ESO 201A: Thermodynamics
2016-2017-I semester

Entropy: part 5

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Learning objectives

- Apply the second law of thermodynamics to processes.
- Define a new property called *entropy* to quantify the second-law effects.
- Establish the *increase of entropy principle*.
- Examine a special class of idealized processes, called *isentropic processes*, and develop the property relations for these processes.
- Calculate the entropy changes that take place during processes for pure substances, incompressible substances, and ideal gases.
- Examine a special class of idealized processes, called *isentropic processes*, and develop the property relations for these processes.
- Derive the reversible steady-flow work relations.
- Develop the isentropic efficiencies for various steady-flow devices.
- Introduce and apply the entropy balance to various systems.

Entropy balance

$$\begin{pmatrix}\text{Total}\\\text{entropy}\\\text{entering}\end{pmatrix} - \begin{pmatrix}\text{Total}\\\text{entropy}\\\text{leaving}\end{pmatrix} + \begin{pmatrix}\text{Total}\\\text{entropy}\\\text{generated}\end{pmatrix} = \begin{pmatrix}\text{Change in the}\\\text{total entropy}\\\text{of the system}\end{pmatrix}$$

Increase in entropy principle

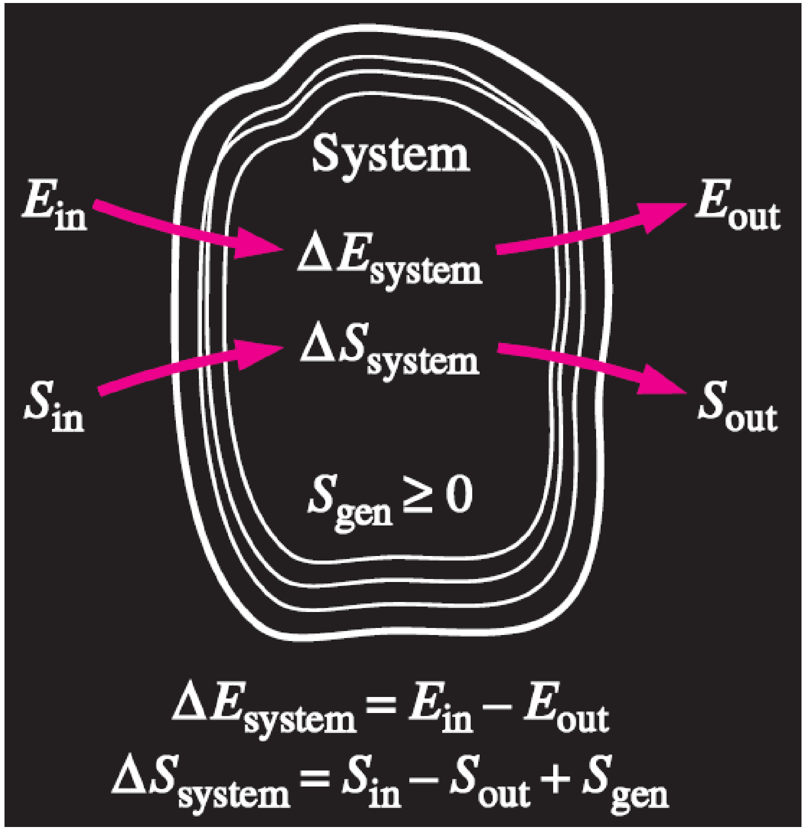
$$S_{\text{in}} - S_{\text{out}} + S_{\text{gen}} = \Delta S_{\text{system}}$$

Entropy Change of a System, ΔS_{system}

$$\Delta S_{\text{system}} = S_{\text{final}} - S_{\text{initial}} = S_2 - S_1$$

When the properties of the system are not uniform

$$S_{\text{system}} = \int s\,\delta m = \int_V s\rho\, dV$$



Energy and entropy balances for a system.

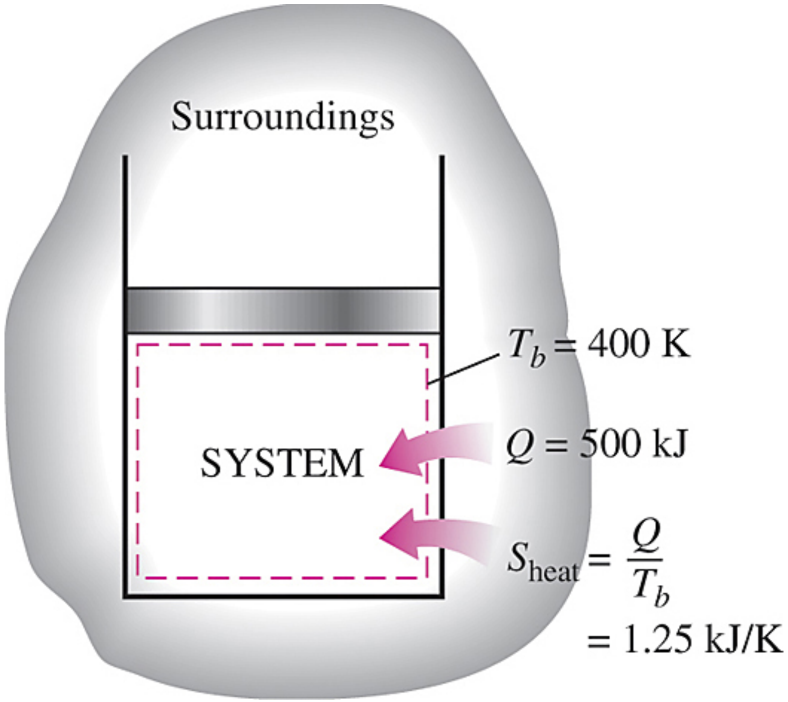
Mechanisms of entropy transfer, S_{in} and S_{out}

1 Heat Transfer

Entropy transfer by heat transfer:

$$S_{heat} = \frac{Q}{T} \qquad (T = \text{constant})$$

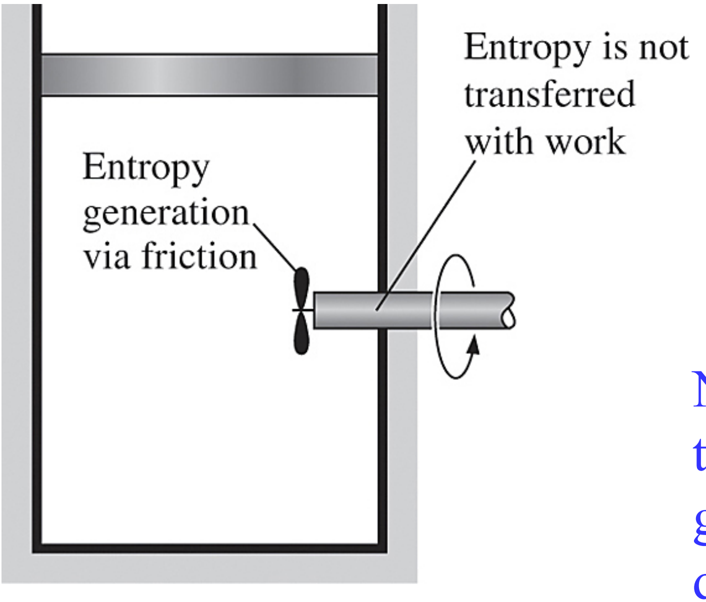
$$S_{heat} = \int_1^2 \frac{\delta Q}{T} \cong \sum \frac{Q_k}{T_k}$$



Heat transfer is always accompanied by entropy transfer in the amount of Q/T, where T is the boundary temperature.

Entropy transfer by

$$S_{work} = 0$$



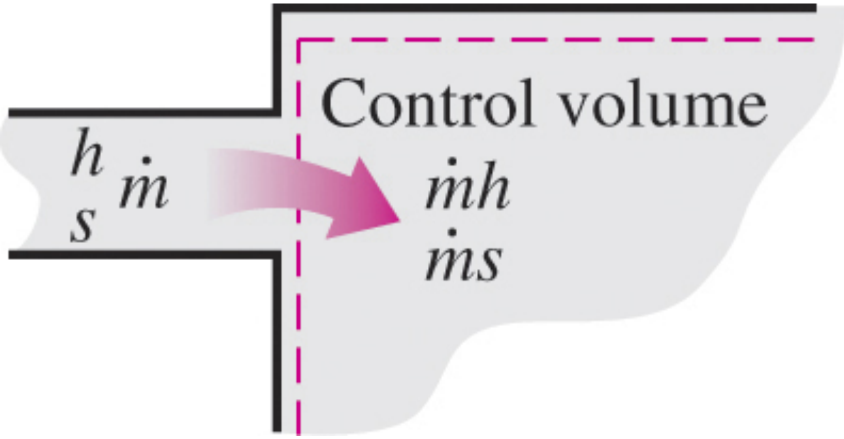
No entropy accompanies work as it crosses the system boundary. But entropy may be generated within the system as work is dissipated into a less useful form of energy.

Mechanisms of entropy transfer, S_{in} and S_{out}

2 Mass Flow

Entropy transfer by mass:

$$S_{\text{mass}} = ms$$



When the properties of the mass change during the process

$$\dot{S}_{\text{mass}} = \int s\rho V_n \, dA_c$$

$$S_{\text{mass}} = \int s \, \delta m = \int_{\Delta t} \dot{S}_{\text{mass}} \, dt$$

Mass contains entropy as well as energy, and thus mass flow into or out of system is always accompanied by energy and entropy transfer.

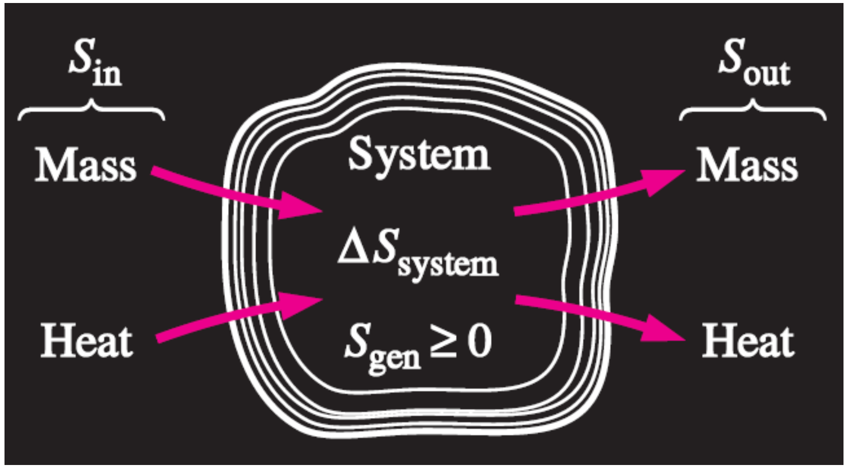
Entropy generation

$$\underbrace{S_{\rm in} - S_{\rm out}}_{\substack{\text{Net entropy transfer} \\ \text{by heat and mass}}} + \underbrace{S_{\rm gen}}_{\substack{\text{Entropy} \\ \text{generation}}} = \underbrace{\Delta S_{\rm system}}_{\substack{\text{Change} \\ \text{in entropy}}} \qquad ({\rm kJ/K})$$

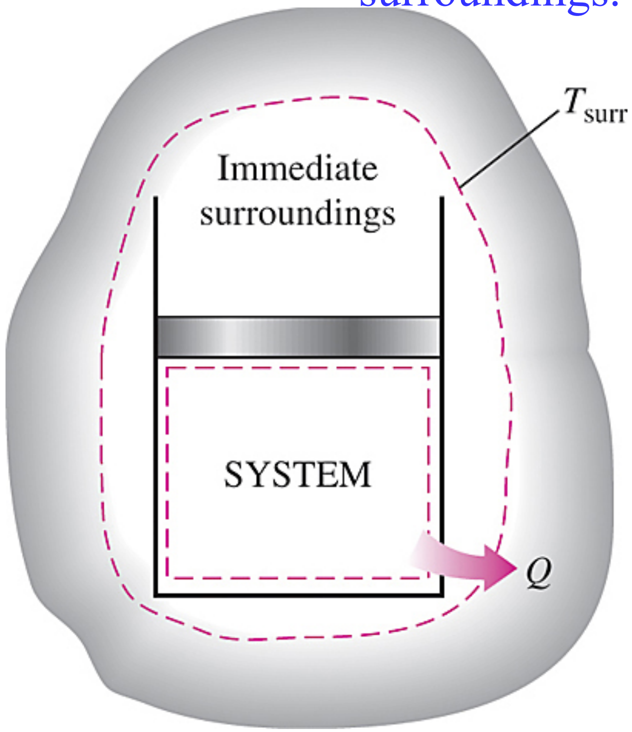
$$\underbrace{\dot{S}_{\rm in} - \dot{S}_{\rm out}}_{\substack{\text{Rate of net entropy} \\ \text{transfer by heat} \\ \text{and mass}}} + \underbrace{\dot{S}_{\rm gen}}_{\substack{\text{Rate of entropy} \\ \text{generation}}} = \underbrace{dS_{\rm system}/dt}_{\substack{\text{Rate of change} \\ \text{in entropy}}} \qquad ({\rm kW/K})$$

$$(s_{\rm in} - s_{\rm out}) + s_{\rm gen} = \Delta s_{\rm system} \qquad ({\rm kJ/kg \cdot K})$$

Entropy generation outside system boundaries can be accounted for by writing an entropy balance on an extended system that includes the system and its immediate surroundings.



Mechanisms of entropy transfer for a general system.



Closed sytem

The entropy change of a closed system during a process is equal to the sum of the net entropy transferred through the system boundary by heat transfer and the entropy generated within the system boundaries.

Closed system: $$\sum \frac{Q_k}{T_k} + S_{\text{gen}} = \Delta S_{\text{system}} = S_2 - S_1 \qquad \text{(kJ/K)}$$

Adiabatic closed system: $$S_{\text{gen}} = \Delta S_{\text{adiabatic system}}$$

Any closed system + surrounding can be considered as adiabatic

System + Surroundings: $$S_{\text{gen}} = \sum \Delta S = \Delta S_{\text{system}} + \Delta S_{\text{surroundings}}$$

$$\Delta S_{\text{system}} = m(s_2 - s_1)$$

Entropy change of the surrounding $\Delta S_{\text{surr}} = Q_{\text{surr}}/T_{\text{surr}}$

Control volume

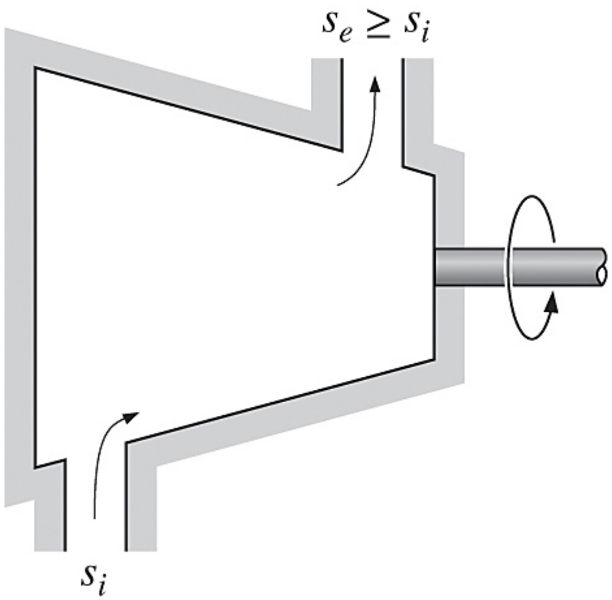
$$\sum \frac{Q_k}{T_k} + \sum m_i s_i - \sum m_e s_e + S_{\text{gen}} = (S_2 - S_1)_{\text{CV}} \qquad \text{(kJ/K)}$$

$$\sum \frac{\dot{Q}_k}{T_k} + \sum \dot{m}_i s_i - \sum \dot{m}_e s_e + \dot{S}_{\text{gen}} = dS_{\text{CV}}/dt \qquad \text{(kW/K)}$$

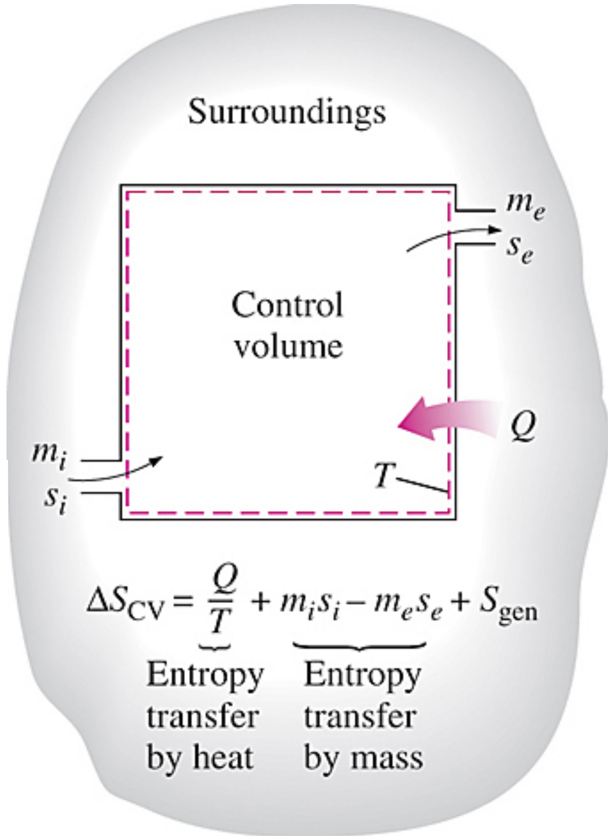
Steady-flow: $\dot{S}_{\text{gen}} = \sum \dot{m}_e s_e - \sum \dot{m}_i s_i - \sum \frac{\dot{Q}_k}{T_k}$

Steady-flow, single-stream: $\dot{S}_{\text{gen}} = \dot{m}(s_e - s_i) - \sum \frac{\dot{Q}_k}{T_k}$

Steady-flow, single-stream, adiabatic: $\dot{S}_{\text{gen}} = \dot{m}(s_e - s_i)$



The entropy of a substance always increases (or remains constant in the case of a reversible process) as it flows through a single-stream, adiabatic, steady-flow device.



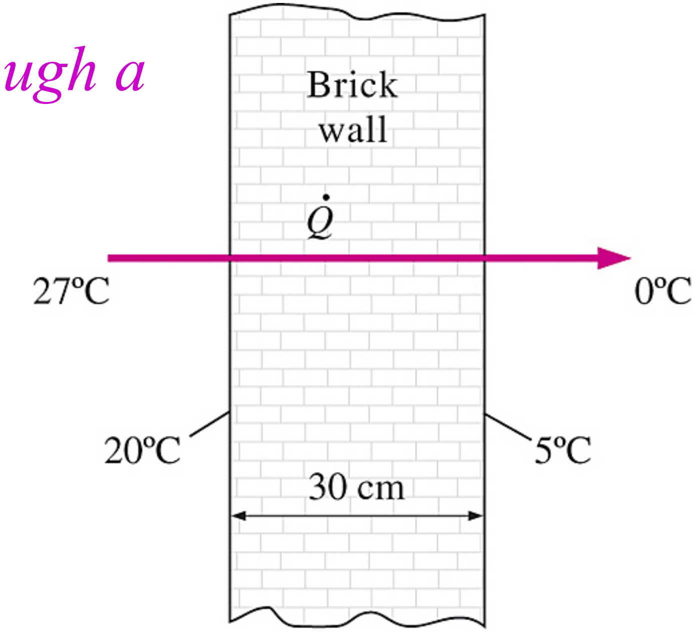
The entropy of a control volume changes as a result of mass flow as well as heat transfer.

Examples

Entropy balance for heat transfer through a wall

$$\underbrace{\dot{S}_{in} - \dot{S}_{out}}_{\substack{\text{Rate of net entropy}\\ \text{transfer by heat}\\ \text{and mass}}} + \underbrace{\dot{S}_{gen}}_{\substack{\text{Rate of entropy}\\ \text{generation}}} = \underbrace{dS_{system}/dt}_{\substack{\text{Rate of change}\\ \text{in entropy}}} \qquad \text{(kW/K)}$$

$$\left(\frac{\dot{Q}}{T}\right)_{in} - \left(\frac{\dot{Q}}{T}\right)_{out} + \dot{S}_{gen} = 0$$

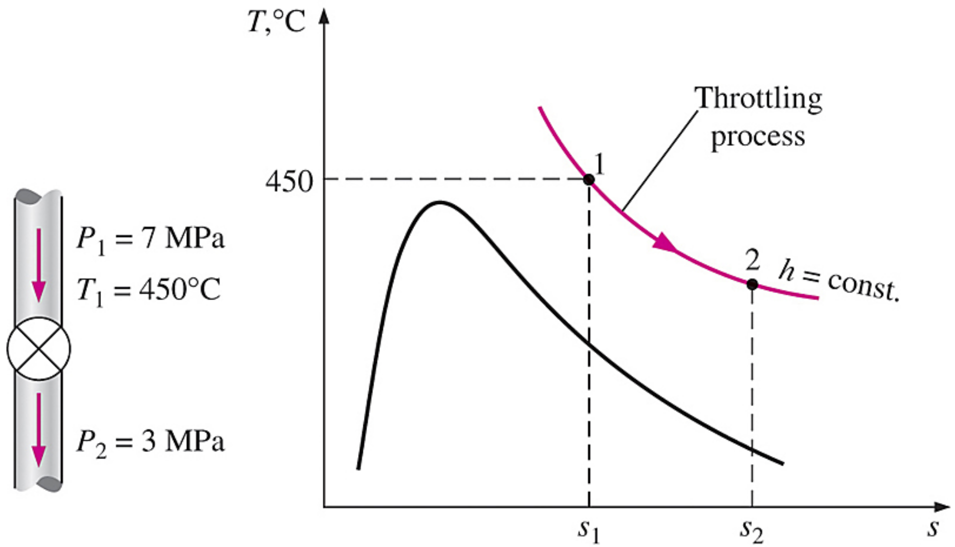


Entropy balance for a throttling process

$$\underbrace{\dot{S}_{in} - \dot{S}_{out}}_{\substack{\text{Rate of net entropy}\\ \text{transfer by heat}\\ \text{and mass}}} + \underbrace{\dot{S}_{gen}}_{\substack{\text{Rate of entropy}\\ \text{generation}}} = \underbrace{dS_{system}/dt}_{\substack{\text{Rate of change}\\ \text{in entropy}}}^{\nearrow 0 \text{ (steady)}}$$

$$\dot{m}s_1 - \dot{m}s_2 + \dot{S}_{gen} = 0$$

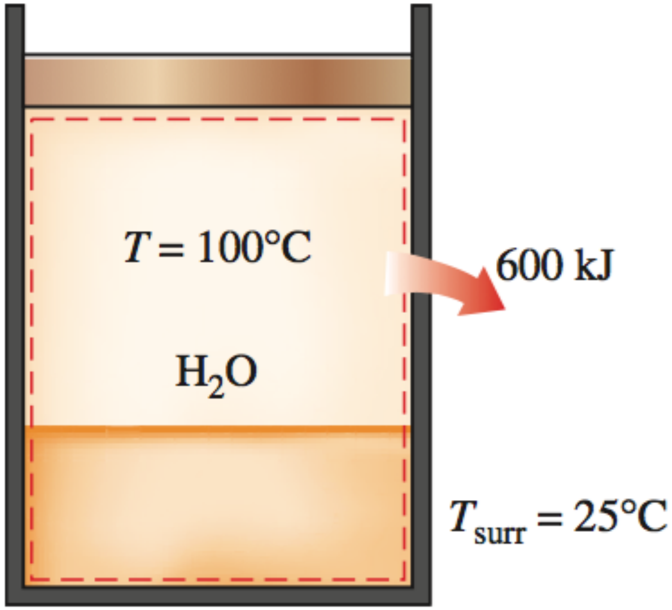
$$\dot{S}_{gen} = \dot{m}(s_2 - s_1)$$



Examples

A frictionless piston–cylinder device contains a saturated liquid–vapor mixture of water at 100°C. During a constant-pressure process, 600 kJ of heat is transferred to the surrounding air at 25°C. As a result, part of the water vapor contained in the cylinder condenses. Determine (a) the entropy change of the water and (*b*) the total entropy generation during this heat transfer process.

$$\Delta S_{\text{system}} = \frac{Q}{T_{\text{system}}} = \frac{-600 \text{ kJ}}{(100 + 273 \text{ K})} = \mathbf{-1.61 \text{ kJ/K}}$$



The entropy balance for this extended system (system + immediate surroundings) yields

$$\underbrace{S_{\text{in}} - S_{\text{out}}}_{\substack{\text{Net entropy transfer} \\ \text{by heat and mass}}} + \underbrace{S_{\text{gen}}}_{\substack{\text{Entropy} \\ \text{generation}}} = \underbrace{\Delta S_{\text{system}}}_{\substack{\text{Change} \\ \text{in entropy}}}$$

$$-\frac{Q_{\text{out}}}{T_b} + S_{\text{gen}} = \Delta S_{\text{sysem}}$$

$$S_{\text{gen}} = \frac{Q_{\text{out}}}{T_b} + \Delta S_{\text{system}} = \frac{600 \text{ kJ}}{(25 + 273) \text{ K}} + (-1.61 \text{ kJ/K}) = \mathbf{0.40 \text{ kJ/K}}$$

Summary

- Entropy
- The Increase of entropy principle
- Some remarks about entropy
- Entropy change of pure substances
- Isentropic processes
- Property diagrams involving entropy
- What is entropy?
- The *T ds* relations
- Entropy change of liquids and solids
- The entropy change of ideal gases
- Reversible steady-flow work
- Minimizing the compressor work
- Isentropic efficiencies of steady-flow devices
- Entropy balance