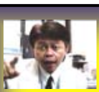

Thermodynamics Lecture Series

Assoc. Prof. Dr. J.J.

Entropy – Quantifying Energy Degradation

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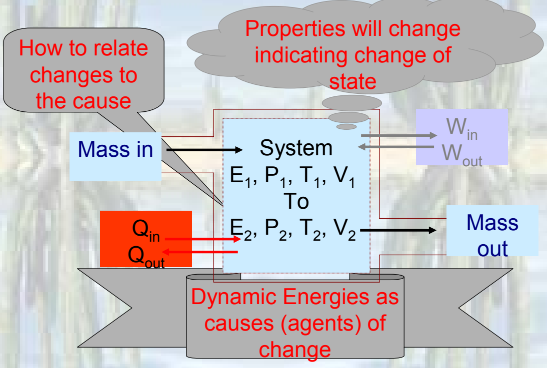
Quotes

- "The principal goal of education is to create men and women who are capable of doing new things, not simply repeating what other generations have done" Jean Piaget
- "What we have to learn to do, we learn by doing" Einstein

Review - First Law



Review - First Law

Energy Entering a system	-	Energy Leaving a system	=	Change of system's energy

Energy Balance

$E_{in} - E_{out} = \Delta E_{sys}$, kJ or

$e_{in} - e_{out} = \Delta e_{sys}$, kJ/kg or

$\dot{E}_{in} - \dot{E}_{out} = \Delta \dot{E}_{sys}$, kW

Review - First Law

Mass Entering a system	-	Mass Leaving a system	=	Change of system's mass

Mass Balance

$m_{in} - m_{out} = \Delta m_{sys}$, kg or

$\dot{m}_{in} - \dot{m}_{out} = \Delta \dot{m}_{sys}$, kg / s

Review - First Law

Energy Balance – Control Volume Steady-Flow

Steady-flow is a flow where all properties within boundary of the system remains constant with time

$\Delta E_{sys} = 0$, kJ; $\Delta e_{sys} = 0$, kJ/kg, $\Delta V_{sys} = 0$, m^3;

$\Delta m_{sys} = 0$ or $m_{in} = m_{out}$, kg $\Delta \dot{m}_{sys} = 0$, kg/s

$\dot{m}_{in} - \dot{m}_{out} = 0$ or $\dot{m}_{in} = \dot{m}_{out}$, kg/s

Review - First Law

Mass & Energy Balance–Steady-Flow: Single Stream

Mass balance

$$\Delta \dot{m}_{sys} = 0.\ So,\ \ \dot{m}_{in} = \dot{m}_{out}\ ,\ kg/s$$

Energy balance $\Delta \dot{E}_{sys} = 0.\ So,\ \ \dot{E}_{in} = \dot{E}_{out}\ ,\ kJ/s$

$$\dot{Q}_{in} - \dot{Q}_{out} + \dot{W}_{in} - \dot{W}_{out} = \left(\dot{m}\,\vartheta\right)_{out} - \left(\dot{m}\,\vartheta\right)_{in}\ ,\ kW$$

$$q_{in} - q_{out} + \omega_{in} - \omega_{out} = \theta_{out} - \theta_{in},\ kJ/kg$$

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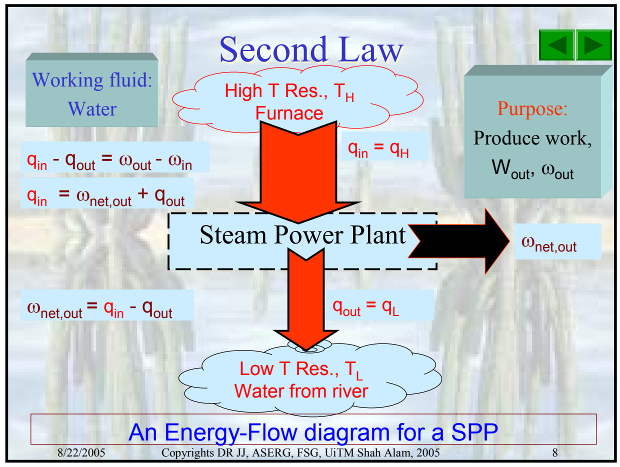

Second Law

Thermal Efficiency for steam power plants

$$\eta = \frac{desired\ \ output}{required\ \ input} = \frac{\omega_{net,out}}{q_{in}}$$

$$\eta = \frac{\omega_{net,out}}{q_{in}} = \frac{q_{in} - q_{out}}{q_{in}} = \frac{q_{in}}{q_{in}} - \frac{q_{out}}{q_{in}}$$

$$= 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{q_L}{q_H}$$

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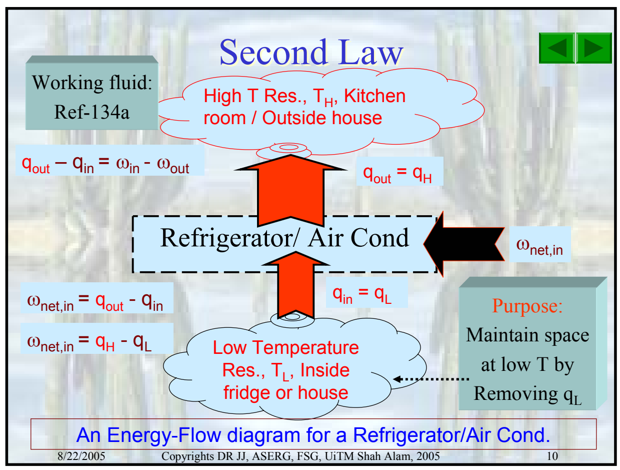

Second Law

Coefficient of Performance for a Refrigerator

$$COP_R = \frac{desired\ \ output}{required\ \ input} = \frac{q_{in}}{\omega_{net,in}}$$

$$COP_R = \frac{q_{in}}{\omega_{net,in}} = \frac{q_{in}}{q_{out} - q_{in}}$$

$$= \frac{1}{\frac{q_{out}}{q_{in}} - \frac{q_{in}}{q_{in}}} = \frac{1}{\frac{q_{out}}{q_{in}} - 1} = \frac{1}{\frac{q_H}{q_L} - 1}$$

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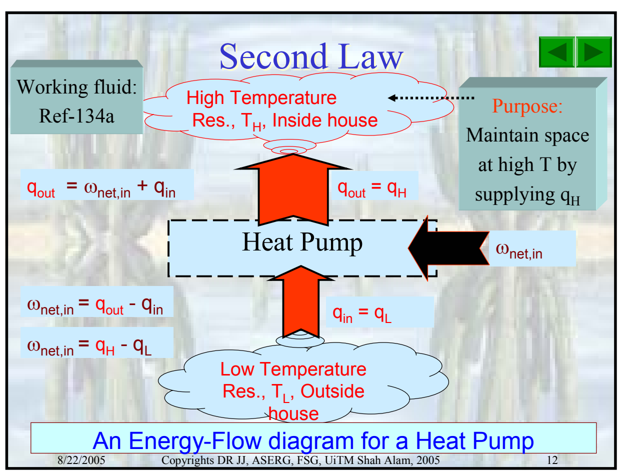

Second Law

Coefficient of Performance for a Heat Pump

$$COP_{HP} = \frac{desired\ \ output}{required\ \ input} = \frac{q_{out}}{\omega_{net,in}}$$

$$COP_{HP} = \frac{q_{out}}{\omega_{net,in}} = \frac{q_{out}}{q_{out} - q_{in}}$$

$$= \frac{1}{\frac{q_{out}}{q_{out}} - \frac{q_{in}}{q_{out}}} = \frac{1}{1 - \frac{q_{in}}{q_{out}}} = \frac{1}{1 - \frac{q_L}{q_H}}$$

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Second Law – Energy Degrade

What is the maximum performance of real engines if it can never achieve 100%??

Factors of irreversibilities

- less heat can be converted to work
  - Friction between 2 moving surfaces
  - Processes happen too fast
  - Non-isothermal heat transfer

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Second Law – Dream Engine

Carnot Cycle

- **Isothermal expansion**

❖Slow adding of Q resulting in work done by system (system expand)

❖$Q_{in} – W_{out} = \Delta U = 0$. So, $Q_{in} = W_{out}$. Pressure drops.

- **Adiabatic expansion**

❖$0 – W_{out} = \Delta U$. Final U smaller than initial U.

❖T & P drops.

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Second Law – Dream Engine

Carnot Cycle

- Isothermal compression

❖Work done on the system

❖Slow rejection of Q

❖$- Q_{out} + W_{in} = \Delta U = 0$. So, $Q_{out} = W_{in}$.

❖Pressure increases.

- Adiabatic compression

❖$0 + W_{in} = \Delta U$. Final U higher than initial U.

❖T & P increases.

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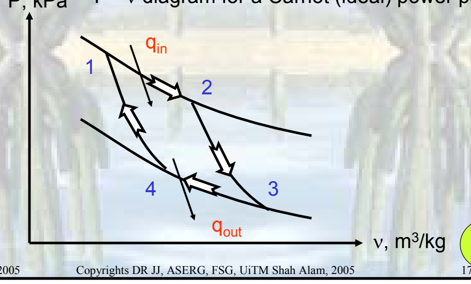
Second Law – Dream Engine

Carnot Cycle

P - ν diagram for a Carnot (ideal) power plant



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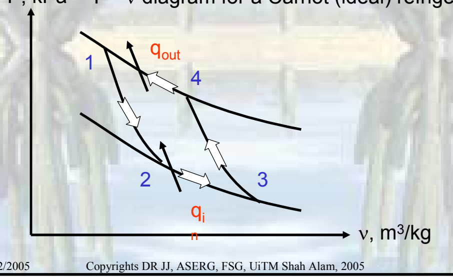
Second Law – Dream Engine

Reverse Carnot Cycle

P - ν diagram for a Carnot (ideal) refrigerator



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Second Law – Dream Engine

Carnot Principles

- For heat engines in contact with the same hot and cold reservoir
  - ❖All reversible engines have the same performance.
  - ❖Real engines will have lower performance than the ideal engines.

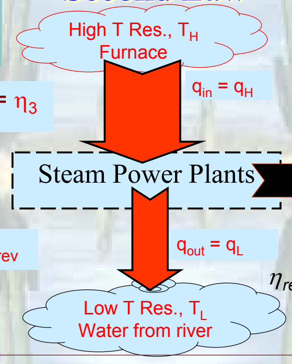
$$\left(\frac{q_H}{q_L}\right)_{rev} = \frac{T_H\ (K)}{T_L\ (K)}$$

Second Law

Working fluid: Not a factor

P1: $\eta_1 = \eta_2 = \eta_3$

P2: $\eta_{real} < \eta_{rev}$



$$\eta_{real} = 1 - \frac{q_L}{q_H}$$

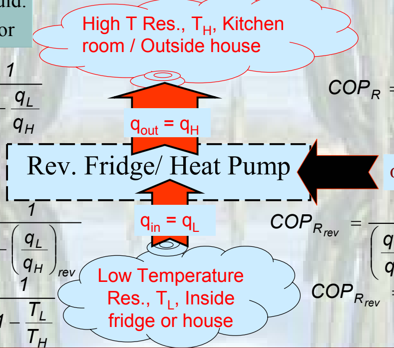
$$\eta_{rev} = 1 - \frac{T_L\ (K)}{T_H\ (K)}$$

An Energy-Flow diagram for a Carnot SPPs

Second Law

Working fluid: Not a factor

$$COP_{HP} = \frac{1}{1 - \frac{q_L}{q_H}} \qquad COP_R = \frac{1}{\frac{q_H}{q_L} - 1}$$



$$COP_{HP_{rev}} = \frac{1}{1 - \left(\frac{q_L}{q_H}\right)_{rev}} \qquad COP_{R_{rev}} = \frac{1}{\left(\frac{q_H}{q_L}\right)_{rev} - 1}$$

$$COP_{HP_{rev}} = \frac{1}{1 - \frac{T_L}{T_H}} \qquad COP_{R_{rev}} = \frac{1}{\frac{T_H}{T_L} - 1}$$

An Energy-Flow diagram for Carnot Fridge/Heat Pump

Second Law – Will a Process Happen

Carnot Principles

- For heat engines in contact with the same hot and cold reservoir
  - ❖P1: $\eta_1 = \eta_2 = \eta_3$ (Equality)
  - ❖P2: $\eta_{real} < \eta_{rev}$ (Inequality)

$$\eta_{real} \le \eta_{rev}$$

Processes satisfying Carnot Principles obeys the Second Law of Thermodynamics

Second Law – Will a Process Happen

Clausius Inequality :

- Sum of Q/T in a cyclic process must be zero for reversible processes and negative for real processes

$$\oint \frac{\delta Q}{T} \le 0,\ \frac{kJ}{K} \qquad \oint \frac{\delta q}{T} \le 0,\ \frac{kJ}{kg \bullet K}$$

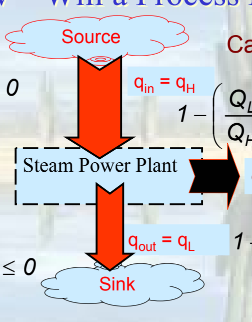
$$\oint \frac{\delta Q}{T} = 0,\ \text{reversible}$$

$$\oint \frac{\delta Q}{T} < 0,\ \text{real}$$

$$\oint \frac{\delta Q}{T} > 0,\ \text{impossible}$$

Second Law – Will a Process Happen

Carnot SPP



$$\oint \frac{\delta Q}{T} = \frac{Q_H}{T_H} - \frac{Q_L}{T_L} \le 0$$

$$\frac{Q_H}{T_H} - \frac{Q_L}{T_L} \le 0$$

$$\frac{Q_H}{T_H}\frac{T_H}{Q_H} - \frac{T_H}{Q_H}\frac{Q_L}{T_L} \le 0$$

$$1 - \left(\frac{Q_L}{Q_H}\right)_{rev}\frac{T_H}{T_L} \le 0$$

$$1 - \frac{T_L}{T_H}\frac{T_H}{T_L} \le 0$$

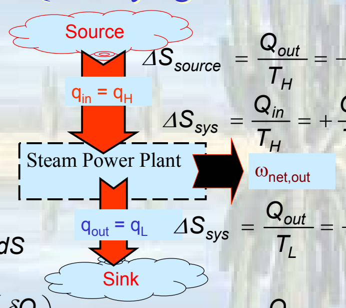
$$1 - 1 = 0$$

Processes satisfying Clausius Inequality obeys the Second Law of Thermodynamics

Entropy – Quantifying Disorder

Entropy

$$dS = \left(\frac{\delta Q}{T}\right)_{int\ rev}$$



$$\Delta S_{source} = \frac{Q_{out}}{T_H} = -\frac{Q_H}{T_H}$$

$$\Delta S_{sys} = \frac{Q_{in}}{T_H} = +\frac{Q_H}{T_H}$$

$$\Delta S_{sys} = \frac{Q_{out}}{T_L} = -\frac{Q_L}{T_L}$$

$$\Delta S_{sink} = \frac{Q_{in}}{T_L} = +\frac{Q_L}{T_L}$$

Entropy Change in a process

$$\Delta S = S_2 - S_1 = \int_1^2 dS$$

$$\Delta S = S_2 - S_1 = \int_1^2 \left(\frac{\delta Q}{T}\right)_{int\ rev}$$

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Entropy – Quantifying Disorder

- Entropy
  - ✓Quantitative measure of disorder or chaos
  - ✓Is a system's property, just like the others
  - ✓Does not depend on process path
  - ✓Has values at every state

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Entropy – Quantifying Disorder

Entropy

- ✓ Quantifies lost of energy quality
- ✓ Can be transferred by heat and mass or
- ✓ generated due to irreversibilty factors:
  - ➢ Frictional forces between moving surfaces.
  - ➢ Fast expansion & compression.
  - ➢ Heat transfer at finite temperature difference.

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Entropy – Quantifying Disorder

Increase of Entropy Principle

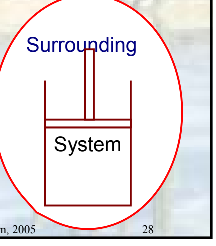
The entropy of an isolated (closed and adiabatic) system undergoing any process, will always increase.

$$\Delta S_{isolated} = \Delta S_{sys} + \Delta S_{surr} \geq 0$$

For pure substance:

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

$$\Delta S_{surr} = \frac{(Q_{in} - Q_{out})_{surr}}{T_{surr}}$$



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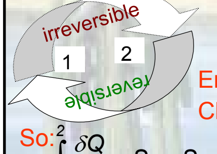
Entropy – Quantifying Disorder

Increase of Entropy Principle Proven

– Consider the following cyclic process containing an irreversible forward path and a reversible return path

Clausius Inequality

$$\oint \frac{\delta Q}{T} = \int_1^2 \frac{\delta Q}{T} + \int_2^1 \left(\frac{\delta Q}{T}\right)_{int\ rev} \leq 0$$



Entropy Change

$$S_1 - S_2 = \int_2^1 dS = \int_2^1 \left(\frac{\delta Q}{T}\right)_{int\ rev}$$

So:

$$\int_1^2 \frac{\delta Q}{T} + S_1 - S_2 \leq 0$$

Then:

$$S_2 - S_1 \geq \int_1^2 \frac{\delta Q}{T}$$

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Entropy – Quantifying Disorder

Increase of Entropy Principle Proven

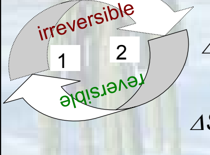
– Consider the following cyclic process containing an irreversible forward path and a reversible return path

Then entropy change for the closed system:

$$\Delta S_{sys} = S_2 - S_1 \geq \int_1^2 \frac{\delta Q}{T}$$

$$\Delta S_{sys} = S_2 - S_1 = \int_1^2 \frac{\delta Q}{T}, \text{ rev.}$$

$$\Delta S_{sys} = S_2 - S_1 > \int_1^2 \frac{\delta Q}{T}, \text{ irrev.}$$



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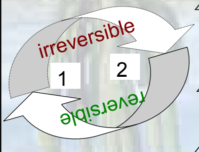
Entropy – Quantifying Disorder

Increase of Entropy Principle Proven

– Consider the following cyclic process containing an irreversible forward path and a reversible return path

Then entropy change for the closed system:



$$\Delta S_{sys} = S_2 - S_1 \geq \int_1^2 \frac{\delta Q}{T}$$

$$\Delta S_{sys} = S_2 - S_1 = \int_1^2 \frac{\delta Q}{T} + S_{gen}$$

$$\Delta S_{sys} = S_2 - S_1 = S_{heat} + S_{gen}$$

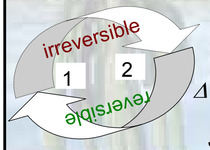
Entropy – Quantifying Disorder

Increase of Entropy Principle Proven

– Consider the following cyclic process containing an irreversible forward path and a reversible return path

Then entropy change for the closed system:

$$\Delta S_{sys} = S_2 - S_1 = S_{heat} + S_{gen}$$



For adiabatic process:

$$\Delta S_{adiab\ sys} = S_2 - S_1 = 0 + S_{gen}$$

$$S_2 - S_1 = S_{gen}$$

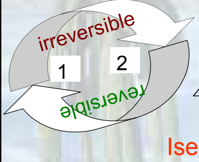
Entropy – Quantifying Disorder

Increase of Entropy Principle Proven

– Consider the following cyclic process containing an irreversible forward path and a reversible return path

Then entropy change for the closed system:

$$\Delta S_{sys} = S_2 - S_1 = S_{heat} + S_{gen}$$



For adiabatic reversible system:

$$\Delta S_{iso\ sys} = S_2 - S_1 = 0 + 0 \qquad S_2 = S_1$$

Isentropic or constant entropy process

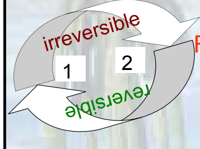
Entropy – Quantifying Disorder

Increase of Entropy Principle Proven

– Consider the following cyclic process containing an irreversible forward path and a reversible return path

Then entropy change for the closed system:

$$\Delta S_{sys} = S_2 - S_1 = S_{heat} + S_{gen}$$



For isolated (adiabatic & closed) system

$$\Delta S_{iso\ sys} = 0 + S_{gen} \geq 0$$

$$S_{gen} = \Delta S_{sys} + \Delta S_{surr} \geq 0$$

Entropy – Quantifying Disorder

T – S diagram

Area of curve under P – V diagram represents total work done

Area of curve under T – S diagram represents total heat transfer

Recall $dS = \left(\frac{\delta Q}{T}\right)_{int\ rev}$

Then $\delta Q_{int\ rev} = TdS$

Hence total heat transfer is

$$Q = \int_1^2 \delta Q_{int\ rev} = \int_1^2 TdS$$

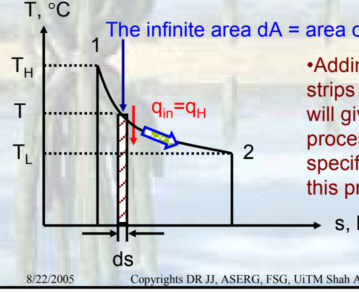
Area under T- S diagram is amount of heat in a process

Entropy – Quantifying Disorder

T – s diagram

$$A = \int_1^2 dA = \int_1^2 Tds = q_{in}$$

The infinite area dA = area of strip = Tds



•Adding all the area of the strips from state 1 to state 2 will give the total area under process curve. It represents specific heat received for this process

Entropy – Quantifying Disorder

Factors affecting Entropy (disorder)

- Entropy will change when there is
  - Heat transfer (receiving heat increases entropy)
  - Mass transfer (moving mass changes entropy)
  - Irreversibilities (entropy will always be generated)

Entropy – Quantifying Disorder

Entropy Balance

- For any system undergoing any process,
  - Energy must be conserved ($E_{in} - E_{out} = \Delta E_{sys}$)
  - Mass must be conserved ($m_{in} - m_{out} = \Delta m_{sys}$)
  - Entropy will always be generated except for reversible processes
    - Entropy balance is ($S_{in} - S_{out} + S_{gen} = \Delta S_{sys}$)

Entropy – Quantifying Disorder

Entropy Balance –Closed system

Energy Balance: $q_{in} - q_{out} + \omega_{in} - \omega_{out} = \Delta u + \Delta ke + \Delta pe$

Entropy Balance: $s_{in} - s_{out} + s_{gen} = \Delta s_{sys}, \quad \frac{kJ}{kg \bullet K}$

$$(s_{heat} + s_{mass})_{in} - (s_{heat} + s_{mass})_{out} + s_{gen} = \Delta s_{sys}$$

$$s_{gen} = \Delta s_{sys} + (s_{heat} + 0)_{out} - (s_{heat} + 0)_{in}, \quad \frac{kJ}{kg \bullet K}$$

$$s_{gen} = m(s_2 - s_1)_{sys} + \left(\frac{q_{out}}{T_{out}} - \frac{q_{in}}{T_{in}}\right)_{sys}, \quad \frac{kJ}{kg \bullet K}$$

Entropy – Quantifying Disorder

Entropy Balance –Steady-flow device

$$\dot{Q}_{in} - \dot{Q}_{out} + \dot{W}_{in} - \dot{W}_{out} = \left(\dot{m}\,\vartheta\right)_{out} - \left(\dot{m}\,\vartheta\right)_{in}, \; kW$$

$$\dot{S}_{in} - \dot{S}_{out} + \dot{S}_{gen} = \Delta S_{sys} = 0 \qquad So, \; \dot{S}_{gen} = \dot{S}_{out} - \dot{S}_{in}$$

Then: $\dot{S}_{gen} = \left(\dot{S}_{heat} + \dot{S}_{mass}\right)_{out} - \left(\dot{S}_{heat} + \dot{S}_{mass}\right)_{in}$

$$\dot{S}_{gen} = \frac{\dot{Q}_{out}}{T_{out}} + \left(\sum \dot{m}\,s\right)_{exit} - \frac{\dot{Q}_{in}}{T_{in}} - \left(\sum \dot{m}\,s\right)_{inlet}$$

Entropy – Quantifying Disorder

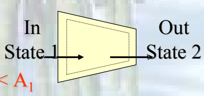
Entropy Balance –Steady-flow device

Nozzle: $\dot{Q}_{in} - \dot{Q}_{out} + \dot{W}_{in} - \dot{W}_{out} = \dot{m}(\vartheta_{exit} - \vartheta_{inlet})$, kW

Assume adiabatic, no work done, $\Delta pe_{mass} = 0$ where $\dot{m}_{inlet} = \dot{m}_{exit} = \dot{m}$

$$0 - 0 + 0 - 0 = \dot{m}(h_2 + ke_2 - h_1 - ke_1), \text{kW}$$

Entropy Balance $\dot{S}_{gen} = \frac{\dot{Q}_{out}}{T_{out}} - \frac{\dot{Q}_{in}}{T_{in}} + \dot{m}_2 s_2 - \dot{m}_1 s_1, \quad \frac{kW}{K}$



$$\dot{S}_{gen} = 0 - 0 + \dot{m}(s_2 - s_1), \quad \frac{kW}{K}$$

$A_2 << A_1$

Entropy – Quantifying Disorder

Entropy Balance –Steady-flow device

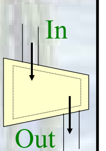
Turbine: $\dot{Q}_{in} - \dot{Q}_{out} + \dot{W}_{in} - \dot{W}_{out} = \dot{m}(\vartheta_{exit} - \vartheta_{inlet})$, kW

Assume adiabatic, $\Delta ke_{mass} = 0$, $\Delta pe_{mass} = 0$ where $\dot{m}_{inlet} = \dot{m}_{exit} = \dot{m}$

$$0 - 0 + 0 - \dot{W}_{out} = \dot{m}(h_2 - h_1), \text{kW}$$

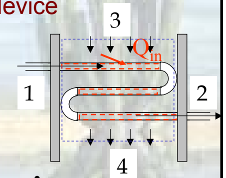
Entropy Balance $\dot{S}_{gen} = \frac{\dot{Q}_{out}}{T_{out}} - \frac{\dot{Q}_{in}}{T_{in}} + \dot{m}_2 s_2 - \dot{m}_1 s_1, \quad \frac{kW}{K}$

$$\dot{S}_{gen} = 0 - 0 + \dot{m}(s_2 - s_1), \quad \frac{kW}{K}$$



Entropy – Quantifying Disorder

Entropy Balance –Steady-flow device



Heat exchanger: energy balance; 2 cases

where $\dot{m}_{inlet} = \dot{m}_{exit} = \dot{m}$

Assume $\Delta ke_{mass} = 0, \Delta pe_{mass} = 0$

Case 1 $\dot{Q}_{in} - \dot{Q}_{out} + \dot{W}_{in} - \dot{W}_{out} = \dot{m}(\vartheta_{exit} - \vartheta_{inlet})$, kW

$$0 = \dot{m}_4 h_4 - \dot{m}_3 h_3 + \dot{m}_2 h_2 - \dot{m}_1 h_1, kW$$

Case 2 $\dot{Q}_{in} - \dot{Q}_{out} = \dot{m}_2 h_2 - \dot{m}_1 h_1, kW$

$$\dot{Q}_{in} - 0 = \dot{m}_2 h_2 - \dot{m}_1 h_1, kW$$

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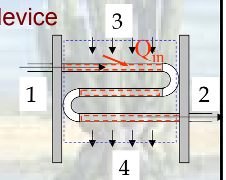
Entropy – Quantifying Disorder

Entropy Balance –Steady-flow device



Heat exchanger:

Entropy Balance

where $\dot{m}_{inlet} = \dot{m}_{exit} = \dot{m}$

Case 1

$$\dot{S}_{gen} = 0 - 0 + \dot{m}_4 s_4 - \dot{m}_3 s_3 + \dot{m}_2 s_2 - \dot{m}_1 s_1, \frac{kW}{K}$$

Case 2

$$\dot{S}_{gen} = \frac{\dot{Q}_{out}}{T_{out}} - \frac{\dot{Q}_{in}}{T_{in}} + \dot{m}_2 s_2 - \dot{m}_1 s_1, \frac{kW}{K}$$

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Entropy – Quantifying Disorder

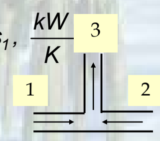
Entropy Balance –Steady-flow device

Mixing Chamber:

$$\dot{Q}_{in} - \dot{Q}_{out} + \dot{W}_{in} - \dot{W}_{out} = \sum\left(\dot{m}\,\vartheta\right)_{exit} - \sum\left(\dot{m}\,\vartheta\right)_{inlet}, kW$$

$$\dot{Q}_{in} - \dot{Q}_{out} + \dot{W}_{in} - \dot{W}_{out} = \dot{m}_3 h_3 - \dot{m}_2 h_2 - \dot{m}_1 h_1, kW$$

$$\dot{S}_{gen} = \frac{\dot{Q}_{out}}{T_{out}} - \frac{\dot{Q}_{in}}{T_{in}} + \dot{m}_3 s_3 - \dot{m}_2 s_2 - \dot{m}_1 s_1, \frac{kW}{K}$$



where $\dot{m}_{inlet} = \dot{m}_{exit}$

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