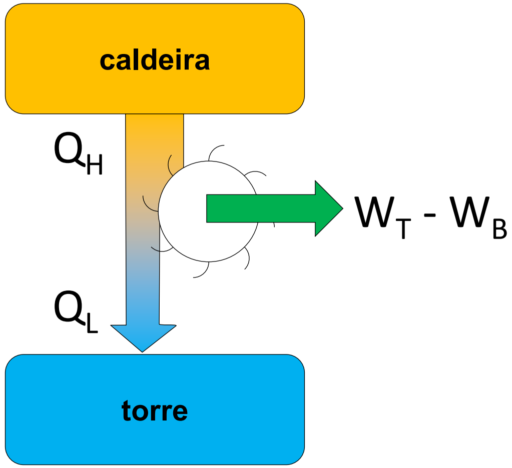
CURSO INTENSIVO

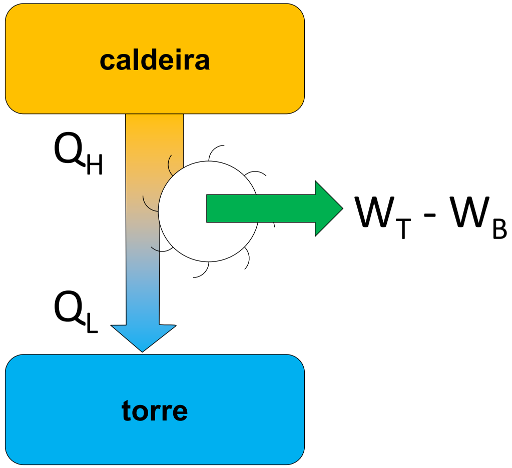
TERMODINÂMICA E APLICAÇÕES DE ENGENHARIA

CICLOS DE POTÊNCIA A VAPOR – Parte 1
o ciclo motor de Rankine

Paulo Seleghim Jr.
Universidade de São Paulo

Attention to Filler Words


caldeira
Q_H
W_T - W_B
Q_L
torre


caldeira
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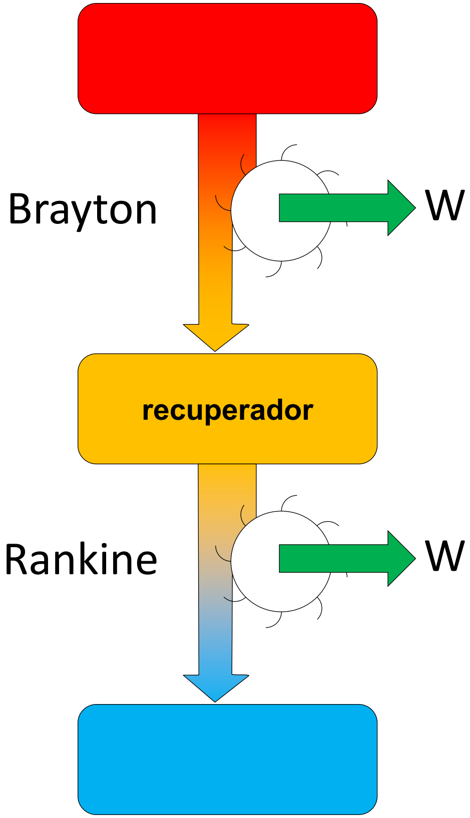
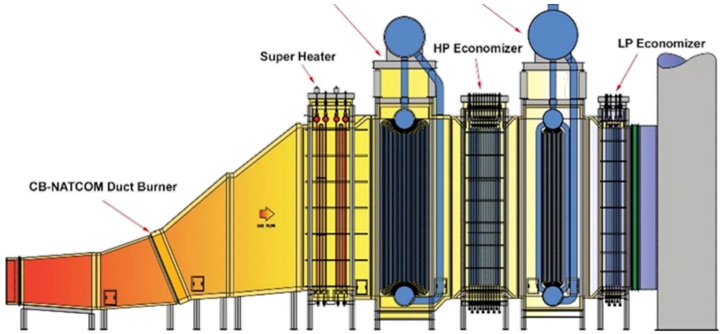
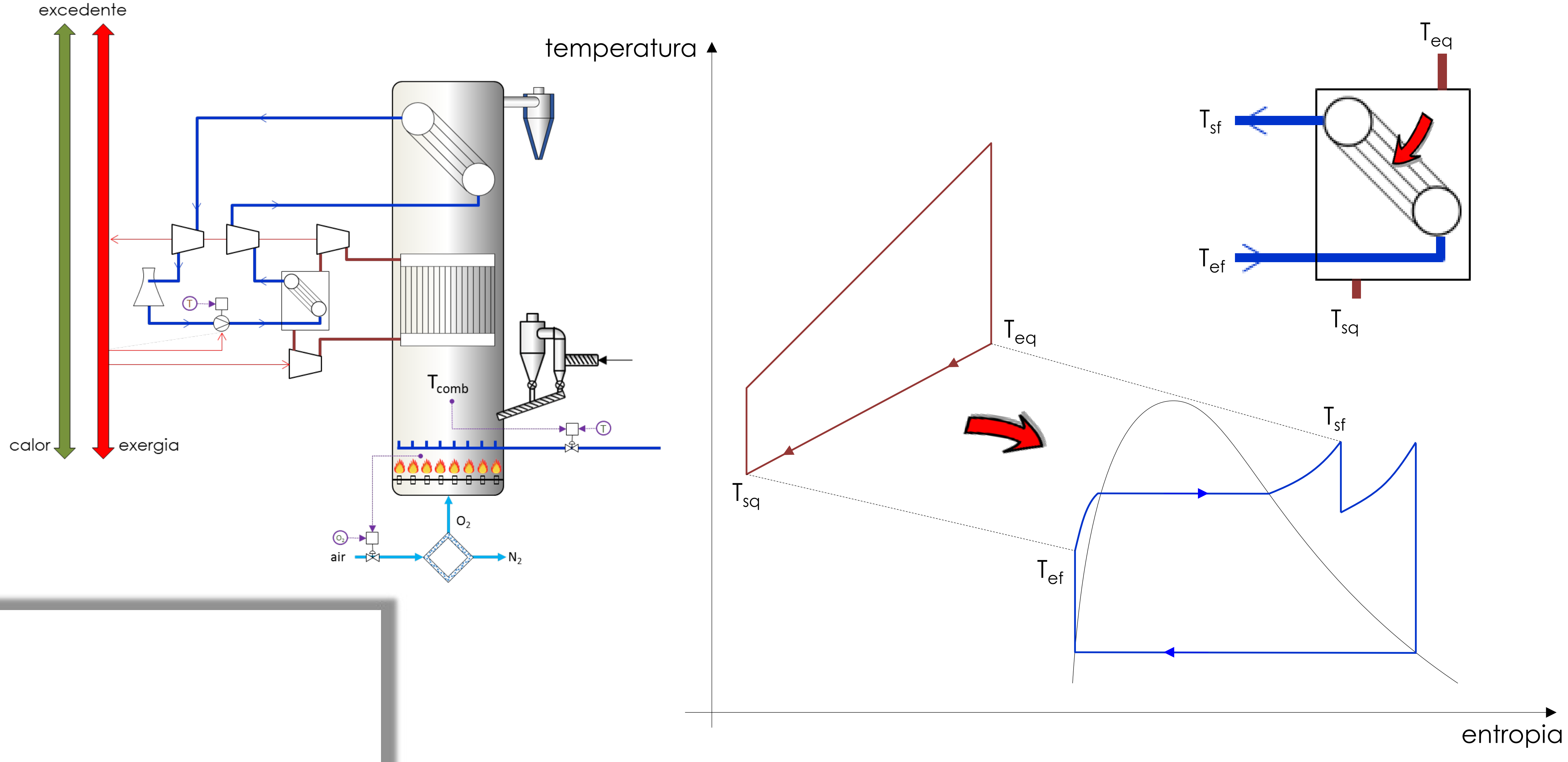


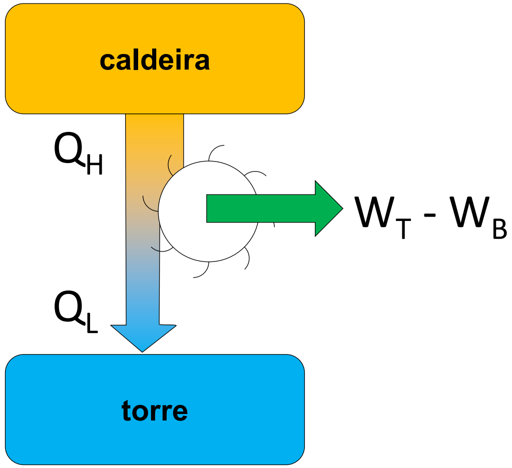
Ciclos combinados / avançados



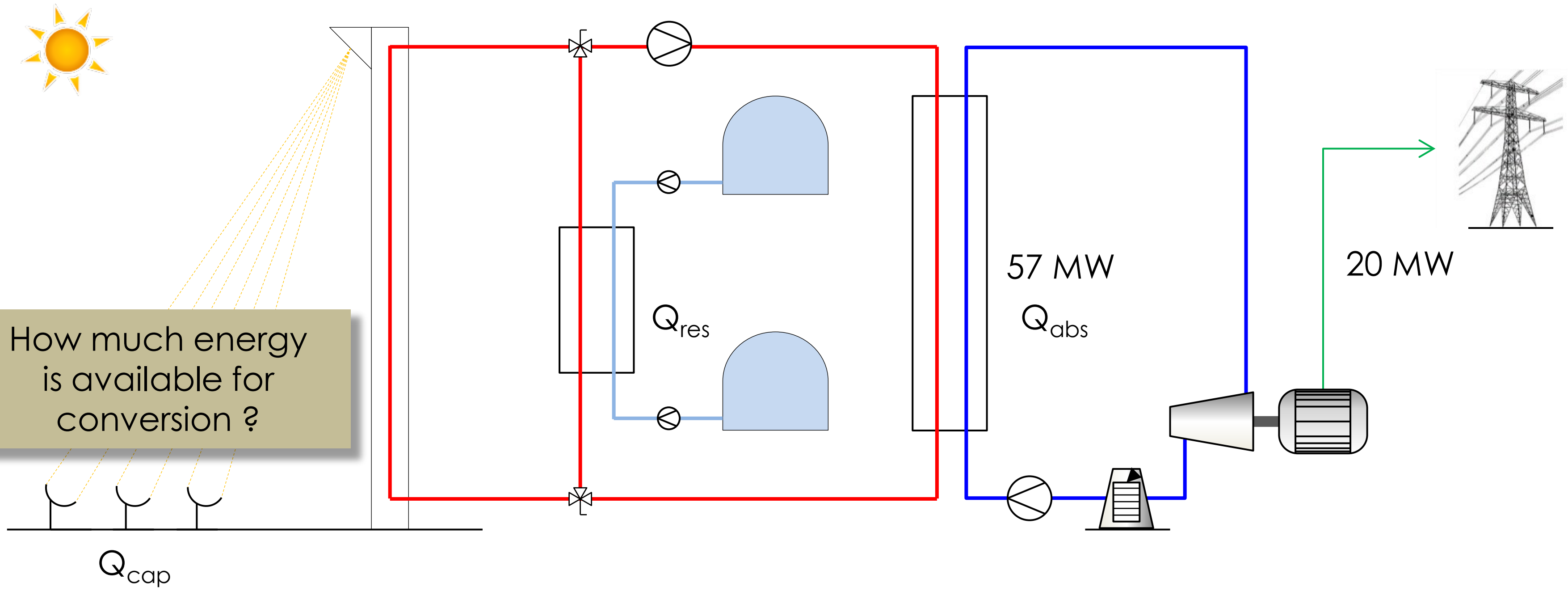
Aulas 14 e 15: Ciclos Avançados

Ciclo de Brayton associado a um ciclo de Rankine com reaquecimento




caldeira
QH
WT - WB
QL
torre

CONCEPTUAL DESIGN OF A THERMOSOLAR POWER PLANT…

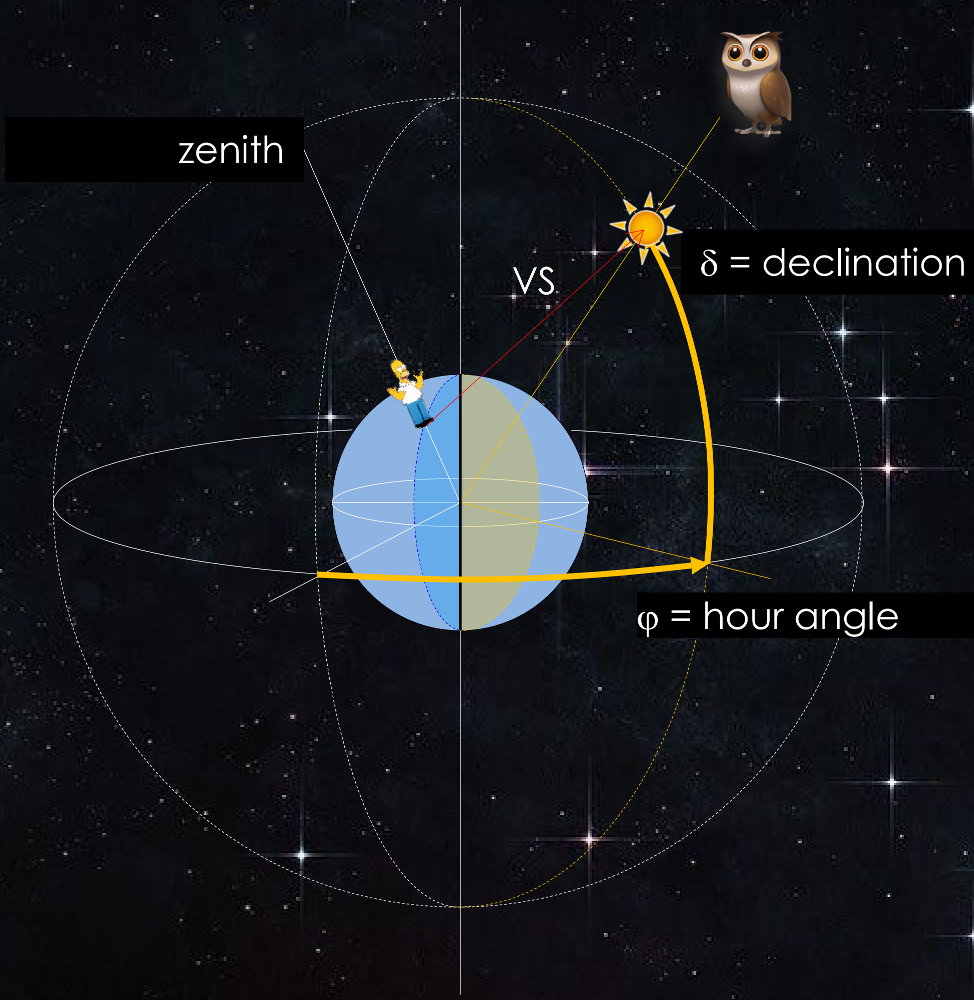


Average solar energy (W/m²) collected at earth's surface by a 2D collector placed at latitude ϕ, disregarding the presence of clouds and other random losses.

$$\overline{Q}_{cap}(\phi) \cong \frac{1}{365 \cdot 12} \int_{day} \int_{hour} (\text{ solar energy }) \, d\varphi \, dn$$

Definitions and working formulae...

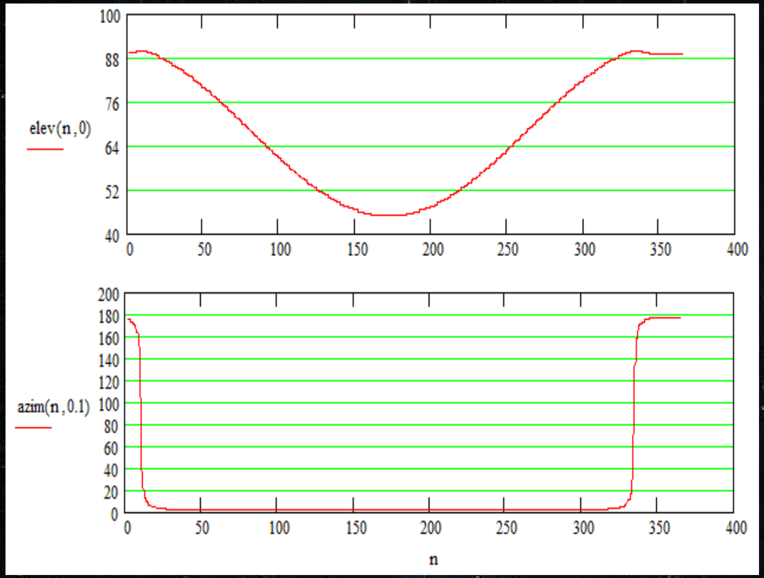
SUN'S **EQUATORIAL** COORDINATES



Obs.: depends on the day of the year

Obs.: depends on the hour of the day (local hour; 12h00 → $\varphi = 0$)

Definitions and working formulae...



Sun's elevation at noon in São Carlos (22°01''S = - 22,017°)

Definition of the day of the year and of the hour of the day

$$n = 1,2 \cdots 365 \qquad \varphi = -90°, -89°, \cdots + 90°$$

Calculus of the solar elevation (h):

$$\sin(h) = \sin(\phi)\sin(\delta) + \cos(\phi)\cos(\delta)\cos(\varphi)$$

Calculus of the solar azimuth (A):

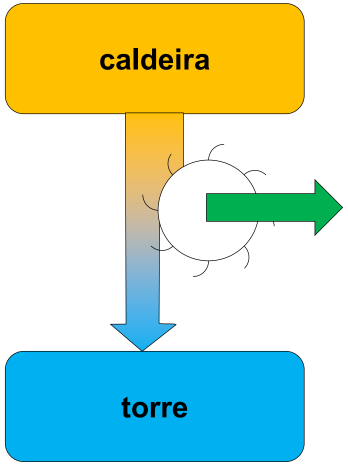
$$\cos(A) = \frac{\sin(\phi)\sin(h) - \sin(\delta)}{\cos(\phi)\cos(h)}$$

Definition of the solar vector (VS):

$$VS = \cos(h)\cos(A)\,\hat{\imath} + \cos(h)\sin(A)\,\hat{\jmath} + \sin(h)\,\hat{k}$$

Análise dos ciclos a vapor:
O ciclo de Rankine

Ciclo de Carnot: definição

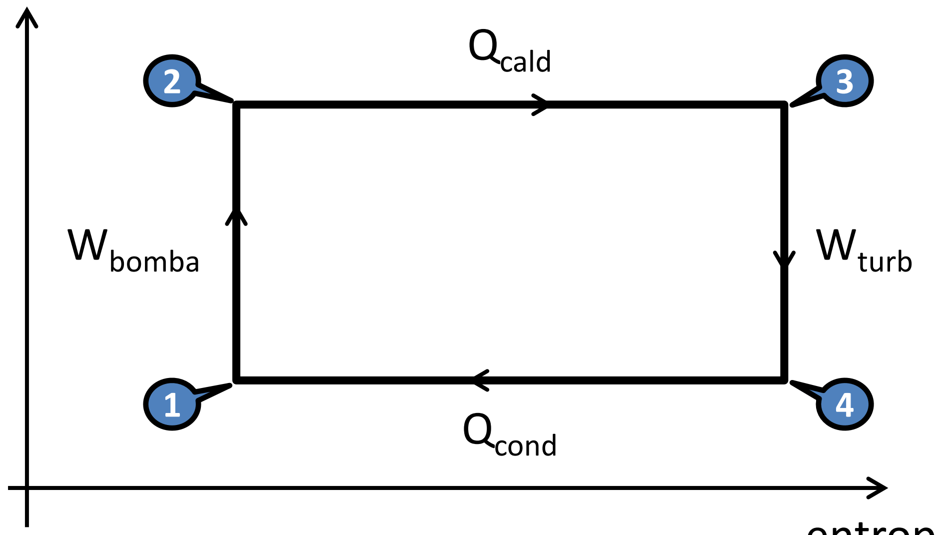


1-2) Compressão isentrópica (bomba)

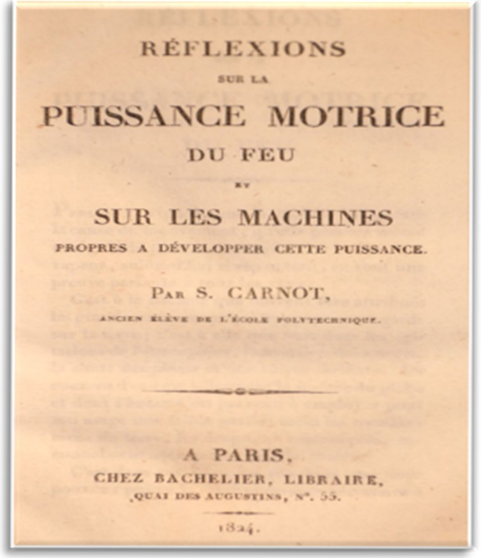
2-3) Aquecimento isotérmico (caldeira)

3-4) Expansão isentrópica (turbina)

4-1) Resfriamento isotérmico (condensador)

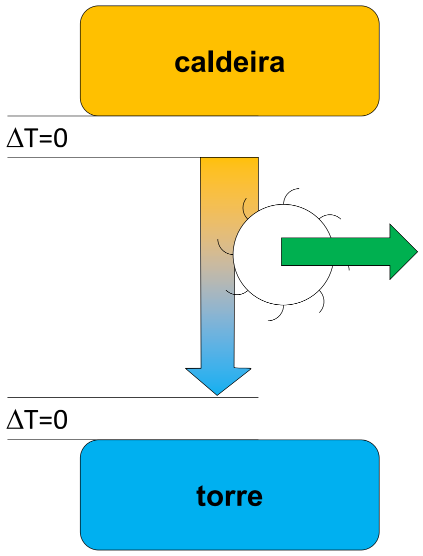


Nicolas Léonard Sadi Carnot
em 1824, aos 28 anos de idade...


RÉFLEXIONS
SUR LA
PUISSANCE MOTRICE
DU FEU
ET
SUR LES MACHINES
PROPRES A DÉVELOPPER CETTE PUISSANCE.
PAR S. CARNOT,
ANCIEN ÉLÈVE DE L'ÉCOLE POLYTECHNIQUE.
A PARIS,
CHEZ BACHELIER, LIBRAIRE,
QUAI DES AUGUSTINS, N°. 55.
1824.

Attention to Filler Words

Ciclo de Carnot: definição



1-2) Compressão isentrópica (bomba)

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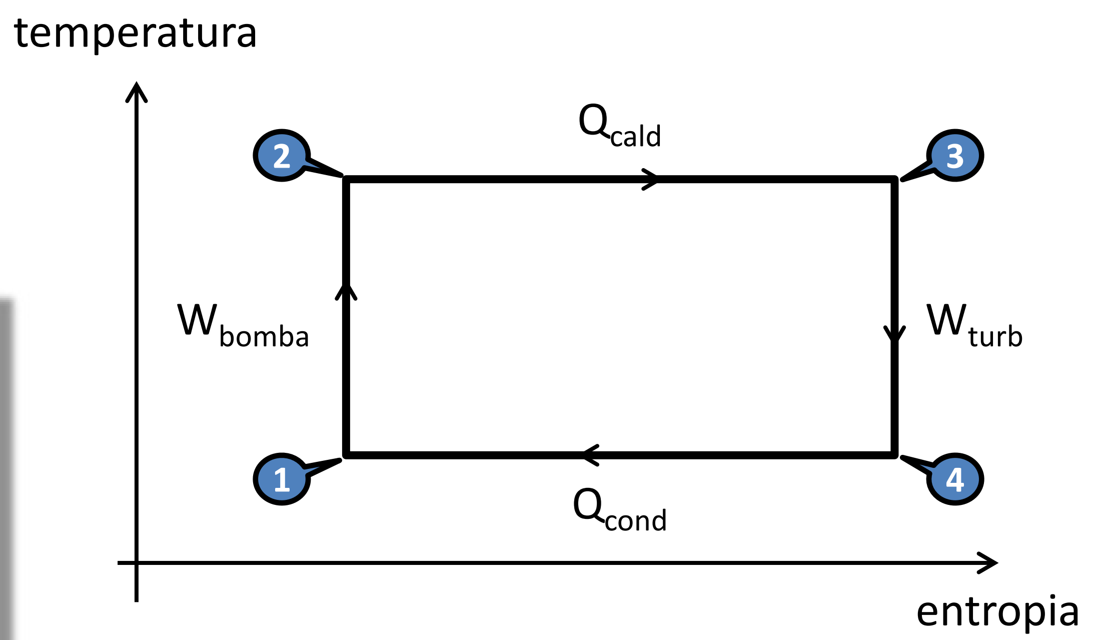

Nicolas Léonard Sadi Carnot
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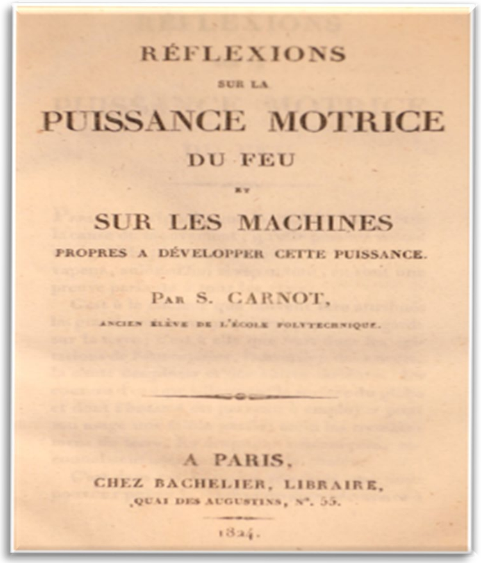

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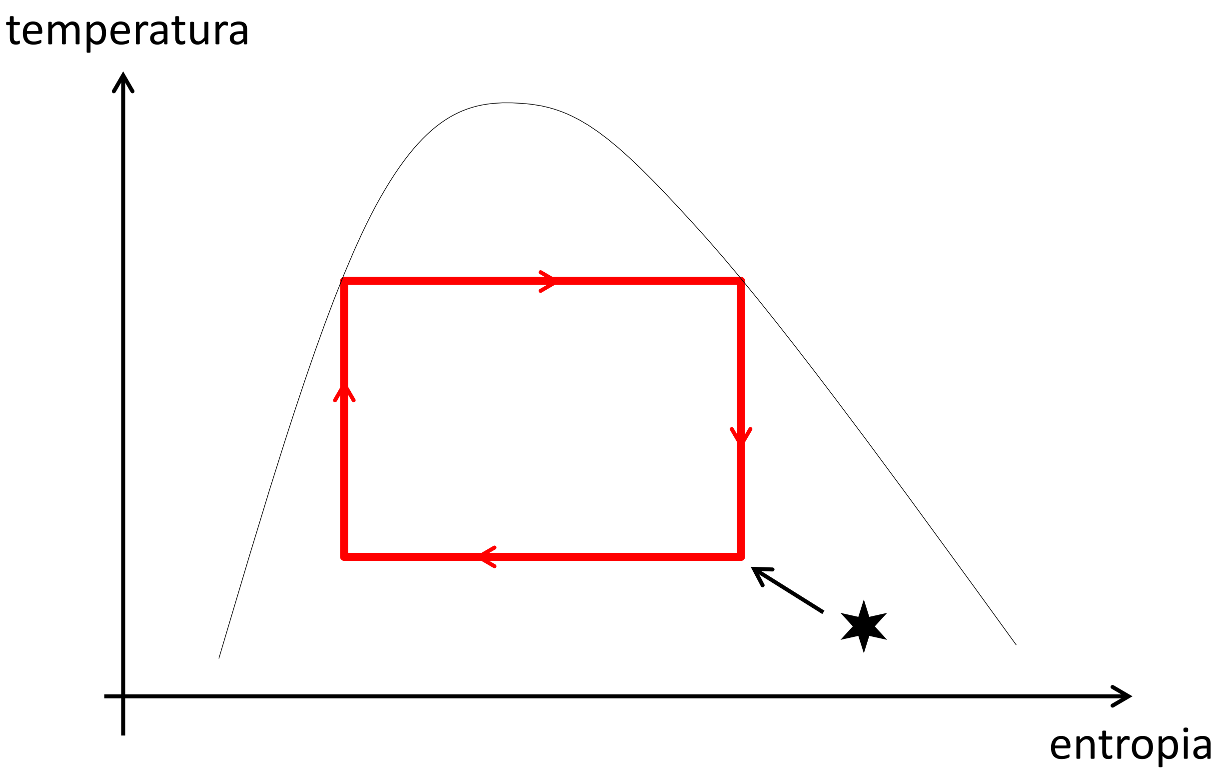
1824.

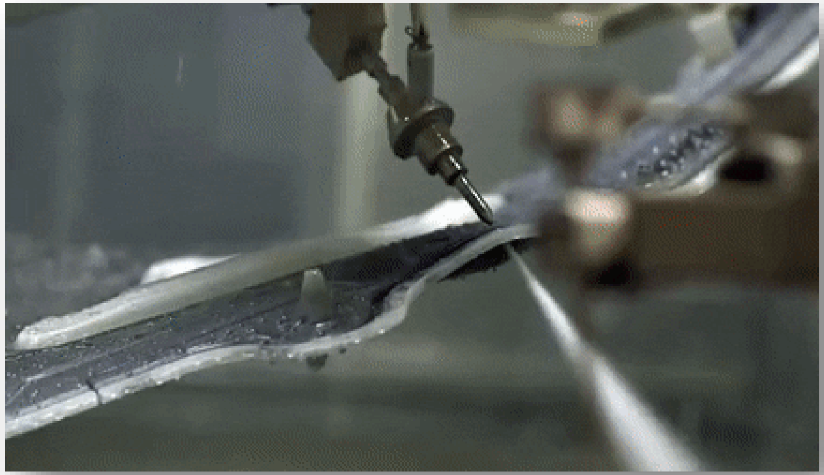
Ciclo de Carnot: dificuldades de realização prática

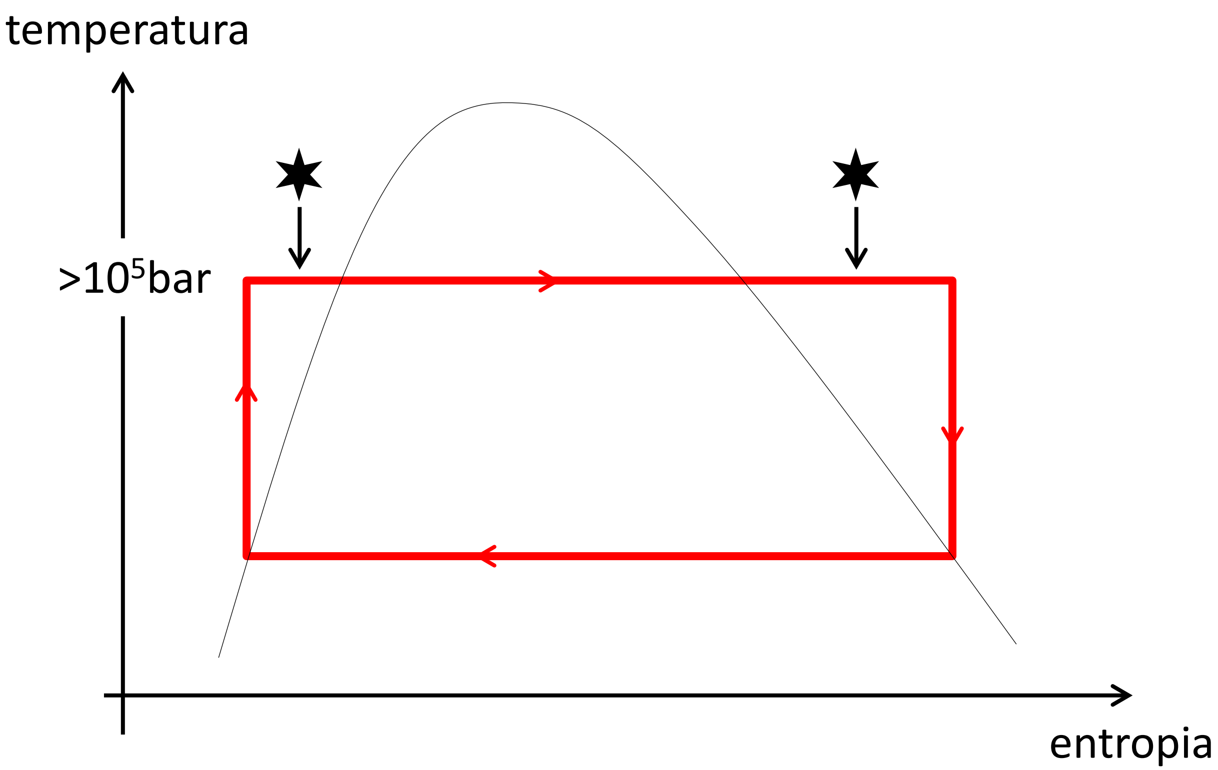
- Okay controle da temperatura
- Erosão na turbina devido à formação de gotas (✶)
- Baixa eficiência hidromecânica no bombeamento de uma mistura bifásica



Ciclo de Carnot: dificuldades de realização prática

- Okay bomba, turbina e controle da temperatura condensador
- Pressão líquido comprimido impossivelmente elevada
- Difícil controle da temperatura nas regiões monofásicas (✶)





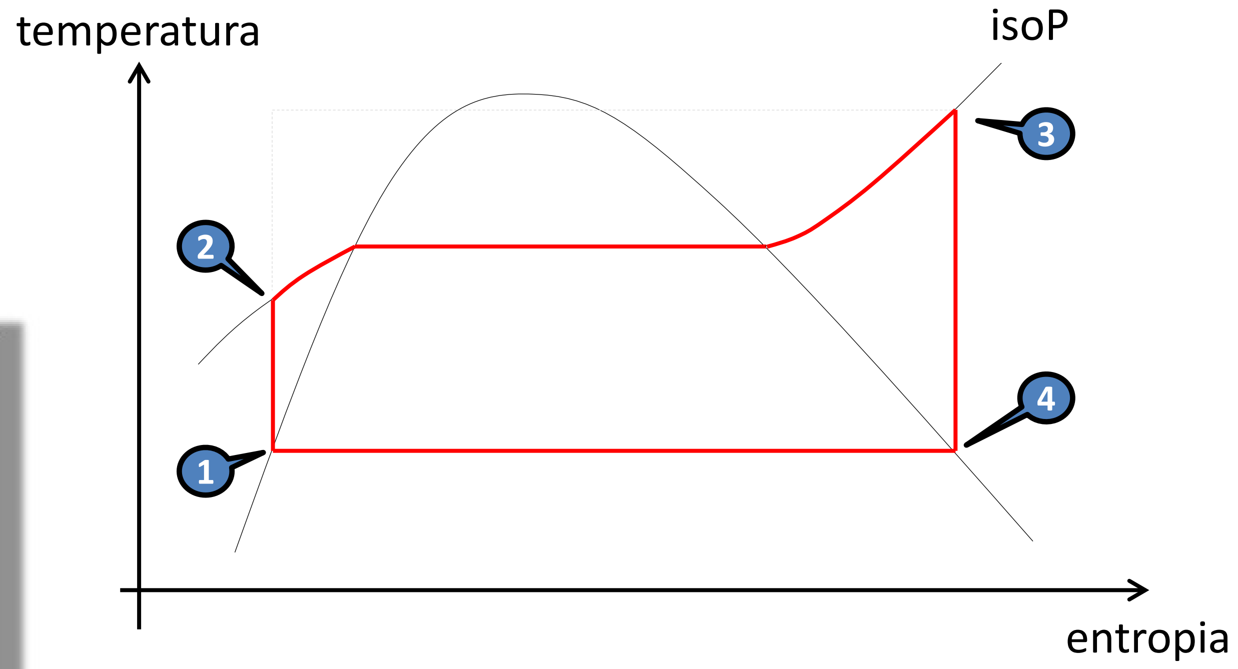
Ciclo de Rankine: definição

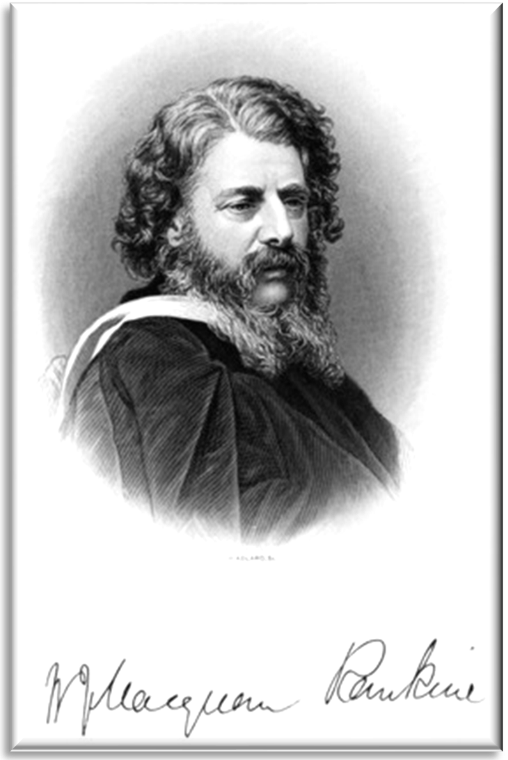
1-2) Compressão isentrópica (bomba)

2-3) Aquecimento isobárico (caldeira)

3-4) Expansão isentrópica (turbina)

4-1) Resfriamento isotérmico (condensador)





William John Macquorn Rankine

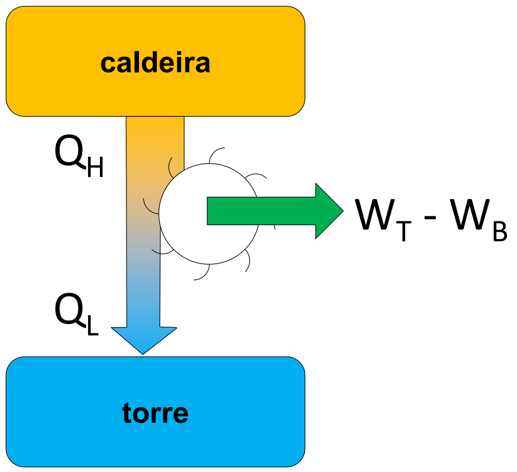
University of Glasgow

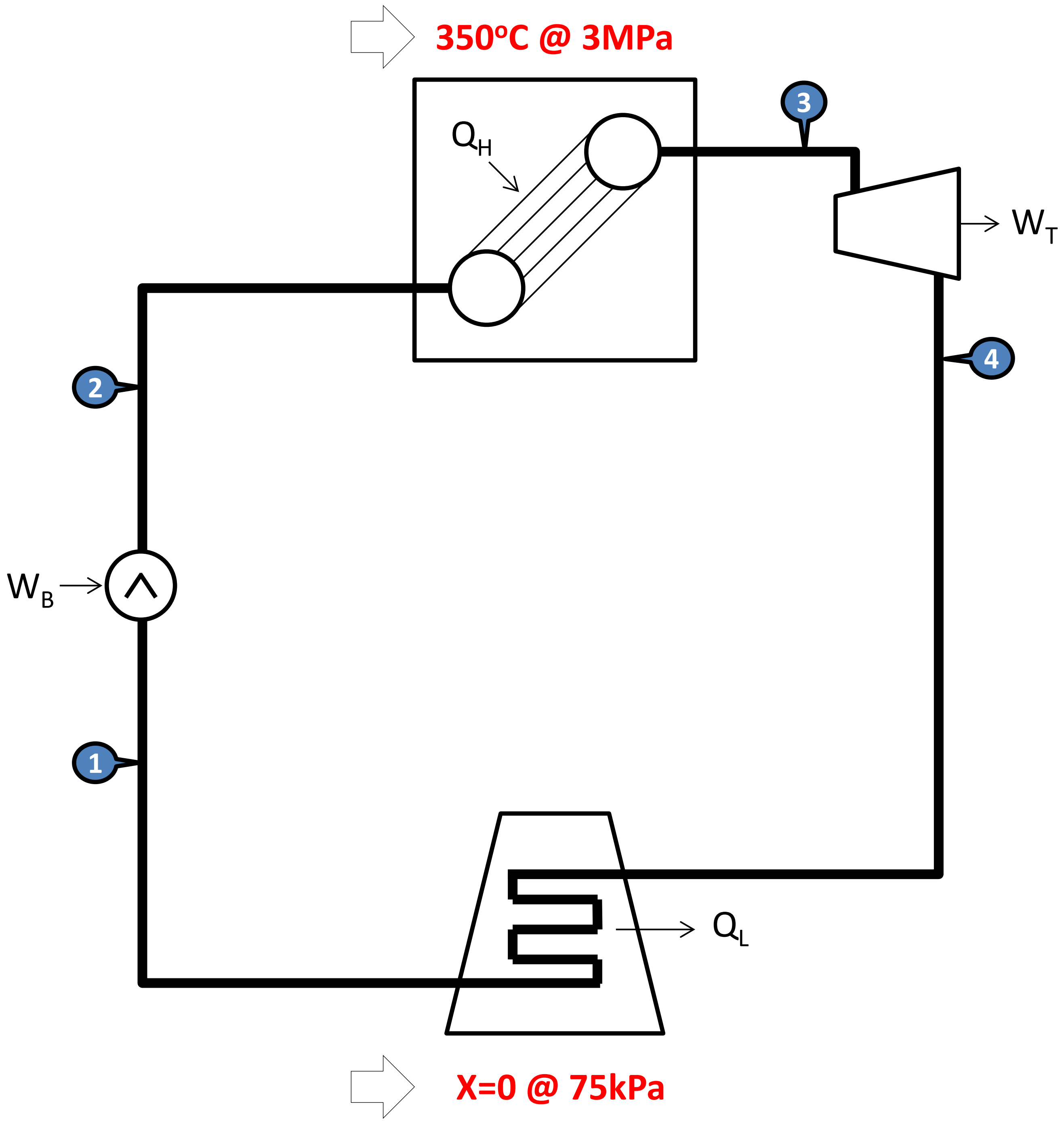
VIA VERITAS VITA

Exemplos...

Ciclo de Rankine Padrão

1-2: bombeamento isentrópico
2-3: aquecimento isobárico
3-4: expansão isentrópica
4-1: resfriamento isobárico

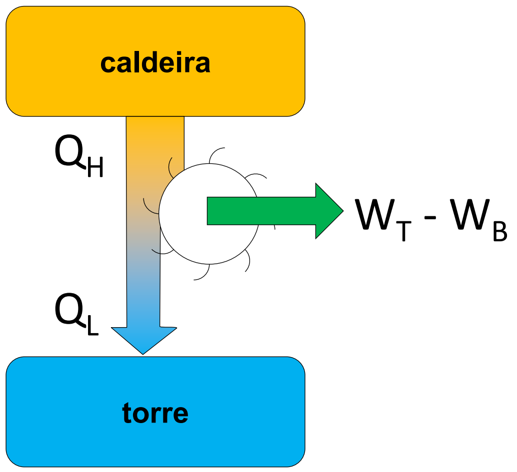


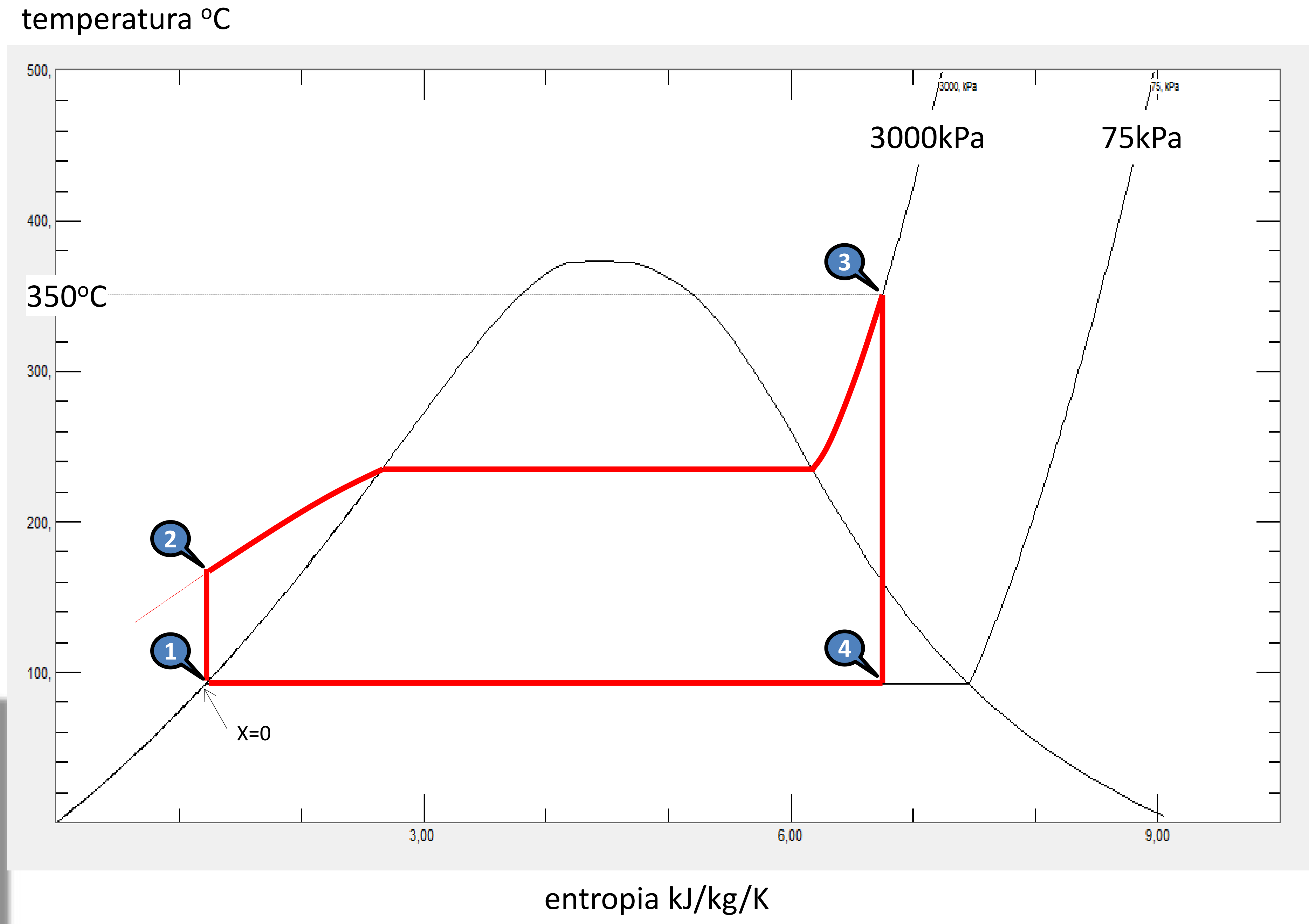


Attention to Filler Words

Ciclo de Rankine Padrão

1-2: bombeamento isentrópico
2-3: aquecimento isobárico
3-4: expansão isentrópica
4-1: resfriamento isobárico



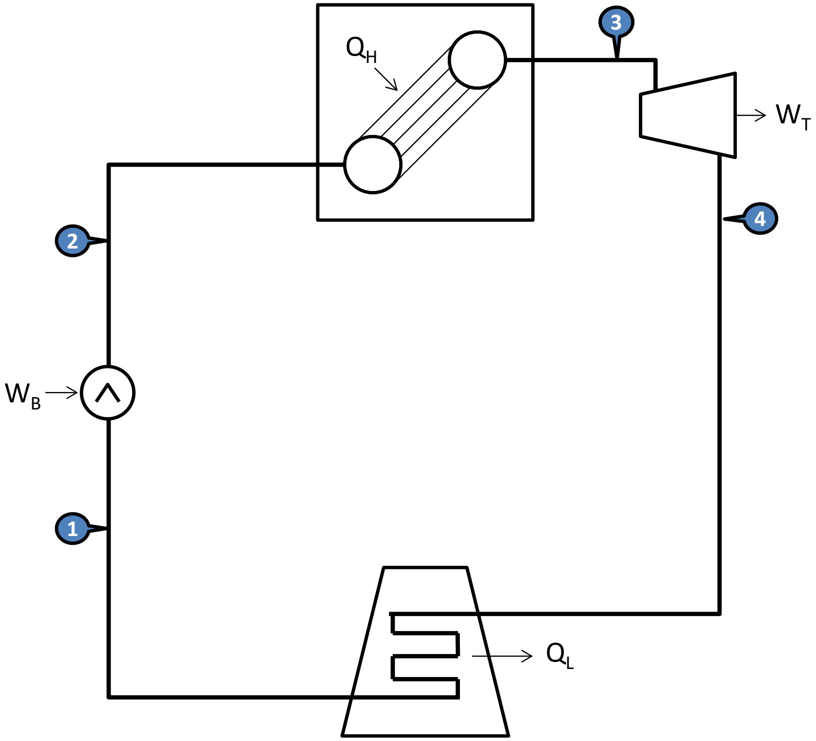


Cálculo do trabalho demandado pela bomba

$$Q_{bba} - W_{bba} = \dot{m} \cdot h_2 - \dot{m} \cdot h_1$$

$$\cancel{Q_{bba}} - W_{bba} = \dot{m} \cdot h_2 - \dot{m} \cdot h_1$$

$$\frac{W_{Bba}}{\dot{m}} = h_1 - h_2$$



$$w_{bba} = h_1 - h_2$$

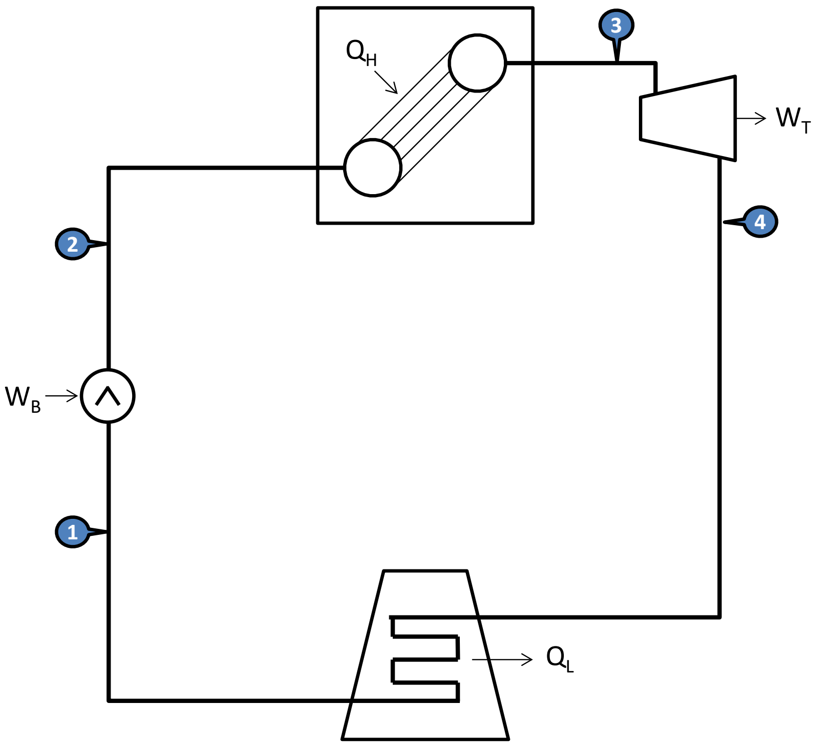
$w_{bba} < 0 \rightarrow$ absorvido

Cálculo do calor gerado na caldeira

$$Q_{cal} - W_{cal} = \dot{m} \cdot h_3 - \dot{m} \cdot h_2$$

$$Q_{cal} - \cancel{W_{cal}} = \dot{m} \cdot h_3 - \dot{m} \cdot h_2$$

$$\frac{Q_{cal}}{\dot{m}} = h_3 - h_2$$



$$q_{cal} = h_3 - h_2$$

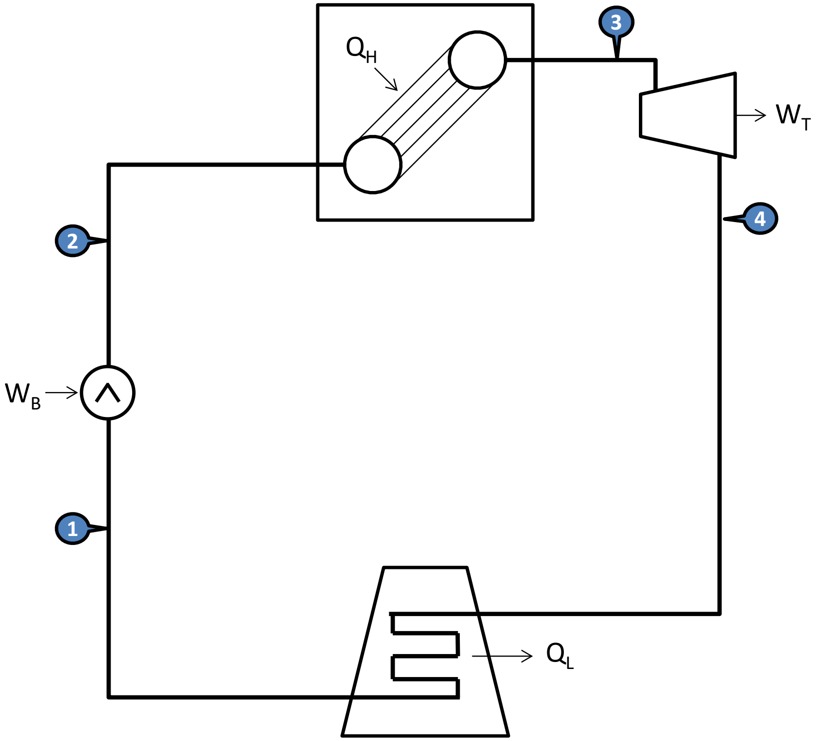
$q_{cal} > 0 \rightarrow$ absorvido

Cálculo do trabalho produzido na turbina

$$Q_{tur} - W_{tur} = \dot{m} \cdot h_4 - \dot{m} \cdot h_3$$

$$\cancel{Q_{tur}} - W_{tur} = \dot{m} \cdot h_4 - \dot{m} \cdot h_3$$

$$\frac{W_{tur}}{\dot{m}} = h_3 - h_4$$



$$w_{tur} = h_3 - h_4$$

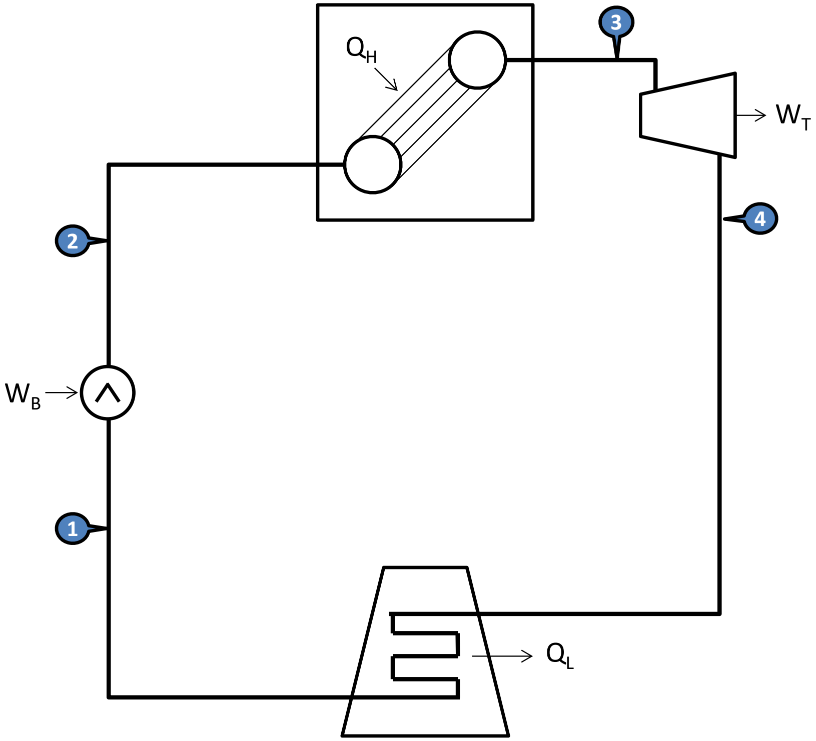
$w_{tur} > 0 \rightarrow$ rejeitado

Cálculo do calor rejeitado na torre de resfriamento

$$Q_{con} - W_{con} = \dot{m} \cdot h_1 - \dot{m} \cdot h_4$$

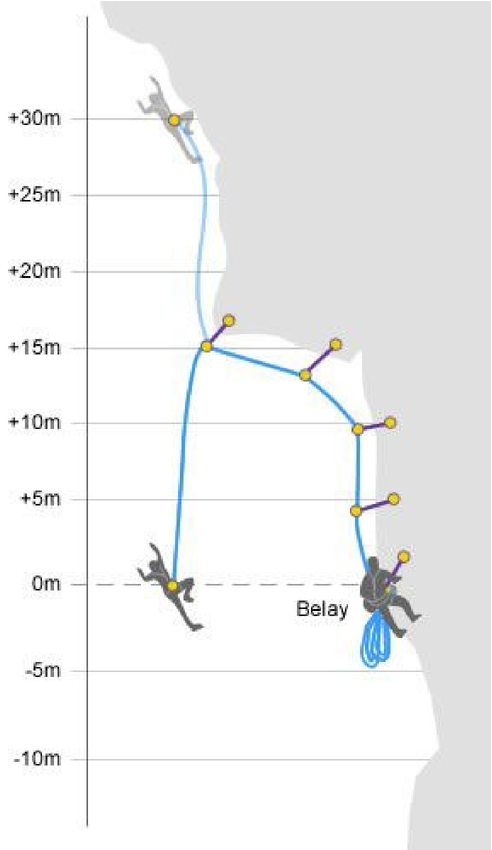
$$Q_{con} - \not{W}_{con} = \dot{m} \cdot h_1 - \dot{m} \cdot h_4$$

$$\frac{Q_{con}}{\dot{m}} = h_1 - h_4$$



$$q_{con} = h_1 - h_4$$

$q_{con} < 0 \rightarrow$ rejeitado



$x = 0$ @ 75kPa

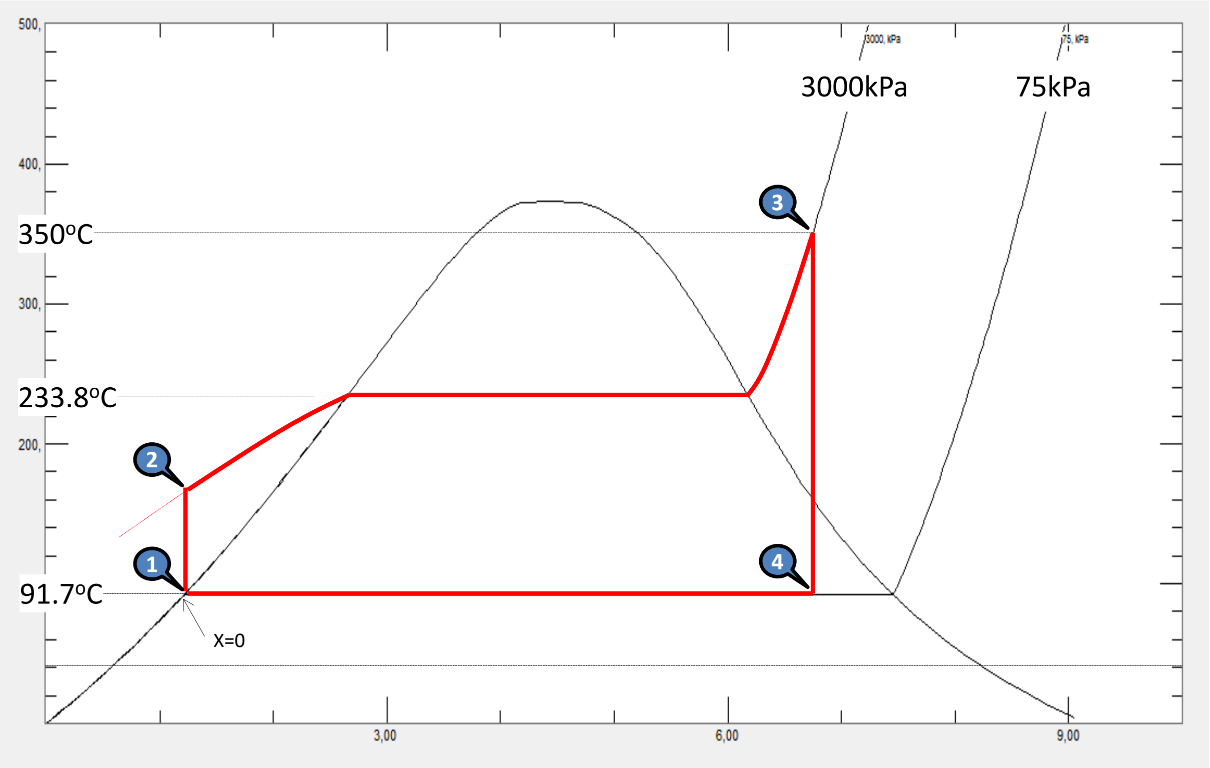
$h_1 = 384,44$ kJ/kg/K

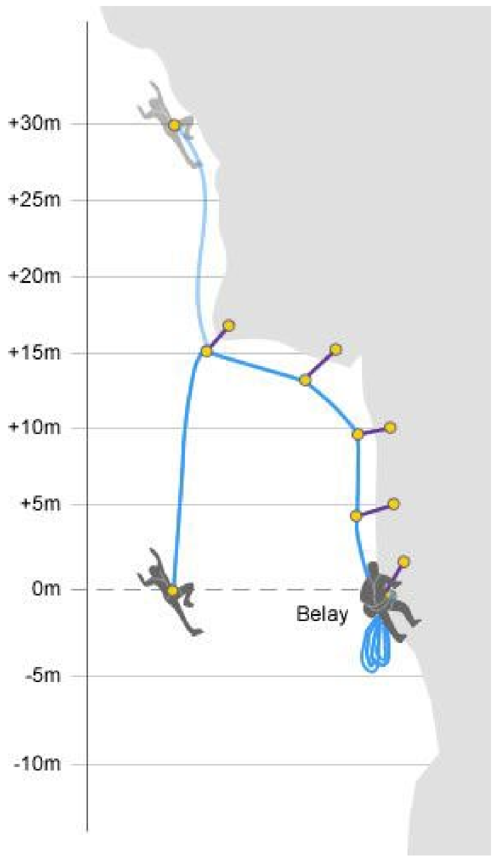
$s_1 = 1,2132$ kJ/kg/K

$S_1 = S_2$ @ 3MPa

$h_2 = 387,44$ kJ/kg/K

$T_2 = 91,946\ ^oC$





350^oC @ 3MPa

$h_3 = 3116{,}1$ kJ/kg

$s_3 = 6{,}7449$ kJ/kg/K

$S_3 = S_4$ @ 75kPa

$s_{liq} = 1{,}2132$ kJ/kg/K

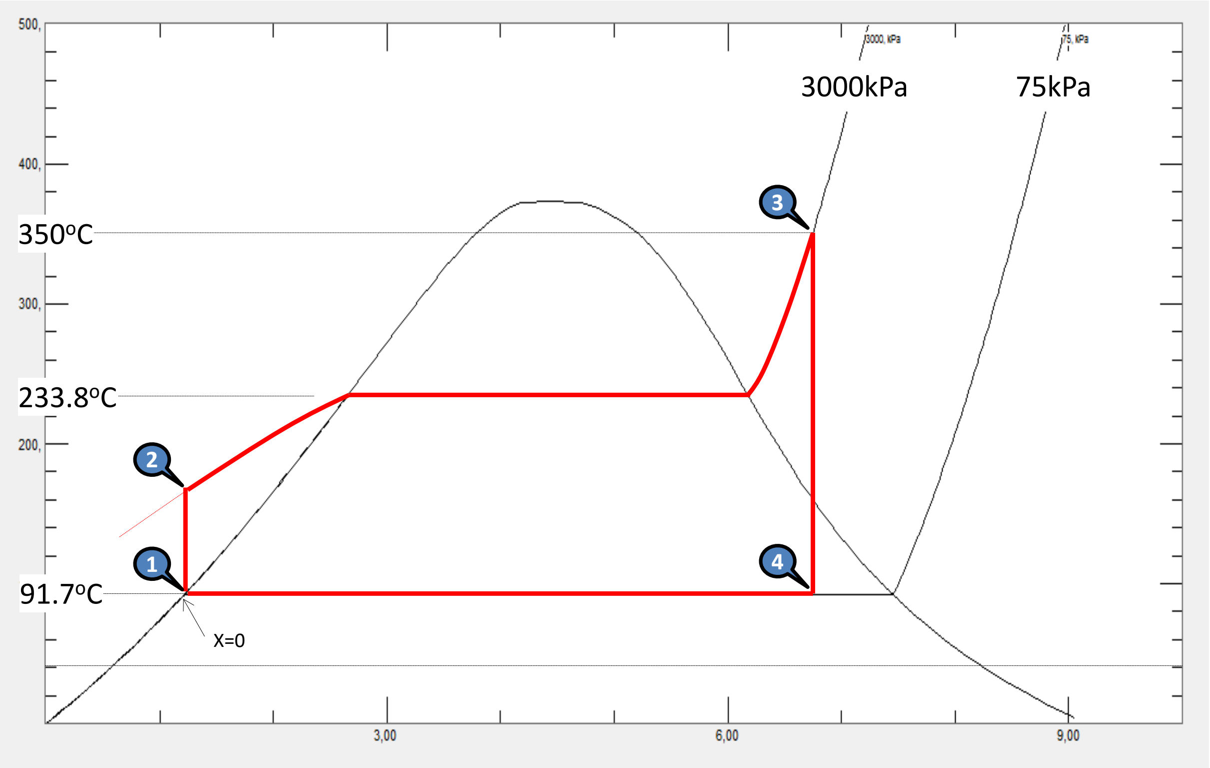
$s_{vap} = 7{,}4557$ kJ/kg/K

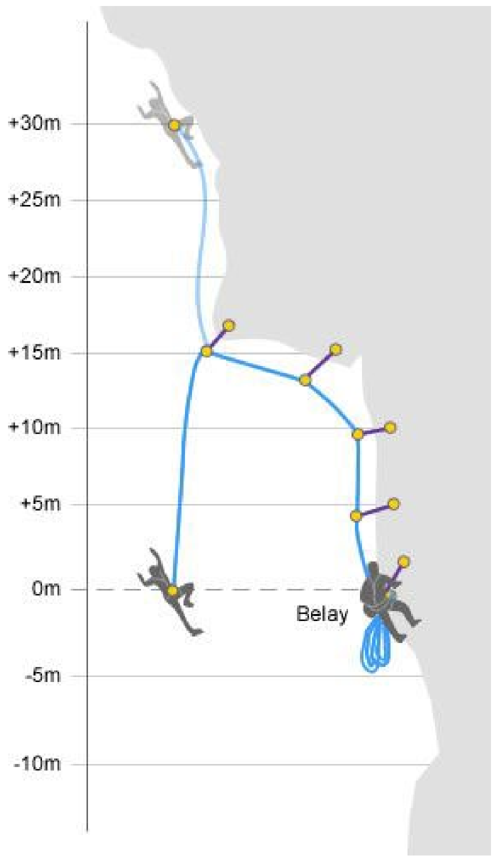
$x = 0{,}886$

$h_{liq} = 384{,}45$ kJ/kg

$h_{vap} = 2662{,}4$

$h_4 = 2402{,}7$ kJ/kg



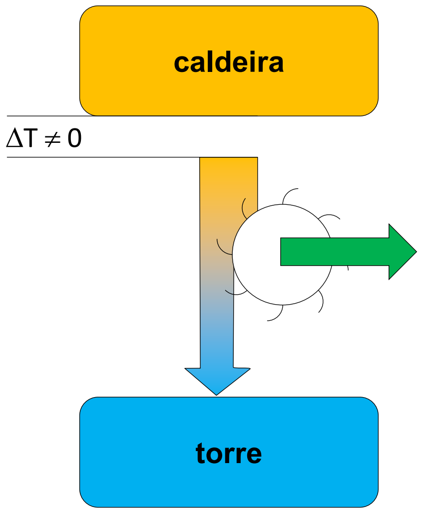


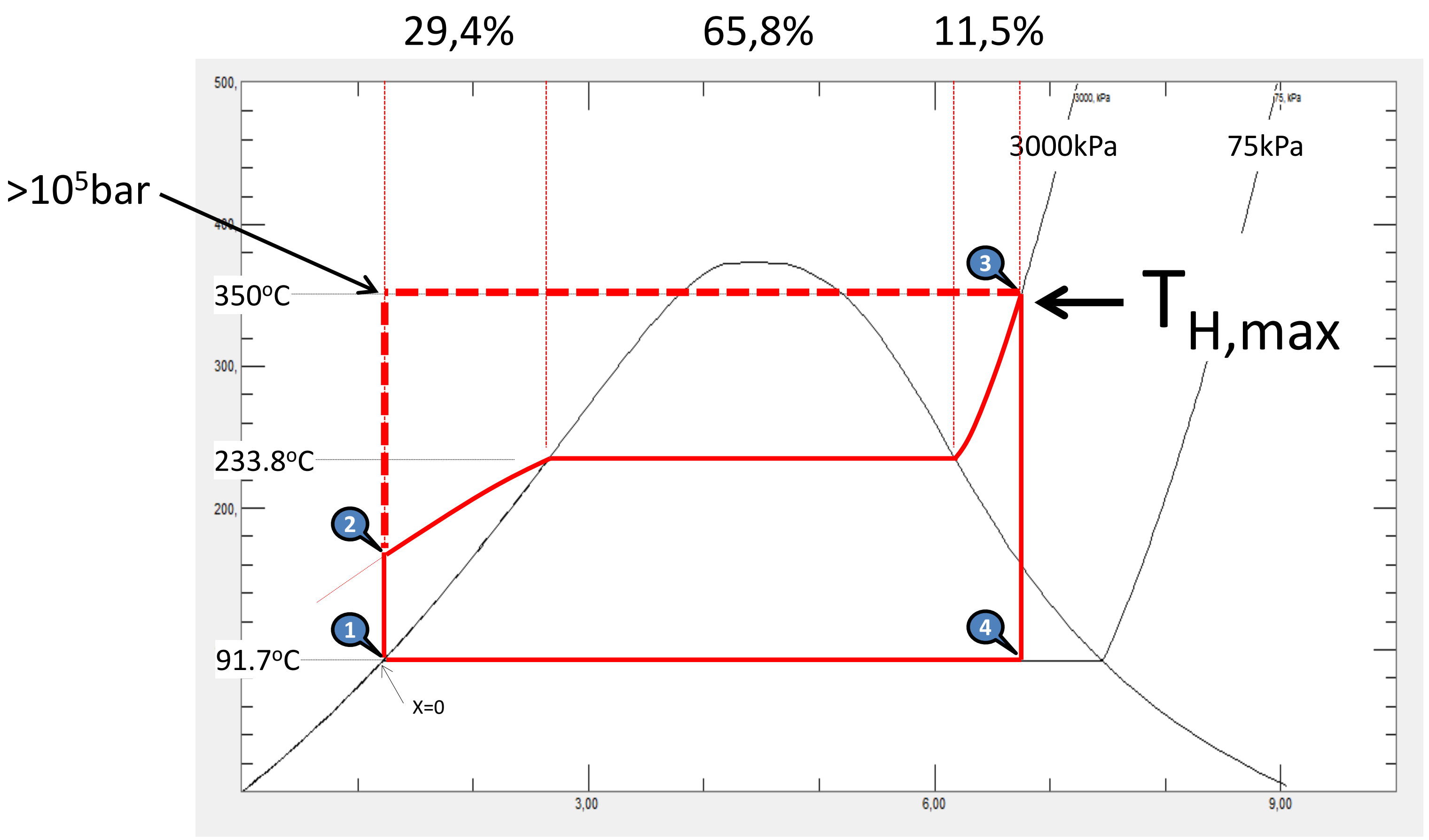
$$\eta = \frac{\sum W_T - \sum W_B}{\sum Q_C}$$

$$\eta = \frac{(h_3 - h_4) - (h_2 - h_1)}{(h_3 - h_2)}$$

$$\eta = \frac{(3116{,}1 - 2402{,}7) - (387{,}48 - 384{,}44)}{(3116{,}1 - 387{,}48)}$$

$\eta = 0{,}263$ ⇨ $\eta = 0{,}263$





$T_{L,min}$ = 91,7ºC

$T_{H,max}$ = 350ºC

$$\eta_{Carnot} = 1 - T_L/T_H$$

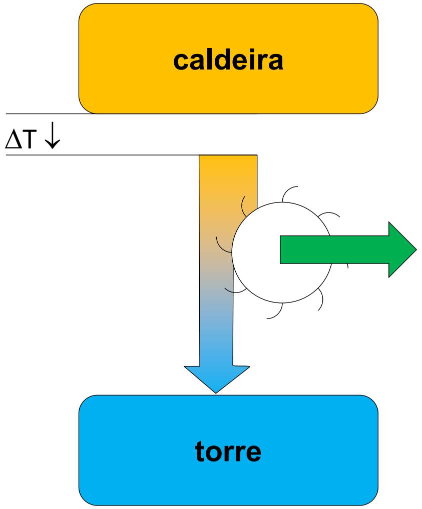
$$\eta_{Carnot} = 1 - (91.7+273)/(350+273)$$

$$\eta_{Carnot} = 0{,}415 \quad \eta_{Rankine} = 0{,}263$$

Absorção de calor a baixas temperaturas

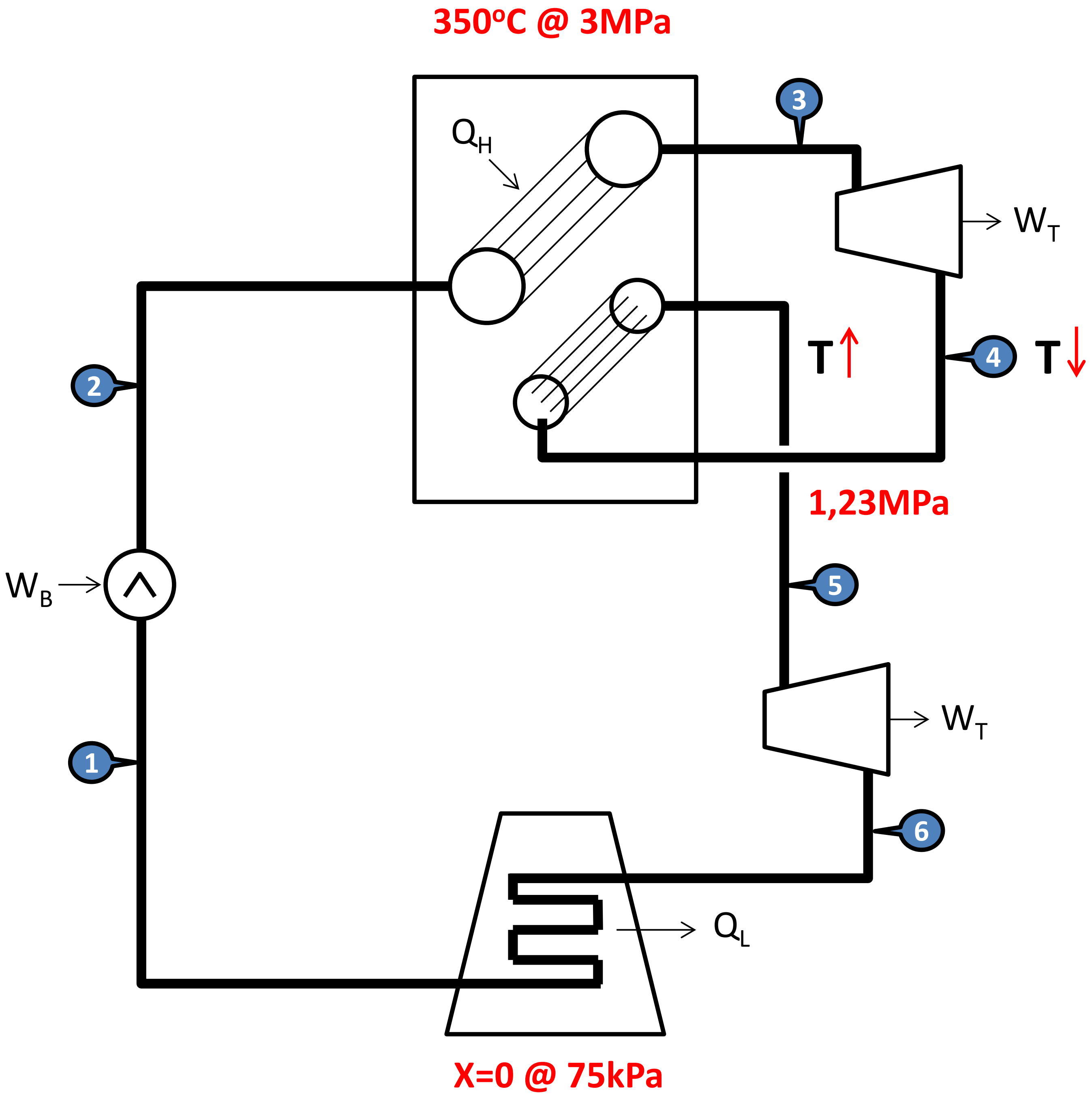
Redução da eficiência de conversão

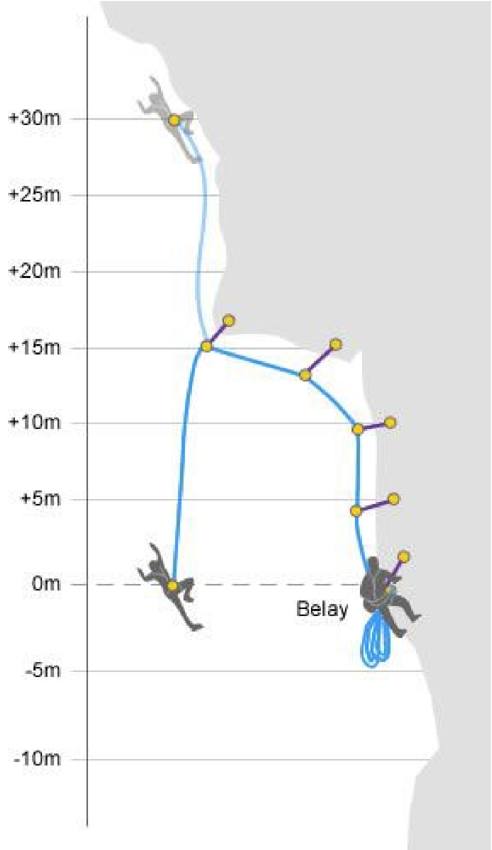
Ciclo de Rankine com reaquecimento de vapor

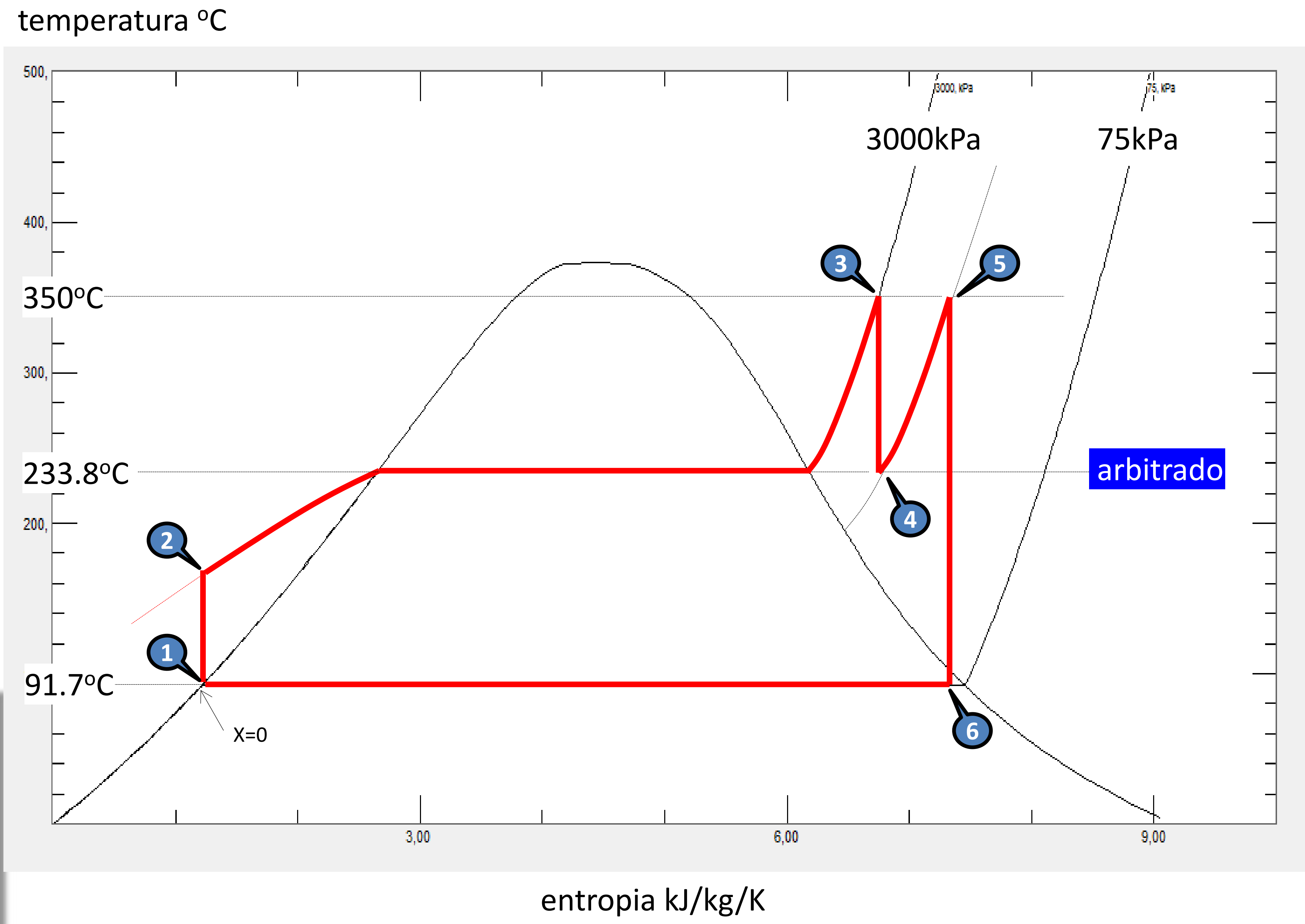


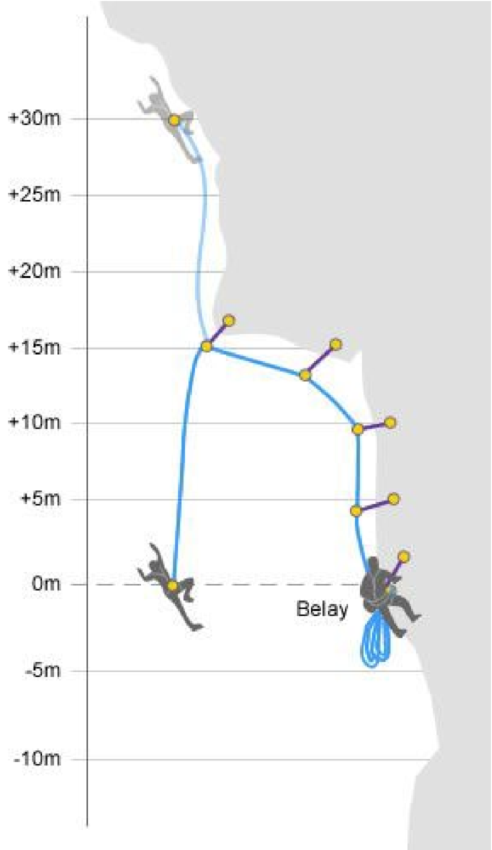
$$\eta = \frac{w_{12} + w_{34} + w_{56}}{q_{23} + q_{45}}$$

Attention to Filler Words




+30m
+25m
+20m
+15m
+10m
+5m
0m
-5m
-10m
Belay


temperatura ºC
500,
400,
300,
200,
350ºC
233.8ºC
91.7ºC
3000, kPa
75, kPa
3000kPa
75kPa
arbitrado
1
2
3
4
5
6
X=0
3,00
6,00
9,00
entropia kJ/kg/K



$x = 0$ @ 75kPa

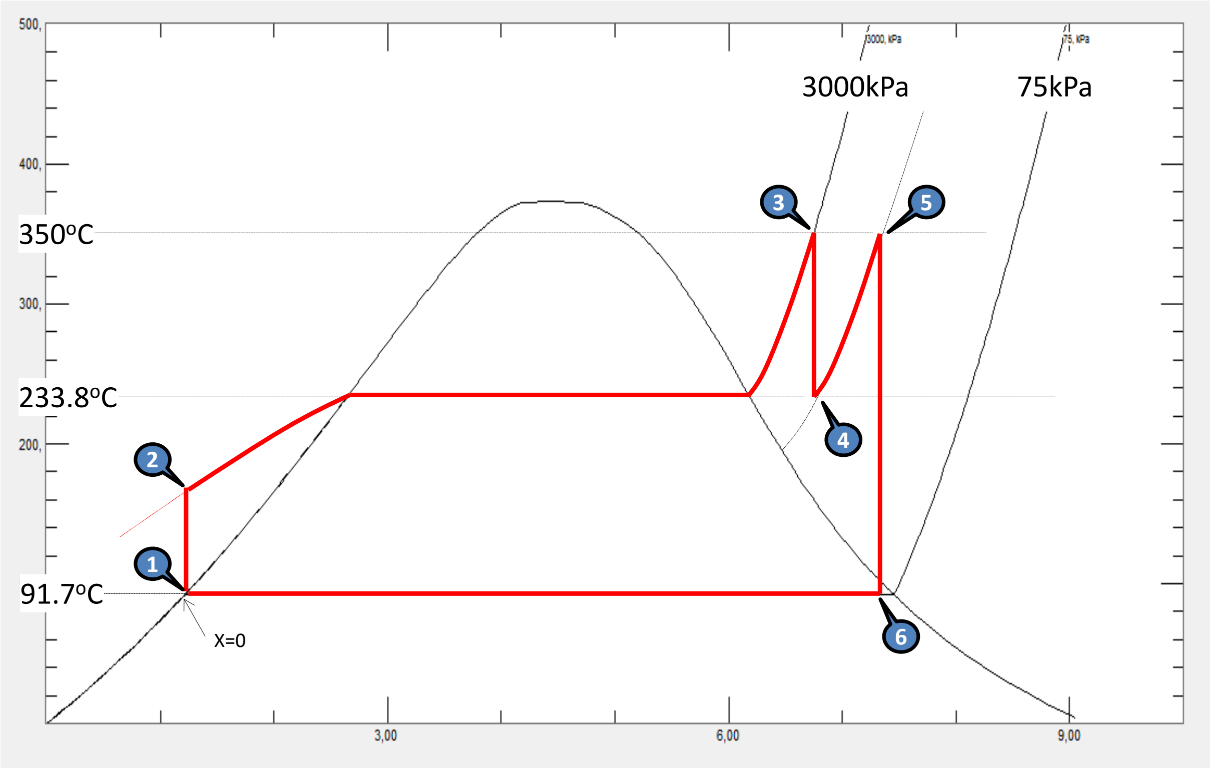
$h_1 = 384{,}44$ kJ/kg/K

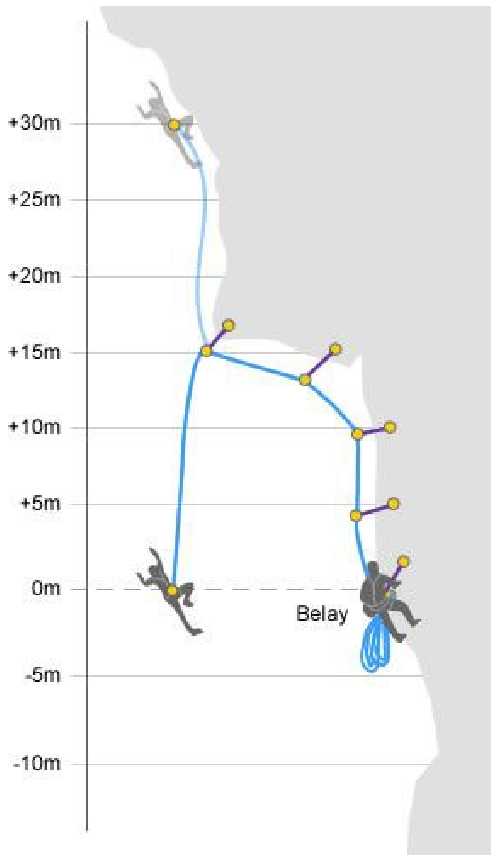
$s_1 = 1{,}2132$ kJ/kg/K

$S_1 = S_2$ @ 3MPa

$h_2 = 387{,}48$ kJ/kg/K

$T_2 = 91{,}946\ ^oC$





350°C @ 3MPa

h_3 = 3116,1 kJ/kg

s_3 = 6,7449 kJ/kg/K

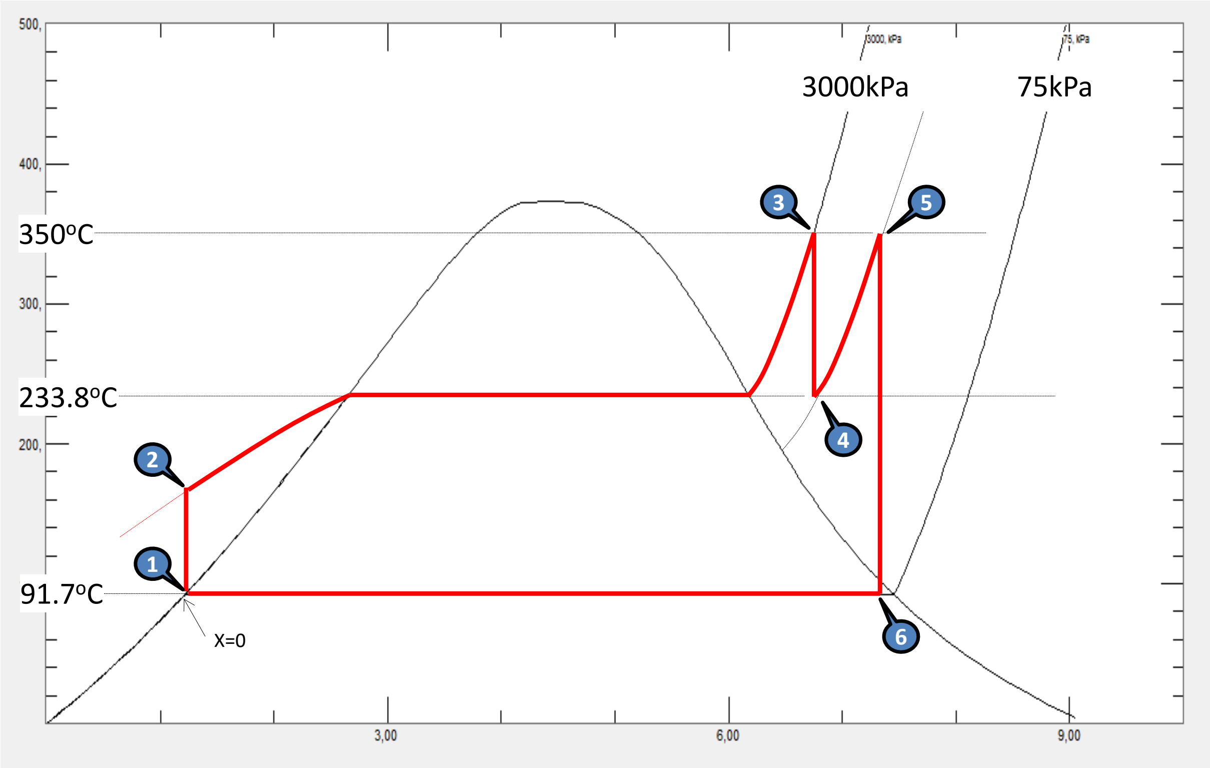
$S_3 = S_4$ @ T_{sat} / 3MPa

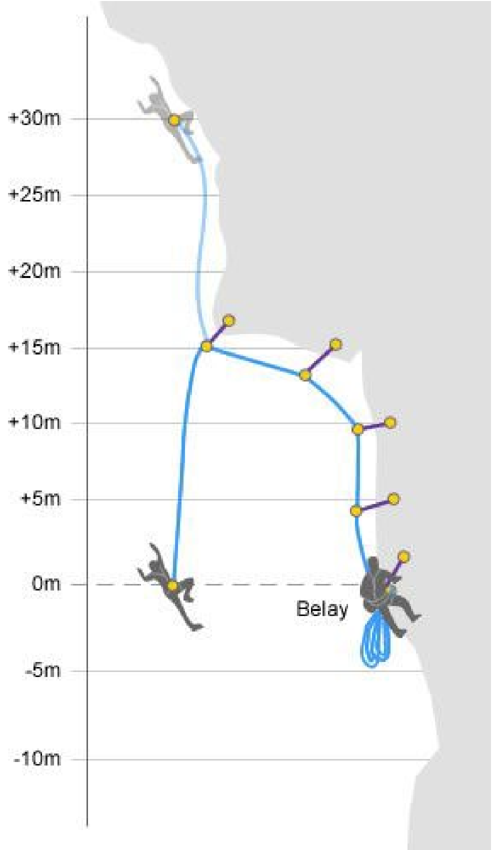
s_4 = 6,7449 kJ/kg/K

T_{sat} = 233,8 °C

P_s = 1,231 MPa

h_4 = 2897,0 kJ/kg





350^oC @ 1,231 MPa

$h_5 = 3153{,}5$ kJ/kg

$s_5 = 7{,}2012$ kJ/kg/K

$S_5 = S_6$ @ 75kPa

$s_{liq} = 1{,}2132$ kJ/kg/K

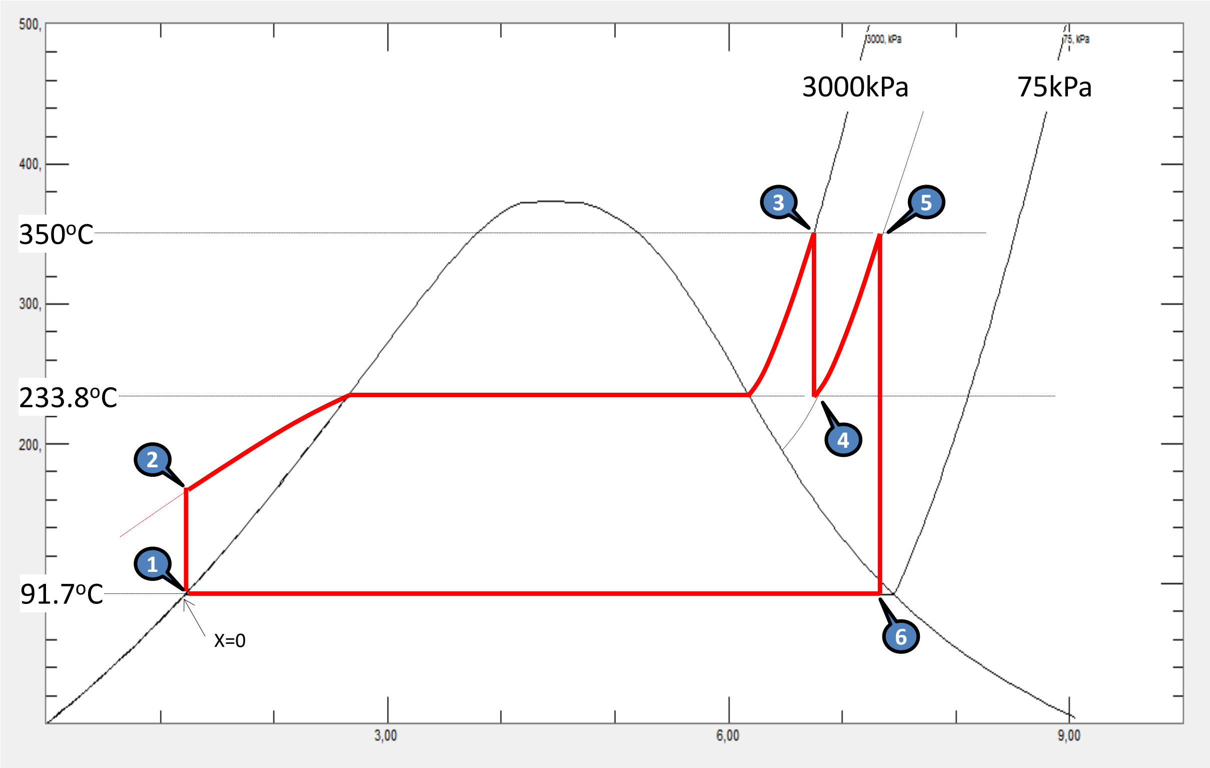
$s_{vap} = 7{,}4557$ kJ/kg/K

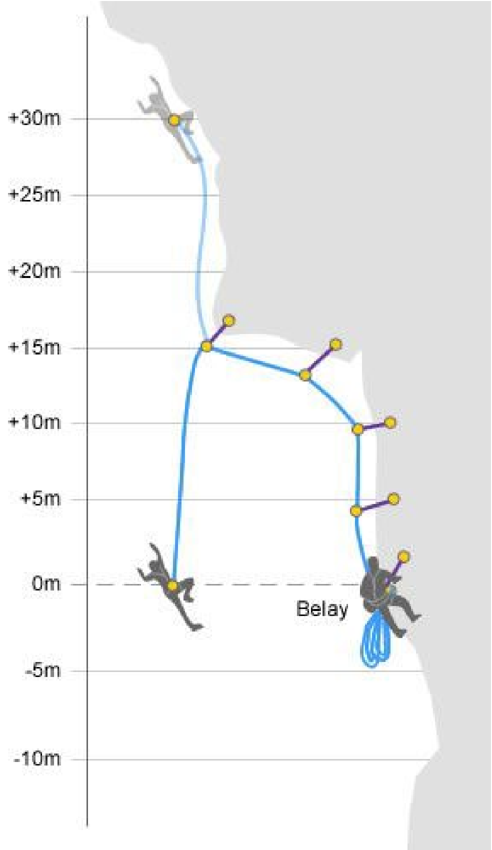
$x = 0{,}959$

$h_{liq} = 384{,}44$ kJ/kg

$h_{vap} = 2662{,}4$

$h_6 = 2569{,}0$ kJ/kg





$$\eta = \frac{\sum W_T - \sum W_B}{\sum Q_C}$$

$$\eta = \frac{[(h_3 - h_4) + (h_5 - h_6)] - (h_2 - h_1)}{(h_3 - h_2) + (h_5 - h_4)}$$

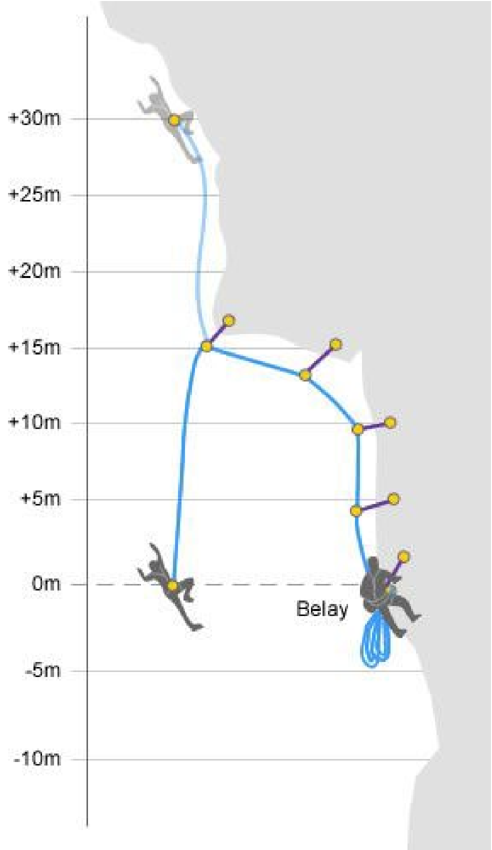
$$\eta = \frac{[(3116{,}1 - 2897{,}0) + (3153{,}5 - 2569{,}0)] - (387{,}48 - 384{,}44)}{(3116{,}1 - 387{,}48) + (3153{,}5 - 2897{,}0)}$$

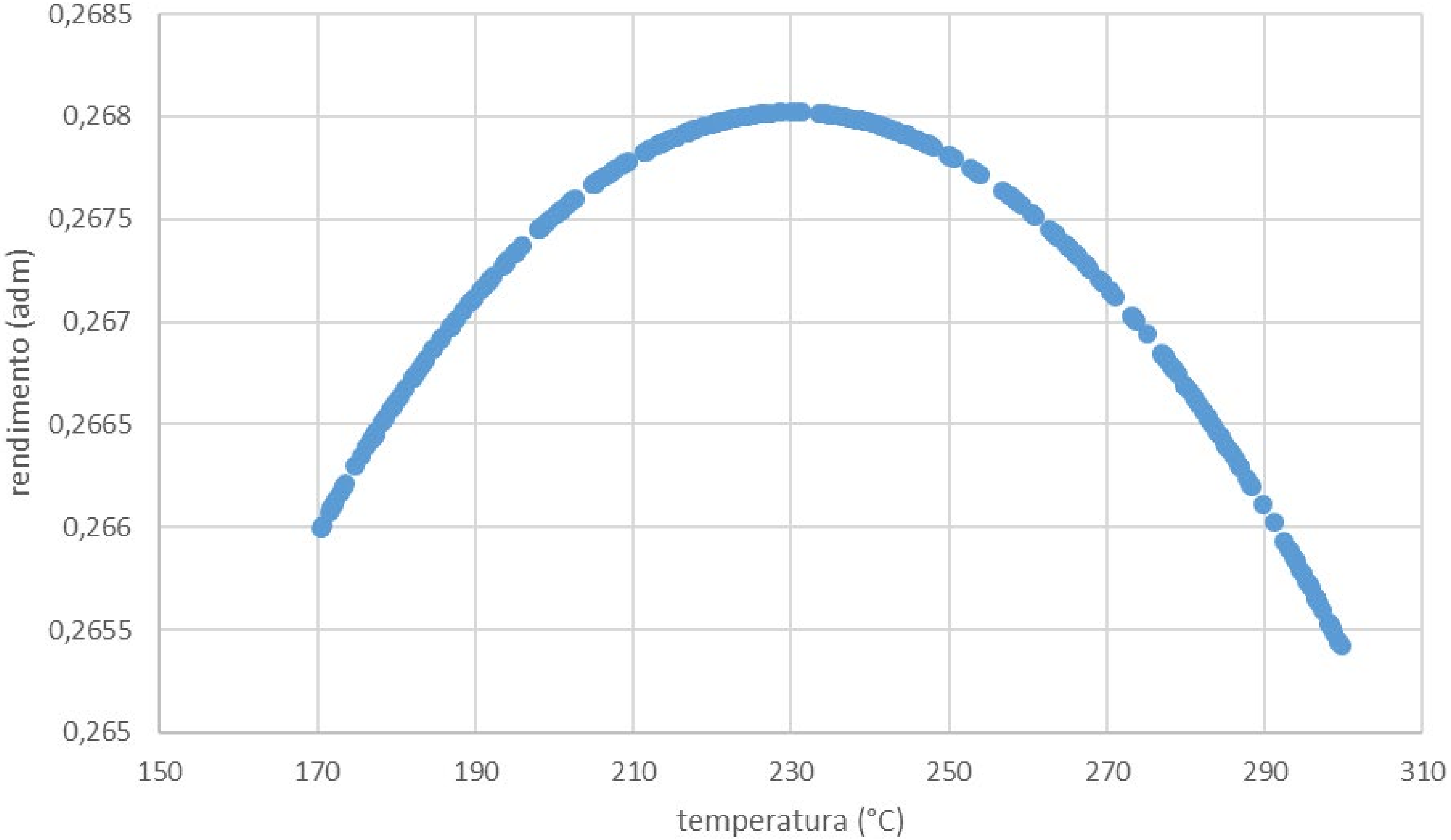
$$\eta = \frac{\uparrow\uparrow W_T - W_B}{\uparrow Q_C} \Rightarrow$$

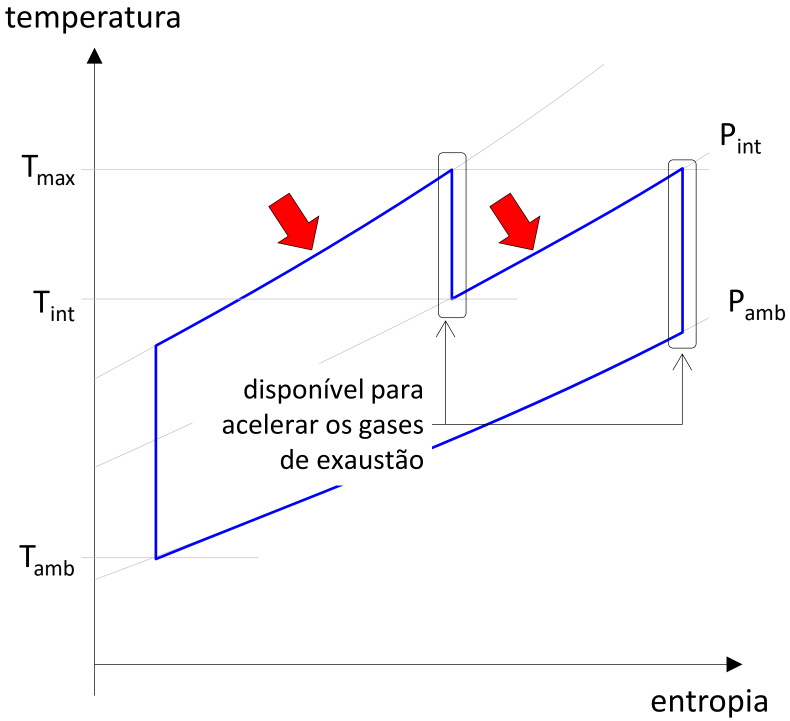
$$\eta_{reaq} = 0{,}268$$

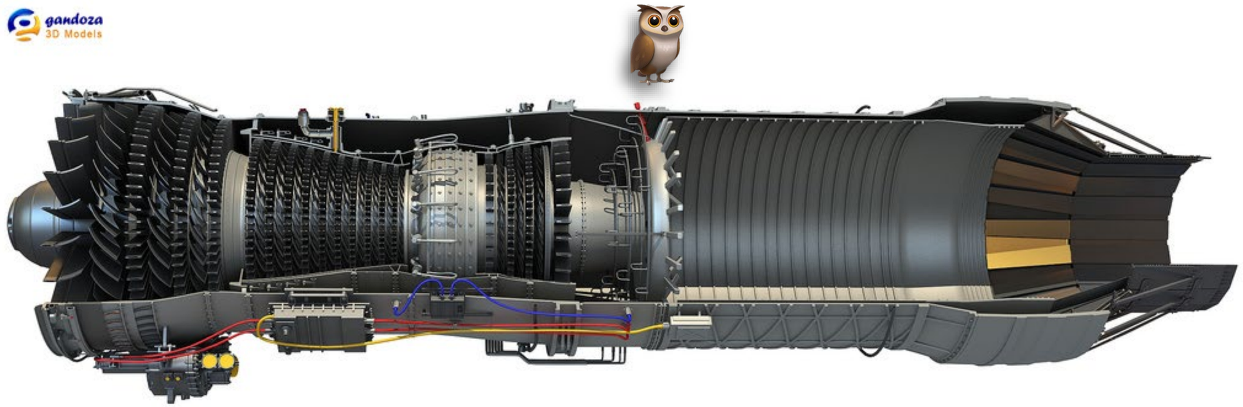
$$\eta_{Rank} = 0{,}263$$

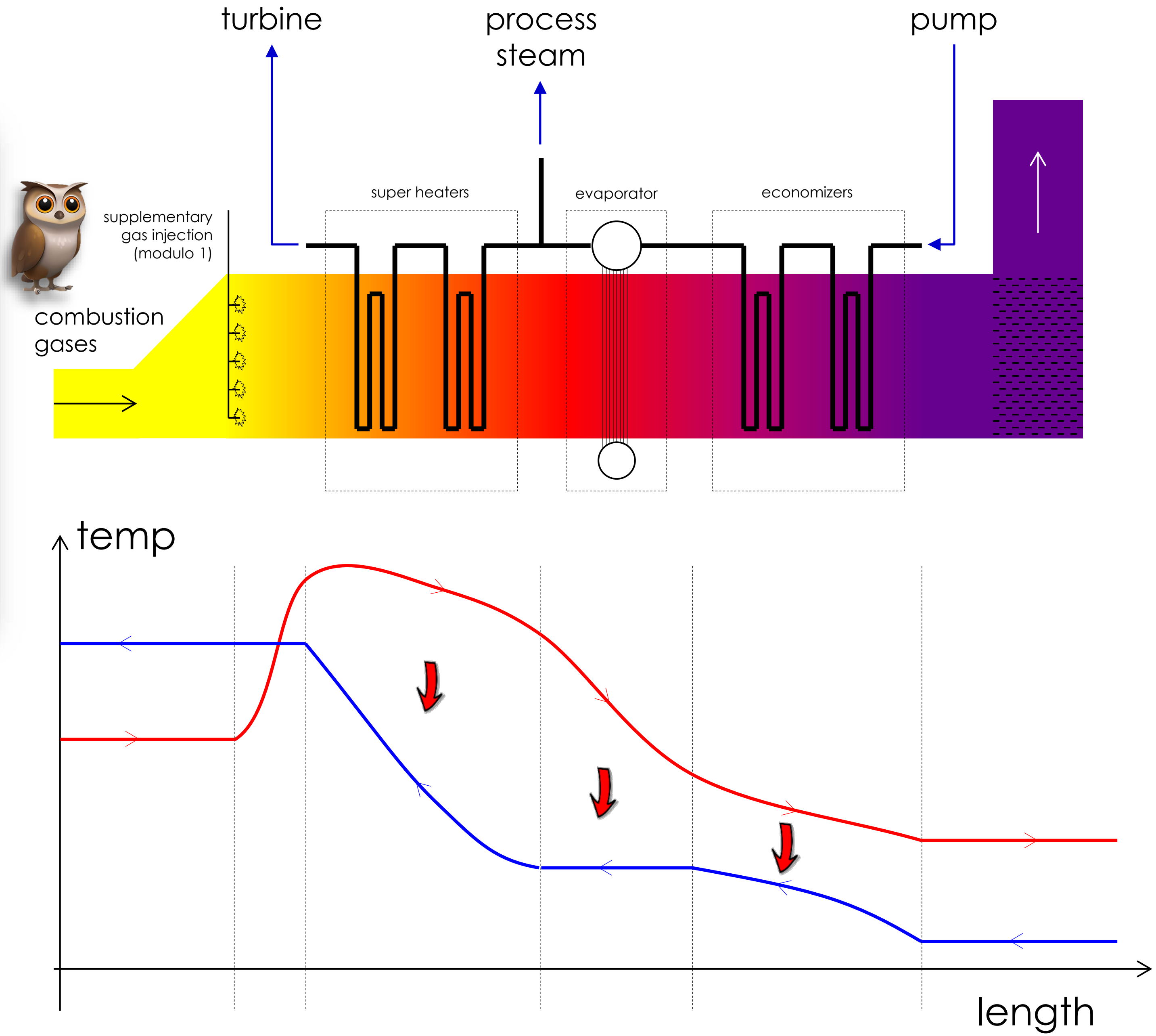
Otimização da pressão do estágio intermediário...


+30m
+25m
+20m
+15m
+10m
+5m
0m
-5m
-10m
Belay


0,2685
0,268
0,2675
0,267
0,2665
0,266
0,2655
0,265
rendimento (adm)
150
170
190
210
230
250
270
290
310
temperatura (°C)


temperatura
T max
T int
T amb
P int
P amb
disponível para
acelerar os gases
de exaustão
entropia

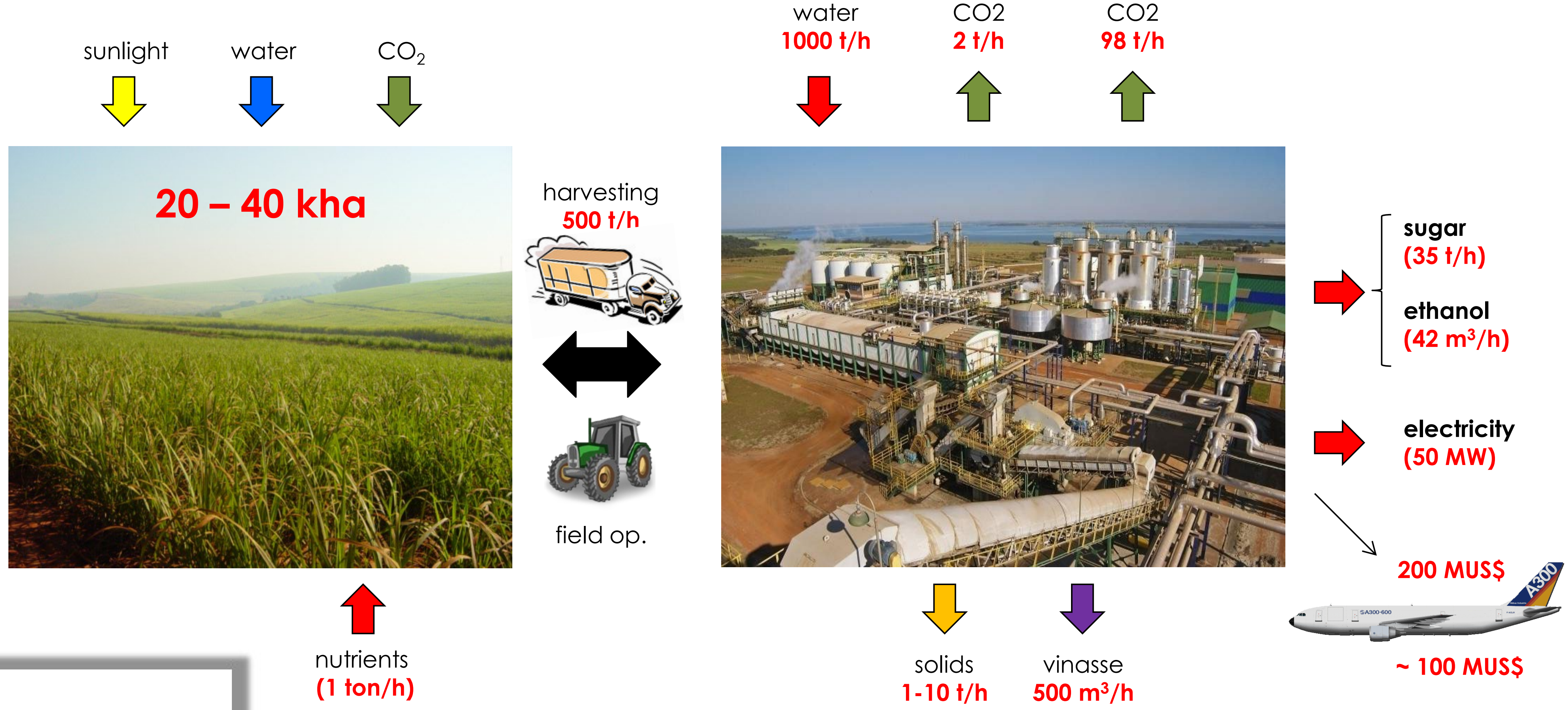

gandoza
3D Models



turbine
process steam
pump
super heaters
evaporator
economizers
supplementary gas injection (modulo 1)
combustion gases
temp
length

APLICAÇÕES COM DEMANDA SIMULTÂNEA DE TRABALHO MECÂNICO E CALOR DE PROCESSO

USINA DE CANA DE AÇÚCAR CONVENCIONAL – AÇÚCAR, ETANOL E ELETRICIDADE

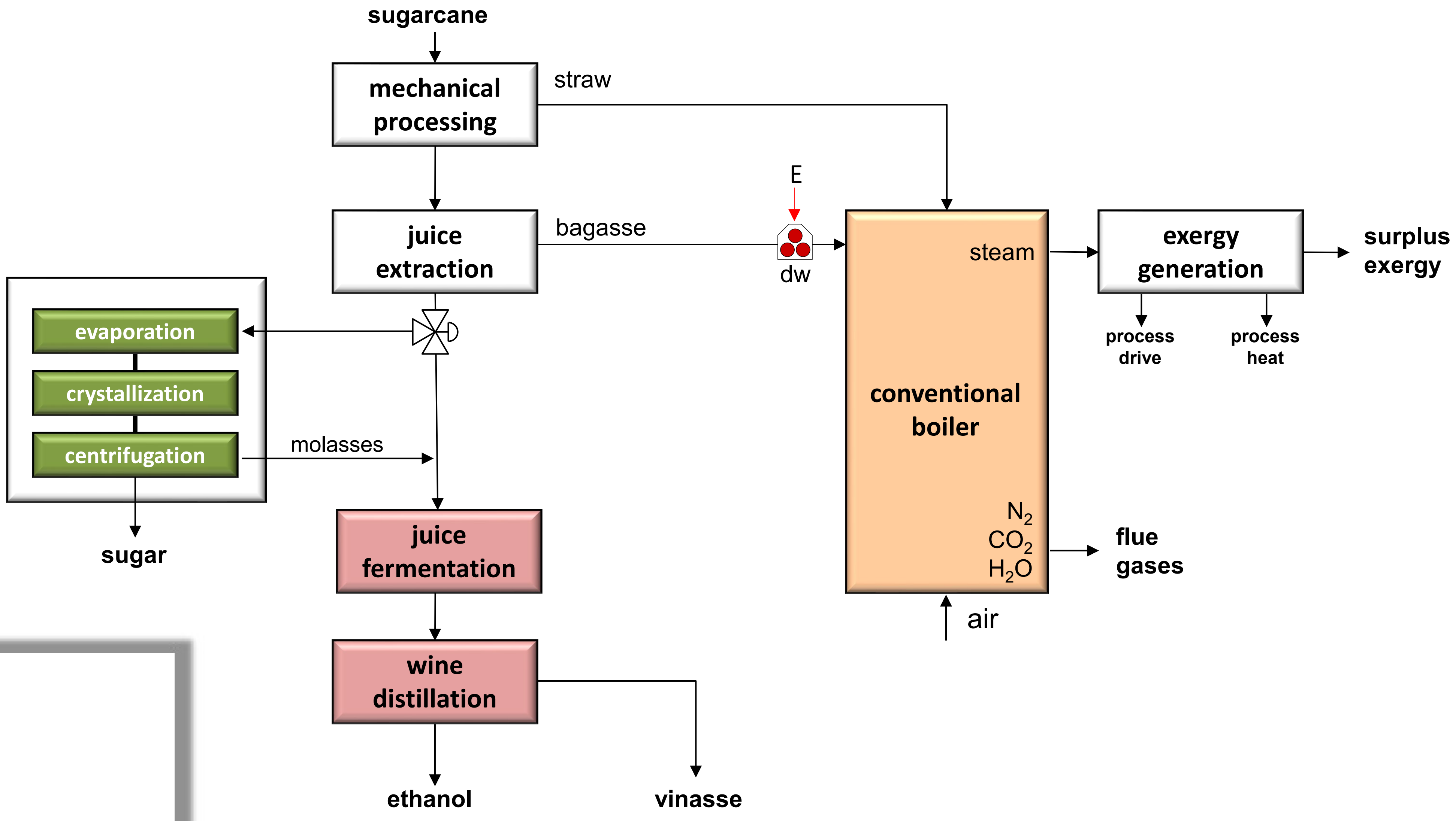


TRL 9 → "Turn Key" contracts

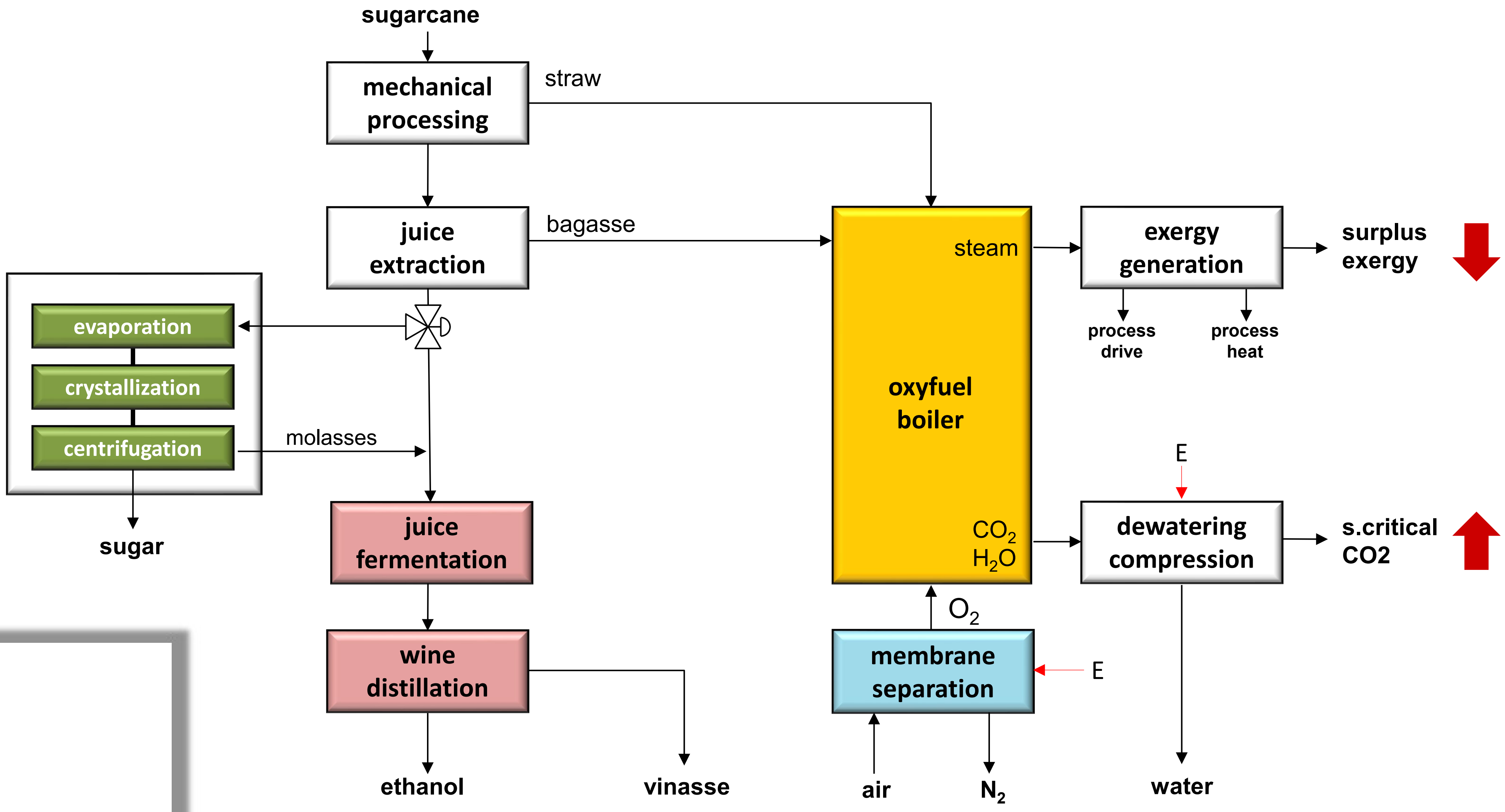
Attention to Filler Words

USINA DE CANA DE AÇÚCAR CONVENCIONAL – AÇÚCAR, ETANOL E ELETRICIDADE

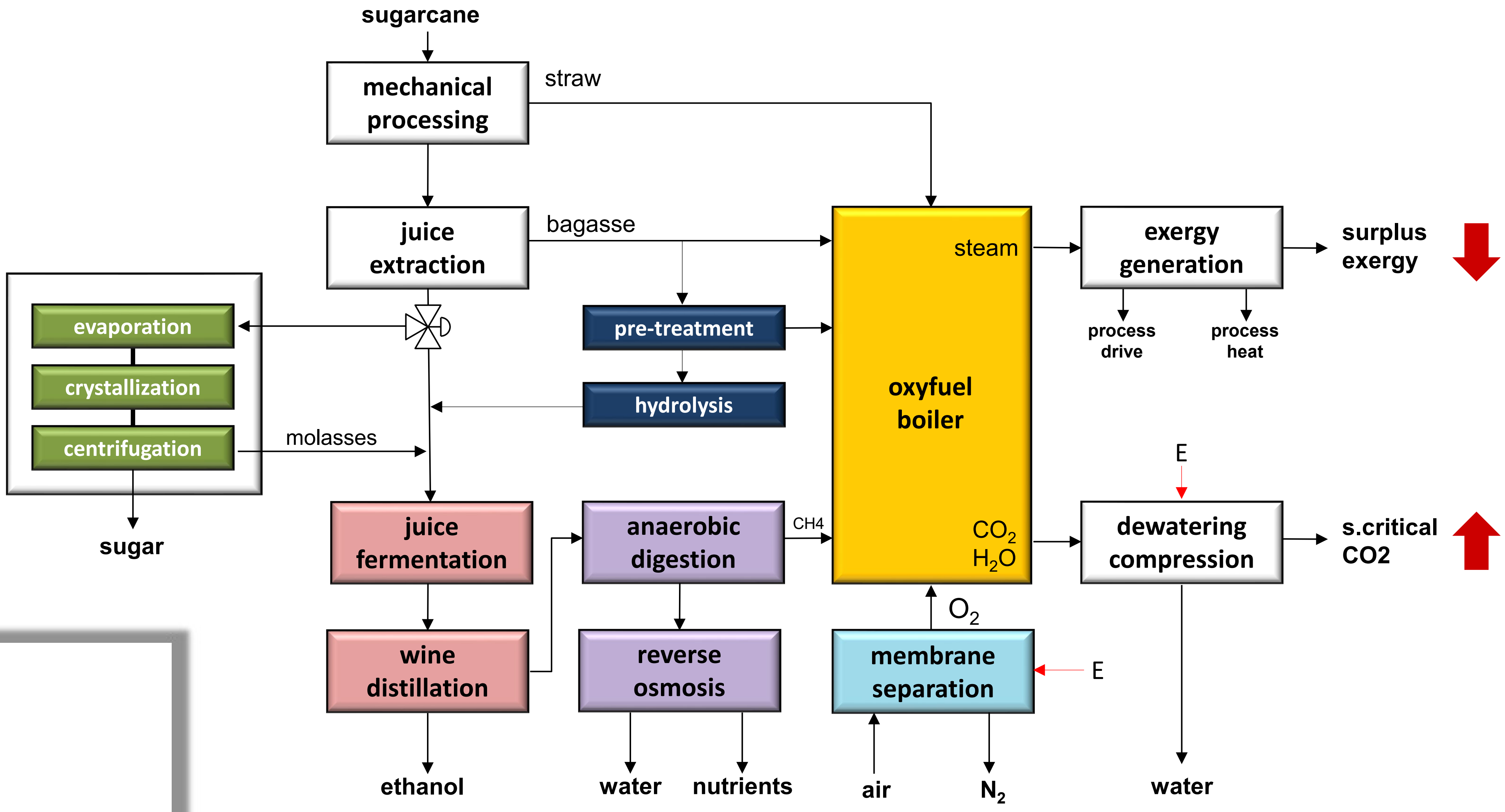
USINA DE CANA DE AÇÚCAR CONVENCIONAL – AÇÚCAR, ETANOL E ELETRICIDADE

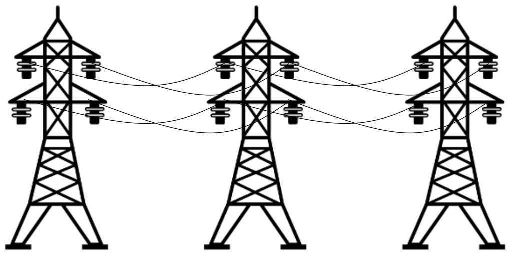


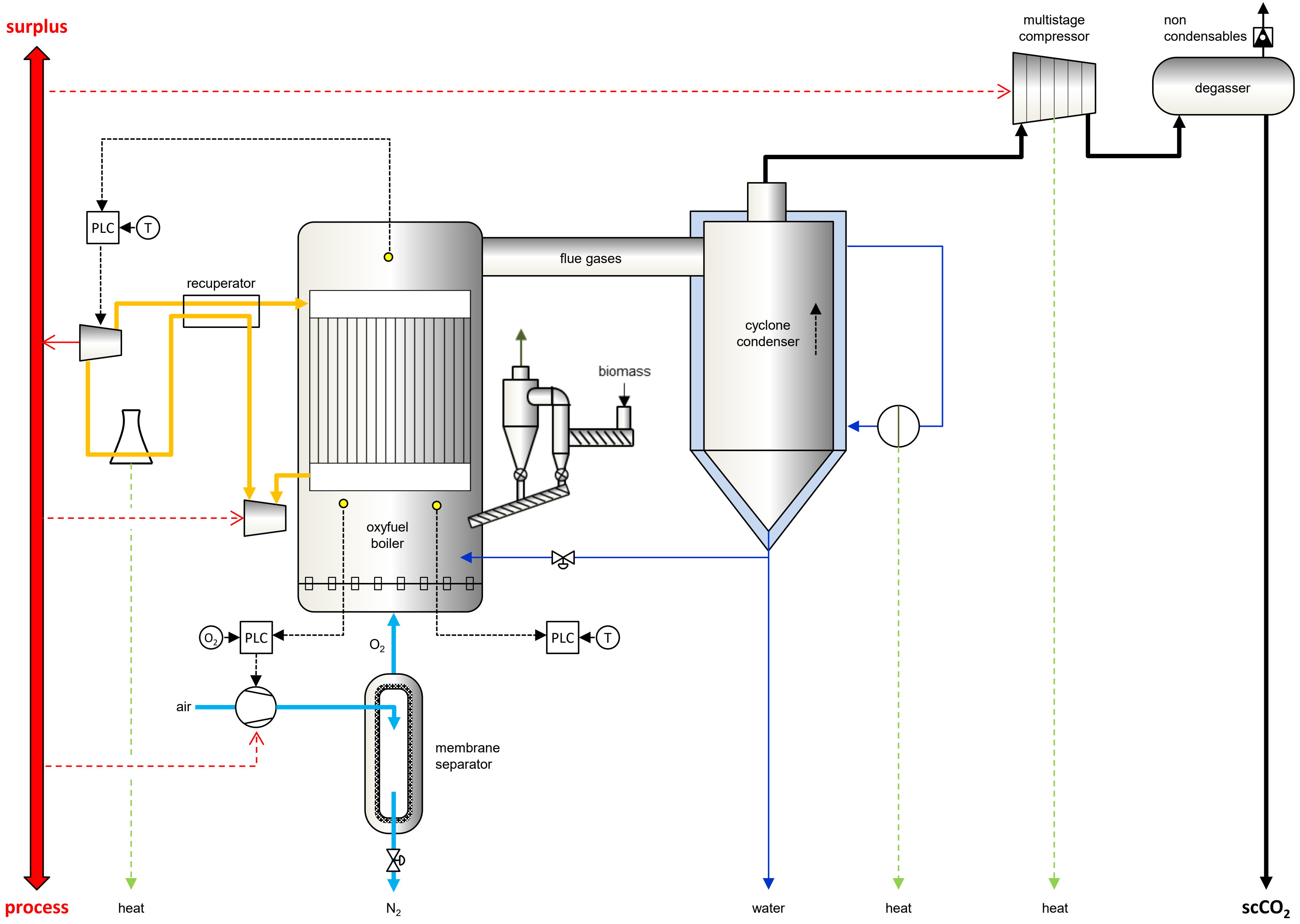
USINA DE CANA DE AÇÚCAR AVANÇADA – AÇÚCAR, ETANOL, ELETRICIDADE, CO2 SUPERCRÍTICO, ETC.

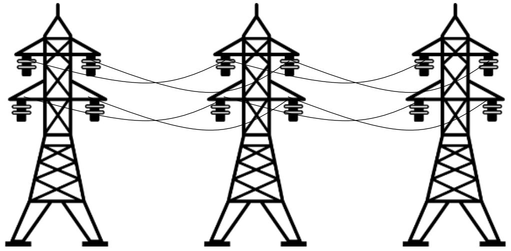


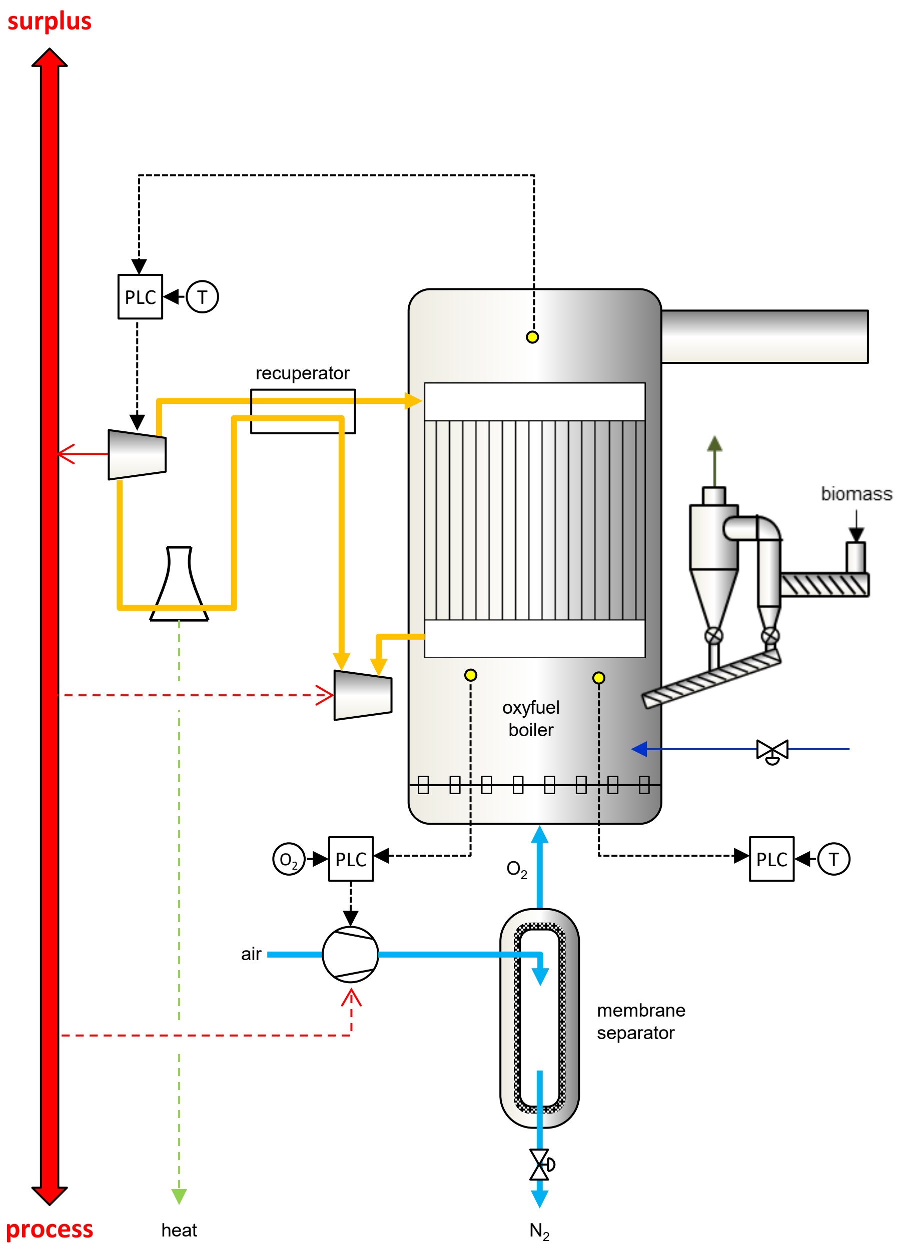
USINA DE CANA DE AÇÚCAR AVANÇADA – AÇÚCAR, ETANOL, ELETRICIDADE, CO2 SUPERCRÍTICO, ETC.

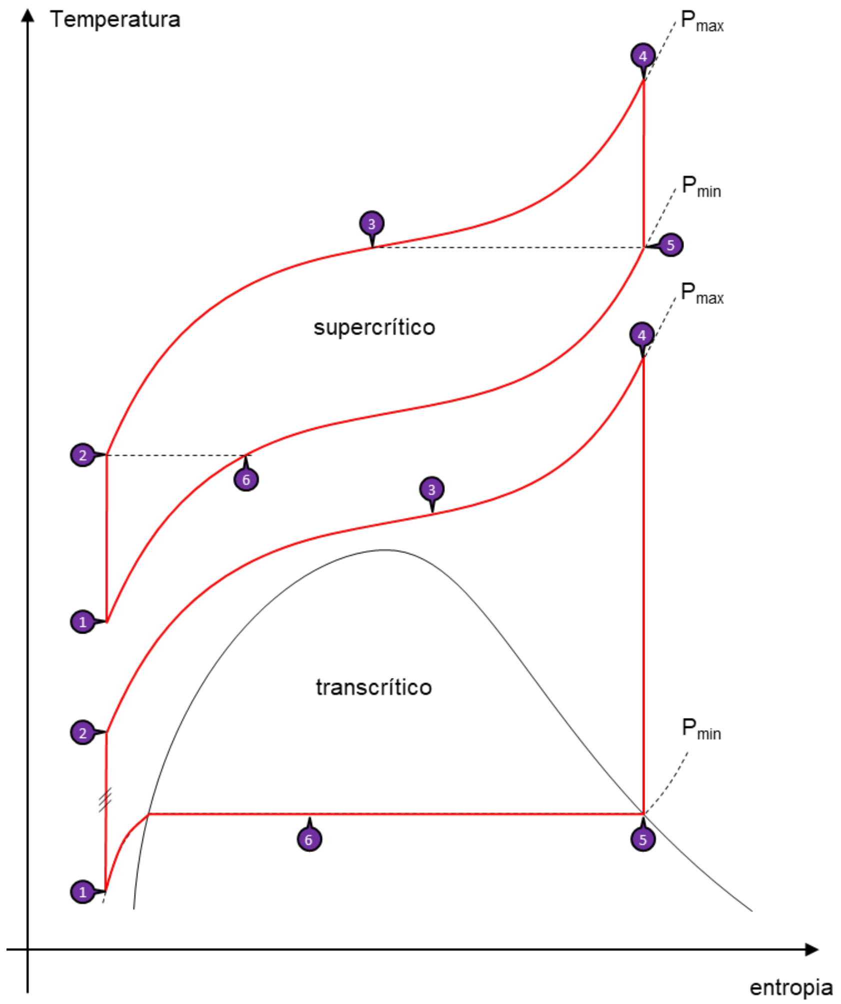


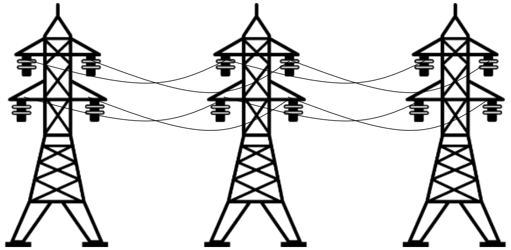


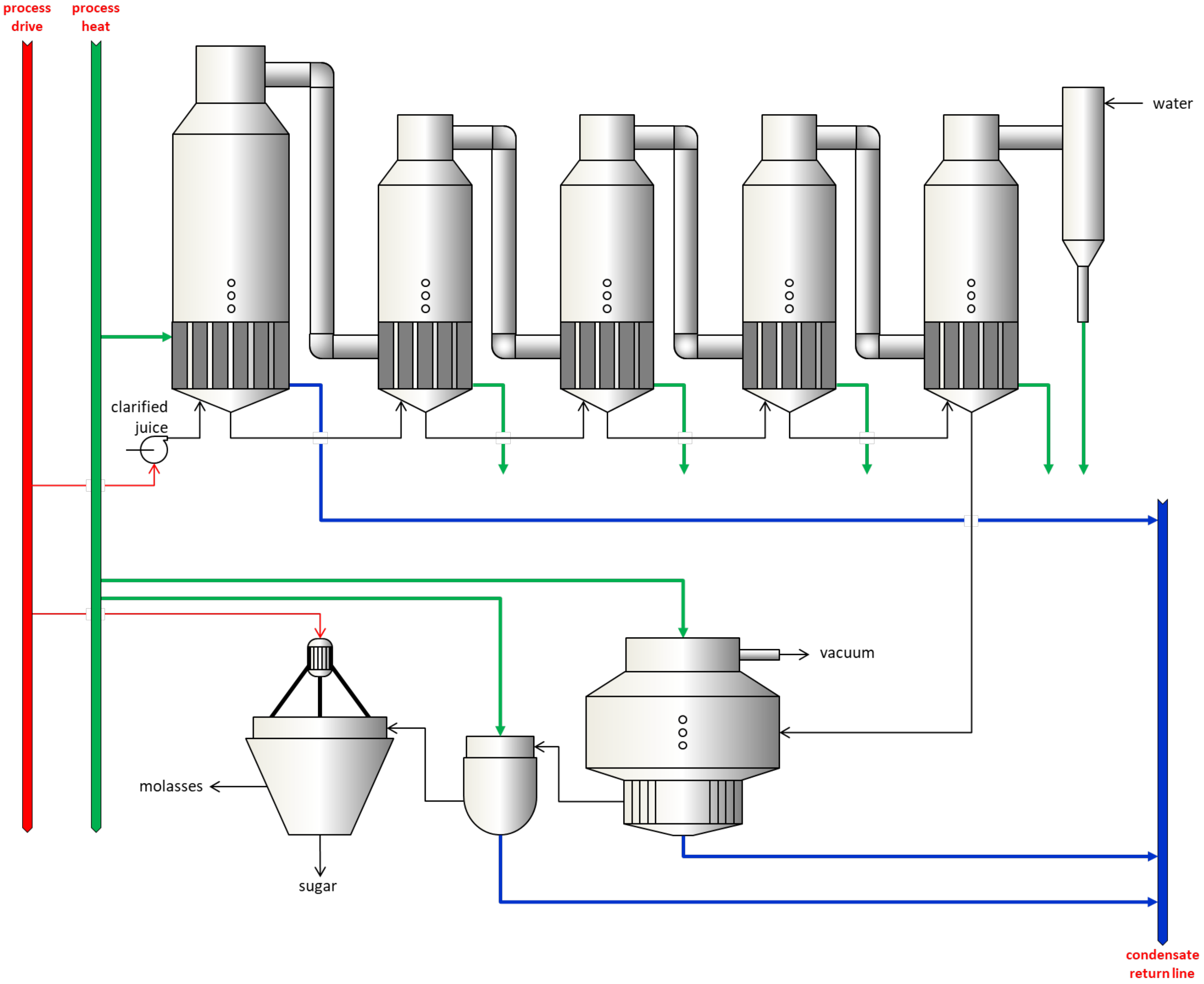

surplus
multistage
compressor
non
condensables
degasser
PLC
T
recuperator
flue gases
cyclone
condenser
biomass
oxyfuel
boiler
O_2
PLC
PLC
T
O_2
air
membrane
separator
process
heat
N_2
water
heat
heat
$scCO_2$



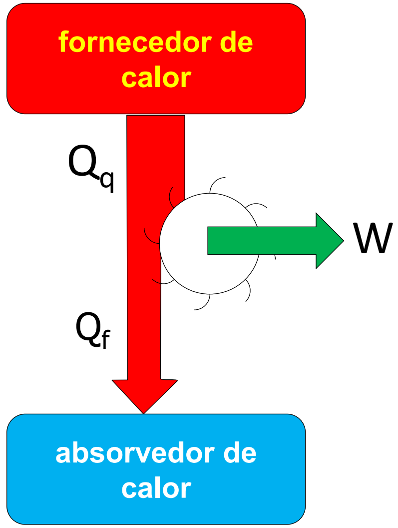

surplus
PLC
T
recuperator
biomass
oxyfuel
boiler
O2
PLC
T
air
membrane
separator
process
heat
N2


Temperatura
Pmax
Pmin
Pmax
supercrítico
transcrítico
Pmin
entropia



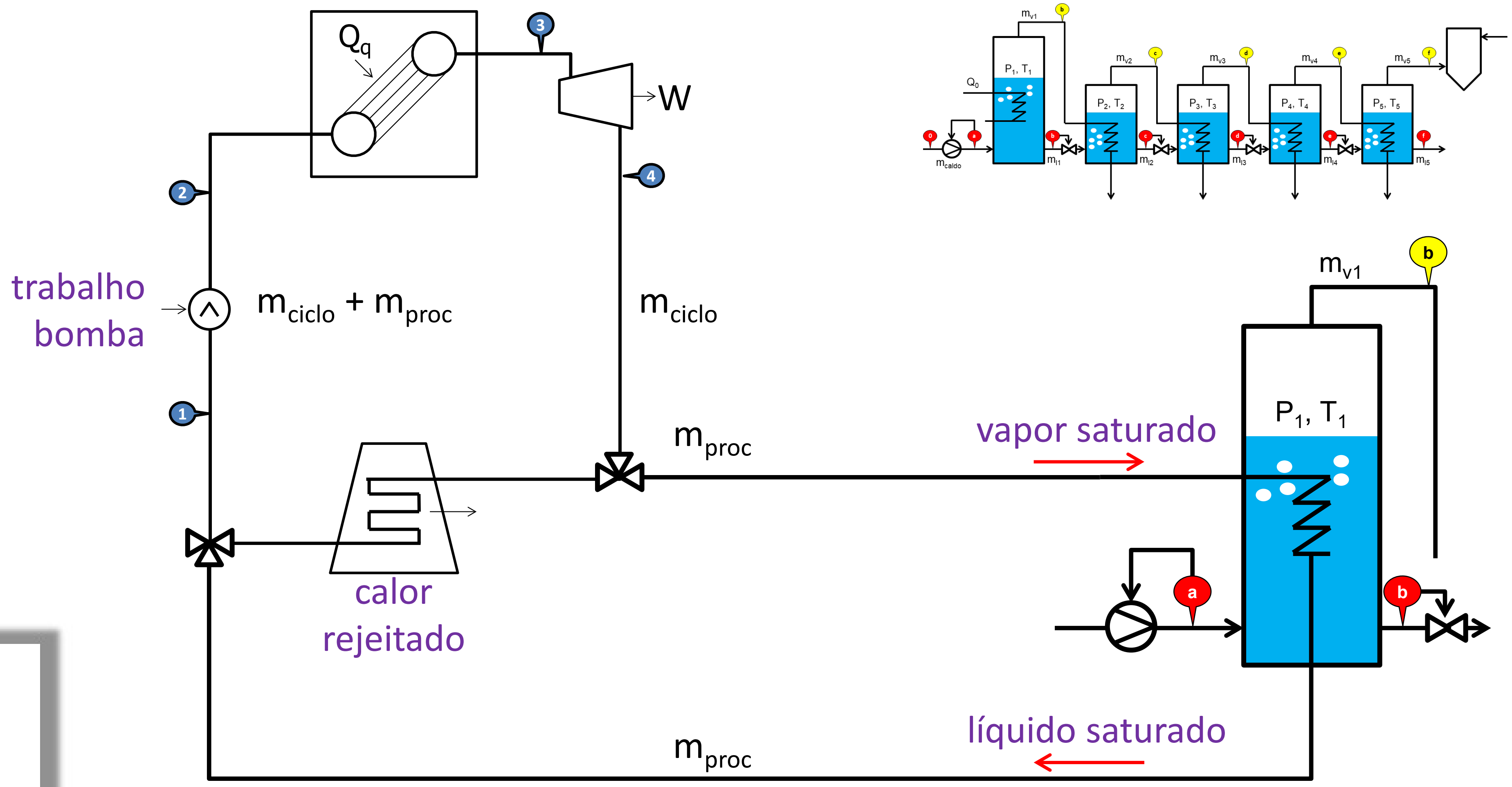

process drive
process heat
water
clarified juice
vacuum
molasses
sugar
condensate return line

Aproveitamento do calor rejeitado (2ª Lei da Termodinâmica)

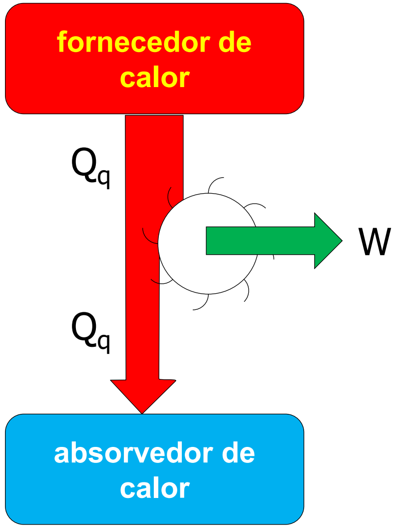


1° Lei: $Q_q = Q_f + W$

2° Lei: $W/Q_q < 100\%$



Aproveitamento do calor rejeitado (2ª Lei da Termodinâmica)



1° Lei: $Q_q = Q_f + W$

2° Lei: $W/Q_q < 100\%$

$$\eta_{cog} \hat{=} \frac{W_{liq} + Q_{proc}}{Q_q} \leq 1$$

$$\eta_{cog} = \left| \frac{m_{ciclo} \cdot \left[(h_3 - h_4) - (h_2 - h_1)\right] + m_{proc} \cdot (h_4 - h_1)}{m_{ciclo} \cdot (h_3 - h_2)} \right|$$

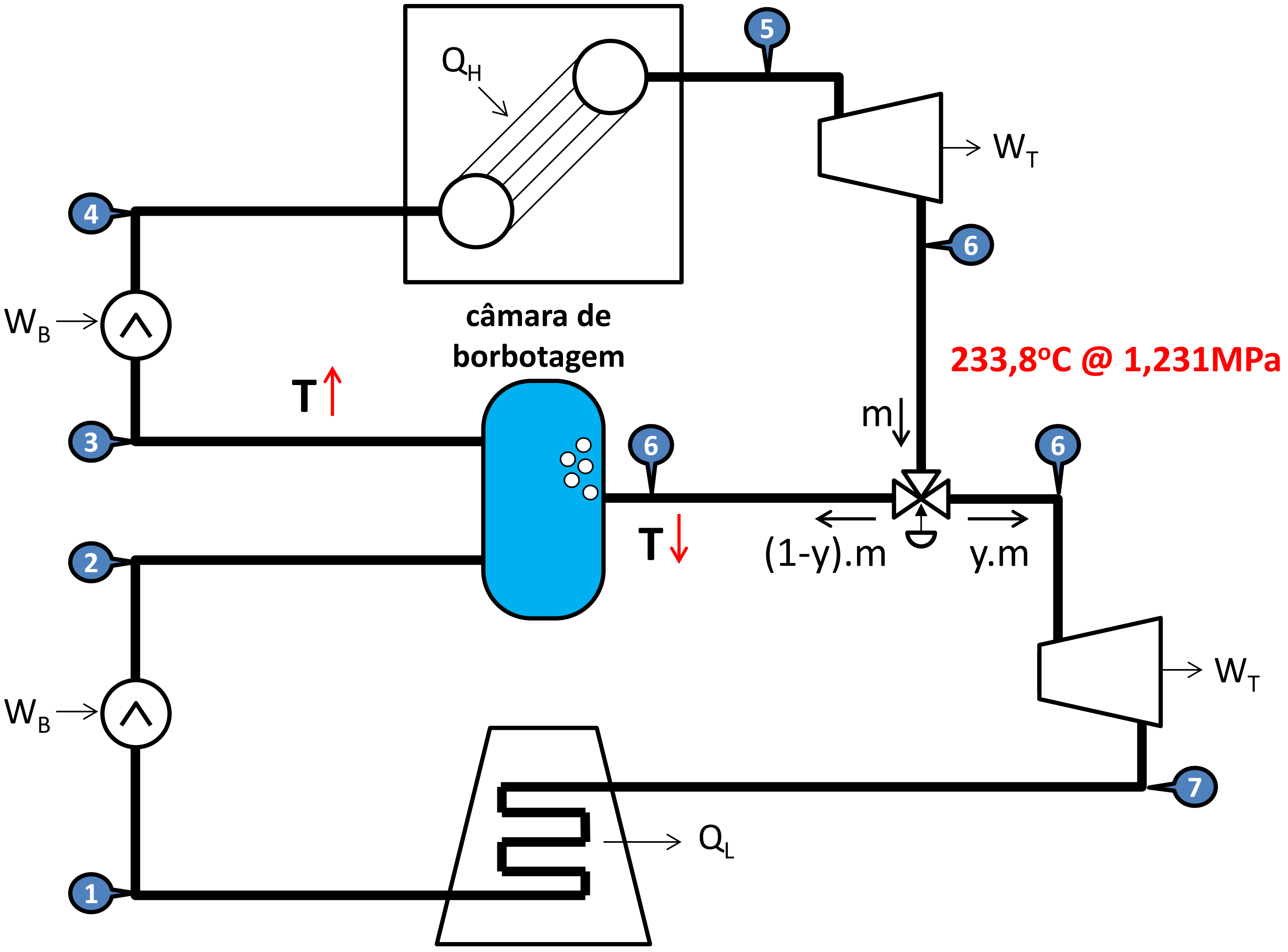
$$\downarrow \quad m_{ciclo} = m_{proc}$$

$$\eta_{cog} = \left| \frac{\left[(h_3 - h_4) - (h_2 - h_1)\right] + (h_4 - h_1)}{(h_3 - h_2)} \right|$$

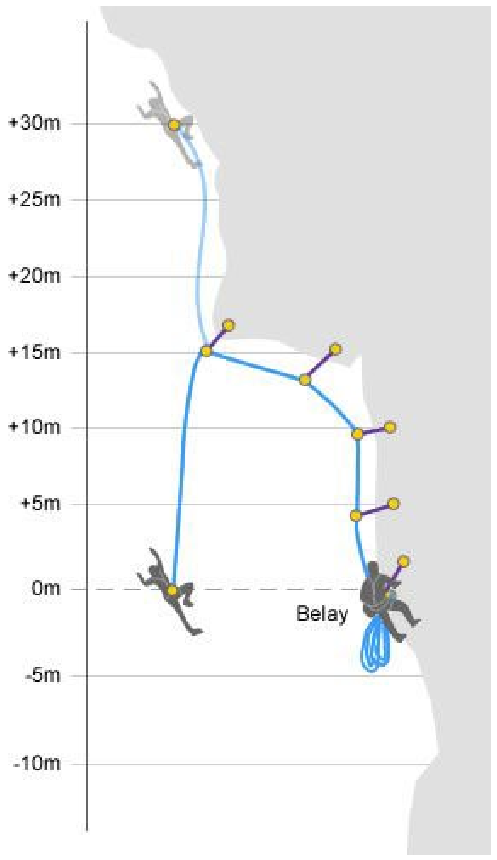
$$\eta_{cog} = 1$$

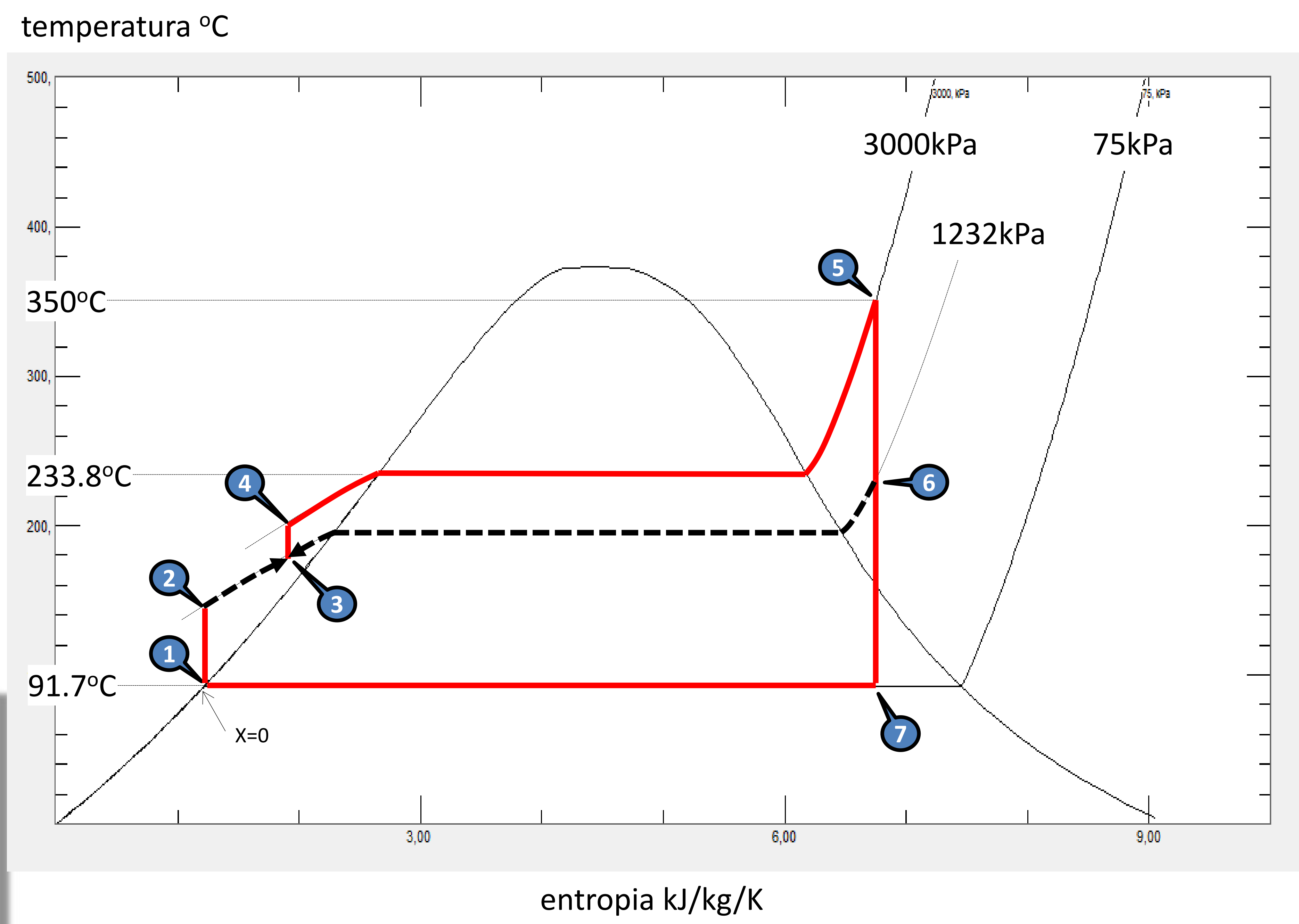
Ciclo de Rankine com aquecimento regenerativo

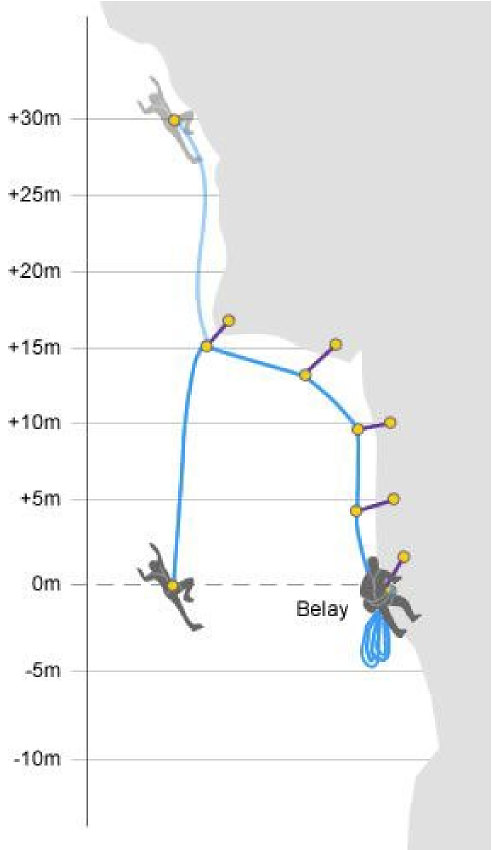
$$\eta = \frac{w_{12} + w_{34} + w_{56} + w_{67}}{q_{45}}$$



Attention to Filler Words


+30m
+25m
+20m
+15m
+10m
+5m
0m
Belay
-5m
-10m


temperatura ºC
500,
400,
350ºC
300,
233.8ºC
200,
91.7ºC
3000kPa
75kPa
1232kPa
1
2
3
4
5
6
7
X=0
3,00
6,00
9,00
entropia kJ/kg/K



$x = 0$ @ 75kPa

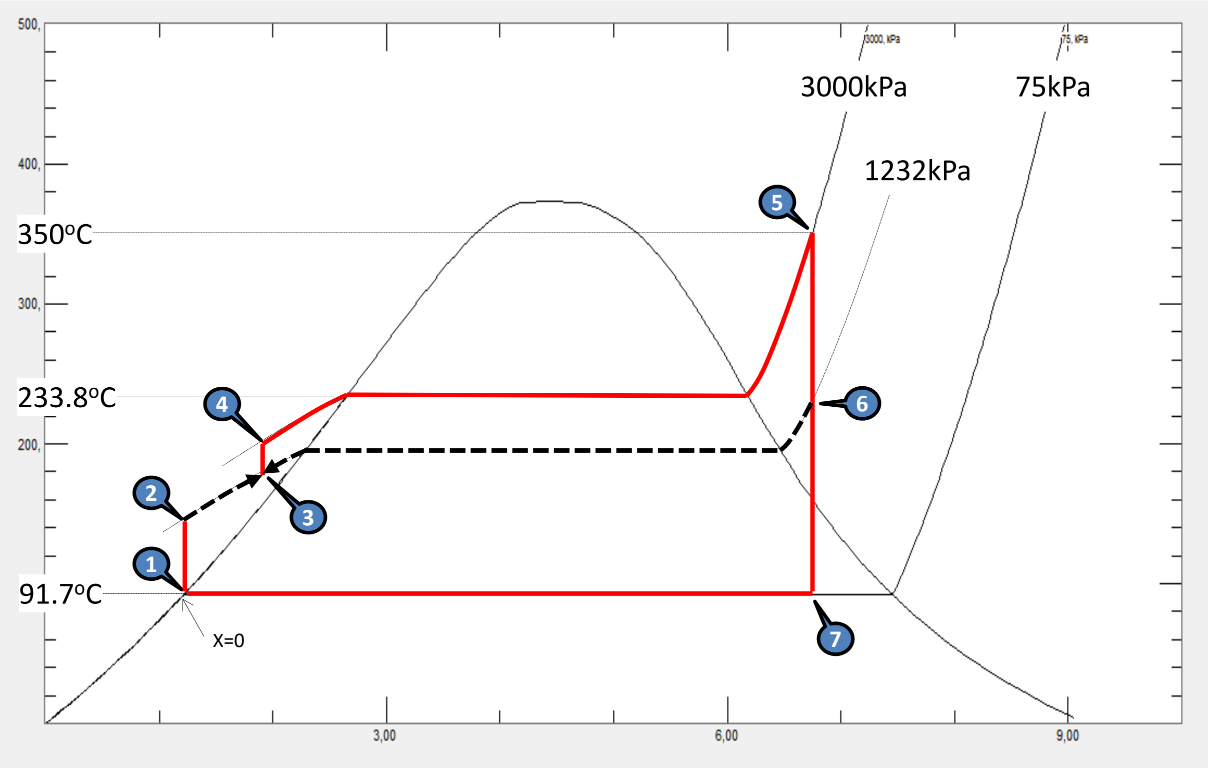
$h_1 = 384{,}44$ kJ/kg/K

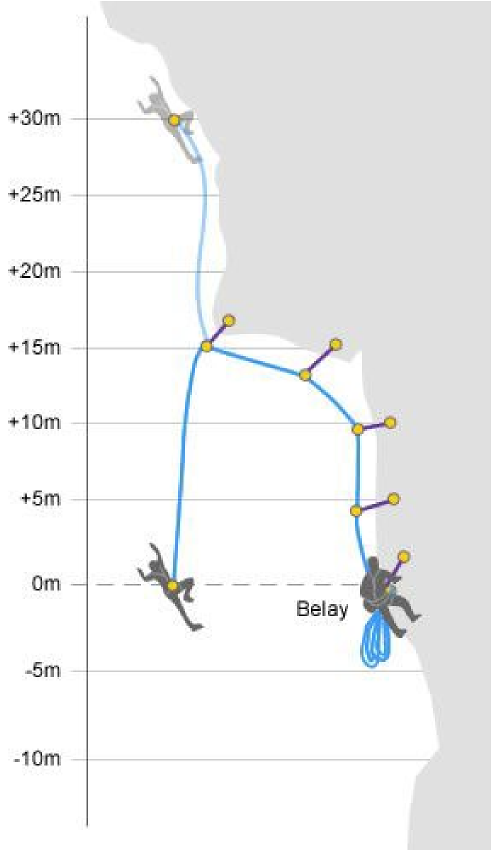
$s_1 = 1{,}2132$ kJ/kg/K

$S_1 = S_2$ @ 1,231MPa

$h_2 = 385{,}65$ kJ/kg/K

$T_2 = 91{,}834$ °C





equação de mistura

$h_3 = \ldots$

$h_4 = \ldots$

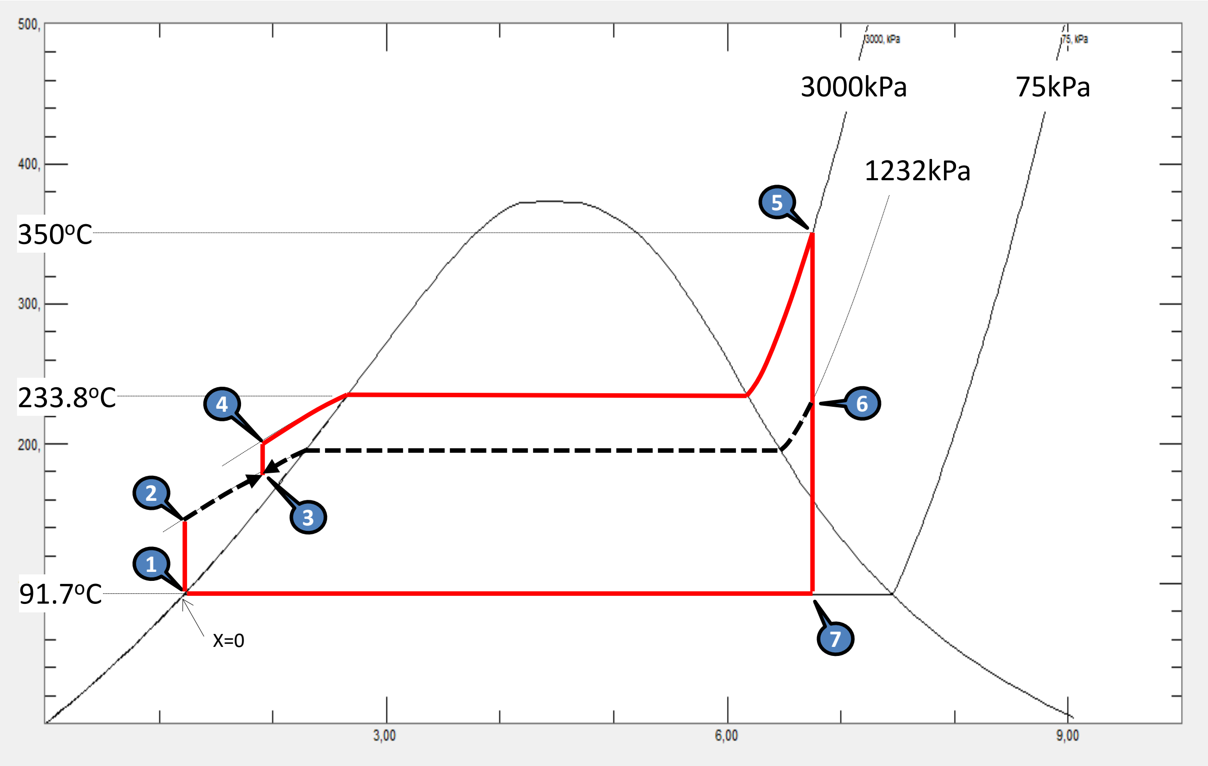
$s_3 = \ldots$

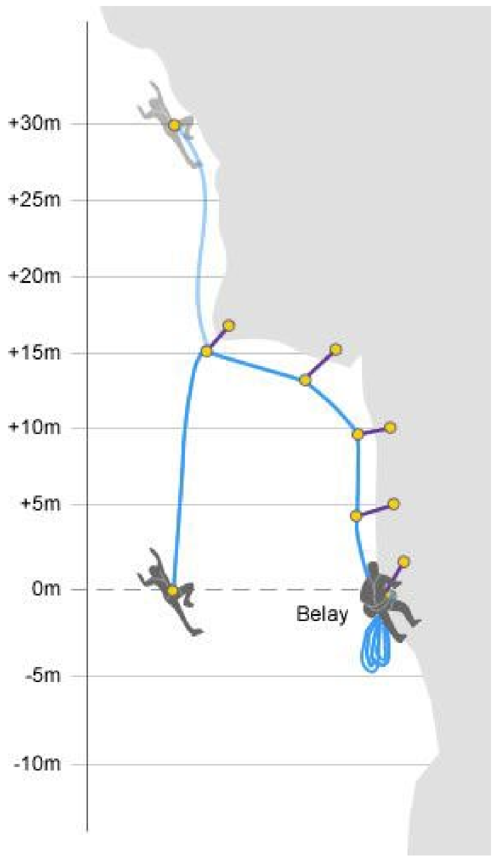
$s_4 = \ldots$

350ºC @ 3 MPa

$h_5 = 3116{,}1$ kJ/kg

$s_5 = 6{,}7449$ kJ/kg/K





$S_5 = S_6$ @ 1,231 MPa

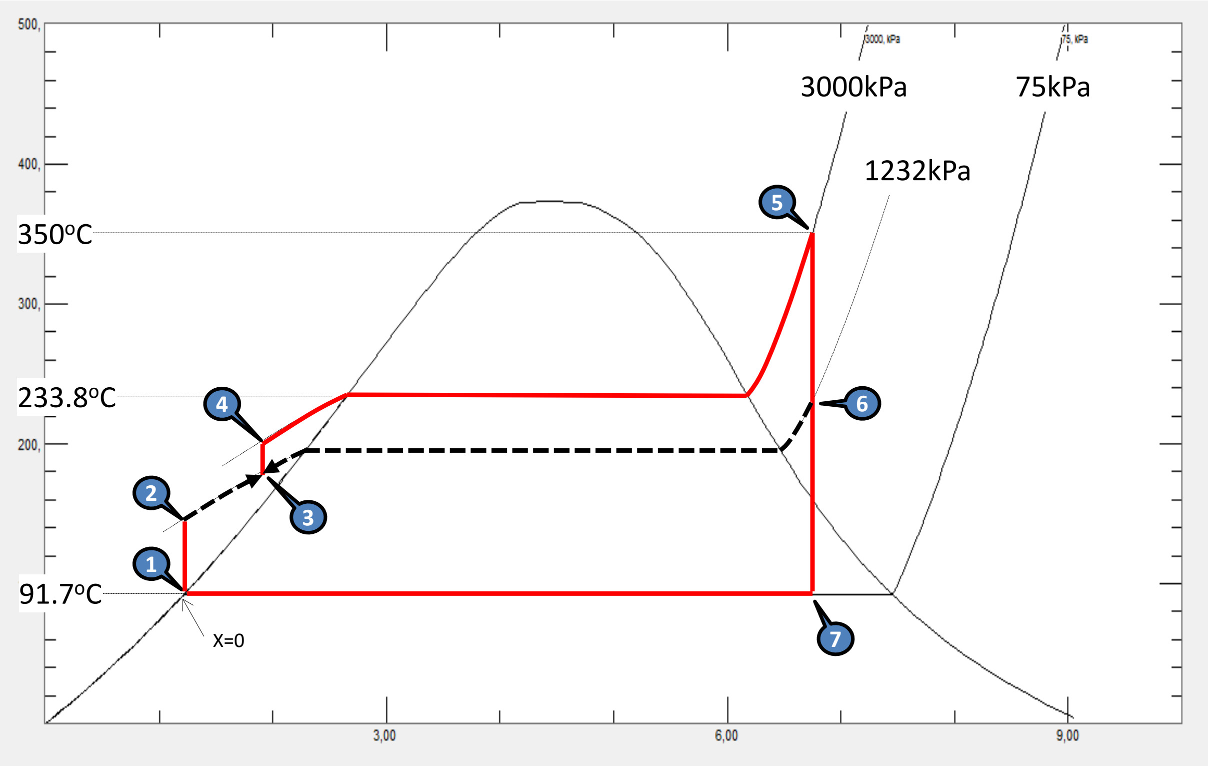
$h_6 = 2896,9$ kJ/kg

$s_6 = 6,7449$ kJ/kg/K

$S_6 = S_7$ @ 75kPa

$h_7 = 2403,0$ kJ/kg

$x_7 = 0,88614$ kg/kg

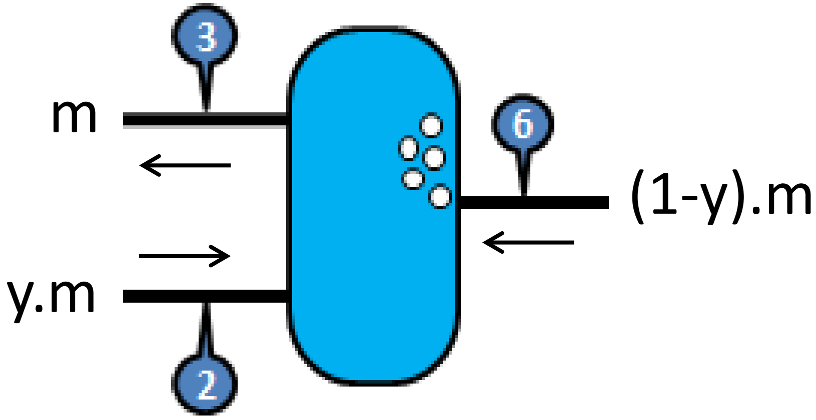


Determinação do estado da mistura vapor/líquido

$h_3 = (1\text{-}y)\cdot h_6 + y \cdot h_2$

$h_3 \leq h_{sat,liq}\,|_{1,23MPa} = 803{,}64$ kJ/kg

$s_3 = h[\, P_3, h_3(y)\,]$



Parâmetros arbitrados no projeto (e.g. $y = 0{,}98$, $P_3 = 12{,}31$bar)

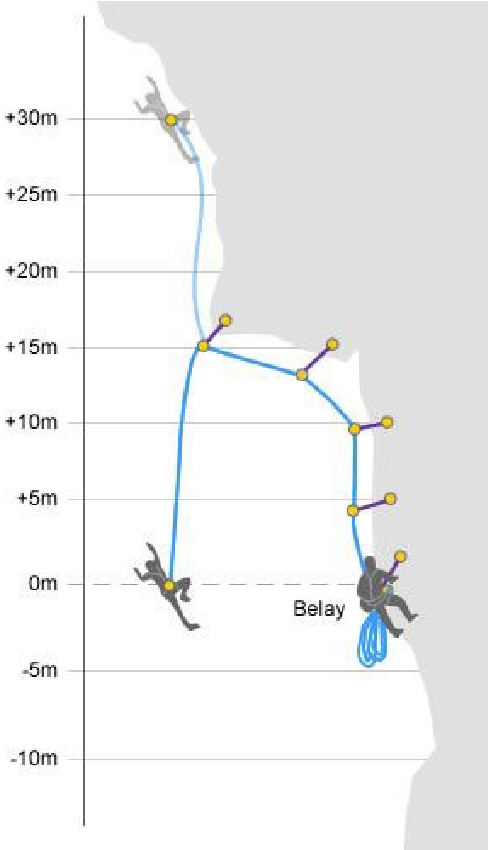
$h_3 = (1\text{-}0.98)\cdot 2896{,}9 + 0{,}98\cdot 385{,}65 = 435.87$ kJ/kg

$s_3 = h(P_3\,,\, h_3) = 1{,}3486$ kJ/kg/K $\qquad s_3 \overset{?}{=} (1\text{-}y)\cdot s_6 + y \cdot s_2$

$s_3 \overset{?}{>} (1\text{-}0.98)\cdot 6{,}7449 + 0{,}98\cdot 1{,}2132 = 1{,}324$ kJ/kg/K

O processo de mistura gera entropia

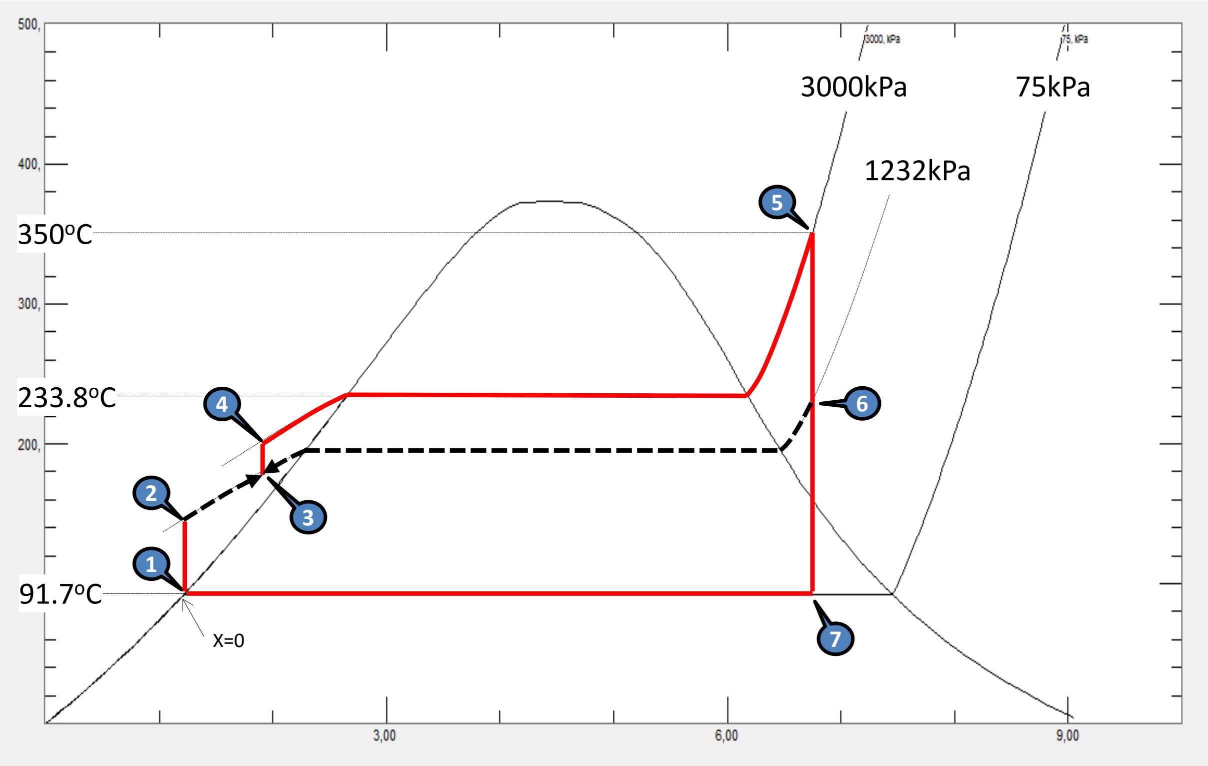
equação de mistura



$P_4 = 3000$ kPa

$h_4 = 437{,}72$ kJ/kg/K

$s_4 = 1{,}3486$ kJ/kg/K



$$\eta = \frac{\sum W_T - \sum W_B}{\sum Q_C}$$

$$\eta = \frac{[m \cdot (h_5 - h_6) + ym \cdot (h_6 - h_7)] - [ym \cdot (h_2 - h_1) + m \cdot (h_4 - h_3)]}{m \cdot (h_5 - h_4)}$$

$$\eta = \frac{[\cancel{m} \cdot (h_5 - h_6) + y\cancel{m} \cdot (h_6 - h_7)] - [y\cancel{m} \cdot (h_2 - h_1) + \cancel{m} \cdot (h_4 - h_3)]}{\cancel{m} \cdot (h_5 - h_4)}$$

$$\eta = \frac{[(h_5 - h_6) + y \cdot (h_6 - h_7)] - [y \cdot (h_2 - h_1) + (h_4 - h_3)]}{(h_5 - h_4)}$$

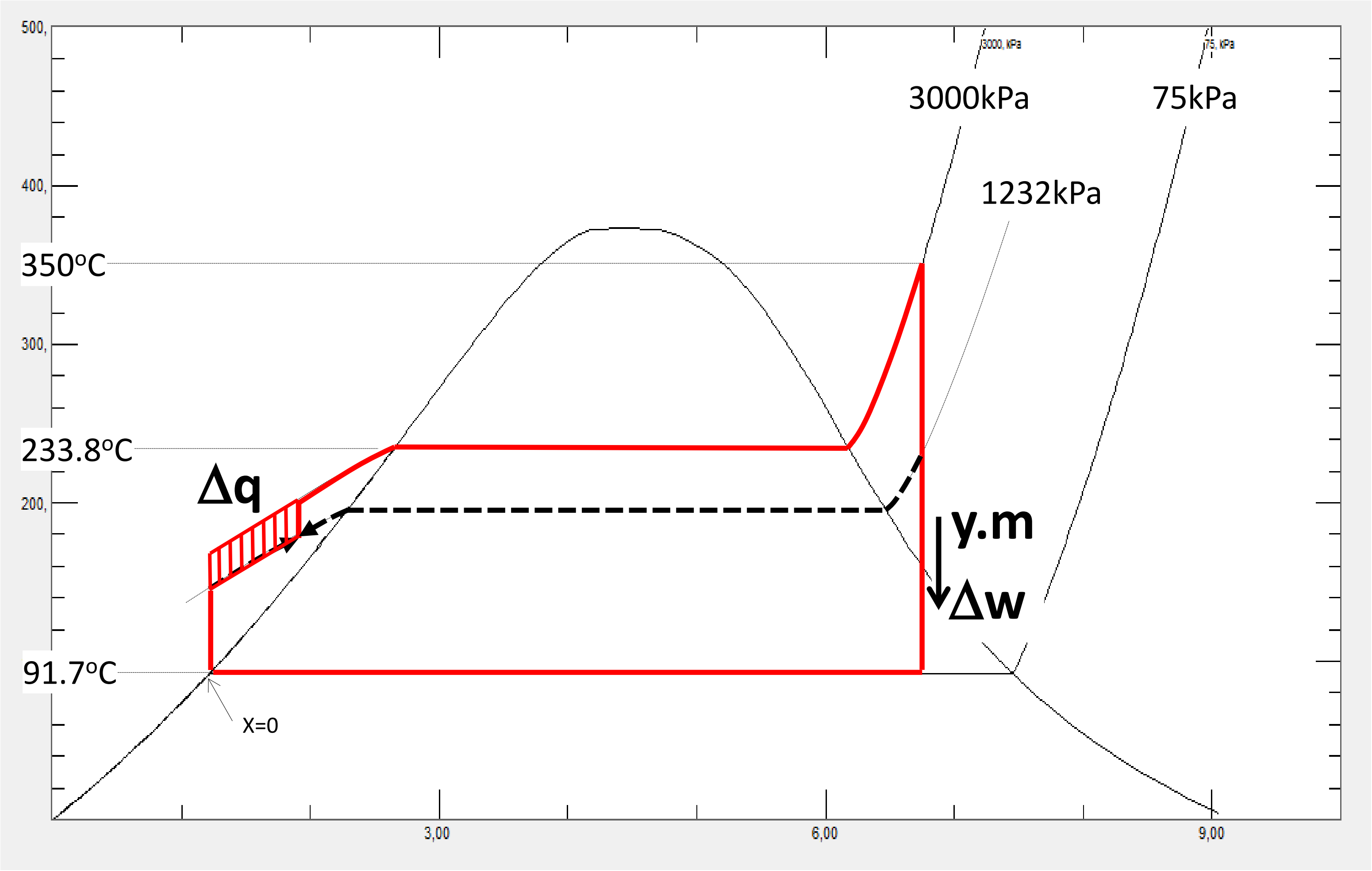
$$\eta_{reaq} = 0{,}268$$

$$\eta_{Rank} = 0{,}263$$

$$\eta_{regen} = 0{,}261$$

Devem ser comparadas as configs otimizadas

$$\eta = \frac{\downarrow\downarrow\downarrow w_t - w_b}{\downarrow q_c}$$



Curso de Termodinâmica

CICLOS A VAPOR
parte 1/2

aula 12/20