

Thermodynamics
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Lecture 77
Tutorial Problem (2 number)

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If 5 kg of saturated water vapour at 100 °C is condensed to a saturated liquid at 100 °C in a constant-pressure process by heat transfer to the surrounding air, which is at 25 °C, what is the net increase in entropy of the water plus surroundings?

m = 5 kg sat. water vap @ 100°C
↓
sat. liq @ 100°C

Q to air @ 25°C
Δs for H₂O, air

Q_{sur} = mTΔs for air

$$\Delta S = \frac{Q_{sur}}{T_{air}} = \frac{11282}{298}$$

$$\Delta S = 37.8 \text{ kJ/K}$$

Δs₁₋₂ = -6.0469 kJ/kgK

$$\Delta S = m\Delta s = 5 \times 6.0469 = -30.23 \frac{\text{kJ}}{\text{K}}$$

Q for water = -m h_{fg}

$$= -5 \times 2257.4 \text{ kJ/kg}$$

$$= -11282 \text{ kJ}$$

$$\Delta S_{univ} = -30.23 + 37.8^{5/7}$$

$$= 7.57 \text{ kJ/K}$$







Figure 1.

Solution of the problem in Fig. 1:

$$m = 5 \text{ kg}, T = 100 \text{ °C} = 373 \text{ K}, T_{air} = 25 \text{ °C} = 298 \text{ K}$$

Process 1-2, the process of condensation, is shown on a T-v diagram in Fig. 1. During this process, the temperature and pressure remain constant.

From the steam tables, at 100 °C, the saturation pressure is 1.014 bar. Hence, at 100 °C and 1.014 bar, the difference between entropy of the saturated vapor and the saturated liquid is $s_{fg} = 6.0469$ kJ/kg·K. For the process from 1 to 2 on the T-v diagram (Fig. 1), $\Delta s_{1-2} = -6.0469$ kJ/kg · K . Hence, $\Delta S_{1-2} = m\Delta s = -30.23 \frac{\text{kJ}}{\text{K}}$.

For the surrounding air, the process is isothermal as the surrounding atmosphere is huge. The heat transfer to the air in the condensation process will not change the air's temperature. Hence, the process is reversible for the air.

Hence, integrating $dS = \frac{\delta Q}{T}$ gives $\Delta S_{air} = \frac{Q_{rev}}{T}$. $T = 298$ K. We need to find Q_{rev} .

The heat lost by vapor and water in the condensation process equals the heat gained by the air. The heat transfer is negative for the water and vapor, whereas it is positive for the air.

The heat transfer in the condensation process $Q = -mh_{fg}(at 100\text{ }^\circ\text{C}) = -5 \times 2256.4 = -11282$ kJ (h_{fg} is the enthalpy of vaporization. It is positive for vaporization and negative for condensation).

Now, $\Delta S_{air} = \frac{Q_{rev}}{T} = \frac{11282}{298} = 37.8 \frac{kJ}{K}$ (Q_{rev} is positive for air)

$\Delta S_{universe} = \Delta S_{air} + \Delta S_{1-2} = 7.57$ kJ/K = net increase in entropy of water plus surrounding.

The entropy of the universe has increased as the process of condensation is irreversible because heat transfer occurs because of a finite temperature difference between the system (condensing water and vapor) and surrounding air.

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Properties of Saturated Water - Temperature Table									
Temp. °C	Pressure kPa	Specific Volume m ³ /kg	Internal Energy kJ/kg	Enthalpy kJ/kg	Entropy kJ/kg·K	Specific Volume m ³ /kg	Internal Energy kJ/kg	Enthalpy kJ/kg	Entropy kJ/kg·K
0.01	0.0001	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
5	0.00072	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
10	0.00123	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
15	0.00170	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
20	0.00226	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
25	0.00290	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
30	0.00361	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
35	0.00439	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
40	0.00525	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
45	0.00618	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
50	0.00719	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
55	0.00827	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
60	0.00943	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
65	0.01066	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
70	0.01197	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
75	0.01336	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
80	0.01483	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
85	0.01638	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
90	0.01801	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
95	0.01972	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
100	0.02161	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
105	0.02360	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
110	0.02569	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
115	0.02789	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
120	0.03019	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
125	0.03260	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
130	0.03512	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
135	0.03775	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
140	0.04049	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
145	0.04334	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
150	0.04630	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
155	0.04938	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
160	0.05257	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
165	0.05588	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
170	0.05930	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
175	0.06284	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
180	0.06650	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
185	0.07028	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
190	0.07418	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
195	0.07820	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
200	0.08234	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
205	0.08660	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
210	0.09098	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
215	0.09548	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
220	0.10009	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
225	0.10482	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
230	0.10967	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
235	0.11464	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
240	0.11973	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
245	0.12494	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
250	0.13027	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
255	0.13572	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
260	0.14129	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
265	0.14698	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
270	0.15279	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
275	0.15872	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
280	0.16478	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
285	0.17096	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
290	0.17727	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
295	0.18371	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
300	0.19028	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
305	0.19698	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
310	0.20381	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
315	0.21077	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
320	0.21786	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
325	0.22508	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
330	0.23243	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
335	0.23991	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
340	0.24752	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
345	0.25526	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
350	0.26313	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
355	0.27114	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
360	0.27928	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
365	0.28756	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
370	0.29597	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
375	0.30452	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
380	0.31321	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
385	0.32204	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
390	0.33101	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
395	0.34013	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
400	0.34939	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
405	0.35880	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
410	0.36836	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
415	0.37807	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
420	0.38793	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
425	0.39795	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
430	0.40812	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
435	0.41845	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
440	0.42893	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
445	0.43957	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
450	0.45036	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
455	0.46131	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
460	0.47241	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
465	0.48367	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
470	0.49508	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
475	0.50665	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
480	0.51837	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
485	0.53024	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001
490	0.54226	0.001000	0.0001	0.0001	0.0001	0.001000	0.0001	0.0001	0.0001

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A closed tank, $V = 10\text{ L}$, containing 3 kg of water initially at 20°C , is heated to 180°C by a heat pump that is receiving heat from the surroundings at 20°C . Assume that this process is reversible. Find the heat transfer to the water and the work input to the heat pump.



$V_1 = V_2 = 10\text{ L} = 10 \times 10^{-3}\text{ m}^3 \Rightarrow v_1 = v_2 = \frac{0.01 \times 10}{3}$
 $m_1 = 3\text{ kg} = m_2$
 $T_1 = 20^\circ\text{C} = 293\text{ K}$
 $T_2 = 180^\circ\text{C} = 453\text{ K}$
 $Q = m(u_2 - u_1)$
 at 20°C
 $v_f = 0.001002$
 $v_g = 57.76\text{ m}^3/\text{kg}$
 $v_1 = v_f + x(v_g - v_f)$
 $\Rightarrow x_1 = \frac{v_1 - v_f}{v_g - v_f} = 3.97 \times 10^{-5}$
 $u_1 = u_f + x(u_g - u_f) = 83.9 + x(2402.5 - 83.9)$



Figure 2.

$T_2 = 180^\circ\text{C}$
 $v_f = 0.001127\text{ m}^3/\text{kg}$
 $v_g = 0.1938\text{ m}^3/\text{kg}$
 $v_2 = 0.0033\text{ m}^3/\text{kg}$
 $u_2 = 762.6\text{ kJ/kg}$
 ${}_1Q_2 = 3 \times (762.6 - 84)$
 $Q_H = {}_1Q_2 = 2035.9\text{ kJ}$
 $W = ?$
 $\frac{Q_H}{Q_L} = \frac{T_H}{T_L} = \frac{453}{293}$
 $Q_L = Q_H \times \frac{293}{453} = 1316\text{ kJ}$
 $|W| = (Q_H) - (Q_L) = 718\text{ kJ}$

$u_1 = 84\text{ kJ/kg}$
 $u_2 = v_f + x(u_g - v_f)$
 $x_2 = \frac{v_2 - v_f}{v_g - v_f} = \frac{0.0033 - 0.001127}{0.1938 - 0.001127}$
 $x_2 = 4 \times 10^{-4}$
 $u_f = 761.9\text{ kJ/kg}$
 $u_g = 2582.8\text{ kJ/kg}$
 $u_2 = u_f + x(u_g - u_f)$
 $u_2 = 762.6\text{ kJ/kg}$
 $W = -718\text{ kJ}$



Solution of the problem in Fig. 2:

A schematic of a closed tank containing water receiving heat from a heat pump is shown in Fig. 2.

For the closed tank containing water, $V_1 = V_2 = 10\text{ L} = 0.01\text{ m}^3$, $m_1 = m_2 = m = 3\text{ kg}$, $T_1 = 20^\circ\text{C} = 293\text{ K}$, $T_2 = 180^\circ\text{C} = 453\text{ K}$, $v_1 = v_2 = \frac{V}{m} = 0.0033\frac{\text{m}^3}{\text{kg}}$.

The heat addition process for water is a constant volume process. Hence, work interaction is 0.

The first law in the integrated form is $Q = \Delta U = m(u_2 - u_1)$(1)

From steam tables, at 20 °C, $v_f = 0.001002 \frac{m^3}{kg}$, $v_g = 57.76 \frac{m^3}{kg}$. Since, $v_f < v_1 < v_g$, we have a mixture of water and steam at state 1. Hence, the quality at state 1, $x_1 = \frac{v_1 - v_f}{v_g - v_f} = 3.97 \times 10^{-5}$.

Hence, $u_1 = [u_f + x_1(u_g - u_f)]_{20^\circ C} = 84 \frac{kJ}{kg}$.

At $T_2 = 180$ °C, $v_f = 0.001127 \frac{m^3}{kg}$, $v_g = 0.1938 \frac{m^3}{kg}$. Again, $v_f < v_2 < v_g$. Hence, we have a mixture of water and steam at state 2. Hence, $x_2 = \frac{v_2 - v_f}{v_g - v_f} = 4 \times 10^{-4}$.

Hence, $u_2 = [u_f + x_2(u_g - u_f)]_{180^\circ C} = 762.6 \frac{kJ}{kg}$

Equation (1) implies $Q = \Delta U = m(u_2 - u_1) = 2035.9 kJ$ =heat transfer to the water=heat given out by the reversible heat pump = Q_H .

For the reversible heat pump (see the schematic in Fig. 2), $\frac{Q_H}{Q_L} = \frac{T_H}{T_L} = \frac{453}{293} \rightarrow Q_L = 1316 kJ$.

According to the first law for the pump, $|W| = |Q_H| - |Q_L| = 718 kJ$.

This is the work input to the pump. Hence, $W = -718 kJ$.

