ABE 201
Biological Thermodynamics 1

Module 12: 2nd Law Balances

Review

- Entropy is **<u>not</u>** conserved ($s_{gen} \geq 0$)

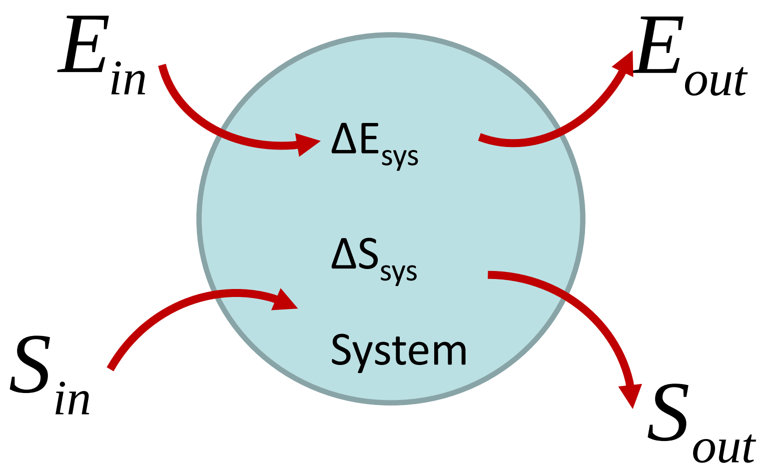
- Entropy balances

- Steady state/flow: $$\frac{dS_{sys}}{dt} = 0$$

- Isentropic: $$\Delta S = S_2 - S_1 = 0,\ \text{closed system}$$
  $$S_{gen} = 0,\ \text{open system}$$

Entropy Balance

Accumulation=In- Out + Generation - Consumption



$$\Delta E_{sys} = E_{in} - E_{out} \longrightarrow \Delta U + \Delta E_K + \Delta E_P = Q - W$$ **1st Law!**

$$\Delta S_{sys} = S_{in} - S_{out} + S_{gen}$$ **2nd Law!**

$$\frac{dS_{sys}}{dt} = \dot{S}_{in} - \dot{S}_{out} + \dot{S}_{gen} \quad \text{(rate form)}$$

$$S_{gen} \geq 0$$

$$S_{gen} = 0 \quad \text{for a reversible process}$$

$$then, \quad S_{in} - S_{out} = \Delta S_{sys}$$

S_{in} and S_{out}

1. Entropy transfer associated with heat transfer

$$S_{heat} = \frac{Q}{T} \quad \text{(T=constant)} \quad \text{for adiabatic, } S_{heat} = 0$$

$$S_{heat} = \int_1^2 \frac{\delta Q}{T} \approx \sum \frac{Q_k}{T_k} \quad \text{(when T is not constant)}$$

2. Entropy transfer associated with mass flow

$$\dot{S}_{mass} = \dot{m}\hat{s}$$

$$\dot{S}_{mass} = \dot{m}\hat{s} = 0 \quad \text{(for no mass flow, closed system)}$$

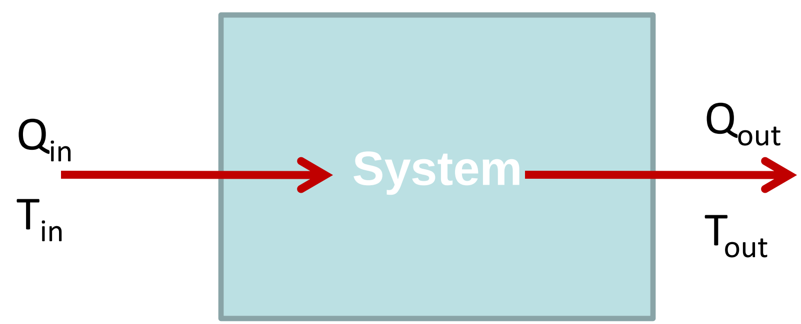
Entropy Balance for Closed Systems

Closed system=no mass flow

$$S_{in} - S_{out} + S_{gen} = \Delta S_{sys}$$

$$\sum \frac{Q_k}{T_k} + \sum m_{in}\hat{s} - \sum m_{out}\hat{s} + S_{gen} = \Delta S_{sys}$$

$$\left(\frac{Q_{in}}{T_{in}} + \cancelto{0}{m_{in}\hat{s}_{in}} \right) - \left(\frac{Q_{out}}{T_{out}} + \cancelto{0}{m_{out}\hat{s}_{out}} \right) + S_{gen} = \Delta S_{sys}$$



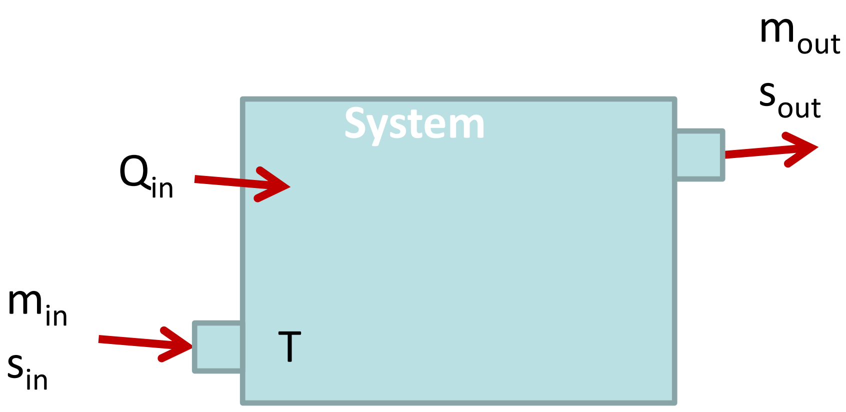
Entropy Balance for Open Systems with Control Volumes

$$S_{in} - S_{out} + S_{gen} = \Delta S_{sys}$$

Control vol.= a fixed vol. in space through which fluid flows.

$$\sum \frac{\dot{Q}_k}{T_k} + \sum \dot{m}_{in}\hat{s}_{in} - \sum \dot{m}_{out}\hat{s}_{out} + \dot{S}_{gen} = \frac{dS_{sys}}{dt}$$

$$\left(\frac{\dot{Q}_{in}}{T_{in}} + \dot{m}_{in}s_{in}\right) - \left(\frac{\dot{Q}_{out}}{T_{out}} + \dot{m}_{out}s_{out}\right) + \dot{S}_{gen} = \Delta\dot{S}_{sys}$$



Example 1

Consider steady heat transfer through a brick wall of a house. Outdoor temperature is 0C and indoor is at 20C. The temperatures of the inner and outer surfaces of the brick wall are measured to be 15C and 5 C, respectively. The rate of heat transfer through the wall is 100 kW. Determine the rate of entropy generation in the wall ($S_{gen\ wall}$) and the rate of total entropy generation associated with this heat transfer process ($S_{gen\ total}$).

$$\sum \frac{\dot{Q}_k}{T_k} + \dot{S}_{gen} = \frac{dS_{sys}}{dt}$$

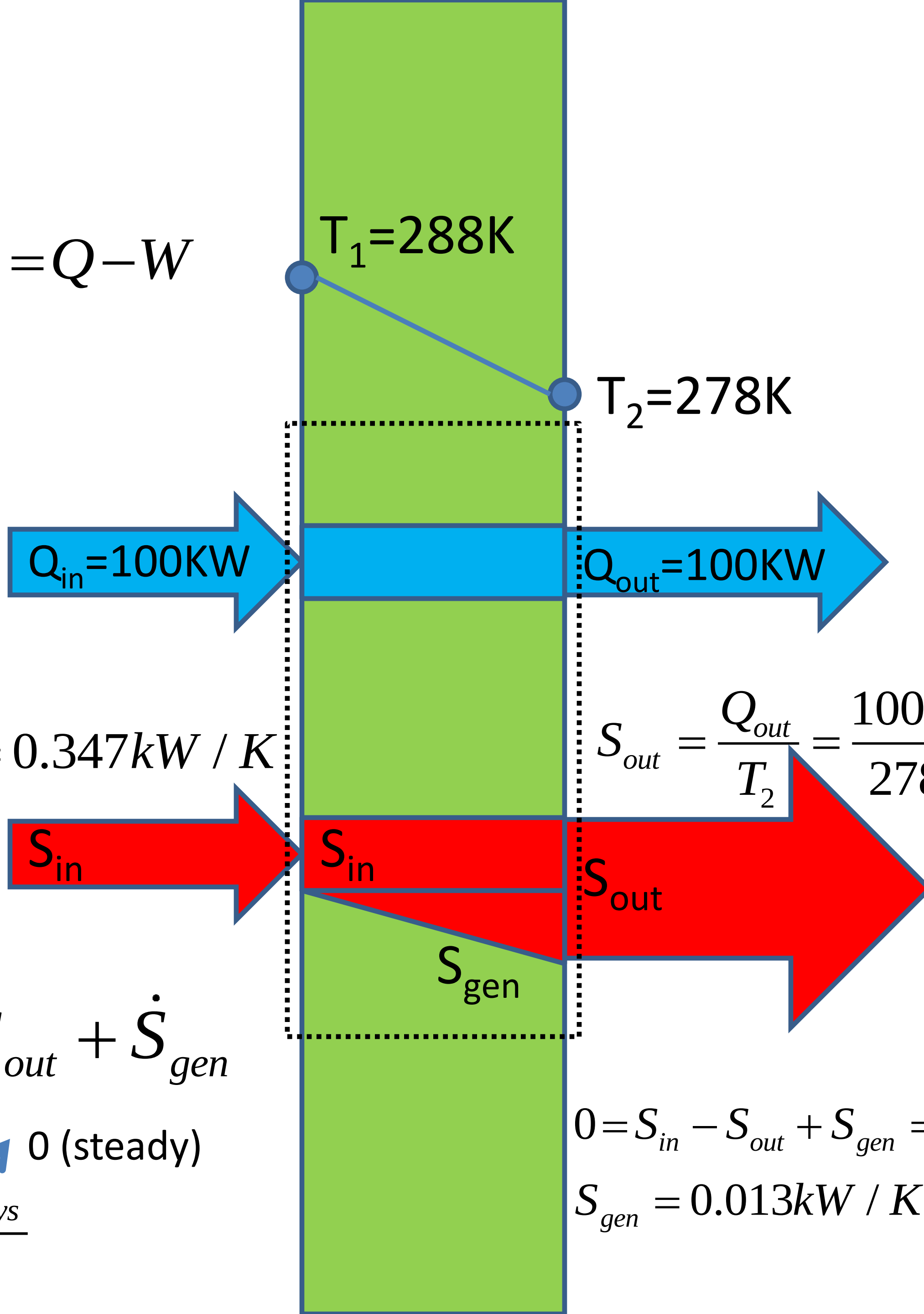
$$\frac{dS_{sys}}{dt} = 0 \text{ (steady flow)}$$

$$\frac{\dot{Q}_{in}}{T_{in}} - \frac{\dot{Q}_{out}}{T_{out}} + \dot{S}_{gen} = 0$$

$$\dot{S}_{gen} = \frac{\dot{Q}_{out}}{T_{out}} - \frac{\dot{Q}_{in}}{T_{in}} = \frac{100kW}{278K} - \frac{100kW}{288K} = 0.013kW / K$$

$$\Delta U + \Delta E_k + \Delta E_p = Q - W$$

$$Q_{in} = Q_{out}$$



$$S_{in} = \frac{Q_{in}}{T_1} = \frac{100kW}{288K} = 0.347kW / K$$

$$S_{out} = \frac{Q_{out}}{T_2} = \frac{100kW}{278K} = 0.360kW / K$$

$$\frac{dS_{sys}}{dt} = \dot{S}_{in} - \dot{S}_{out} + \dot{S}_{gen}$$

0 (steady)

$$\sum \frac{\dot{Q}_k}{T_k} + \dot{S}_{gen} = \cancel{\frac{dS_{sys}}{dt}}$$

$$0 = S_{in} - S_{out} + S_{gen} = 0.347 - 0.360 + S_{gen}$$

$$S_{gen} = 0.013kW / K$$

Example 2

A 50 kg block of iron at 500 K is thrown into a large lake that is at 285K. The iron block eventually reaches thermal equilibrium with the lake water. Assuming an average specific heat of 0.45 kJ/kg K for the iron, determine:

(a) How much heat leaves the block?
(b) What is the entropy change of the iron block?
(c) What is the entropy change of the lake?
(d) Is this process reversible or irreversible?

$$\Delta U_{iron} + \Delta E_{k,\mathrm{iron}} + \Delta E_{P,\mathrm{iron}} = Q - W$$

$$\Delta U_{iron} = Q$$

$$\Delta U_{iron} = \int mc_P dT = mc_P \int dT = mc_P (T_2 - T_1)$$

$$\Delta U_{iron} = 50 \cdot 0.45 \cdot (285 - 500) = -4838 kJ$$

$$dS_{iron} = \frac{Q}{T} = \frac{\int m_{iron} * C_p dt}{T} = \int \frac{m_{iron} * C_p}{T_{iron}} dt$$

$$dS_{iron} = m_{iron} * C_p \int \frac{1}{T_{iron}} dt = m_{iron} * C_p \ln\left(\frac{T_2}{T_1}\right)$$

$$dS_{iron} = (50)(0.45) \ln\left(\frac{285}{500}\right) = -12.65 \frac{kJ}{K}$$

$$\Delta U_{universe} + \Delta E_{k,\text{universe}} + \Delta E_{P,\text{universe}} = Q - W$$

$$\Delta U_{universe} = 0$$

$$\Delta U_{iron} = \Delta U_{lake}$$

Assume that T_{lake} does not change!

$$dS_{lake} = \frac{Q_{lake}}{T_{lake}} = \left(\frac{4838 kJ}{285 K}\right) = 16.97 \frac{kJ}{K}$$

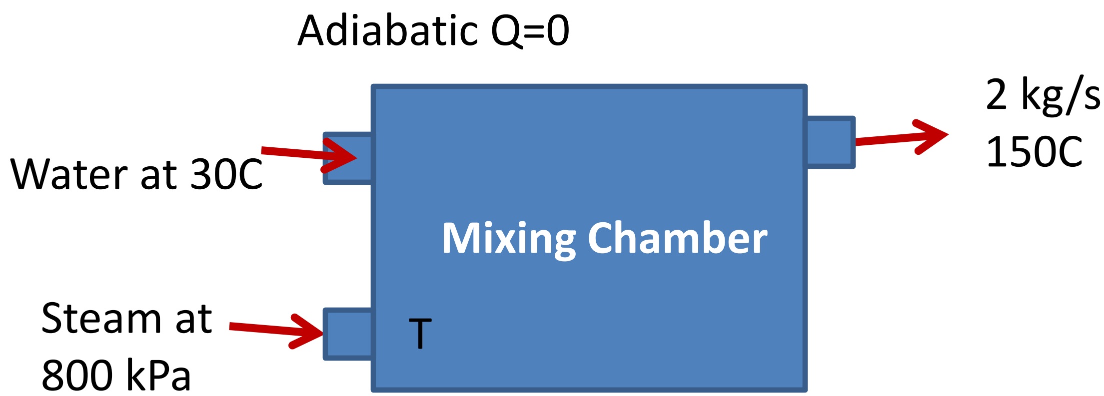
$$\Delta S_{universe} = \Delta S_{lake} + \Delta S_{iron}$$

$$0 = 16.97 - 12.65$$

$$\Delta S_{universe} = 4.32 kJ / K > 0$$ Irreversible

Example 3

At one inlet to an adiabatic mixing chamber maintained at 800 kPa steam enters with a quality of 90%. At the second inlet water enters at 30^{o}C. At the exit the temperature is 150^{o}C, pressure is 800 kPa, and mass flow rate is 2kg/s. Ignore height and velocity changes. Determine the rate of entropy production for this steady-flow, mixing process, in kJ/s.K.



$$\Delta H + \Delta E_K + \Delta E_P = Q - W_S$$

$$\Delta E_K = \Delta E_P = Q = W_S = 0$$

$$\left(\dot{m}_1\hat{H}_1 + \dot{m}_2\hat{H}_2\right) - \dot{m}_3\hat{H}_3 = 0$$

$$\hat{H}_{1,\mathrm{water}} = 720.87 kJ / kg$$

$$\hat{H}_{1,steam} = 2768.30 kJ / kg$$

$$\hat{H}_1 = 0.9 * 2768.30 + 0.1 * 720.87 = 2563.56 kJ / kg$$

$$\hat{H}_2 = 125.74 kJ / kg$$

$$\hat{H}_3 (T_{sat} = 170 @ 0.8\,\mathrm{MPa}) = 632.18 kJ / kg$$

$$\left(\dot{m}_1\hat{H}_1+\dot{m}_2\hat{H}_2\right)-\dot{m}_3\hat{H}_3=0$$

$$\left(\dot{m}_1+\dot{m}_2\right)-\dot{m}_3=\left(\dot{m}_1+\dot{m}_2\right)-2=0$$

$$\left((2-\dot{m}_2)(2563.56)+\dot{m}_2(126.47)\right)-2(632.18)=0$$

$$\dot{m}_2=1.58kg/s$$

$$\dot{m}_1=2-\dot{m}_2=0.42kg/s$$

$$\sum\frac{\dot{Q}_k}{T_k}+\sum\dot{m}_{in}\hat{s}_{in}-\sum\dot{m}_{out}\hat{s}_{out}+\dot{S}_{gen}=\frac{dS_{sys}}{dt}$$

$$0+\left(\dot{m}_1\hat{s}_1+\dot{m}_2\hat{s}_2\right)-\dot{m}_3\hat{s}_3+\dot{S}_{gen}=0$$

$$\left((0.42)(0.9*6.6615+0.1*2.0460)+(1.58)(0.4366)\right)-2(1.8416)+\dot{S}_{gen}=0$$

$$\dot{S}_{gen}=0.3894kW/K$$

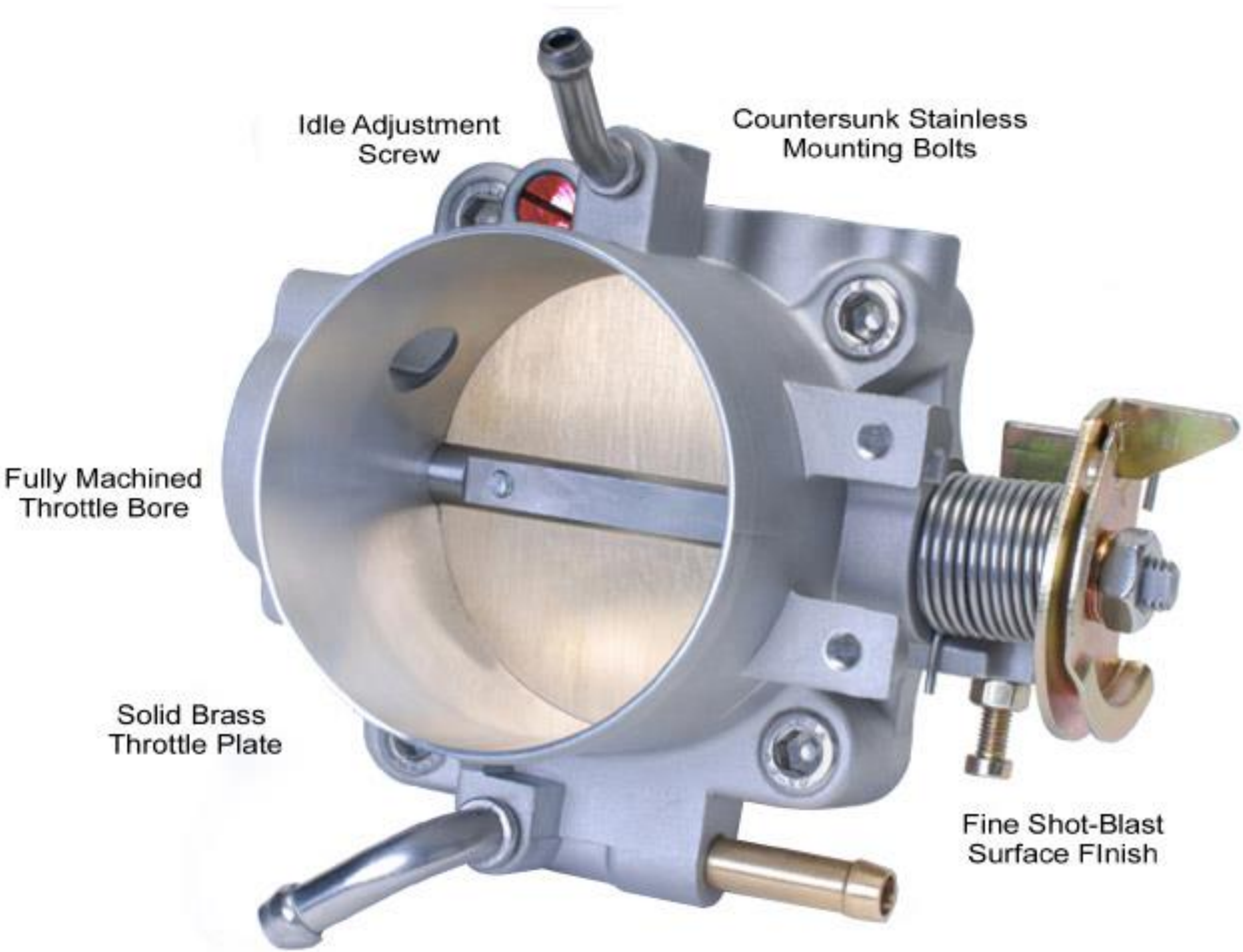
Example 4: Throttling

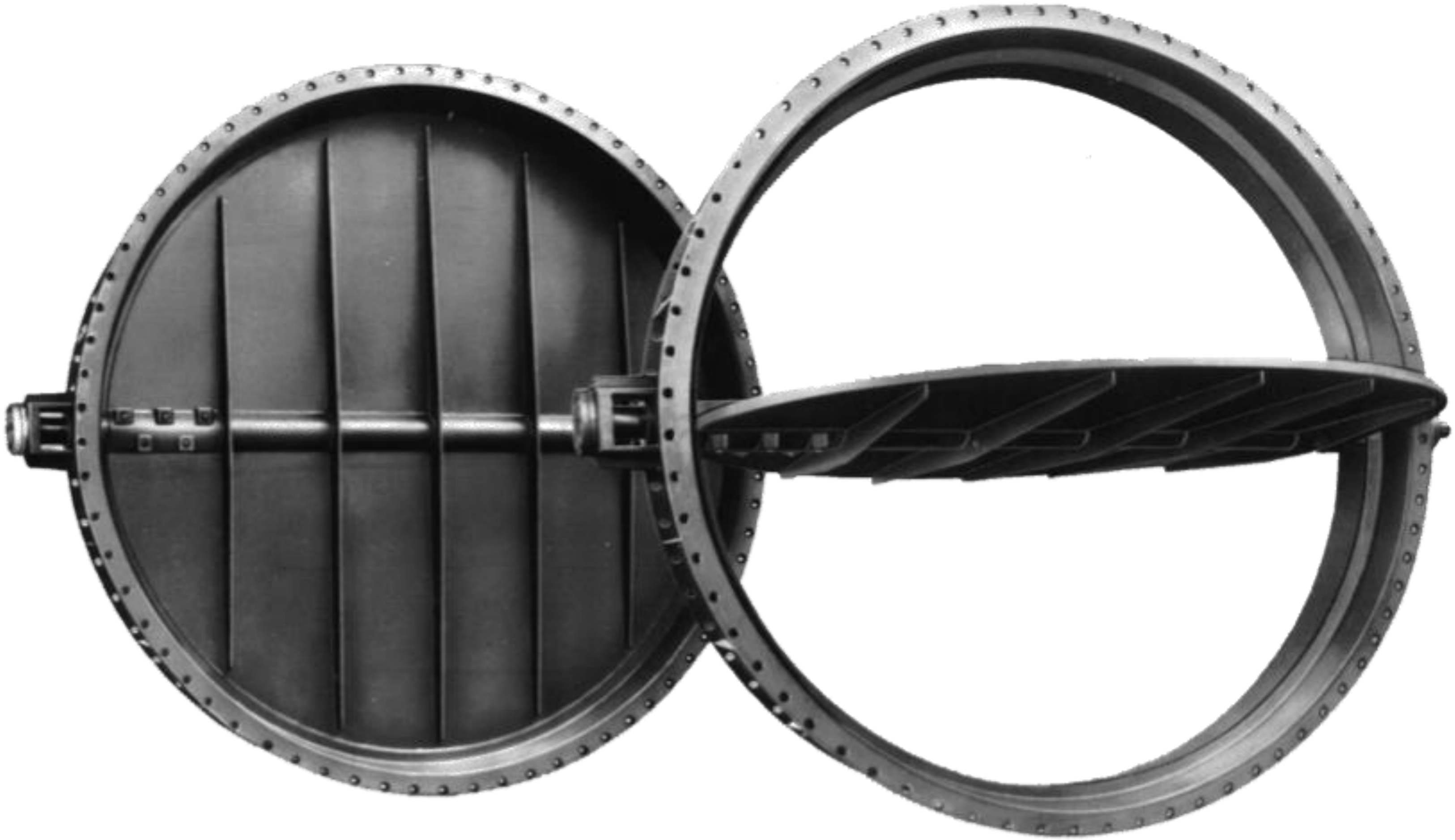
A valve can be used to reduce the pressure of steam without extracting work. Steam at 0.2 MPa and 200 C is throttled to 0.1 MPa.

Assume:

- adiabatic operation
- steady-state/steady-flow
- insignificant velocity changes in the steam

a) What is the temperature of the steam leaving the throttle?
b) At what rate is the throttle generating entropy?

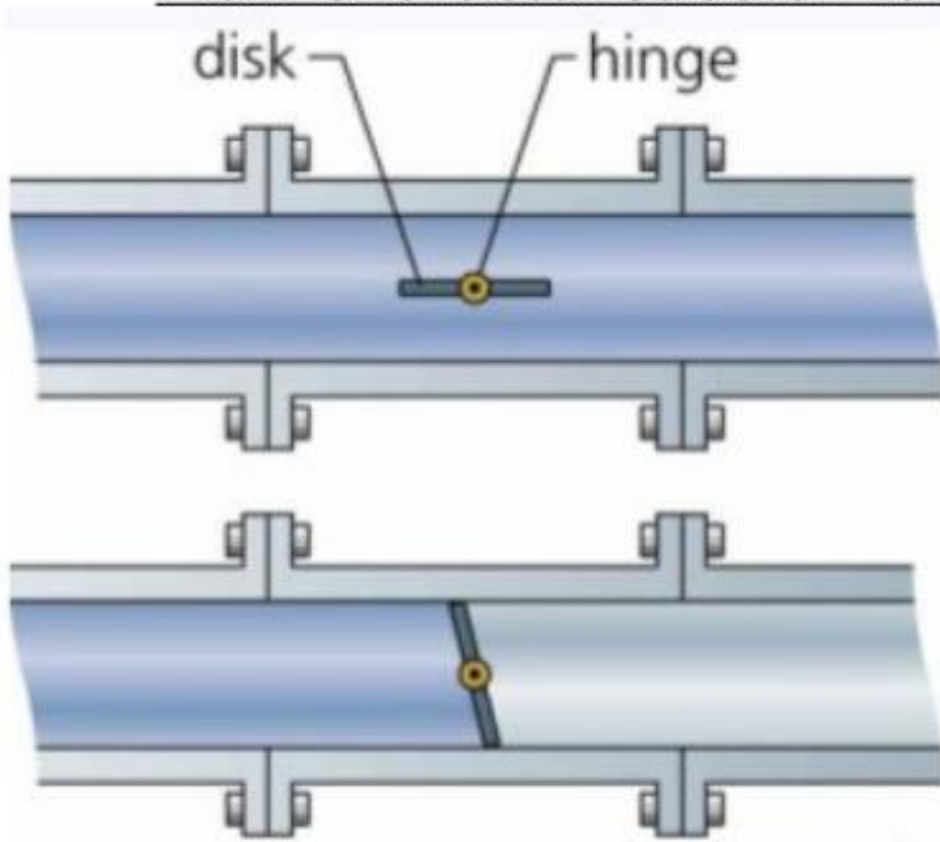

Idle Adjustment Screw
Countersunk Stainless Mounting Bolts
Fully Machined Throttle Bore
Solid Brass Throttle Plate
Fine Shot-Blast Surface FInish






BUTTERFLY VALVE

Flow Characteristics of Valve



Butterfly valves, in addition to serving as shutoffs, can also be used for throttling applications. An index of the excellent throttling characteristics of the butterfly valve is the fact that it has a control rangeability of 45 to 1. A rubber-seat butterfly valve can be used for throttling service and, when required, can be moved to the full closed position to give tight shutoff.

Needle Valve

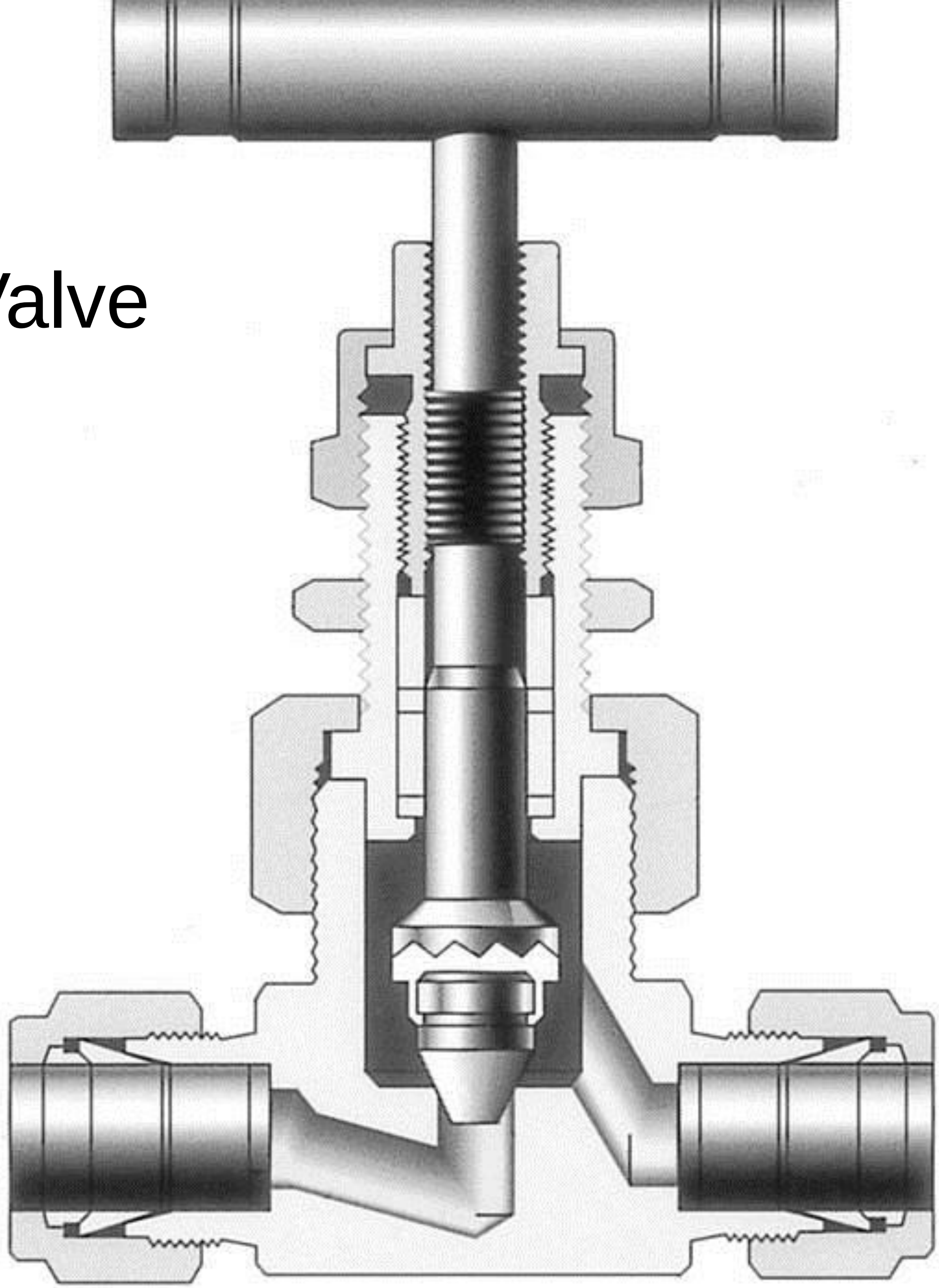


Table 3. Compressed Water and Superheated Steam (continued)

0.16 MPa (t_s = 113.297 °C)					0.18 MPa (t_s = 116.911 °C)					0.20 MPa (t_s = 120.210 °C)			
v	ρ	h	s	t, °C	v	ρ	h	s	t, °C	v	ρ	h	s
1.054 40	948.41	475.38	1.4551	t_s(L)	1.057 56	945.57	490.70	1.4945	t_s(L)	1.060 52	942.94	504.70	1.5302
1091.4	0.916 29	2696.0	7.2014	t_s(V)	977.47	1.0230	2701.4	7.1621	t_s(V)	885.68	1.1291	2706.2	7.1269
1.000 13	999.87	0.12	-0.000 14	**0**	1.000 12	999.88	0.14	-0.000 14	**0**	1.000 11	999.89	0.16	-0.000 14
1.000 00	1000.00	21.18	0.076 25	**5**	0.999 99	1000.01	21.20	0.076 25	**5**	0.999 98	1000.02	21.22	0.076 25
1.000 27	999.73	42.18	0.151 07	**10**	1.000 26	999.74	42.20	0.151 07	**10**	1.000 25	999.75	42.22	0.151 07
1.000 87	999.13	63.13	0.224 44	**15**	1.000 86	999.14	63.15	0.224 44	**15**	1.000 85	999.15	63.17	0.224 43
1.001 77	998.23	84.06	0.296 45	**20**	1.001 76	998.24	84.08	0.296 45	**20**	1.001 75	998.25	84.10	0.296 44
1353.5	0.738 83	2872.6	7.6141	**200**	1201.8	0.832 07	2871.7	7.5582	**200**	1080.5	0.925 51	2870.7	7.5081
1383.1	0.723 04	2892.6	7.6559	**210**	1228.2	0.814 21	2891.7	7.6002	**210**	1104.3	0.905 56	2890.8	7.5501
1412.6	0.707 94	2912.6	7.6968	**220**	1254.5	0.797 14	2911.8	7.6412	**220**	1128.0	0.886 50	2910.9	7.5913
1442.0	0.693 49	2932.5	7.7369	**230**	1280.7	0.780 81	2931.8	7.6814	**230**	1151.7	0.868 28	2931.0	7.6316
1471.4	0.679 64	2952.5	7.7762	**240**	1306.9	0.765 17	2951.8	7.7208	**240**	1175.3	0.850 83	2951.1	7.6712
1500.7	0.666 35	2972.5	7.8148	**250**	1333.0	0.750 17	2971.9	7.7595	**250**	1198.9	0.834 10	2971.2	7.7100
1530.0	0.653 59	2992.6	7.8528	**260**	1359.1	0.735 76	2991.9	7.7975	**260**	1222.4	0.818 05	2991.3	7.7480
1559.3	0.641 32	3012.6	7.8901	**270**	1385.2	0.721 92	3012.1	7.8349	**270**	1245.9	0.802 62	3011.5	7.7855
1588.5	0.629 52	3032.7	7.9267	**280**	1411.2	0.708 61	3032.2	7.8716	**280**	1269.4	0.787 78	3031.6	7.8223
1617.7	0.618 16	3052.9	7.9628	**290**	1437.2	0.695 79	3052.4	7.9078	**290**	1292.8	0.773 50	3051.8	7.8584

Table 3. Compressed Water and Superheated Steam (continued)

0.10 MPa (t_s = 99.606 °C)				t, °C	0.11 MPa (t_s = 102.292 °C)				t, °C	0.12 MPa (t_s = 104.784 °C)			
v	ρ	h	s		v	ρ	h	s		v	ρ	h	s
1.043 15	958.63	417.50	1.3028	t_s(L)	1.045 27	956.69	428.84	1.3330	t_s(L)	1.047 27	954.86	439.36	1.3609
1693.9	0.590 34	2674.9	7.3588	t_s(V)	1549.5	0.645 39	2679.2	7.3269	t_s(V)	1428.4	0.700 10	2683.1	7.2977
1.000 16	*999.84*	*0.06*	*-0.000 15*	**0**	*1.000 15*	*999.85*	*0.07*	*-0.000 15*	**0**	*1.000 15*	*999.85*	*0.08*	*-0.000 15*
1.000 03	999.97	21.12	0.076 25	**5**	1.000 03	999.97	21.13	0.076 25	**5**	1.000 02	999.98	21.14	0.076 25
1.000 30	999.70	42.12	0.151 08	**10**	1.000 29	999.71	42.13	0.151 08	**10**	1.000 29	999.71	42.14	0.151 08
1.000 90	999.10	63.08	0.224 45	**15**	1.000 89	999.11	63.09	0.224 45	**15**	1.000 89	999.11	63.09	0.224 45
1.001 80	998.21	84.01	0.296 46	**20**	1.001 79	998.21	84.02	0.296 46	**20**	1.001 79	998.22	84.02	0.296 46

2054.9	0.486 64	2826.1	7.7284	**175**	1866.9	0.535 66	2825.5	7.6834	**175**	1710.2	0.584 74	2824.9	7.6422
2078.5	0.481 13	2836.0	7.7503	**180**	1888.3	0.529 57	2835.4	7.7054	**180**	1729.9	0.578 08	2834.9	7.6643
2102.0	0.475 74	2845.8	7.7719	**185**	1909.8	0.523 63	2845.3	7.7271	**185**	1749.6	0.571 58	2844.8	7.6860
2125.5	0.470 48	2855.7	7.7934	**190**	1931.2	0.517 82	2855.2	7.7486	**190**	1769.2	0.565 22	2854.7	7.7076
2149.0	0.465 34	2865.6	7.8146	**195**	1952.5	0.512 15	2865.1	7.7698	**195**	1788.8	0.559 02	2864.6	7.7289
2172.4	0.460 31	2875.5	7.8356	**200**	1973.9	0.506 61	2875.0	7.7908	**200**	1808.5	0.552 96	2874.5	7.7499
2219.3	0.450 59	2895.2	7.8769	**210**	2016.6	0.495 89	2894.8	7.8322	**210**	1847.6	0.541 23	2894.3	7.7914
2266.1	0.441 29	2915.0	7.9174	**220**	2059.2	0.485 63	2914.6	7.8728	**220**	1886.7	0.530 01	2914.2	7.8320
2312.8	0.432 37	2934.8	7.9572	**230**	2101.7	0.475 80	2934.4	7.9126	**230**	1925.8	0.519 27	2934.1	7.8719
2359.5	0.423 82	2954.6	7.9962	**240**	2144.2	0.466 37	2954.3	7.9517	**240**	1964.8	0.508 96	2953.9	7.9111

$$\Delta H + \Delta E_K + \Delta E_P = Q - W_S$$

$$\Delta E_K = \Delta E_P = Q = W_S = 0$$

$$\hat{H}_{in} = \hat{H}_{out}$$

$$\hat{H}_{in} = 2870.7 kJ / kg$$

$$P_{out} = 0.1 \text{MPa}$$

$$H_{195C} = 2865.6, H_{200C} = 2875.5$$

$$\frac{2865.6 - 2870.7}{195 - T_{out}} = \frac{2875.5 - 2870.7}{200 - T_{out}}$$

$$T_{out} = 197.6\,^{0}C$$

$$\hat{s}_{in} = 7.5081 kJ / kgK$$

$$\hat{s}_{0.1MPa,195C} = 7.8146 kJ / kgK$$

$$\hat{s}_{0.1MPa,200C} = 7.8356 kJ / kgK$$

$$\hat{s}_{0.1MPa,197.6C} = 7.8255 kJ / kgK$$

$$\sum \frac{\dot{Q}_k}{T_k} + \sum \dot{m}_{in}\hat{s}_{in} - \sum \dot{m}_{out}\hat{s}_{out} + \dot{S}_{gen} = \frac{dS_{sys}}{dt}$$

$$\dot{m}\hat{s}_{in} - m\hat{s}_{out} + \dot{S}_{gen} = 0$$

$$7.5081 - 7.8255 + \dot{S}_{gen} = 0$$

$$\dot{S}_{gen} = 0.3174 kJ / \mathrm{kg}\, K$$