

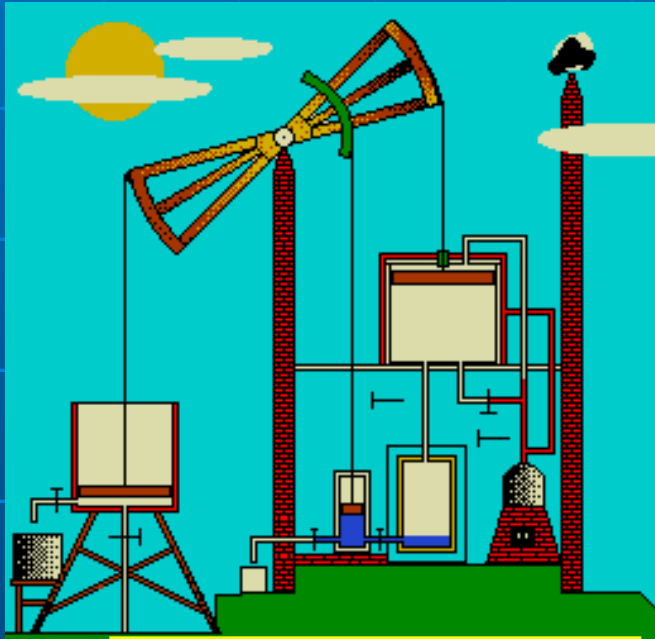
EXERGIA E IRREVERSIBILIDADE

2ª Lei

Qualidade

Quantidade

1ª Lei

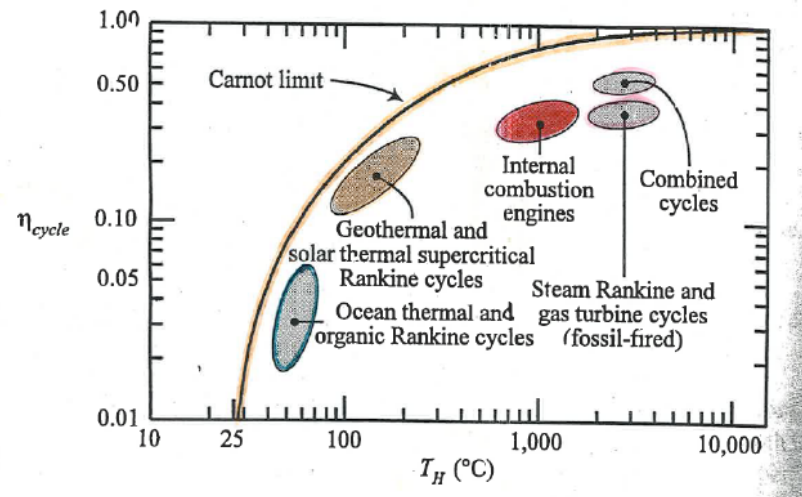


Máquina de Newcomen (1712)

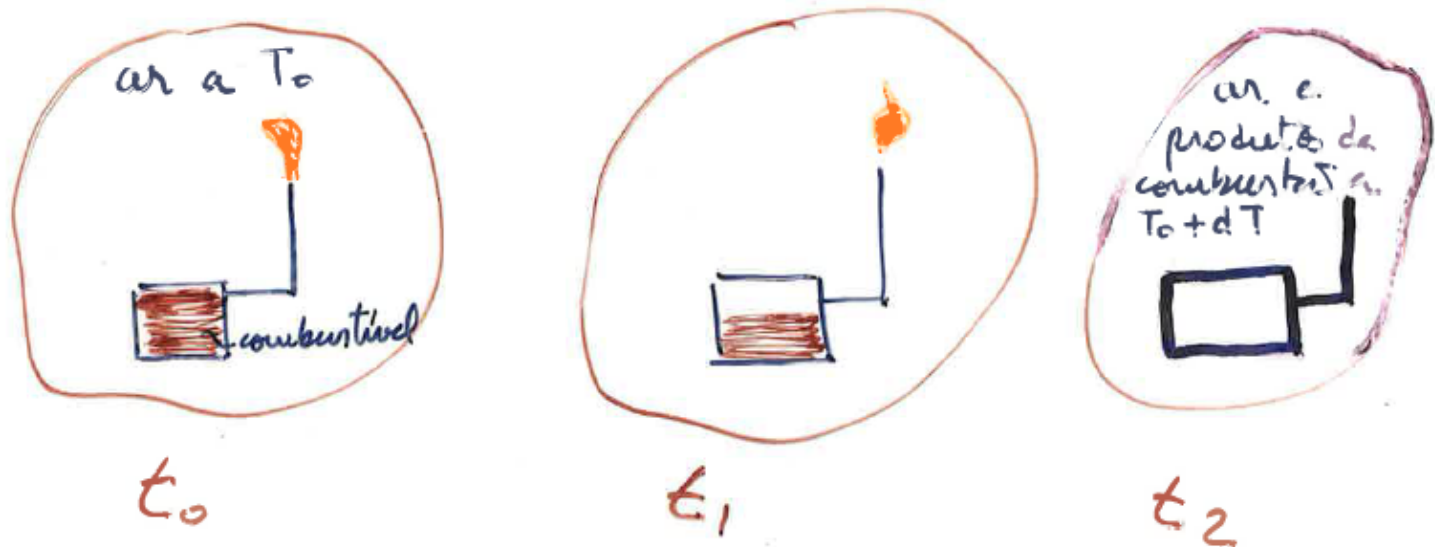
Le plus important est la détermination de la température à laquelle il est le plus convenable d'employer la vapeur. En effet, plus elle est chaude, plus sa force élastique est considérable, et par conséquent plus elle produit d'effort sur la surface du piston qu'elle presse, le vide étant toujours de l'autre côté. Mais aussi il faut consommer plus de charbon pour produire une vapeur plus chaude; en sorte que le profit ou le désavantage de la température est un élément à déterminer.

(J. B. Biot, *Traité de Physique Expérimentale et Mathématique*, tome 4, p. 739, Paris, Deterville, 1816.)

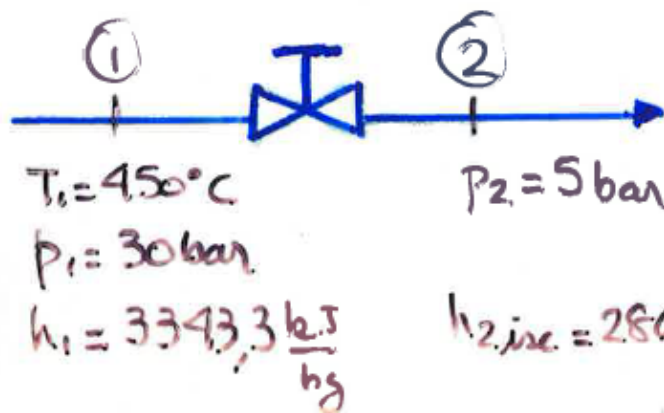
RENDIMENTOS TÍPICOS DE MÁQUINAS TÉRMICAS



Utilidade da Energia



→ energia = cte
 → utilidade da energia diminui



$$W_{inc} = 477.0 \frac{\text{kJ}}{\text{kg}}$$

Trabalho Reversível

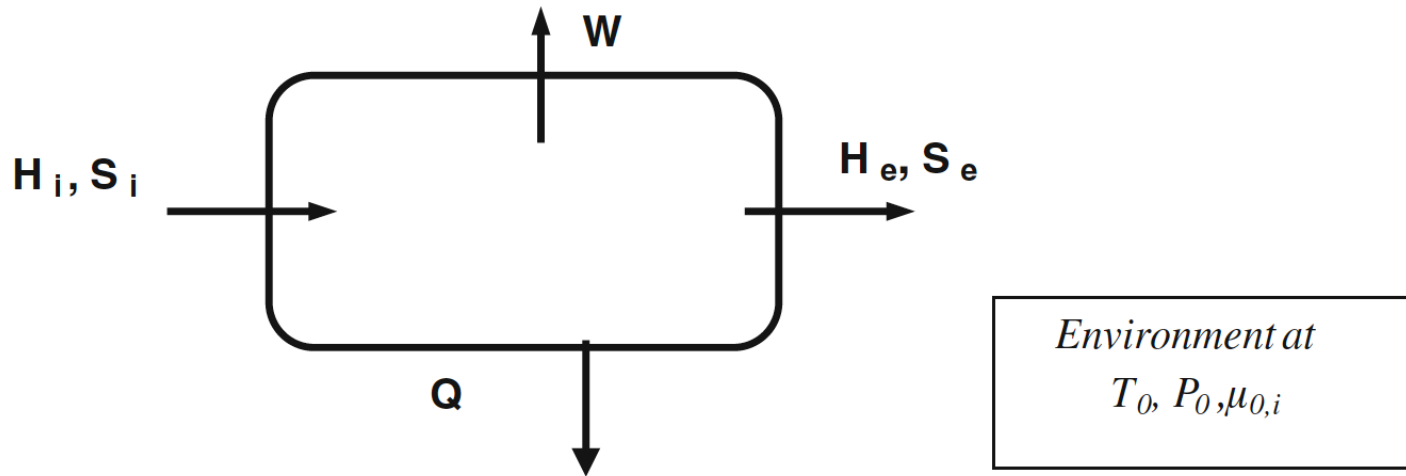
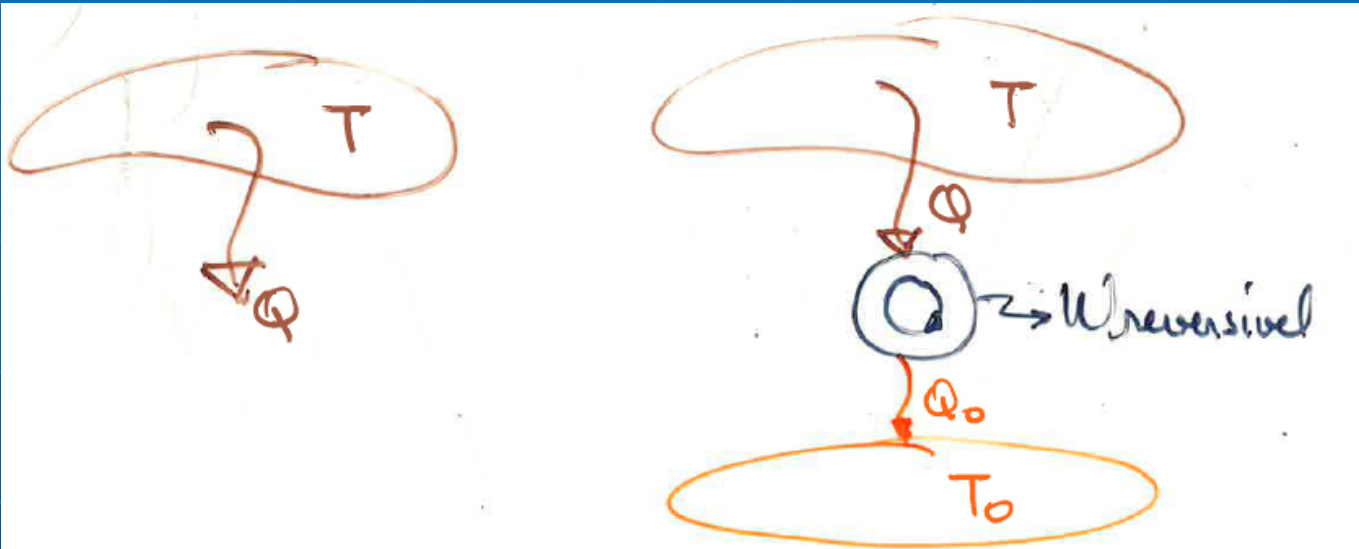
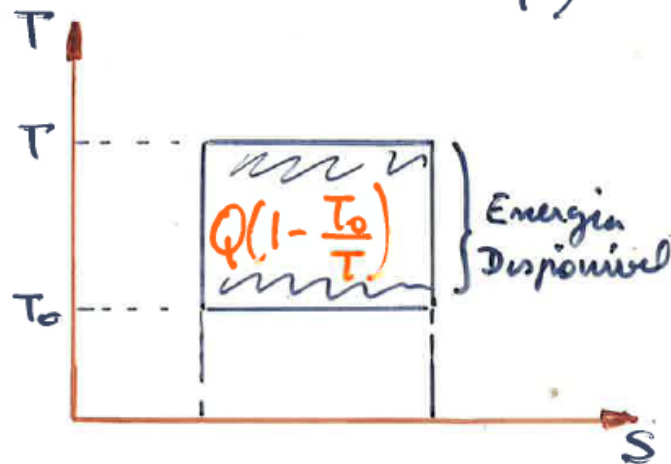


Fig. 2.1 Control volume with one inlet and one outlet

Trabalho Reversível



$$W_{\text{reversível}} = Q \left(1 - \frac{T_0}{T} \right)$$



Trabalho Reversível

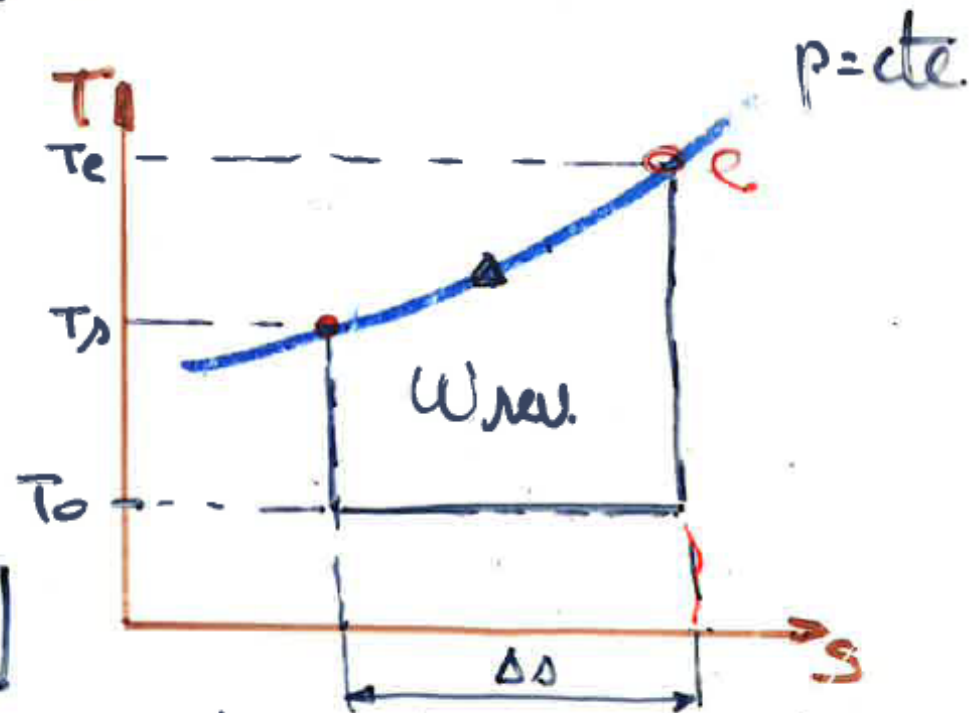


$$\dot{Q} = (\dot{h}_e - \dot{h}_s) \dot{m}$$

$$\dot{W}_{rev} = \dot{Q} - T_0 \dot{m} \Delta s$$

$$\dot{W}_{rev} = \dot{m} [\dot{h}_e - \dot{h}_s - T_0 (\dot{s}_e - \dot{s}_s)]$$

$$w_{rev} = \frac{\dot{W}_{rev}}{\dot{m}} = h_e - h_s - T_0 (s_e - s_s)$$



Trabalho Reversível

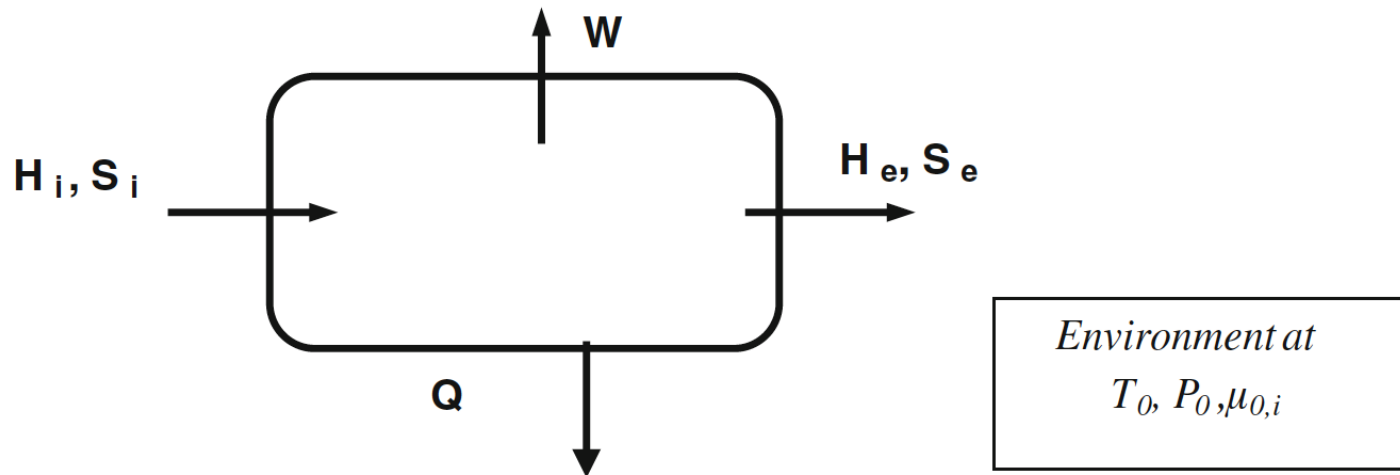


Fig. 2.1 Control volume with one inlet and one outlet

Pergunta:

For the chosen control volume, one could ask the following question: ‘What is the maximum work that can be performed giving the same thermodynamic states at the inlet and outlet sections of the control volume?’ This maximum work is determined under the following conditions:

- all the processes within the control volume are reversible;
- the maximum work that can be generated using the heat rejected by the control volume is the one obtained from a Carnot engine, operating between temperatures T_i and T_e and the environment temperature where the control volume is placed (T_0).

$$q = h_e - h_i + w \quad (2.1)$$

$$s_e - s_i = \int \frac{\delta q}{T} + s_{\text{ger}} \quad (2.2)$$

$$q_0 = h_e - h_i + w_{\text{max}} \quad (2.3)$$

$$s_e - s_i = q_0/T_0 \quad (2.4)$$

$$w_{\text{max}} = h_i - h_e - T_0(s_i - s_e) \quad (2.5)$$

This development could be done for the original condition where there are irreversible processes inside the control volume as well as the original values of w and q . In this case, the maximum work could be obtained in a similar way: including a Carnot engine that operates by using q and rejecting q'_0 to the environment.

For the reversible engine, it can be written:

$$\oint \frac{\delta Q}{T} = 0 = \int_{T_i}^{T_e} \left(\frac{\delta q}{T} \right) + \int \left(\frac{\delta q'_0}{T_0} \right) \quad (2.6)$$

$$s_e - s_i = q'_0/T_0 + s_{\text{ger}} \quad (2.7)$$

$$q'_0 = h_e - h_i + w + w_{\text{mr}} \quad (2.8)$$

$$w_{\text{mr}} = q - q'_0 \quad (2.9)$$

$$T_0(s_e - s_i) - T_0 s_{\text{ger}} = h_e - h_i + w + q\eta_{\text{mr}} \quad (2.10)$$

$$w_{\text{mr}} = q\eta_{\text{mr}} \quad (2.11)$$

$$h_i - h_e - T_0(s_i - s_e) = w + q\eta_{\text{mr}} + T_0 s_{\text{ger}}$$

$$\eta_{\text{mr}} = 1 - \frac{T_0}{q} \int_{T_i}^{T_e} \left(\frac{\delta q}{T} \right) \quad (2.12)$$

It is evident that, as shown by Eq. 2.5, the term $[h_i - h_e - T_0(s_i - s_e)]$ also characterizes a potential for doing work that in the occurrence of irreversible processes is reduced by the product $T_0 s_{\text{ger}}$, or the so-called irreversibility. Eventually, this potential is completely destroyed, or:

$$h_i - h_e - T_0(s_i - s_e) = T_0 s_{\text{ger}} \quad (2.13)$$

Exergia

Equation 2.10 can simply be obtained by multiplying the entropy balance by $-T_0$ and adding this equation to the energy balance. The result, a linear combination of the entropy and energy balances, gives:

$$[h_i - h_e - T_0(s_i - s_e)] = w + q \left[1 - \frac{T_0}{q} \int_{T_i}^{T_e} \left(\frac{\delta q}{T} \right) \right] + T_0 s_{\text{ger}} \quad (2.14)$$

In the case where all processes inside the control volume are reversible, the control volume interacts only with the environment, and the mass flow rate at the outlet section is in thermodynamic equilibrium with the environment ($h = h_0$ and $s = s_0$), Eq. 2.14 becomes the expression of the maximum reversible work associated to the inlet flow rate state of the control volume:

$$[h_i - h_e - T_0(s_i - s_e)] = w + q \left[1 - \frac{T_0}{q} \int_{T_i}^{T_e} \left(\frac{\delta q}{T} \right) \right] = w_{\max} \quad (2.15)$$

This maximum reversible work is called specific exergy of the flow rate at the inlet section of the control volume:

$$b = [h_i - h_0 - T_0(s_i - s_0)] \quad (2.16)$$

It is worth to note that the specific exergy is a function of properties of two thermodynamic states: the state in which the mass flow rate is and the state where this mass flow rate would be in thermodynamic equilibrium with the environment components. In that sense, the specific exergy is a special thermodynamic property, function of two thermodynamic states, and its value gives the maximum potential for doing work.

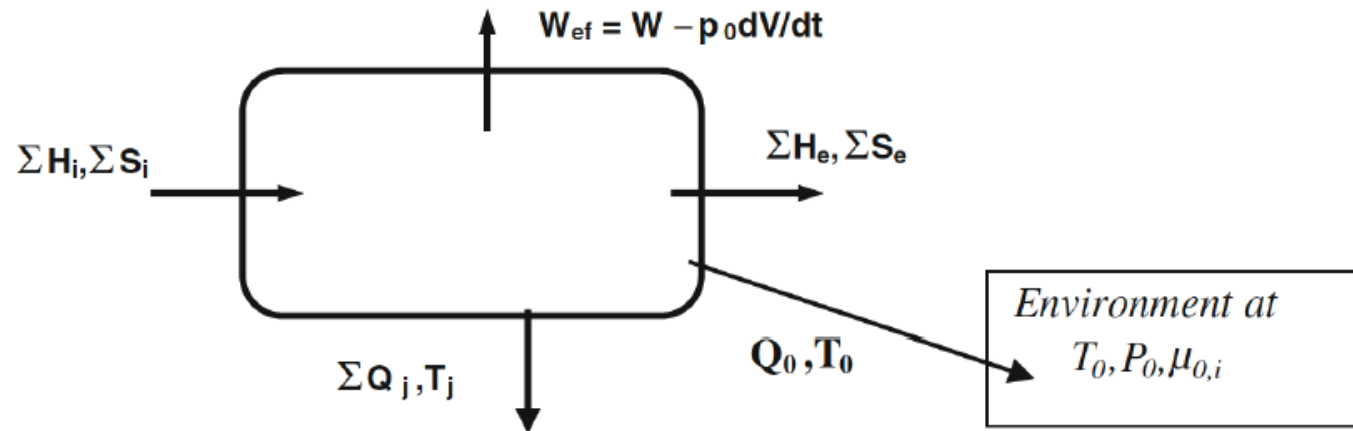


Fig. 2.2 Control volume with several inlets and outlets, heat transfer, and temperatures at T_i

$$\frac{d}{dt}(\mathbf{E} + P_0 V - T_0 S) = \frac{d\mathbf{B}}{dt} = \sum_j \left(1 - \frac{T_0}{T_j}\right) Q_j - W_{ef} + \sum_i m_i (h_i - T_0 s_i) - \sum_e m_e (h_e - T_0 s_e) - T_0 S_{ger} \quad (2.17)$$

Exergy is the maximum theoretical useful work (shaft work or electrical work) obtainable from a given energy quantity by using the environmental parameters as the reference state.

ENTROPIA = EVOLUÇÃO

ENERGIA → E_N = Interno
ERG = TRABALHO

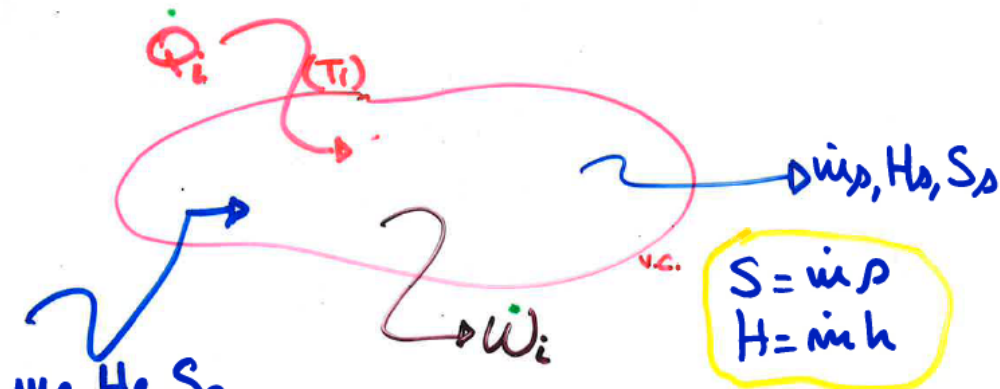
EXERGIA → E_X = Externo
ERG = TRABALHO

Table 2.1 Exergy and related concepts [16]

Year	Author	Designation
1824	Carnot	Puissance motrice du feu
1872	Thomson (Kelvin)	Motivity
1873	Gibbs	Available energy of the body and medium
1881	Gouy	Energie utilisable
1898	Stodola	Freie technische energie
1925	Debaufre	Available energy
1935	Bonsjakovic	Technische arbeitsfähigkeit
1944	Thring	Virtue of energy
1953	Schmidt	Technische maximale arbeit
1955	Gibert	Energie non dégradée
1956	Grigull	Ekthalpie
1956	Rant	EXERGIE

BALANÇO DE EXERGIA

(Regime Permanente, $\Delta E.C = \Delta E.P = 0$)



1ª Lei: $\sum \dot{Q}_i - \sum \dot{W}_i = \sum \dot{H}_p - \sum \dot{H}_e + \dot{q}$

2ª Lei: $\sum \frac{\dot{Q}_i}{T_i} + \dot{S}_{gen} = \sum \dot{S}_p - \sum \dot{S}_e$ ($\dot{q} = T_0 \dot{S}_{gen}$)

$$\sum \dot{Q}_i \left(1 - \frac{T_0}{T_i}\right) - \sum \dot{W}_i - T_0 \dot{S}_{gen} = \sum \dot{H}_p - \sum \dot{H}_e - T_0 (\sum \dot{S}_p - \sum \dot{S}_e)$$

Balanco de Exergia

$$\sum \dot{Q}_i \left(1 - \frac{T_0}{T_i}\right) - \sum \dot{W}_i - T_0 \dot{S}_{gen} = \sum \dot{B}_p - \sum \dot{B}_e$$

exergia associada à transferência

exergia pura

exergia destruída

variação dos fluxos de exergia

Inevitabilidade (EXERGIA DESTRUIDA)

- $I = B_{\text{dest}} = T_0 S_{\text{ger}} = W_{\text{rev}} - W_{\text{real}}$ •

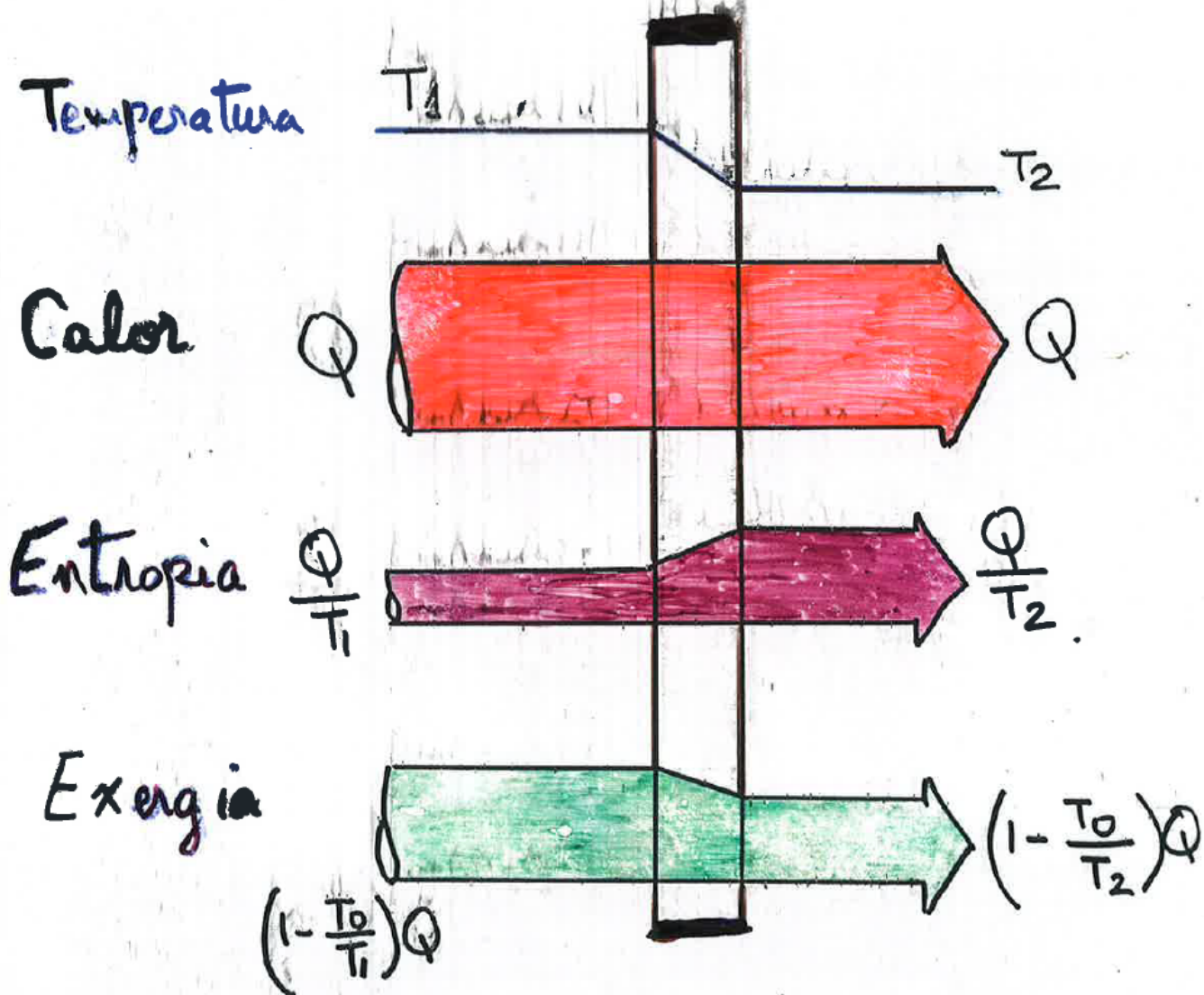
Exergia Física Específica de um Fluxo

- $b = h - h_0 - T_0(p - p_0)$ •

Exergia Física Específica de um Sistema

- $b_s = \underbrace{e - e_0 + p_0(v - v_0)}_{u - u_0 \text{ (desprezando-se } \Delta E_c \text{ e } \Delta E_p)} - T_0(p - p_0)$ •

TRANSFERÊNCIA DE CALOR



Exercícios

EXAMPLE 1

A mercury condenser and steam boiler of a binary power plant is shown below. The heat transfer rate is 5 MW and there are not heat losses to the environment. Using data given in the figure calculate the thermal exergy rate transferred from mercury, thermal exergy rate transferred to water and the destroyed exergy rate ($T_0=290$ K).

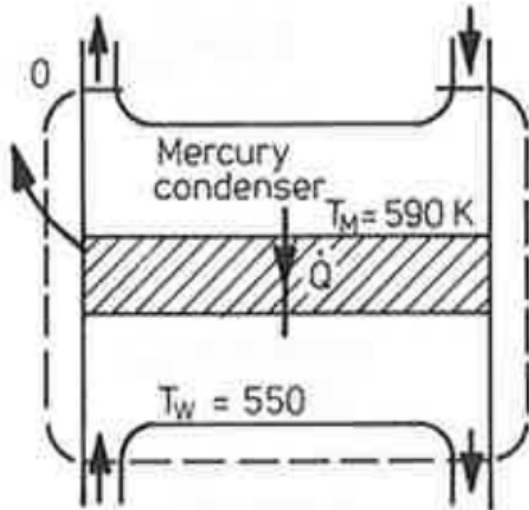


Fig. Scheme of a mercury condenser and steam boiler of a binary power plant.

Solution:

No pressure drop for both flows

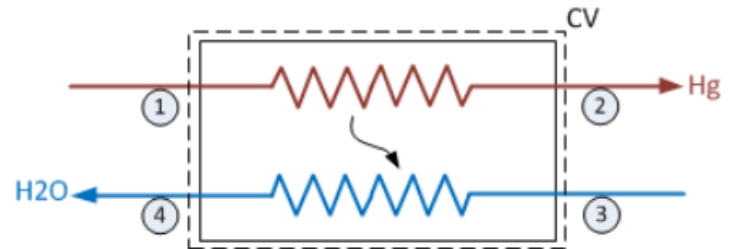
For the chosen C.V.:

- Mass balance: $\dot{m}_1 = \dot{m}_2 = \dot{m}_{Hg}$ and $\dot{m}_3 = \dot{m}_4 = \dot{m}_{H_2O}$
- Energy balance: $\dot{m}_{Hg}(h_1 - h_2) = \dot{m}_{H_2O}(h_4 - h_3) = \dot{Q} = 5 \text{ MW}$
- Exergy balance: $\dot{m}_1 b_1 + \dot{m}_3 b_3 = \dot{m}_2 b_2 + \dot{m}_4 b_4 + \dot{B}_{dest}$
or
 $\dot{m}_{Hg}(b_1 - b_2) = \dot{m}_{H_2O}(b_4 - b_3) + \dot{B}_{dest}$
with

$$b_1 - b_2 = h_1 - h_2 - T_0(s_1 - s_2) = (h_1 - h_2) \left(1 - T_0 \frac{s_1 - s_2}{h_1 - h_2} \right)$$

$$b_4 - b_3 = h_4 - h_3 - T_0(s_4 - s_3) = (h_4 - h_3) \left(1 - T_0 \frac{s_4 - s_3}{h_4 - h_3} \right)$$

$$\dot{m}_{Hg}(b_1 - b_2) = \underbrace{\dot{m}_{Hg}(h_1 - h_2)}_{\dot{Q}} \left(1 - \frac{T_0}{\left(\frac{h_1 - h_2}{s_1 - s_2} \right)} \right)$$



As

$$Tds = dh - v \underbrace{dp}_0 \text{ (pure substance)}$$

$$T = \frac{dh}{ds}$$

Then:

$$\dot{m}_{Hg}(b_1 - b_2) = \dot{Q} \left(1 - \frac{T_0}{T_{Hg}} \right) = \dot{Q} \theta_{Hg}$$

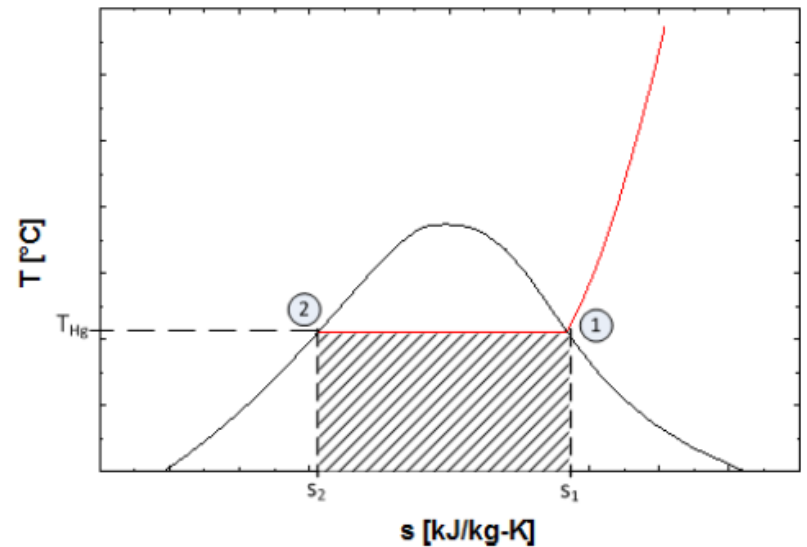
Analogously: $\dot{m}_{H_2O}(b_4 - b_3) = \dot{Q} \theta_{H_2O}$

Then: $\dot{B}_{dest} = \dot{Q}(\theta_{Hg} - \theta_{H_2O})$

$$\dot{m}_{Hg}(b_1 - b_2) = 2,54 \text{ MW}$$

$$\dot{m}_{H_2O}(b_4 - b_3) = 2,36 \text{ MW}$$

$$\dot{B}_{dest} = 0,18 \text{ MW}$$



Exercícios

2) A única irreversibilidade de um motor térmico que opera segundo um ciclo de Carnot resulta das diferenças de temperatura existentes nos processos de troca de calor. As temperaturas da fonte de calor e do ambiente são 900 K e 300 K e as duas diferenças de temperatura são $DT = 20$ K. Calcule a taxa de destruição de exergia se a potência fornecida pelo motor é de 10 MW.

3) Considere uma indústria onde vapor a 30 bar e 700°C é disponível. Num dos processos desta indústria deve-se utilizar vapor a 20 bar e 400°C. Um engenheiro sugere que o vapor nas condições requeridas pode ser obtido expandindo o vapor a 30 bar através de uma válvula até 20 bar e a seguir resfriando-o até 400°C, através de uma troca de calor para o meio a 20°C.

- Analise esta sugestão a partir dos conceitos de exergia e irreversibilidade.
- Estimando o custo da exergia a 0,08 US\$ por kWh, calcule o custo anual desta alternativa para uma vazão mássica de vapor de 1 kg/s e supondo que a indústria opera 8000 horas por ano.
- Proponha um método alternativo para obter vapor nas condições requeridas que seja "termodinamicamente mais atrativo".

DADOS: Temperatura do meio, $T_o = 20^\circ\text{C}$
Pressão do meio, $P_o = 1$ atm

4) Calcule a exergia destruída devido ao escoamento de um fluxo de vapor d'água ($m=1$ kg/s) através de uma válvula redutora de pressão nas seguintes condições:

Entrada: $p=21$ bar, $T= 280^\circ\text{C}$
Saída: $p= 1,5$ bar