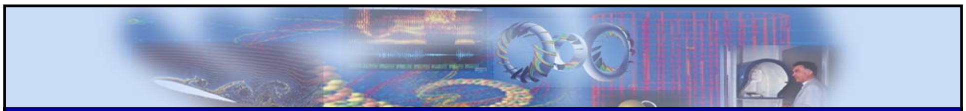

Second law, exergy, and consequences on low-temperature heat-recovery

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Workshop
Energy for Sustainable Science
Energy Management for Large-Scale Research Infrastructures

EUROPEAN SPALLATION SOURCE

ERF European Association of National Research Facilities Open to International Access

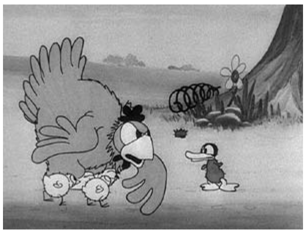
Energy for Sustainable Science Workshop, Lund, 13-14 October 2011

Tribute to H.C. Andersen

(April 1805, Odense - August 1875, Copenhagen)

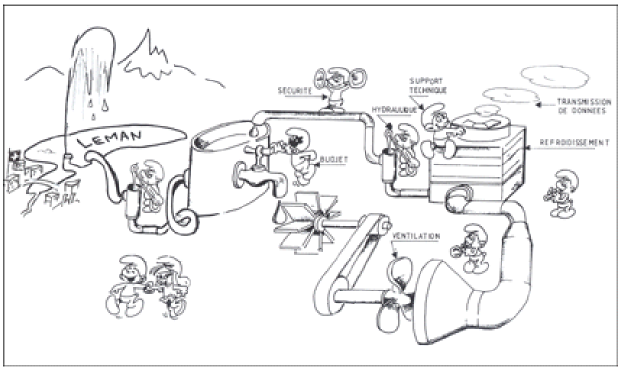
and especially to the tale

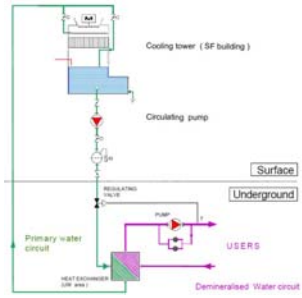
The Ugly Duckling



Can one produce energy out of a huge amount of heat delivered at 40-50°C?

- 23 cooling towers in running condition exist at CERN. These are situated all over the CERN territory with cooling power ranging from 1.25 MW to 70 MW.





Can one produce energy out of a huge amount of heat delivered at 40-50°C?

- *Immediate answer: NO*
- ANY GOOD REASON?
- *Yes, the second law*!
- … …
  So, come and tell us.

- **Summary**
- The first law and its consequences on energy conversion systems
- The second law and its consequences on energy conversion systems
- Exergy (entropy and irreversibility)
- Consequences on energy recovery at low temperature

Framework

- Macroscopic systems …
  - globally out of equilibrium,
  - at local thermodynamic equilibrium at microscopic level.
  - *Mechanics of continuous media*

- Systems in periodic regime
  - Changes in internal quantities have zero integrals

- Exchanges with *constant*-characteristics sources:
  - Heat <-> with thermostats (constant *Temperature*)
  - Mass <-> infinite reservoirs (constant *Pressure*, composition …)

First law: total energy is conserved

- The change in total energy equals the inputs of work plus heat. $$\mathrm{d}E = \delta W + \delta Q$$

- Work=action of forces
  Heat=gradient of heat flux
  $$\frac{\partial(\rho e)}{\partial t} + \nabla.(\rho e \mathbf{v}) = -\nabla.(\mathbf{P}.\mathbf{v} + \mathbf{q}) + \rho \mathbf{F}.\mathbf{v}$$

- Total energy = internal energy + kinetic energy: $$E = U + E_k$$ $$e = u + \mathbf{v}.\mathbf{v}/2$$

$$\rho(\dot{u} + \mathbf{v}.\dot{\mathbf{v}}) + (u + \mathbf{v}.\mathbf{v}/2)(\dot{\rho} + \rho\nabla.\mathbf{v}) = -\nabla.\mathbf{q} - (\nabla.\mathbf{P}).\mathbf{v} - \mathbf{P}^T : \nabla\mathbf{v} + \rho\mathbf{F}.\mathbf{v}$$

$$\dot{\rho} + \rho\nabla.\mathbf{v} = 0$$

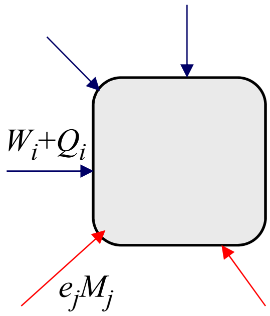
$$\rho\dot{\mathbf{v}} + \nabla.\mathbf{P} - \rho\mathbf{F} = 0$$

$$\rho\dot{u} = -\nabla.\mathbf{q} - \mathbf{P}^T : \nabla\mathbf{v}$$

Consequences on energy conversion systems

- Consider a machine for energy conversion operated periodically and exchanging energy fluxes W_i and Q_i with different sources:

$$\sum_i \left(W_i + Q_i\right) = 0$$



- If also exchanging mass fluxes, M_j with average energy e_j:

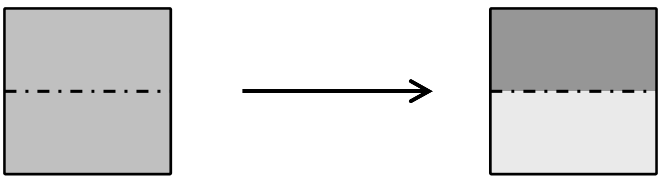
$$\sum_j \left(M_j\right) = 0$$

$$\sum_i \left(W_i + Q_i\right) + \sum_j \left(e_j M_j\right) = 0$$

Now imagine ...

- ... 1+1 kg of steel initially at uniform temperature T_0 ...

  ... and with final state = 1 kg at T_0+DT and 1 kg at T_0-DT .



- Everyone knows that such a transfer *never occurs spontaneously*, although it would perfectly conserve energy. Then, Why?
  - Because of the *second law*.

The second law (1)

- Introduction: There exists a function of state s from which (macroscopic) temperature T can defined such that:

$$T\mathrm{d}s = \mathrm{d}u - \frac{p}{\rho^2}\mathrm{d}\rho - \sum_k \mu_k \mathrm{d}c_k \quad (= \mathrm{d}u - \delta w = \delta q)$$

- The transport equation for **entropy** is:

$$\frac{\partial}{\partial t}(\rho s) + \nabla.(\rho s \mathbf{v}) = -\nabla.\left[\frac{1}{T}\left(\mathbf{q} - \sum_k \mu_k \mathbf{J}^{\mathrm{d}}{}_k\right)\right] + \delta s^+$$

Conductive heat flux density ($\mathbf{q}$)

mass flux density ($\mathbf{J}^{\mathrm{d}}{}_k$)

- Non-zero source term: entropy is not conserved.

The second law (2)

- **Statement of the second law**:
the source term σ^S cannot be negative

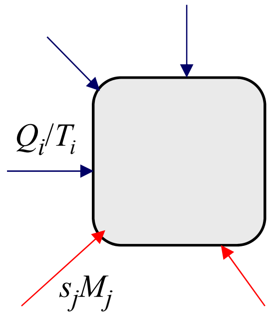
$$\delta s^+ = \mathbf{q}.\nabla\left(\frac{1}{T}\right) - \frac{1}{T}p^v\nabla.\mathbf{v} - \frac{1}{T}\overset{0}{\mathbf{P}}{}^v : \overset{0}{\mathbf{V}} - \sum_k \mathbf{J}^{\mathrm{d}}{}_k.\nabla\left(\frac{\mu_k}{T}\right) + \frac{\rho}{T}\sum_l \mathcal{A}_l\dot{\xi}_l + \frac{1}{T}\boldsymbol{\varepsilon}.\mathbf{i}$$

- **Five irreversible phenomena:**
Conduction – friction (bulk and shear)
mass diffusion – chemical reactions – Joule effect

Balances in energy conversion systems

$$\sum_j (M_j) = 0 \qquad \sum_i (W_i + Q_i) + \sum_j (e_j M_j) = 0$$

- Heat sources at constant temperatures T_i exchanging entropy fluxes Q_i/T_i



- mass fluxes M_j with average entropy s_j:

$$\sum_i (Q_i / T_i) + \sum_j (s_j M_j) + \Delta S^+ = 0$$

$$\Delta S^+ \geq 0$$

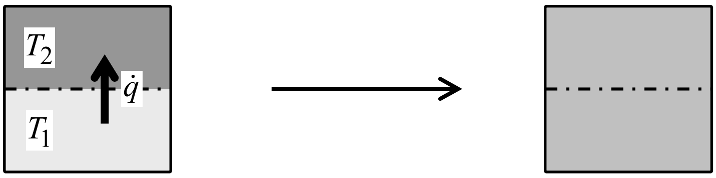
- ΔS^+=0 <=> Reversibility

Heat transfer from T_1 to T_2

- The same two kilograms of steel *(e.g.)*, one at T_1, one at T_2, with T_1<T_2, and $\dot{q}$ the heat flux from 1 to 2 …

  By virtue of the second law $\delta \dot{s}^+ = \dot{q}(T_2^{-1} - T_1^{-1}) \geq 0$
  one has: $\dot{q} \leq 0$

Heat is transferred from 'hot' (T_2) to 'cold' (T_1) leading to uniformity.



More general expression of the second-law

- None of the six terms can be negative:

$$\delta s^{+} = \mathbf{q}.\nabla\left(\frac{1}{T}\right) \quad -\frac{1}{T}p^{v}\nabla.\mathbf{v} \quad -\frac{1}{T}\overset{0}{\mathbf{P}^{v}} : \overset{0}{\mathbf{V}}$$

$$-\sum_{k}\mathbf{J}^{\mathrm{d}}{}_{k}.\nabla\left(\frac{\mu_k}{T}\right) \quad +\frac{\rho}{T}\sum_{l}\mathcal{A}_l\dot{\xi}_l \quad +\frac{1}{T}\boldsymbol{\varepsilon}.\mathbf{i}$$

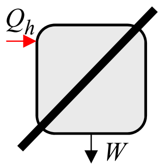
- Coefficients such as conductivity, viscosity (bulk- and shear-), diffusion coefficient, chemical affinity and resistivity *cannot be negative*.

Consequences on energy conversion systems

- Can a heat engine produce mechanical work out of one heat source only?

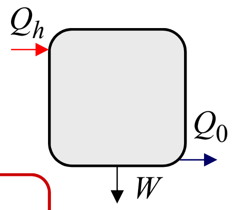
$$\left.\begin{array}{l} Q_h = -W \geq 0 \\ \Delta S^{+} = -Q_h / T_h \geq 0 \end{array}\right\} \Rightarrow Q_h = 0$$

- No!



- There must be (at least) two heat sources, one of them is the environment (subscript 0):

$$\left.\begin{array}{l} Q_h + Q_0 + W = 0 \\ \dfrac{Q_h}{T_h} + \dfrac{Q_0}{T_0} + \Delta S^{+} = 0 \\ \Delta S^{+} \geq 0 \\ W \leq 0 \end{array}\right\} \Rightarrow \left\{\begin{array}{l} (T_h \geq T_0) \\ Q_h \geq 0 \\ Q_0 \leq 0 \\ \boxed{\dfrac{-W}{Q_h} = 1 - \dfrac{T_0}{T_h} - \dfrac{\Delta S^{+} T_0}{Q_h} \leq 1 - \dfrac{T_0}{T_h} < 1} \end{array}\right.$$



Introduction of exergy

- Total energy is conserved, but
not any energy can be *entirely* converted into work.

- The conversion efficiency is bounded by an **upper limit**
called **the *Carnot* efficiency =** $1 - T_0/T_h$
(the Carnot cycle is reversible, *i.e.* with Π_S=0).

- This upper limit is obtained by combining the balances
of total energy *E* and of entropy *S*, according to: $E_{tot} - T_0.S$.

T_0 = temperature of the heat source where
heat can be released (or from which heat can be extracted) for free,
= temperature of the environment (outdoor air).

- The quantity $B = E_{tot} - T_0.S$ is called **EXERGY**.

Definition of exergy

- Exergy =

the **maximal amount** of **mechanical work**

that can be produced when using,

either a *flux of energy*(1), or a *given mass*(2),

by **reversible processes** operated in a **given environment**

(temperature T_0, pressure, composition, etc.).

- Notation: *B* (or *b* …) – Unit: J (or $J.kg^{-1}$ …)

Definition of exergy (2)

- Exergy = maximal amount of mechanical work produced from, either a flux of energy(1), or a given mass(2), by reversible processes in a given environment (temperature T_0, pressure, composition, etc.).

- (1) considering a <u>flux of energy</u> *E* characterized by a flux of entropy *S*, then the flux of exergy *B* is:

$$\dot{B} = \dot{E} - T_0\dot{S} = \dot{W} + \dot{Q} - T_0.\dot{Q}/T$$

$$\dot{B} = \dot{W} + \left(1 - T_0/T\right)\dot{Q}$$

- (2) considering <u>mass</u>, exergy = state function, with changes:

$$\mathrm{d}b = \mathrm{d}e - T_0.\mathrm{d}s = \mathrm{d}e_k + \mathrm{d}u - T_0\left(T^{-1}\mathrm{d}u + T^{-1}p\rho^{-2}\mathrm{d}\rho + T^{-1}\sum_k \mu_k \mathrm{d}c_k\right)$$

$$\mathrm{d}b = \mathrm{d}e_k + \left(1 - T_0/T\right)\mathrm{d}u + \left(T_0/T\right)\left(p\rho^{-2}\mathrm{d}\rho + \sum_k \mu_k \mathrm{d}c_k\right)$$

  - Note: any term related to heat (Q, $\mathrm{d}u$) is multiplied by $\mathbf{(1 - T_0/T)}$, called the *Carnot factor*.

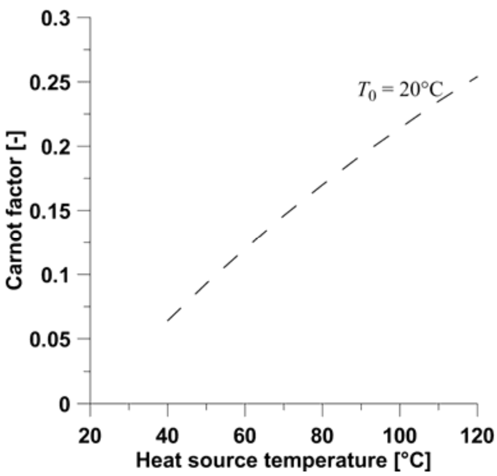
The present concern: to produce work out of heat

$(1 - T_0/T)$ = Carnot factor = *B/Q*

Efficiency of a *Carnot* cycle operated between sources at temperatures *T* and T_0, (T_0: environment, *T*: point under consideration).

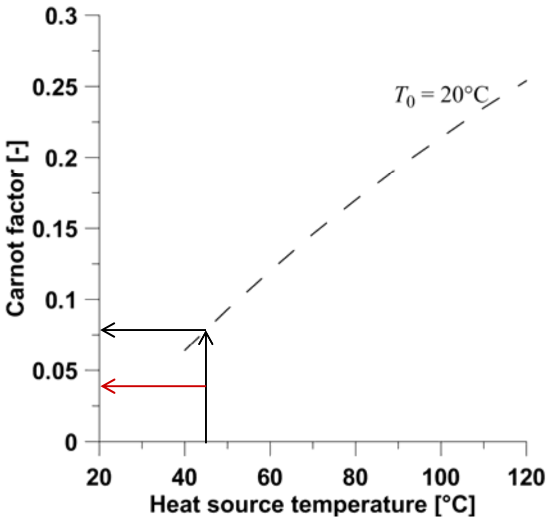
B/Q = Conversion efficiency of <u>reversible</u> engine cycles with a heat source at T = upper limit.

Here with environment at 20°C



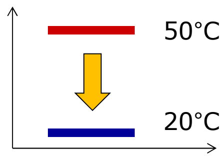
Heat flux *Q* released at 45°C (1)

- Carnot factor B/Q = 0.08
- The exergy content of heat delivered at 45°C in environment at 20°C is only 8%: only less than 8% can be converted into work.
- Considering now a **real process** heat to electricity: the likely efficiency $W_e/Q_h \approx 0.04$ (4% only of Q_h is converted into electricity).



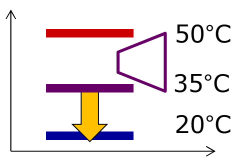
Heat flux *Q* released at 45°C (2)

- **96% of Q_h must still be rejected to the environment** (negligible saving) …
- … but with a temperature difference between the heat-exchanger and the ambient air now reduced by a factor 2, if not more;



Heat transfer only

- **Consequences**
  - 1: much larger heat-exchange surface with ambient air : $S = Q/(h.\Delta T)$,
  - 2: larger air flow-rate for heat rejection,
  - 3: *larger electricity consumption in fans*.

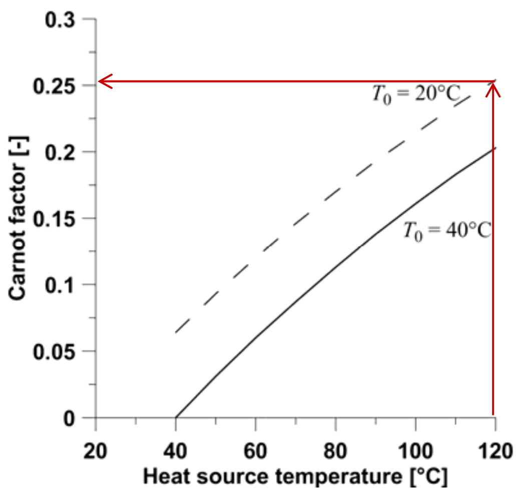


Work production

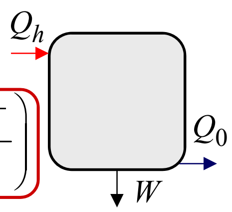
- The net benefit may be very limited (if any considering investment).

Any solution?

- Usually, low-grade heat-recovery is achieved with heat delivered at 90-100°C, and preferably more (120°C).
- At 120°C, the exergy content is 0.25, then one can hope to obtain an effective conversion efficiency of 10% (still low but non-negligible).



About process efficiency



- Conversion efficiency:

$$\frac{-W}{Q_h} = \left(1-\frac{T_0}{T_h}\right)\left(1-\frac{\Delta S^+ T_0}{Q_h(1-T_0/T_h)}\right) = \left(1-\frac{T_0}{T_h}\right)\left(1-\frac{\Delta B^-}{B_h}\right)$$

- More generally:

$$Eff = Eff_{rev}\cdot\left(1-\frac{\Delta B^-}{B_{in}}\right)$$

$$B_{in} = B_{out} - \Delta B^-$$

$$\delta b^- = T_0 \mathbf{q}.\nabla\left(\frac{1}{T}\right) - \frac{T_0}{T} p^v \nabla.\mathbf{v} - \frac{T_0}{T} \overset{0}{\mathbf{P}^v} : \overset{0}{\mathbf{V}} - T_0 \sum_k \mathbf{J}^{\mathrm{d}}{}_k.\nabla\left(\frac{\mu_k}{T}\right) + \frac{T_0 \rho}{T}\sum_l \mathcal{A}_l \dot{\xi}_l + \frac{T_0}{T}\boldsymbol{\varepsilon}.\mathbf{i} \quad \text{with}\left(\delta b^- \geq 0\right)$$

- Using exergy losses (or entropy productions), one can compare on a same basis (change in process efficiency) the effects of reducing this, or that, irreversibility: the process can be optimized (*e.g.* at given power).

Conclusion

- Because of the temperature level, the exergy content of heat rejected by cooling towers is so low that (re-)conversion into electricity is not worth.

- Two possible ways:
  - Recover heat at high temperature levels, *i.e.* up-hill the cooling tower loops (but still with limited conversion potential),
  - Save energy (probably larger potential) :
    - *Increase insulation of the zones which are at high or low temperature*
    - *Improve energetic efficiency of electricity consuming devices, auxiliaries, components, etc.*

Thank you

for your attention,

and your questions.

Laboratoire d' Informatique pour la Mécanique et les Sciences de l'Ingénieur
Energy for Sustainable Science Workshop, Lund, 13-14 October 2011