	2979.0	3288.3	6.6353	0.038194	2967.8	3273.3	6.5579
500	0.05667	3083.1	3423.1	6.8826	0.048157	3074.3	3411.4	6.8000	0.041767	3065.4	3399.5	6.7266

$$\left.\begin{array}{r} P_1 = 7MPa \\ T_1 = 500°\mathrm{C} \end{array}\right\} \gg \left\{\begin{array}{l} h_1 = ? \\ s_1 = ? \end{array}\right.$$

$$\left.\begin{array}{r} P_2 = 100kPa \\ s_{2s} = s_1 = ? \end{array}\right\} \gg \{h_{2s} = 2466.6\mathrm{kJ/kg}$$

the power output if the expansion was isentropic would be

$$\dot{W}_s = \frac{\dot{W}_a}{\eta_T}$$

An energy balance on the turbine for the isentropic process may be used to determine the mass flow rate of the steam

$$\dot{m}\left(h_1 + \frac{V_1^2}{2}\right) = \dot{m}\left(h_{2s} + \frac{V_2^2}{2}\right) + \dot{W}_s$$

Substituting,

$$\dot{m} = ?$$

(b) An energy balance on the turbine for the actual process may be used to determine actual enthalpy at the exit

$$\dot{m}\left(h_1 + \frac{V_1^2}{2}\right) = \dot{m}\left(h_2 + \frac{V_2^2}{2}\right) + \dot{W}_a$$

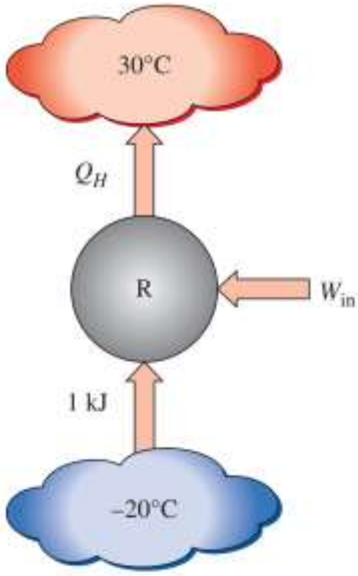
Now, other properties at the exit state may be obtained

$$\left.\begin{array}{r} P_2 = 100\ kPa \\ h_2 = ? \end{array}\right\} \gg \left\{\begin{array}{l} T_2 = 103.7°\mathrm{C} \\ s_2 = 7.3817kJ/kg.K \end{array}\right.$$

(c) Since the turbine is adiabatic, the entropy generation is the entropy change of steam as it flows in the turbine

$$\dot{S}_{gen} = \dot{m}(s_2 - s_1)$$

2. A refrigerator with a coefficient of performance of 4 transfers heat from a cold region at –20°C to a hot region at 30°C. Calculate the total entropy change of the regions when 1 kJ of heat is transferred from the cold region. Is the second law satisfied? Will this refrigerator still satisfy the second law if its coefficient of performance is 6? **(20 Points)**



The source and sink temperature and the COP of a refrigerator are given. The total entropy change of the two reservoirs is to be calculated and it is to be determined if this refrigerator satisfies the second law.

Assumptions

The refrigerator operates steadily

Analysis

Combing the first law and the definition of the coefficient of performance produces

$$Q_H = Q_L\left(1 + \frac{1}{COP_R}\right)$$

When COP=4, the entropy change of everything is then

$$\Delta S_{total} = \Delta S_H + \Delta S_L = \left(\frac{Q_H}{T_H}\right) + \left(\frac{Q_L}{T_L}\right)$$

Since the entropy increases, a refrigerator with COP=4, ?.

When the coefficient of performance is increased to 6,

$$Q_H = Q_L\left(1 + \frac{1}{COP_R}\right)$$

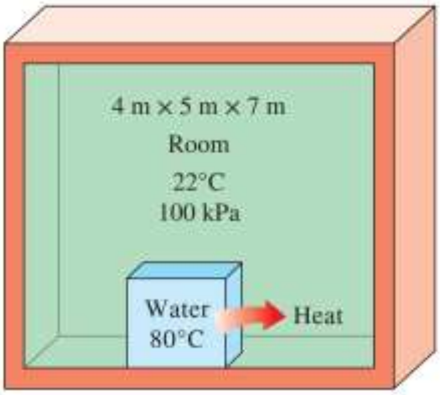
and the net entropy change is

$$\Delta S_{total} = \Delta S_H + \Delta S_L = \left(\frac{Q_H}{T_H}\right) + \left(\frac{Q_L}{T_L}\right)$$

and the refrigerator can no longer be possible.

Because this total entropy change is negative which is violate with the entropy increase principle.

3. One ton of liquid water at 80°C is brought into a well-insulated and well-sealed 4-m × 5-m × 7-m room initially at 22°C and 100 kPa. Assuming constant specific heats for both air and water at room temperature, determine (a) the final equilibrium temperature in the room and (b) the total entropy change during this process, in kJ/K. **(20 Points)**



One ton of liquid water at 80 °C is brought into a room. The final equilibrium temperature in the room and the entropy change during this process are to be determined.

Assumptions

1. The room is well insulated and well sealed.
2. The thermal properties of water and air are constant at room temperature
3. The system is stationary and thus the kinetic and potential energy changes are zero
4. There are no work interactions involved.

Properties

The gas constant of air is R=0.287kPa.m^3/kg.K (Table A-1). The specific heat of water at room temperature is c= 4.18kJ/kg.°C (table A-3). For air is c_v=0.718kJ/kg.°C at room temperature.

Analysis

(a) The volume and the mass of the air in the room are:

$$V_1 = Length * Width * Height$$

$$m_{air} = \frac{P_1 V_1}{RT_1}$$

Taking the contents of the room, including the water, as our system, the energy balance can be written as.

$$E_{in} - E_{out} = \Delta E_{system}$$

$$0 = \Delta U = \Delta U_{water} + \Delta U_{air}$$

or

$$[mc(T_2 - T_1)]_{water} + [mc_v(T_2 - T_1)]_{air} = 0$$

Substituting,

$$T_2 = ?$$

It gives the final equilibrium temperature in the room to be

$$T_2 = ?$$

(b) Considering that the system is well-insulated and no mass is entering and leaving, the total entropy during this process is the sum of the entropy changes of water and room air.

$$\Delta S_{total} = \Delta S_{gen} = \Delta S_{air} + \Delta S_{water}$$

Where

$$\Delta S_{air} = mc_v ln\left(\frac{T_2}{T_1}\right) + mRln\left(\frac{V_2}{V_1}\right)$$

$$\Delta S_{water} = mcln\left(\frac{T_2}{T_1}\right)$$

Substituting, the total entropy change is determined to be

$$\Delta S_{total} = ?$$

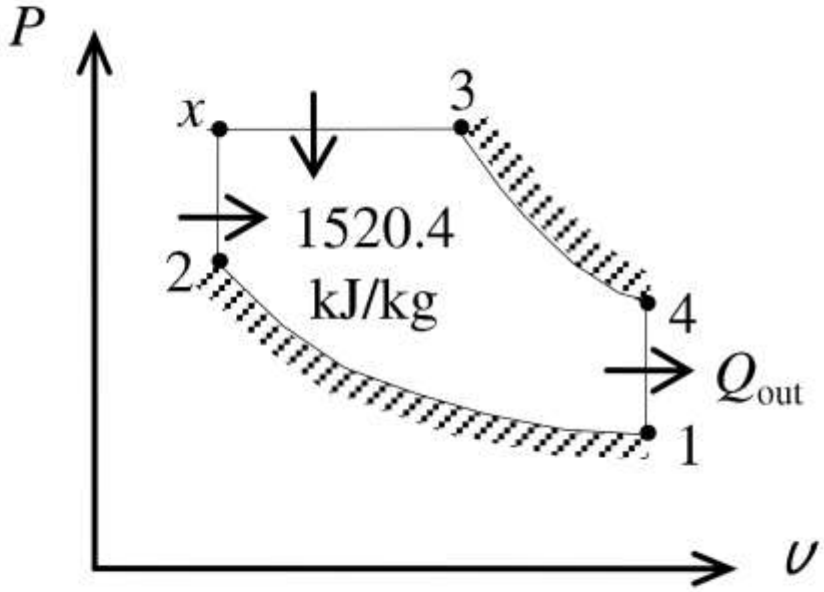
4. The compression ratio of an ideal dual cycle is 14. Air is at 100 kPa and 300 K at the beginning of the compression process and at 2200 K at the end of the heat-addition process.

Heat transfer to air takes place partly at constant volume and partly at constant pressure, and it amounts to 1520.4 kJ/kg. Assuming variable specific heats for air, determine (a) the fraction of heat transferred at constant volume and (b) the thermal efficiency of the cycle. (c) Comparing the thermal efficiency if varying the compression ratio from 12 to16 (12, 13, 14, 15, 16). **(20 Points)**

An ideal dual cycle with air as the working fluid has a compression ratio of 14. The fraction of heat transferred at constant volume and the thermal efficiency of the cycle to be determined.

Assumptions

1. The air-standard assumptions are applicable.
2. Kinetic and potential energy changes are negligible
3. Air is an ideal gas with variable specific heats.



Properties

The properties of AIR are given in Table A-17

TABLE A-17

Ideal-gas properties of air

T K	h kJ/kg	P_r	u kJ/kg	υ_r	s° kJ/kg·K	T K	h kJ/kg	P_r	u kJ/kg	υ_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

TABLE A–17

Ideal-gas properties of air *(Concluded)*

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
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

Analysis

(a) Process 1-2: isentropic compression

$$T_1 = 300K \rightarrow \begin{cases} u_1 = 214.07kJ/kg \\ v_1 = 621.2 \end{cases}$$

$$v_{r2} = \frac{v_2}{v_1} v_{r1} \rightarrow \begin{cases} T_2 = 823.1K \\ u_2 = 611.2kJ/kg \end{cases} \; here \; \frac{v_2}{v_1} = compression\,ratio$$

think about if we change the compression ratio from 12 to 16 (e.g., 12, 13, 14, 15, 16) how does the compression ratio affects the value.

process 2-x, x-3: heat addition

$$T_3 = 2200K \rightarrow \begin{cases} h_3 = 2503.2kJ/kg \\ v_{r3} = 2.012 \end{cases}$$

$$q_{in} = q_{x-2,in} + q_{3-x,in} = (u_x - u_2) + (h_3 - h_x)$$

Here $q_{in} = 1520.4\ kJ/kg, u_2 = 611.2kJ/kg, h_3 = 2503.2kJ/kg$

Therefore $h_x - u_x = 371.6\ kJ/kg,$

check the table A-17, the value at $T_x = 1300K$ is satisfying the requirement

$$h_x = 1395.97, u_x = 1022.82kJ/kg$$

Thus,

$$q_{x-2,in} = u_x - u_2 = ?$$

and

$$fraction\ of\ heat\ transfer = \frac{q_{x-2,in}}{q_{in}}$$

(b) Based on the idea gas equation

$$\frac{P_3 v_3}{T_3} = \frac{P_x v_x}{T_x} \rightarrow \frac{v_3}{v_x} = \frac{T_3}{T_x} = r_c$$

here r_c is the compression ratio

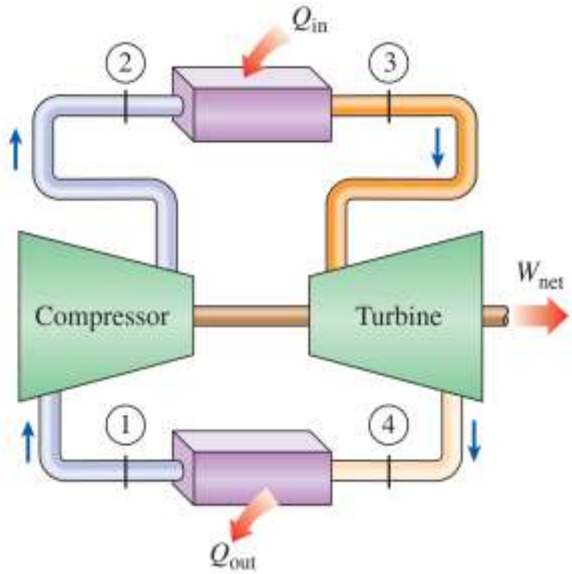
$$v_{r4} = \frac{v_4}{v_3} v_{r3} = \frac{v_4}{r_c * v_2} v_{r3} = \frac{r}{r_c} v_{r3}$$

Process 4-1: $v = constant\ heat\ rejection$

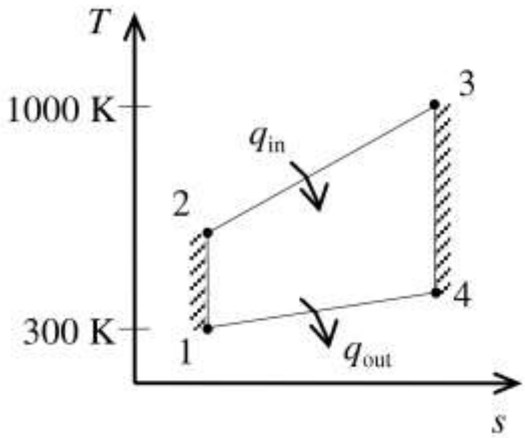
$$q_{out} = u_4 - u_1 = ?$$

$$\eta_{th} = 1 - \frac{q_{out}}{q_{in}}$$

5. A simple ideal Brayton cycle operates with air with minimum and maximum temperatures of 27°C and 727°C. It is designed so that the maximum cycle pressure is 2000 kPa and the minimum cycle pressure is 100 kPa. Determine the net work produced per unit mass of air each time this cycle is executed and the cycle's thermal efficiency. Use constant specific heats at room temperature. **(20 Points)**



A simple ideal Brayton cycle with air as the working fluid operates between the specified temperature and pressure limits. The net work and the thermal efficiency are to be determined.



Assumption

1. Steady operating conditions exits.
2. The air-standard assumptions are applicable
3. Kinetical and potential energy changes are negligible

4. Air is an ideal gas with constant specific heats

Properties

The properties of air at room temperature are cp=1.005kJ/kg.K and k=1.4 (Table A-2a)

Analysis

Using the isentropic relations for an ideal gas,

$$T_2 = T_1 \left(\frac{P_2}{P_1}\right)^{(k-1)/k}$$

Similarly,

$$T_4 = T_3 \left(\frac{P_4}{P_3}\right)^{(k-1)/k}$$

Applying the first law to the constant-pressure heat addition process 2-3 produces

$$q_{in} = (h_3 - h_2) = c_p(T_3 - T_2)$$

Similarly,

$$q_{out} = (h_4 - h_1) = c_p(T_4 - T_1)$$

The net work production is then

$$w_{net} = q_{in} - q_{out} =$$

and the thermal efficiency of this cycle is

$$\eta_{th} = \frac{w_{net}}{q_{in}}$$

6. **Your free feedback on the third weeks and time spent on this learning exercise.** (This does not affect the grading)