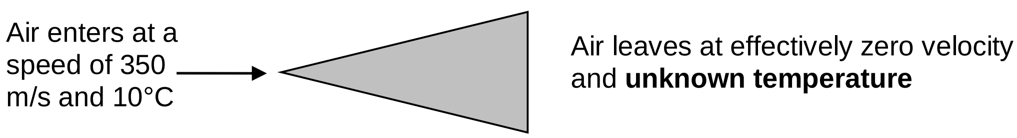
Tutorial Sheet 8: Diagrams and flow processes

1. A steam turbine operates at steady-state with inlet conditions of 6 bar and 250°C. The steam leaves the turbine at two possible pressures depending on the circumstances:

(a) 3 bar (b) 1 bar

For each pressure, calculate the work produced (*W*) per kg of steam passing through the turbine. You may ignore heat transfer (*Q*) between the system (steam) and surroundings and you may assume that the turbine operates **isentropically**. Changes in the kinetic and potential energy can be ignored. You will need **Steam Tables** to carry out these calculations.

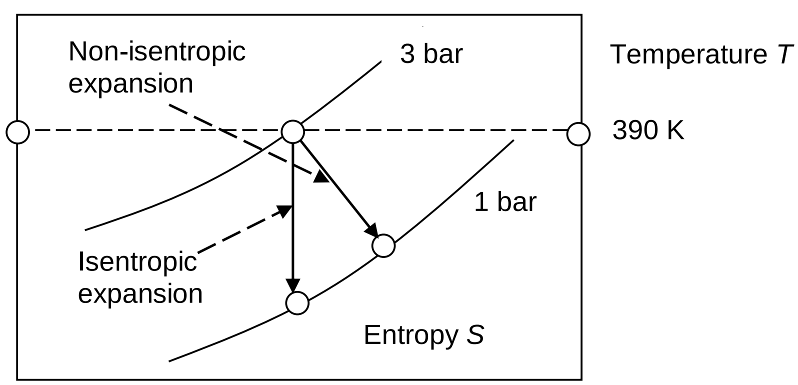
2. A **diffuser** is a simple device for converting kinetic energy into internal energy (and enthalpy) by changing the cross-sectional area through which the fluid flows.



The intake to the engine of a jet consists of a diffuser that must reduce the air velocity to zero so that it can enter a compressor. An aeroplane is travelling at an altitude where the temperature is 10°C, and the cruising speed is 350 m/s.

Write down the general form of the First Law for steady-flow systems, including the kinetic and potential energy terms. Use this to calculate the temperature of the air leaving the diffuser. Consider a constant c_P of 1.005 kJ/kgK for air.

3. An expander/turbine operating at steady-state has an inlet supply of nitrogen at a pressure of 3 bar, and a temperature of 390 K. The nitrogen leaves the turbine at a pressure of 1 bar. The work produced by the turbine is measured as 2140 kJ/kmol. The turbine operates **adiabatically** and changes in kinetic and potential energy can be **neglected**. For nitrogen, the value of c_P can be taken as **constant** over the operating range: $c_P = \frac{7}{2}R$



(a) Show that the entropy change (ΔS) (assuming constant C_P) between states 1 and 2 is:

$$\Delta S = C_P \ln(T_2/T_1) - nR\ln(P_2/P_1)$$

and use this to calculate the **outlet temperature** for an isentropic process.

(b) Calculate Δh for the **isentropic process** and show that the efficiency of the real turbine is close to 70%.

P/kPa (t^{sat}/°C)		sat. liq.	sat. vap.	TEMPERATURE: t °C (TEMPERATURE: T kelvins) 75 (348.15)	100 (373.15)	125 (398.15)	150 (423.15)	175 (448.15)	200 (473.15)	225 (498.15)	250 (523.15)
	V	1.000	129200.	160640.	172180.	183720.	195270.	206810.	218350.	229890.	241430.
1	U	29.334	2385.2	2480.8	2516.4	2552.3	2588.5	2624.9	2661.7	2698.8	2736.3
(6.98)	H	29.335	2514.4	2641.5	2688.6	2736.0	2783.7	2831.7	2880.1	2928.7	2977.7
	S	0.1060	8.9767	9.3828	9.5136	9.6365	9.7527	9.8629	9.9679	10.0681	10.1641
	V	1.010	14670.	16030.	17190.	18350.	19510.	20660.	21820.	22980.	24130.
10	U	191.822	2438.0	2479.7	2515.6	2551.6	2588.0	2624.5	2661.4	2698.6	2736.1
(45.83)	H	191.832	2584.8	2640.0	2687.5	2735.2	2783.1	2831.2	2879.6	2928.4	2977.4
	S	0.6493	8.1511	8.3168	8.4486	8.5722	8.6888	8.7994	8.9045	9.0049	9.1010
	V	1.017	7649.8	8000.0	8584.7	9167.1	9748.0	10320.	10900.	11480.	12060.
20	U	251.432	2456.9	2478.4	2514.6	2550.9	2587.4	2624.1	2661.0	2698.3	2735.8
(60.09)	H	251.453	2609.9	2638.4	2686.3	2734.2	2782.3	2830.6	2879.2	2928.0	2977.1
	S	0.8321	7.9094	7.9933	8.1261	8.2504	8.3676	8.4785	8.5839	8.6844	8.7806
	V	1.022	5229.3	5322.0	5714.4	6104.6	6493.2	6880.8	7267.5	7653.8	8039.7
30	U	289.271	2468.6	2477.1	2513.6	2550.2	2586.8	2623.6	2660.7	2698.0	2735.6
(69.12)	H	289.302	2625.4	2636.8	2685.1	2733.3	2781.6	2830.0	2878.7	2927.6	2976.8
	S	0.9441	7.7695	7.8024	7.9363	8.0614	8.1791	8.2903	8.3960	8.4967	8.5930
	V	1.027	3993.4	....	4279.2	4573.3	4865.8	5157.2	5447.8	5738.0	6027.7
40	U	317.609	2477.1	....	2512.6	2549.4	2586.2	2623.2	2660.3	2697.7	2735.4
(75.89)	H	317.650	2636.9	....	2683.8	2732.3	2780.9	2829.5	2878.2	2927.2	2976.5
	S	1.0261	7.6709	....	7.8009	7.9268	8.0450	8.1566	8.2624	8.3633	8.4598
	V	1.030	3240.2	....	3418.1	3654.5	3889.3	4123.0	4356.0	4588.5	4820.5
50	U	340.513	2484.0	....	2511.7	2548.6	2585.6	2622.7	2659.9	2697.4	2735.1
(81.35)	H	340.564	2646.0	....	2682.6	2731.4	2780.1	2828.9	2877.7	2926.8	2976.1
	S	1.0912	7.5947	....	7.6953	7.8219	7.9406	8.0526	8.1587	8.2598	8.3564
	V	1.037	2216.9	....	2269.8	2429.4	2587.3	2744.2	2900.2	3055.8	3210.9
75	U	384.374	2496.7	....	2509.2	2546.7	2584.2	2621.6	2659.0	2696.7	2734.5
(91.79)	H	384.451	2663.0	....	2679.4	2728.9	2778.2	2827.4	2876.6	2925.8	2975.3
	S	1.2131	7.4570	....	7.5014	7.6300	7.7500	7.8629	7.9697	8.0712	8.1681
	V	1.043	1693.7	....	1695.5	1816.7	1936.3	2054.7	2172.3	2289.4	2406.1
100	U	417.406	2506.1	....	2506.6	2544.8	2582.7	2620.4	2658.1	2695.9	2733.9
(99.63)	H	417.511	2675.4	....	2676.2	2726.5	2776.3	2825.9	2875.4	2924.9	2974.5
	S	1.3027	7.3598	....	7.3618	7.4923	7.6137	7.7275	7.8349	7.9369	8.0342
	V	1.044	1673.0	....	1673.0	1792.7	1910.7	2027.7	2143.8	2259.3	2374.5
101.325	U	418.959	2506.5	....	2506.5	2544.7	2582.6	2620.4	2658.1	2695.9	2733.9
(100.00)	H	419.064	2676.0	....	2676.0	2726.4	2776.2	2825.8	2875.3	2924.8	2974.5
	S	1.3069	7.3554	....	7.3554	7.4860	7.6075	7.7213	7.8288	7.9308	8.0280
	V	1.049	1374.6	....	....	1449.1	1545.6	1641.0	1735.6	1829.6	1923.2
125	U	444.224	2513.4	....	....	2542.9	2581.2	2619.3	2657.2	2695.2	2733.3
(105.99)	H	444.356	2685.2	....	....	2724.0	2774.4	2824.4	2874.2	2923.9	2973.7
	S	1.3740	7.2847	....	....	7.3844	7.5072	7.6219	7.7300	7.8324	7.9300
	V	1.053	1159.0	....	....	1204.0	1285.2	1365.2	1444.4	1523.0	1601.3
150	U	466.968	2519.5	....	....	2540.9	2579.7	2618.1	2656.3	2694.4	2732.7
(111.37)	H	467.126	2693.4	....	....	2721.5	2772.5	2822.9	2872.9	2922.9	2972.9
	S	1.4336	7.2234	....	....	7.2953	7.4194	7.5352	7.6439	7.7468	7.8447
	V	1.057	1003.34	....	....	1028.8	1099.1	1168.2	1236.4	1304.1	1371.3
175	U	486.815	2524.7	....	....	2538.9	2578.2	2616.9	2655.3	2693.7	2732.1
(116.06)	H	487.000	2700.3	....	....	2719.0	2770.5	2821.3	2871.7	2921.9	2972.0
	S	1.4849	7.1716	....	....	7.2191	7.3447	7.4614	7.5708	7.6741	7.7724
	V	1.061	885.44	....	....	897.47	959.54	1020.4	1080.4	1139.8	1198.9
200	U	504.489	2529.2	....	....	2536.9	2576.6	2615.7	2654.4	2692.9	2731.4
(120.23)	H	504.701	2706.3	....	....	2716.4	2768.5	2819.8	2870.5	2920.9	2971.2
	S	1.5301	7.1268	....	....	7.1523	7.2794	7.3971	7.5072	7.6110	7.7096
	V	1.064	792.97	....	....	795.25	850.97	905.44	959.06	1012.1	1064.7
225	U	520.465	2533.2	....	....	2534.8	2575.1	2614.5	2653.5	2692.2	2730.8
(123.99)	H	520.705	2711.6	....	....	2713.8	2766.5	2818.2	2869.3	2919.9	2970.4
	S	1.5705	7.0873	....	....	7.0928	7.2213	7.3400	7.4508	7.5551	7.6540
	V	1.068	718.44	....	....	....	764.09	813.47	861.98	909.91	957.41
250	U	535.077	2536.8	....	....	....	2573.5	2613.3	2652.5	2691.4	2730.2
(127.43)	H	535.343	2716.4	....	....	....	2764.5	2816.7	2868.0	2918.9	2969.6
	S	1.6071	7.0520	....	....	....	7.1689	7.2886	7.4001	7.5050	7.6042
	V	1.071	657.04	....	....	....	693.00	738.21	782.55	826.29	869.61
275	U	548.564	2540.0	....	....	....	2571.9	2612.1	2651.6	2690.7	2729.6
(130.60)	H	548.858	2720.7	....	....	....	2762.5	2815.1	2866.8	2917.9	2968.7
	S	1.6407	7.0201	....	....	....	7.1211	7.2419	7.3541	7.4594	7.5590
	V	1.073	605.56	....	....	....	633.74	675.49	716.35	756.60	796.44
300	U	561.107	2543.0	....	....	....	2570.3	2610.8	2650.6	2689.9	2729.0
(133.54)	H	561.429	2724.7	....	....	....	2760.4	2813.5	2865.5	2916.9	2967.9
	S	1.6716	6.9909	....	....	....	7.0771	7.1990	7.3119	7.4177	7.5176

V = SPECIFIC VOLUME cm^3 g^{-1}

U = SPECIFIC INTERNAL ENERGY kJ kg^{-1}

H = SPECIFIC ENTHALPY kJ kg^{-1}

S = SPECIFIC ENTROPY kJ kg^{-1} K^{-1}

				TEMPERATURE: t °C (TEMPERATURE: T kelvins)							
P/kPa (t^{sat}/°C)		sat. liq.	sat. vap.	150 (423.15)	175 (448.15)	200 (473.15)	220 (493.15)	240 (513.15)	260 (533.15)	280 (553.15)	300 (573.15)
	V	1.076	561.75	583.58	622.41	660.33	690.22	719.81	749.18	778.39	807.47
325	U	572.847	2545.7	2568.7	2609.6	2649.6	2681.2	2712.7	2744.0	2775.3	2806.6
(136.29)	H	573.197	2728.3	2758.4	2811.9	2864.2	2905.6	2946.6	2987.5	3028.2	3069.0
	S	1.7004	6.9640	7.0363	7.1592	7.2729	7.3585	7.4400	7.5181	7.5933	7.6657
	V	1.079	524.00	540.58	576.90	612.31	640.18	667.75	695.09	722.27	749.33
350	U	583.892	2548.2	2567.1	2608.3	2648.6	2680.4	2712.0	2743.4	2774.8	2806.2
(138.87)	H	584.270	2731.6	2756.3	2810.3	2863.0	2904.5	2945.7	2986.7	3027.6	3068.4
	S	1.7273	6.9392	6.9982	7.1222	7.2366	7.3226	7.4045	7.4828	7.5581	7.6307
	V	1.081	491.13	503.29	537.46	570.69	596.81	622.62	648.22	673.64	698.94
375	U	594.332	2550.6	2565.4	2607.1	2647.7	2679.6	2711.3	2742.8	2774.3	2805.7
(141.31)	H	594.737	2734.7	2754.1	2808.6	2861.7	2903.4	2944.8	2985.9	3026.9	3067.8
	S	1.7526	6.9160	6.9624	7.0875	7.2027	7.2891	7.3713	7.4499	7.5254	7.5981
	V	1.084	462.22	470.66	502.93	534.26	558.85	583.14	607.20	631.09	654.85
400	U	604.237	2552.7	2563.7	2605.8	2646.7	2678.8	2710.6	2742.2	2773.7	2805.3
(143.62)	H	604.670	2737.6	2752.0	2807.0	2860.4	2902.3	2943.9	2985.1	3026.2	3067.2
	S	1.7764	6.8943	6.9285	7.0548	7.1708	7.2576	7.3402	7.4190	7.4947	7.5675
	V	1.086	436.61	441.85	472.47	502.12	525.36	548.30	571.01	593.54	615.95
425	U	613.667	2554.8	2562.0	2604.5	2645.7	2678.0	2709.9	2741.6	2773.2	2804.8
(145.82)	H	614.128	2740.3	2749.8	2805.3	2859.1	2901.2	2942.9	2984.3	3025.5	3066.6
	S	1.7990	6.8739	6.8965	7.0239	7.1407	7.2280	7.3108	7.3899	7.4657	7.5388
	V	1.088	413.75	416.24	445.38	473.55	495.59	517.33	538.83	560.17	581.37
450	U	622.672	2556.7	2560.3	2603.2	2644.7	2677.1	2709.2	2741.0	2772.7	2804.4
(147.92)	H	623.162	2742.9	2747.7	2803.7	2857.8	2900.2	2942.0	2983.5	3024.8	3066.0
	S	1.8204	6.8547	6.8660	6.9946	7.1121	7.1999	7.2831	7.3624	7.4384	7.5116
	V	1.091	393.22	393.31	421.14	447.97	468.95	489.62	510.05	530.30	550.43
475	U	631.294	2558.5	2558.6	2601.9	2643.7	2676.3	2708.5	2740.4	2772.2	2803.9
(149.92)	H	631.812	2745.3	2745.5	2802.0	2856.5	2899.1	2941.1	2982.7	3024.1	3065.4
	S	1.8408	6.8365	6.8369	6.9667	7.0850	7.1732	7.2567	7.3363	7.4125	7.4858
	V	1.093	374.68	....	399.31	424.96	444.97	464.67	484.14	503.43	522.58
500	U	639.569	2560.2	....	2600.6	2642.7	2675.5	2707.8	2739.8	2771.7	2803.5
(151.84)	H	640.116	2747.5	....	2800.3	2855.1	2898.0	2940.1	2981.9	3023.4	3064.8
	S	1.8604	6.8192	....	6.9400	7.0592	7.1478	7.2317	7.3115	7.3879	7.4614
	V	1.095	357.84	....	379.56	404.13	423.28	442.11	460.70	479.11	497.38
525	U	647.528	2561.8	....	2599.3	2641.6	2674.6	2707.1	2739.2	2771.2	2803.0
(153.69)	H	648.103	2749.7	....	2798.6	2853.8	2896.8	2939.2	2981.1	3022.7	3064.1
	S	1.8790	6.8027	....	6.9145	7.0345	7.1236	7.2078	7.2879	7.3645	7.4381
	V	1.097	342.48	....	361.60	385.19	403.55	421.59	439.38	457.00	474.48
550	U	655.199	2563.3	....	2598.0	2640.6	2673.8	2706.4	2738.6	2770.6	2802.6
(155.47)	H	655.802	2751.7	....	2796.8	2852.5	2895.7	2938.3	2980.3	3022.0	3063.5
	S	1.8970	6.7870	....	6.8900	7.0108	7.1004	7.1849	7.2653	7.3421	7.4158
	V	1.099	328.41	....	345.20	367.90	385.54	402.85	419.92	436.81	453.56
575	U	662.603	2564.8	....	2596.6	2639.6	2672.9	2705.7	2738.0	2770.1	2802.1
(157.18)	H	663.235	2753.6	....	2795.1	2851.1	2894.6	2937.3	2979.5	3021.3	3062.9
	S	1.9142	6.7720	....	6.8664	6.9880	7.0781	7.1630	7.2436	7.3206	7.3945
	V	1.101	315.47	....	330.16	352.04	369.03	385.68	402.08	418.31	434.39
600	U	669.762	2566.2	....	2595.3	2638.5	2672.1	2705.0	2737.4	2769.6	2801.6
(158.84)	H	670.423	2755.5	....	2793.3	2849.7	2893.5	2936.4	2978.7	3020.6	3062.3
	S	1.9308	6.7575	....	6.8437	6.9662	7.0567	7.1419	7.2228	7.3000	7.3740
	V	1.103	303.54	....	316.31	337.45	353.83	369.87	385.67	401.28	416.75
625	U	676.695	2567.5	....	2593.9	2637.5	2671.2	2704.2	2736.8	2769.1	2801.2
(160.44)	H	677.384	2757.2	....	2791.6	2848.4	2892.3	2935.4	2977.8	3019.9	3061.7
	S	1.9469	6.7437	....	6.8217	6.9451	7.0361	7.1217	7.2028	7.2802	7.3544
	V	1.105	292.49	....	303.53	323.98	339.80	355.29	370.52	385.56	400.47
650	U	683.417	2568.7	....	2592.5	2636.4	2670.3	2703.5	2736.2	2768.5	2800.7
(161.99)	H	684.135	2758.9	....	2789.8	2847.0	2891.2	2934.4	2977.0	3019.2	3061.0
	S	1.9623	6.7304	....	6.8004	6.9247	7.0162	7.1021	7.1835	7.2611	7.3355
	V	1.106	282.23	....	291.69	311.51	326.81	341.78	356.49	371.01	385.39
675	U	689.943	2570.0	....	2591.1	2635.4	2669.5	2702.8	2735.6	2768.0	2800.3
(163.49)	H	690.689	2760.5	....	2788.0	2845.6	2890.1	2933.5	2976.2	3018.5	3060.4
	S	1.9773	6.7176	....	6.7798	6.9050	6.9970	7.0833	7.1650	7.2428	7.3173
	V	1.108	272.68	....	280.69	299.92	314.75	329.23	343.46	357.50	371.39
700	U	696.285	2571.1	....	2589.7	2634.3	2668.6	2702.1	2735.0	2767.5	2799.8
(164.96)	H	697.061	2762.0	....	2786.2	2844.2	2888.9	2932.5	2975.4	3017.7	3059.8
	S	1.9918	6.7052	....	6.7598	6.8859	6.9784	7.0651	7.1470	7.2250	7.2997
	V	1.110	263.77	....	270.45	289.13	303.51	317.55	331.33	344.92	358.36
725	U	702.457	2572.2	....	2588.3	2633.2	2667.7	2701.3	2734.3	2767.0	2799.3
(166.38)	H	703.261	2763.4	....	2784.4	2842.8	2887.7	2931.5	2974.6	3017.0	3059.1
	S	2.0059	6.6932	....	6.7404	6.8673	6.9604	7.0474	7.1296	7.2078	7.2827

CP203 - Thermodynamics Tutorial Solutions Week 8
Group 17

1.

a) Since we are told that the process is isentropic, we know that the entropy will remain constant whereas the temperature will not. Using the known entropy we can then use linear interpolation to determine the enthalpy. We know that $\Delta H = W$ for an adiabatic turbine.

From steam tables, at 600kPa and 250°C, the value for entropy is 7.18235 $\mathrm{kJ\,kg^{-1}\,K^{-1}}$. We can also see that the enthalpy at these conditions is 2957.55 $\mathrm{kJ\,kg^{-1}}$.

Using linear interpolation we can determine the enthalpy at the final condition of 3 bar. Knowing this and the initial allows us to find the work.

$$
\begin{aligned}
y &= y_1 + (y_2 - y_1)\frac{x - x_1}{x_2 - x_1} \\
y &= 2760.4 + (2813.5 - 2760.4)\frac{7.18235 - 7.0771}{7.1990 - 7.0771} \\
y &= 2806.25\,\mathrm{kJ\,kg^{-1}} \\
\Delta H &= 2806.25 - 2957.55 \\
&\boxed{W = -151.3\,\mathrm{kJ\,kg^{-1}}}
\end{aligned}
$$

b) Since at 100 kPa there will be condensation, we have to take into account the fact that we will have a vapour / liquid composition. We then know that;

$$
\begin{aligned}
S_t &= x_L S_L + x_v S_v \\
S_t &= (1 - x_v)S_L + x_v S_v \\
S_t &= S_L - S_L x_v + x_v S_v \\
S_t &= S_L + (S_v - S_L)x_v \\
x_v &= \frac{S_t - S_L}{S_v - S_L} \\
x_v &= \frac{7.18235 - 1.3027}{7.3598 - 1.3027} \\
x_v &= 0.97
\end{aligned}
$$

Knowing that this is the mole fraction of vapour in the phase equilibrium at 100 kPa, we can then apply this to the enthalpy of the fully saturated vapour phase.

$$
\begin{aligned}
H_2 &= 0.97 \cdot 2675.4 \\
H_2 &= 2597.02\,\mathrm{kJ\,kg^{-1}} \\
\Delta H &= W \\
W &= 2597.02 - 2957.55 \\
&\boxed{W = -360.53\,\mathrm{kJ\,kg^{-1}}}
\end{aligned}
$$

2.

$$\Delta H = Q + W - \left(\frac{1}{2}mv_2^2 - \frac{1}{2}mv_1^2\right) - (mz_2g - mz_1g)$$

$$\Delta H = \cancelto{0}{Q} + \cancelto{0}{W} - \left(\frac{1}{2}mv_2^2 - \frac{1}{2}mv_1^2\right) - \cancelto{0}{(mz_2g - mz_1g)}$$

$$\Delta H = -\left(\frac{1}{2}mv_2^2 - \frac{1}{2}mv_1^2\right)$$

$$\Delta H = -\left(\cancelto{0}{\frac{1}{2}mv_2^2} - \frac{1}{2}mv_1^2\right)$$

$$\Delta H = \frac{1}{2}mv_1^2$$

$$\Delta H = C_p m \Delta T$$

$$C_p \cancel{m} \Delta T = \frac{\cancel{m}v_1^2}{2}$$

$$\Delta T = \frac{v_1^2}{2C_p}$$

$$T_2 = \frac{v_1^2}{2C_p} + T_1$$

$$T_2 = \frac{350^2}{2 \cdot 1.005 \times 10^3} + 10$$

$$T_2 = 70.9^\circ\mathrm{C}$$

$$\boxed{T_2 = 71^\circ\mathrm{C}}$$

3.

a)

$$dS = \frac{C_p}{T}dT - \left(\frac{\partial V}{T}\right)_P dP$$

$$\Delta S = \int \frac{C_p}{T}dT - \int \left(\frac{\partial V}{T}\right)_P dP$$

$$V = \frac{nRT}{P}$$

$$\Delta S = C_p \int \frac{1}{T}dT - \int \left(\frac{nRT}{PT}\right)_P dP$$

$$\Delta S = C_p \int \frac{1}{T}dT - \int \left(\frac{nR\cancel{T}}{P\cancel{T}}\right)_P dP$$

$$\Delta S = C_p \int \frac{1}{T}dT - nR \int \frac{1}{P}dP$$

$$\Delta S = C_p \ln \frac{T_2}{T_1} - nR \ln \frac{P_2}{P_1}$$

$$Q.E.D$$

From this we can calculate the outlet temperature;

$$
\begin{aligned}
\Delta S &= C_p \ln \frac{T_2}{T_1} - nR \ln \frac{P_2}{P_1} \\
0 &= C_p \ln \frac{T_2}{T_1} - nR \ln \frac{P_2}{P_1} \\
C_p \ln \frac{T_2}{T_1} &= nR \ln \frac{P_2}{P_1} \\
\ln \frac{T_2}{T_1} &= \frac{nR}{C_p} \ln \frac{P_2}{P_1} \\
\frac{T_2}{T_1} &= \frac{P_2}{P_1}^{\frac{nR}{C_p}} \\
T_2 &= \frac{P_2}{P_1}^{\frac{nR}{C_p}} T_1 \\
T_2 &= \frac{1}{3}^{\frac{2}{7}} \cdot 390 \\
&\boxed{T_2 = 285\text{K}}
\end{aligned}
$$

b)

$$
\begin{aligned}
\eta &= \frac{\Delta H_{flow}}{\Delta H_{\Delta S=0}} \\
\Delta H_{\Delta S=0} &= C_p \Delta T \\
&= \frac{7}{2} \cdot 8.3145(285 - 390) \\
&= -3055.6 \\
\eta &= \frac{-2140}{-3055.6} \\
\eta &= 0.70 \\
&\boxed{\eta = 70\%}
\end{aligned}
$$