ESO201A

TUTORIAL 7: PROBLEMS AND SOLUTIONS

7–20 Air is compressed by a 15-kW compressor from P1 to P2. The air temperature is maintained constant at 25°C during this process as a result of heat transfer to the surrounding medium at 20°C. Determine the rate of entropy change of the air. State the assumptions made in solving this problem.

Solution:

Air is compressed steadily by a compressor. The air temperature is maintained constant by heat rejection to the surroundings. The rate of entropy change of air is to be determined.

Assumptions:

1. This is a steady-flow process since there is no change with time.
2. Kinetic and potential energy changes are negligible.
3. Air is an ideal gas.
4. The process involves no internal irreversibilities such as friction, and thus it is an isothermal, internally reversible process.

Properties:

Noting that h = h(T) for ideal gases, we have $h_1 = h_2$ since $T_1 = T_2 = 25°C$.

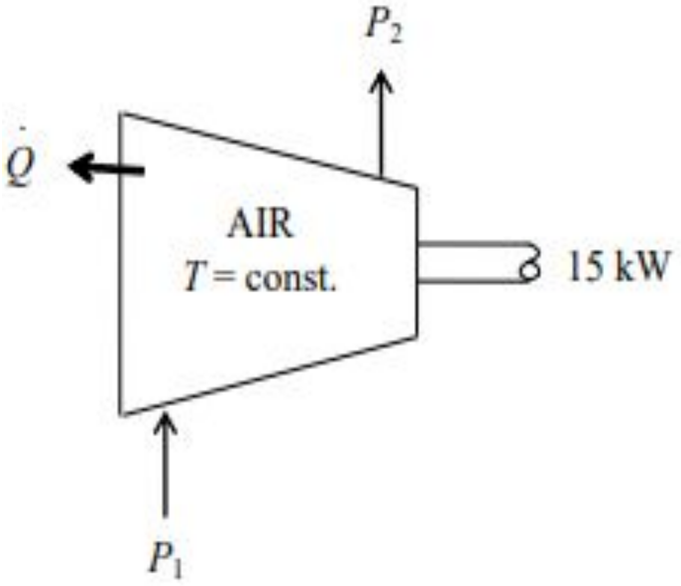
Analysis:

We take the compressor as the system. Noting that the enthalpy of air remains constant, the energy balance for this steady-flow system can be expressed in the rate form as

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta \dot{E}_{system}^{\nearrow 0 \text{ (steady)}}}_{\substack{\text{Rate of change in internal, kinetic,} \\ \text{potential, etc. energies}}} = 0$$

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{W}_{in} = \dot{Q}_{out}$$



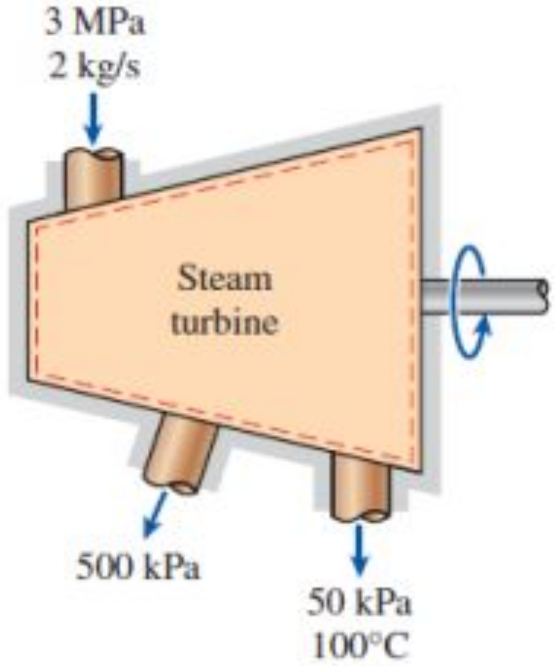
Therefore,

$$\dot{Q}_{out} = \dot{W}_{in} = 15\,\text{kW}$$

Noting that the process is assumed to be an isothermal and internally reversible process, the rate of entropy change of air is determined to be

$$\Delta \dot{S}_{air} = -\frac{\dot{Q}_{out,air}}{T_{sys}} = -\frac{15\,\text{kW}}{298\,\text{K}} = -\mathbf{0.0503 kW/K}$$

7-49 An **isentropic steam** turbine processes 5kg/s of steam at 3MPa, which is exhausted at 50 kPa and 100 °C. 5 percent of this flow is diverted for feedwater heating at 500 kPa. Determine the power produced by this turbine, in kW.

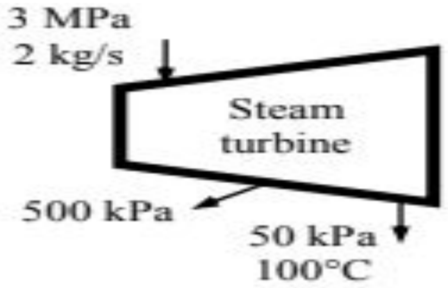


Assumptions:

1. This is a steady-flow process since there is no change with time.
2. The process is isentropic (i.e., reversible-adiabatic).

Analysis: There is one inlet and two exits. We take the turbine as the system, which is a control volume since mass crosses the boundary. The energy balance for this steady-flow system can be expressed in the rate form as.

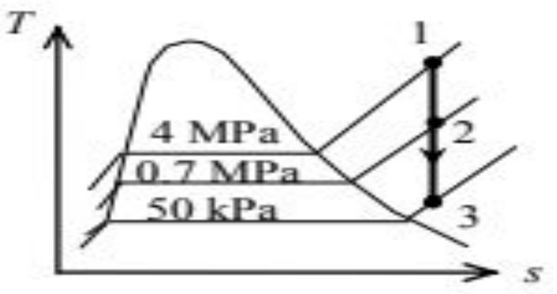
$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta \dot{E}_{system}^{\nearrow 0 \text{ (steady)}}}_{\substack{\text{Rate of change in internal, kinetic,} \\ \text{potential, etc. energies}}} = 0$$



$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{m}_1 h_1 = \dot{m}_2 h_2 + \dot{m}_3 h_3 + \dot{W}_{out}$$

$$\dot{W}_{out} = \dot{m}_1 h_1 - \dot{m}_2 h_2 - \dot{m}_3 h_3$$



From a mass balance,

$$\dot{m}_2 = 0.05\dot{m}_1 = (0.05)(5\ \text{kg/s}) = 0.25\ \text{kg/s}$$

$$\dot{m}_3 = 0.95\dot{m}_1 = (0.95)(5\ \text{kg/s}) = 4.75\ \text{kg/s}$$

Noting that the expansion process is isentropic, the enthalpies at three states are determined as follows:

$$\left.\begin{array}{l} P_3 = 50\ \text{kPa} \\ T_3 = 100°\text{C} \end{array}\right\} \begin{array}{l} h_3 = 2682.4\ \text{kJ/kg} \\ s_3 = 7.6953\ \text{kJ/kg}\cdot\text{K} \end{array} \quad \text{(Table A-6)}$$

T °C	v m^3/kg	u kJ/kg	h kJ/kg	s kJ/kg·K
		P = 0.05 MPa (81.32°C)		
100	3.4187	2511.5	2682.4	7.6953

$$\left.\begin{array}{l} P_1 = 3\ \text{MPa} \\ s_1 = s_3 = 7.6953\ \text{kJ/kg}\cdot\text{K} \end{array}\right\} h_1 = 3851.2\ \text{kJ/kg} \quad \text{(Table A-6)}$$

By linear interpolation

T °C	v m^3/kg	u kJ/kg	h kJ/kg	s kJ/kg·K
		P = 3.00 MPa (233.85°C)		
600	0.13245	3285.5	3682.8	7.5103
700	0.14841	3467.0	3912.2	7.7590

$$\left.\begin{array}{l} P_2 = 500\,\text{kPa} \\ s_2 = s_3 = 7.6953\,\text{kJ/kg}\cdot\text{K} \end{array}\right\} h_2 = 3206.5\,\text{kJ/kg} \quad \text{(Table A-6)}$$

T °C	v m^3/kg	u kJ/kg	h kJ/kg	s kJ/kg·K
		P = 0.50 MPa (151.83°C)		
350	0.57015	2883.0	3168.1	7.6346
400	0.61731	2963.7	3272.4	7.7956

Substituting,

$$\begin{aligned} \dot{W}_{out} &= \dot{m}_1 h_1 - \dot{m}_2 h_2 - \dot{m}_3 h_3 \\ &= (2\,\text{kg/s})(3851.2\,\text{kJ/kg}) - (0.1\,\text{kg/s})(3206.5\,\text{kJ/kg}) - (1.9\,\text{kg/s})(2682.4\,\text{kJ/kg}) \\ &= \mathbf{2285\,kW} \end{aligned}$$

7-81 Air enters a nozzle steadily at 280 kPa and 77 °C with a velocity of 50 m/s and exits at 85 kPa and 320 m/s. The heat losses from the nozzle to the surrounding medium at 20 °C are estimated to be 3.2 kJ/kg. Determine:

(*a*) the exit temperature and

(*b*) the total entropy change for this process.

Solution: Air is accelerated in an nozzle, and some heat is lost in the process. The exit temperature of air and the total entropy change during the process are to be determined

Assumptions: 1 Air is an ideal gas with variable specific heats.

2 The nozzle operates steadily.

Analysis (*a*) Assuming variable specific heats, the inlet properties are determined to be

$$T_1 = 350\text{ K} \longrightarrow \begin{array}{l} h_1 = 350.49\text{ kJ/kg} \\ s_1^\circ = 1.85708\text{/ kJ/kg}\cdot\text{K} \end{array} \quad \text{(Table A-17)}$$

TABLE A–17

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
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

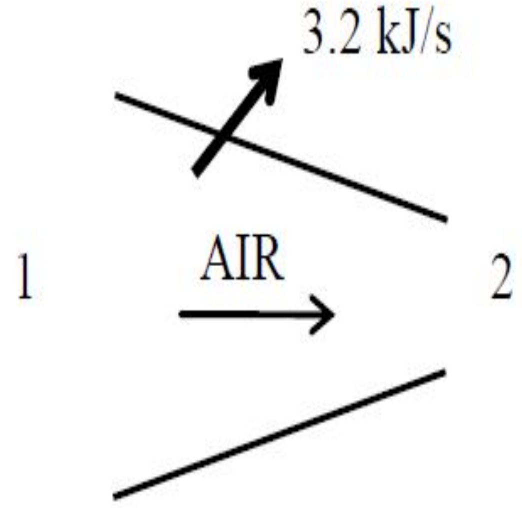
We take the nozzle as the system, which is a control volume. The energy balance for this steady-flow system can be expressed in the rate form as

$$\underbrace{\dot{E}_{\text{in}} - \dot{E}_{\text{out}}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta \dot{E}_{\text{system}}^{\nearrow 0 \text{ (steady)}}}_{\substack{\text{Rate of change in internal, kinetic,} \\ \text{potential, etc. energies}}} = 0$$

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{m}(h_1 + V_1^2/2) = \dot{m}(h_2 + V_2^2/2) + \dot{Q}_{\text{out}}$$

$$0 = q_{\text{out}} + h_2 - h_1 + \frac{V_2^2 - V_1^2}{2}$$



Therefore,

$$h_2 = h_1 - q_{\text{out}} - \frac{V_2^2 - V_1^2}{2} = 350.49 - 3.2 - \frac{(320\ \text{m/s})^2 - (50\ \text{m/s})^2}{2}\left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right)$$

$$= 297.34\ \text{kJ/kg}$$

At this h_2 value we read, from Table A-17, $T_2 = \mathbf{297.2\ K}$, $s_2^\circ = 1.6924\ \text{kJ/kg}\cdot\text{K}$

TABLE A–17

Ideal-gas properties of air

T K	*h* kJ/kg	P_r	*u* kJ/kg	v_r	*s*° kJ/kg·K
285	285.14	1.1584	203.33	706.1	1.65055
290	290.16	1.2311	206.91	676.1	1.66802
295	295.17	1.3068	210.49	647.9	1.68515
298	298.18	1.3543	212.64	631.9	1.69528
300	300.19	1.3860	214.07	621.2	1.70203
305	305.22	1.4686	217.67	596.0	1.71865

(*b*) The total entropy change is the sum of the entropy changes of the air and of the surroundings, and is determined from

$$\Delta s_{\text{total}} = \Delta s_{\text{air}} + \Delta s_{\text{surr}}$$

Where

$$\Delta s_{\text{air}} = s_2^\circ - s_1^\circ - R\ln\frac{P_2}{P_1} = 1.6924 - 1.85708 - (0.287\ \text{kJ/kg}\cdot\text{K})\ln\frac{85\ \text{kPa}}{280\ \text{kPa}} = 0.1775\ \text{kJ/kg}\cdot\text{K}$$

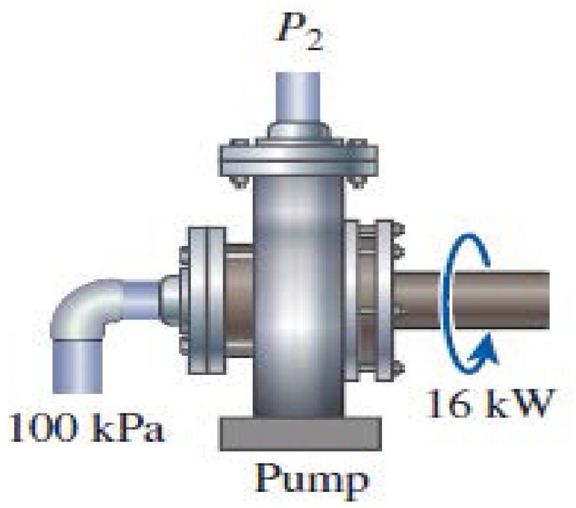
And

$$\Delta s_{\text{surr}} = \frac{q_{\text{surr,in}}}{T_{\text{surr}}} = \frac{3.2\ \text{kJ/kg}}{293\ \text{K}} = 0.0109\ \text{kJ/kg}\cdot\text{K}$$

Thus,

$$\Delta s_{\text{total}} = 0.1775 + 0.0109 = \mathbf{0.1884\ kJ/kg\cdot K}$$

7-106 Liquid water enters a 16 kW pump at 100 kPa pressure at a rate of 5 kg/s. Determine the highest pressure the liquid water can have at the exit of the pump. Neglect the kinetic and potential energy changes of water, and take the specific volume of water to be 0.001 m^3/kg.



Assumptions:

1. Liquid water is an incompressible substance.
2. Kinetic and potential energy changes are negligible.
3. The process is assumed to be reversible since we will determine the limiting case.

Properties:

The specific volume of liquid is given as v_1=0.001m^3/kg

Analysis:

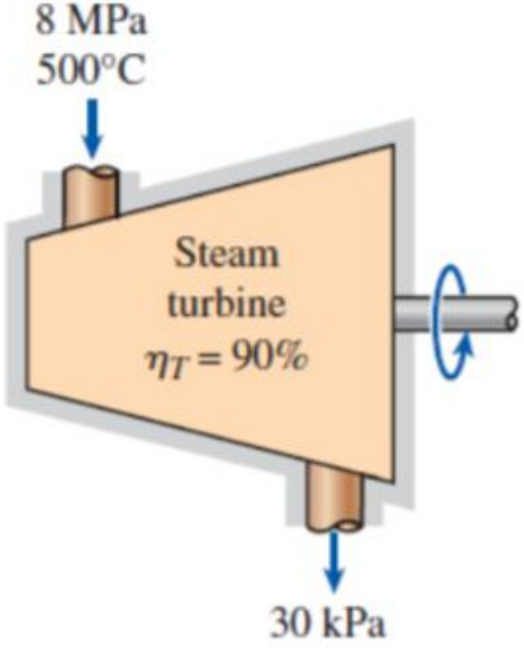
The highest pressure of the liquid can be at the pump exit and can be determined from the reversible steady-flow work relation for a liquid.

W_{in}= m ($\int_1^2 v\,dP$ +ΔKE+ΔPE)= $mv_1(P_2-P_1)$ (see page 360)

16= 5*0.001(P_2-100)

P_2= 3300 kPa

7-120 Steam enters an adiabatic turbine at 8 MPa and 500°C with a mass flow rate of 3 kg/s and leaves at 30 kPa. The isentropic efficiency of the turbine is 0.90. Neglecting the kinetic energy change of the steam, determine (a) the temperature at the turbine exit and *(b)* the power output of the turbine.



Assumptions:

1. This is a steady-flow process since there is no change with time.
2. Kinetic and potential energy changes are negligible.
3. The device is adiabatic and thus heat transfer is negligible.

Analysis:

(a) From the steam tables (Tables A-4 through A-6),

$$\left.\begin{aligned} P_1 &= 8\ \text{MPa} \\ T_1 &= 500^\circ\text{C} \end{aligned}\right\} \begin{aligned} h_1 &= 3399.5\ \text{kJ/kg} \\ s_1 &= 6.7266\ \text{kJ/kg}\cdot\text{K} \end{aligned}$$

	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg·K
	P = 8.0 MPa (295.01°C)			
450	0.038194	2967.8	3273.3	6.5579
500	0.041767	3065.4	3399.5	6.7266
550	0.045172	3160.5	3521.8	6.8800

$$\left.\begin{aligned} P_{2s} &= 30\ \text{kPa} \\ s_{2s} &= s_1 \end{aligned}\right\} \begin{aligned} x_{2s} &= \frac{s_{2s} - s_f}{s_{fg}} = \frac{6.7266 - 0.9441}{6.8234} = 0.8475 \\ h_{2s} &= h_f + x_{2s} h_{fg} = 289.27 + (0.8475)(2335.3) = 2268.3\ \text{kJ/kg} \end{aligned}$$

Press., *P* kPa	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
25	271.96	2345.5	2617.5	0.8932	6.9370	7.8302
30	289.27	2335.3	2624.6	0.9441	6.8234	7.7675
40	317.62	2318.4	2636.1	1.0261	6.6430	7.6691

From the isentropic efficiency relation,

$$n_T = \frac{h_1 - h_{2a}}{h_1 - h_{2s}} \Rightarrow \quad h_{2a} = h_1 - \eta_T(h_1 - h_{2s}) = 3399.5 - (0.9)(3399.5 - 2268.3) = 2381.4 \text{ kJ/kg}$$

Thus,

$$\left.\begin{aligned} P_{2a} &= 30 \text{ kPa} \\ h_{2a} &= 2381.4 \text{ kJ/kg} \end{aligned}\right\} T_{2a} = T_{\text{sat@30 kPa}} = \mathbf{69.09°C}$$

Press., P kPa	Sat. temp., T_{sat} °C
25	64.96
30	69.09
40	75.86

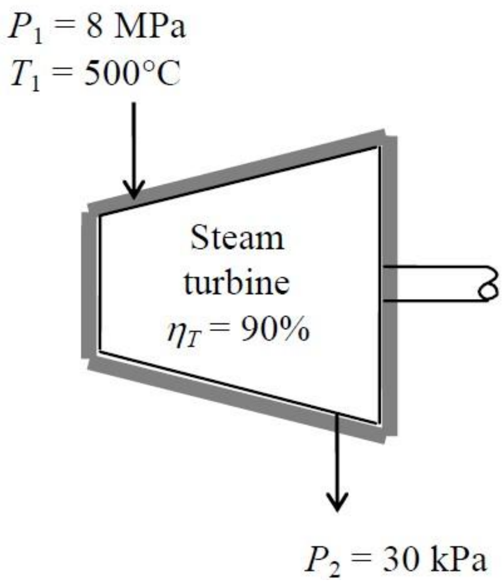
(b) There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. We take the actual turbine as the system, which is a control volume since mass crosses the boundary. The energy balance for this steady-flow system can be expressed in the rate form as

$$\underbrace{\dot{E}_{\text{in}} - \dot{E}_{\text{out}}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta \dot{E}_{\text{system}}^{\nearrow 0 \text{ (steady)}}}_{\substack{\text{Rate of change in internal, kinetic,} \\ \text{potential, etc. energies}}} = 0$$

$$\dot{E}_{\text{in}} = \dot{E}_{\text{out}}$$

$$\dot{m}h_1 = \dot{W}_{\text{a,out}} + \dot{m}h_2 \quad (\text{since } \dot{Q} \cong \Delta\text{ke} \cong \Delta\text{pe} \cong 0)$$

$$\dot{W}_{\text{a,out}} = \dot{m}(h_1 - h_2)$$



Substituting; $W_{a,out}$= (3 kg/s)*(3399.5-2381.4) kJ/kg= 3054 kW