Exergy analysis in conversion and process units.

Summary

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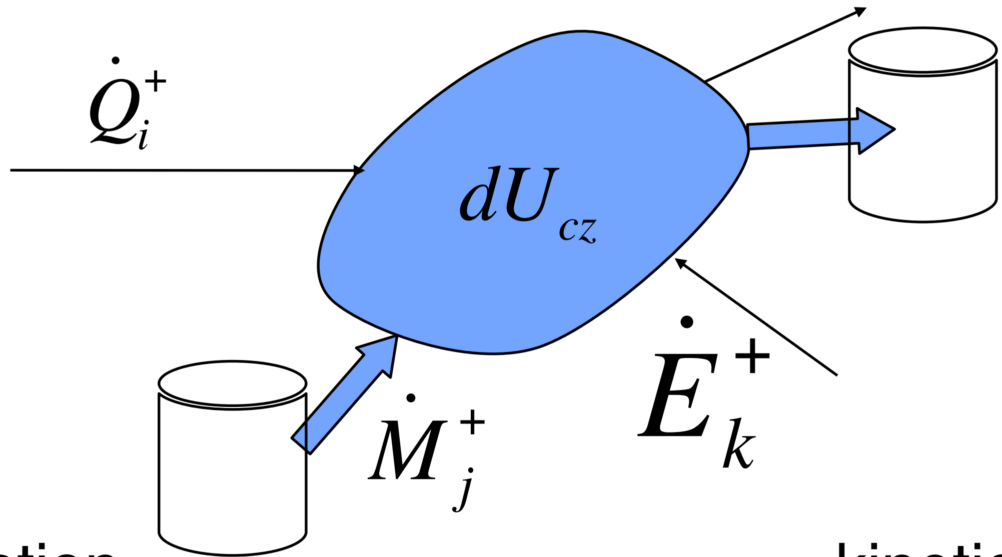
References : Borel-Favrat : Chapters 11-12-13-14

Energy balance of a system

First law of thermodynamics



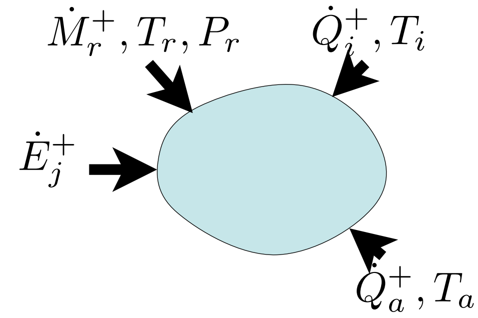
Accumulation

kinetic

$$\frac{dU_{cz}}{dt} = \sum_k \dot{E}_k^+ + \sum_i \dot{Q}_i^+ + \sum_j \left(h_j + \frac{c_j^2}{2} + g z_j\right) \dot{M}_j^+$$

enthalpy Potential

Notion of exergy : Generalisation



1st principle: energy balance

$$\sum \dot{E}_j^+ + \sum \dot{Q}_i^+ + \sum \dot{M}_r^+ h_r(T_r, P_r, X_r) + \dot{Q}_a^+ = 0 \qquad \textbf{(1)}$$

2nd principle: entropy balance

$$dS = \sum_i \frac{\dot{Q}_i^+}{T_i} + \sum_r \dot{M}_r^+ s_r(T_r, P_r, X_r) + \frac{\dot{Q}_a^+}{T_a} \geq 0$$

$$\Rightarrow T_a dS = \sum_i \frac{T_a \dot{Q}_i^+}{T_i} + \sum_r \dot{M}_r^+ T_a s_r(T_r, P_r, X_r) + \dot{Q}_a^+ \geq 0 \qquad \textbf{(2)}$$

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(1) - (2) $$\sum_j \dot{E}_j^+ + \sum_i \dot{Q}_i^+ (1 - \frac{T_a}{T_i}) + \sum_r \dot{M}_r^+ (h_r - T_a s_r) \leq 0$$

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then $$\sum_j \dot{E}_j^- \leq \sum_i \dot{Q}_i^+ (1 - \frac{T_a}{T_i}) + \sum_r \dot{M}_r^+ (h_r - T_a s_r)$$

therefore $$E_{max}^- = \sum_i \dot{Q}_i^+ (1 - \frac{T_a}{T_i}) + \sum_r \dot{M}_r^+ (h_r - T_a s_r)$$ Exergy = max work

$$\dot{L} = \dot{E}_{max}^- - \sum_j \dot{E}_j^- \geq 0$$ Exergy loss
=> wrt max work

Exergy

The **exergy** associated with an energy transfer or an energy storage is defined as the **maximal work** that it would ideally be possible to produce out of each energy unit transfered or stored through the help of reversible transformations that exchange only with the environment.

The exergy approach allows for **quantifying** in a coherent way at the same time the **quantity and the quality** of the different forms of energy involved.

The exergy has the big advantage that it allows for defining efficiencies that are adaptable to every situation (combined heat and power, trigeneration, refrigeration, heat pumps, etc.) and for every domain of energy utilization. These **efficiencies, that are always lower than 100%,** give an appreciation of the relative quality of the different technical concepts.

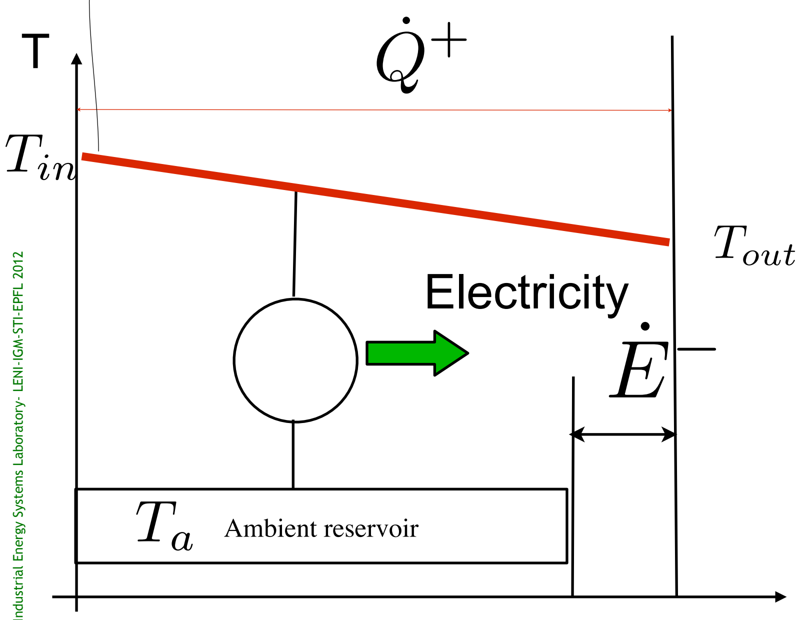
Exergy content : environment

- Thermal exergy : Ambient temperature
- Pressure : Atmospheric pressure
- Composition : Partial pressure vs environment
- Material flows : exergy of formation (vs compounds in environment).

The exergy value of a heat source

$$E^{-}_{max} = \dot{M}_h((h(T_{in}) - T_a s(T_{in})) - (h(T_{out}) - T_a s(T_{out})))$$

$$d\dot{E}^{-}_{max} = d\dot{Q}^{+} * (1 - \frac{T_a}{T})$$



$$\dot{Q}^{-}_a = \dot{Q}^{+} - \dot{E}^{-}$$

$$\dot{E}^{-}_{max} = \int_{T_{in}}^{T_{out}} (1 - \frac{T_a}{T}) \cdot d\dot{Q}$$

$$E^{-}_{max} = \dot{M}_h \int_{T_{in}}^{T_{out}} cp(T)(1 - \frac{T_a}{T})dT$$

When a fluid is cooled down from T_{in} to T_{out} with a heat load of $\dot{Q}^{-}$, it has the capacity of delivering $\dot{E}^{-}_{max}$ by exchanging heat with the environment at T_a

if c_{p_h} is constant

$$\dot{E}^{-}_{max} = \int_{T_{in}}^{T_{out}} d\dot{E}^{-}_{max} = \dot{M}_h c_{\mathrm{p}_h} \int_{T_{in}}^{T_{out}} (1 - \frac{T_a}{T}) dT$$

$$\dot{E}^{-}_{max} = \dot{M}_h c_{\mathrm{p}_h} \{(T_{in} - T_{out}) - T_a(ln(T_{in}) - ln(T_{out}))\}$$

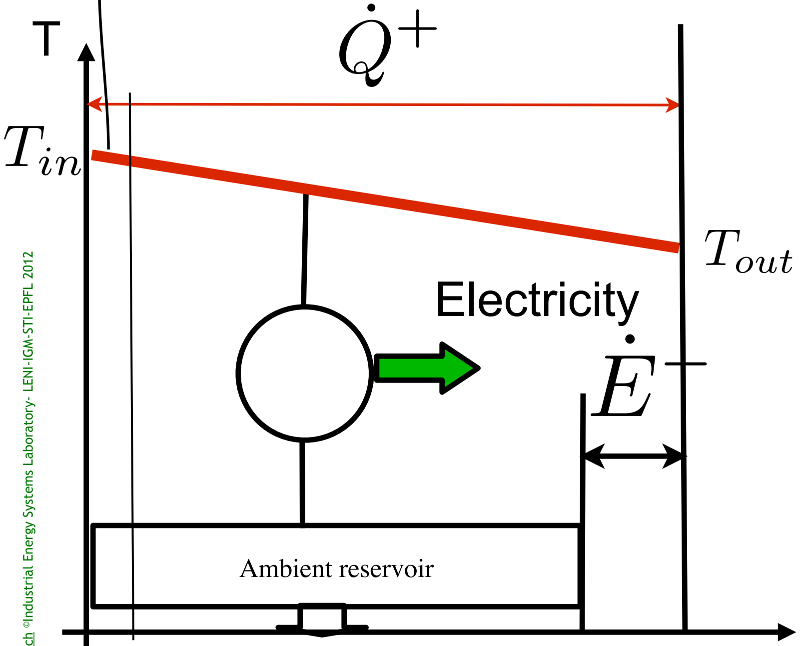
$$\dot{Q}^{+} = \dot{M}_h c_{p_h} (T_{in} - T_{out}) \qquad T_{lm} = \frac{T_{in} - T_{out}}{ln(T_{in}) - ln(T_{out})}$$

$$\boxed{\dot{E}^{-}_{max} = \dot{Q}^{+} * (1 - \frac{T_a}{T_{lm}})}$$

Carnot factor is calculated with the logarithmic mean of temperatures in (K)

The exergy value of a heat source

$$d\dot{E}^-_{max} = d\dot{Q}^+ * (1 - \frac{T_a}{T})$$



$$\dot{Q}^-_a = \dot{Q}^+ - \dot{E}^-$$

$\dot{E}^-_{max}$ is the maximum possible production

$$\dot{E}^-_{max} = \dot{Q}^+ * (1 - \frac{T_a}{T_{lm}})$$

$\dot{E}^-$ is the effective possible production

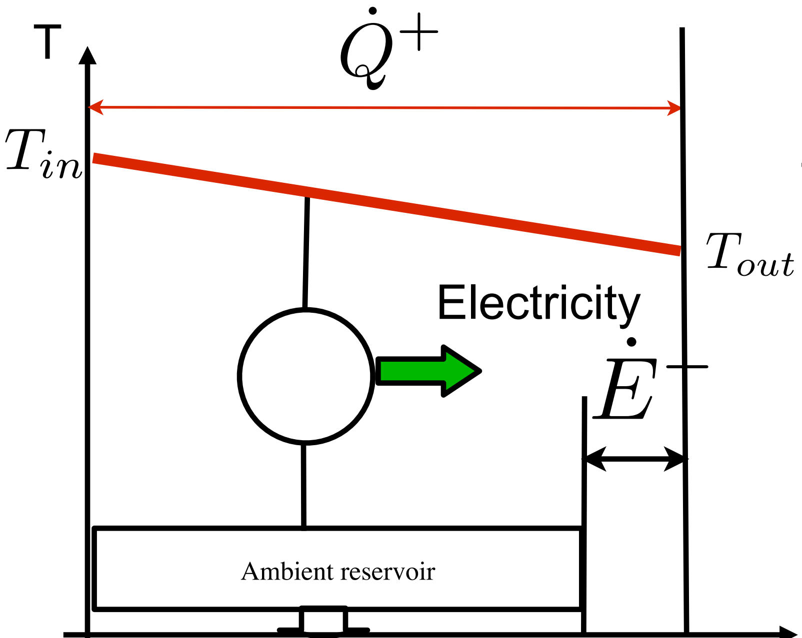
$$\dot{E}^- = \dot{E}^-_{max} \cdot \eta_{Carnot}$$

η_{Carnot} is the efficiency that engineers typically reach today

$$\eta_{Carnot} \simeq 0.55$$

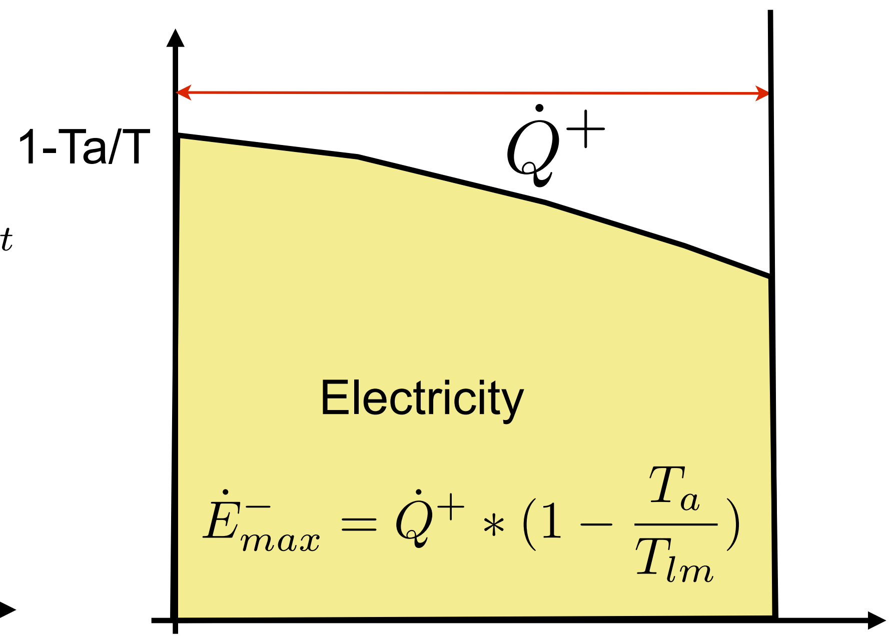
$\dot{Q}^-_a$ is the heat to be released in the environment

The exergy value of a heat exchange



$$\dot{Q}_a^- = \dot{Q}^+ - \dot{E}^-$$

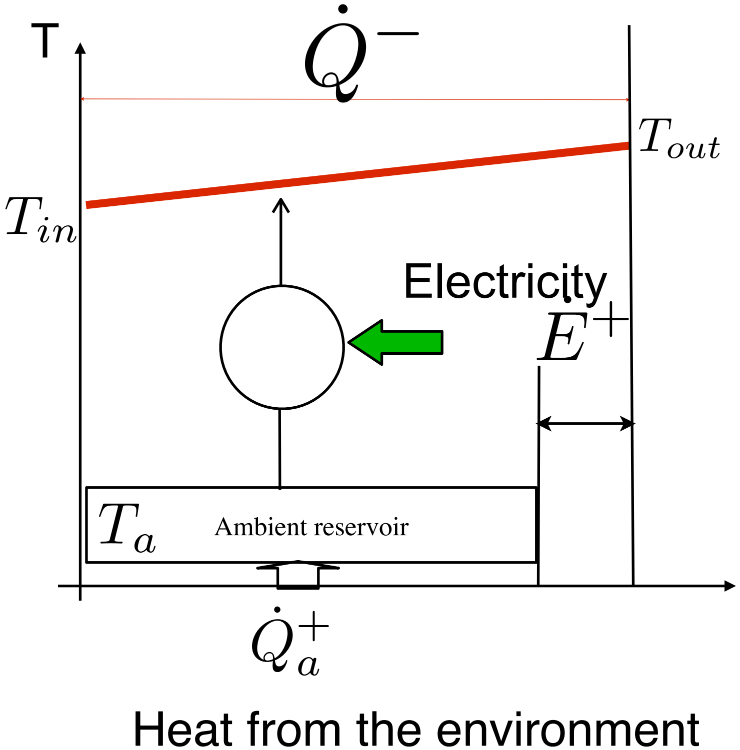
Carnot composite curve



$$T_{lm} = \frac{T_{in} - T_{out}}{ln(T_{in}) - ln(T_{out})}$$

The exergy value of a heat demand (reversible)

$$\dot{E}^{+}_{min} = \dot{Q}^{-} * (1 - \frac{T_a}{T_{lm}})$$



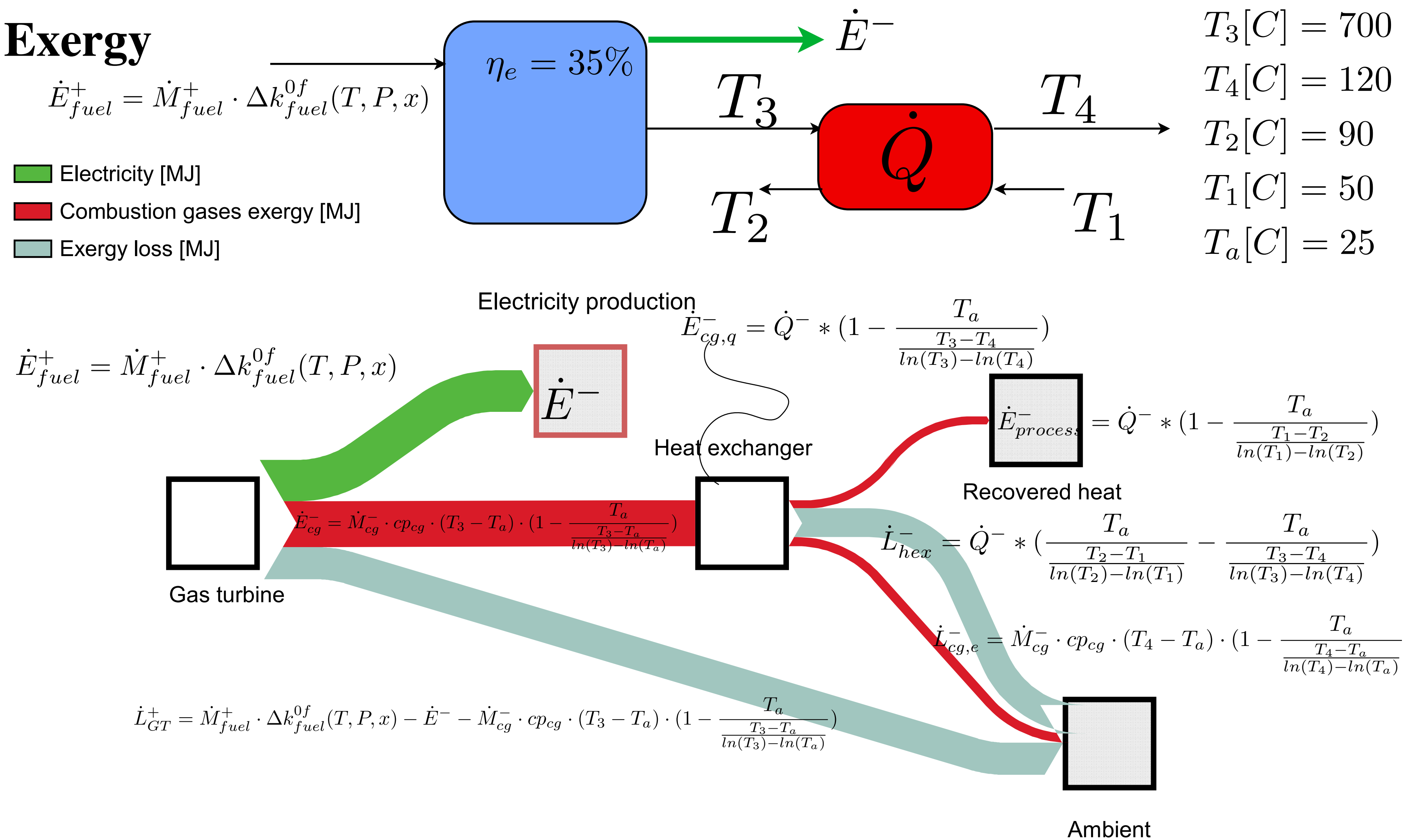
$$T_{lm} = \frac{T_{in} - T_{out}}{ln(T_{in}) - ln(T_{out})}$$

$$\dot{E}^{+} = \frac{\dot{E}^{+}_{min}}{\eta_{Carnot}}$$

$$\eta_{Carnot} \simeq 0.55$$

$$\dot{Q}^{-} = \dot{Q}^{+}_{a} + \dot{E}^{+}$$

Sankey diagram: exergy destruction path

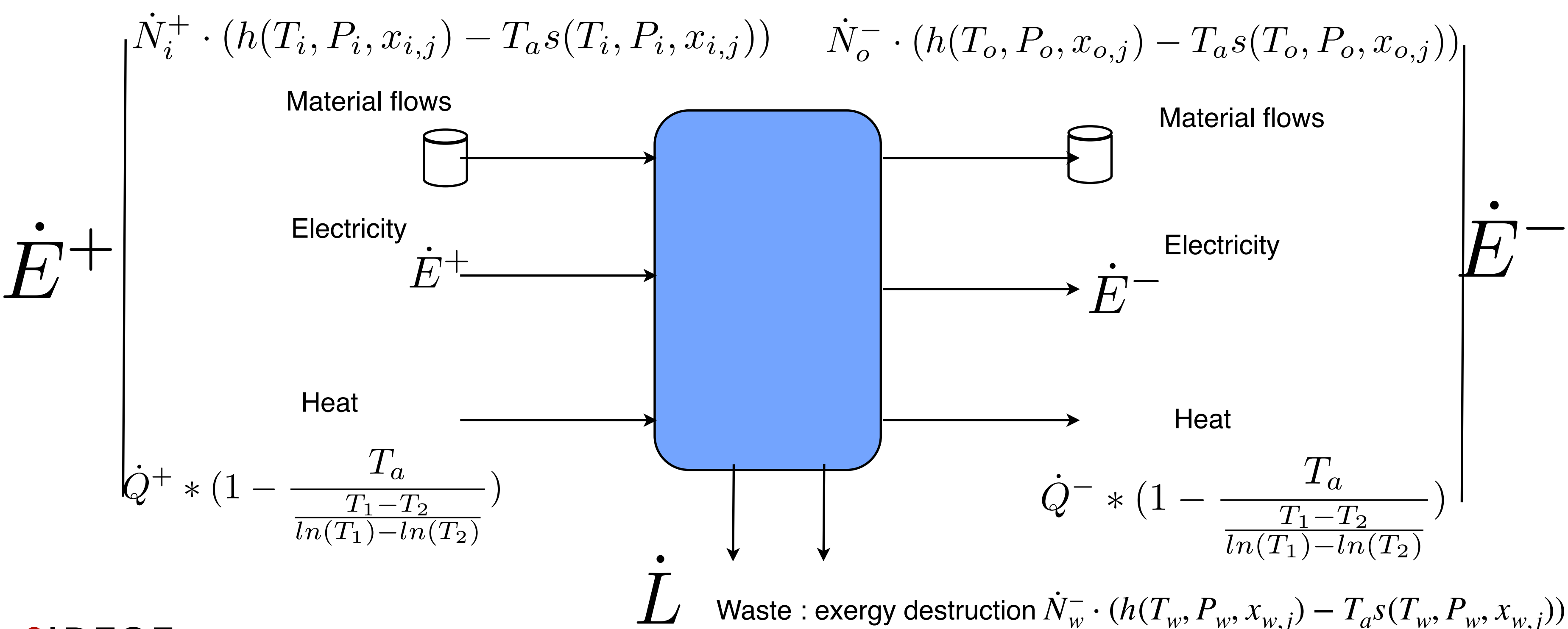


Exergy efficiency of a conversion unit

$$\eta = \frac{\dot{E}^-(delivered)}{\dot{E}^+(consumed)} = \frac{\dot{E}^+ - \dot{L}}{\dot{E}^+} = 1 - \frac{\dot{L}}{\dot{E}^+}$$

$\dot{L}$ includes :

- the losses inside the system
- what is released in the environment



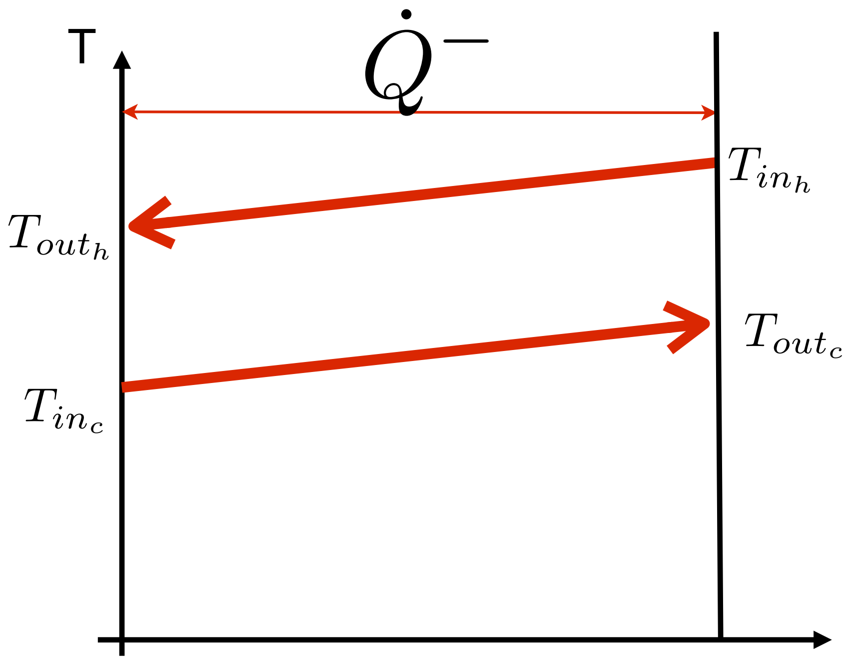
Delivered vs consumed

- Delivered : needed by the process
- Consumed : what is paid (from a tank or pipe)
- Energy balance is always closed
- what is released to the environment has an exergy value vs the environment but that is destroyed if released to the environment
  - e.g. heat released at T_{out}

$$\dot{L} = \dot{m} \cdot cp \cdot (T_{out} - T_a)(1 - \frac{T_a}{\frac{T_{out} - T_a}{ln(T_{out}) - ln(T_a)}})$$

Example : Exergy loss in a heat exchanger

$$\dot{E}^{+}_{max} = \dot{Q}^{-} \cdot (1 - \frac{T_a}{T_{lm}})$$

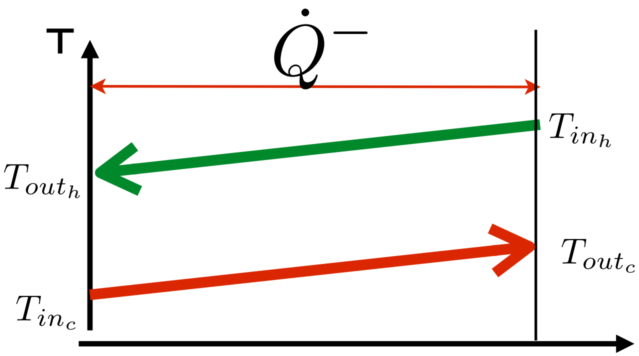


$$T_{lm} = \frac{T_{in} - T_{out}}{ln(T_{in}) - ln(T_{out})}$$

$$\dot{L} = \dot{Q}^{-} * (1 - \frac{T_a}{T_{h_{lm}}}) - \dot{Q}^{-} * (1 - \frac{T_a}{T_{c_{lm}}})$$

The exergy loss is the amount of electricity that could have been produced by the heat exchange

Exergy analysis

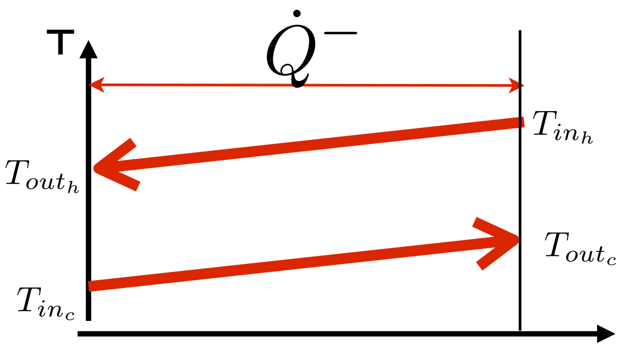


Hot utility

Fuel ($\dot{E}^+_{fuel}$) produces $\dot{Q}^-$ with cogeneration of $\dot{E}^-$

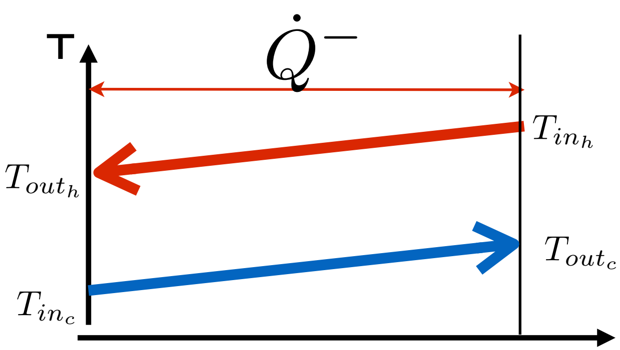
$$\dot{L}_{utility} = \dot{E}^+_{fuel} - \dot{E}^- - \dot{Q}^- \cdot \left(1 - \frac{T_a}{\frac{T_{out_c} - T_{in_c}}{ln(T_{out_c}) - ln(T_{in_c})}}\right)$$

Consider the exergy value of the input flows



Heat recovery

$$\dot{L}_{exchange} = \dot{Q}^- * \left(1 - \frac{T_a}{T_{h_{lm}}}\right) - \dot{Q}^- * \left(1 - \frac{T_a}{T_{c_{lm}}}\right)$$



Cold utility

the heat released in the environment has no exergy value

$$\dot{L}_{utility} = \dot{Q} \cdot \left(1 - \frac{T_a}{\frac{T_{in_h} - T_{out_h}}{ln(T_{in_h}) - ln(T_{out_h})}}\right)$$

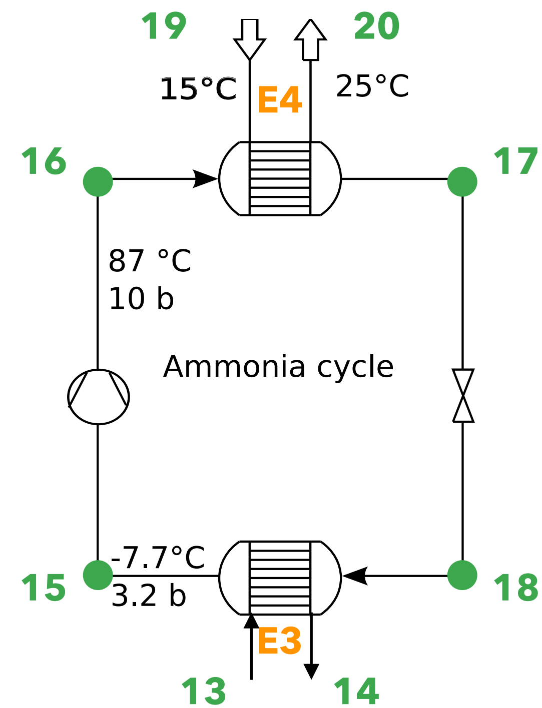
if released in environment the exergy is destroyed

EXAMPLE

REFRIGERATION CYCLE

$$k_{15} = h_{15} - T_0 s_{15} \qquad k_{18} = h_{18} - T_0 s_{18}$$

$$k_{16} = h_{16} - T_0 s_{16} \qquad k_{17} = h_{17} - T_0 s_{17}$$



$$\dot{L}_{E3} = \dot{m}_{amm}(k_{18} - k_{15}) - \dot{m}_{gl}C_{p,gl}[(T_{14} - T_{13}) - T_0 ln(\frac{T_{14}}{T_{13}})]$$

$$\dot{L}_{comp} = \dot{m}_{amm}(k_{15} - k_{16}) - \dot{W}_{comp}$$

$$\dot{L}_{E4} = \dot{m}_{amm}(k_{16} - k_{17}) - \dot{m}_{w}C_{p,w}[(T_{19} - T_{20}) - T_0 ln(\frac{T_{19}}{T_{20}})]$$

$$\dot{L}_{valv} = \dot{m}_{amm}(k_{17} - k_{18})$$

$$\dot{L}_{refrigeration} = \dot{L}_{valv} + \dot{L}_{comp} + \dot{L}_{E4} + \dot{L}_{E3}$$

where is Exergy lost ?

- **Exergy losses in process unit operation**
  - Efficiency of equipment realising the process unit operation
    - entropy creation (friction, leakages)
    - temperature differences in heat exchangers (driving forces)
    - pressure losses (pressure drops)
    - dilution (mixing)
- **Exergy losses in conversion**
  - difference between exergy content of resources and exergy delivered
    - combustion to produced heat
    - Heat pumping
    - combined heat and power
    - pressure of compressed air usage
- **Exergy destruction in the environment**
  - Flows leaving without being in equilibrium with environment
    - combustion gases
    - hot water
    - steam vented

Module 1 questions

B1: Exergy Analysis

a. Explain what is exergy and how exergy balances can be formulated on the basis of First and Second Law of Thermodynamics.
b. Explain the different types of exergy losses: thermal, physical, chemical, …
c. Explain and demonstrate what are the exergy losses and characterize the exergy losses of a heat exchanger
d. Define the exergy losses in a mixer/splitter.
e. Define the exergy efficiency of a refrigeration cycle. Explain the different losses in the different process units.
f. explain a Sankey diagram for exergy analysis

Advanced energetics : Process requirement analysis

- Analyse the process flows
  - input-output flows
- Block flow diagram
  - Material conversion in a process
- Process unit operations
  - Physical units (e.g. separation)
  - Chemical units (e.g. combustion, reaction)
  - Competing technologies
- Energy requirement :
  different form/different usage/different quality
  - Exergy analysis
  - Heat transfer requirement
    - streams to be heated up or cooled down
  - Compressors - pumps

videos are available on moodle