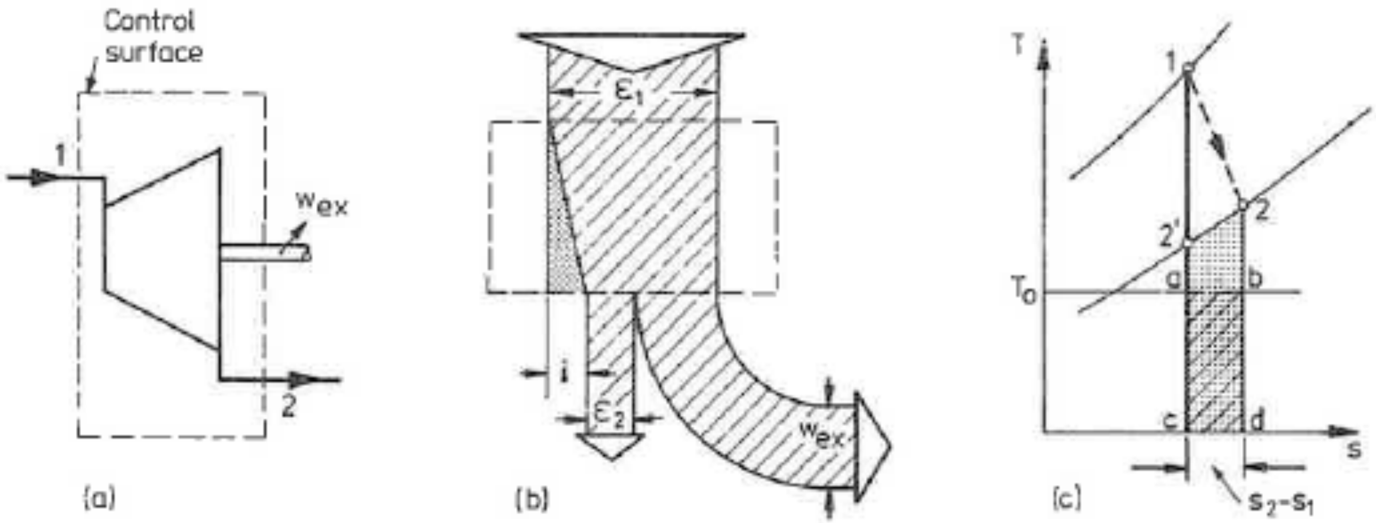
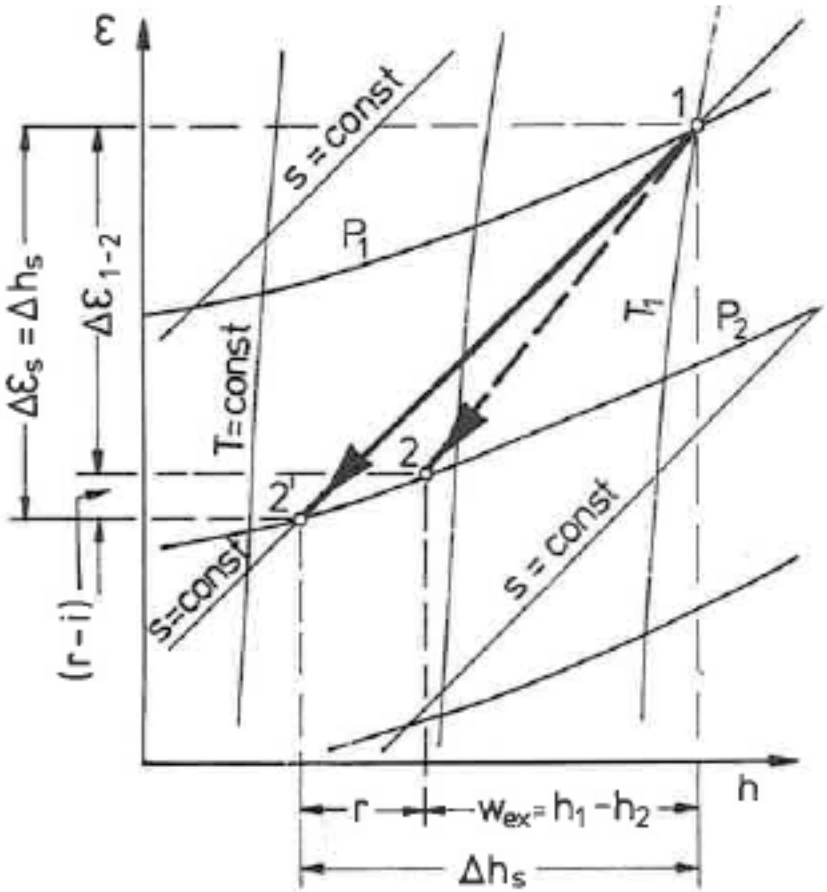
EXERGY ANALYSIS OF SIMPLE PROCESSES

1. EXPANSION (turbine)



Expansion in an adiabatic turbine (Kotas, 1985).

$$\eta_b = \frac{h_1 - h_2}{(h_1 - h_2) + T_o(s_2 - s_1)} \qquad \eta_{ise} = \frac{h_1 - h_2}{h_1 - h_{2ise}} \qquad (1)$$



Expansion in an adiabatic turbine in a exergy-enthalpy diagram (Kotas, 1985).

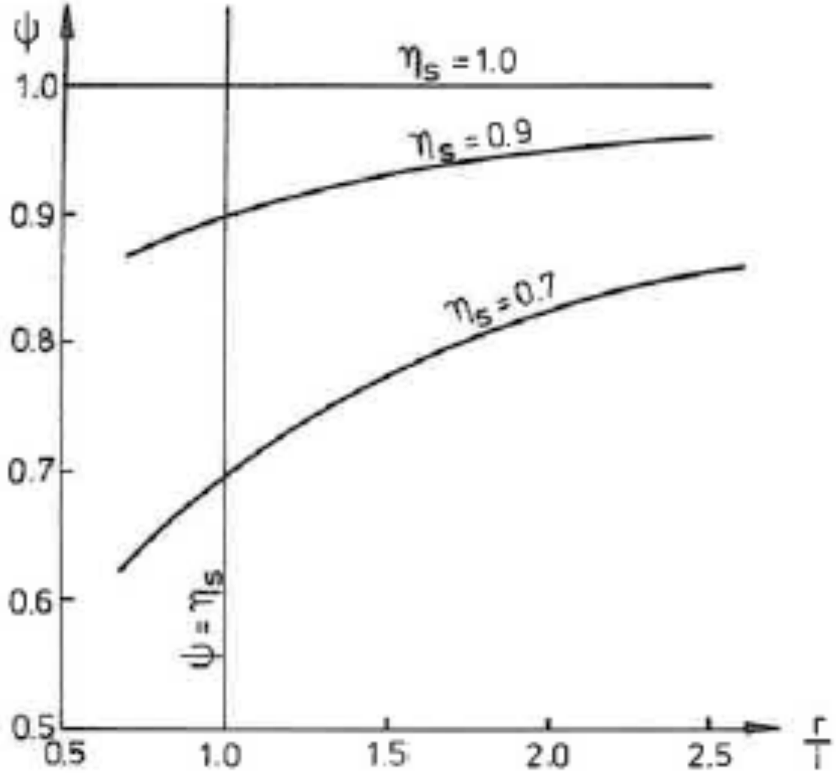
$$\mathrm{r} = \mathrm{h}_2 - \mathrm{h}_{2\mathrm{ise}} \qquad i = T_O(s_2 - s_1) \tag{2}$$

$$\eta_b = \frac{h_1 - h_2}{(h_1 - h_2) + T_O(s_2 - s_1)} = \frac{h_1 - h_2}{(h_1 - h_2) + i} \tag{3}$$

$$\eta_{ise} = \frac{h_1 - h_2}{(h_1 - h_2) + (h_2 - h_{2ise})} = \frac{h_1 - h_2}{(h_1 - h_2) + r} \tag{4}$$

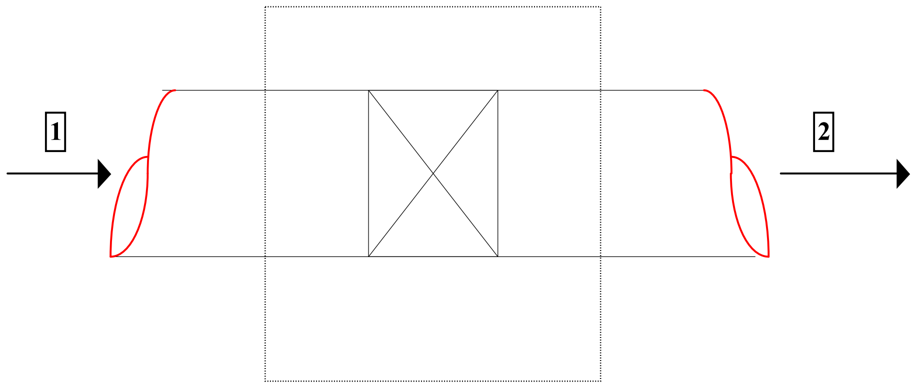
$$\frac{\eta_b}{\eta_{ise}} = \frac{1}{\eta_{ise} + i / W_{ise}} \tag{5}$$

$$\eta_b = \frac{\eta_{ise}}{i / r + \eta_{ise}(1 - i / r)} \tag{6}$$



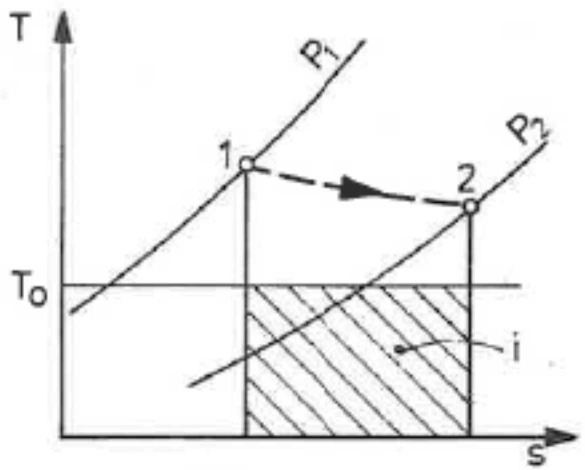
Relationship between isentropic efficiency and exergy efficiency for an expansion process (Kotas, 1985).

2. THROTTLING PROCESS (Pressure reduction valve)

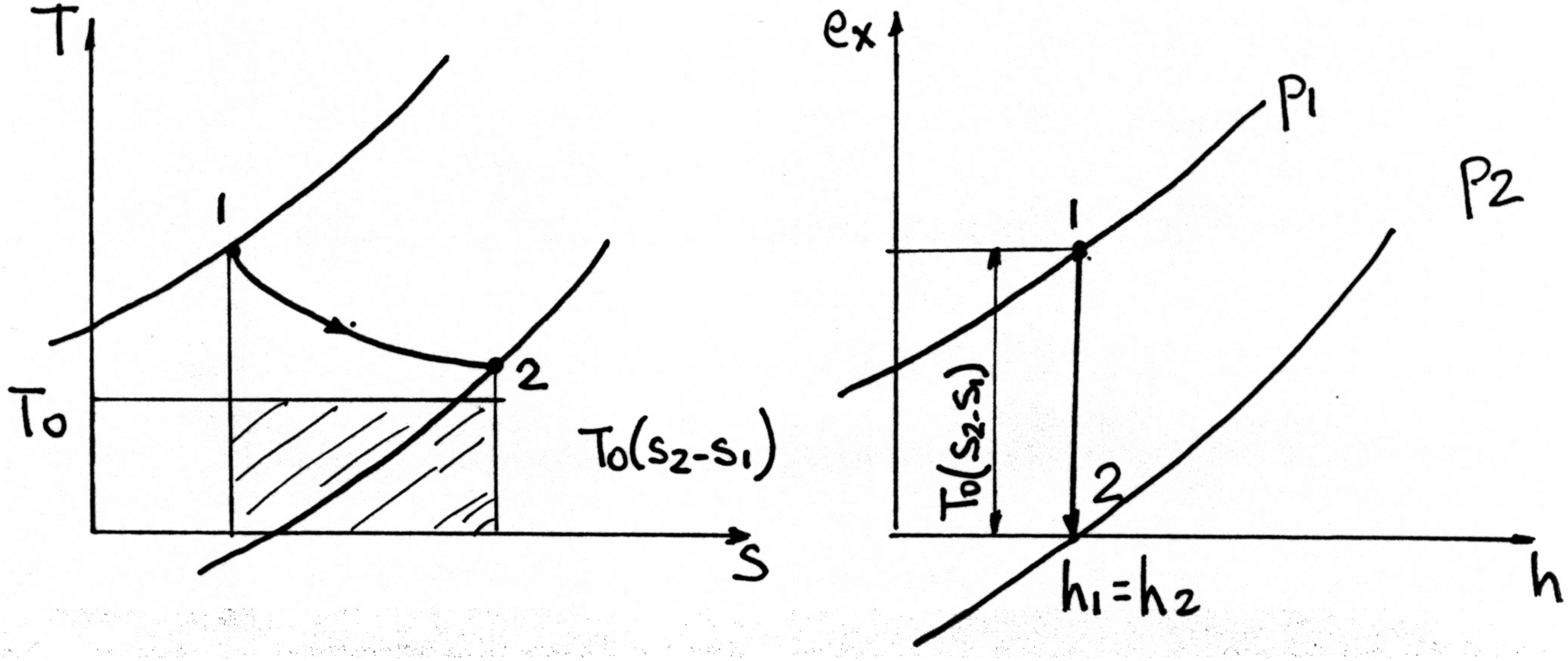


$$b_1 = b_2 + i \qquad (7)$$

Q = 0

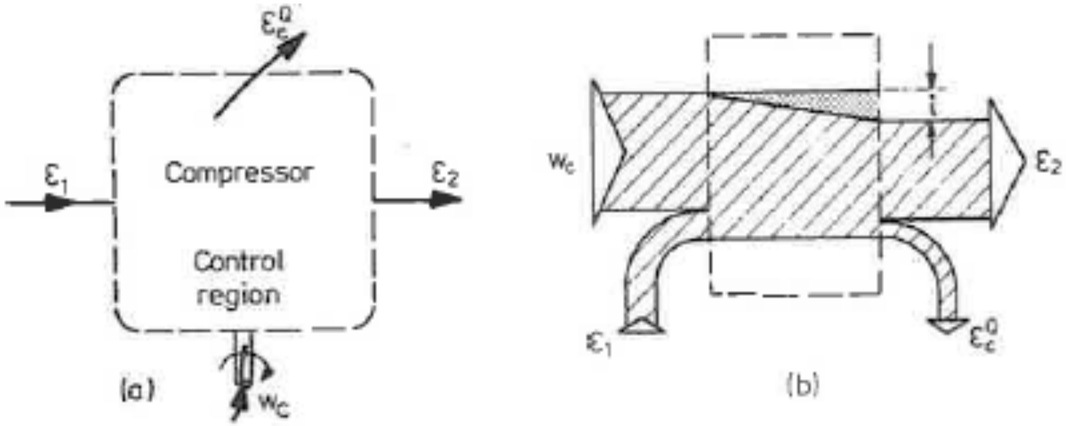


Adiabatic throttling process (Kotas, 1985).



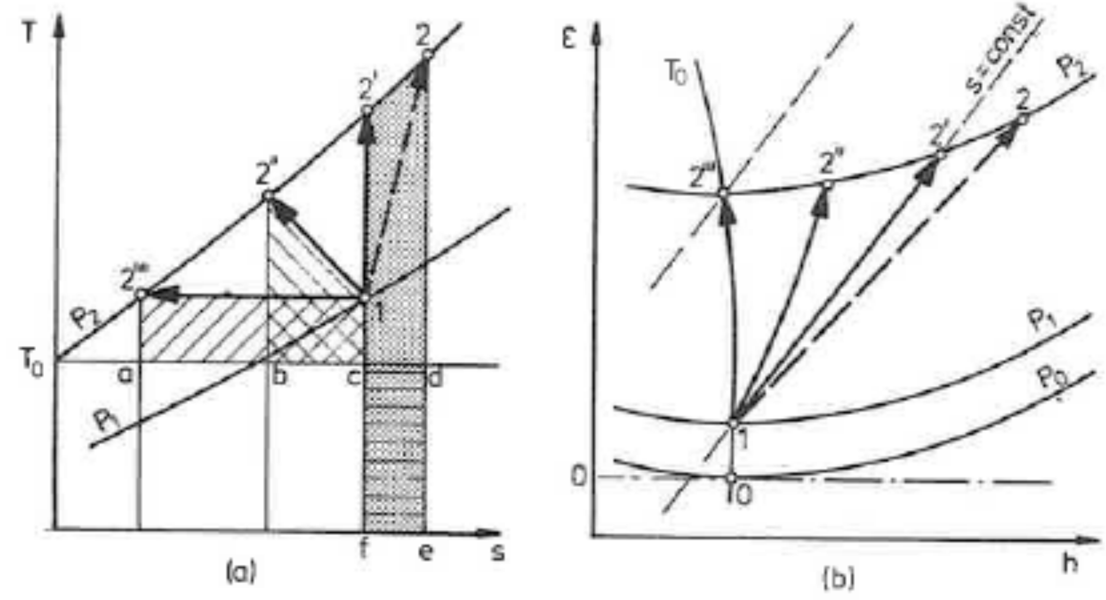
Adiabatic throttling process

3. COMPRESSION



Compression process: (a) control volume and (b) Grassmann diagram (Kotas, 1985).

$$b_1 + w_c = b_2 + i + b_Q \tag{8}$$



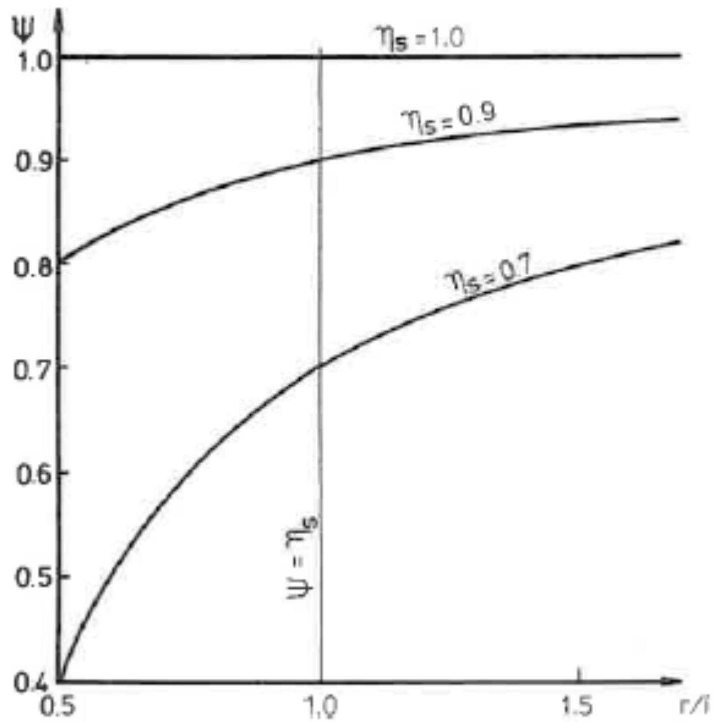
Compression process: (a) in T-s coordinates for $T_1>T_0$ and (b) in exergy-enthalpy for $T_1=T_0$ (Kotas, 1985).

Adiabatic Compressor:

$$\eta_b = \frac{b_2 - b_1}{w_c} = 1 - \frac{T_o(s_2 - s_1)}{h_2 - h_1} \tag{9}$$

$$\eta_{ise} = 1 - \frac{r}{w} \tag{10}$$

$$\therefore \ \eta_b = 1 - \frac{i}{r}(1 - \eta_{ise}) \tag{11}$$



Relationship between isentropic efficiency and exergy efficiency for a compression process (Kotas, 1985).

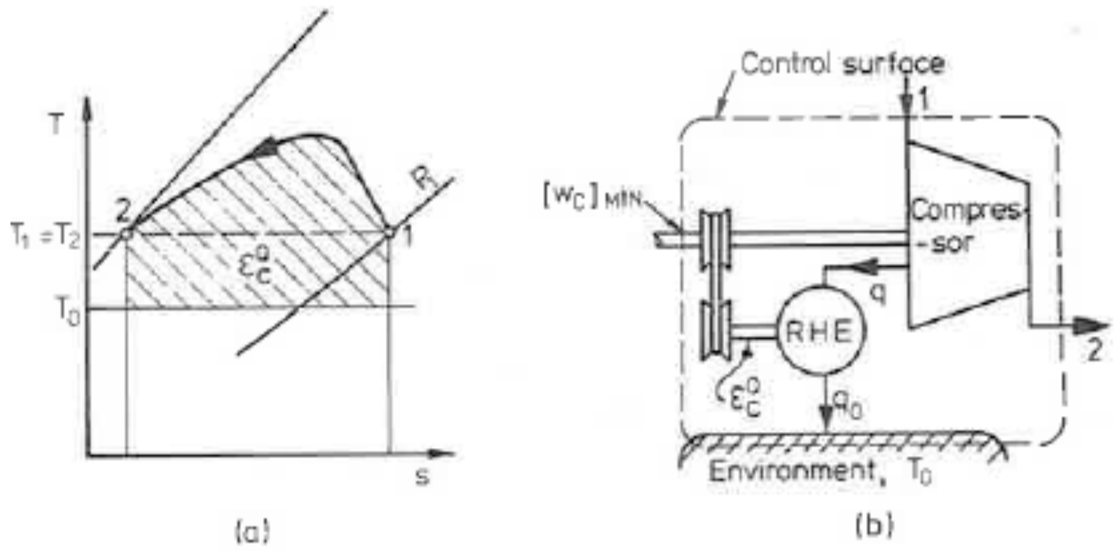
Non- adiabatic compressor

1-’’: polytrophic

1-2’’’: isothermal

$$\eta_{iso} = \frac{isothermic\ work}{real\ work} \tag{12}$$

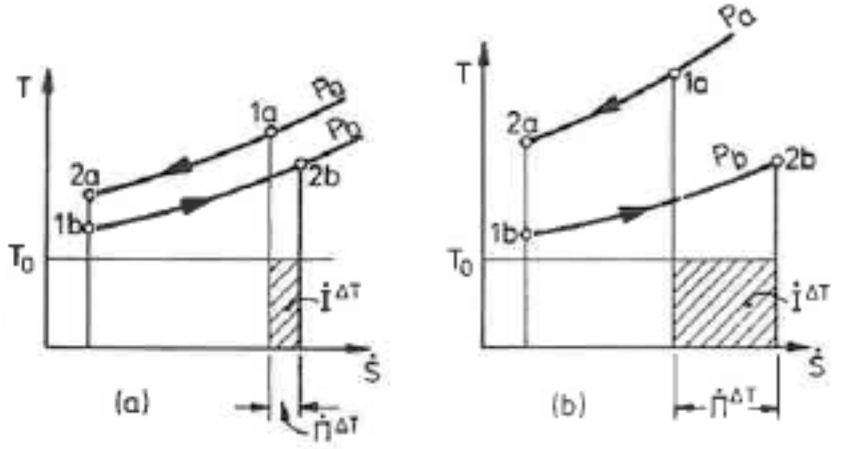
$$\eta_b = \frac{RT_o \ell n\,(p_2 / p_1)}{w_c} = \frac{T_o}{T_1}\eta_{iso} \tag{13}$$



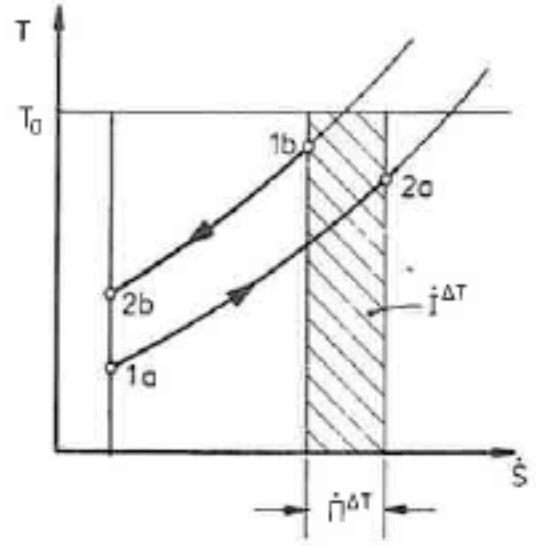
Reversible non-adiabatic compression process, $T_1=T_2$ (Kotas, 1985).

$$[W_c]_{min} = R\,T_0 \ln (p_2/p_1) \qquad (14)$$

4. HEAT TRANSFER



Isobaric heat transfer: (a) counter-flow and (b) parallel-flow heat exchanger (Kotas, 1985).



Isobaric heat transfer at sub-environmental temperatures (Kotas, 1985).

- Group I: The thermal component of one stream increases at the expense of a reduction in the thermal component of exergy of the other stream.

- Group II: there is a heat transfer to or from the environment (cooling towers, condensers ($T > T_0$), heat pump evaporators ($T < T_0$)) $\Rightarrow$ In either case the exergy of the stream decreases as a result of the heat transfer from/to the environment $\Rightarrow$ dissipative process

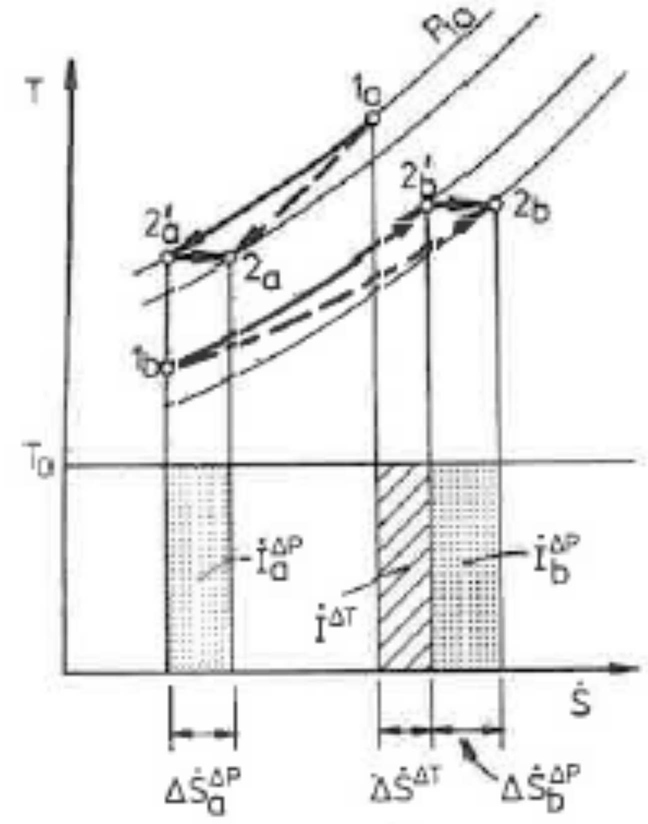
- Irreversible processes:

  - Heat exchange with temperature difference;

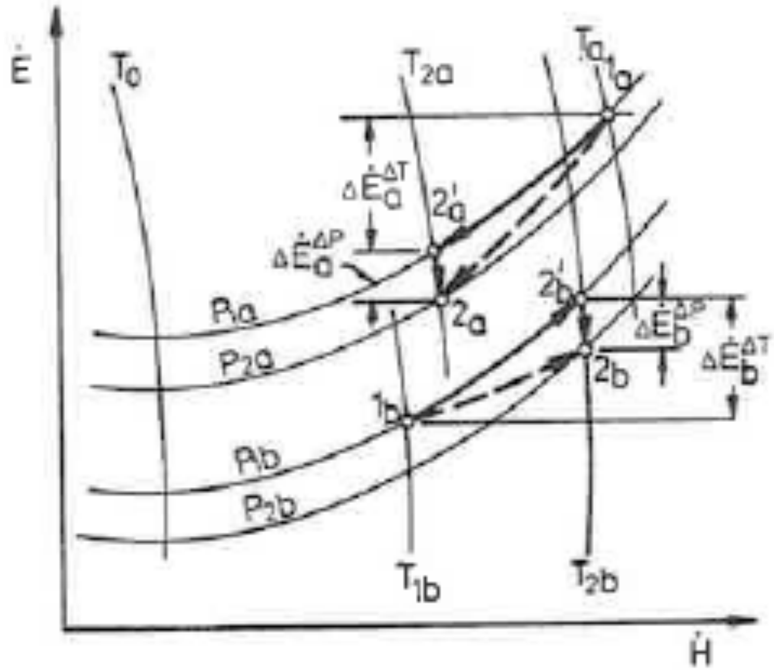
  - Head loss

  - Thermal interactions with environment (insulation)

  - Streamwise conduction in the walls of the heat exchanger



Heat transfer process in T-S coordinates (Kotas, 1985).



Heat transfer process in B-H coordinates (Kotas, 1985).

$$\left(\Delta B\right)_A \rangle \left(\Delta B^{\Delta T}\right)_A \quad e \left(\Delta B\right)_B \langle \left(\Delta B^{\Delta T}\right)_B \tag{15}$$

$$\left[\left(\Delta B^{\Delta T}\right)_A + \left(\Delta B^{\Delta P}\right)_A\right] - \left[\left(\Delta B^{\Delta T}\right)_B + \left(\Delta B^{\Delta P}\right)_B\right] = \dot{I} = T_o\left(\Delta S_A + \Delta S_B\right) \tag{16}$$

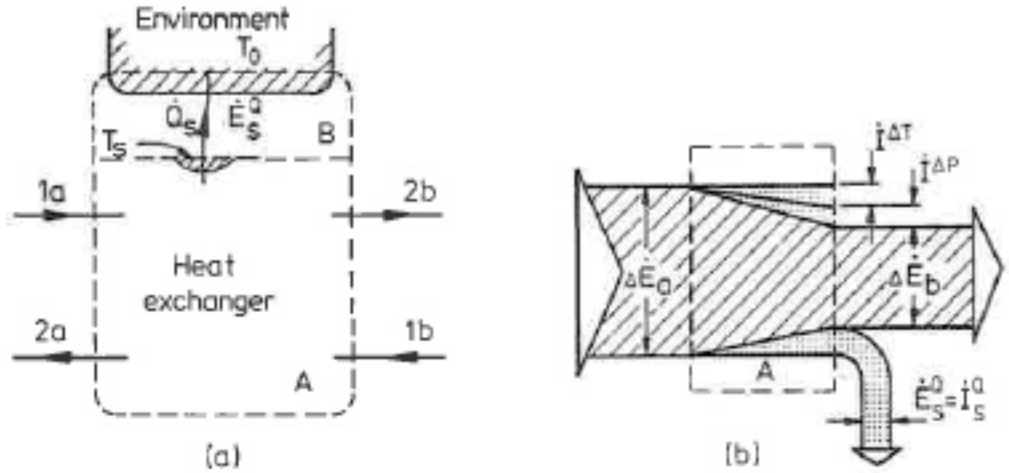
For ideal gases, h = f (T):

$$\dot{I}^{\Delta T} = T_o\left(\dot{m}_B \int_{T_{1B}}^{T_{2B}} cp_B \frac{dT}{T} - \dot{m}_A \int_{T_{2A}}^{T_{1A}} cp_A \frac{dT}{T}\right) \tag{17}$$

$$\dot{I}_A^{\Delta p} = \dot{m}_A R_A T_o \ln\left({p_{1A}}/{p_{2A}}\right) \tag{18}$$

$$\dot{I}_B^{\Delta p} = \dot{m}_B R_B T_o \ln\left({p_{1B}} \big/ {p_{2B}} \right) \tag{19}$$

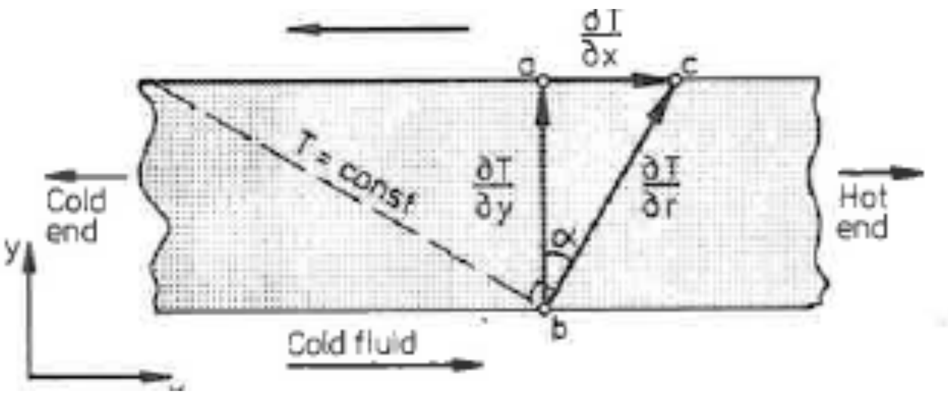
- Heat losses



Heat exchange with heat losses to the environment (Kotas, 1985).

$$\dot{I}_S^Q = \dot{Q}_S \frac{\overline{T}_S - T_o}{T_o} \tag{20}$$

- Streamwise conduction in the walls of a heat exchanger



Temperature gradients in a streamwise cross-section of the wall between heat transfer media (Kotas, 1985).

* Small heat exchangers and heat exchangers for cryogenic applications

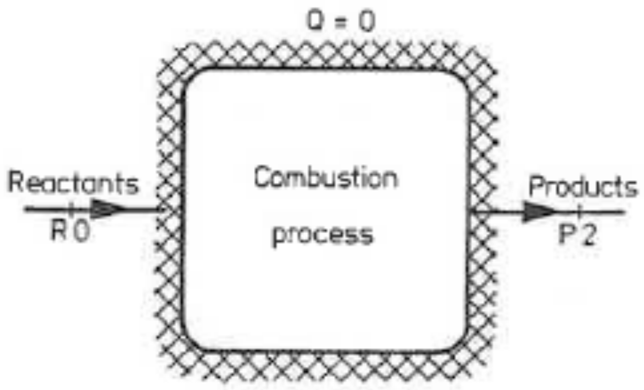
- Exergy efficiency of a heat exchanger

$$\eta_b = \frac{\left(B_{2B} - B_{1B}\right)}{\left(B_{1A} - B_{2A}\right)} \tag{21}$$

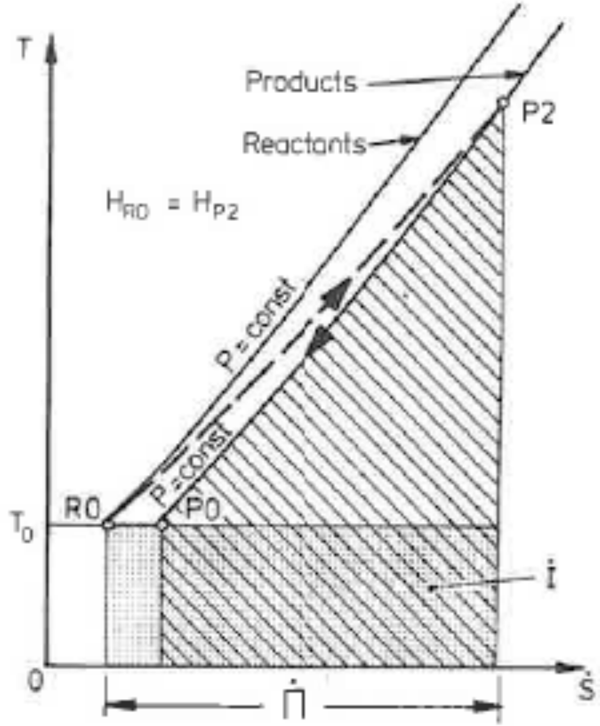
$$\eta_b = \frac{\Delta B_B^{\Delta T} - \Delta B_B^{\Delta p}}{\Delta B_A^{\Delta T} + \Delta B_A^{\Delta p}} \tag{22}$$

5. COMBUSTION

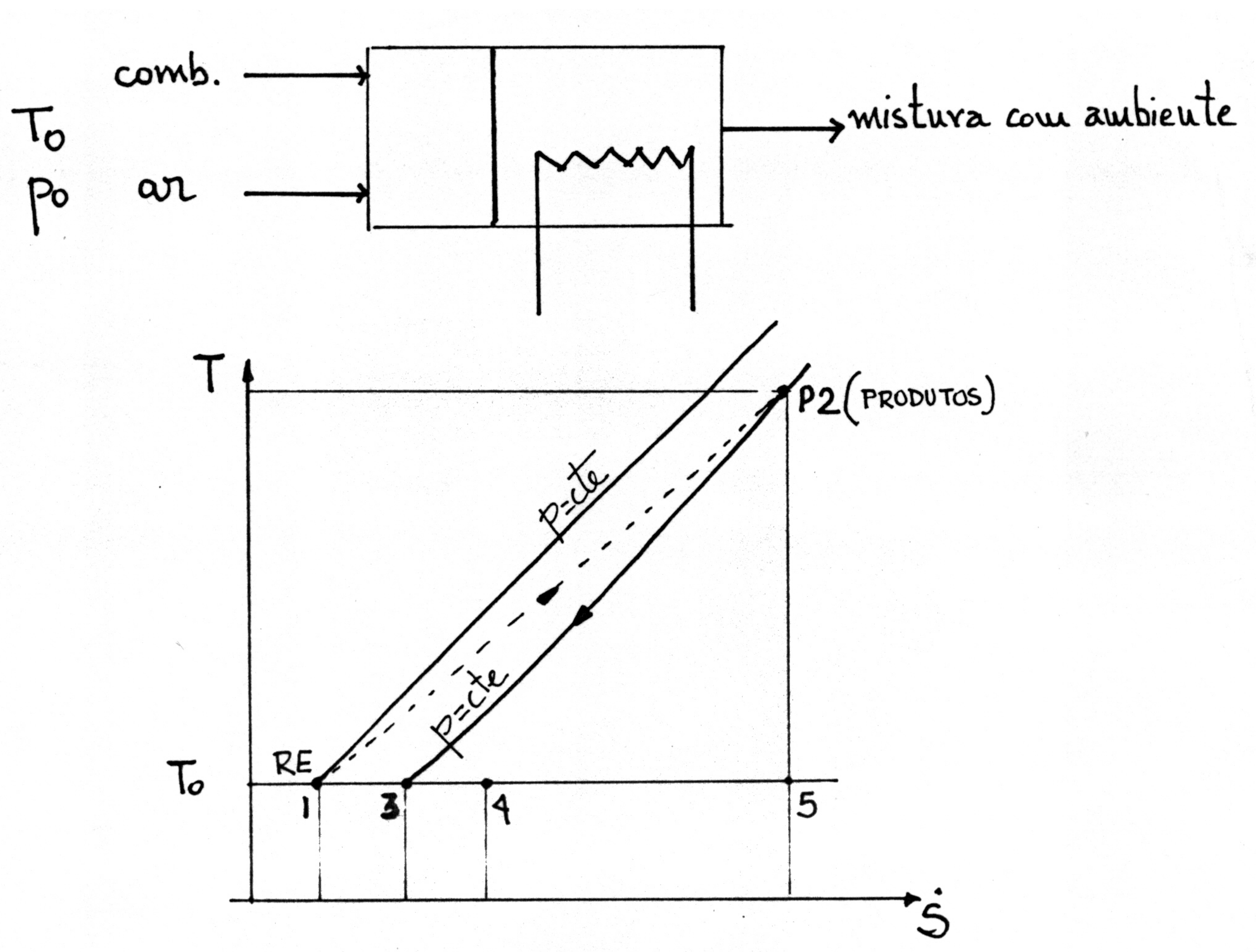
Irreversible processes → chemical reaction
heat exchange
mixture + head loss



Adiabatic combustion chamber (Kotas, 1985).

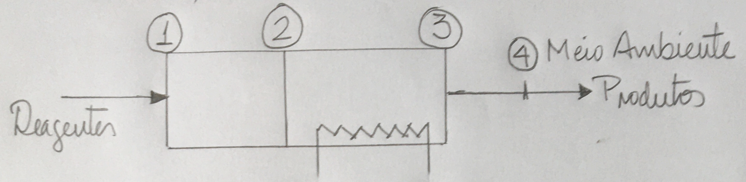


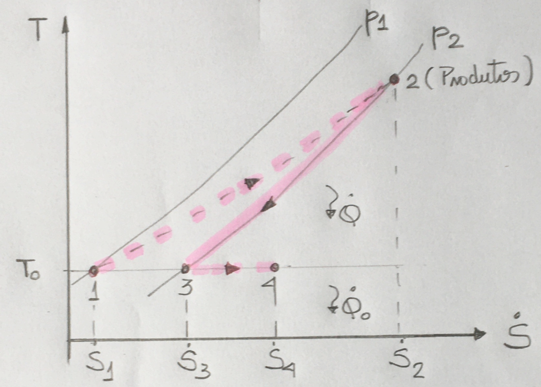
Irreversibility in an adiabatic combustion process (Kotas, 1985).



$$\dot{I} = (B)_{RE} - (B)_{p2} = T_O\left(\dot{S}_{p2} - \dot{S}_{RE}\right) = T_O\left(\dot{S}_2 - \dot{S}_1\right) \tag{23}$$

Relação entre b_{ch} e PCI





Balanço de exergia para a reação $\dot{B}_1 - \dot{B}_2 = (\dot{B}_{dest})_{reação} = T_0(\dot{S}_2 - \dot{S}_1)$

$$\cancel{\dot{B}_2} - \cancel{\dot{B}_3} = \underbrace{\int_3^2 T\,d\dot{S}} - T_0(\cancel{\dot{S}_2} - \cancel{\dot{S}_3}) = \overline{\dot{PCI}} - T_0(\cancel{\dot{S}_2} - \cancel{\dot{S}_3})$$

$$\cancel{\dot{B}_3} - \dot{B}_4 = T_0(\dot{S}_4 - \cancel{\dot{S}_3}) = (\dot{B}_{ch})_{\text{produtos da combustão}}$$

Somando as três equações:

$$\dot{B}_1 - \dot{B}_4 = \overline{\dot{PCI}} + T_0(\dot{S}_4 - \dot{S}_1) \quad \text{e como } \dot{B}_4 = 0$$

$$\dot{B}_1 = \overline{\dot{PCI}} + T_0(\dot{S}_4 - \dot{S}_1) = (\dot{B}_{ch})_{reagentes}$$

$$\text{Fuel heating value} = \int_3^2 T d\dot{S} \tag{24}$$

OBS.: $$T_o\left(\dot{S}_{p2} - \dot{S}_{RE}\right) \rangle\rangle\, T_o\left(\dot{S}_3 - \dot{S}_1\right) \tag{25}$$

The chemical exergy of the combustion gases is:

$$\left(B_{ch}\right)_{combustion\ gases} = T_O\left(\dot{S}_4 - \dot{S}_3\right) \tag{26}$$

The chemical exergy of the fuel:

$$\left(B_{ch}\right)_{fuel} = \int_3^2 T\, d\dot{S} + T_O(\dot{S}_4 - \dot{S}_1) \tag{27}$$

Destroyed exergy during combustion process:

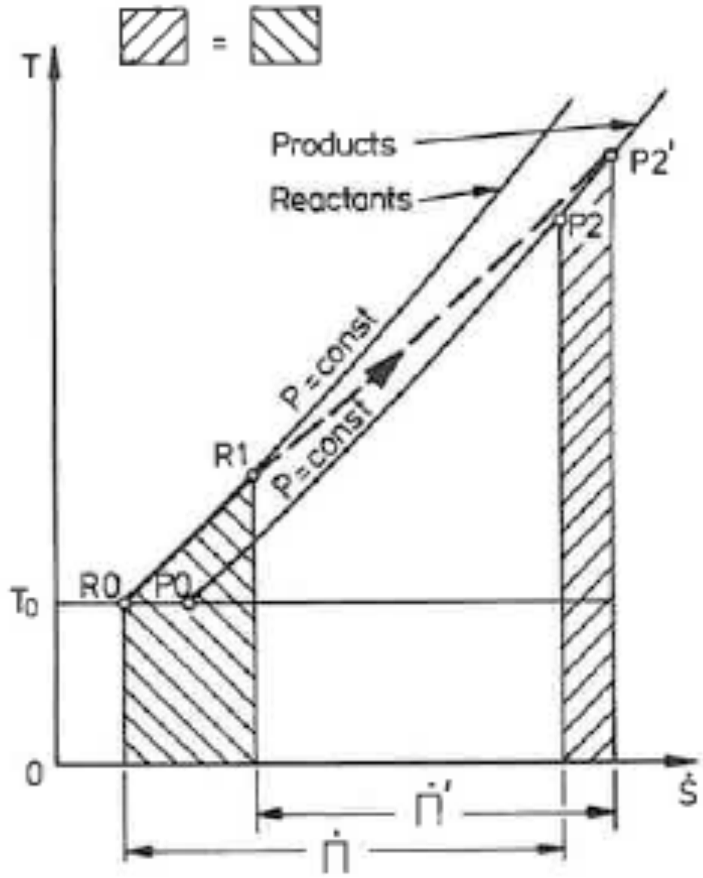
$$(B)_{dest} = \dot{I} = T_o(\dot{S}_2 - S_1) \tag{28}$$

- Irreversibility reduction (increase of T_{p2}):

  . Isochoric combustion

  . Oxygen enrichment of the reactants

  . Preheating of the reactants


=
T
Products
Reactants
P2'
P2
P = const
P = const
R1
R0
P0
T0
0
Ṡ
Π̇'
Π̇

Effect of reactants preheating on the irreversibility rate in as adiabatic combustion process (Kotas, 1985).

$$S_{2'} - S_{1'} \langle S_2 - S_1 \tag{29}$$

- Other forms of Irreversibility

. Heat losses

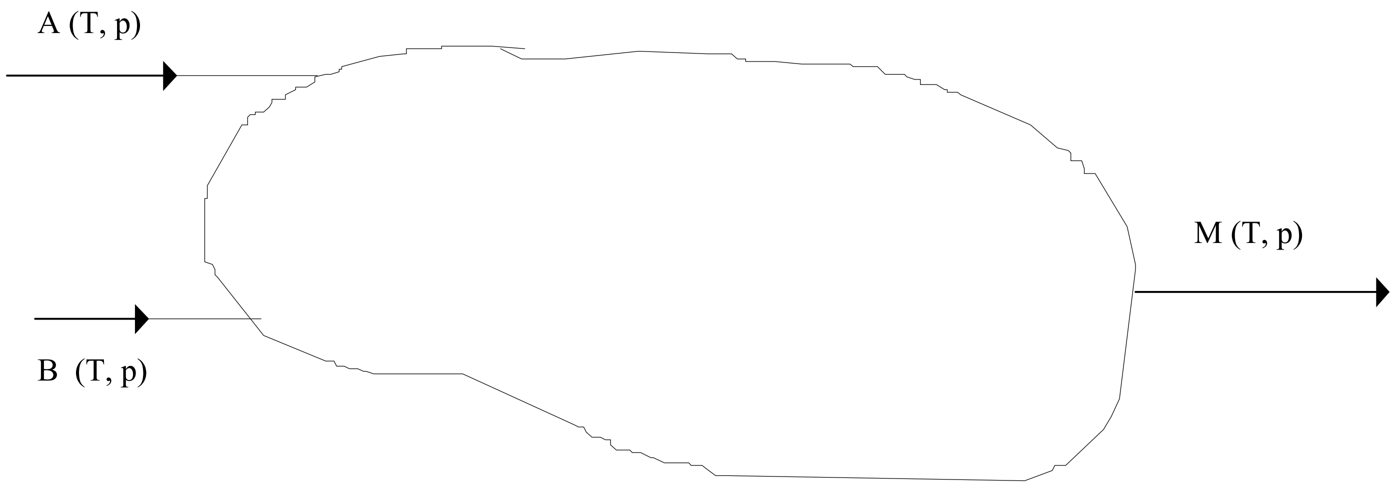
. Incomplete combustion

. Exhaust losses

6. SEPARATION AND MIXING PROCESSES

- Petroleum processing
- Air separation
- Sea water desalinization
- Absorption cycles

Enthalpy and entropy of mixing (mixture of two substances at T and p)



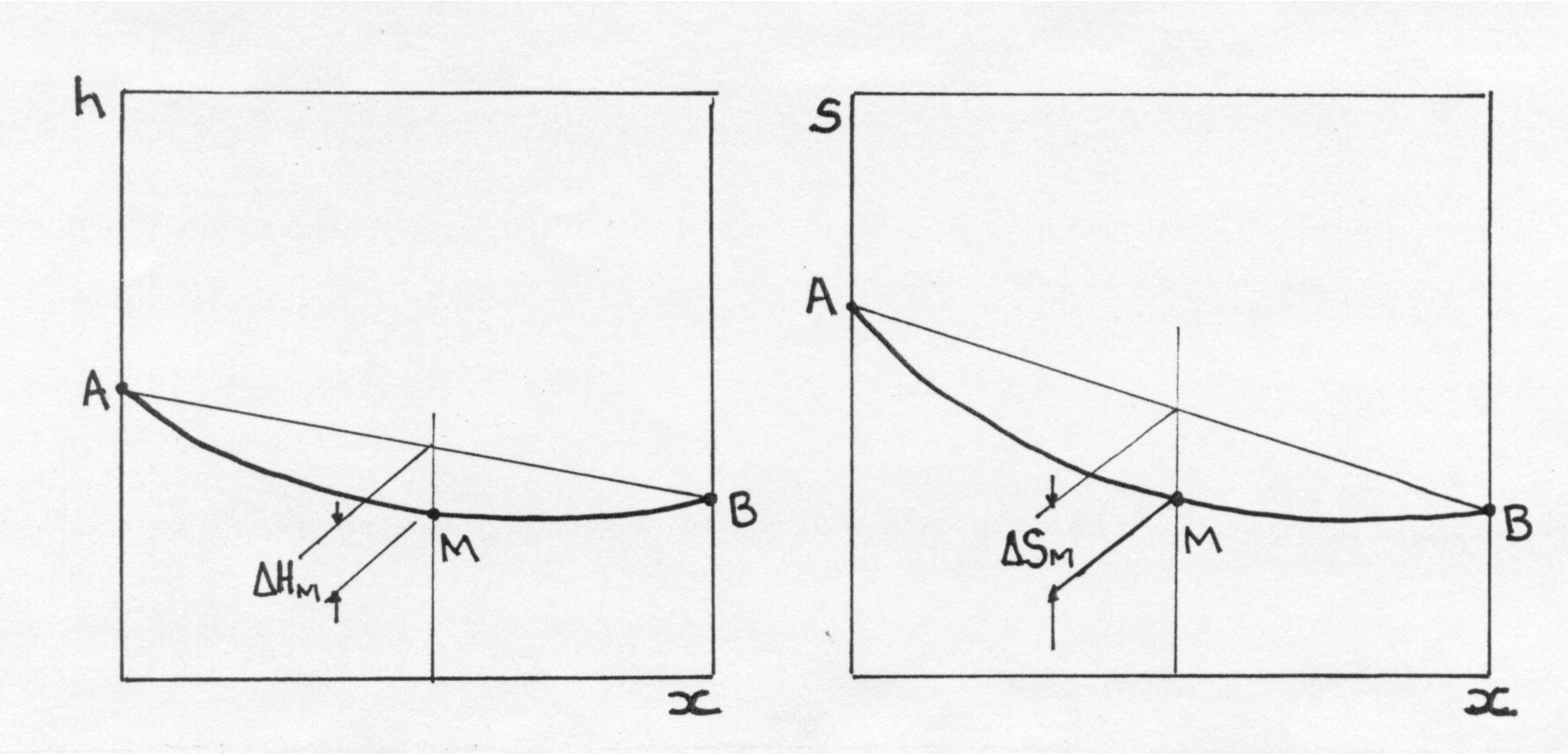


Diagram enthalpy – composition and entropy – composition for a binary mixture

Energy balance and 2nd Law for the mixing process:

1a Law:

$$m_A h_A + m_B h_B = (m_B + m_A) h_M + Q_M \,(same\ P, T) \tag{30}$$

$$x_A h_A + x_B h_B = h_M + q_M \qquad with\ \ q_M = Q_M / (m_A + m_B) \tag{31}$$

$$x_A h_A + (1 - x_A) h_B = h_M + q_M = h_M + \underbrace{\Delta H_M}_{\substack{\uparrow \\ mixing \\ enthalpy}} \tag{32}$$

2a Law:

$$\left(\mathrm{m_A} + \mathrm{m_B}\right) \mathrm{s_M} - \mathrm{m_A s_A} - \mathrm{m_B s_B} = \left(\frac{\Delta \mathrm{H_M}}{\mathrm{T}} + \Delta \mathrm{S_{ir}}\right)\left(\mathrm{m_A} + \mathrm{m_B}\right) \tag{33}$$

$$s_M = x_A s_A + \left(1 - x_A\right) s_B + \frac{\Delta H_M}{T} + \Delta S_{ir} \tag{34}$$

with:

$$\Delta S_{ir} = -R\left[x_A \ln\left(\gamma_A x_A\right) + \left(1 - x_A\right)\ln\left(\gamma_B (1 - x_A)\right)\right] \tag{35}$$

$$s_M = x_A s_A + x_B s_B + \frac{\Delta H_M}{T} - R\left[x_A \ln\left(\gamma_A x_A\right) + \left(1 - x_A\right)\ln\left(\gamma_B (1 - x_A)\right)\right] \tag{36}$$

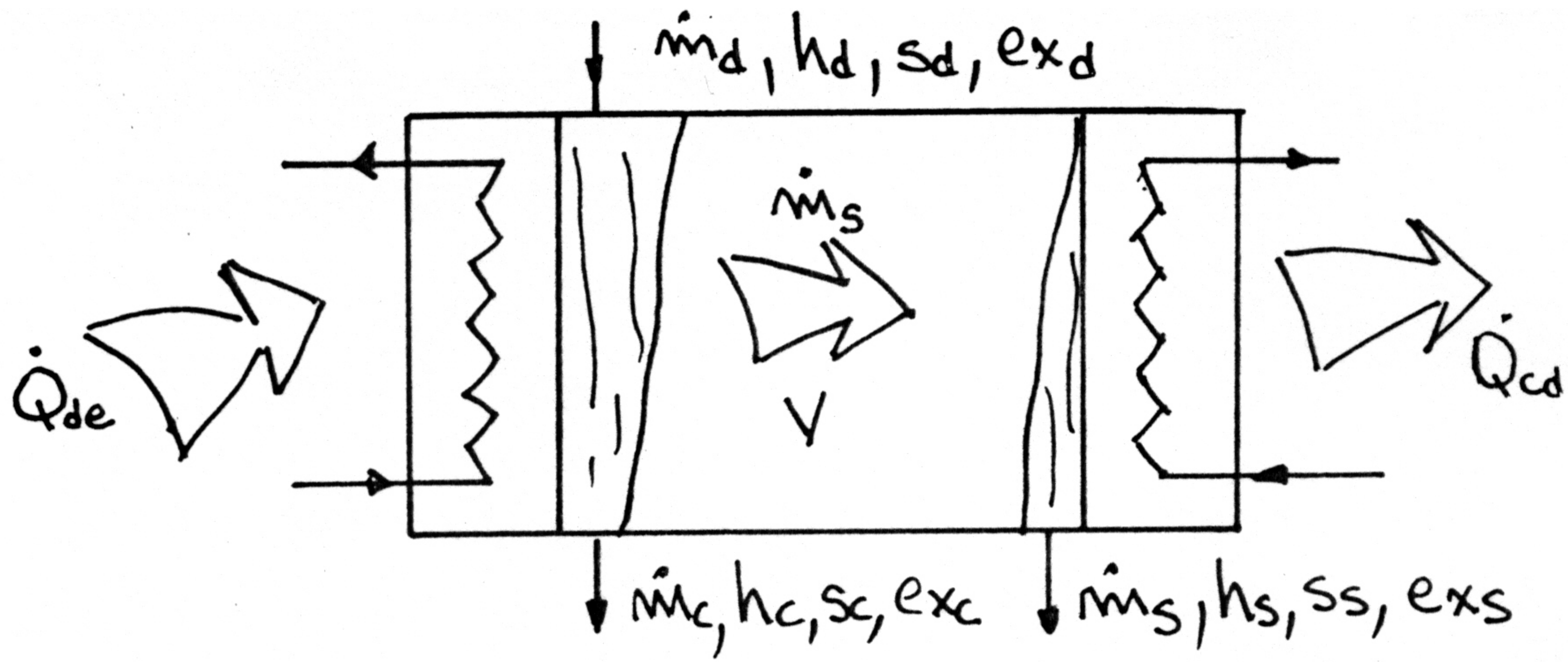
Exergy balance:

$$\left(\Delta B\right)_{mixture} = \Delta H_M - T_o\left(\Delta H_M / T - R\left[x_A \ell n\left(\gamma_A x_A\right) + x_B \ell n\left(\gamma_B x_B\right)\right]\right) \tag{37}$$

$$\left(\Delta B\right)_{mixture} = \Delta H_M \left(1 - \frac{T_O}{T}\right) + \underbrace{T_O R\left[x_A \ell n\left(\gamma_A x_A\right) + x_B \ell n\left(\gamma_B x_B\right)\right]}_{\uparrow \atop -destroyed\ exergy}$$

For an ideal mixture:

$$\left.\begin{array}{l} \Delta H_M = 0 \\ \gamma_A = \gamma_B = 1 \end{array}\right\} \qquad (38)$$



Separator of a binary mixture

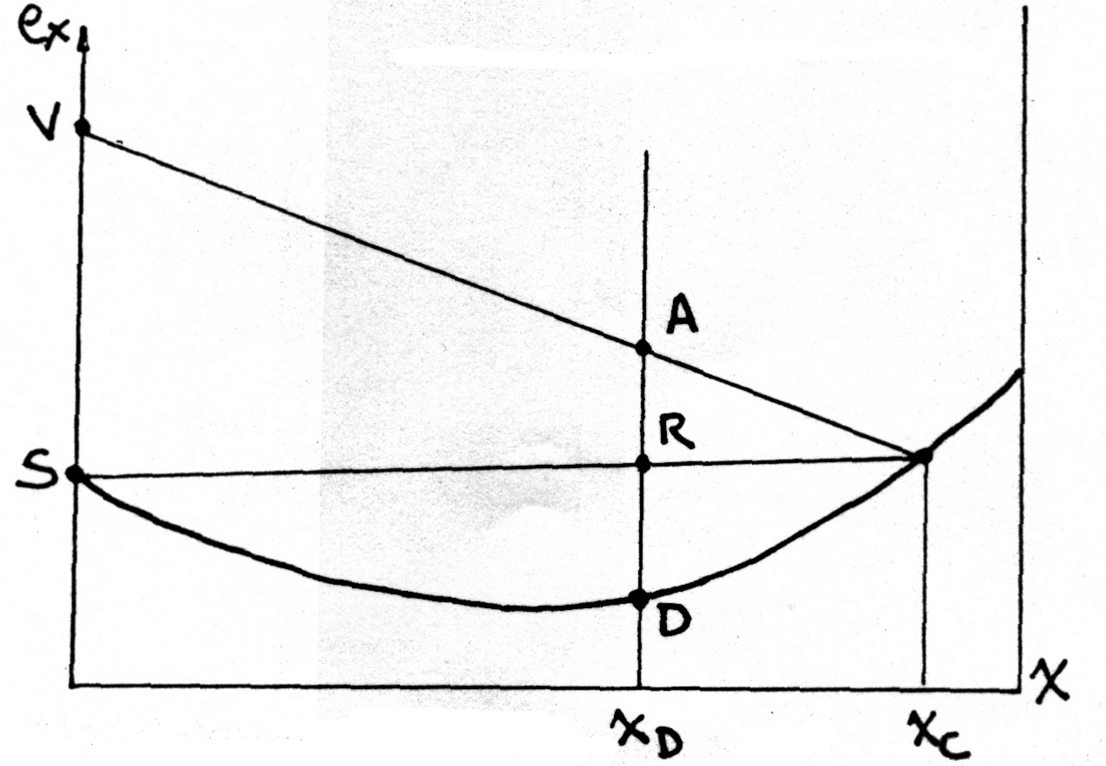


Diagram exergy - composition

Exergy balance for the separator

$$\dot{Q}_{DE}\theta_{DE} + \dot{m}_d b_d = \dot{Q}_{CD}\theta_{CD} + \dot{m}_c b_c + \dot{m}_s b_s + \dot{I} \tag{39}$$

$$\dot{m}_d b_R = \dot{m}_s b_s + \dot{m} b_c \tag{40}$$

$$b_R = \frac{\dot{m}_s b_s + \dot{m} b_c}{\dot{m}_d} \tag{41}$$

$$b_D = \frac{\dot{Q}_{CD}\theta_{CD} - \dot{Q}_{DE}\theta_{DE}}{\dot{m}_d} + \frac{\dot{I}}{\dot{m}_d} + \frac{\dot{m}_c b_c + \dot{m}_s b_s}{\dot{m}_d} \tag{42}$$

$$\mathrm{ex}_{\mathrm{R}} - \mathrm{ex}_{\mathrm{D}} = \mathrm{w}_{\mathrm{min}} = \frac{\dot{\mathrm{Q}}_{\mathrm{DE}}\theta_{\mathrm{DE}} - \dot{\mathrm{Q}}_{\mathrm{CD}}\theta_{\mathrm{CD}}}{\dot{\mathrm{m}}_{\mathrm{d}}} - \frac{\dot{\mathrm{I}}}{\dot{\mathrm{m}}_{\mathrm{d}}} \tag{43}$$

- For an ideal mixture: $w_{\min} = -RT\left(\sum x_i \ln x_i\right)$ (44)

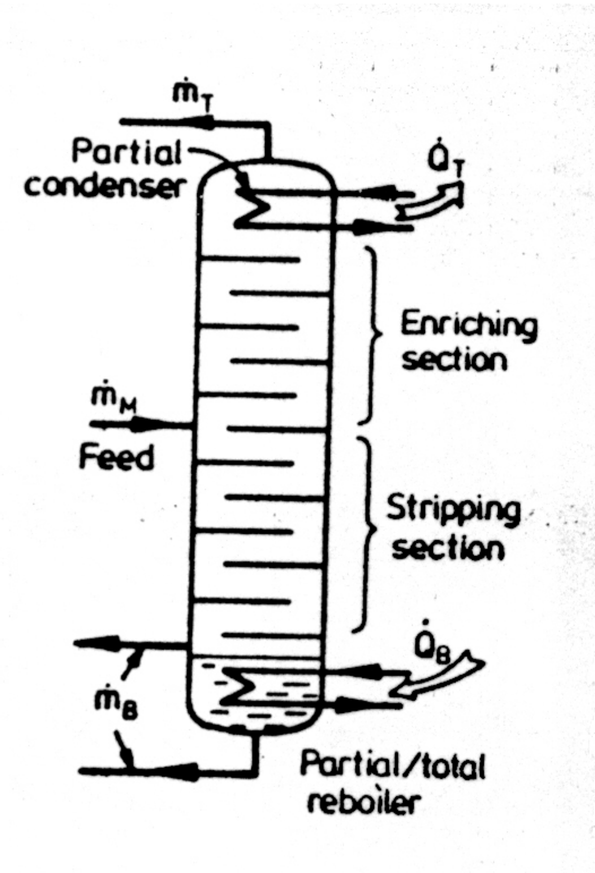
- Separator exergy efficiency

$$\left(\eta_b\right)_{sep} = \frac{\left(\Delta b\right)_{sep}}{\dot{Q}_{de}\overline{\theta}_{de} - \dot{Q}_{cd}\overline{\theta}_{cd}} \tag{45}$$

- Mixer exergy efficiency

$$\left(\eta_b\right)_{mist} = \frac{\dot{Q}_{ab}\overline{\theta}_{ab} - \dot{Q}_{ev}\overline{\theta}_{ev}}{\left(\Delta b\right)_{mist}} \tag{46}$$

* Adiabatic distillation column



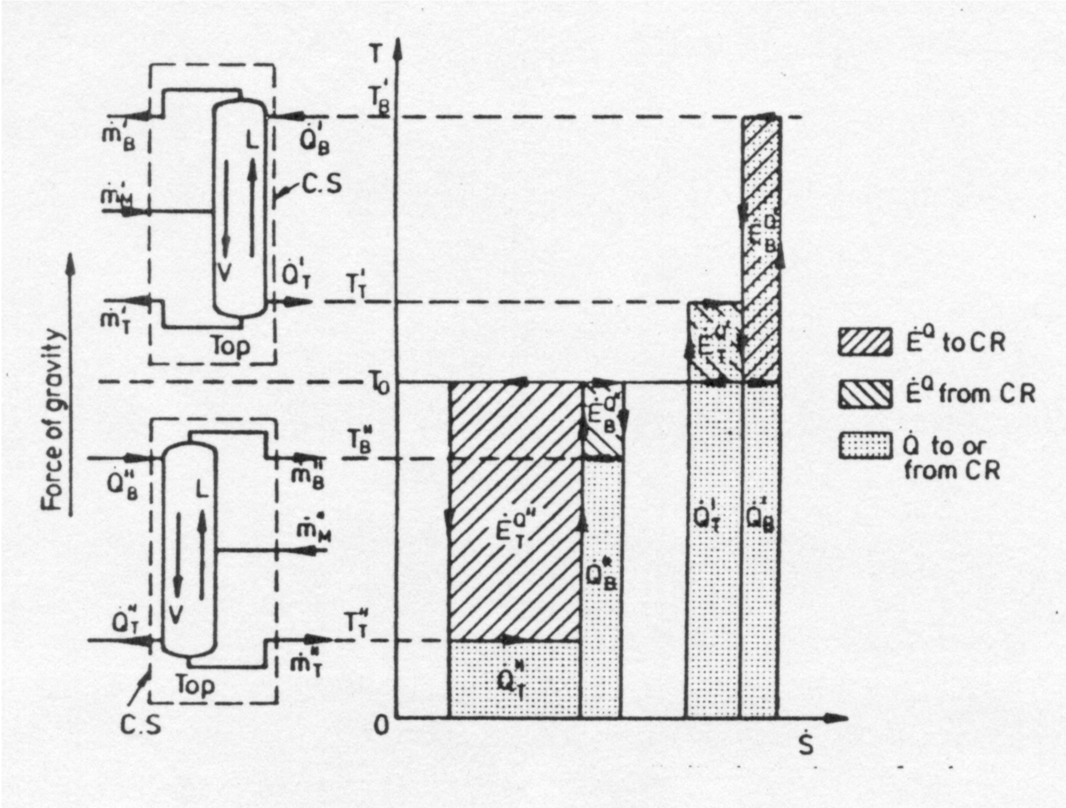
Schematic diagram of a distillation column (Kotas, 1985).

- Energy balance:

$$\dot{Q}_B - \dot{Q}_T = \underbrace{\dot{H}_T + \dot{H}_B - \dot{H}_M}_{\Delta H\ separation} \tag{47}$$

- Exergy balance

$$B_B^Q + B_T^Q = \underbrace{B_T + B_B - B_M + \dot{I}}_{(\Delta B_x)_{separation}} \tag{48}$$



Heat and exergy transfers in adiabatic distillation columns for $T>T_0$ and $T<T_0$ (Kotas, 1985).