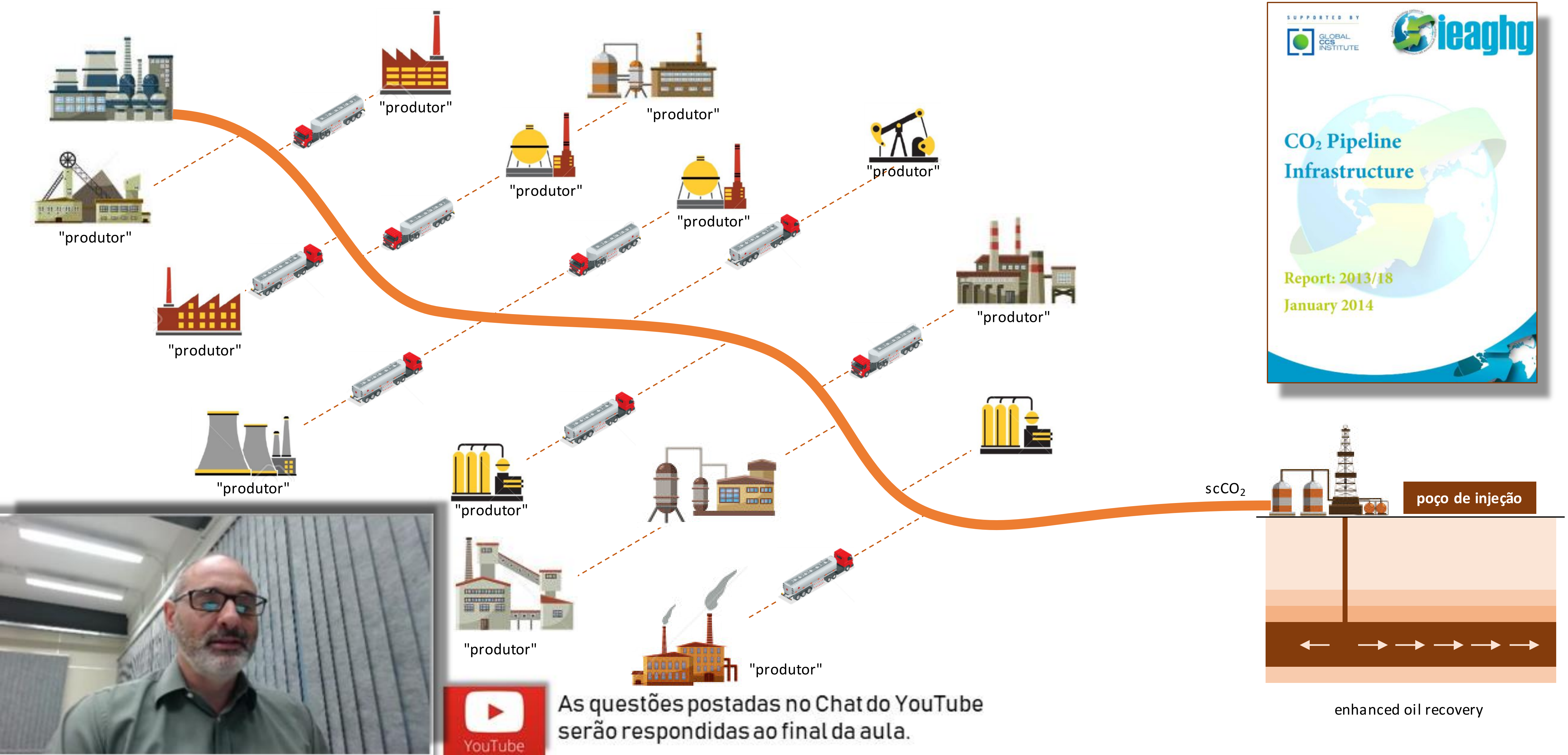
Exergy Analysis of a Biomass Power Plant Integrated to a Supercritical CO2 Production System

Prof. Paulo Seleghim Jr.
Universidade de São Paulo

Carbon capture, transportation and geological storage



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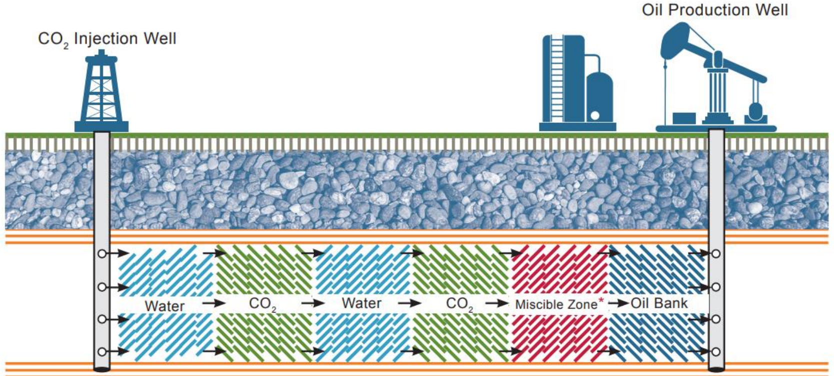
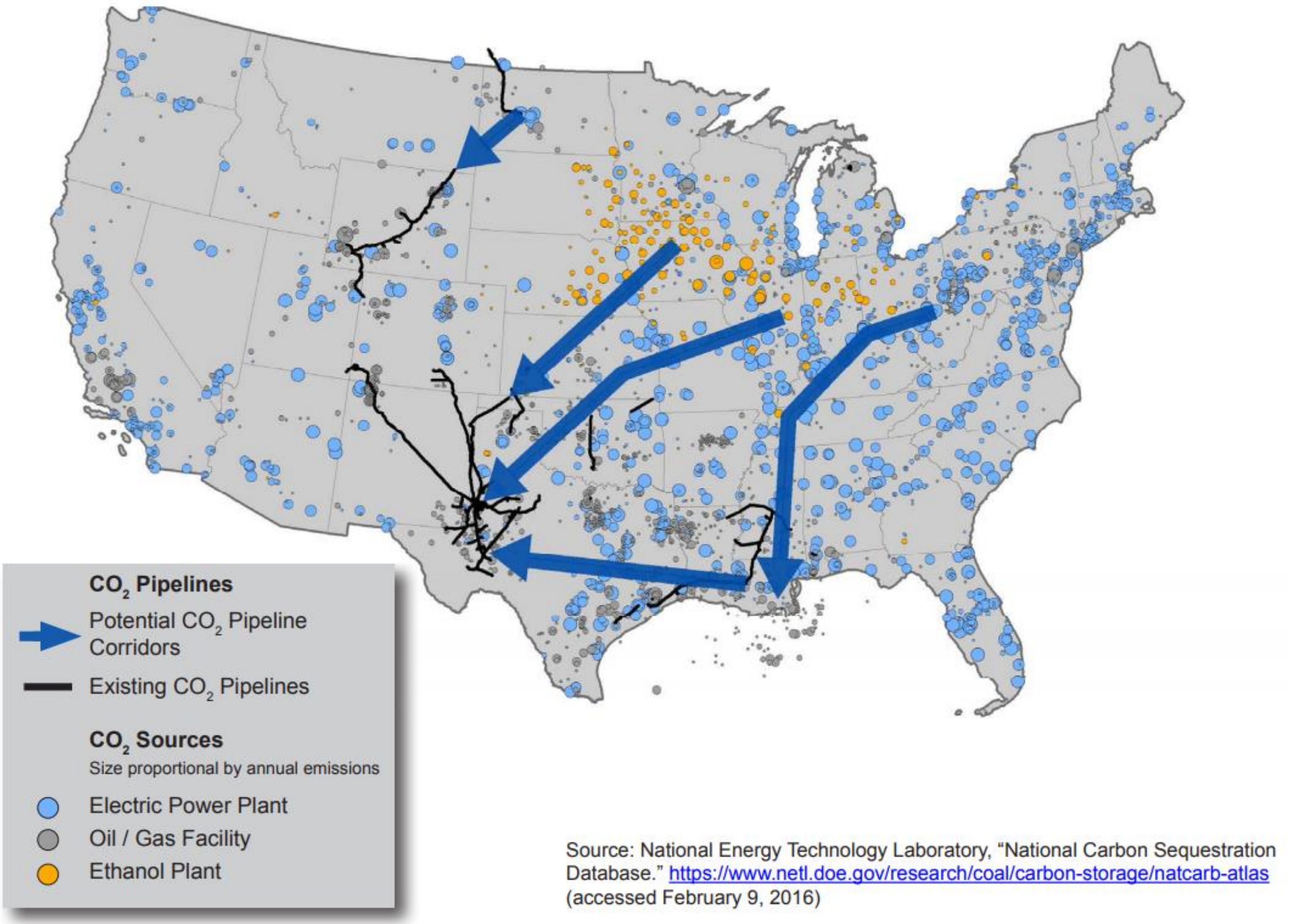
21st Century Energy Infrastructure:
Policy Recommendations for Development of American CO_2 Pipeline Networks



*Miscible Zone = Injected CO_2 encounters trapped oil → CO_2 and oil mix → Oil expands and moves towards producing well



Source: National Energy Technology Laboratory, "National Carbon Sequestration Database." https://www.netl.doe.gov/research/coal/carbon-storage/natcarb-atlas (accessed February 9, 2016)

Prepared by the State CO_2-EOR Deployment Work Group

YouTube

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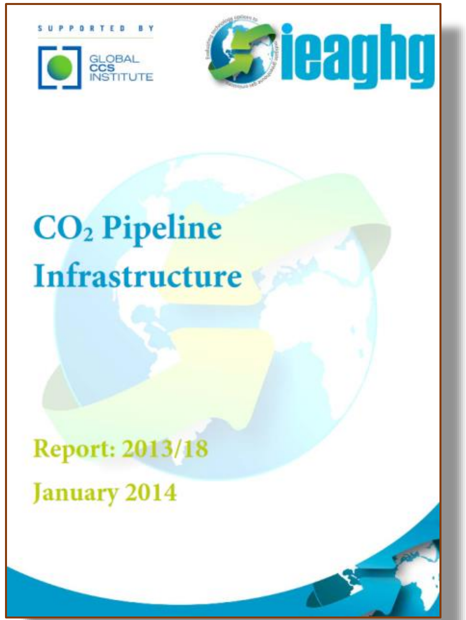

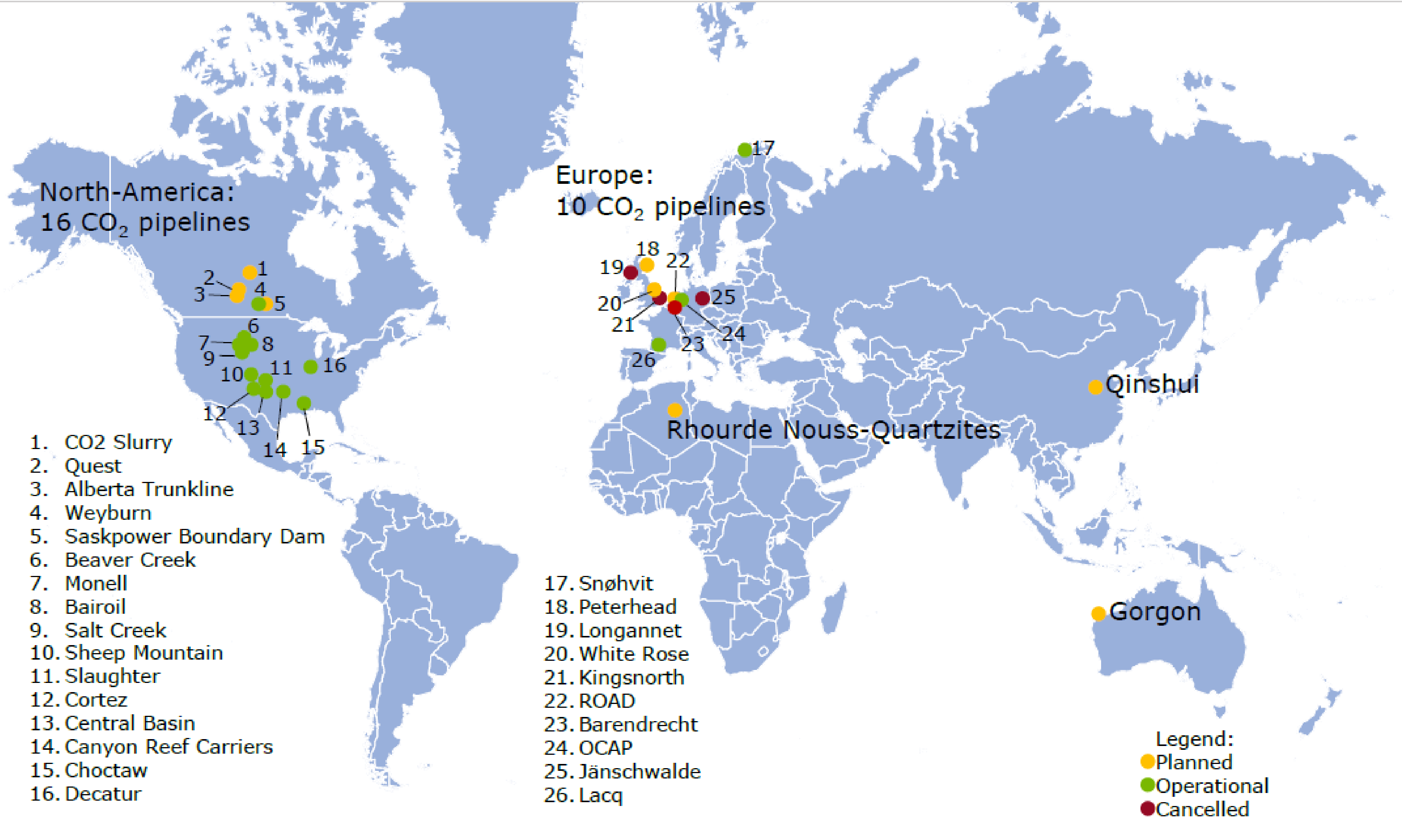

Figure 1 – Overview of CO_2 pipelines included in the study.

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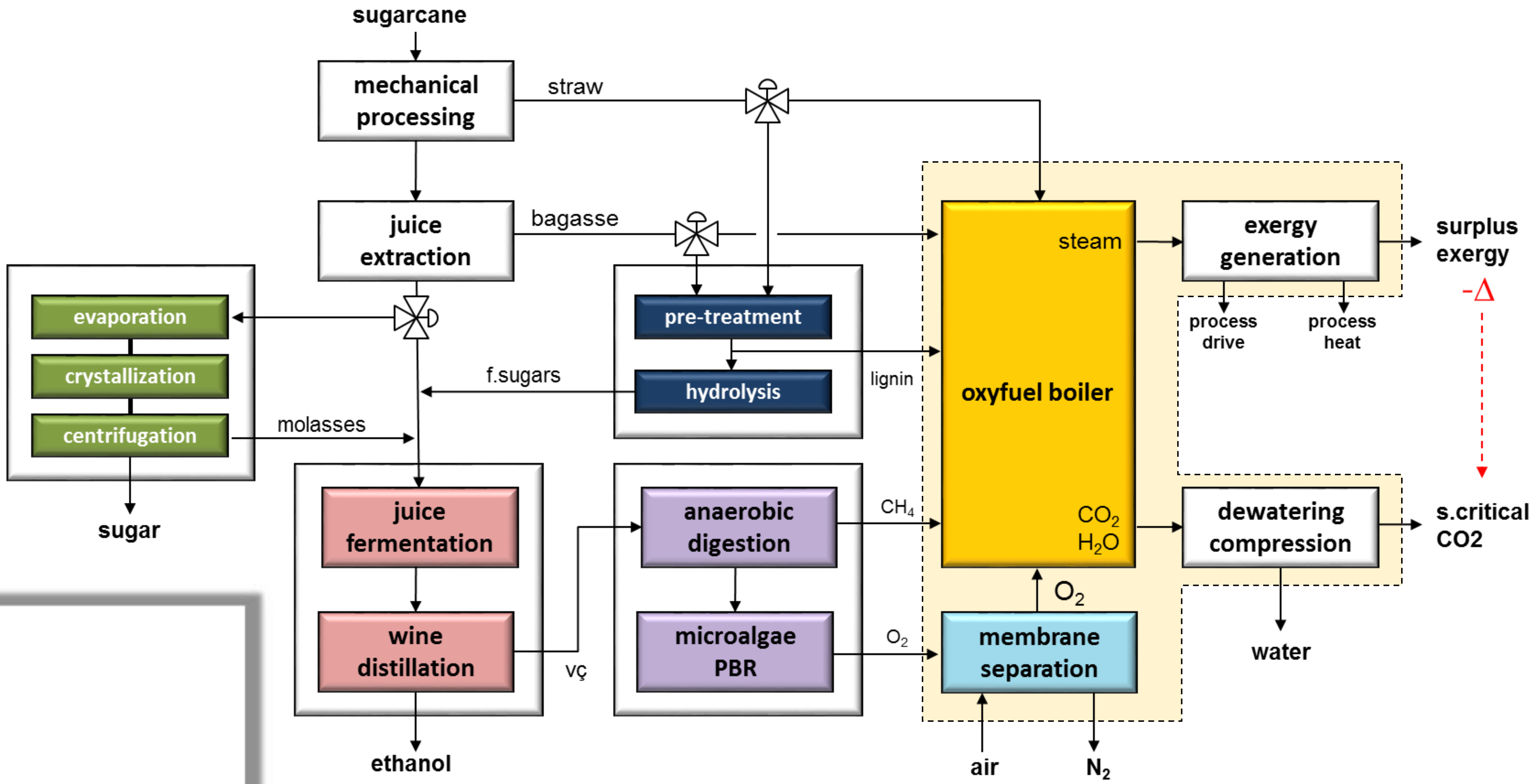
How to transform GHG emitting industrial units to producers of $scCO_2$ for geological storage ?

“Retrofitting1G sugarcane mills into Sun Powered CCS Machine...”



Exergy Analysis:
fuel to exergy + CO_2 carrier

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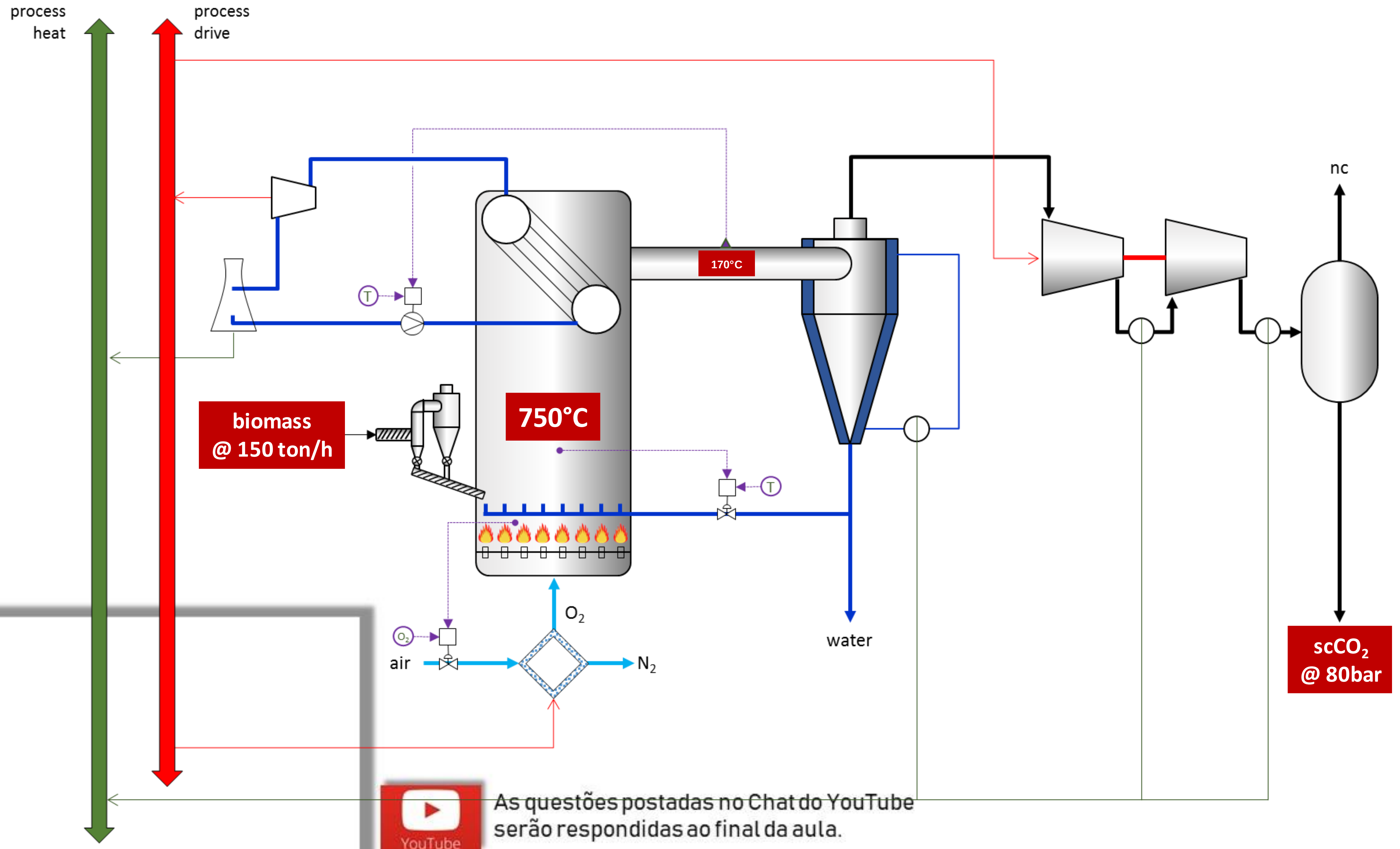
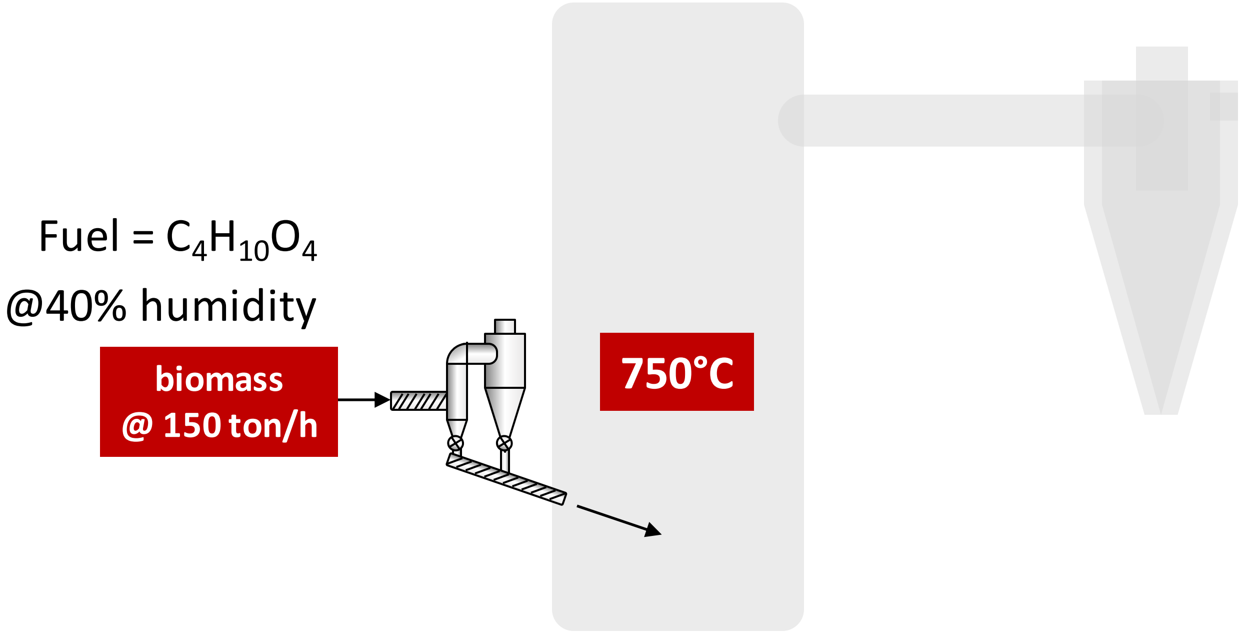


process heat
process drive
170°C
nc
biomass @ 150 ton/h
750°C
T
T
O_2
air
O_2
N_2
water
$scCO_2$ @ 80bar



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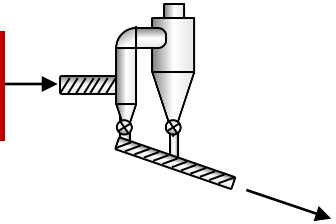
$$e_F^{ch} = 2193\frac{kJ}{mol}\cdot\left(122.12\cdot\frac{kg}{10^{+3}mol}\right)^{-1} = 17.958\frac{MJ}{kg}$$

Fuel = $C_4H_{10}O_4$

@40% humidity

biomass @ 150 ton/h



$$\dot{E}_F = 17.958\frac{MJ}{kg}\cdot 150\frac{10^3 kg}{3600\,s}\cdot 60\% = \ldots$$

$$\dot{E}_F = 448.95\,MW$$

Thermodynamic Properties of Plant Biomass Components. Heat Capacity, Combustion Energy, and Gasification Equilibria of Lignin

Por: Voitkevich, Olga V.; Kabo, Gennady J.; Blokhin, Andrey V.; et al.

JOURNAL OF CHEMICAL AND ENGINEERING DATA Volume: 57 Edição: 7 Páginas: 1903-1909 Publicado: JUL 2012

S·F·X | Texto integral do editor | Visualizar resumo

Thermodynamic Properties of Plant Biomass Components. Heat Capacity, Combustion Energy, and Gasification Equilibria of Cellulose

Por: Blokhin, Andrey V.; Voitkevich, Olga V.; Kabo, Gennady J.; et al.

JOURNAL OF CHEMICAL AND ENGINEERING DATA Volume: 56 Edição: 9 Páginas: 3523-3531 Publicado: SEP 2011

S·F·X | Texto integral do editor | Visualizar resumo

Table A.4.2 Enthalpy and exergy of formation for organic substances at reference state (T_0 = 298.15 K, P_0 = 101.325 kPa)

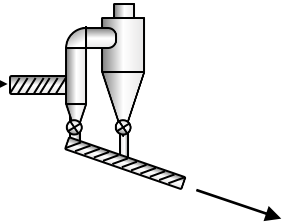
Chemical formula	Namne	State	Molar mass kg/kmol	Enthalpy of formation [kJ/mol]	Exergy [kJ/mol]
$C_4H_{10}O_4$	Erythrite	s	122.1219	1874.7	2193.0
$C_4H_6O_4$	Succinic acid	s	118.09002	1356.9	1609.4
$C_4H_4O_4$	Malonic acid	s	116.07408	1271.3	1495.7
$C_4H_4O_4$	Fumaric acid	s	116.07408	1249.1	1471.5
C_6H_6O	Phenol	s	94.11412	2925.9	3128.5
$C_6H_{14}O_6$	Dulcite	s	182.17488	2729.6	3196.3
$C_6H_{14}O_6$	Mannit	s	182.17488	2739.6	3204.8
$C_6H_{12}O_6$	α-D-Galactose	s	180.15894	2529.6	2928.8
$C_6H_{12}O_6$	L-Sorbose	s	180.15894	2544.6	2939.0
$C_7H_6O_2$	Benzoic acid	s	122.12467	3097.2	3343.5
$C_7H_6O_3$	Hydroxybenzoic acid	s	138.12407	2888.1	3151.2
$C_8H_4O_3$	Phthalic acid anhydride	s	148.11928	3173.8	3434.8
$C_8H_6O_4$	Phthalic acid	s	166.13462	3094.3	3412.6

$$e^{ch}_{H2O} = 45\frac{kJ}{10^{+3}mol}\cdot\left(18.02\cdot\frac{kg}{10^{+3}mol}\right)^{-1} = 2.497\frac{kJ}{kg}$$

Fuel = $C_4H_{10}O_4$

@40% humidity

biomass
@ 150 ton/h

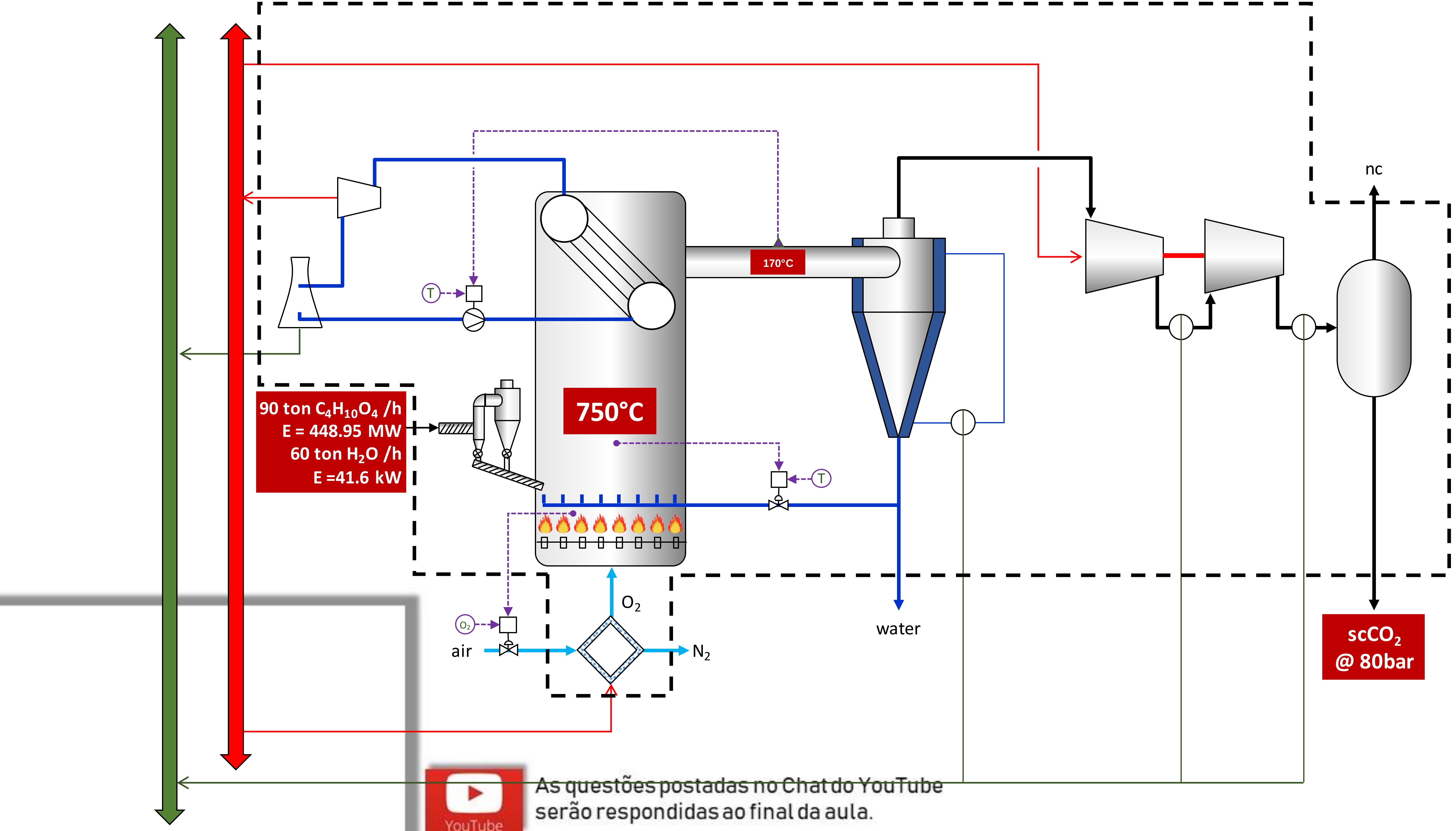


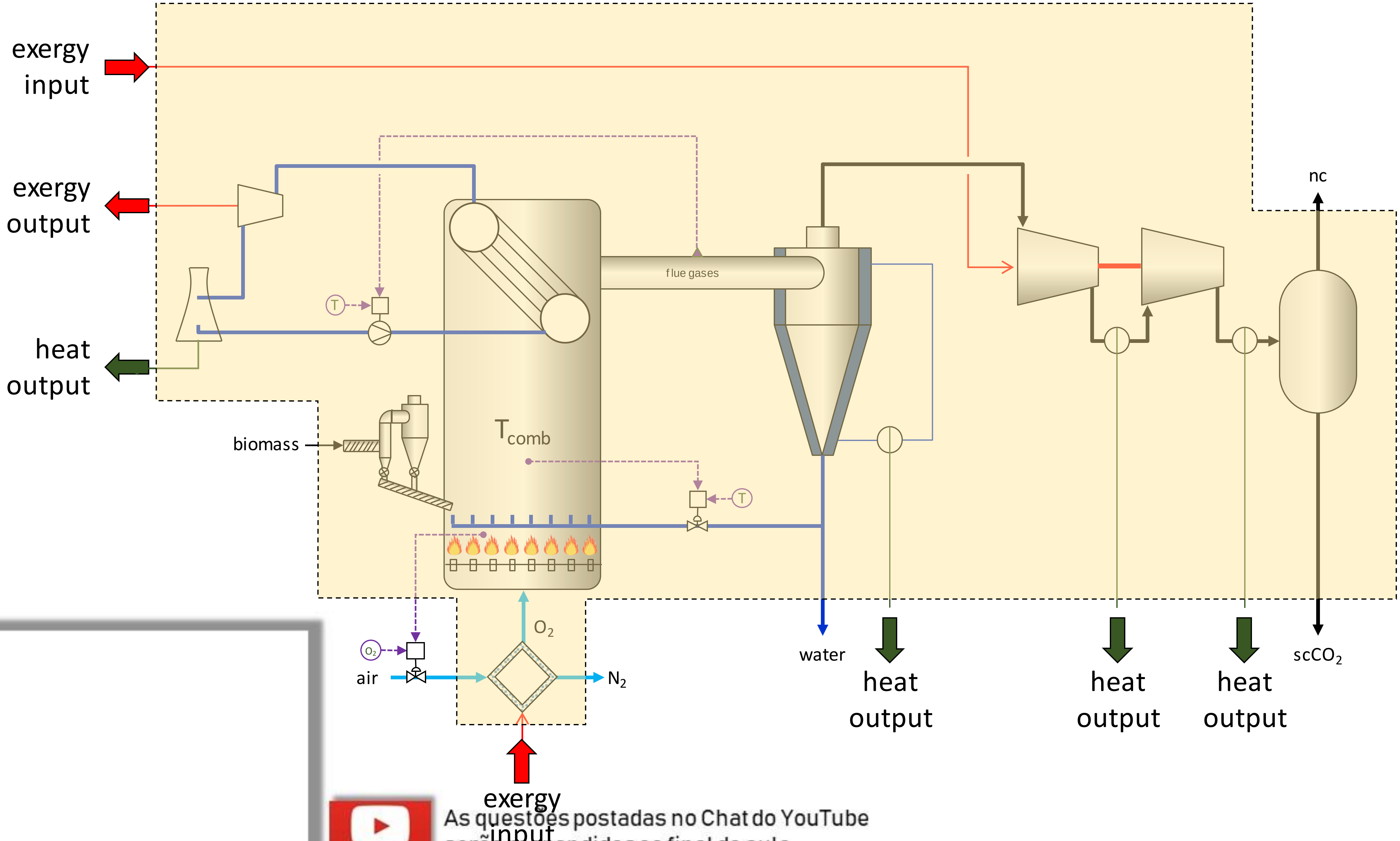
$$\dot{E}_{H2O} = 2.497\frac{kJ}{kg}\cdot 150\frac{10^3 kg}{3600 s}\cdot 40\% = \ldots$$

$$\dot{E}_{H2O} = 41.62\ kW$$

TABLE A-26 Standard Molar Chemical Exergy, $\bar{e}^{ch}$ (kJ/kmol), of Selected Substances at 298 K and p_0

Substance	Formula	Model I[a]	Model II[b]
Nitrogen	$N_2(g)$	640	720
Oxygen	$O_2(g)$	3,950	3,970
Carbon dioxide	$CO_2(g)$	14,175	19,870
Water	$H_2O(g)$	8,635	9,500
Water	$H_2O(l)$	45	900
Carbon (graphite)	C(s)	404,590	410,260
Hydrogen	$H_2(g)$	235,250	236,100
Sulfur	S(s)	598,160	609,600
Carbon monoxide	CO(g)	269,410	275,100
Sulfur dioxide	$SO_2(g)$	301,940	313,400


90 ton $C_4H_{10}O_4$ /h
E = 448.95 MW
60 ton H_2O /h
E =41.6 kW
750°C
170°C
T
T
O_2
O_2
air
N_2
water
nc
$scCO_2$
@ 80bar



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exergy input

exergy output

heat output

$$\sum \dot{m}_s - \sum \dot{m}_e = 0$$

$$\sum \dot{Q}_k - \sum \dot{W}_k = \sum \dot{m}_s e_s - \sum \dot{m}_e e_e$$

massa e energia

mass output

balanço exergético $\rightarrow$ Sankey

mass input

$$\sum \left(1 - \frac{T_0}{T_k}\right)\dot{Q}_k - \left(\dot{W} - P_0 \frac{dV_{vc}}{dt}\right) + \sum \dot{m}_e x_e - \sum \dot{m}_s x_s - \dot{X}_{dest} = \frac{dX_{vc}}{dt}$$

mass input

mass output

heat output

heat output

heat output

mass output

exergy input

mass output

Thermodynamic Analysis…

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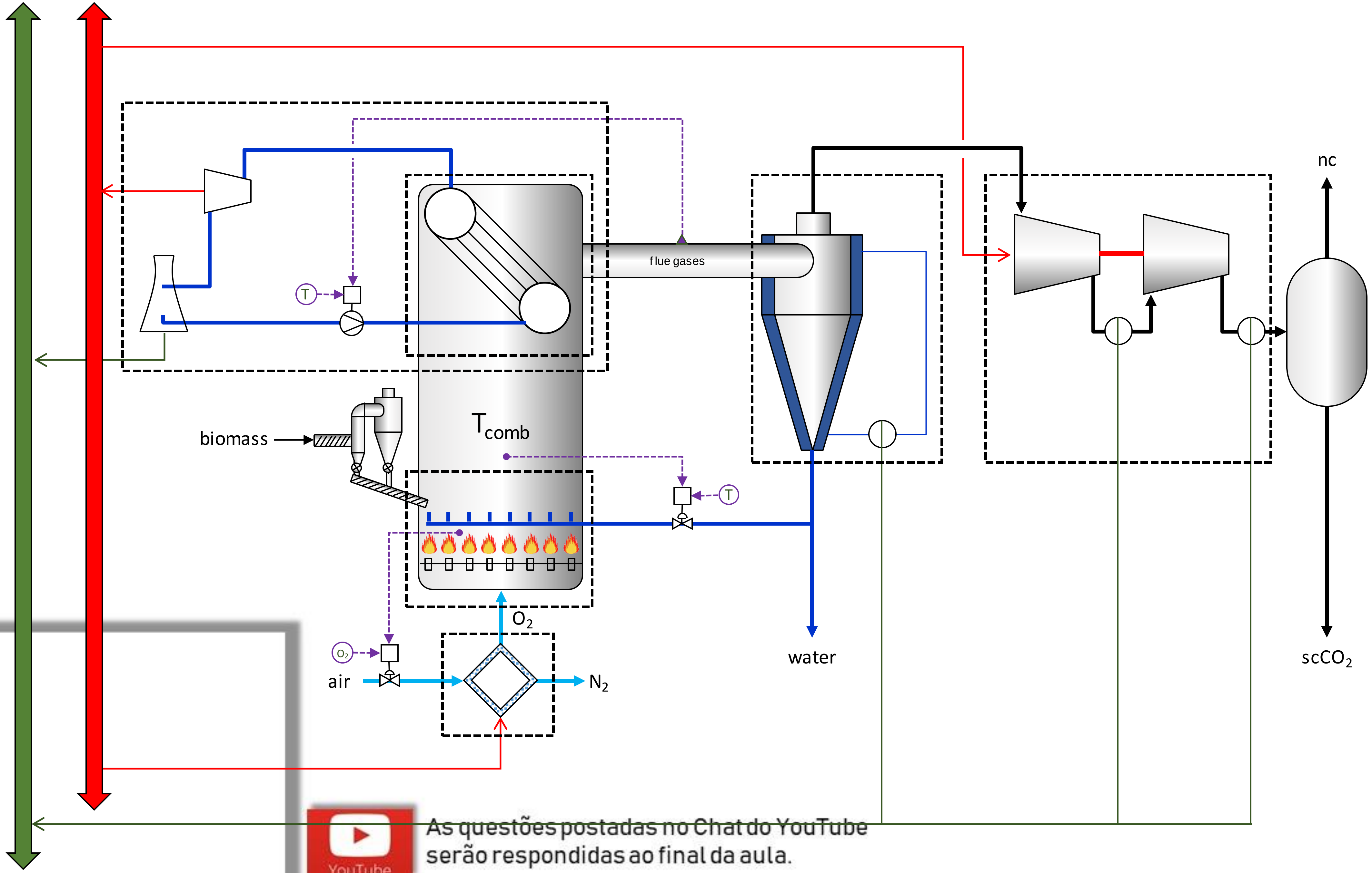
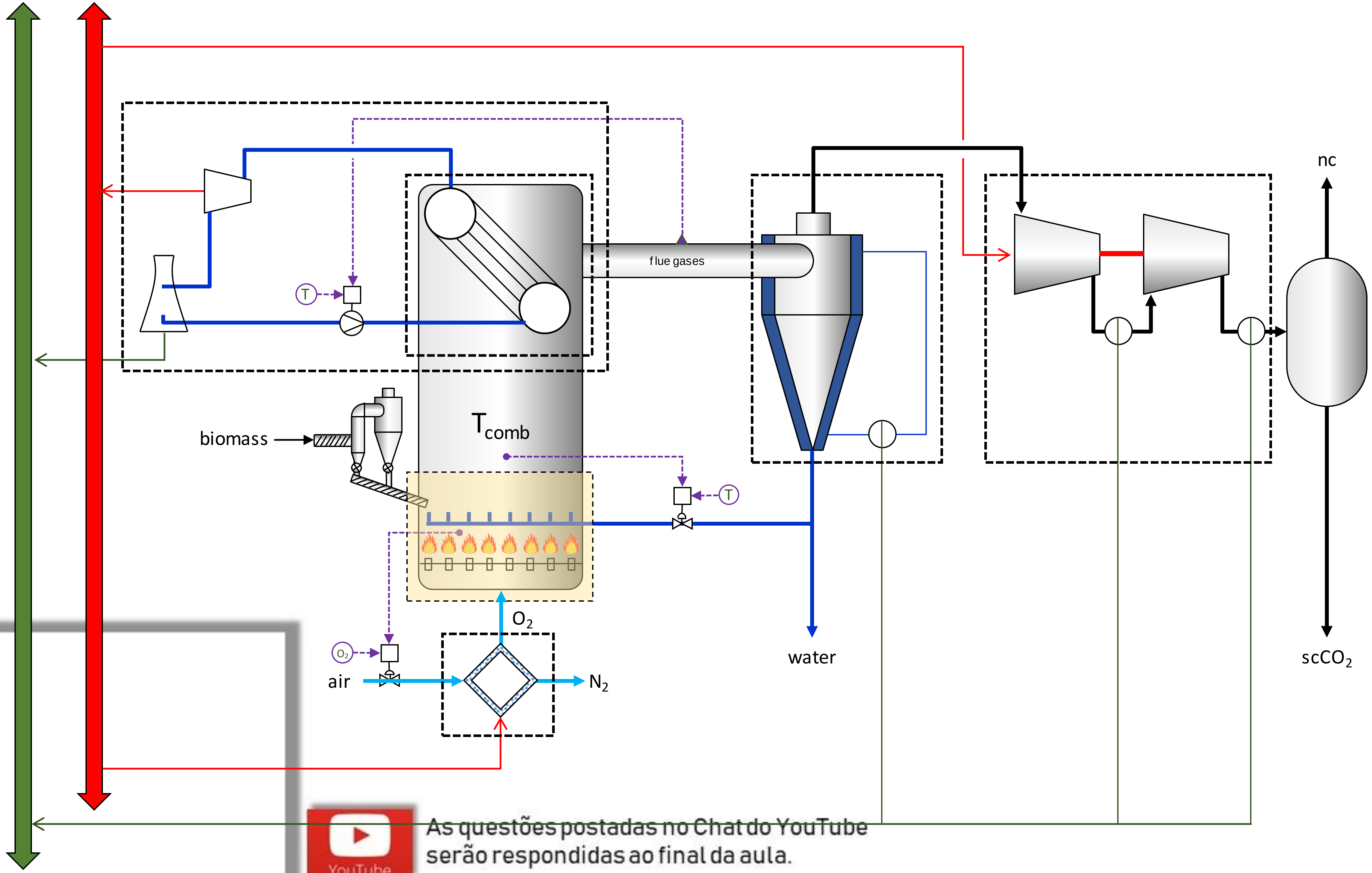
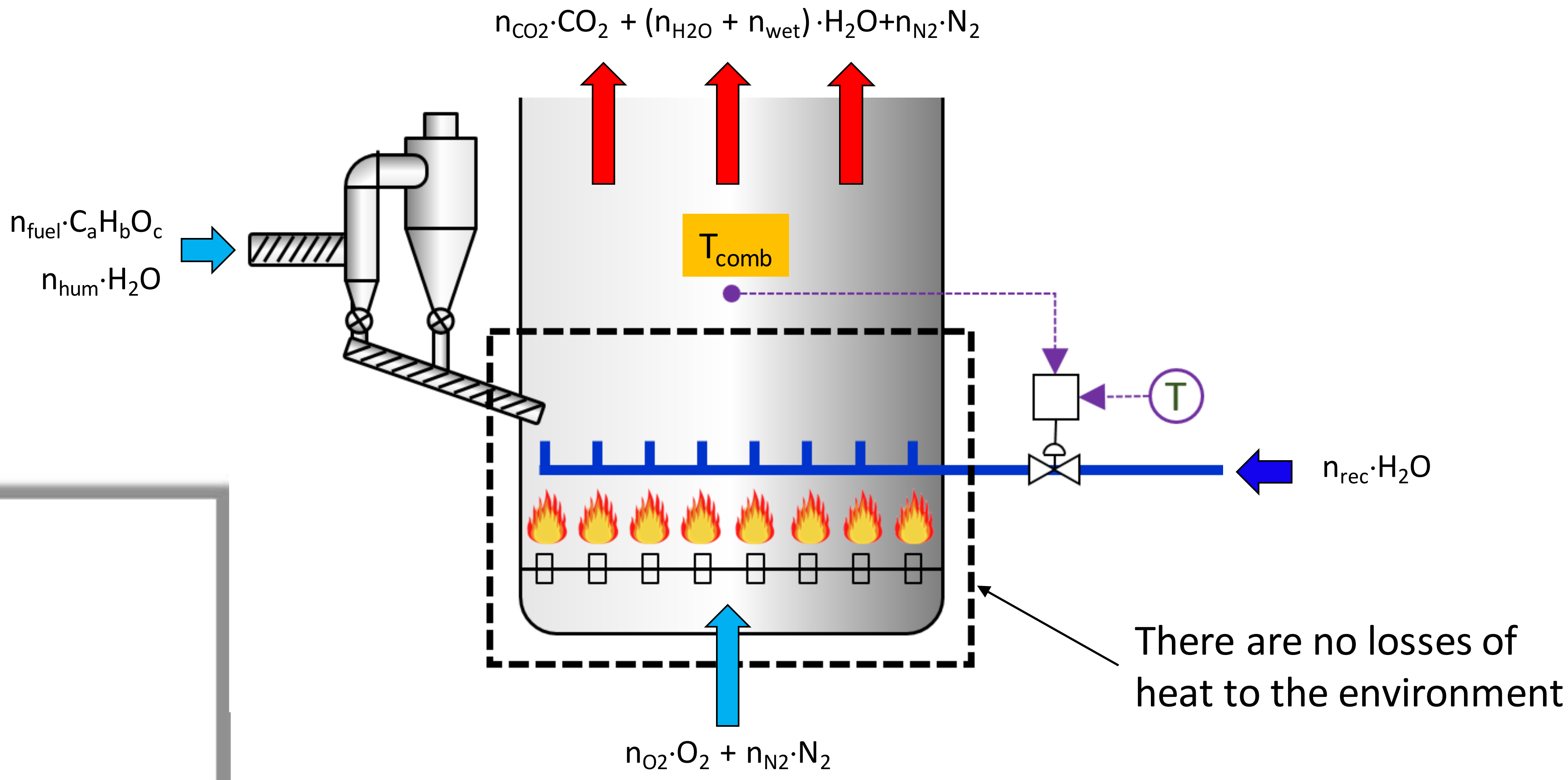

flue gases
nc
T
T
T_{comb}
biomass
T
O_2
O_2
air
N_2
water
$scCO_2$

Biomass Combustion Analysis


nc
flue gases
T
T
T_{comb}
biomass
O_2
O_2
air
N_2
water
$scCO_2$

$$n_{fuel}\cdot C_aH_bO_c + n_{O2}\cdot O_2 + n_{N2}\cdot N_2 + n_{wat}\cdot H_2O \rightarrow n_{CO2}\cdot CO_2 + (n_{H2O}+n_{wat})\cdot H_2O + n_{N2}\cdot N_2$$



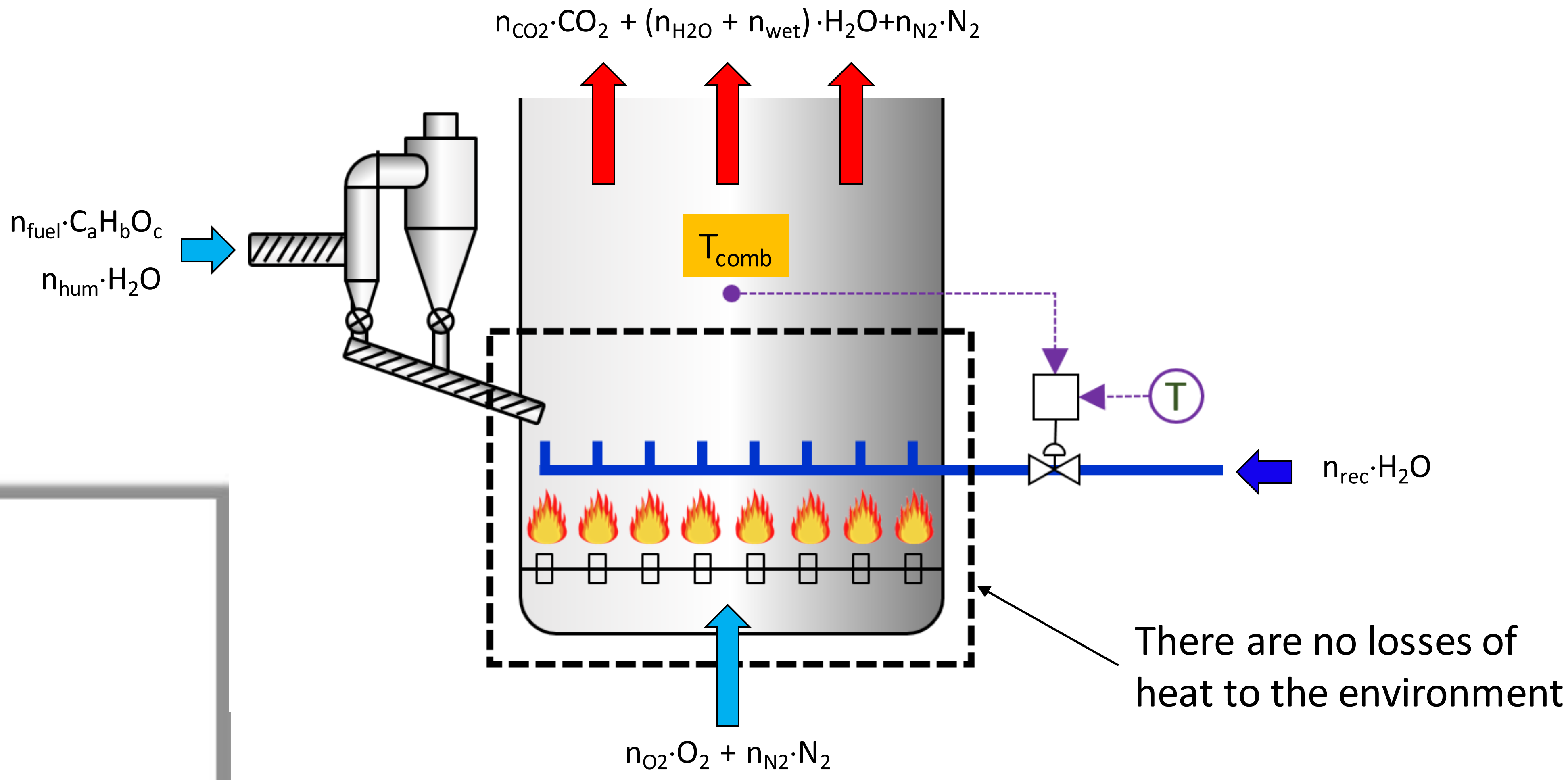
$n_{wat} = n_{hum} + n_{rec}$

adiabático

H: the reaction is supposed to be complete

$$n_{fuel} \cdot C_aH_bO_c + n_{O2} \cdot O_2 + n_{N2} \cdot N_2 + n_{wat} \cdot H_2O \rightarrow n_{CO2} \cdot CO_2 + (n_{H2O} + n_{wat}) \cdot H_2O + n_{N2} \cdot N_2$$

25°C | T_{comb}



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$$n_{fuel}\cdot C_aH_bO_c + n_{O2}\cdot O_2 + n_{N2}\cdot N_2 + n_{wat}\cdot H_2O \rightarrow n_{CO2}\cdot CO_2 + (n_{H2O}+n_{wat})\cdot H_2O + n_{N2}\cdot N_2$$

25°C | T_{comb}

Obs: Reaction Stoichiometry

$$a\cdot n_{fuel} = 1\cdot n_{CO2}$$

$$b\cdot n_{fuel} = 2\cdot n_{H2O}$$

$$c\cdot n_{fuel} + 2\cdot n_{O2} = 2\cdot n_{CO2} + 1\cdot n_{H2O}$$

$$n_{CO2} = a\cdot n_{fuel}$$

$$n_{H2O} = b\cdot n_{fuel}/2$$

$$n_{O2} = n_{fuel}\cdot(a+b/4 - c/2)$$

Obs: biomass humidity

$$n_{wat} = n_{rec} + n_{hum}$$

$$n_{hum} = w_{fuel}\cdot n_{fuel}$$

n_{rec} = recirculated water...

adiabático

$$n_{fuel}\cdot C_aH_bO_c + n_{O2}\cdot O_2 + n_{N2}\cdot N_2 + n_{wat}\cdot H_2O \rightarrow n_{CO2}\cdot CO_2 + (n_{H2O}+n_{wat})\cdot H_2O + n_{N2}\cdot N_2$$

25°C | T_{comb}

$$\cancel{Q} - \cancel{W} = \sum_{prod} n_k h_k(P_k, T_k) - \sum_{reag} n_k h_k(P_k, T_k)$$

adiabático W=0

$$\sum_{prod} n_k h_k(P_k, T_k) = \sum_{reag} n_k h_k(P_k, T_k)$$

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adiabático

$$n_{fuel}\cdot C_aH_bO_c + n_{O2}\cdot O_2 + n_{N2}\cdot N_2 + n_{wat}\cdot H_2O \rightarrow n_{CO2}\cdot CO_2 + (n_{H2O}+n_{wat})\cdot H_2O + n_{N2}\cdot N_2$$

25°C | T_{comb}

$$\cancel{Q} - \cancel{W} = \sum_{prod} n_k h_k(P_k, T_k) - \sum_{reag} n_k h_k(P_k, T_k)$$

adiabático W=0

The generated thermal energy is fully absorbed by the combustion products, which raises T_{comb}

$$\sum_{prod} n_k h_k(P_k, T_k) = \sum_{reag} n_k h_k(P_k, T_k)$$

Enthalpies of different substances may have different reference states (h=0) and, therefore, it is necessary to normalize them.

adiabático

$$n_{fuel}\cdot C_aH_bO_c + n_{O2}\cdot O_2 + n_{N2}\cdot N_2 + n_{wat}\cdot H_2O \rightarrow n_{CO2}\cdot CO_2 + (n_{H2O}+n_{wat})\cdot H_2O + n_{N2}\cdot N_2$$

25°C | T_{comb}

$$\cancel{Q} - \cancel{W} = \sum_{prod} n_k h_k(P_k, T_k) - \sum_{reag} n_k h_k(P_k, T_k)$$

adiabático W=0

The generated thermal energy is fully absorbed by the combustion products, which raises T_{comb}

$$\sum_{prod} n_k h_k(P_k, T_k) = \sum_{reag} n_k h_k(P_k, T_k)$$

Enthalpies of different substances may have different reference states (h=0) and, therefore, it is necessary to normalize them.

$$h(P,T) = \underbrace{h^0(P^0, T^0)}_{\text{entalpia de formação}} + \underbrace{\left[h^\theta(P,T) - h^\theta(P^0, T^0)\right]}_{\text{entalpias em um referencial arbitrário}}$$

$\Delta H_{reação}$

$$n_{fuel} \cdot C_aH_bO_c + n_{O2} \cdot O_2 + n_{N2} \cdot N_2 + n_{wat} \cdot H_2O \rightarrow n_{CO2} \cdot CO_2 + (n_{H2O} + n_{wat}) \cdot H_2O + n_{N2} \cdot N_2$$

25°C | 25°C

Germain Henri Hess

Hess Law

$\equiv$

$\Delta H_{sensível}$

$$\Delta H_{reação} = \Delta H_{sensível}$$

$$n_{CO2} \cdot CO_2 + n_{H2O} \cdot H_2O + n_{rec} \cdot H_2O + n_{N2} \cdot N_2$$

T_{comb}

$$h(P,T) = \underbrace{h^0(P^0,T^0)}_{\text{entalpia de formação}} + \underbrace{\left[h^\theta(P,T) - h^\theta(P^0,T^0)\right]}_{\text{entalpias em um referencial arbitrário}}$$

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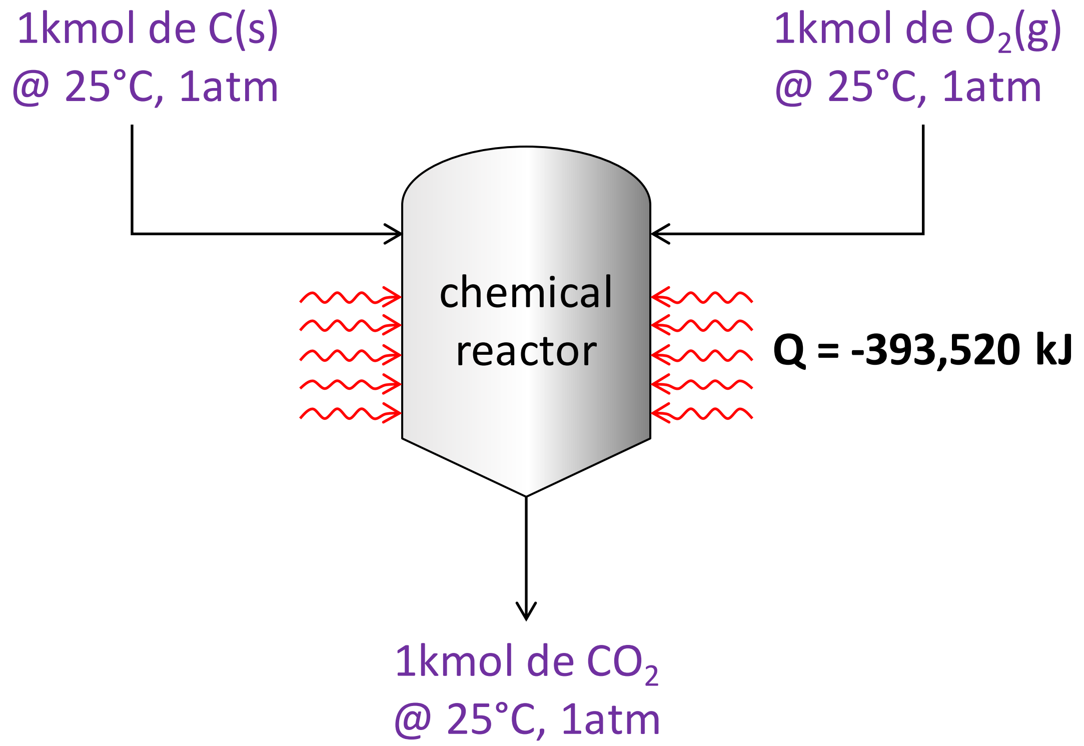
Enthalpy of formation of a substance is the heat absorbed during its formation reaction from the corresponding constituent elements, products and reagents being at a reference state "0" (25°C, 1bar)



$$H_{2,gas} + 0.5O_{2,gas} \rightarrow H_2O_{liq} + (-285.8kJ)$$

$$C_{solid} + 0.5O_{2,gas} \rightarrow CO_{gas} + (-110.5kJ)$$

$$H_{2,gas} + 0.5O_{2,gas} \rightarrow H_2O_{gas} + (-241.8kJ)$$

Species	Phase	Chemical formula	ΔH_f^o (kJ/mol)
Water	Liquid	H_2O	−285.8
Carbon	Gas	C	716.67
Carbon dioxide	Gas	CO_2	−393.509
Carbon disulfide	Gas	CS_2	116.7
Carbon monoxide	Gas	CO	−110.525
Hydrogen	Gas	H_2	0
Water	Gas	H_2O	−241.818
Hydrogen cyanide	Gas	HCN	130.5
Hydrogen chloride	Gas	HCl	−92.30
Hydrogen fluoride	Gas	HF	−273.3
Hydrogen iodide	Gas	HI	26.5
Iodine	Gas	I_2	62.438
Ammonia	Gas	NH_3	−45.90
Nitrogen dioxide	Gas	NO_2	33.2
Nitrous oxide	Gas	N_2O	82.05
Nitric oxide	Gas	NO	90.29

adiabático

$$n_{fuel} \cdot C_aH_bO_c + n_{O2} \cdot O_2 + n_{N2} \cdot N_2 + n_{wat} \cdot H_2O \rightarrow n_{CO2} \cdot CO_2 + (n_{H2O} + n_{wat}) \cdot H_2O + n_{N2} \cdot N_2$$

25°C | T_{comb}

$$\sum_{prod} n_k h_k(P_k, T_k) = \sum_{reag} n_k h_k(P_k, T_k)$$

$$n_{fuel} h_{fuel}\Big|_{25^\circ} + n_{O2} h_{O2}(P_{O2}^{reag}, 25^\circ C) + n_{N2} h_{N2}(P_{N2}^{reag}, 25^\circ C) + n_{wat} \cdot h_{H2O}\Big|_{25^\circ C} = \ldots$$

$$\ldots = n_{CO2} h_{CO2}(P_{CO2}^{prod}, T_{comb}) + (n_{H2O} + n_{wat}) \cdot h_{H2O}(P_{H2O}^{prod}, T_{comb}) + n_{N2} h_{N2}(P_{N2}^{prod}, T_{comb})$$

adiabático

$$n_{fuel}\cdot C_aH_bO_c + n_{O2}\cdot O_2 + n_{N2}\cdot N_2 + n_{wat}\cdot H_2O \rightarrow n_{CO2}\cdot CO_2 + (n_{H2O}+n_{wat})\cdot H_2O + n_{N2}\cdot N_2$$

25°C | T_{comb}

$$\sum_{prod} n_k h_k (P_k, T_k) = \sum_{reag} n_k h_k (P_k, T_k)$$

$$\underset{\uparrow\ \text{solid}}{n_{fuel}} h_{fuel}\big|_{25^\circ} + \underset{\uparrow\ \text{gas}}{n_{O2}} h_{O2}(P_{O2}^{reag}, 25^\circ C) + \underset{\uparrow\ \text{gas}}{n_{N2}} h_{N2}(P_{N2}^{reag}, 25^\circ C) + \underset{\uparrow\ \text{liquid}}{n_{wat}} \cdot h_{H2O}\big|_{25^\circ C} = \ldots$$

$$\ldots = \underset{\uparrow\ \text{gas}}{n_{CO2}} h_{CO2}(P_{CO2}^{prod}, T_{comb}) + (\underset{\uparrow\ \text{gas}}{n_{H2O}} + \underset{\uparrow\ \text{gas}}{n_{wat}}) \cdot h_{H2O}(P_{H2O}^{prod}, T_{comb}) + \underset{\uparrow\ \text{gas}}{n_{N2}} h_{N2}(P_{N2}^{prod}, T_{comb})$$

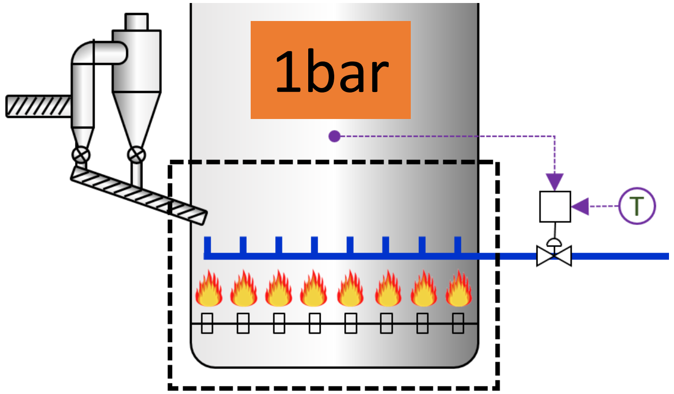
$$\Rightarrow \quad P = \left[P_{O2} + P_{N2} + P_{H2O}\right]_{reag} = \left[P_{CO2} + P_{H2O} + P_{N2}\right]_{prod}$$

$$n_{fuel} h_{fuel}\big|_{25^\circ} + n_{O2} h_{O2}(P_{O2}^{reag}, 25^\circ C) + n_{N2} h_{N2}(P_{N2}^{reag}, 25^\circ C) + n_{wat} \cdot h_{H2O}\big|_{25^\circ C} = \ldots$$

$$\ldots = n_{CO2} h_{CO2}(P_{CO2}^{prod}, T_{comb}) + (n_{H2O} + n_{wat}) \cdot h_{H2O}(P_{H2O}^{prod}, T_{comb}) + n_{N2} h_{N2}(P_{N2}^{prod}, T_{comb})$$

$$P_{N2} = \frac{n_{N2}}{n_{O2} + n_{N2}} \cdot P$$

$$P_{O2} = \frac{n_{O2}}{n_{O2} + n_{N2}} \cdot P$$



$$P_{CO2} = \frac{n_{CO2}}{n_{CO2} + n_{H2O} + \boxed{n_{wat}} + n_{N2}} \cdot P$$

$$P_{H2O} = \frac{n_{H2O} + n_{wat}}{n_{CO2} + n_{H2O} + \boxed{n_{wat}} + n_{N2}} \cdot P$$

$$P_{N2} = \frac{n_{N2}}{n_{CO2} + n_{H2O} + \boxed{n_{wat}} + n_{N2}} \cdot P$$

$$n_{fuel} h_{fuel}\big|_{25^\circ} + n_{O2} h_{O2}(P_{O2}^{reag}, 25^\circ C) + n_{N2} h_{N2}(P_{N2}^{reag}, 25^\circ C) + n_{wat} \cdot h_{H2O}\big|_{25^\circ C} = \ldots$$

$$= n_{CO2} h_{CO2}\left[P_{CO2}^{prod}\boxed{(n_{wat})}, T_{comb}\right] + (n_{H2O} + n_{wat}) \cdot h_{H2O}\left[P_{H2O}^{prod}\boxed{(n_{wat})}, T_{comb}\right] + n_{N2} h_{N2}\left[P_{N2}^{prod}\boxed{(n_{wat})}, T_{comb}\right]$$

However…

… for an ideal gas enthalpy is strongly dependent on temperature and is weakly influenced by pressure.

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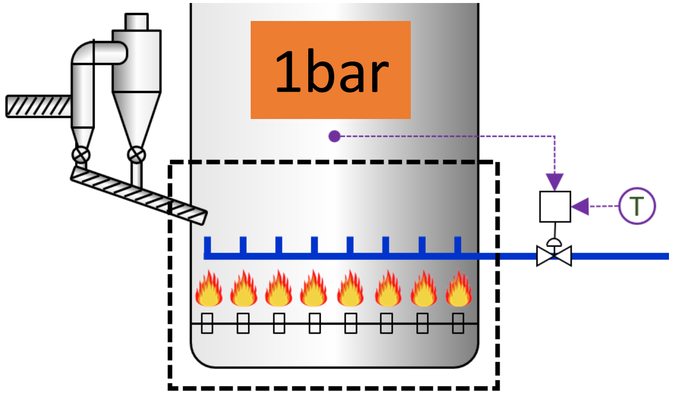
$$n_{fuel}h_{fuel}\big|_{25^\circ} + n_{O2}h_{O2}(P_{O2}^{reag},25^\circ C) + n_{N2}h_{N2}(P_{N2}^{reag},25^\circ C) + n_{wat}\cdot h_{H2O}\big|_{25^\circ C} = \dots$$

$$\dots = n_{CO2}h_{CO2}(P_{CO2}^{prod},T_{comb}) + (n_{H2O}+n_{wat})\cdot h_{H2O}(P_{H2O}^{prod},T_{comb}) + n_{N2}h_{N2}(P_{N2}^{prod},T_{comb})$$

$$P_{N2} = \frac{n_{N2}}{n_{O2}+n_{N2}}\cdot P$$

$$P_{O2} = \frac{n_{O2}}{n_{O2}+n_{N2}}\cdot P$$



$$P_{CO2} = \frac{n_{CO2}}{n_{CO2}+n_{H2O}+n_{wat}+n_{N2}}\cdot P$$

$$P_{H2O} = \frac{n_{H2O}+n_{wat}}{n_{CO2}+n_{H2O}+n_{wat}+n_{N2}}\cdot P$$

$$P_{N2} = \frac{n_{N2}}{n_{CO2}+n_{H2O}+n_{wat}+n_{N2}}\cdot P$$

enthalpy of CO_2 in kJ/kg		pressure (bar)								
		2	1,8	1,6	1,4	1,2	1	0,8	0,6	0,4
temperature (°C)	200	667,9	667,9	668,0	668,1	668,2	668,2	668,3	668,4	668,4
	180	648,0	648,1	648,2	648,3	648,4	648,4	648,5	648,6	648,7
	160	628,5	628,6	628,7	628,8	628,8	628,9	629,0	629,1	629,2
	140	609,3	609,3	609,4	609,5	609,6	609,7	609,8	609,9	610,0
	120	590,3	590,4	590,5	590,6	590,7	590,8	590,9	591,0	591,1
	100	571,7	571,8	571,9	572,0	572,2	572,3	572,4	572,5	572,6
	80	553,4	553,6	553,7	553,8	553,9	554,1	554,2	554,3	554,5
	60	535,5	535,6	535,8	535,9	536,1	536,2	536,4	536,5	536,6
	40	517,9	518,1	518,2	518,4	518,6	518,7	518,9	519,1	519,2

$$h(P,T) \cong C_P(T)\cdot(T - T_{ref}), \quad \forall P$$

$$h(P,T) \cong \overline{C}_P\cdot(T - T_{ref}), \quad \forall P$$

Calculations for $C_4H_{10}O_4$ @ 0% humidity

As questões postadas no Chat do YouTube
serão respondidas ao final da aula.

$$n_{wat} = \cancel{n_{hum}} + n_{rec}$$

adiabático @ 1bar

$$1 \cdot C_4H_{10}O_4 + 4.5 \cdot O_2 + n_{rec} \cdot H_2O \rightarrow 4 \cdot CO_2 + (5+n_{rec}) \cdot H_2O$$

25°C | T_{comb}

$$\sum_{prod} n_k h_k (P_k, T_k) = \sum_{reag} n_k h_k (P_k, T_k)$$

$$1 \cdot h_{fuel}\big|_{25^\circ} + 4.5 \cdot h_{O2}(25^\circ C) + n_{rec} \cdot h_{H2O}(25^\circ C) = 4 \cdot h_{CO2}(T_{comb}) + 5 \cdot h_{H2O}(T_{comb}) + n_{rec} \cdot h_{H2O}(T_{comb})$$

$$n_{wat} = \cancel{n_{hum}} + n_{rec}$$

adiabático @ 1bar

$$1\cdot C_4H_{10}O_4 + 4.5\cdot O_2 + n_{rec}\cdot H_2O \rightarrow 4\cdot CO_2 + (5+n_{rec})\cdot H_2O$$

25°C | T_{comb}

$$\sum_{prod} n_k h_k(P_k, T_k) = \sum_{reag} n_k h_k(P_k, T_k)$$

$$1\cdot \boxed{h_{fuel}\big|_{25^\circ}} + 4.5\cdot h_{O2}(25^\circ C) + n_{rec}\cdot h_{H2O}(25^\circ C) = 4\cdot h_{CO2}(T_{comb}) + 5\cdot h_{H2O}(T_{comb}) + n_{rec}\cdot h_{H2O}(T_{comb})$$

$$h_{fuel} = h^0_{fuel}\Big|_{25^\circ C} + \Delta h_{sensible}\Big|_{25^\circ C}^{25^\circ C} \rightarrow h_{fuel} = -1874.4 kJ/mol\Big|_{25^\circ C}$$

$$n_{wat} = \cancel{n_{hum}} + n_{rec}$$

adiabático @ 1bar

$$1 \cdot C_4H_{10}O_4 + 4.5 \cdot O_2 + n_{rec} \cdot H_2O \rightarrow 4 \cdot CO_2 + (5+n_{rec}) \cdot H_2O$$

25°C | T_{comb}

$$\sum_{prod} n_k h_k (P_k, T_k) = \sum_{reag} n_k h_k (P_k, T_k)$$

$$1 \cdot \boxed{h_{fuel}\big|_{25^\circ}} + 4.5 \cdot h_{O2}(25^\circ C) + n_{rec} \cdot h_{H2O}(25^\circ C) = 4 \cdot h_{CO2}(T_{comb}) + 5 \cdot h_{H2O}(T_{comb}) + n_{rec} \cdot h_{H2O}(T_{comb})$$

$$h_{fuel} = h^0_{fuel}\Big|_{25^\circ C} + \cancel{\Delta h_{sensible}}\Big|_{25^\circ C}^{25^\circ C} \rightarrow h_{fuel} = -1874.4 kJ/mol\Big|_{25^\circ C}$$

$$n_{wat} = \cancel{n_{hum}} + n_{rec}$$

adiabático @ 1bar

$$1 \cdot C_4H_{10}O_4 + 4.5 \cdot O_2 + n_{rec} \cdot H_2O \rightarrow 4 \cdot CO_2 + (5 + n_{rec}) \cdot H_2O$$

25°C | T_{comb}

$$\sum_{prod} n_k h_k(P_k, T_k) = \sum_{reag} n_k h_k(P_k, T_k)$$

$$1 \cdot h_{fuel}\big|_{25^\circ} + 4.5 \cdot \boxed{h_{O2}(25^\circ C)} + n_{rec} \cdot h_{H2O}(25^\circ C) = 4 \cdot h_{CO2}(T_{comb}) + 5 \cdot h_{H2O}(T_{comb}) + n_{rec} \cdot h_{H2O}(T_{comb})$$

$$h_{O2} = h^0_{O2}\big|_{25^\circ C} + \cancel{\Delta h_{sensible}\big|_{25^\circ C}^{25^\circ C}} \rightarrow h_{O2} = 0$$

$$n_{wat} = \cancel{n_{hum}} + n_{rec}$$

adiabático @ 1bar

$$1 \cdot C_4H_{10}O_4 + 4.5 \cdot O_2 + n_{rec} \cdot H_2O \rightarrow 4 \cdot CO_2 + (5+n_{rec}) \cdot H_2O$$

25°C | T_{comb}

$$\sum_{prod} n_k h_k (P_k, T_k) = \sum_{reag} n_k h_k (P_k, T_k)$$

$$1 \cdot h_{fuel}\Big|_{25^\circ} + 4.5 \cdot h_{O2}(25^\circ C) + n_{rec} \cdot \boxed{h_{H2O}(25^\circ C)} = 4 \cdot h_{CO2}(T_{comb}) + 5 \cdot h_{H2O}(T_{comb}) + n_{rec} \cdot h_{H2O}(T_{comb})$$

$$h_{H2O} = h^0_{H2O}\Big|_{25^\circ C} + \cancel{\Delta h_{sensible}\Big|_{25^\circ C}^{25^\circ C}} \rightarrow h_{H2O} = -285.8 kJ/mol\Big|_{25^\circ C}$$

$$n_{wat} = \cancel{n_{hum}} + n_{rec}$$

adiabático @ 1bar

$$1 \cdot C_4H_{10}O_4 + 4.5 \cdot O_2 + n_{rec} \cdot H_2O \rightarrow 4 \cdot CO_2 + (5+n_{rec}) \cdot H_2O$$

25°C | T_{comb}

$$\sum_{prod} n_k h_k(P_k, T_k) = \sum_{reag} n_k h_k(P_k, T_k)$$

$$1 \cdot h_{fuel}\Big|_{25^\circ} + 4.5 \cdot h_{O2}(25^\circ C) + n_{rec} \cdot h_{H2O}(25^\circ C) = 4 \cdot \boxed{h_{CO2}(T_{comb})} + 5 \cdot h_{H2O}(T_{comb}) + n_{rec} \cdot h_{H2O}(T_{comb})$$

$$h_{CO2} = h^0_{CO2}\Big|_{25^\circ C} + \Delta h_{sensible}\Big|_{25^\circ C}^{T_{comb}} \rightarrow h_{CO2} = \left[-393.5\Big|_{25^\circ C} + C_P(T_{comb}) \cdot 10^{-3} \cdot (T_{comb} - 25)\right] \ kJ/mol$$

$$C_P(T) = 0.0123 \cdot T + 43.738$$

0.5 – 0.8 bar / 200 – 1400 °C

$$n_{wat} = \cancel{n_{hum}} + n_{rec}$$

adiabático @ 1bar

$$1 \cdot C_4H_{10}O_4 + 4.5 \cdot O_2 + n_{rec} \cdot H_2O \rightarrow 4 \cdot CO_2 + (5 + n_{rec}) \cdot H_2O$$

25°C | T_{comb}

$$\sum_{prod} n_k h_k (P_k, T_k) = \sum_{reag} n_k h_k (P_k, T_k)$$

$$1 \cdot h_{fuel}\Big|_{25^\circ} + 4.5 \cdot h_{O2}(25^\circ C) + n_{rec} \cdot h_{H2O}(25^\circ C) = 4 \cdot h_{CO2}(T_{comb}) + 5 \cdot \boxed{h_{H2O}(T_{comb})} + n_{rec} \cdot h_{H2O}(T_{comb})$$

$$h_{H2O} = h^0_{H2O}\Big|_{25^\circ C} + \Delta h_{sensible}\Big|_{25^\circ C}^{T_{comb}} \rightarrow h_{H2O} = \left[-241.8\Big|_{25^\circ C} + C_P(T_{comb}) \cdot 10^{-3} \cdot (T_{comb} - 25)\right] \text{ kJ/mol}$$

$$C_P(T) = 0.0115 \cdot T + 32.907$$

0.5 – 0.8 bar / 200 – 1400 °C

$$n_{wat} = \cancel{n_{hum}} + n_{rec}$$

adiabático @ 1bar

$$1 \cdot C_4H_{10}O_4 + 4.5 \cdot O_2 + n_{rec} \cdot H_2O \rightarrow 4 \cdot CO_2 + (5+n_{rec}) \cdot H_2O$$

25°C | T_{comb}

$$\sum_{prod} n_k h_k (P_k, T_k) = \sum_{reag} n_k h_k (P_k, T_k)$$

$$1 \cdot h_{fuel}\big|_{25°} + 4.5 \cdot h_{O2}(25°C) + n_{rec} \cdot h_{H2O}(25°C) = 4 \cdot h_{CO2}(T_{comb}) + 5 \cdot h_{H2O}(T_{comb}) + n_{rec} \cdot \boxed{h_{H2O}(T_{comb})}$$

$$h_{H2O} = h^0_{H2O}\big|_{25°C} + \Delta h_{lat}\big|_{1bar} + \Delta h_{sensible}\big|_{25°C}^{T_{comb}} \rightarrow h_{H2O} = \left[-241.8\big|_{25°C} + 40.6686 + C_P(T_{comb}) \cdot 10^{-3} \cdot (T_{comb} - 25)\right] \text{ kJ/mol}$$

$$C_P(T) = 0.0115 \cdot T + 32.907$$

0.5 – 0.8 bar / 200 – 1400 °C

$$n_{wat} = \cancel{n_{hum}} + n_{rec}$$

adiabático @ 1bar

$$1 \cdot C_4H_{10}O_4 + 4.5 \cdot O_2 + n_{rec} \cdot H_2O \rightarrow 4 \cdot CO_2 + (5+n_{rec}) \cdot H_2O$$

25°C | T_{comb}

$$\sum_{prod} n_k h_k(P_k, T_k) = \sum_{reag} n_k h_k(P_k, T_k)$$

$$\boxed{1 \cdot h_{fuel}\big|_{25^\circ} + 4.5 \cdot h_{O2}(25^\circ C) + n_{rec} \cdot h_{H2O}(25^\circ C) = 4 \cdot h_{CO2}(T_{comb}) + 5 \cdot h_{H2O}(T_{comb}) + n_{rec} \cdot h_{H2O}(T_{comb})}$$

$$1 \cdot (-1874.4) + n_{rec} \cdot (-285.8) = 4 \cdot \left[-393.5 + (0.0123 \cdot T_{comb} + 43.738) \cdot 10^{-3} \cdot (T_{comb} - 25)\right] + \ldots$$

$$\ldots + (5 + n_{rec}) \cdot \left[-241.8 + (0.0115 \cdot T_{comb} + 32.907) \cdot 10^{-3} \cdot (T_{comb} - 25)\right] + n_{rec} \cdot (+40.6686)$$

$$n_{rec} = \frac{1.83417 \cdot 10^9 - 6.73639 \cdot 10^5 \cdot T_{comb} - 2.134 \cdot 10^2 \cdot T_{comb}^2}{1.676918 \cdot 10^8 + 6.5239 \cdot 10^4 \cdot T_{comb} + 23 \cdot T_{comb}^2}$$

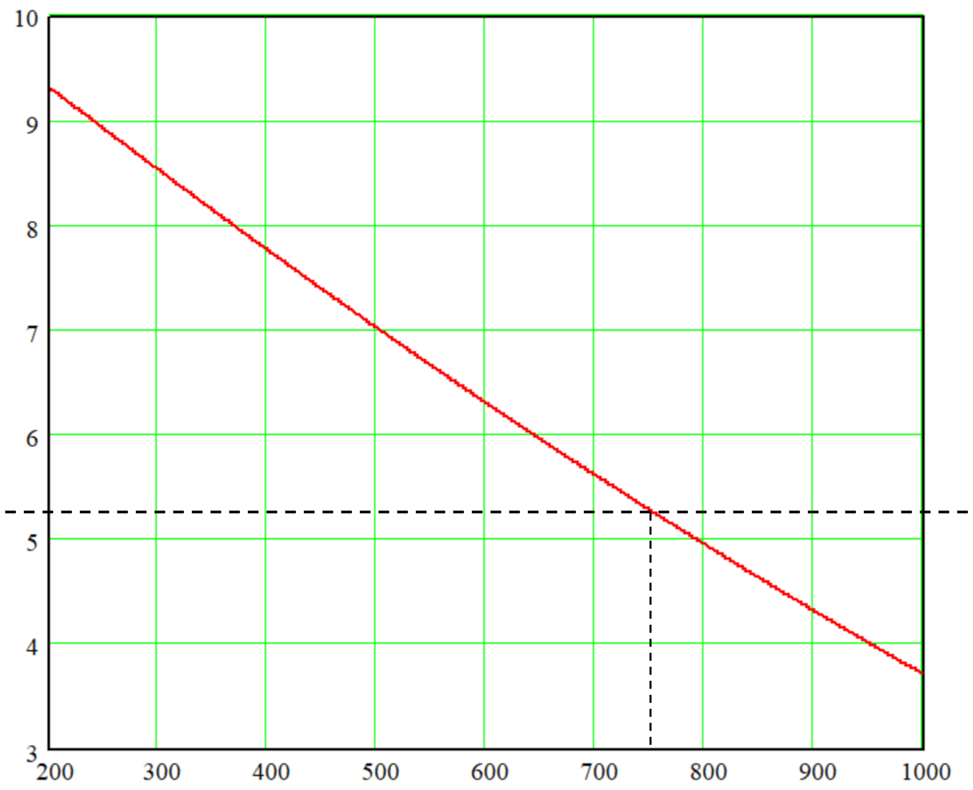
$n_{wat} = \cancel{n_{hum}} + n_{rec}$

adiabático @ 1bar

$$1 \cdot C_4H_{10}O_4 + 4.5 \cdot O_2 + n_{rec} \cdot H_2O \rightarrow 4 \cdot CO_2 + (5 + n_{rec}) \cdot H_2O$$

25°C | T_{comb}

$n_{rec}(T_{comb})$
mol/mol



T_{comb} (°C)

5.266 mol/mol

0.777 kg de H_2O / kg de $C_4H_{10}O_4$

$$5.266 \cdot \frac{18.02}{122.12} = 0.777$$

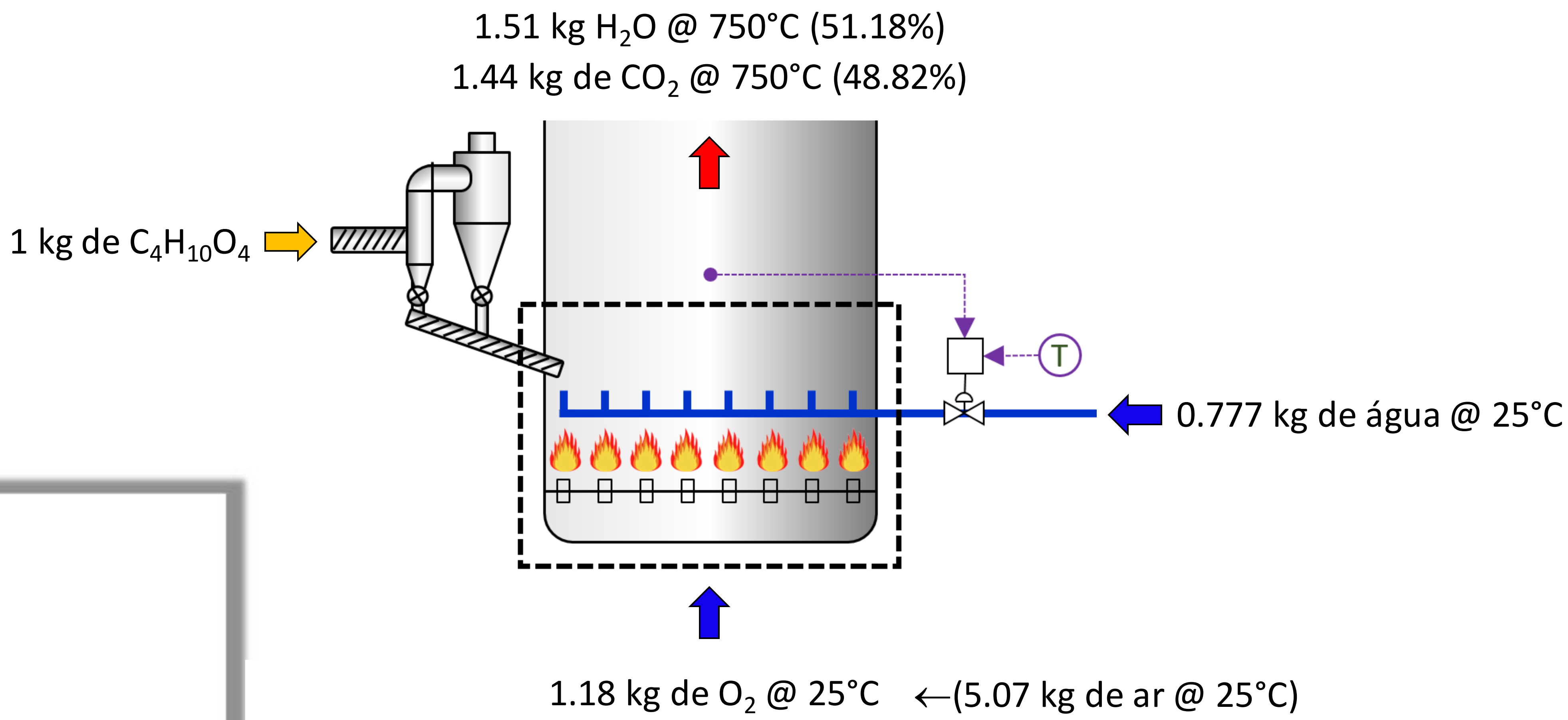
YouTube

As questões postadas no Chat do YouTube serão respondidas ao final da aula.

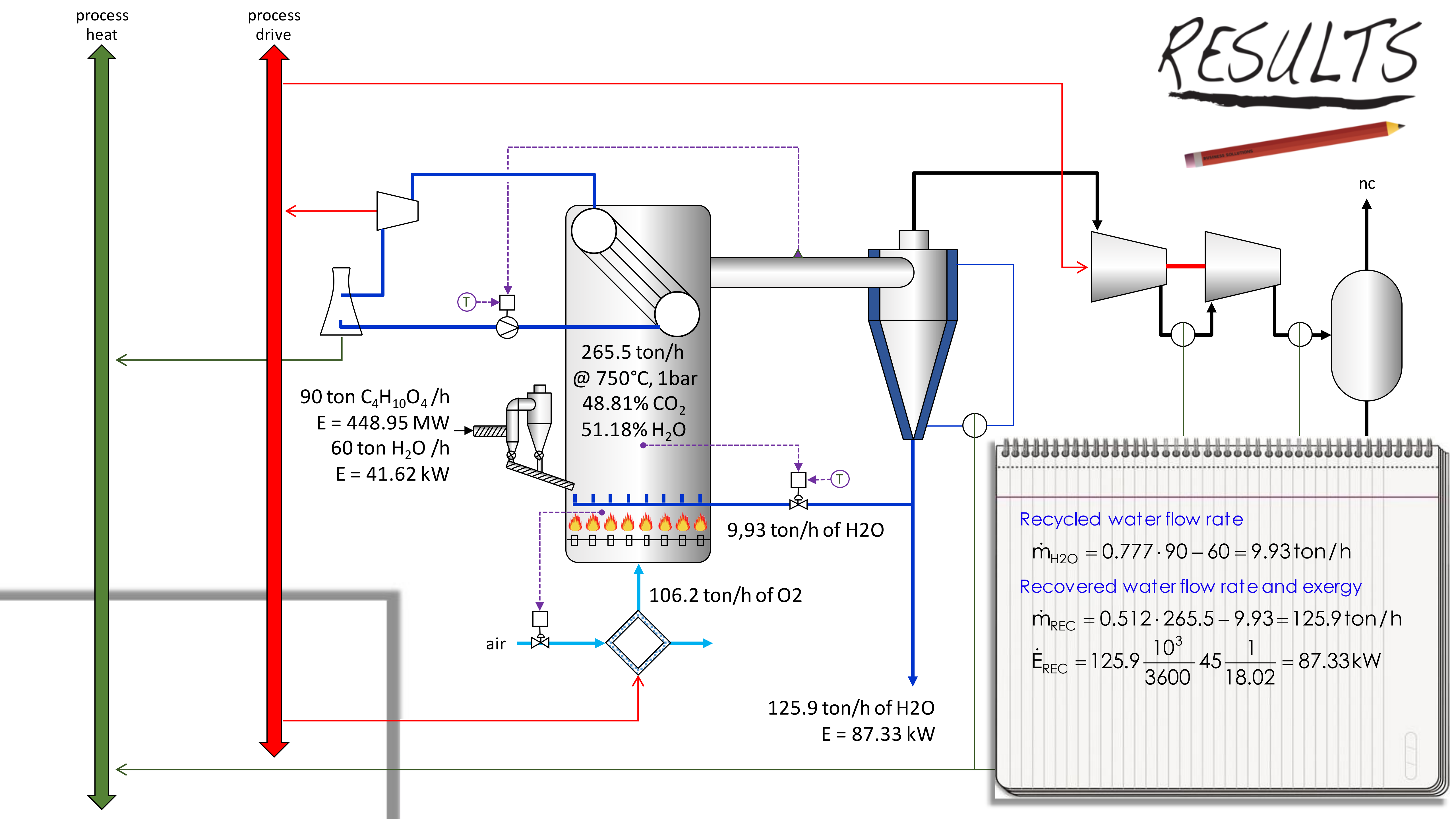
adiabático @ 1bar

$$1\cdot C_4H_{10}O_4 + 4.5\cdot O_2 + n_{rec}\cdot H_2O \rightarrow 4\cdot CO_2 + \overset{5.266}{(5+n_{rec})}\cdot H_2O$$

25°C | 750°C



RESULTS



Recycled water flow rate

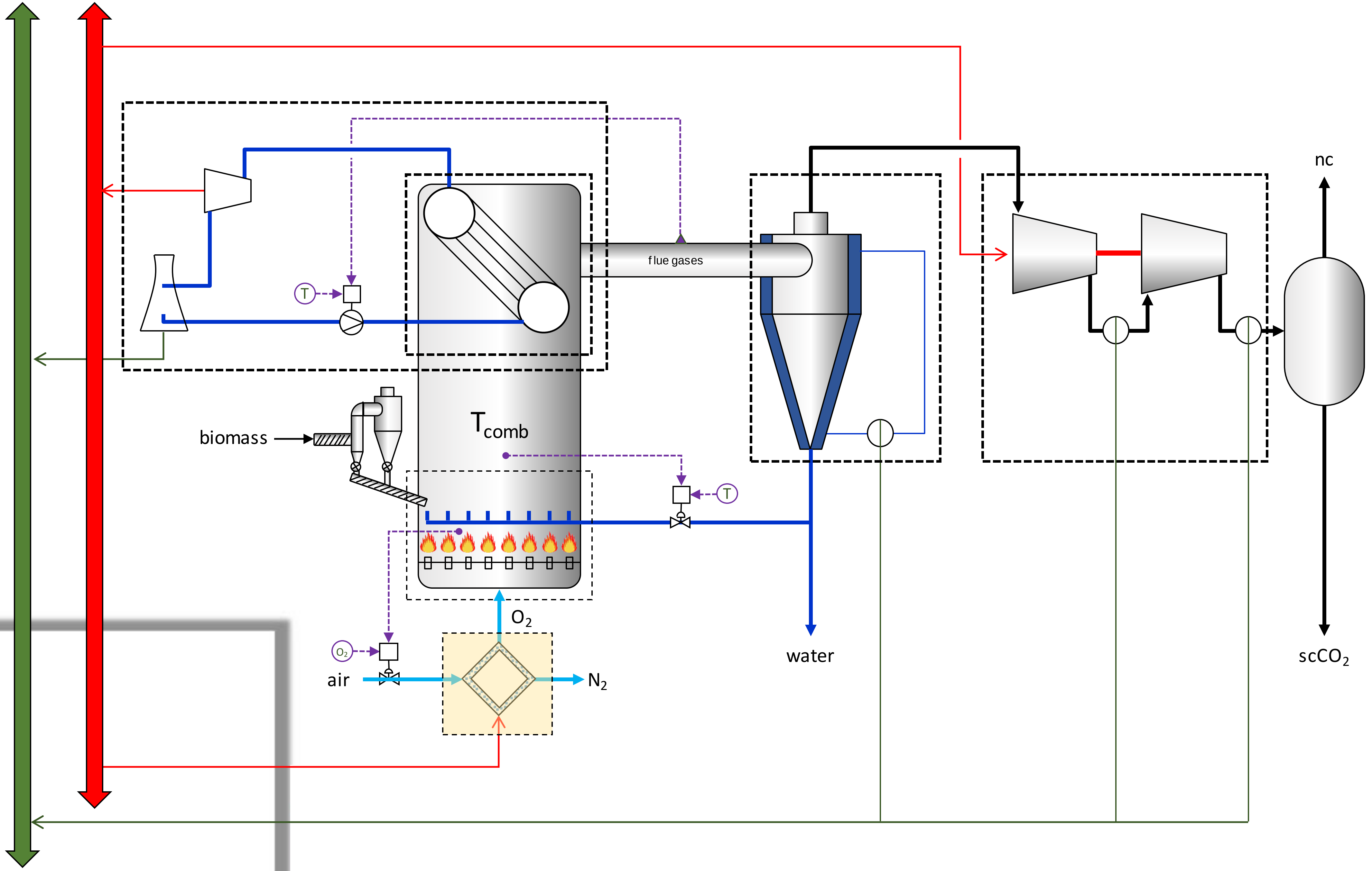
$$\dot{m}_{H2O} = 0.777 \cdot 90 - 60 = 9.93 \, \text{ton/h}$$

Recovered water flow rate and exergy

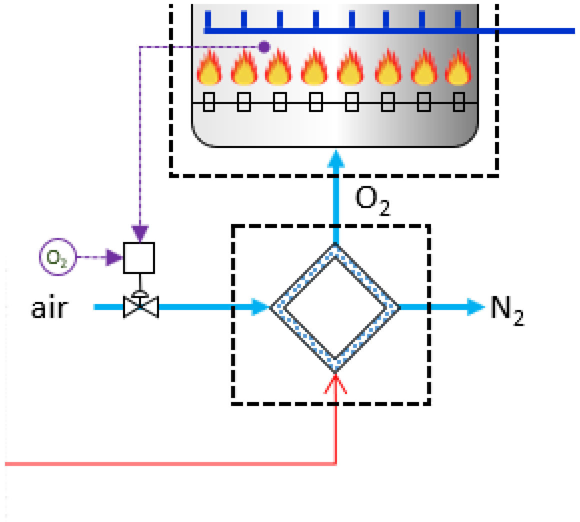
$$\dot{m}_{REC} = 0.512 \cdot 265.5 - 9.93 = 125.9 \, \text{ton/h}$$

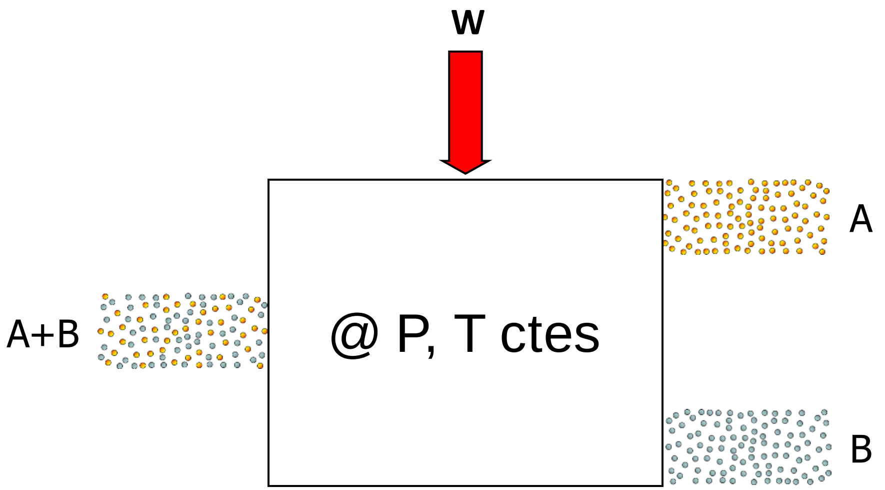
$$\dot{E}_{REC} = 125.9 \frac{10^3}{3600} 45 \frac{1}{18.02} = 87.33 \, \text{kW}$$

Oxygen Separation Process



flue gases
nc
T_{comb}
biomass
T
T
O_2
O_2
air
N_2
water
$scCO_2$

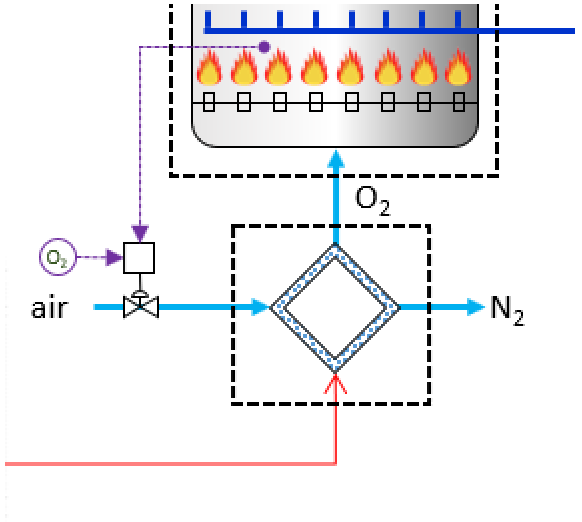


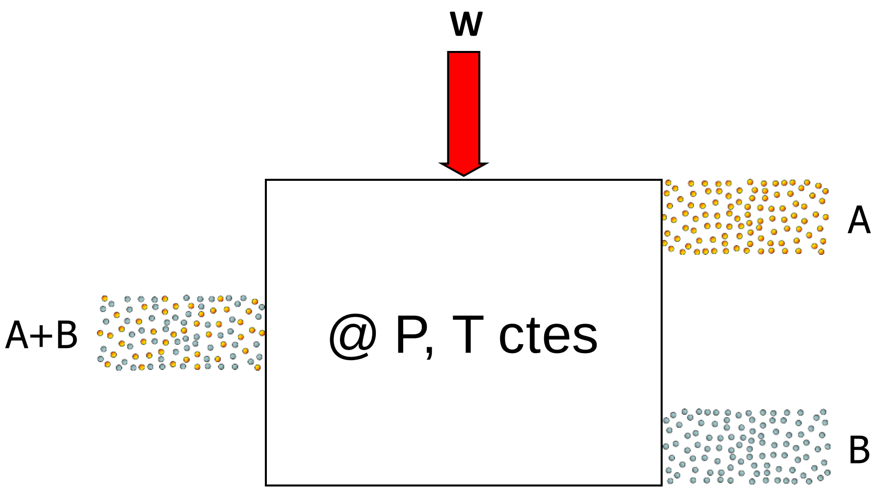


$$\sum_k \left(1-\frac{T_0}{T_k}\right)\dot{Q}_k - \left(\dot{W} - P_0\frac{dV_{vc}}{dt}\right) + \sum_{entra}\dot{m}_k x_k - \sum_{saída}\dot{m}_k x_k - \dot{X}_{dest} = \frac{dX_{vc}}{dt}$$

Obs: by convention W>0
= going out of the cv

Obs: by convention Q>0
= going into the cv



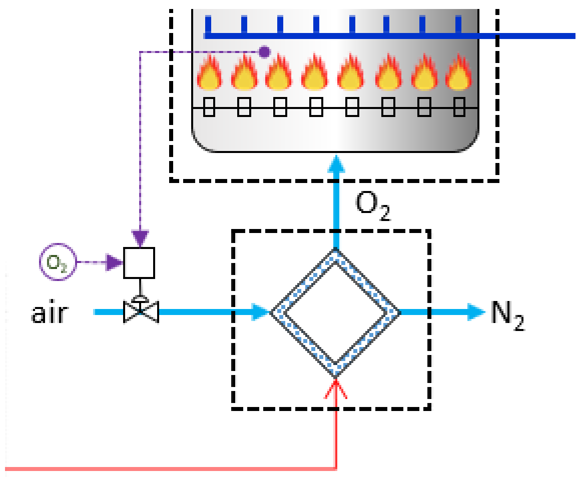


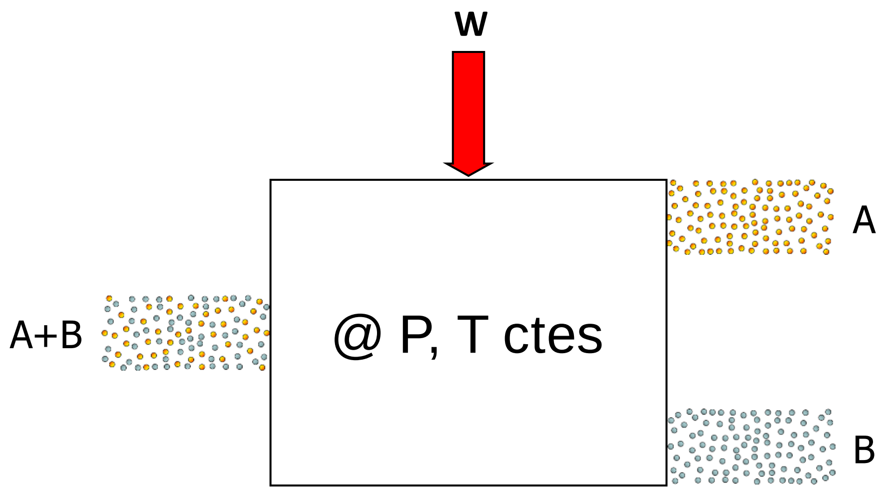
$$\sum_k \cancel{\left(1-\frac{T_0}{T_k}\right)\dot{Q}_k} - \left(\dot{W} - \cancel{P_0\frac{dV_{vc}}{dt}}\right) + \sum_{entra}\dot{m}_k x_k - \sum_{saída}\dot{m}_k x_k - \dot{X}_{dest} = \cancel{\frac{dX_{vc}}{dt}}$$

adiabatic process

permanent regime

permanent regime

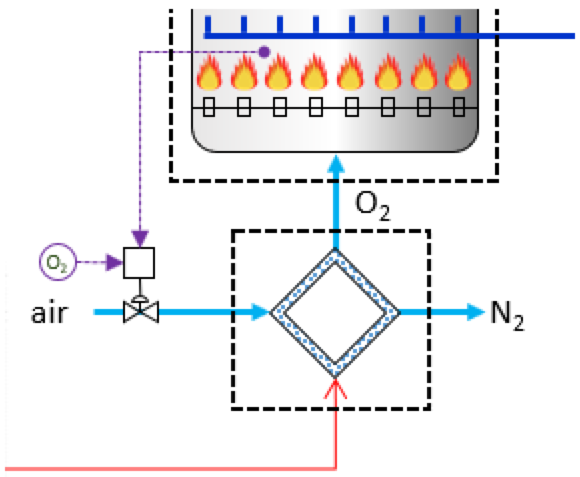


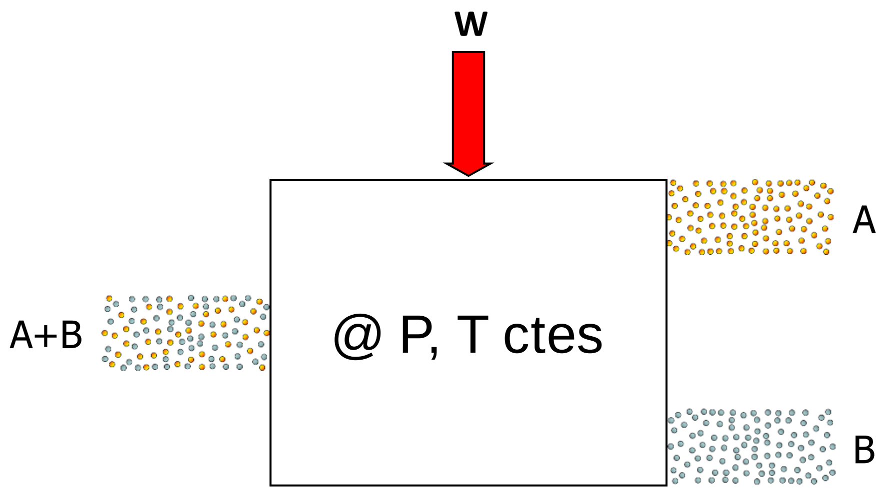


$$\sum_k \cancel{\left(1-\frac{T_0}{T_k}\right)\dot{Q}_k} - \left(\dot{W} - P_0\cancel{\frac{dV_{vc}}{dt}}\right) + \sum_{entra}\dot{m}_k x_k - \sum_{saída}\dot{m}_k x_k - \cancel{\dot{X}_{dest}} = \cancel{\frac{dX_{vc}}{dt}}$$

adiabatic process | minimum separation work | permanent regime | absence of irreversibilities | permanent regime

$$\dot{W} = \sum_{entra}\dot{m}_k x_k - \sum_{saída}\dot{m}_k x_k$$





$$\sum_k \cancel{\left(1-\frac{T_0}{T_k}\right)\dot{Q}_k} - \left(\dot{W} - \cancel{P_0\frac{dV_{vc}}{dt}}\right) + \sum_{entra}\dot{m}_k x_k - \sum_{saída}\dot{m}_k x_k - \cancel{\dot{X}_{dest}} = \cancel{\frac{dX_{vc}}{dt}}$$

adiabatic process

minimum separation work

permanent regime

absence of irreversibilities

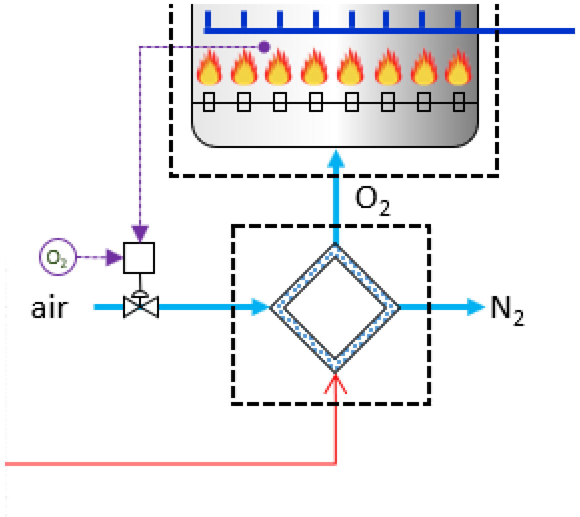
permanent regime

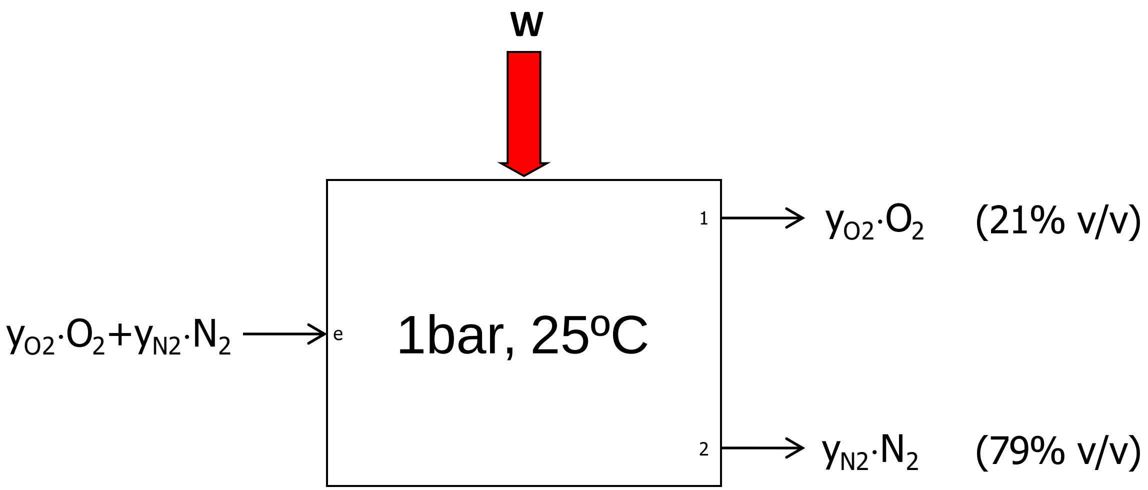
$$\dot{W} = \sum_{entra}\dot{m}_k x_k - \sum_{saída}\dot{m}_k x_k$$

$$x = \cancel{(h-h_0)} - T_0(s-s_0) + \cancel{ep} + \cancel{ec} + \cancel{eq}$$

T=cte; gases ideais

Exergy associated to the process of reduction of the level of disorder...



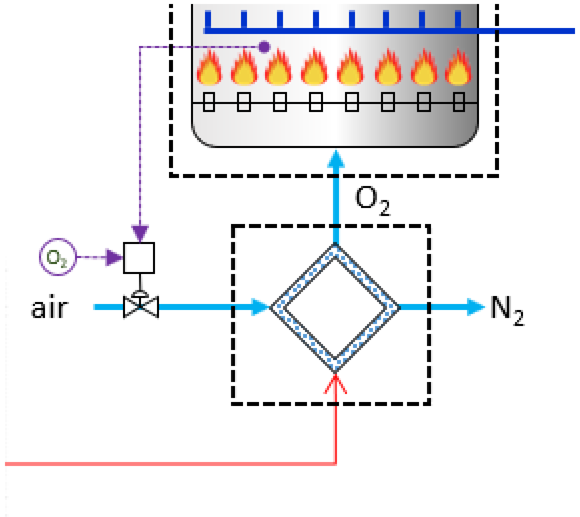


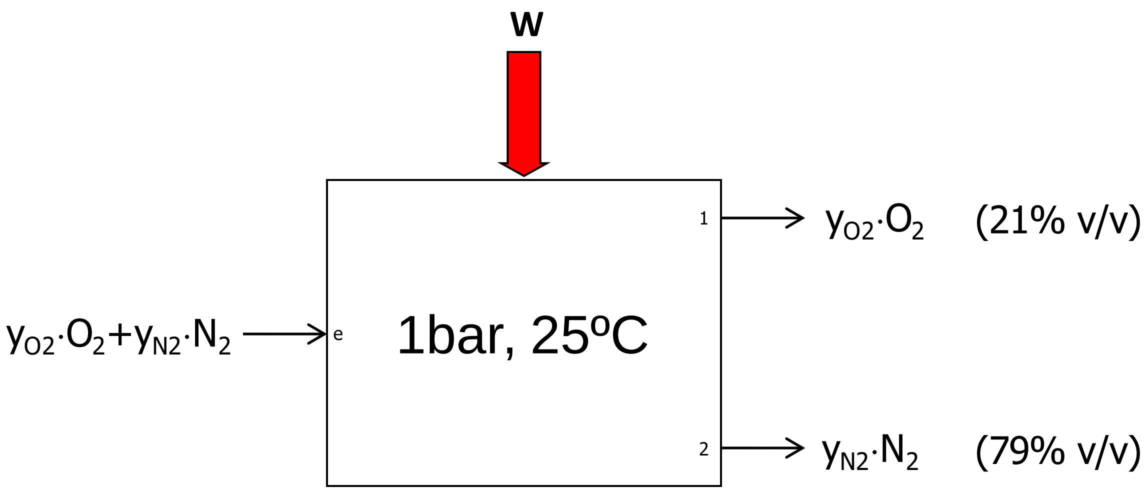
$$\dot{W} = \sum_{\text{entra}} \dot{m}_k x_k - \sum_{\text{saída}} \dot{m}_k x_k$$

$$\dot{W} = \left(\dot{m}_{O_2} x_{O_2} + \dot{m}_{N_2} x_{N_2}\right)_e - \left[\left(\dot{m}_{O_2} x_{O_2}\right)_1 + \left(\dot{m}_{N_2} x_{N_2}\right)_2\right]$$

$$\dot{W} = \dot{m}_{O_2} \cdot \left(x_{O_2,e} - x_{O_2,1}\right) + \dot{m}_{N_2} \cdot \left(x_{N_2,e} - x_{N_2,2}\right)$$

$$\dot{W} = \dot{m}_{O_2} T_0 \cdot \left(s_{O_2,1} - s_{O_2,e}\right) + \dot{m}_{N_2} T_0 \cdot \left(s_{N_2,2} - s_{N_2,e}\right) \qquad h's = cte$$





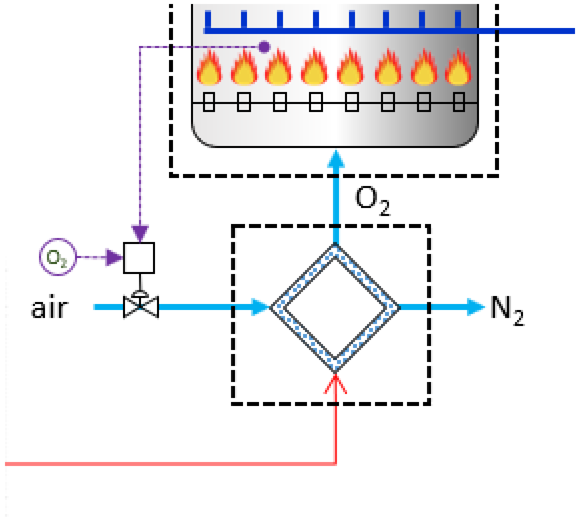
$$\frac{\dot{W}}{\dot{m}_{ar}} = T_0 \cdot \left[\frac{\dot{m}_{O_2}}{\dot{m}_{ar}} \left(s_{O_2,1} - s_{O_2,e} \right) + \frac{\dot{m}_{N_2}}{\dot{m}_{ar}} \left(s_{N_2,2} - s_{N_2,e} \right) \right]$$

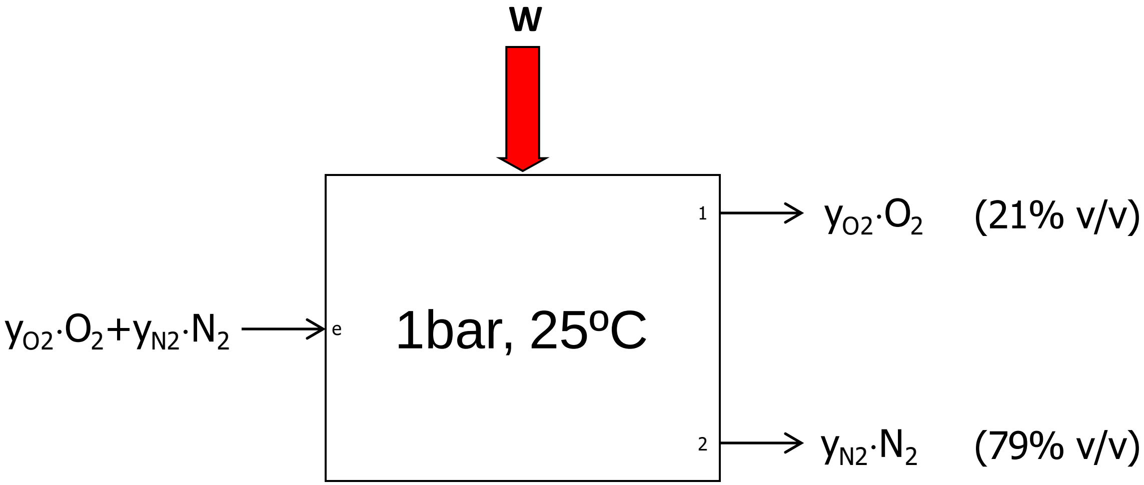
specific work→ $$w = T_0 \cdot \left[y_{O_2} \left(s_{O_2,1} - s_{O_2,e} \right) + y_{N_2} \left(s_{N_2,2} - s_{N_2,e} \right) \right]$$

$$w = T_0 \cdot \left[y_{O_2} \cdot \Delta s_{O_2} + y_{N_2} \cdot \Delta s_{N_2} \right]$$

Exergy necessary for the disorder level reduction process (separation)...

THE TOTAL ENTROPY REDUCES DUE TO THE SEPARATION PROCESS !





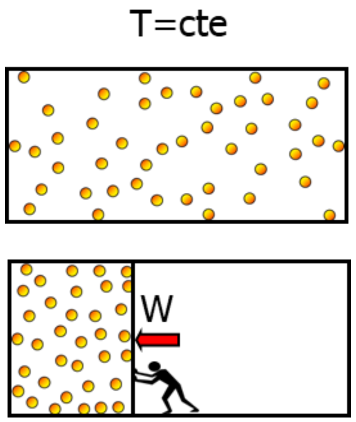
$$W=\int_1^2 P\cdot dV=\int_1^2 \frac{nRT}{V}\cdot dv$$

$$W=nRT\cdot \ln(V_2/V_1)$$

$$W=nRT\cdot \ln(P_1/P_2)$$

$$W=nRT\cdot \ln(y)$$

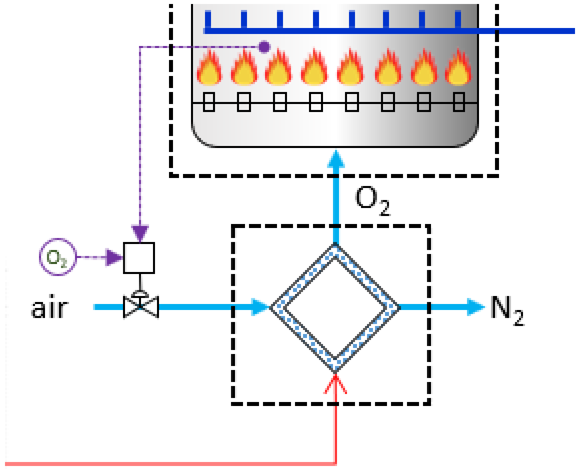
$$Q-W=\Delta U=0$$

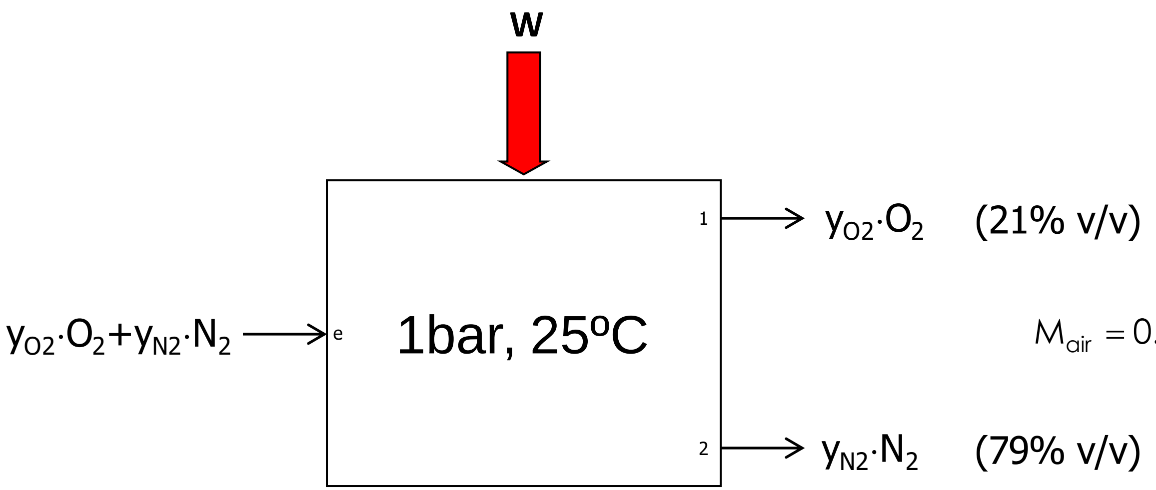


$$\Delta S=\frac{Q}{T}=\frac{W}{T}$$

$$\Delta S=nR\cdot \ln(y)$$

$$\Delta S=R\cdot\sum_k n_k\cdot \ln(y_k)\rightarrow \Delta s=R\cdot\sum_k y_k\cdot \ln(y_k)$$





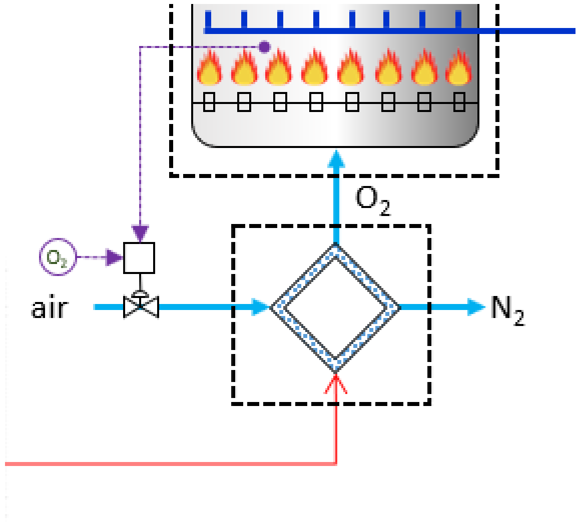
$$M_{air} = 0.21\cdot 32 + 0.79\cdot 28 = 28.8\,g/mol$$

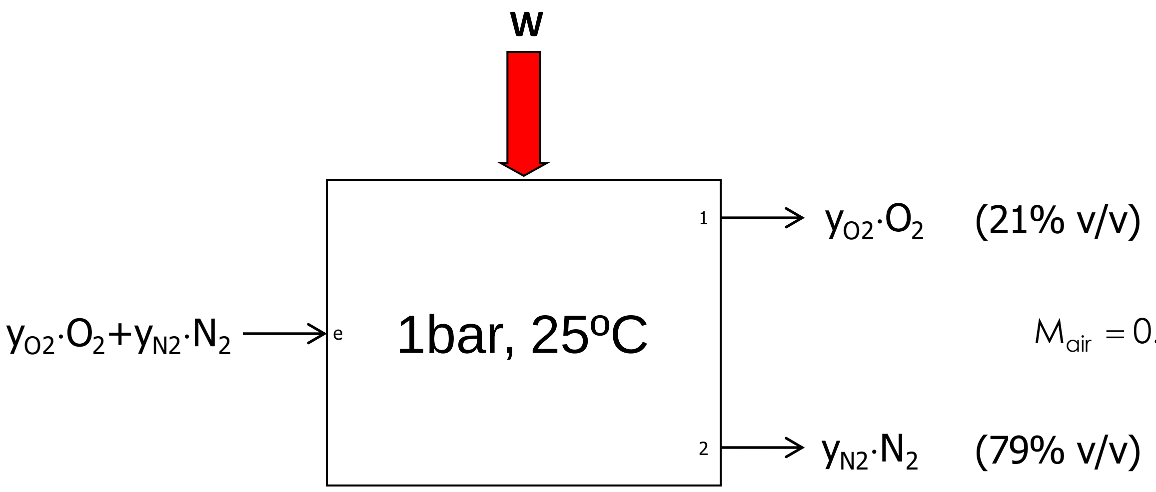
$$\Delta s = R\cdot\sum_k y_k\cdot \ln(y_k)$$

$$w = T_0\cdot\left[y_{O_2}\cdot\Delta s_{O_2} + y_{N_2}\cdot\Delta s_{N_2}\right]$$

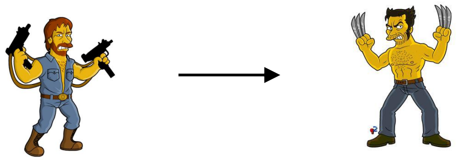
$$\rightarrow w = RT_0\cdot\left[y_{O_2}\cdot\ln(y_{O_2}) + y_{N_2}\cdot\ln(y_{N_2})\right]$$

$$\rightarrow w = RT_0\cdot\sum_k y_k\cdot\ln(y_k)$$





$$M_{air}=0.21\cdot 32+0.79\cdot 28=28.8\,g/mol$$

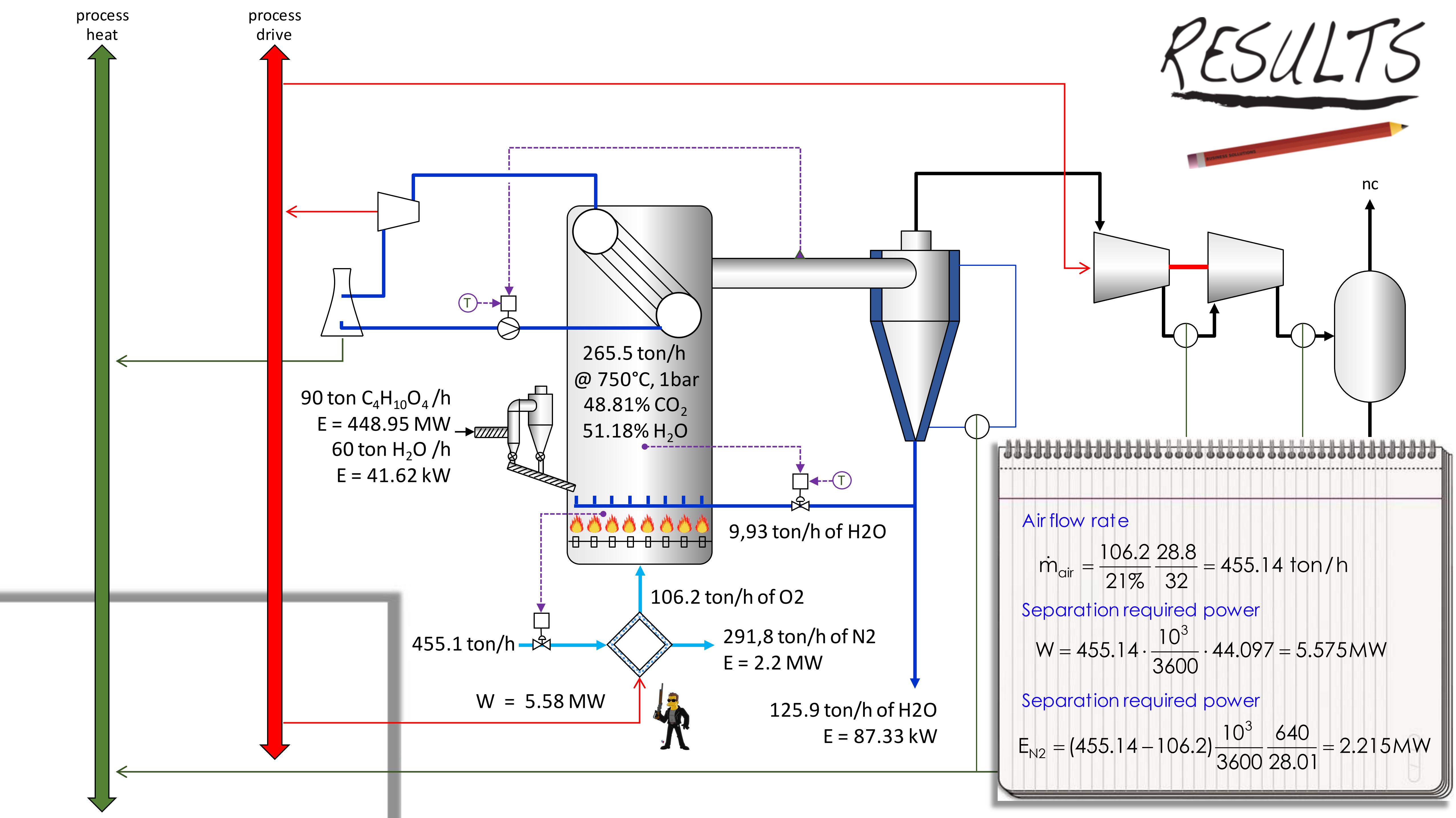


$$\Delta s=R\cdot\sum_k y_k\cdot\ln(y_k)\rightarrow\quad w=T_0\cdot\left[y_{O_2}\cdot\Delta s_{O_2}+y_{N_2}\cdot\Delta s_{N_2}\right]$$

$$w=8{,}314\frac{10^{-3}kJ}{mol\cdot K}(25+273{,}15)K\cdot[0{,}21\cdot\ln(0{,}21)+0{,}79\cdot\ln(0{,}79)]$$

$$w=-1.274\frac{kJ}{mol}\rightarrow\quad w=-1.274\frac{kJ}{mol}\frac{1000}{28.8\,kg/mol}=-44.097\frac{kJ}{kg}$$

RESULTS



Air flow rate

$$\dot{m}_{air} = \frac{106.2}{21\%}\frac{28.8}{32} = 455.14 \text{ ton/h}$$

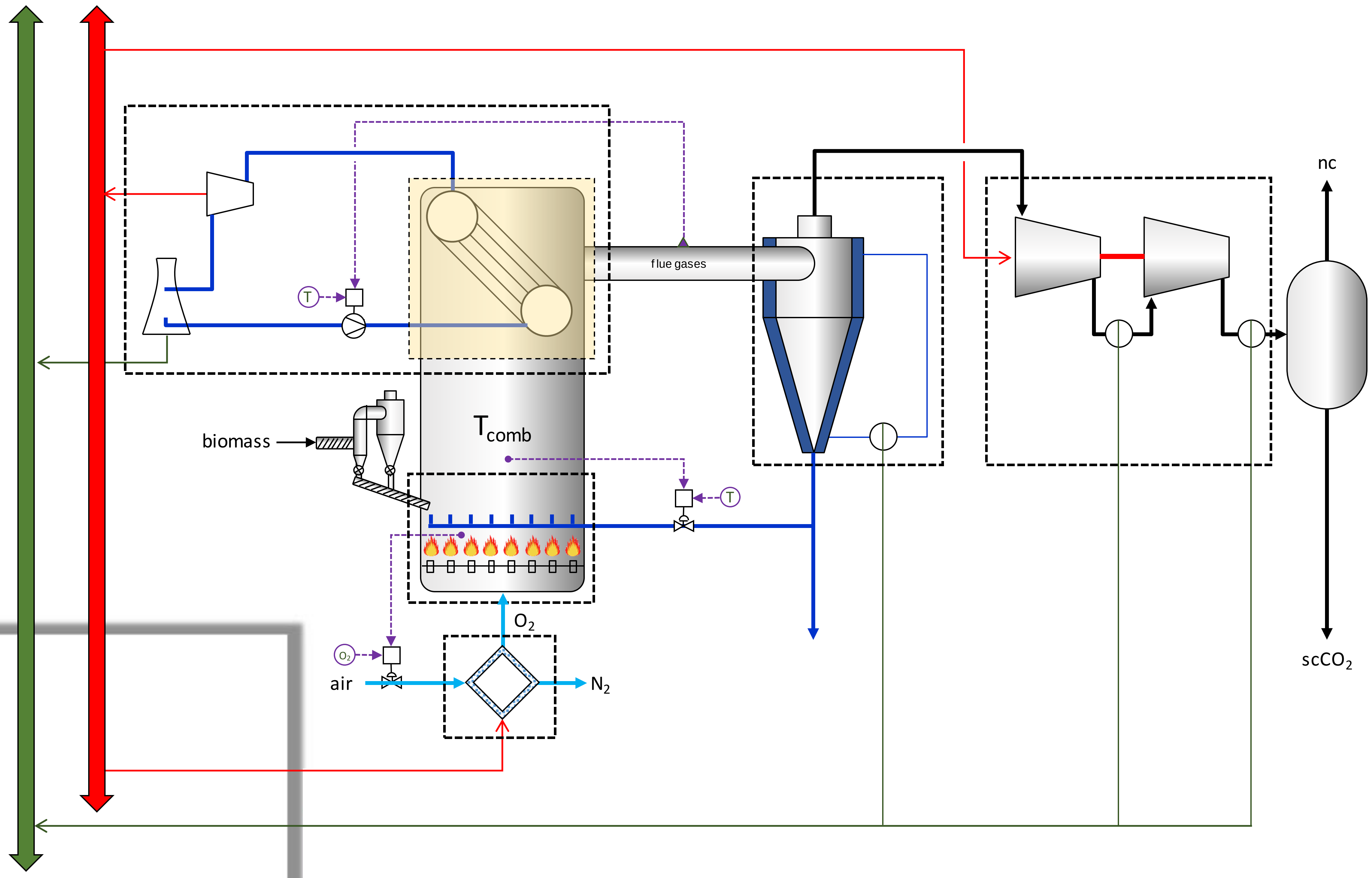
Separation required power

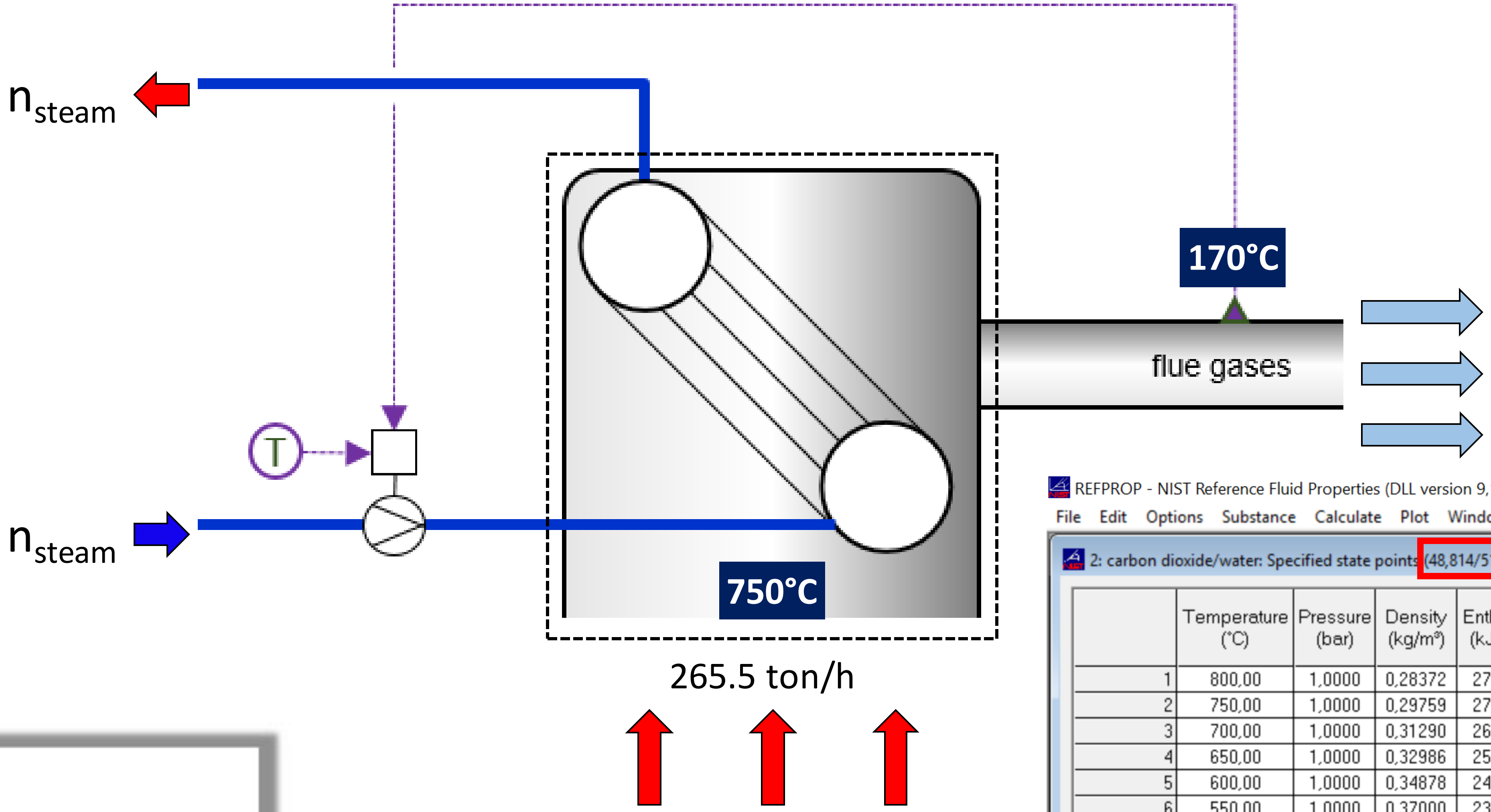
$$W = 455.14 \cdot \frac{10^3}{3600} \cdot 44.097 = 5.575 MW$$

Separation required power

$$E_{N2} = (455.14 - 106.2)\frac{10^3}{3600}\frac{640}{28.01} = 2.215 MW$$

Heat transfer at the boiler tubes…


flue gases
nc
T_{comb}
biomass
O_2
air
N_2
$scCO_2$
T
T
O_2



flue gases @ T_{comb}

1.51 kg H_2O / kg de $C_4H_{10}O_4$

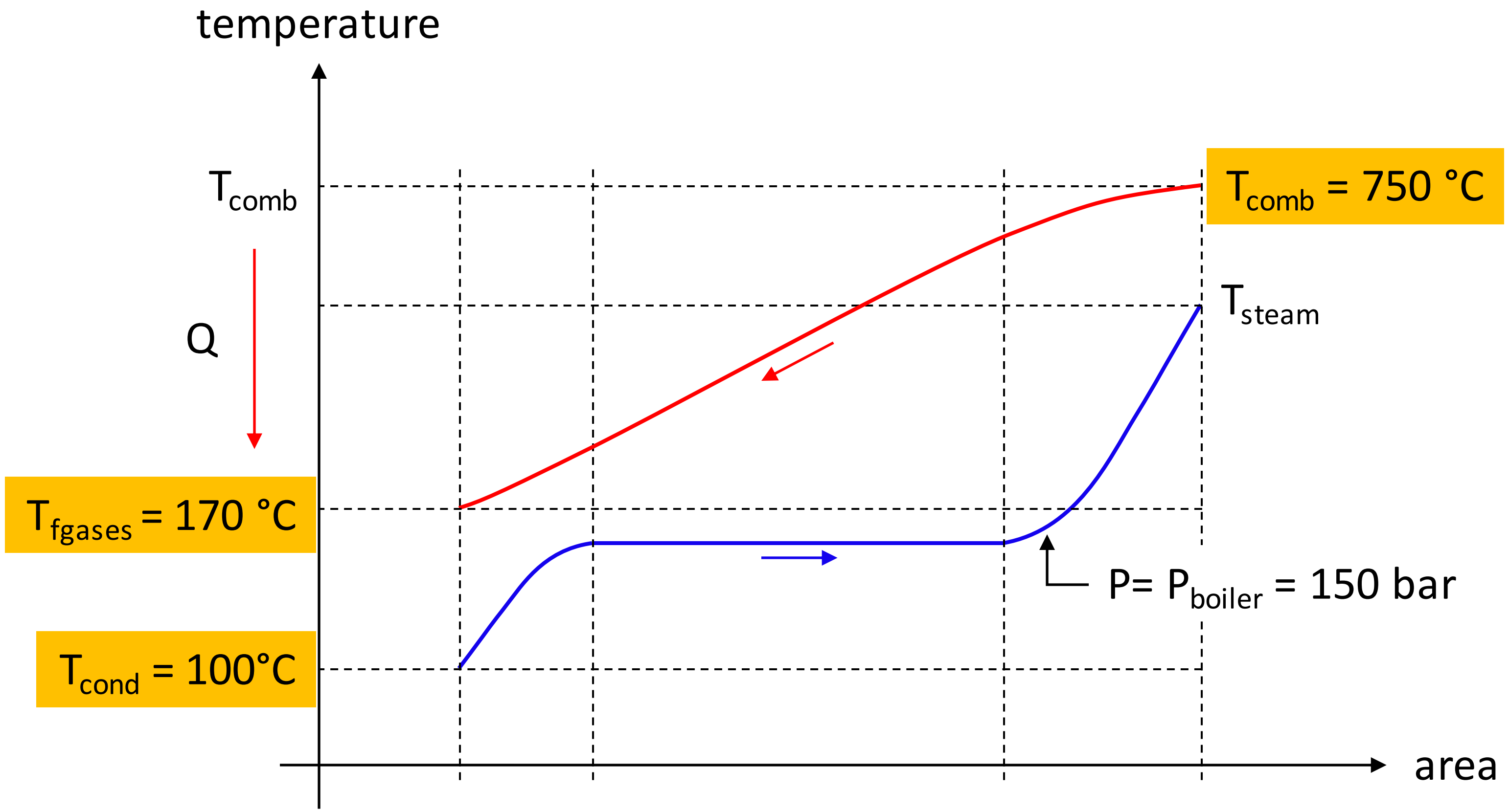
1.44 kg de CO_2 / kg de $C_4H_{10}O_4$

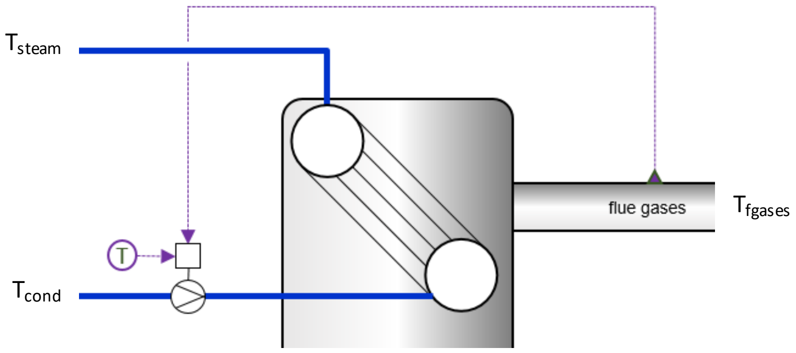
REFPROP - NIST Reference Fluid Properties (DLL version 9,1)

File Edit Options Substance Calculate Plot Window Help Cautions

2: carbon dioxide/water: Specified state points (48,814/51,186)

	Temperature (°C)	Pressure (bar)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/kg-K)	Cp (kJ/kg-K)
1	800,00	1,0000	0,28372	2791,7	7,0894	1,8111
2	750,00	1,0000	0,29759	2701,8	7,0036	1,7870
3	700,00	1,0000	0,31290	2613,1	6,9147	1,7623
4	650,00	1,0000	0,32986	2525,6	6,8224	1,7370
5	600,00	1,0000	0,34878	2439,4	6,7264	1,7111
6	550,00	1,0000	0,37000	2354,5	6,6263	1,6847
7	500,00	1,0000	0,39397	2270,9	6,5215	1,6578
8	450,00	1,0000	0,42128	2188,7	6,4116	1,6304
9	400,00	1,0000	0,45267	2107,9	6,2958	1,6026
10	350,00	1,0000	0,48915	2028,4	6,1732	1,5744
11	300,00	1,0000	0,53205	1950,4	6,0427	1,5460
12	250,00	1,0000	0,58329	1873,9	5,9029	1,5175
13	200,00	1,0000	0,64559	1798,7	5,7519	1,4899
14						





flue gases @ T_{comb}

1.51 kg H_2O / kg de $C_4H_{10}O_4$

1.44 kg de CO_2 / kg de $C_4H_{10}O_4$

Balanços de energia para um trocador de calor...

$$Q = n_{fgases} \cdot \Delta h_{fgases}$$

$$Q = n_{steam} \cdot \Delta h_{steam}$$

$$Q = UA \cdot \Delta T_{ln}$$

c.gases

$$Q = \dot{n}_{fg} \cdot \left[h_{fg}(P, T_{comb}) - h_{fg}(P, T_{fgases})\right]$$

265.5 ton/h → $\dot{n}_{fg}$; 750°C → T_{comb}; 170°C → T_{fgases}

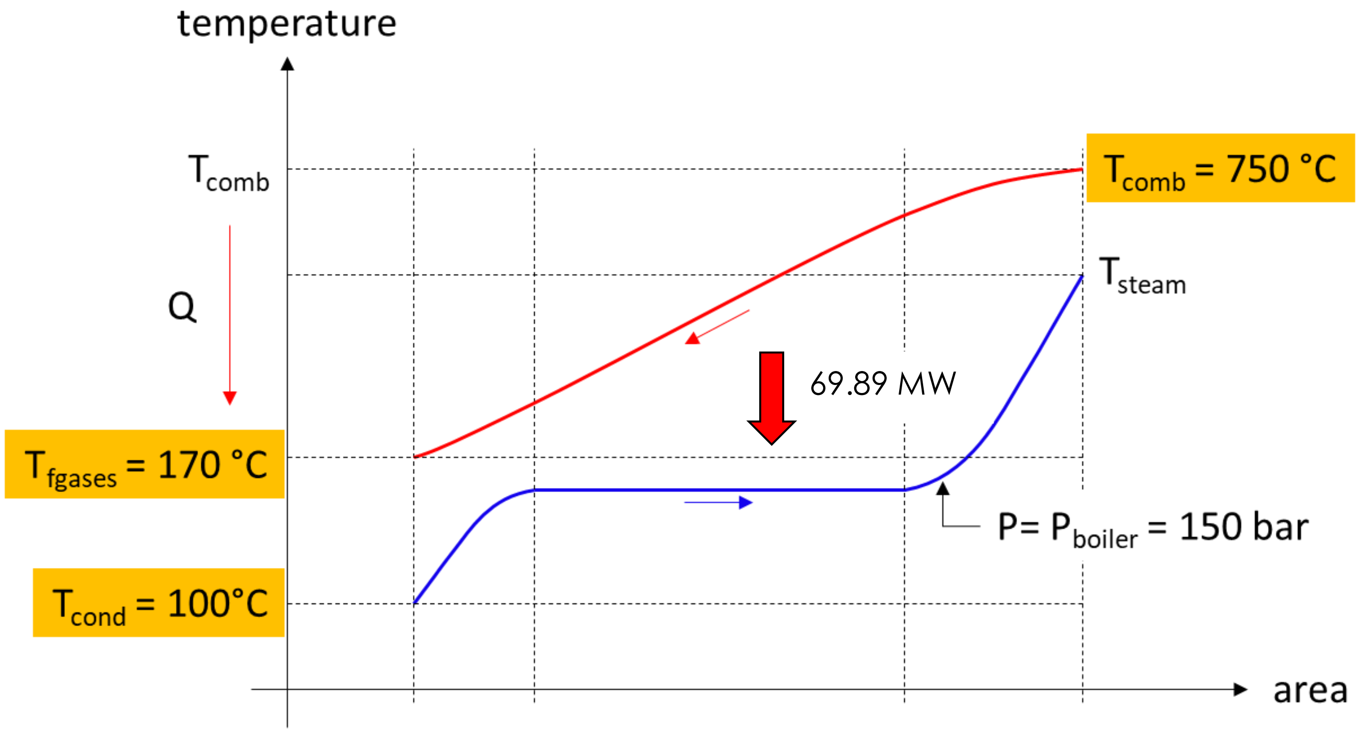
$$Q = \frac{265.5 \cdot 10^3}{3600} \cdot \left[2701.8 - 1754.2\right] \rightarrow Q = 69.89\,MW$$

REFPROP - NIST Reference Fluid Properties (DLL version 9,1)

File Edit Options Substance Calculate Plot Window Help Cautions

3: carbon dioxide/water: Specified state points (48,814/51,186)

	Temperature (°C)	Pressure (bar)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/kg-K)	Cp (kJ/kg-K)
1	750,00	1,0000	0,29759	2701,8	7,0036	1,7870
2	170,00	1,0000	0,68992	1754,2	5,6548	1,4745
3						



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steam

$$\overset{69.89\ \mathrm{MW}}{Q} = n_{ste} \cdot \left[h_{ste}(P, \overset{750°C}{T_{steam}}) - h_{ste}(P, \overset{100°C}{T_{cond}}) \right]$$

$$69.89 \cdot 10^3 = n_{ste} \cdot [3965.2 - 430.39]$$

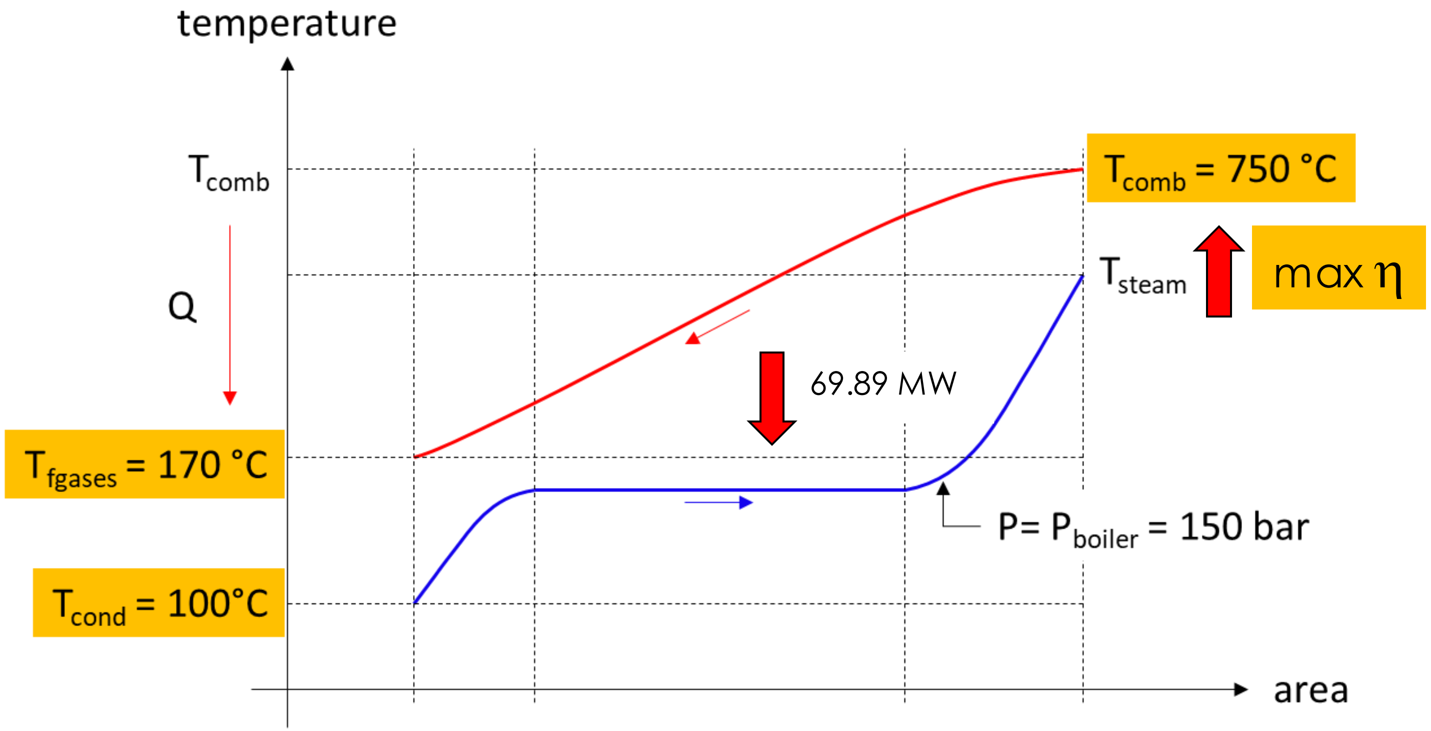
$$n_{ste} = 19.777\,kg/s$$

REFPROP (water) - NIST Reference Fluid Properties (DLL version 9,1)

File Edit Options Substance Calculate Plot Window Help Cautions

5: water: Specified state points

	Temperature (°C)	Pressure (bar)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/kg-K)	Cp (kJ/kg-K)	Quality (kg/kg)
1	750,00	150,00	32,906	3965,2	7,0836	2,5174	Superheated
2	100,00	150,00	965,20	430,39	1,2958	4,1828	Subcooled
3							



YouTube

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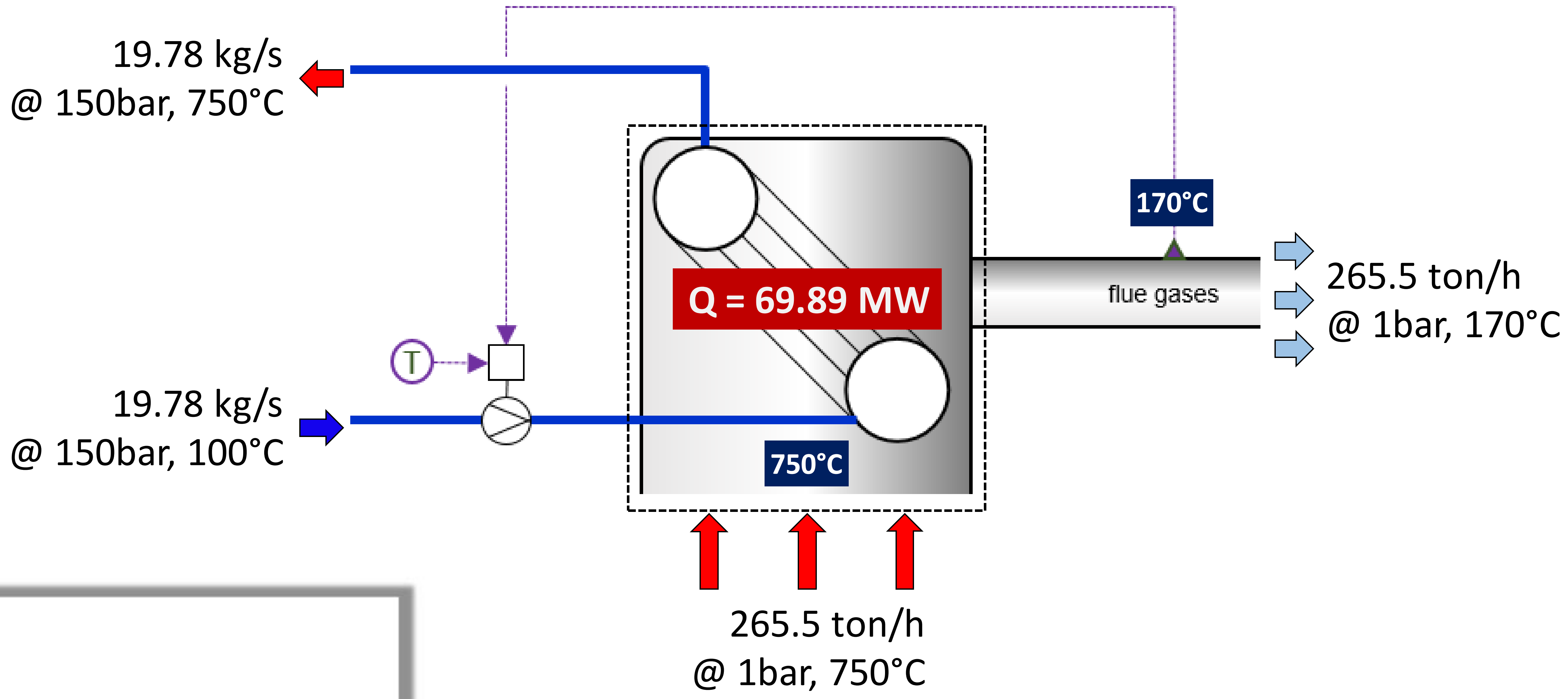
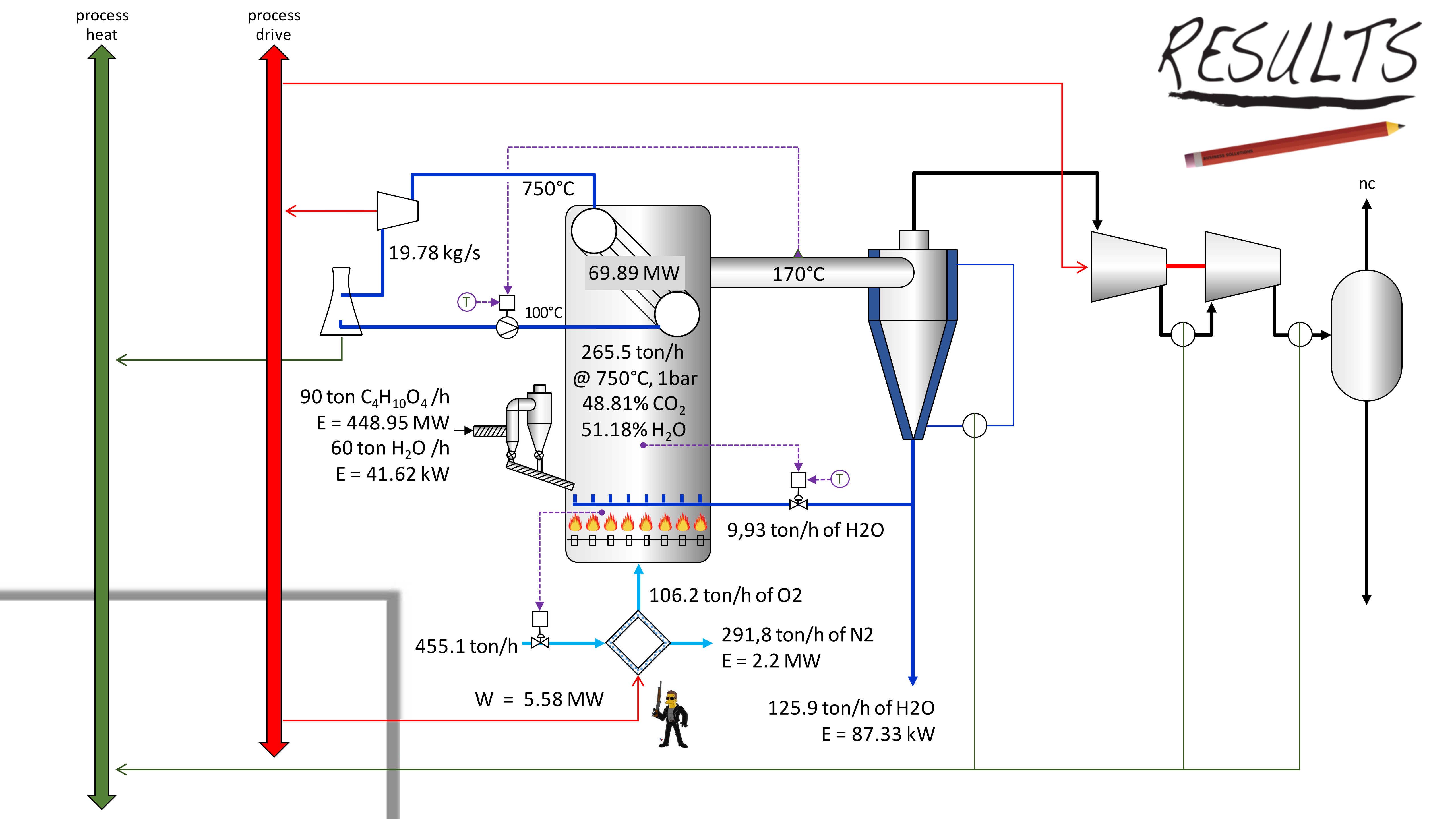
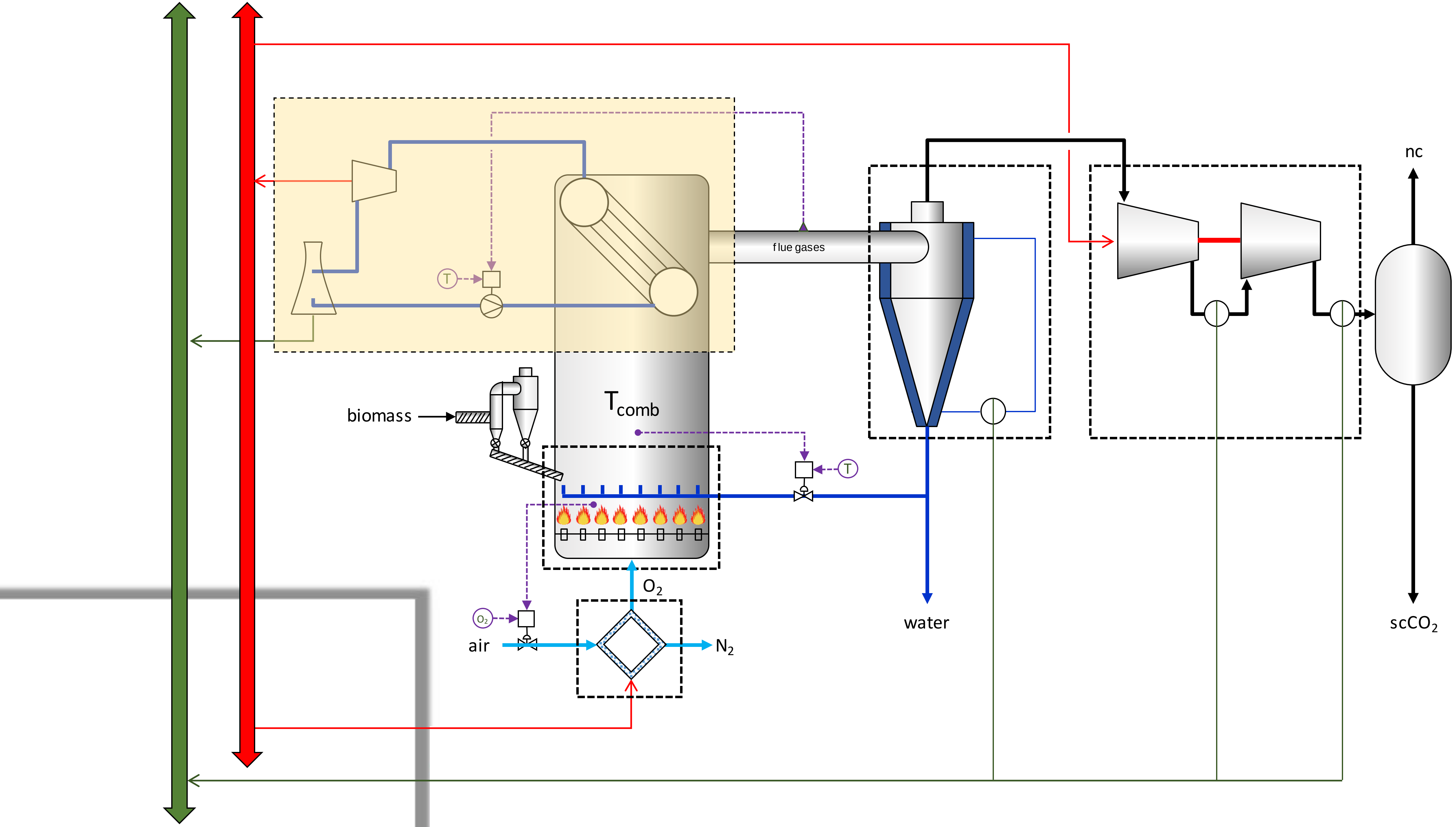

19.78 kg/s
@ 150bar, 750°C
Q = 69.89 MW
170°C
flue gases
265.5 ton/h
@ 1bar, 170°C
T
19.78 kg/s
@ 150bar, 100°C
750°C
265.5 ton/h
@ 1bar, 750°C



process heat
process drive
RESULTS
750°C
19.78 kg/s
69.89 MW
170°C
nc
100°C
265.5 ton/h
@ 750°C, 1bar
48.81% CO_2
51.18% H_2O
90 ton $C_4H_{10}O_4$ /h
E = 448.95 MW
60 ton H_2O /h
E = 41.62 kW
9,93 ton/h of H2O
106.2 ton/h of O2
455.1 ton/h
291,8 ton/h of N2
E = 2.2 MW
W = 5.58 MW
125.9 ton/h of H2O
E = 87.33 kW

Steam Power Cycle…



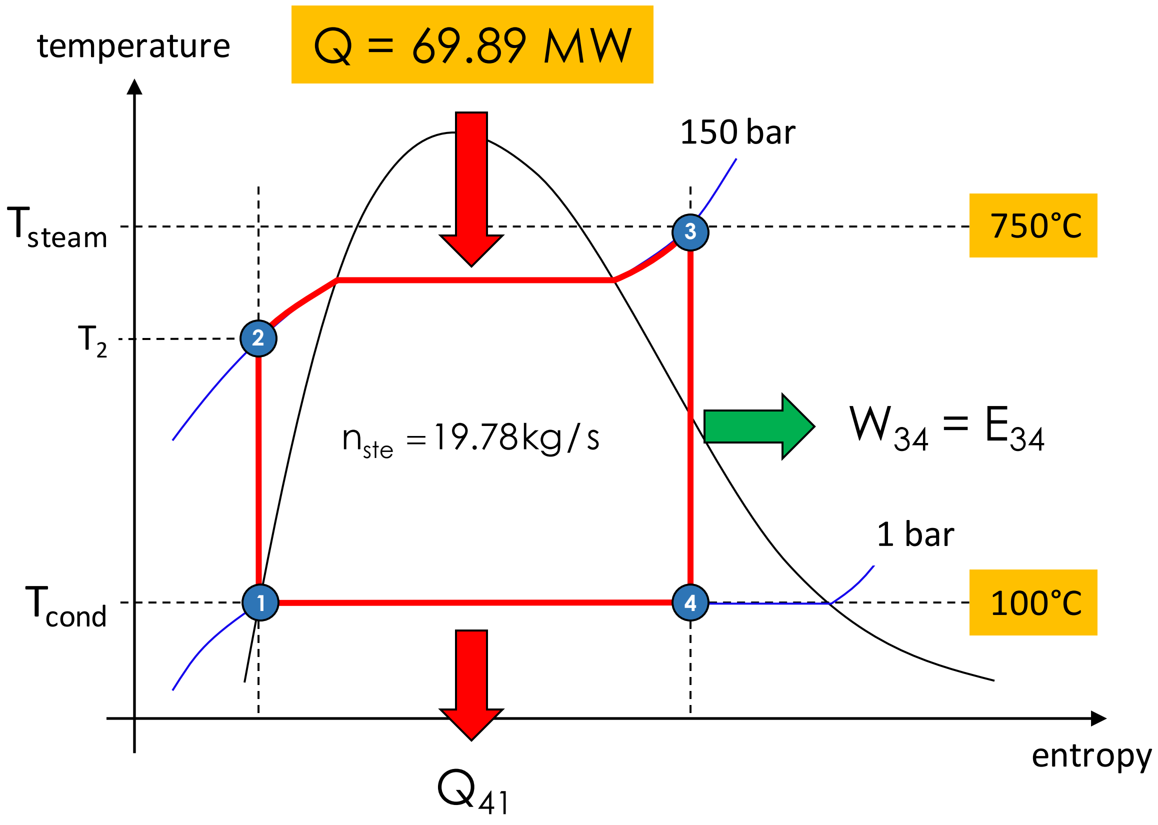
flue gases
T
T_{comb}
biomass
T
O_2
O_2
air
N_2
water
nc
$scCO_2$

Water temperature x entropy diagram

6: water: Specified state points

	Temperature (°C)	Pressure (bar)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/kg-K)	Cp (kJ/kg-K)	Quality (kg/kg)
1	100,00	1,0142	958,35	419,17	1,3072	4,2157	Subcooled
2	101,02	150,00	964,48	434,66	1,3072	4,1838	Subcooled
3	750,00	150,00	32,906	3965,2	7,0836	2,5174	Superheated
4	100,00	1,0142	0,62618	2574,6	7,0836	Undefined	0,95526
5							

Rankine cycle without reheating



$E_{41} = (1 - T_0/T_{cond}) \cdot Q_{41}$

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Water temperature x entropy diagram

6: water: Specified state points

	Temperature (°C)	Pressure (bar)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/kg-K)	Cp (kJ/kg-K)	Quality (kg/kg)
1	100,00	1,0142	958,35	419,17	1,3072	4,2157	Subcooled
2	101,02	150,00	964,48	434,66	1,3072	4,1838	Subcooled
3	750,00	150,00	32,906	3965,2	7,0836	2,5174	Superheated
4	100,00	1,0142	0,62618	2574,6	7,0836	Undefined	0,95526
5							

$$\eta_{1^\circ Lei} = \frac{27.51 - 0.306}{69.89} = 38.9\%$$

$$W_{12} = n_{ste} \cdot [h_1 - h_2]$$

$$W_{12} = 19.78 \cdot [419.17 - 434.66] = -306.39\,kW$$

$$Q_{23} = n_{ste} \cdot [h_3 - h_2]$$

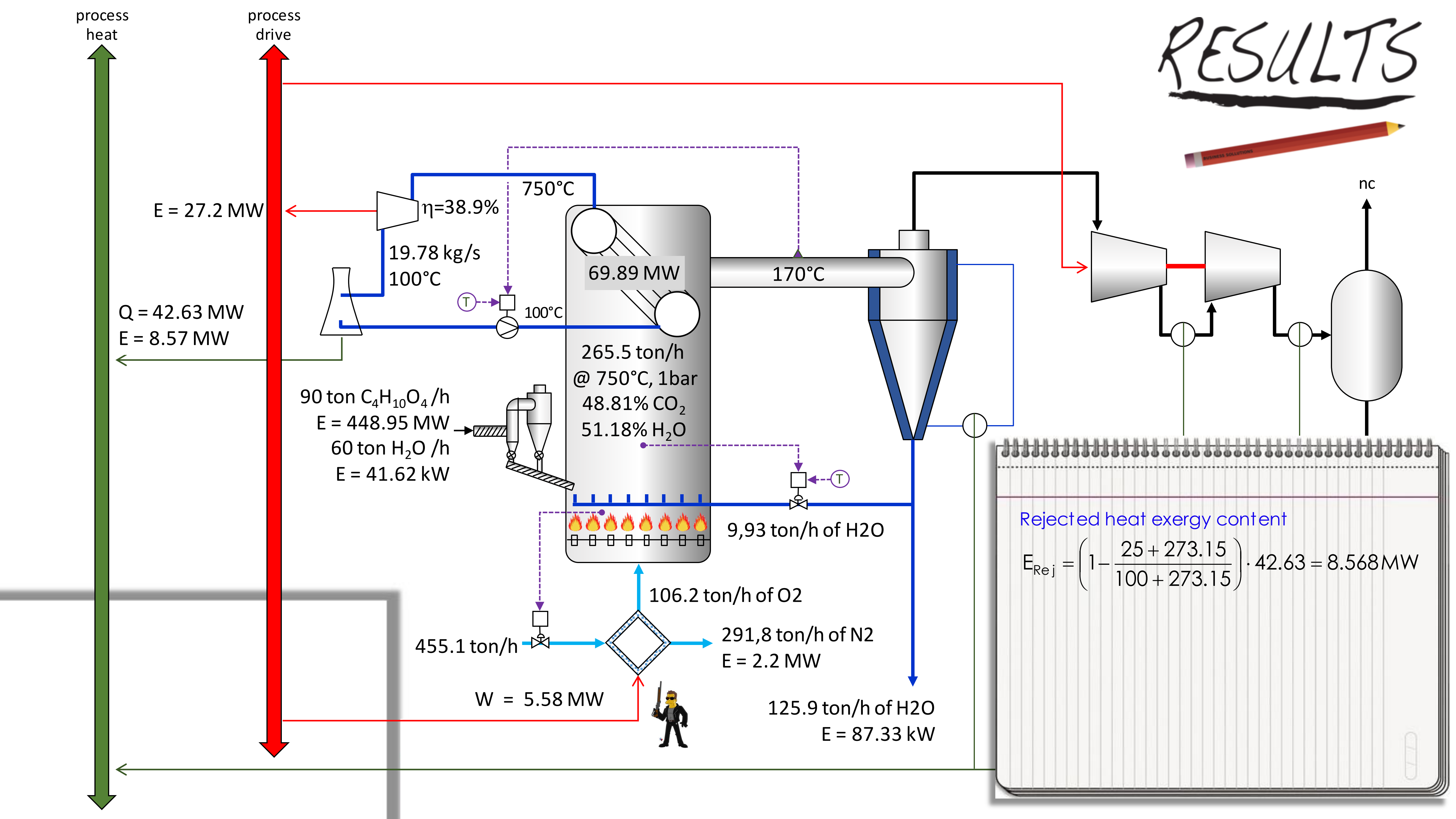
$$Q_{23} = 19.78 \cdot [3965.2 - 434.66)] = 69.83\,MW$$

$$W_{34} = n_{ste} \cdot [h_3 - h_3]$$

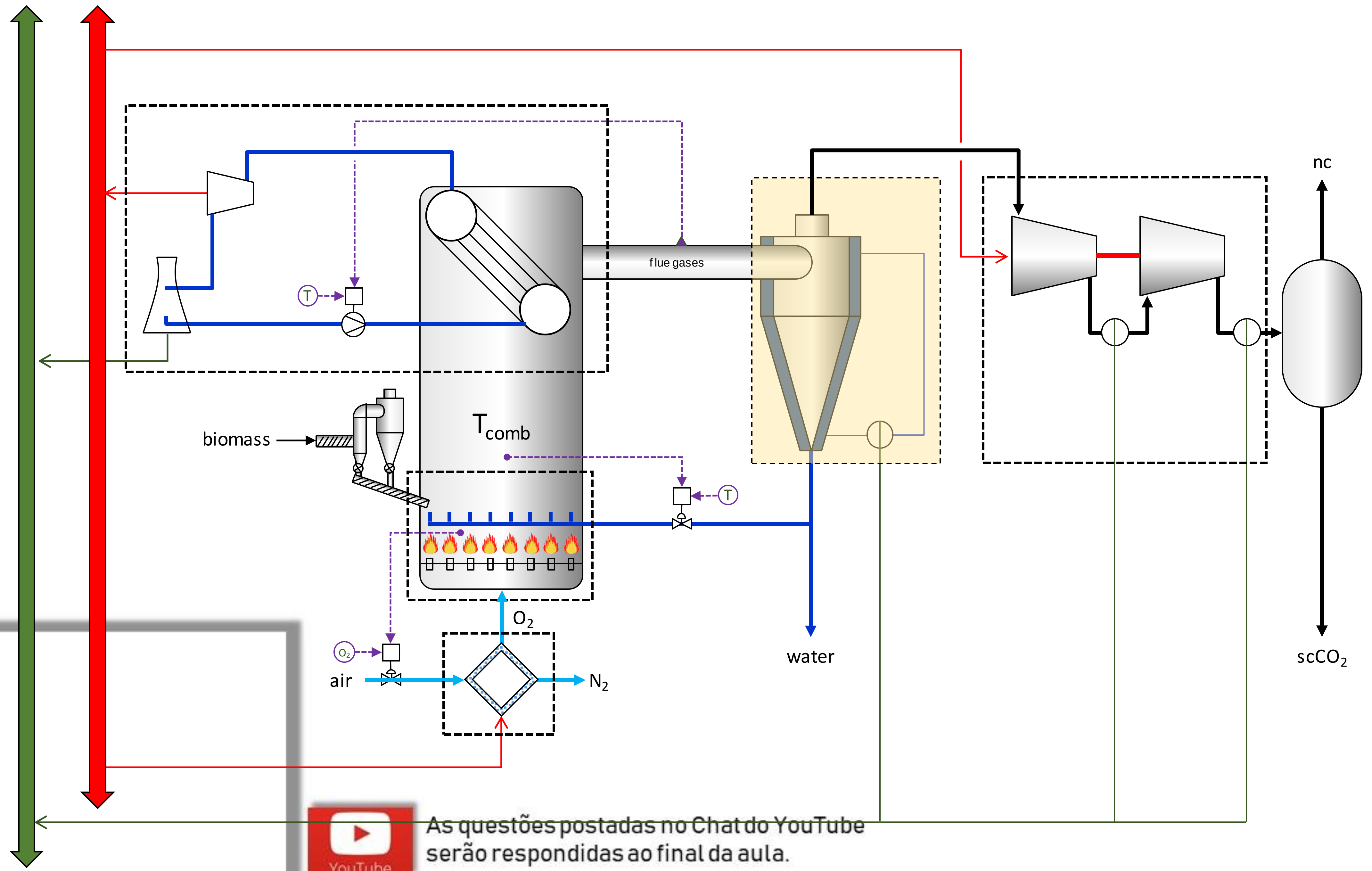
$$W_{34} = 19.78 \cdot [3965.2 - 2574.6] = 27.51\,MW$$

$$Q_{41} = n_{ste} \cdot [h_1 - h_4]$$

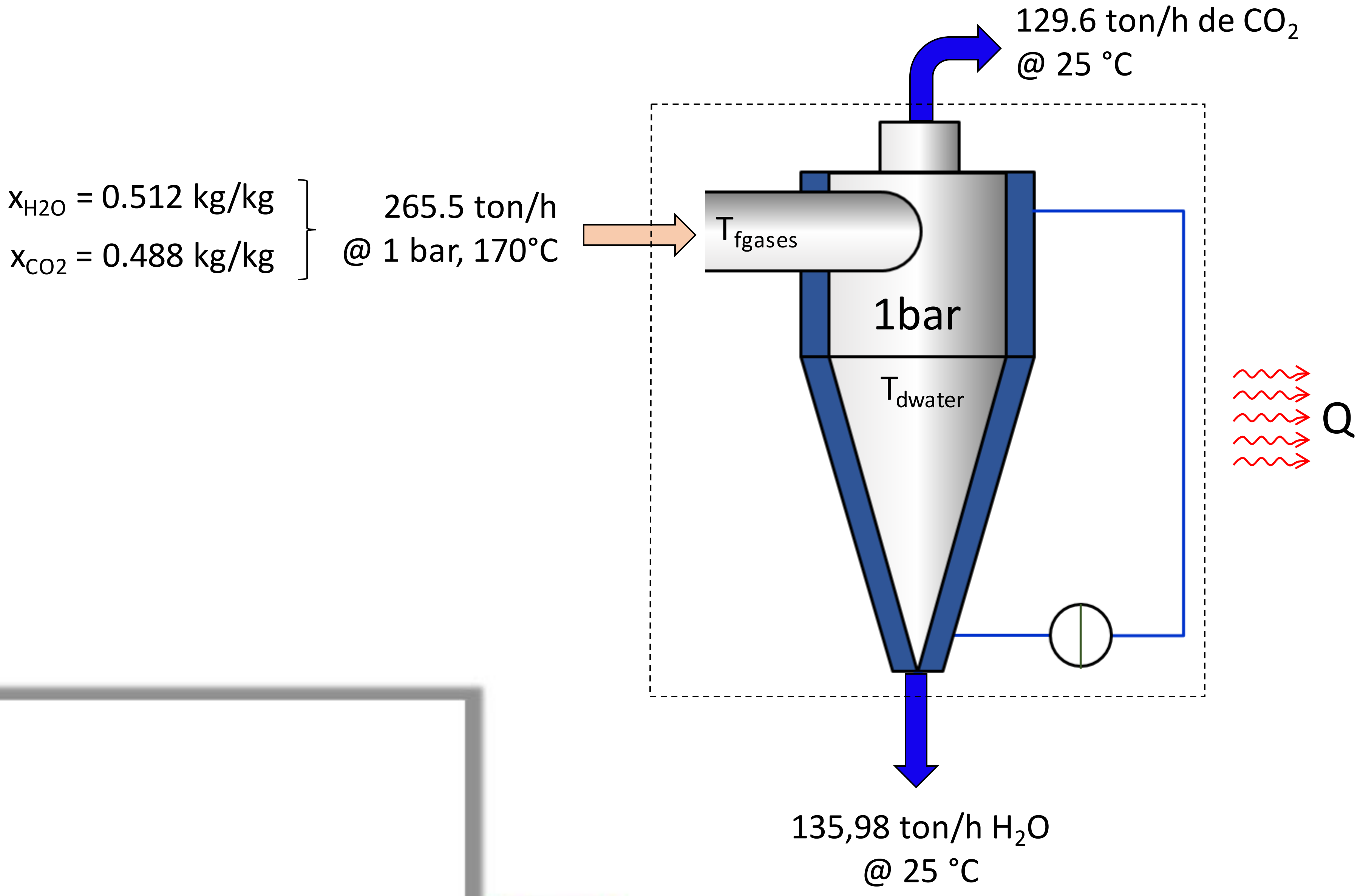
$$Q_{41} = 19.78 \cdot [419.17 - 2574.6] = -42.63\,MW$$


RESULTS
process heat
process drive
E = 27.2 MW
η=38.9%
750°C
19.78 kg/s
100°C
Q = 42.63 MW
E = 8.57 MW
100°C
69.89 MW
170°C
nc
265.5 ton/h
@ 750°C, 1bar
48.81% CO2
51.18% H2O
90 ton C4H10O4 /h
E = 448.95 MW
60 ton H2O /h
E = 41.62 kW
T
T
9,93 ton/h of H2O
106.2 ton/h of O2
455.1 ton/h
291,8 ton/h of N2
E = 2.2 MW
W = 5.58 MW
125.9 ton/h of H2O
E = 87.33 kW
Rejected heat exergy content
E_Rej = (1 − (25 + 273.15)/(100 + 273.15)) · 42.63 = 8.568 MW

Dewatering cyclone…



flue gases
nc
biomass
T_{comb}
O_2
air
N_2
water
$scCO_2$



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adiabático @ 1bar

$1 \cdot C_4H_{10}O_4 + 4.5 \cdot O_2 + n_{rec} \cdot H_2O \rightarrow 4 \cdot CO_2 + (5+n_{rec}) \cdot H_2O$ 5.3

25°C | 750°C

$x_{H2O} = 0.512$ kg/kg

$x_{CO2} = 0.488$ kg/kg

265.5 ton/h
@ 1 bar, 170°C

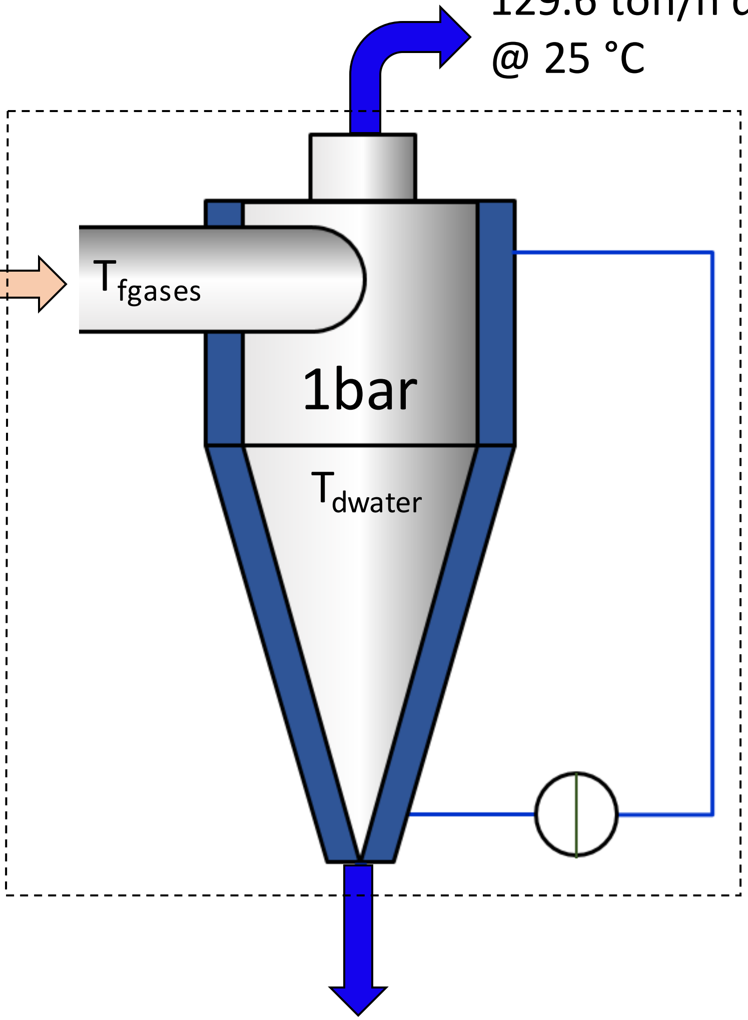
$x_{H2O} = 0.7203$ mol/mol

$x_{CO2} = 0.2797$ mol/mol

$P_{H2O} = 0.7203$ bar

$P_{CO2} = 0.2797$ bar

129.6 ton/h de CO_2
@ 25 °C



135,98 ton/h H_2O
@ 25 °C 1bar

2: carbon dioxide: Specified state points

	Temperature (°C)	Pressure (bar)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/kg-K)	Quality (kg/kg)	Flow Exergy (kJ/kg)
1	170,00	0,27970	0,33420	638,93	3,3418	Superheated	212,57
2	25,000	0,27970	0,49725	506,52	2,9816	Superheated	187,56
3							

$Q = Q_{H2O} + Q_{CO2}$

3: water: Specified state points

	Temperature (°C)	Pressure (bar)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/kg-K)	Quality (kg/kg)	Flow Exergy (kJ/kg)
1	170,00	0,72030	0,35391	2817,9	7,8605	Superheated	637,52
2	25,000	0,27970	997,01	104,85	0,36722	Subcooled	158,63
3							

$$Q_{CO2} = n_{CO2} \cdot \Delta h_{CO2}$$

$$Q_{CO2} = \frac{129.6 \cdot 10^3 kg}{3600 s} \cdot (506.52 - 638.93) \frac{kJ}{kg} = -4.767 kW$$

2: carbon dioxide: Specified state points

	Temperature (°C)	Pressure (bar)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/kg-K)	Quality (kg/kg)	Flow Exergy (kJ/kg)
1	170,00	0,27970	0,33420	638,93	3,3418	Superheated	212,57
2	25,000	0,27970	0,49725	506,52	2,9816	Superheated	187,56
3							

$$Q_{H2O} = n_{H2O} \cdot \Delta h_{H2O}$$

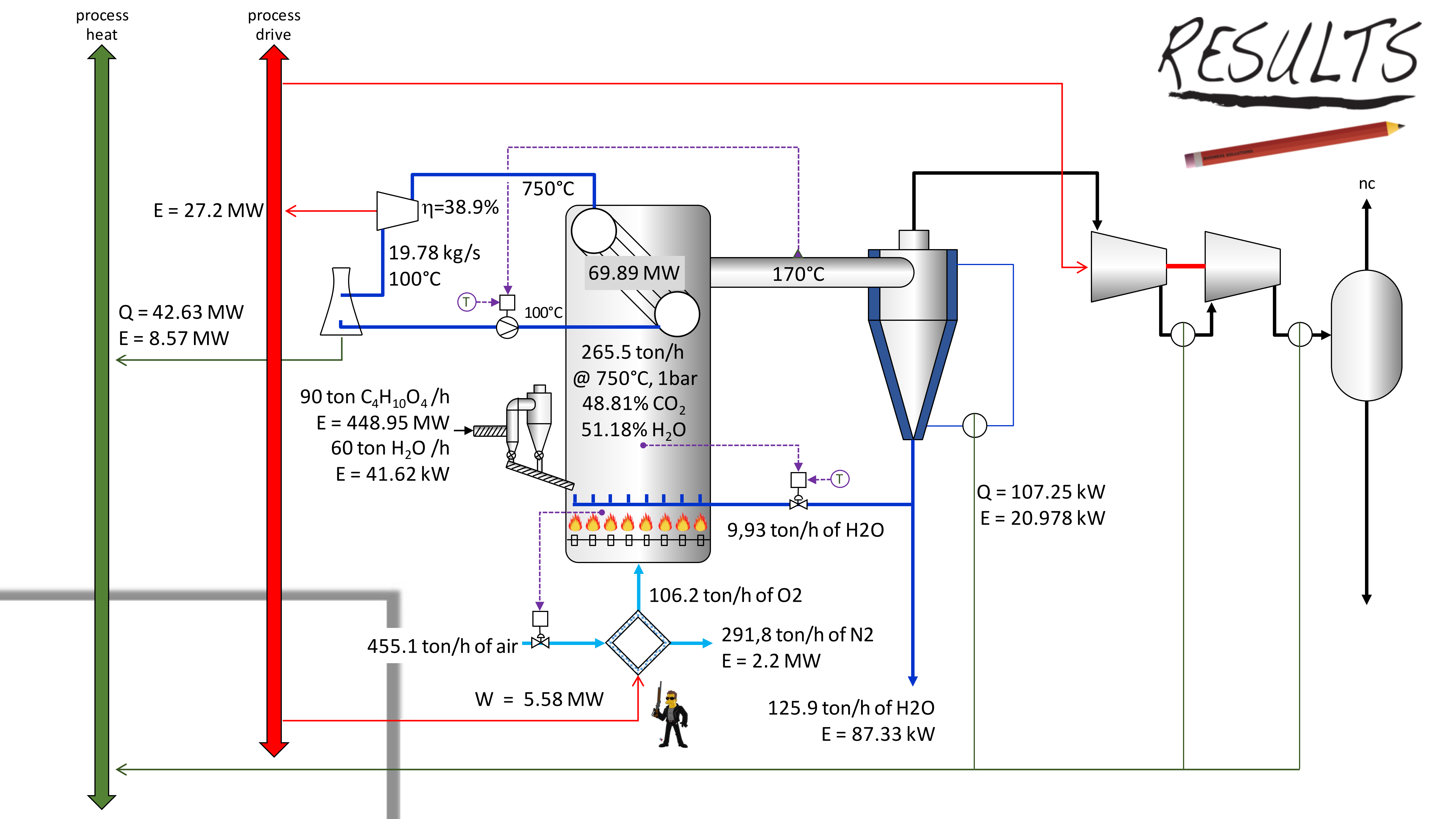
$$Q_{H2O} = \frac{135.98 \cdot 10^3 kg}{3600 s} \cdot (2817.9 - 104.85) \frac{kJ}{kg} = -102.48 kW$$

Q = - 107.25 kW

3: water: Specified state points

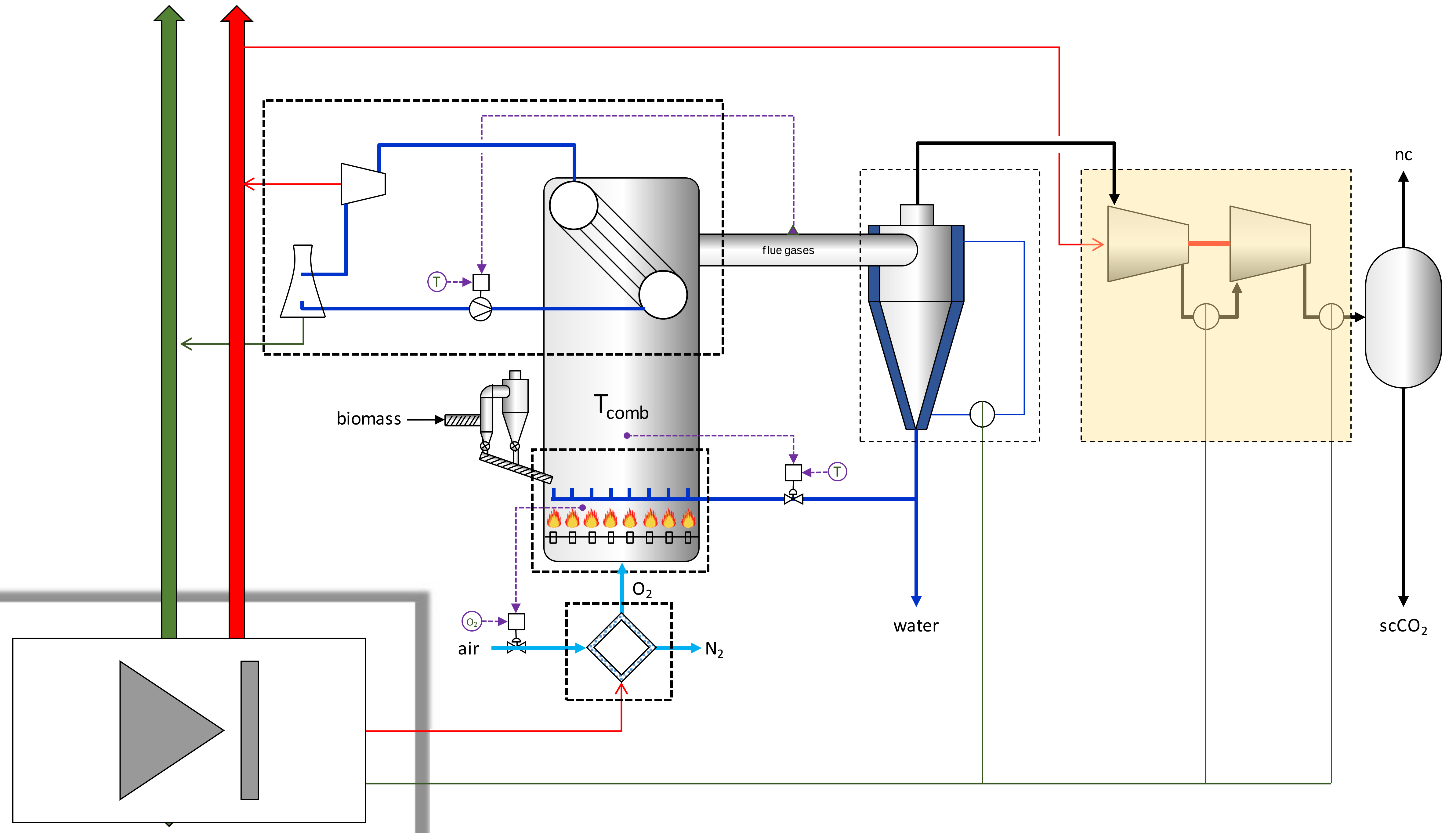
	Temperature (°C)	Pressure (bar)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/kg-K)	Quality (kg/kg)	Flow Exergy (kJ/kg)
1	170,00	0,72030	0,35391	2817,9	7,8605	Superheated	637,52
2	25,000	0,27970	997,01	104,85	0,36722	Subcooled	158,63
3							

$$E_Q = 107.25 \cdot \left(1 - \frac{25 + 275.15}{(170 + 25)/2 + 273.15}\right) = 20.978 kW$$



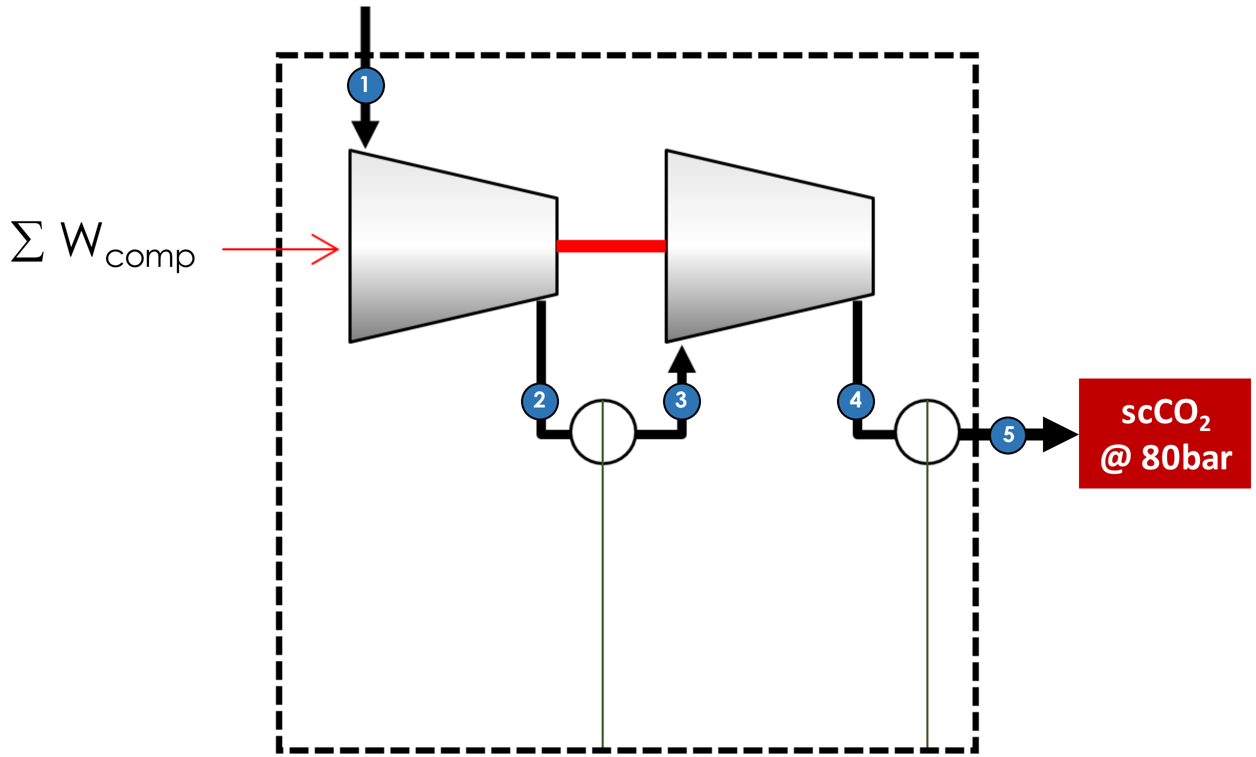
RESULTS
process heat
process drive
E = 27.2 MW
η=38.9%
750°C
19.78 kg/s
100°C
69.89 MW
170°C
nc
Q = 42.63 MW
E = 8.57 MW
100°C
265.5 ton/h
@ 750°C, 1bar
48.81% CO_2
51.18% H_2O
90 ton $C_4H_{10}O_4$ /h
E = 448.95 MW
60 ton H_2O /h
E = 41.62 kW
T
T
9,93 ton/h of H2O
Q = 107.25 kW
E = 20.978 kW
106.2 ton/h of O2
455.1 ton/h of air
291,8 ton/h of N2
E = 2.2 MW
W = 5.58 MW
125.9 ton/h of H2O
E = 87.33 kW

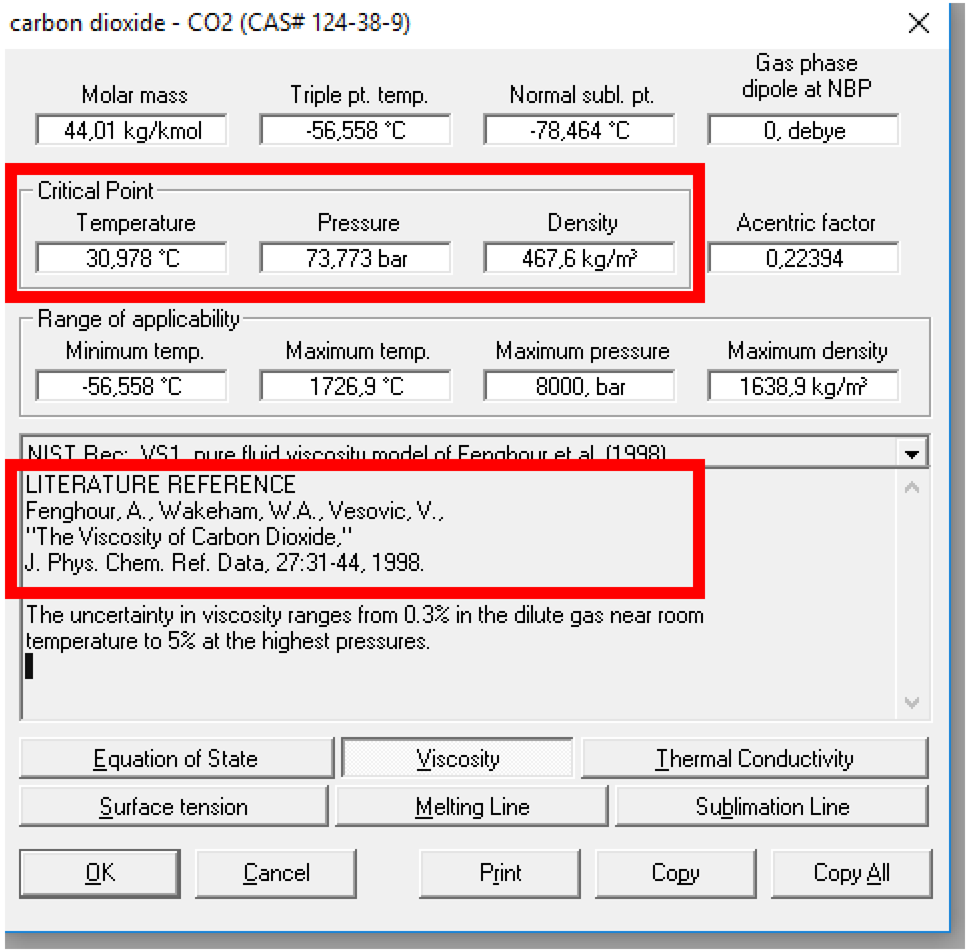
CO_2 compression to $scCO_2$…

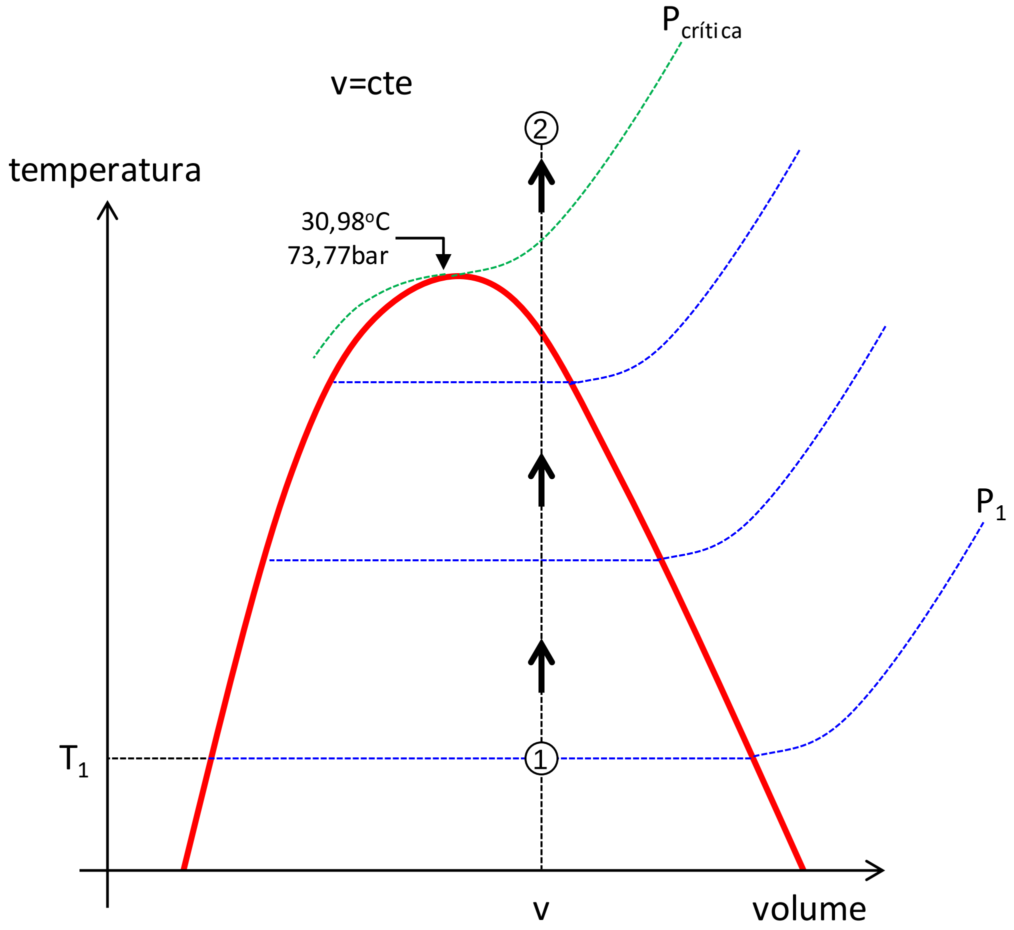


nc
flue gases
T_{comb}
biomass
O_2
water
$scCO_2$
O_2
air
N_2
T
T

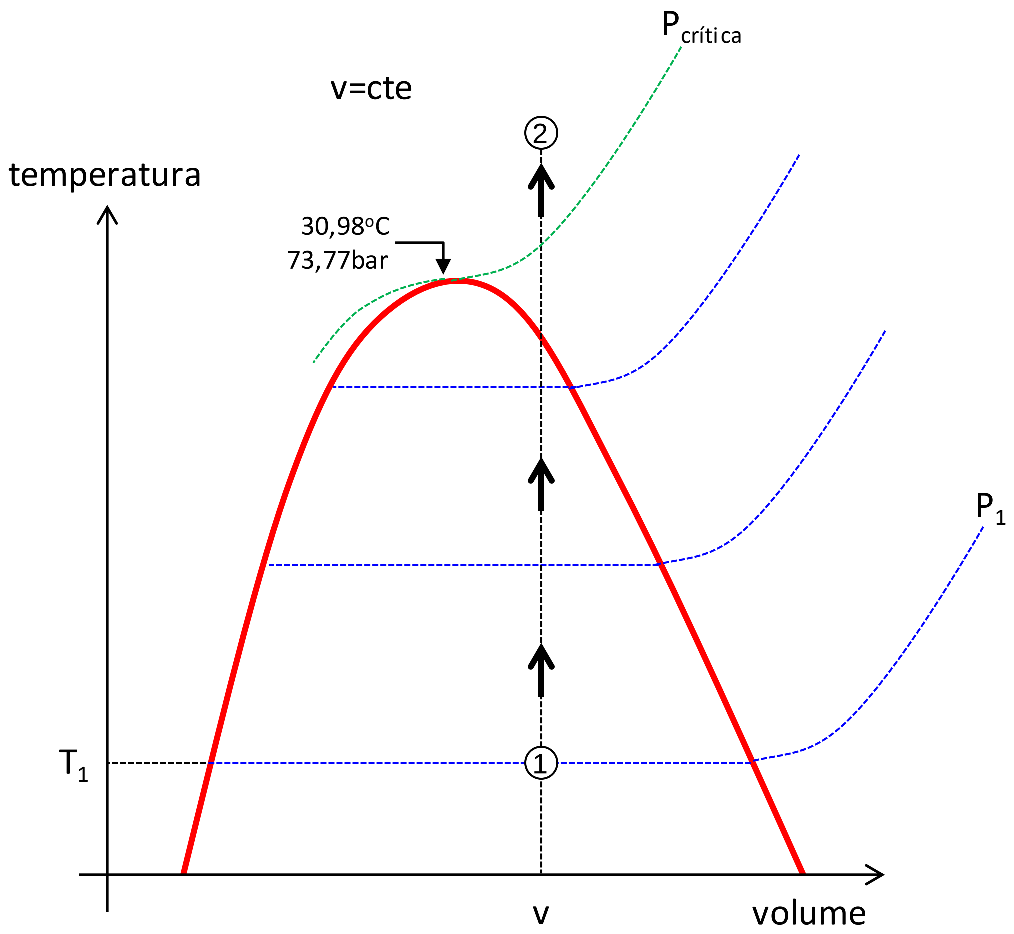
129.6 ton/h de CO_2
@ 0.232 bar, 25 °C







v=cte
$P_{crítica}$
temperatura
30,98ºC
73,77bar
2
P_1
T_1
1
v
volume



$$\nu = \mu / \rho$$

1: carbon dioxide: V/L sat. T=20, to 30, °C

	Temperature (°C)	Pressure (bar)	Liquid Density (kg/m³)	Vapor Density (kg/m³)	Liquid Viscosity (µPa-s)	Vapor Viscosity (µPa-s)	Liquid Kin. Viscosity (cm²/s)	Vapor Kin. Viscosity (cm²/s)	Liquid Flow Exergy (kJ/kg)	Vapor Flow Exergy (kJ/kg)
1	20,000	57,291	773,39	194,20	66,148	18,187	0,00085530	0,00093653	212,62	210,03
2	21,000	58,648	762,40	202,32	64,427	18,501	0,00084505	0,00091446	212,75	210,76
3	22,000	60,031	750,77	211,08	62,670	18,847	0,00083474	0,00089284	212,89	211,46
4	23,000	61,440	738,36	220,62	60,865	19,231	0,00082432	0,00087166	213,05	212,15
5	24,000	62,877	725,02	231,10	58,998	19,663	0,00081374	0,00085086	213,23	212,80
6	25,000	64,342	710,50	242,73	57,048	20,157	0,00080292	0,00083040	213,43	213,43
7	26,000	65,837	694,46	255,86	54,984	20,731	0,00079175	0,00081024	213,65	214,02
8	27,000	67,361	676,36	271,01	52,761	21,417	0,00078007	0,00079027	213,89	214,57
9	28,000	68,918	655,28	289,11	50,302	22,272	0,00076764	0,00077037	214,17	215,08
10	29,000	70,509	629,36	312,03	47,450	23,411	0,00075395	0,00075027	214,49	215,53
11	30,000	72,137	593,31	345,10	43,768	25,170	0,00073769	0,00072936	214,88	215,88

YouTube

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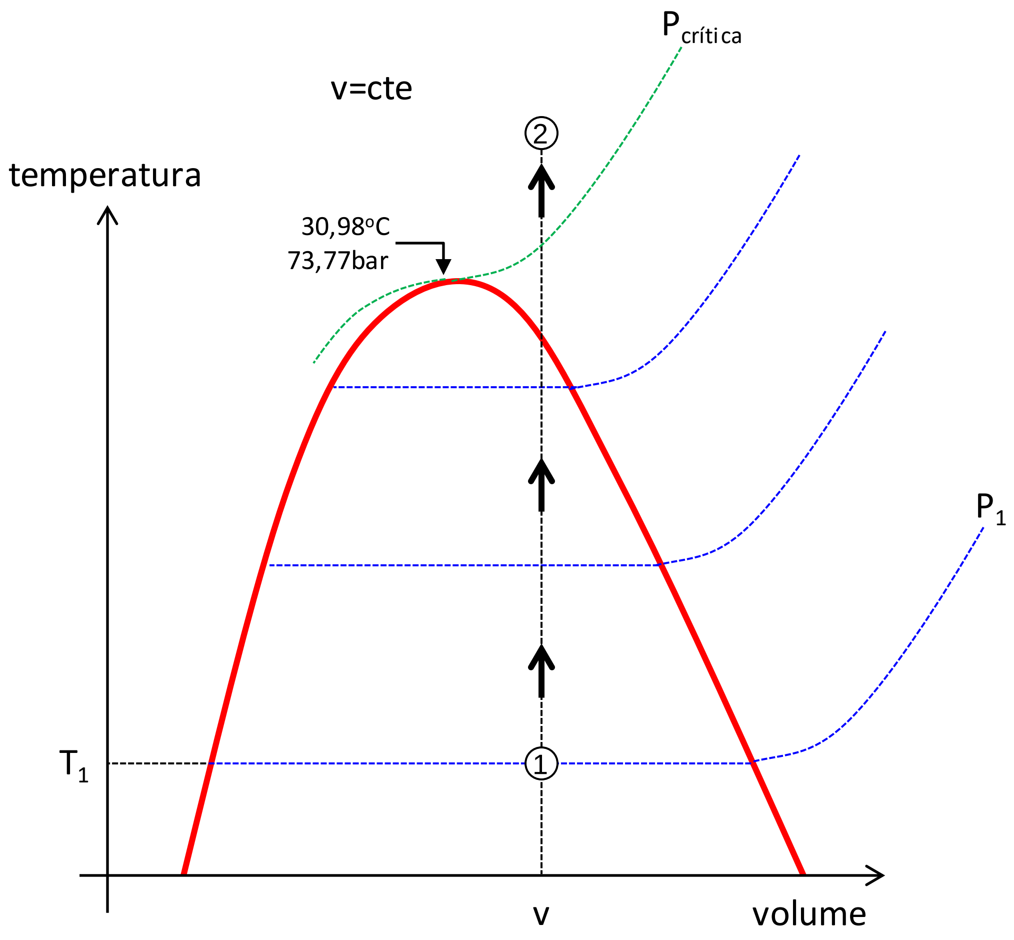
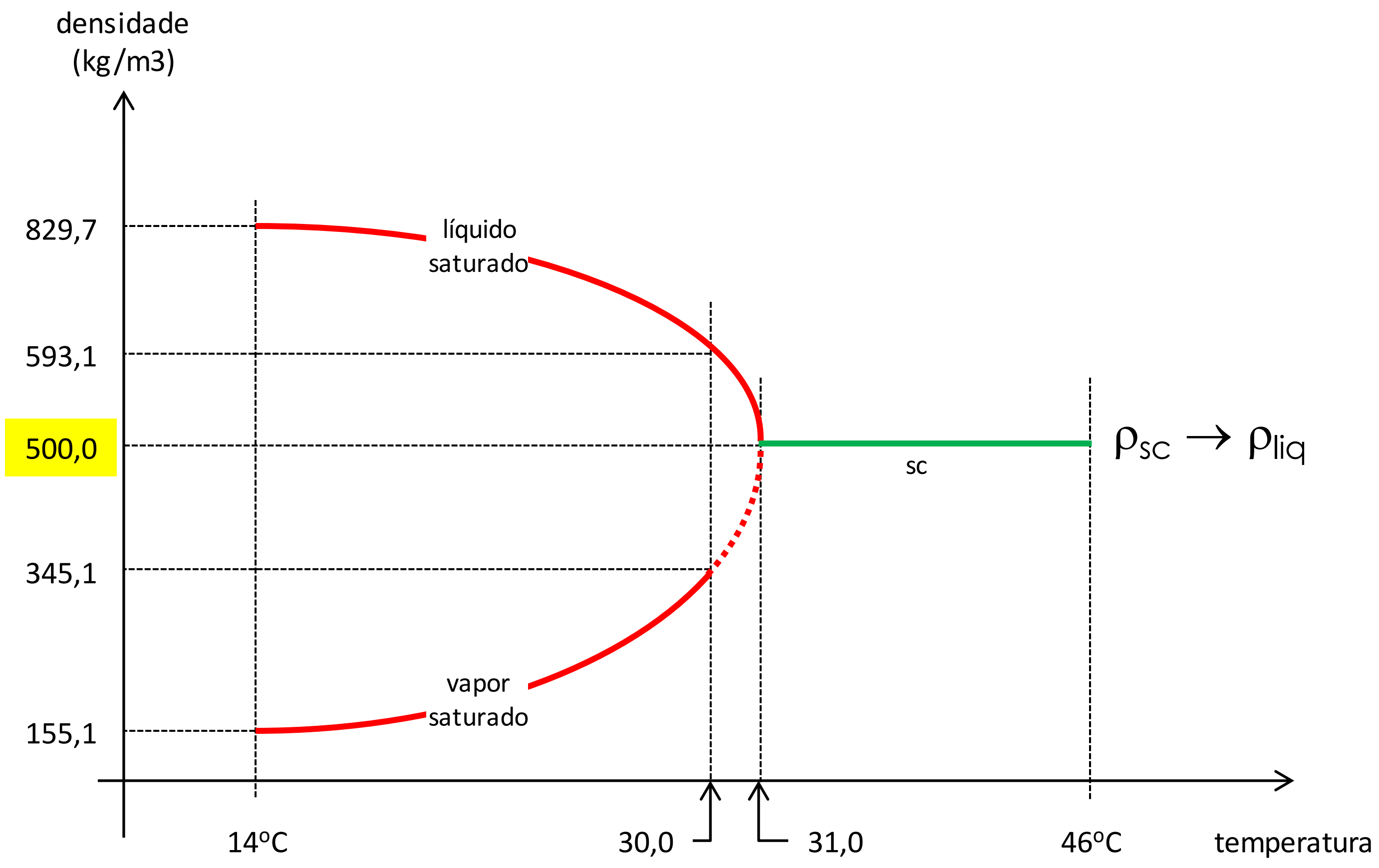
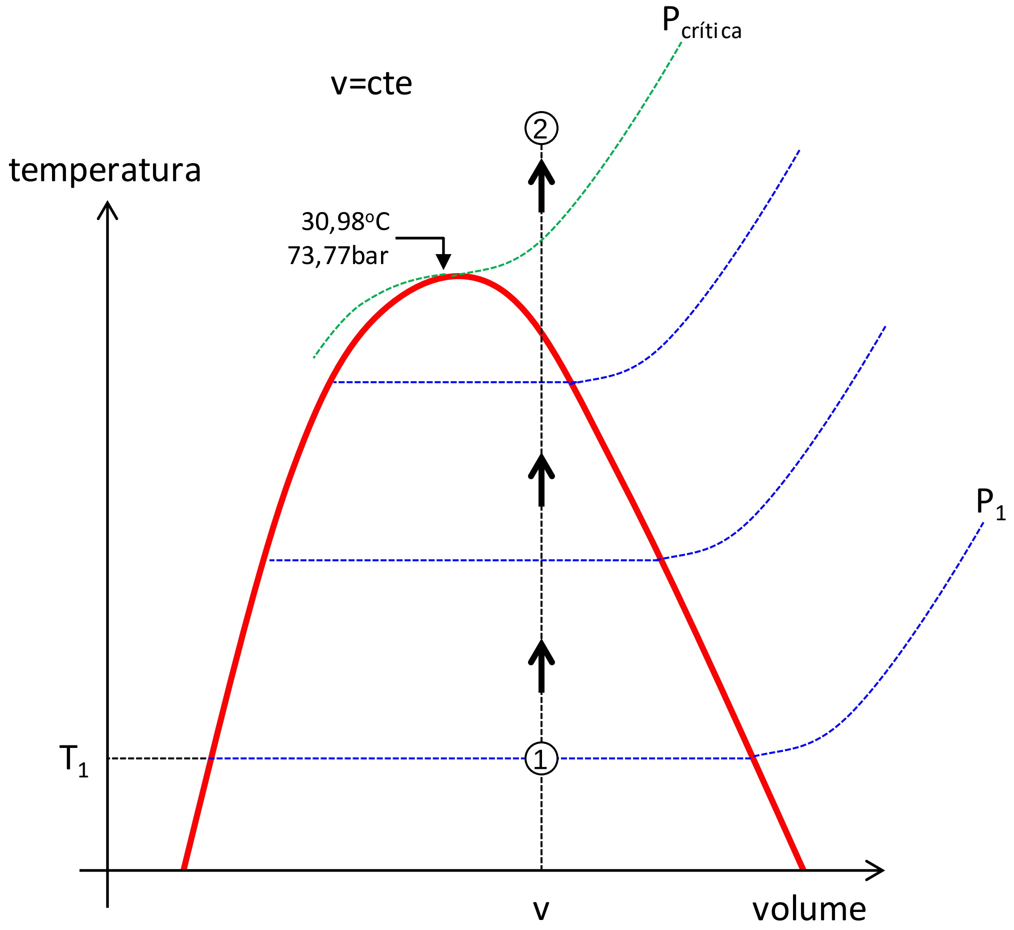


P crítica
v=cte
2
temperatura
30,98°C
73,77bar
P 1
T 1
1
v
volume



densidade
(kg/m3)
829,7
593,1
500,0
345,1
155,1
líquido
saturado
vapor
saturado
sc
ρsc → ρliq
14°C
30,0
31,0
46°C
temperatura

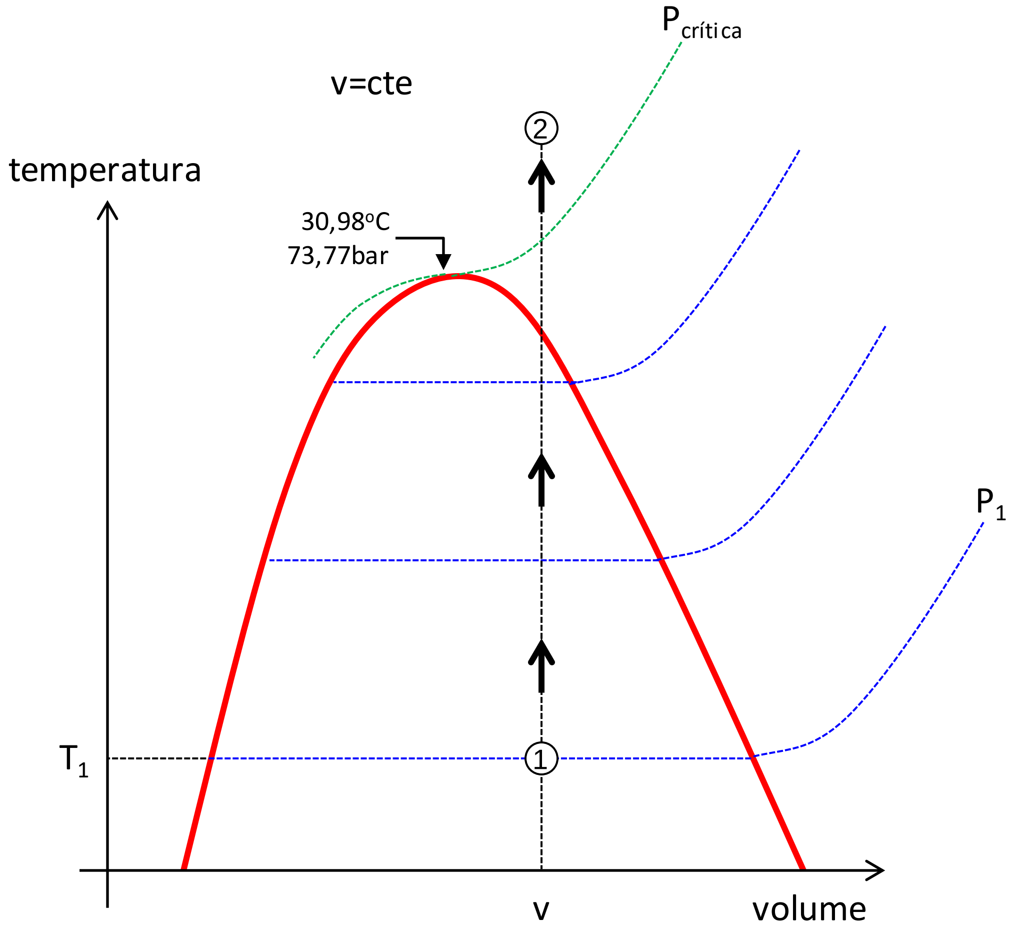


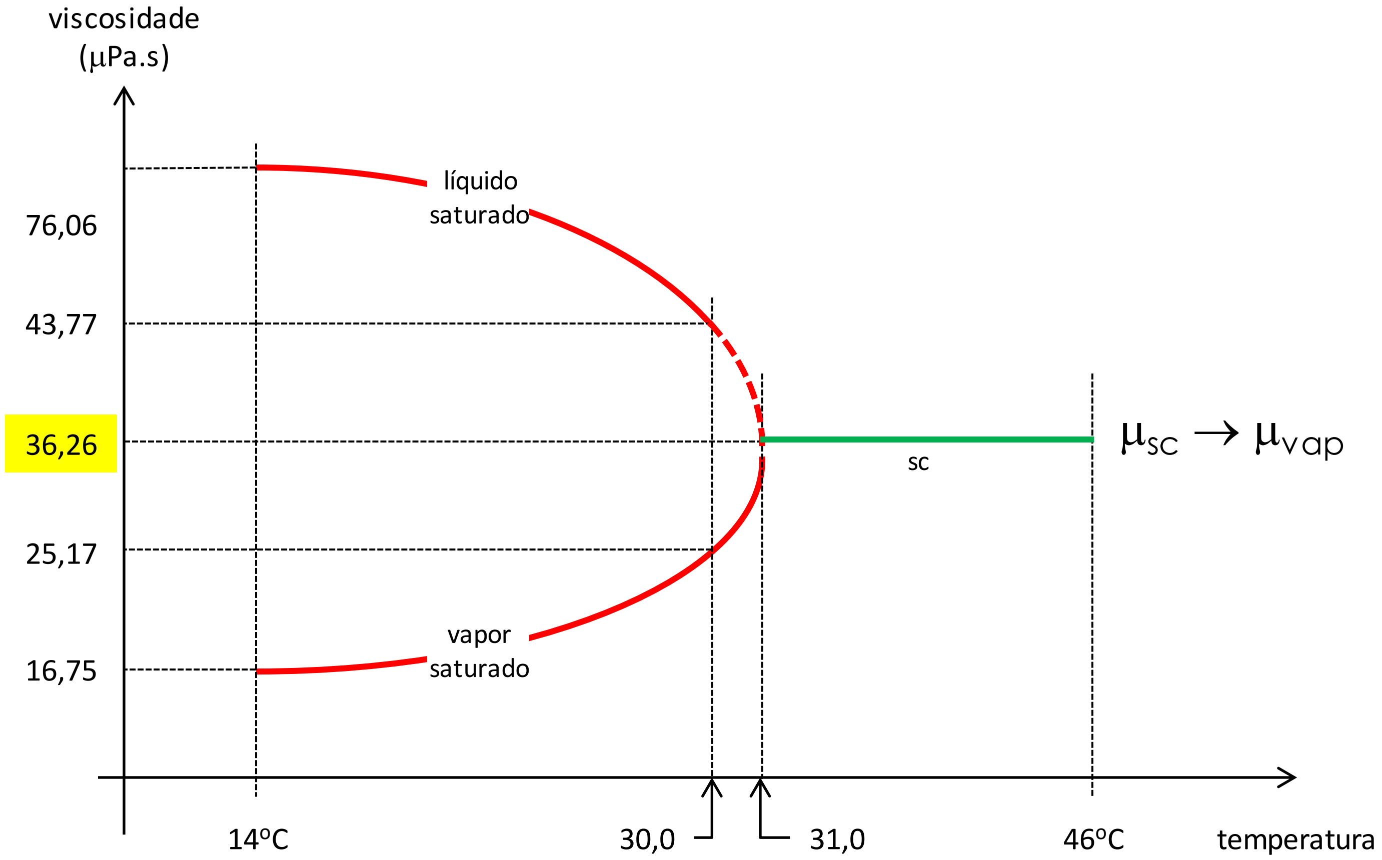
$$\nu = \mu / \rho$$

1: carbon dioxide: V/L sat. T=20, to 30, °C

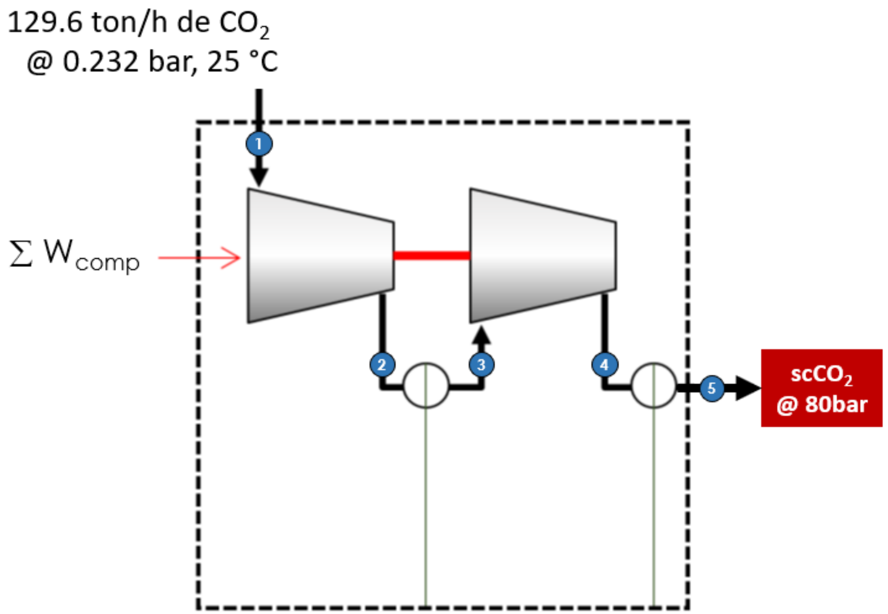
	Temperature (°C)	Pressure (bar)	Liquid Density (kg/m³)	Vapor Density (kg/m³)	Liquid Viscosity (µPa-s)	Vapor Viscosity (µPa-s)	Liquid Kin. Viscosity (cm²/s)	Vapor Kin. Viscosity (cm²/s)	Liquid Flow Exergy (kJ/kg)	Vapor Flow Exergy (kJ/kg)
1	20,000	57,291	773,39	194,20	66,148	18,187	0,00085530	0,00093653	212,62	210,03
2	21,000	58,648	762,40	202,32	64,427	18,501	0,00084505	0,00091446	212,75	210,76
3	22,000	60,031	750,77	211,08	62,670	18,847	0,00083474	0,00089284	212,89	211,46
4	23,000	61,440	738,36	220,62	60,865	19,231	0,00082432	0,00087166	213,05	212,15
5	24,000	62,877	725,02	231,10	58,998	19,663	0,00081374	0,00085086	213,23	212,80
6	25,000	64,342	710,50	242,73	57,048	20,157	0,00080292	0,00083040	213,43	213,43
7	26,000	65,837	694,46	255,86	54,984	20,731	0,00079175	0,00081024	213,65	214,02
8	27,000	67,361	676,36	271,01	52,761	21,417	0,00078007	0,00079027	213,89	214,57
9	28,000	68,918	655,28	289,11	50,302	22,272	0,00076764	0,00077037	214,17	215,08
10	29,000	70,509	629,36	312,03	47,450	23,411	0,00075395	0,00075027	214,49	215,53
11	30,000	72,137	593,31	345,10	43,768	25,170	0,00073769	0,00072936	214,88	215,88

As questões postadas no Chat do YouTube serão respondidas ao final da aula.



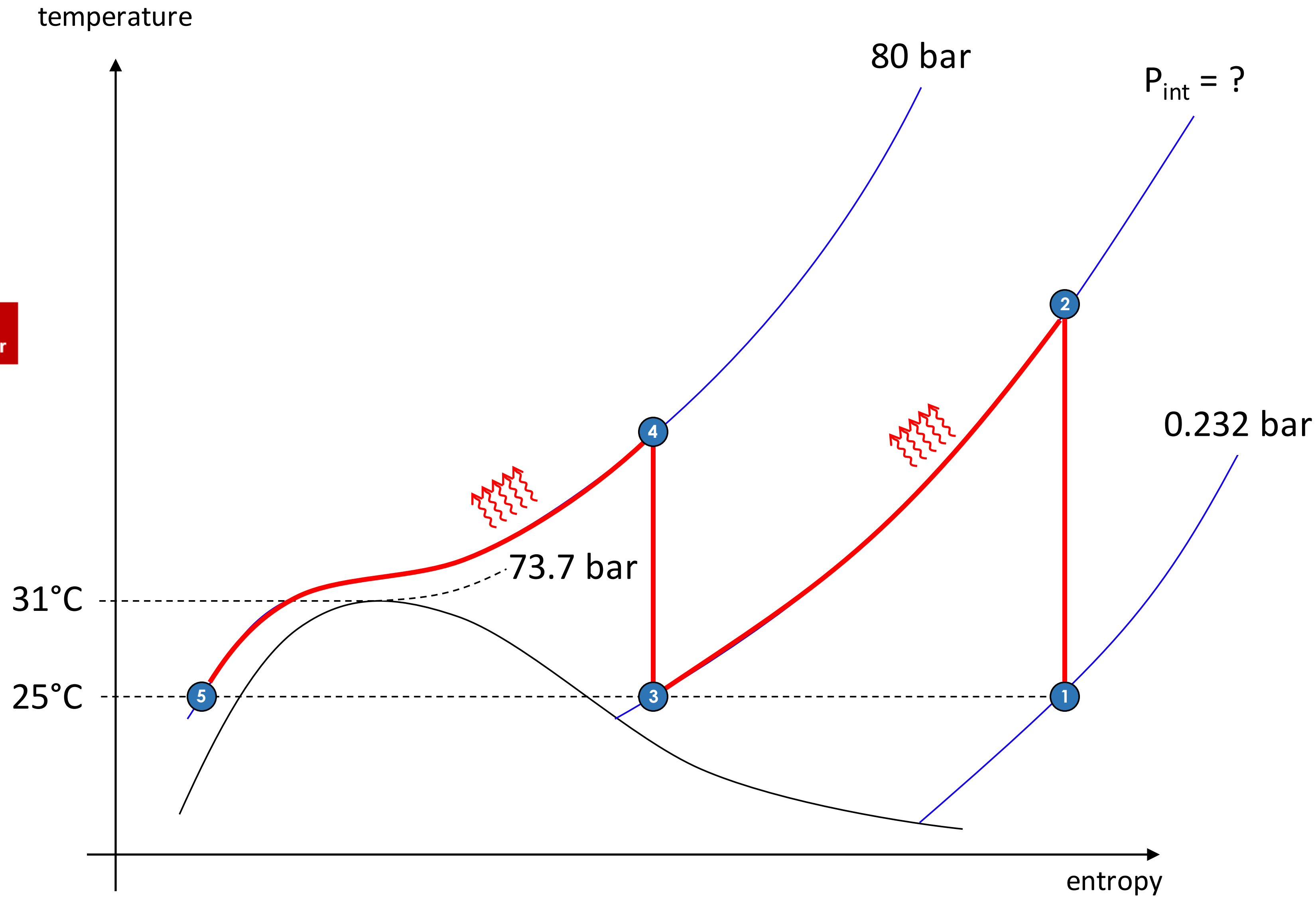


$$\left.\begin{array}{l}\rho_{sc} \rightarrow \rho_{liq} \\ \mu_{sc} \rightarrow \mu_{vap}\end{array}\right\} \quad \nu = \mu / \rho \rightarrow 0$$



$$\Sigma W_{comp} = W_{12} + W_{34}$$

$$\Sigma W_{comp} = f(P_{int})$$



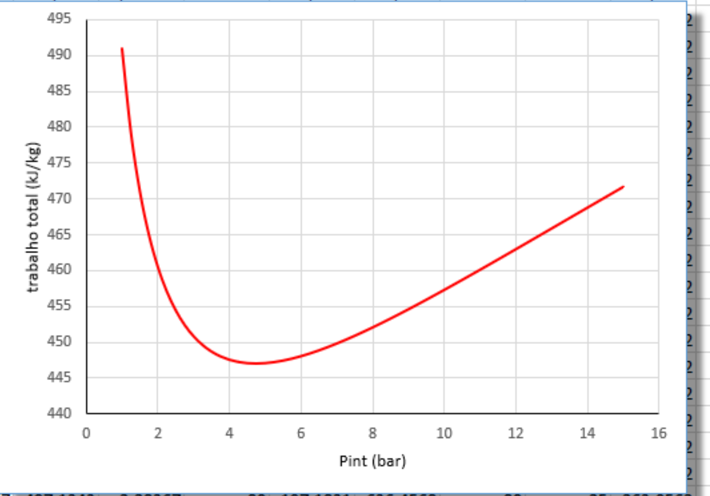
$$\text{minimize } \Sigma W_{comp} = f(P_{int})$$

$$\text{constrained to } (P_1, T_1), (T_3 = 70°C) \ldots$$

min W compressão scCO2.xlsx - Excel

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	T1	25	oC		Pint	w12	q23	w34	q45	soma w	P1	T1	s1	h1	s2 = s1	P2
2	P1	0,232	bar		1	-96,5821	-97,294	-394,325	-637,122	490,9066	0,232	25	3,017013	506,5658	3,017013	1
3	P5	80	bar		1,25	-114,063	-115,008	-365,15	-607,715	479,2133	0,232	25	3,017013	506,5658	3,017013	1,25
4	T5	25	oC		1,5	-128,929	-130,107	-342,079	-584,411	471,008	0,232	25	3,017013	506,5658	3,017013	1,5
5					1,75	-141,915	-143,327	-323,098	-565,196	465,0139	0,232	25	3,017013	506,5658	3,017013	1,75
6					2	-153,481	-155,127	-307,037	-548,901	460,5187	0,232	25	3,017013	506,5658	3,017013	2
7					2,25	-163,931	-165,812	-293,159	-534,788	457,0901	0,232	25	3,017013	506,5658	3,017013	2,25
8					2,5	-173,478	-175,595	-280,97	-522,364	454,4488	0,232	25	3,017013	506,5658	3,017013	2,5
9					2,75	-182,28	-184,632	-270,125	-511,283	452,4055	0,232	25	3,017013	506,5658	3,017013	2,75
10					3	-190,454	-193,042	-260,373	-501,295	450,8272	0,232	25	3,017013	506,5658	3,017013	3
11					3,25	-198,091	-200,916	-251,526	-492,211	449,6173	0,232	25	3,017013	506,5658	3,017013	3,25
12					3,5	-205,264	-208,326	-243,44	-483,887	448,7038	0,232	25	3,017013	506,5658	3,017013	3,5
13					3,75	-212,03	-215,331	-236,002	-476,211	448,0323	0,232	25	3,017013	506,5658	3,017013	3,75
14					4	-218,438	-221,977	-229,122	-469,093	447,5602	0,232	25	3,017013	506,5658	3,017013	4
15					4,25	-224,527	-228,305	-222,728	-462,459	447,2545	0,232	25	3,017013	506,5658	3,017013	4,25
16					4,5	-230,33	-234,347	-216,759	-456,251	447,0885	0,232	25	3,017013	506,5658	3,017013	4,5
17	447				4,75	-235,875	-240,133	-211,166	-450,418	447,0407	0,232	25	3,017013	**506,5658**	3,017013	4,75
18					5	-241,186	-245,684	-205,908	-444,919	447,0938	0,232	25	3,017013	506,5658	3,017013	5
19					5,25	-246,284	-251,024	-200,949	-439,719	447,2333	0,232	25	3,017013	506,5658	3,017013	5,25
20					5,5	-251,187	-256,168	-196,26	-434,788	447,4471	0,232	25	3,017013	506,5658	3,017013	5,5
21					5,75	-255,911	-261,134	-191,815	-430,101	447,7254	0,232	25	3,017013	506,5658	3,017013	5,75
22					6	-260,469	-265,935	-187,591	-425,634	448,0596	0,232	25	3,017013	506,5658	3,017013	6
23					6,25	-264,874	-270,584	-183,569	-421,368	448,4425	0,232	25	3,017013	506,5658	3,017013	6,25
24					6,5	-269,137	-275,09	-179,731	-417,287	448,8681	0,232	25	3,017013	506,5658	3,017013	6,5
25					6,75	-273,267	-279,465	-176,064	-413,375	449,331	0,232	25	3,017013	506,5658	3,017013	6,75
26					7	-277,273	-283,717	-172,554	-409,62	449,8267	0,232	25	3,017013	506,5658	3,017013	7
27					7,25	-281,164	-287,853	-169,188	-406,008	450,3514	0,232	25	3,017013	506,5658	3,017013	7,25
28					7,5	-284,946	-291,881	-165,956	-402,53	450,9014	0,232	25	3,017013	506,5658	3,017013	7,5
29					7,75	-288,625	-295,808	-162,849	-399,176	451,474	0,232	25	3,017013	506,5658	3,017013	7,75
30					8	-292,208	-299,638	-159,858	-395,938	452,0664	0,232	25	3,017013	506,5658	3,017013	8
31					8,25	-295,701	-303,379	-156,976	-392,807	452,6763	0,232	25	3,017013	506,5658	3,017013	8,25
32					8,5	-299,107	-307,034	-154,195	-389,778	453,3018	0,232	25	3,017013	506,5658	3,017013	8,5
33					8,75	-302,432	-310,608	-151,509	-386,843	453,941	0,232	25	3,017013	506,5658	3,017013	8,75
34					9	-305,68	-314,105	-148,913	-383,996	454,5923	0,232	25	3,017013	506,5658	3,017013	9
35					9,25	-308,854	-317,53	-146,401	-381,234	455,2543	0,232	25	3,017013	506,5658	3,017013	9,25
36					9,5	-311,958	-320,885	-143,968	-378,55	455,9257	0,232	25	3,017013	506,5658	3,017013	9,5
37					9,75	-314,996	-324,175	-141,61	-375,94	456,6054	0,232	25	3,017013	506,5658	3,017013	9,75
38					10	-317,97	-327,401	-139,323	-373,401	457,2925	0,232	25	3,017013	506,5658	3,017013	10

	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC
1	T2	h2	P3=P2	T3=T1	s3	h3	s4=s3	P4=P5	T4	h4	P5	T5	h5
2	133,0768	603,1478	1	25	2,739325	505,8538	2,739325	80	428,1986	900,1784	80	25	263,0562
3	151,5157	620,6291	1,25	25	2,696622	505,621	2,696622	80	402,9392	870,771	80	25	263,0562
4	166,9834	635,4944	1,5	25	2,66163	505,3877	2,66163	80	382,8062	847,4671	80	25	263,0562
5	180,3485	648,4812	1,75	25	2,631959	505,154	2,631959	80	366,1297	828,2524	80	25	263,0562
6	192,1421	660,0471	2	25	2,606182	504,9197	2,606182	80	351,9344	811,9571	80	25	263,0562
7	202,7138	670,4967	2,25	25	2,583378	504,6849	2,583378	80	339,6023	797,844	80	25	263,0562
8	212,3064	680,0442	2,5	25	2,56292	504,4496	2,56292	80	328,7184	785,4199	80	25	263,0562
9	221,0957	688,8458	2,75	25	2,544359	504,2138	2,544359	80	318,9906	774,3392	80	25	263,0562
10	229,2134	697,0195	3	25	2,527365	503,9774	2,527365	80	310,2059	764,3509	80	25	263,0562
11	236,7608	704,6566	3,25	25	2,511685	503,7405	2,511685	80	302,2046	755,267	80	25	263,0562
12	243,8173	711,8293	3,5	25	2,497125	503,5031	2,497125	80	294,8636	746,9435	80	25	263,0562
13	250,4467	718,5958	3,75	25	2,48353	503,2652	2,48353	80	288,0865	739,2674	80	25	263,0562
14	256,7008	725,0038	4	25	2,470775	503,0268	2,470775	80	281,7962	732,149	80	25	263,0562
15	262,6223	731,0927	4,25	25	2,458758	502,7878	2,458758	80	275,93	725,5153	80	25	263,0562
16	268,2471	736,8956	4,5	25	2,447394	502,5482	2,447394	80	270,4366	719,3068	80	25	263,0562
17	273,6053	**742,4407**	4,75	25	2,436612	**502,3081**	2,436612	80	265,2732	**713,474**	80	25	**263,0562**
18	278,7225	747,7519	5	25	2,426353	502,0675	2,426353	80	260,4039	707,9752	80	25	263,0562
19	283,6209	752,85	5,25	25	2,416565	501,8263	2,416565	80	255,7983	702,7754	80	25	263,0562
20	288,3196	757,753	5,5	25	2,40720								
21	292,8353	762,4766	5,75	25	2,39823								
22	297,1826	767,0348	6	25	2,38961								
23	301,3745	771,4397	6,25	25	2,38132								
24	305,4223	775,7024	6,5	25	2,3733								
25	309,3363	779,8326	6,75	25	2,36562								
26	313,1257	783,839	7	25	2,35817								
27	316,7986	787,7296	7,25	25	2,35096								
28	320,3625	791,5114	7,5	25	2,34397								
29	323,8241	795,191	7,75	25	2,33719								
30	327,1895	798,7743	8	25	2,33060								
31	330,4642	802,2666	8,25	25	2,32419								
32	333,6533	805,6729	8,5	25	2,31796								
33	336,7615	808,9978	8,75	25	2,31189								
34	339,7931	812,2453	9	25	2,30597								
35	342,752	815,4195	9,25	25	2,30020								
36	345,6419	818,5238	9,5	25	2,29456								
37	348,4661	821,5615	9,75	25	2,28905								
38	351,2277	824,5357	10	25	2,28367	497,1343	2,28367	80	197,1831	636,4568	80	25	263,0562



Planilha1

h_1 = 506.57 kJ/kg

h_2 = 742.44 kJ/kg

h_3 = 502.31 kJ/kg

h_4 = 713.47 kJ/kg

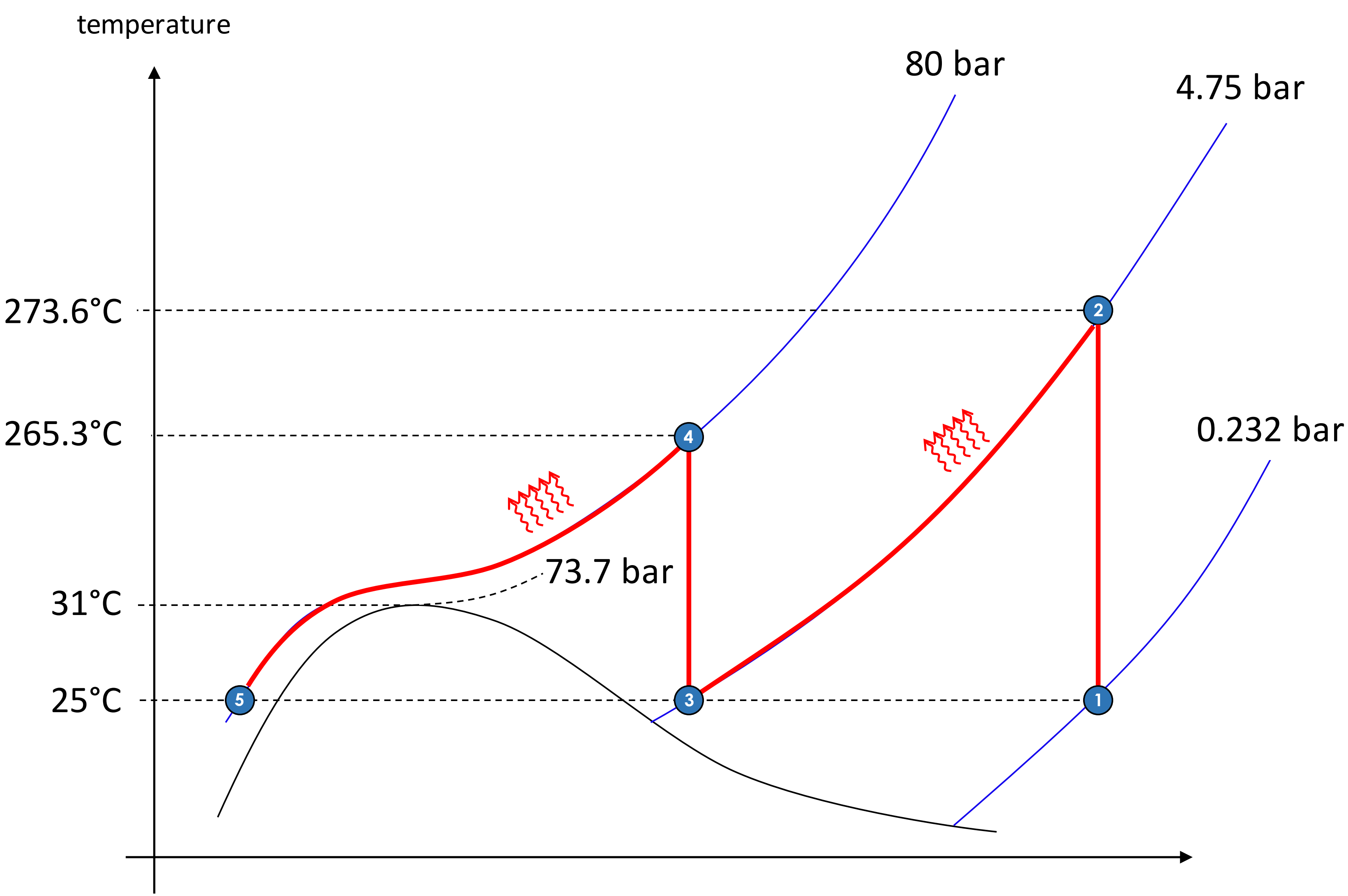
h_5 = 263.06 kJ/kg

w_{12} = -235.87 kJ/kg

q_{23} = -240.13 kJ/kg

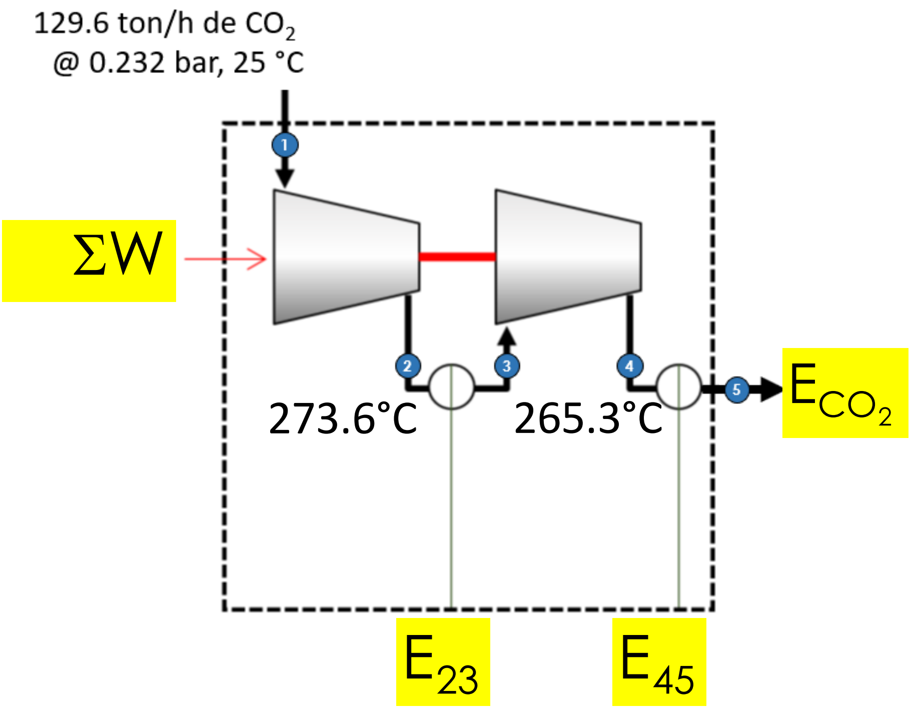
w_{34} = -211.16 kJ/kg

q_{45} = -450.41 kJ/kg



$$\text{minimize}\ \Sigma W_{comp} = f(P_{int})$$

$$\text{constrained to}\ (P_1, T_1), (T_3 = 70°C)\ldots$$

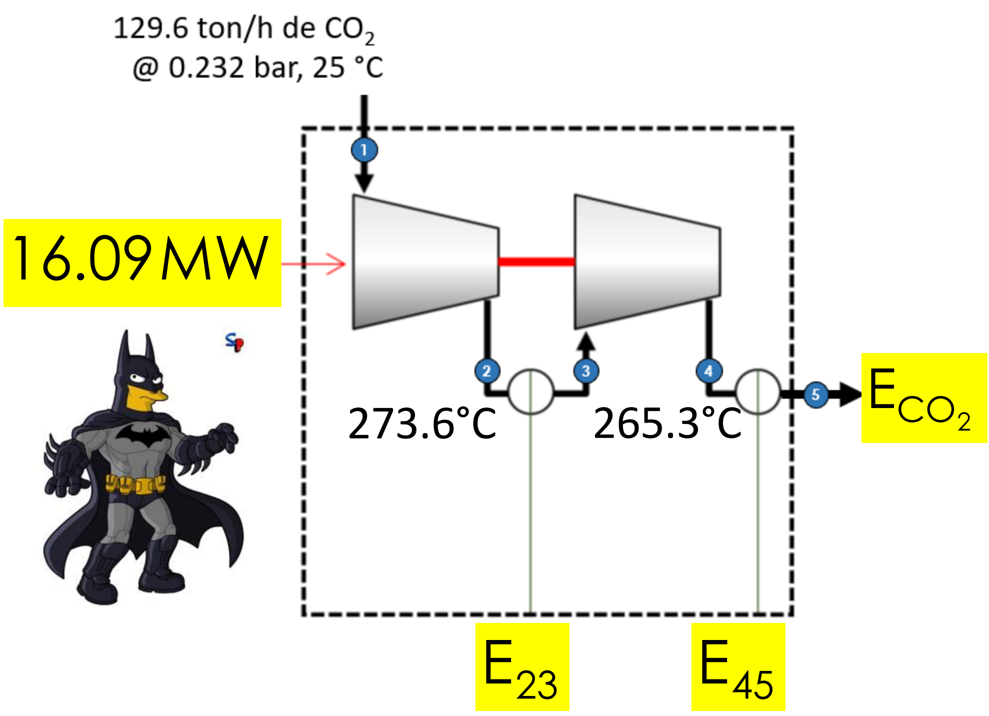


w_{12} = -235.87 kJ/kg

q_{23} = -240.13 kJ/kg

w_{34} = -211.16 kJ/kg

q_{45} = -450.41 kJ/kg



$$W_{12} = \frac{129.6 \cdot 10^3}{3600} \cdot 235.87 = 8.491\,MW$$

$$Q_{23} = \frac{129.6 \cdot 10^3}{3600} \cdot 240.13 = 8.645\,MW$$

$$W_{34} = \frac{129.6 \cdot 10^3}{3600} \cdot 211.16 = 7.602\,MW$$

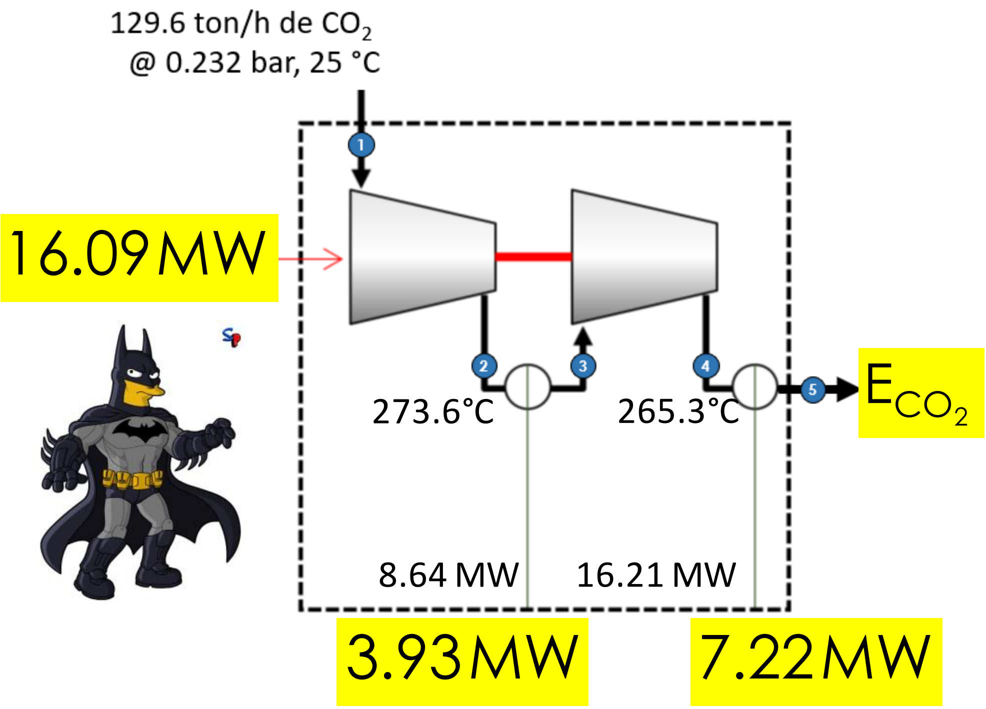
$$Q_{45} = \frac{129.6 \cdot 10^3}{3600} \cdot 450.41 = 16.21\,MW$$

w_{12} = -235.87 kJ/kg

q_{23} = -240.13 kJ/kg

w_{34} = -211.16 kJ/kg

q_{45} = -450.41 kJ/kg



$$E_{23}=\left(1-\frac{25+273.15}{(273.6+25)/2+273.15}\right)\cdot 8.64$$

$$E_{23}=3.928\,\text{MW}$$

$$E_{45}=\left(1-\frac{25+273.15}{(265.3+25)/2+273.15}\right)\cdot 16.21$$

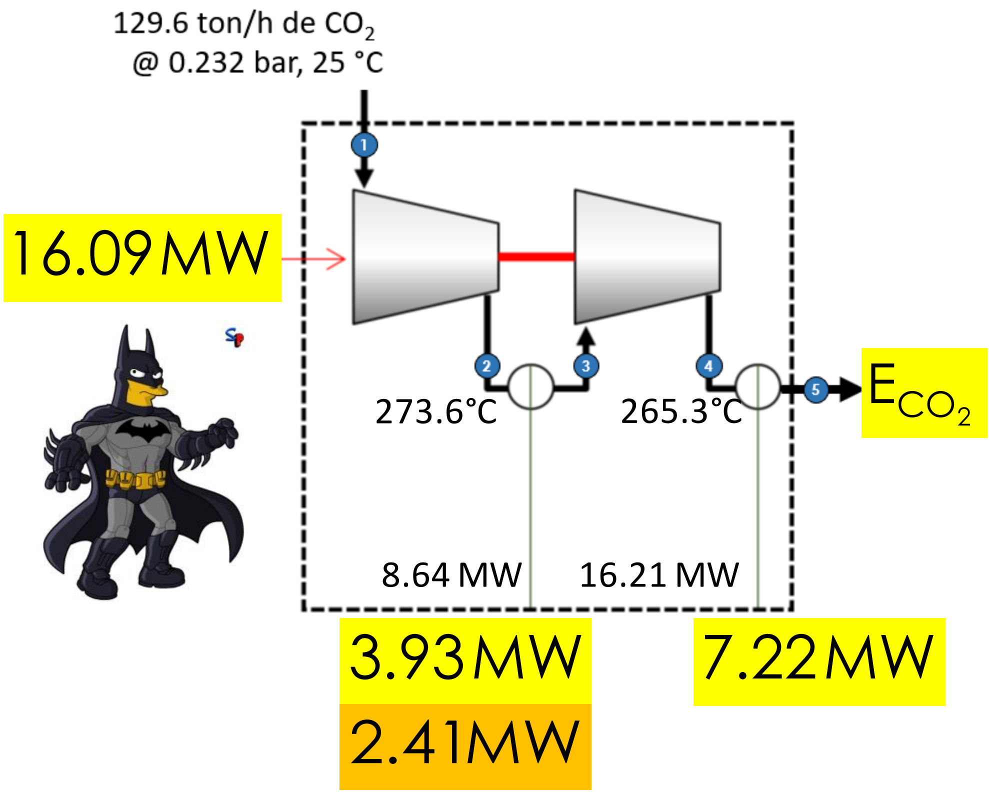
$$E_{45}=7.218\,\text{MW}$$

w_{12} = -235.87 kJ/kg

q_{23} = -240.13 kJ/kg

w_{34} = -211.16 kJ/kg

q_{45} = -450.41 kJ/kg



$$de_{23} = \left(1 - \frac{T_0}{T}\right) \cdot \delta Q = \left(1 - \frac{T_0}{T}\right) \cdot C_P(T) \cdot dT$$

$$e_{23} = \int_{T_2}^{T_3} \left(1 - \frac{T_0}{T}\right) \cdot C_P(T) \cdot dT$$

$$e_{23} = \int_{25}^{273.15} \left(1 - \frac{25 + 273.15}{T + 273.15}\right) \cdot (0.0007 \cdot T + 0.8623) \cdot dT$$

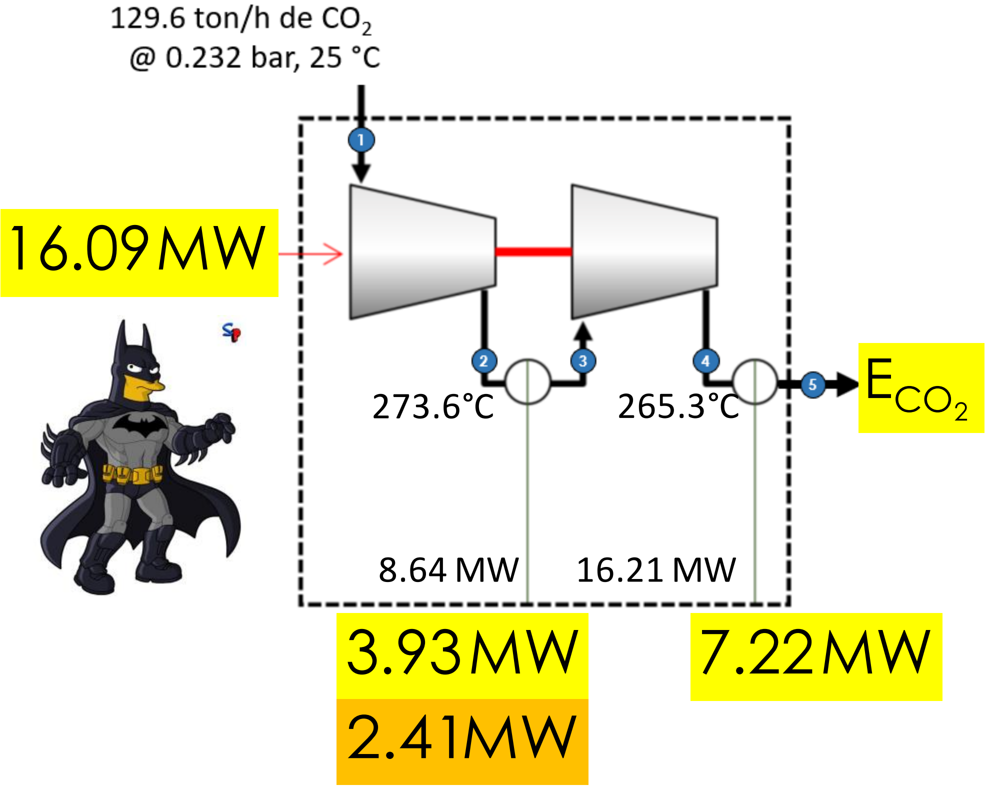
$$e_{23} = 67.133 \, kJ/kg$$

$$E_{23} = \frac{129.6 \cdot 10^3}{3600} 67.133 = 2.417 \, MW$$

$$C_P(T) = 0.0007 \cdot T + 0.8623$$

5: carbon dioxide: Specified state points

	Temperature (°C)	Pressure (bar)	Density (kg/m³)	Enthalpy (kJ/kg)	Cp (kJ/kg-K)
1	300,00	4,7500	4,3942	770,33	1,0643
2	250,00	4,7500	4,8195	717,84	1,0348
3	200,00	4,7500	5,3376	666,89	1,0028
4	150,00	4,7500	5,9835	617,60	0,96824
5	100,00	4,7500	6,8133	570,10	0,93150
6	50,000	4,7500	7,9249	524,46	0,89459
7	25,000	4,7500	8,6399	502,31	0,87797
8					



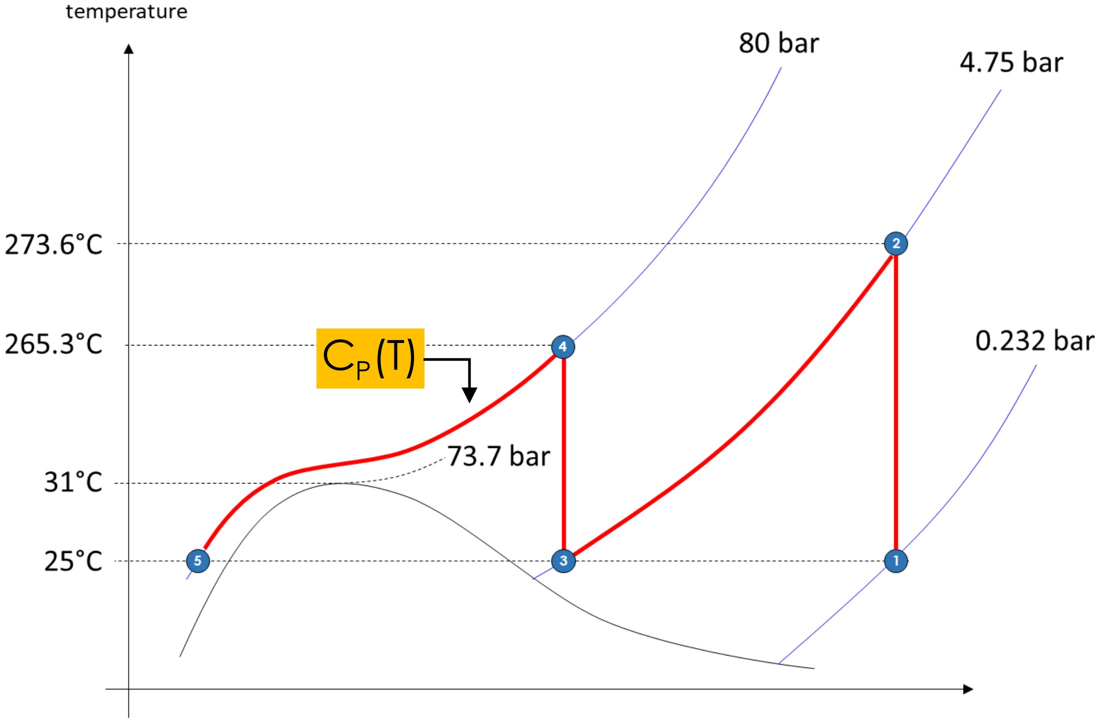
$$C_P(T) = 2.0024\cdot 10^{-9}\cdot T^4 - 1.7633\cdot 10^{-6}\cdot T^3 + \ldots$$
$$\ldots + 5.6896\cdot 10^{-4}\cdot T^2 - 7.9742\cdot 10^{-2}\cdot T + 5.2385$$

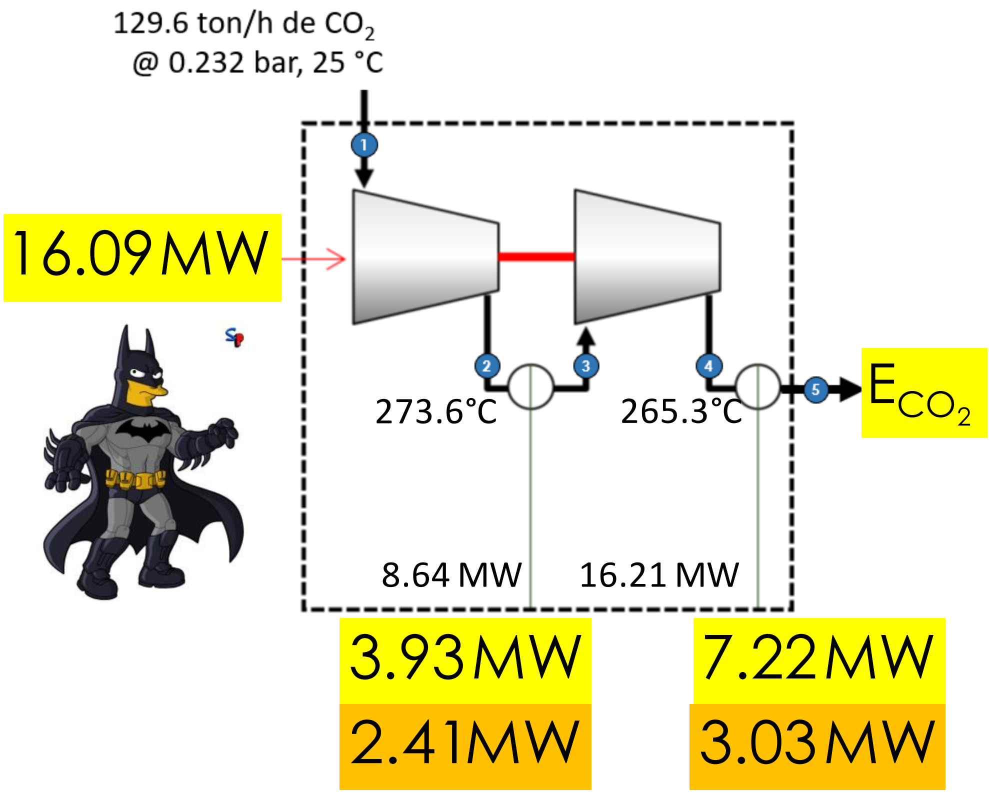
$$de_{45} = \left(1-\frac{T_0}{T}\right)\cdot \delta Q = \left(1-\frac{T_0}{T}\right)\cdot C_P(T)\cdot dT$$

$$de_{45} = \int_{T_4}^{T_5}\left(1-\frac{T_0}{T}\right)\cdot C_P(T)\cdot dT$$

5: carbon dioxide: Specified state points

	Temperature (°C)	Pressure (bar)	Density (kg/m³)	Enthalpy (kJ/kg)	Cp (kJ/kg-K)
1	300,00	4,7500	4,3942	770,33	1,0643
2	250,00	4,7500	4,8195	717,84	1,0348
3	200,00	4,7500	5,3376	666,89	1,0028
4	150,00	4,7500	5,9835	617,60	0,96824
5	100,00	4,7500	6,8133	570,10	0,93150
6	50,000	4,7500	7,9249	524,46	0,89459
7	25,000	4,7500	8,6399	502,31	0,87797
8					





$$C_P(T) = 2.0024 \cdot 10^{-9} \cdot T^4 - 1.7633 \cdot 10^{-6} \cdot T^3 + \ldots$$
$$\ldots + 5.6896 \cdot 10^{-4} \cdot T^2 - 7.9742 \cdot 10^{-2} \cdot T + 5.2385$$

5: carbon dioxide: Specified state points

	Temperature (°C)	Pressure (bar)	Density (kg/m³)	Enthalpy (kJ/kg)	Cp (kJ/kg-K)
1	300,00	4,7500	4,3942	770,33	1,0643
2	250,00	4,7500	4,8195	717,84	1,0348
3	200,00	4,7500	5,3376	666,89	1,0028
4	150,00	4,7500	5,9835	617,60	0,96824
5	100,00	4,7500	6,8133	570,10	0,93150
6	50,000	4,7500	7,9249	524,46	0,89459
7	25,000	4,7500	8,6399	502,31	0,87797
8					

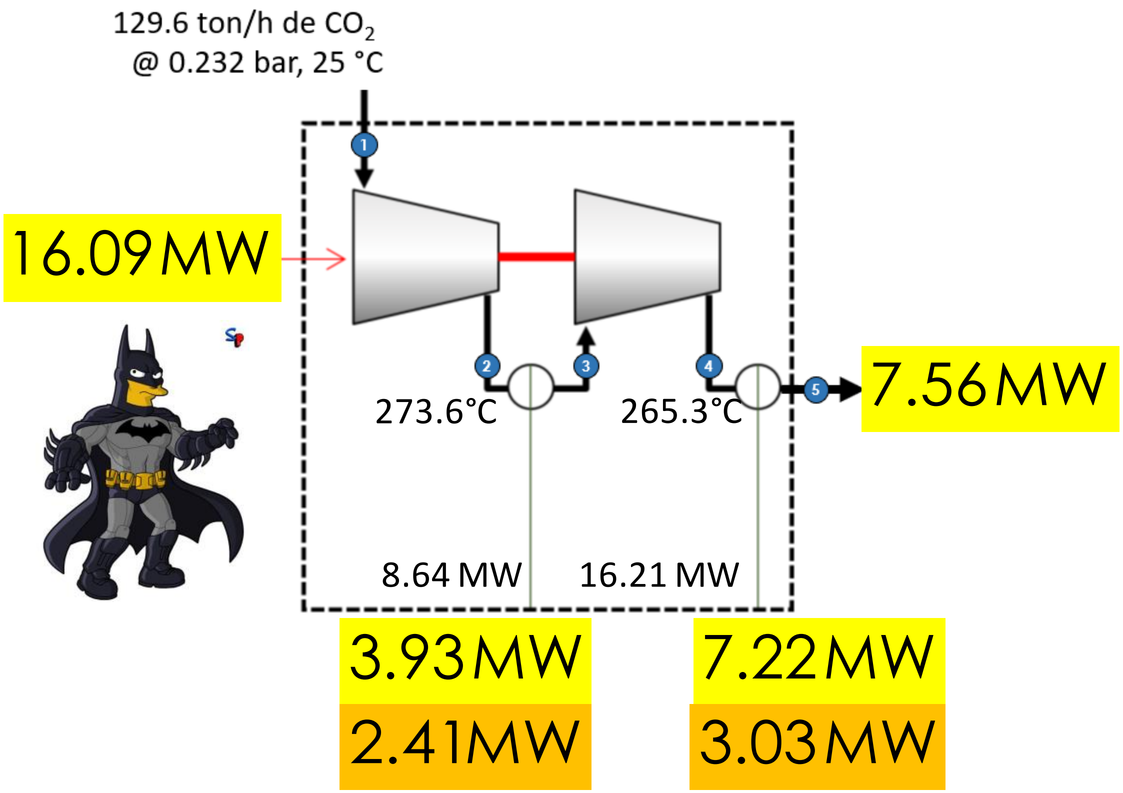
$$de_{45} = \left(1 - \frac{T_0}{T}\right) \cdot \delta Q = \left(1 - \frac{T_0}{T}\right) \cdot C_P(T) \cdot dT$$

$$de_{45} = \int_{T_4}^{T_5} \left(1 - \frac{T_0}{T}\right) \cdot C_P(T) \cdot dT$$

$$e_{23} = \int_{25}^{265.3} \left(1 - \frac{25 + 273.15}{T + 273.15}\right) \cdot \left(2.0024 \cdot 10^{-9} \cdot T^4 + \ldots\right.$$
$$\ldots - 1.7633 \cdot 10^{-6} \cdot T^3 + 5.6896 \cdot 10^{-4} \cdot T^2 - 7.9742 \cdot 10^{-2} \cdot T + \ldots$$
$$\left.\ldots + 5.2385\right) \cdot dT$$

$$e_{23} = 84.167 \, kJ/kg$$

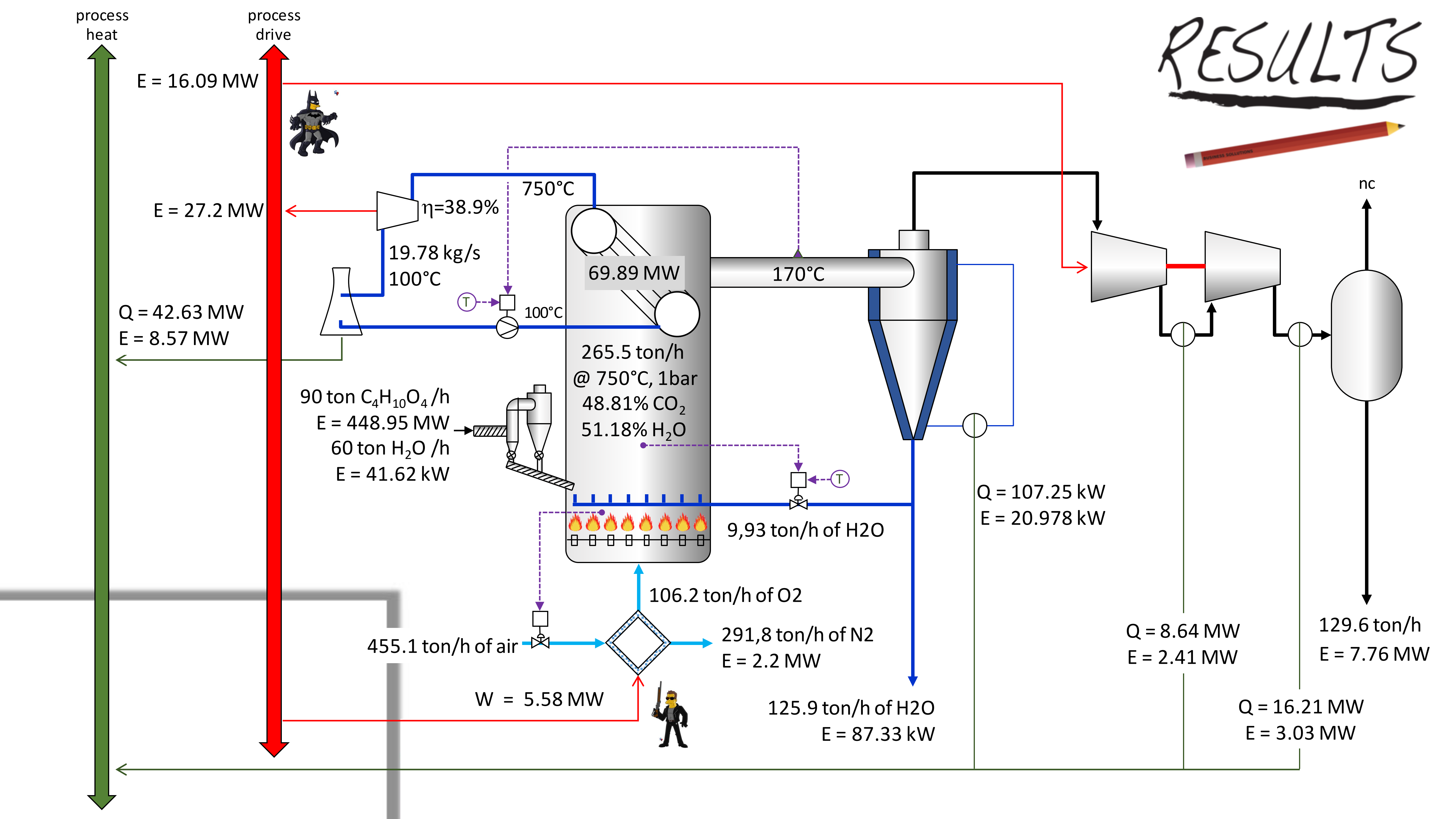
$$E_{23} = \frac{129.6 \cdot 10^3}{3600} 84.167 = 3.03 \, MW$$



$$e_{CO_2}\Big|_{25°C\,80bar} = 215.52\,kJ/kg$$

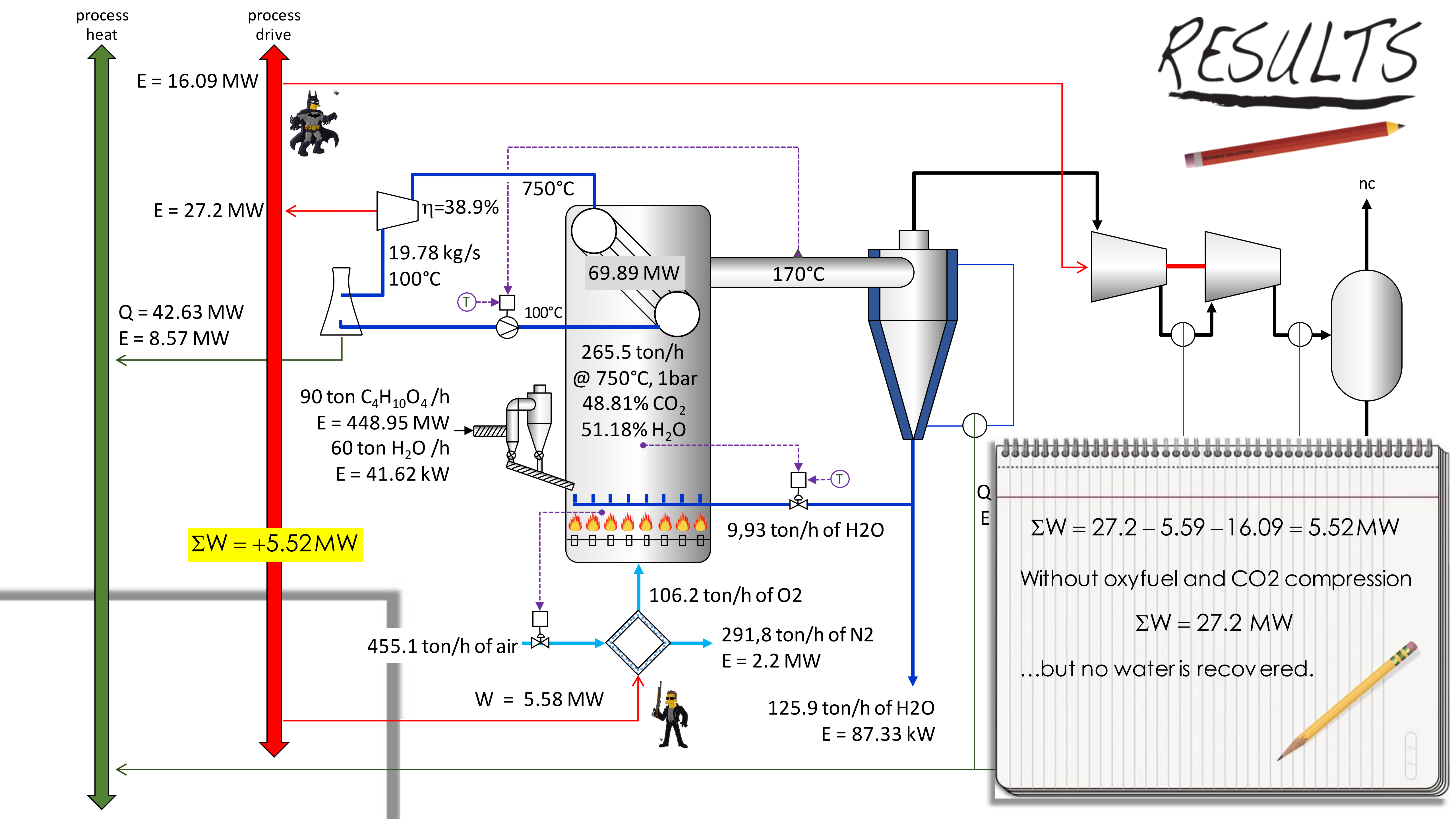
$$E_{CO_2} = \frac{129.6\cdot 10^3}{3600}\,215.52 = \ldots$$

$$E_{CO_2} = 7.759\ MW$$

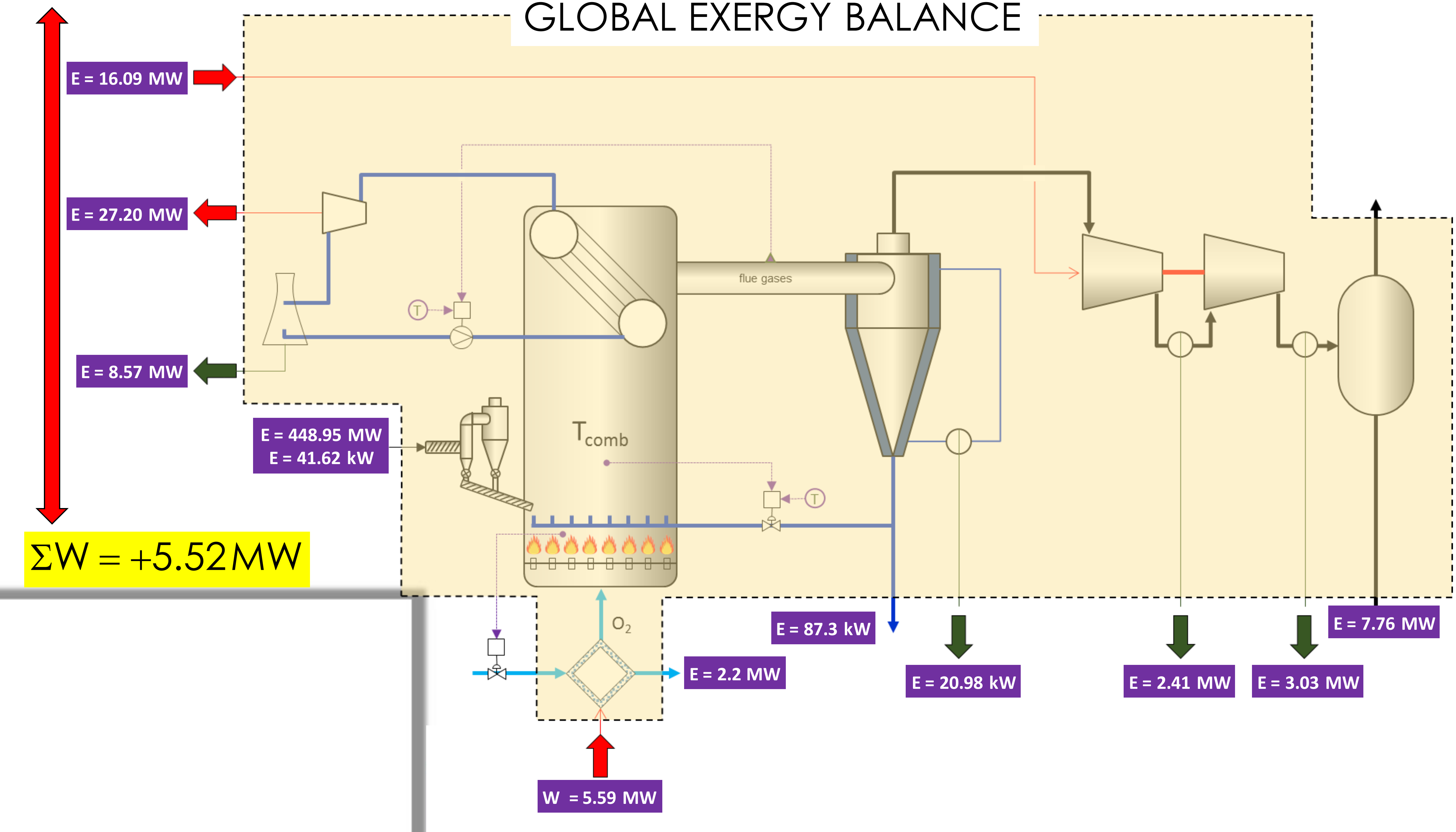


RESULTS
process heat
process drive
E = 16.09 MW
E = 27.2 MW
η=38.9%
750°C
19.78 kg/s
100°C
69.89 MW
170°C
Q = 42.63 MW
E = 8.57 MW
100°C
265.5 ton/h
@ 750°C, 1bar
48.81% CO_2
51.18% H_2O
90 ton $C_4H_{10}O_4$ /h
E = 448.95 MW
60 ton H_2O /h
E = 41.62 kW
9,93 ton/h of H2O
Q = 107.25 kW
E = 20.978 kW
nc
106.2 ton/h of O2
455.1 ton/h of air
291,8 ton/h of N2
E = 2.2 MW
W = 5.58 MW
125.9 ton/h of H2O
E = 87.33 kW
Q = 8.64 MW
E = 2.41 MW
129.6 ton/h
E = 7.76 MW
Q = 16.21 MW
E = 3.03 MW

Results and analysis…


RESULTS
process heat
process drive
E = 16.09 MW
E = 27.2 MW
η=38.9%
750°C
19.78 kg/s
100°C
Q = 42.63 MW
E = 8.57 MW
T
100°C
69.89 MW
170°C
265.5 ton/h
@ 750°C, 1bar
48.81% CO_2
51.18% H_2O
90 ton $C_4H_{10}O_4$ /h
E = 448.95 MW
60 ton H_2O /h
E = 41.62 kW
T
9,93 ton/h of H2O
ΣW = +5.52 MW
106.2 ton/h of O2
455.1 ton/h of air
291,8 ton/h of N2
E = 2.2 MW
W = 5.58 MW
125.9 ton/h of H2O
E = 87.33 kW
Q
E
nc
ΣW = 27.2 – 5.59 – 16.09 = 5.52 MW
Without oxyfuel and CO2 compression
ΣW = 27.2 MW
…but no water is recovered.

GLOBAL EXERGY BALANCE



GLOBAL EXERGY BALANCE

$$\sum\left(1-\frac{T_0}{T_k}\right)\dot{Q}_k-\left(\dot{W}-P_0\frac{dV_{vc}}{dt}\right)+\sum\dot{m}_e x_e-\sum\dot{m}_s x_s-\dot{X}_{dest}=\frac{dX_{vc}}{dt}$$

$$\dot{X}_{dest}=16.09-27.20-8.57+448.95+0.0416+5.59-2.2-0.0873-0.02098-2.41-3.03-7.76$$

$$\dot{X}_{dest}=419.393\,MW$$

$$\eta=\frac{5.52+17.09}{448.95}=5.04\%$$

$$\eta_{exergy}=1-\frac{419.393}{448.95+0.04162}=6.59\%$$

$$\Sigma W=+5.52\,MW$$

E = 16.09 MW

E = 27.20 MW

E = 8.57 MW

E = 448.95 MW
E = 41.62 kW

E = 87.3 kW

E = 2.2 MW

E = 20.98 kW

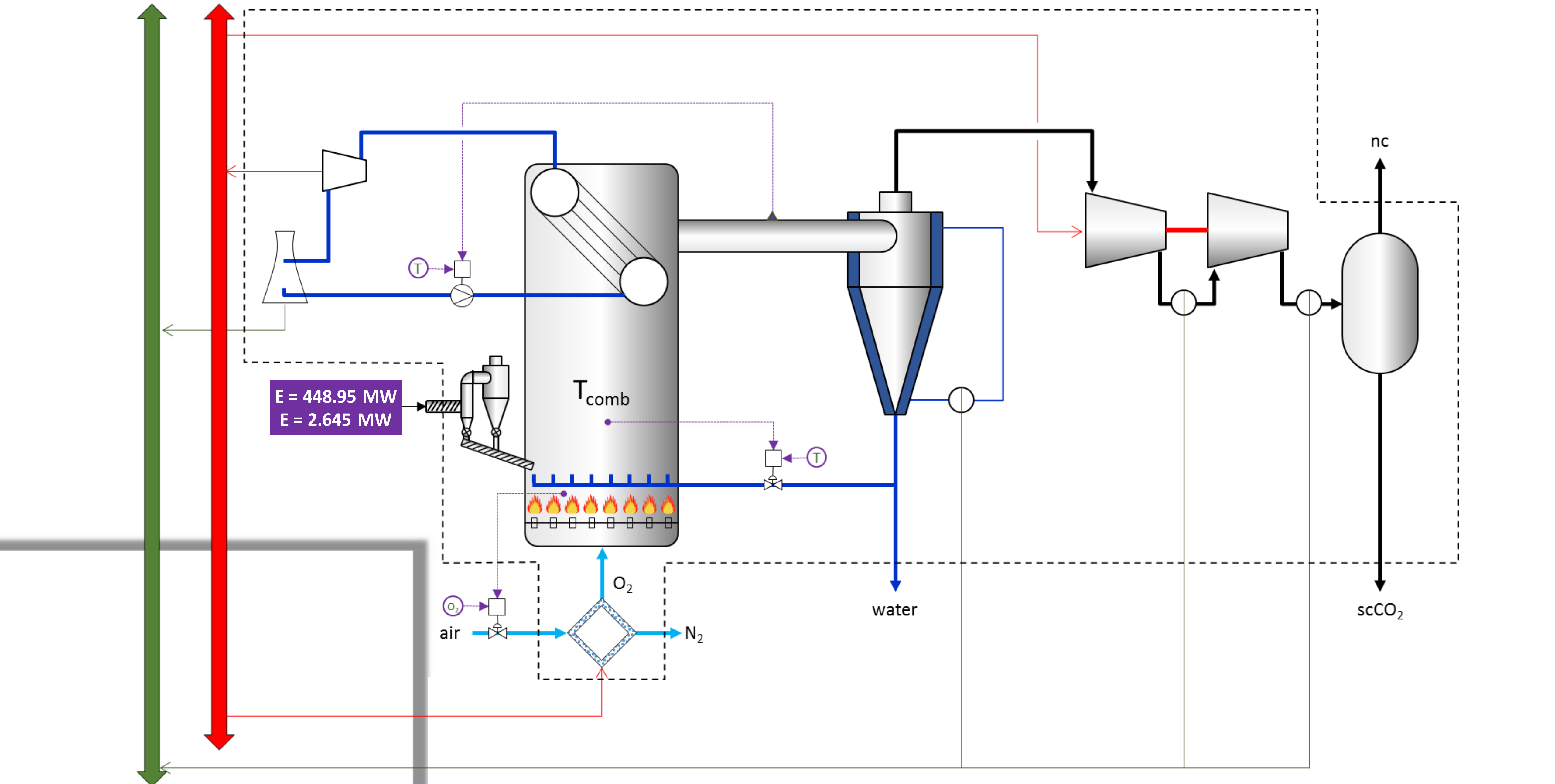
E = 2.41 MW

E = 3.03 MW

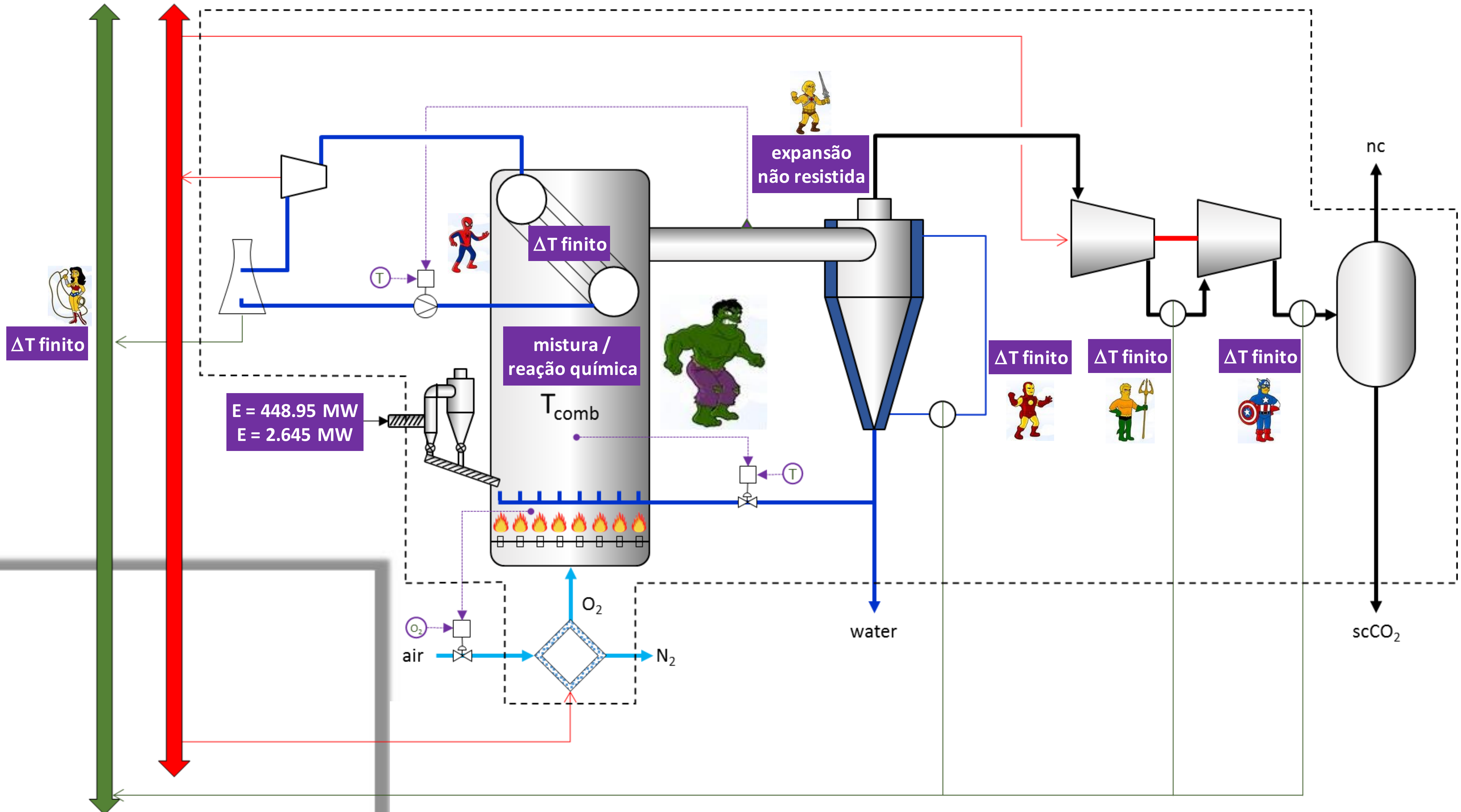
E = 7.76 MW

W = 5.59 MW

Sources of exergy destruction / Design optimizationc



Sources of exergy destruction / Design optimization



Combustion chamber exergy analysis...

$$1 \cdot C_4H_{10}O_4 + 4.5 \cdot O_2 + 5.3 \cdot H_2O \rightarrow 4 \cdot CO_2 + 10.3 \cdot H_2O$$

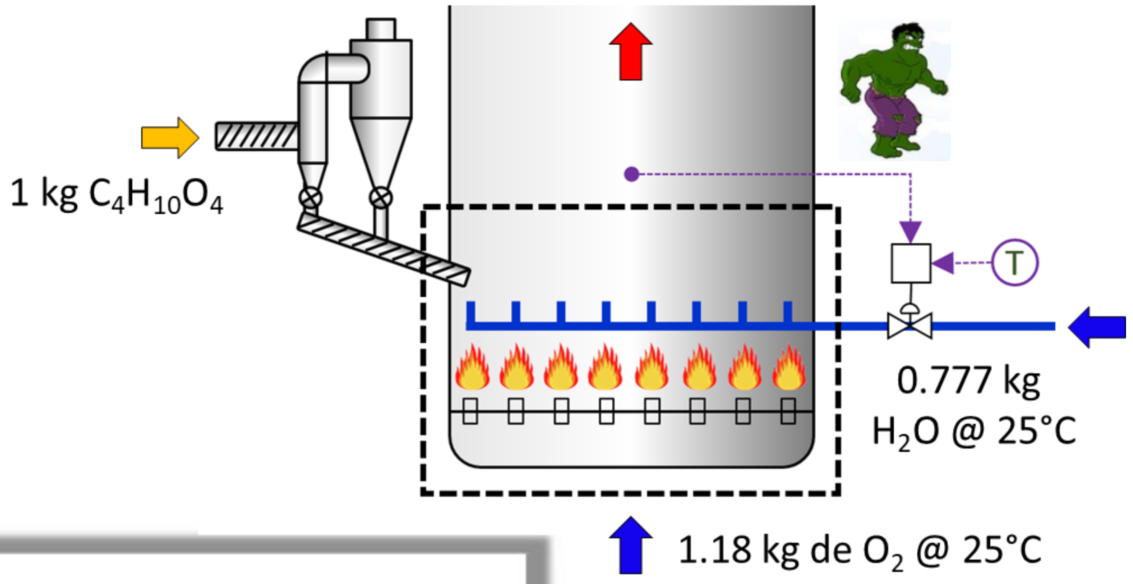


TABLE A-26 Standard Molar Chemical Exergy, $\bar{e}^{ch}$ (kJ/kmol), of Selected Substances at 298 K and p_0

Substance	Formula	Model I[a]	Model II[b]
Nitrogen	$N_2(g)$	640	720
Oxygen	$O_2(g)$	3,950	3,970
Carbon dioxide	$CO_2(g)$	14,175	19,870
Water	$H_2O(g)$	8,635	9,500
Water	$H_2O(l)$	45	900
Carbon (graphite)	$C(s)$	404,590	410,260
Hydrogen	$H_2(g)$	235,250	236,100
Sulfur	$S(s)$	598,160	609,600
Carbon monoxide	$CO(g)$	269,410	275,100
Sulfur dioxide	$SO_2(g)$	301,940	313,400
Nitrogen monoxide	$NO(g)$	88,850	88,900
Nitrogen dioxide	$NO_2(g)$	55,565	55,600
Hydrogen sulfide	$H_2S(g)$	799,890	812,000
Ammonia	$NH_3(g)$	336,685	337,900
Methane	$CH_4(g)$	824,350	831,650
Ethane	$C_2H_6(g)$	1,482,035	1,495,840
Methyl alcohol	$CH_3OH(g)$	715,070	722,300
Methyl alcohol	$CH_3OH(l)$	710,745	718,000
Ethyl alcohol	$C_2H_5OH(g)$	1,348,330	1,363,900
Ethyl alcohol	$C_2H_5OH(l)$	1,342,085	1,357,700

$$X_{dest} = \left[1 \cdot e_F + 4.5 \cdot e_{O2} + 5.3 \cdot e_{H2O}\right]_{@25°C} - \left[4 \cdot e_{CO2} + 10.3 \cdot e_{H2O}\right]_{@750°C}$$

Combustion chamber exergy analysis...

$$1 \cdot C_4H_{10}O_{4(s)} + 4.5 \cdot O_{2(g)} + 5.3 \cdot H_2O_{(\ell)} \rightarrow 4 \cdot CO_{2(g)} + 10.3 \cdot H_2O_{(g)}$$

$$e_F = e_F^{th}\Big|_{25^\circ C, 1bar} + e_F^{ch} = 0 + 2193 kJ/mol$$

$$e_{O2} = e_{O2}^{th}\Big|_{25^\circ C, 1bar} + e_{O2}^{ch} = 0 + 3.950\ kJ/mol$$

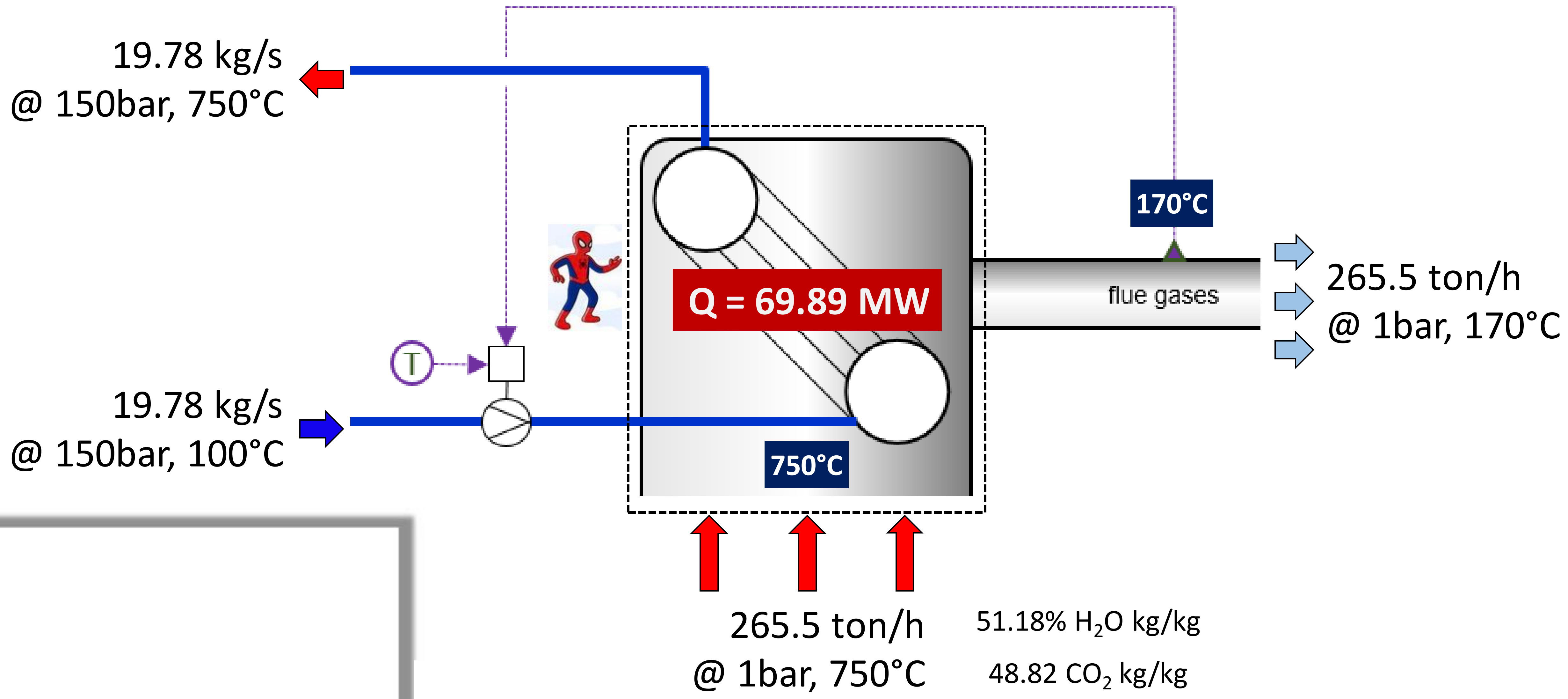
$$e_{H2O} = e_{H2O}^{th}\Big|_{25^\circ C, 1bar} + e_{H2O}^{ch} = 0 + 0.045 = 0.045\ kJ/mol$$

$$e_{CO2} = e_{CO2}^{th}\Big|_{750^\circ C, 0.28 bar} + e_{CO2}^{ch} = 14.598 + 14.175 = 28.773\ kJ/mol$$

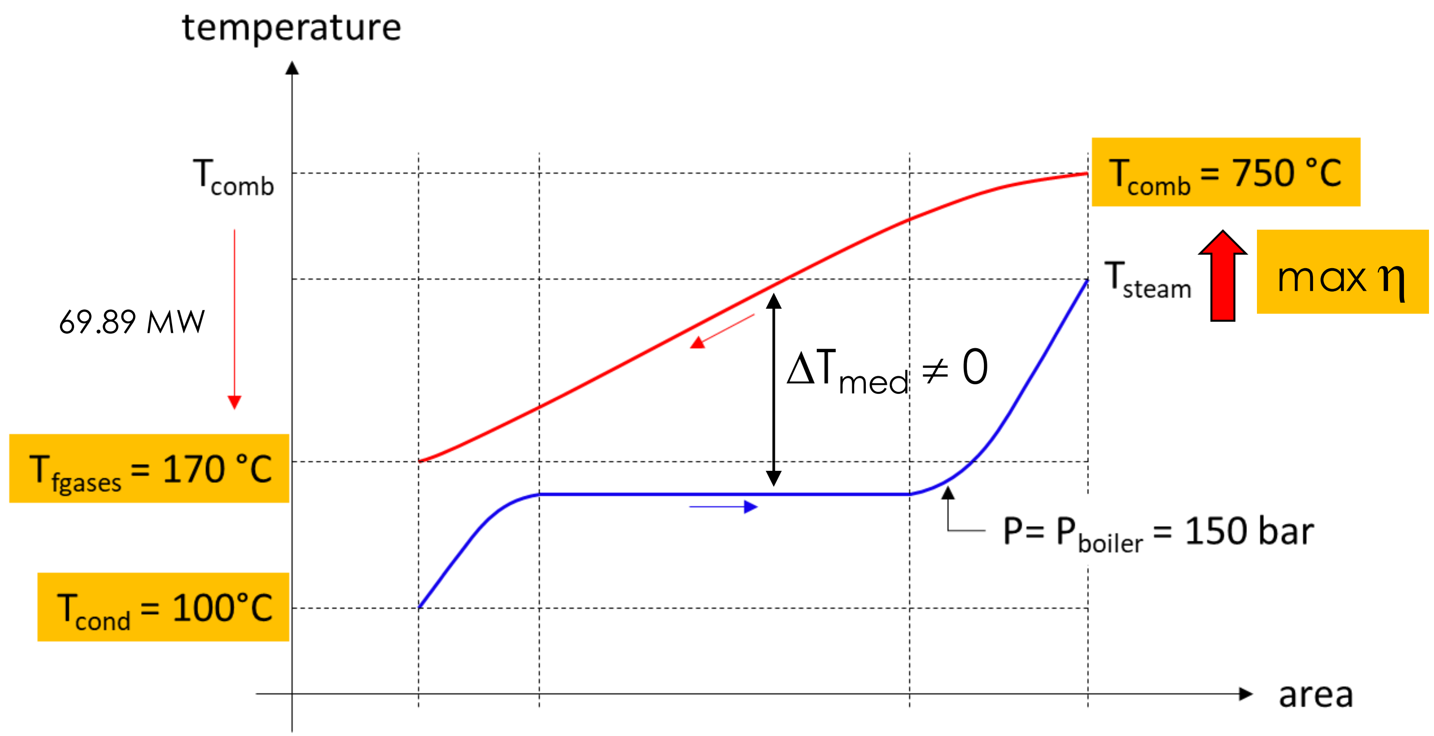
$$e_{H2O} = e_{H2O}^{th}\Big|_{750^\circ C, 0.72 bar} + e_{H2O}^{ch} = 21.33 + 0.045 = 21.375\ kJ/mol$$

$$x_{dest} = 1876 kJ/mol \rightarrow \eta = 1 - 1876/2193 = 14.5\%$$

Boiler heat exchangers exergy analysis…

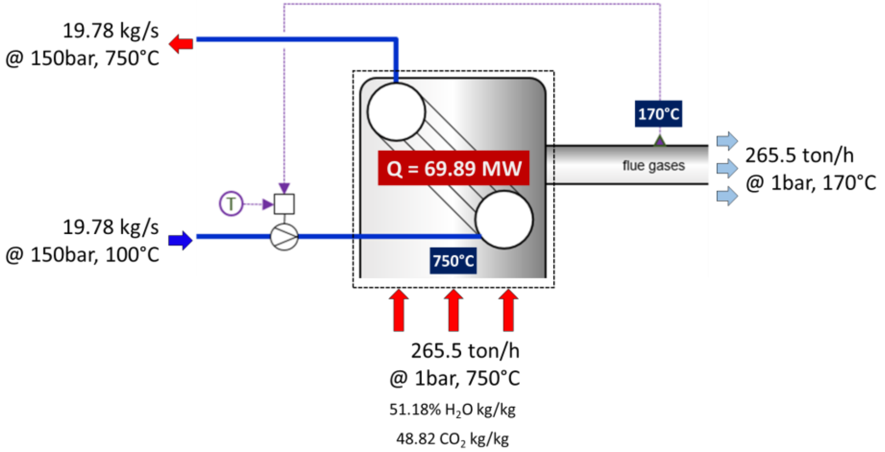


Sources of exergy destruction / Design optimization



Sources of irreversibilities:

- **Heat transfer at finite ΔT**
- Internal friction
- Non resisted expansion / compression
- Mixing of different substances
- Spontaneous chemical reaction
- Passage of electric current through a resistor
- Inelastic deformation of a solid body
- Shock waves in transonic flows



As questões postadas no Chat do YouTube serão respondidas ao final da aula.

$$\sum\left(1-\frac{T_0}{T_k}\right)\dot{Q}_k-\left(\dot{W}-P_0\frac{dV_{vc}}{dt}\right)+\sum\dot{m}_e x_e-\sum\dot{m}_s x_s-\dot{X}_{dest}=\frac{dX_{vc}}{dt}$$

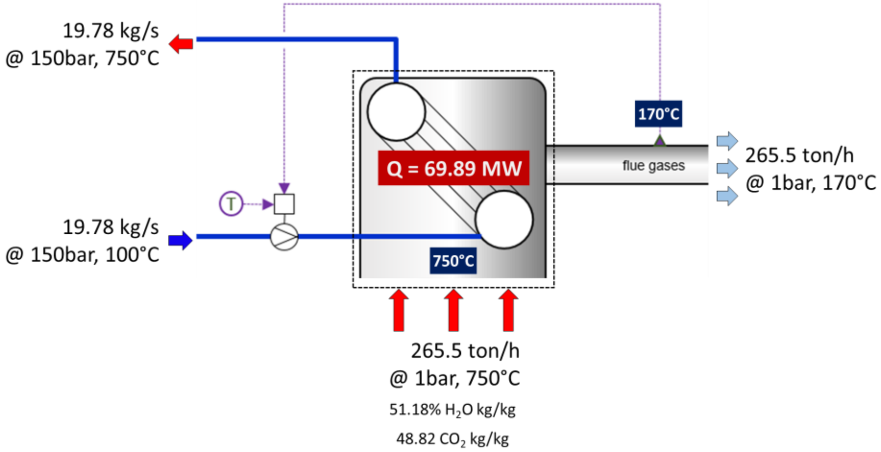
$$\dot{X}_{dest}=m_{steam}\Delta x_{steam}+m_{fgases}\Delta x_{fgases}$$

12: carbon dioxide/water: Specified state points (48,82/51,18)

	Temperature (°C)	Pressure (bar)	Density (kg/m³)	Enthalpy (kJ/kg)	Quality (kg/kg)	Flow Exergy (kJ/kg)
1	750,00	1,0000	0,29761	2701,6	Superheated	1033,6
2	170,00	1,0000	0,68996	1754,1	Superheated	488,11
3						

11: water: Specified state points

	Temperature (°C)	Pressure (bar)	Density (kg/m³)	Enthalpy (kJ/kg)	Quality (kg/kg)	Flow Exergy (kJ/kg)
1	100,00	150,00	965,20	430,39	Subcooled	207,31
2	750,00	150,00	32,906	3965,2	Superheated	2016,5
3						



YouTube

As questões postadas no Chat do YouTube serão respondidas ao final da aula.

$$\sum\left(1-\frac{T_0}{T_k}\right)\dot{Q}_k-\left(\dot{W}-P_0\frac{dV_{vc}}{dt}\right)+\sum\dot{m}_e x_e-\sum\dot{m}_s x_s-\dot{X}_{dest}=\frac{dX_{vc}}{dt}$$

$$\dot{X}_{dest}=m_{steam}\Delta x_{steam}+m_{fgases}\Delta x_{fgases}$$

$$\dot{X}_{dest}=19.78\cdot(207.31-2016.5)+265.5\cdot 10^3/3600\cdot(1033.6-488.11)$$

11: water: Specified state points

	Temperature (°C)	Pressure (bar)	Density (kg/m³)	Enthalpy (kJ/kg)	Quality (kg/kg)	Flow Exergy (kJ/kg)
1	100,00	150,00	965,20	430,39	Subcooled	207,31
2	750,00	150,00	32,906	3965,2	Superheated	2016,5
3						

12: carbon dioxide/water: Specified state points (48,82/51,18)

	Temperature (°C)	Pressure (bar)	Density (kg/m³)	Enthalpy (kJ/kg)	Quality (kg/kg)	Flow Exergy (kJ/kg)
1	750,00	1,0000	0,29761	2701,6	Superheated	1033,6
2	170,00	1,0000	0,68996	1754,1	Superheated	488,11
3						

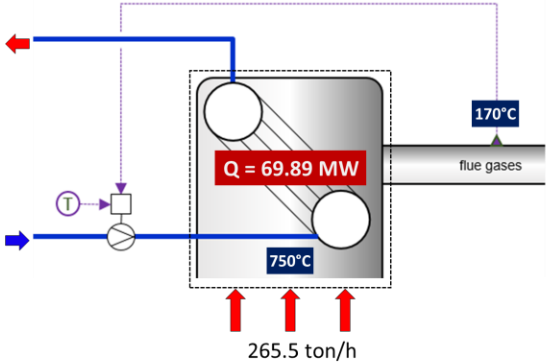
$$\dot{X}_{dest}=-35.79\,MW+40.23\,MW$$

absorvida pelo vapor

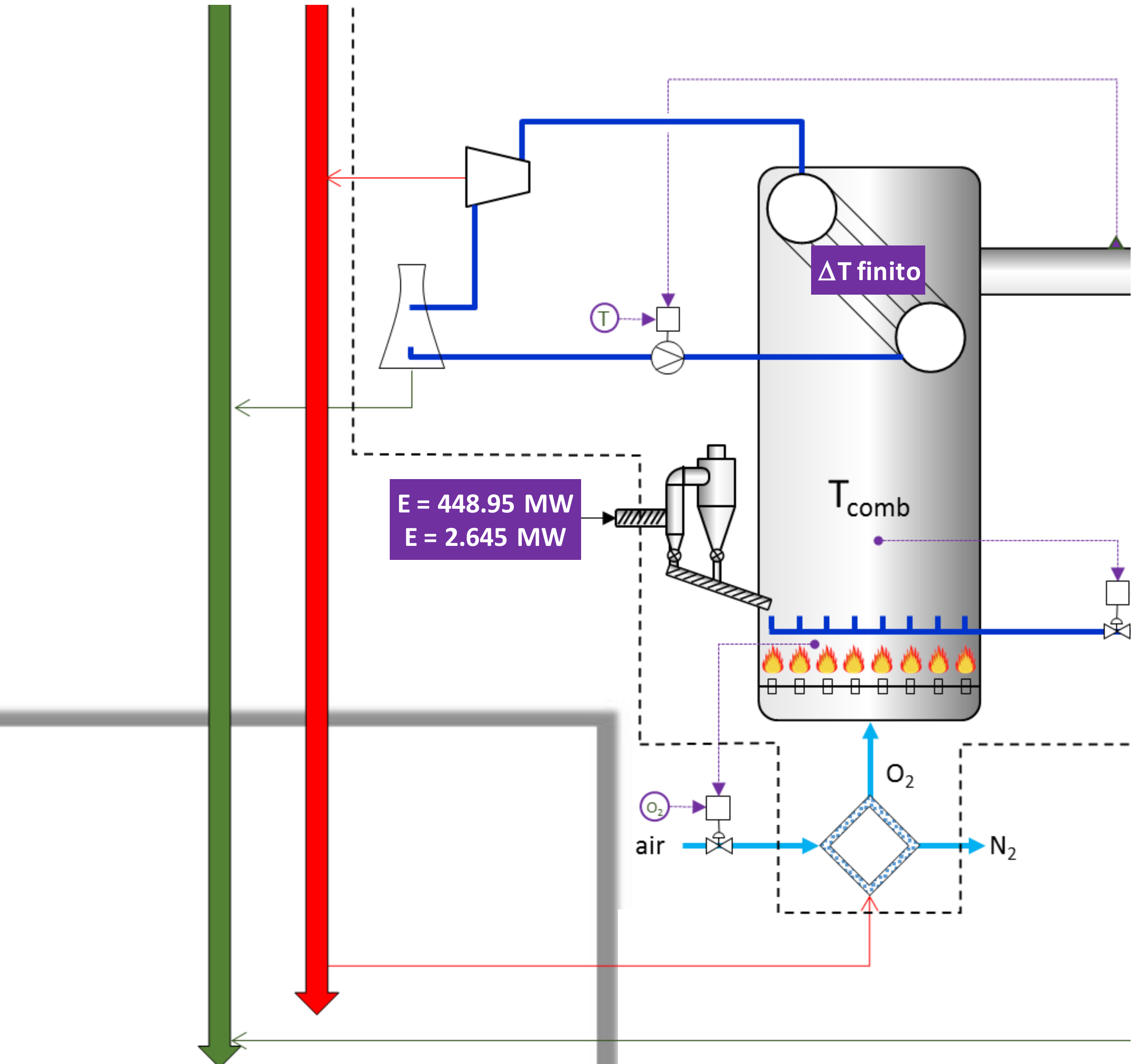
cedida pelos gases de combustão

$$\dot{X}_{dest}=4.44\,MW$$

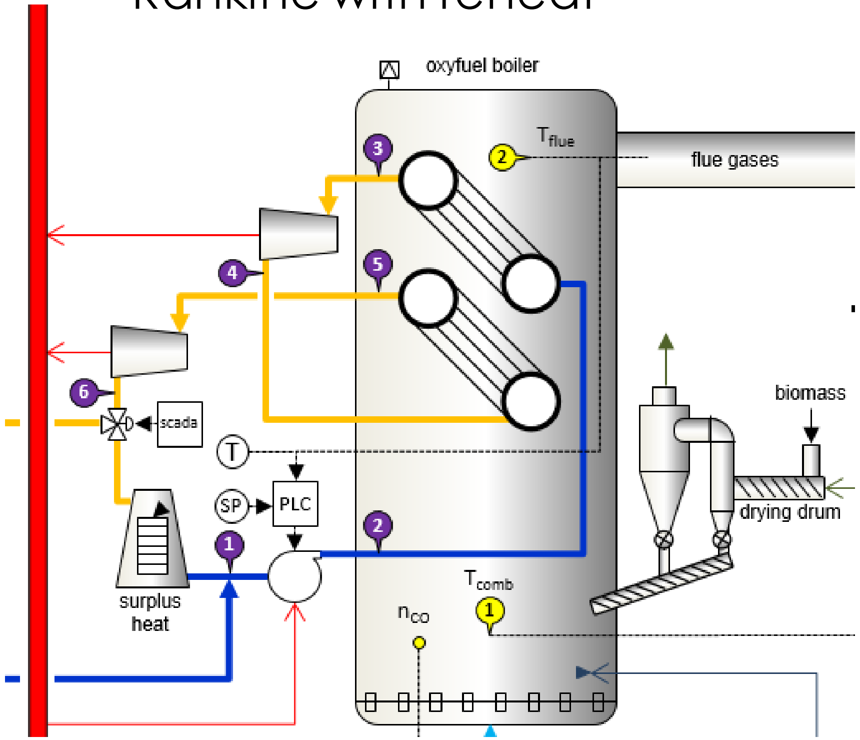
$$\eta=1-4.44/40.23=89\%$$



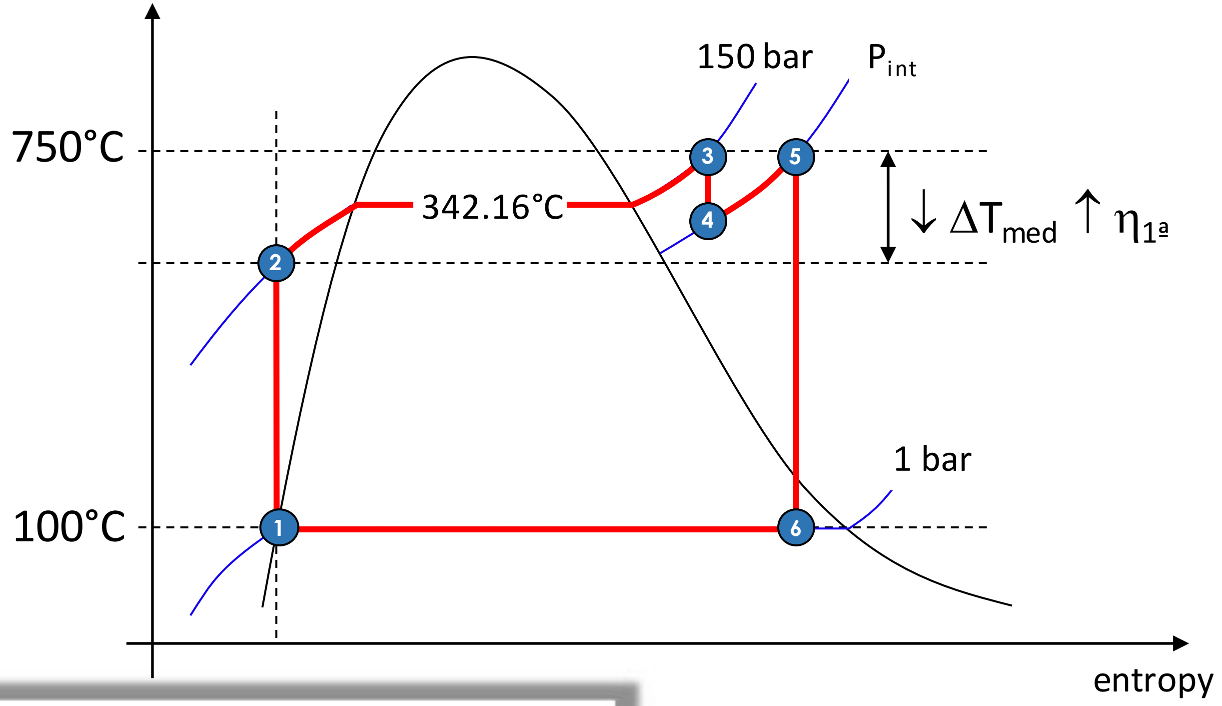
Design Optimization Possibilities



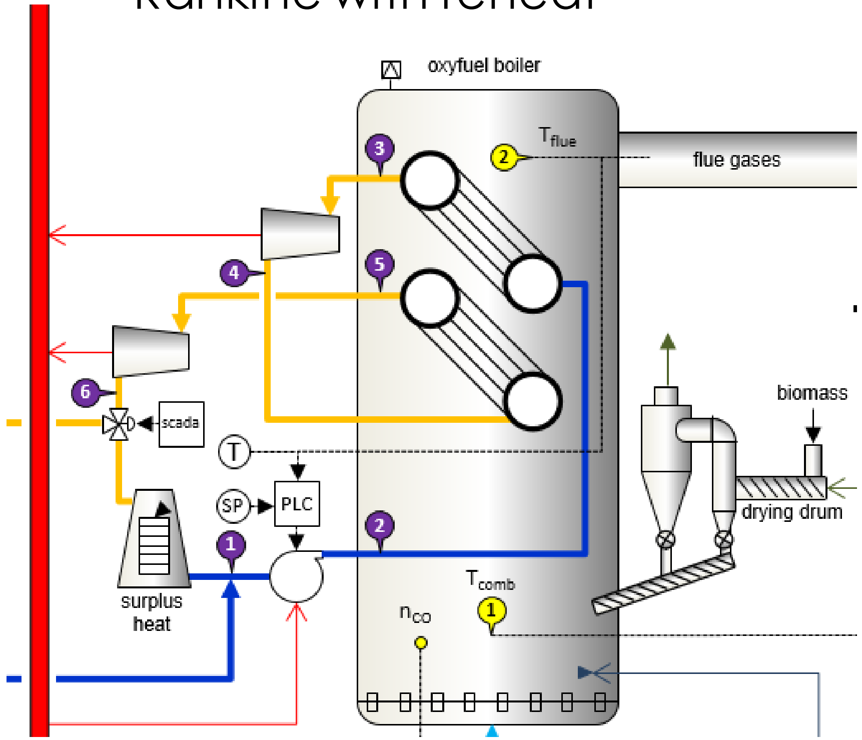
Rankine with reheat



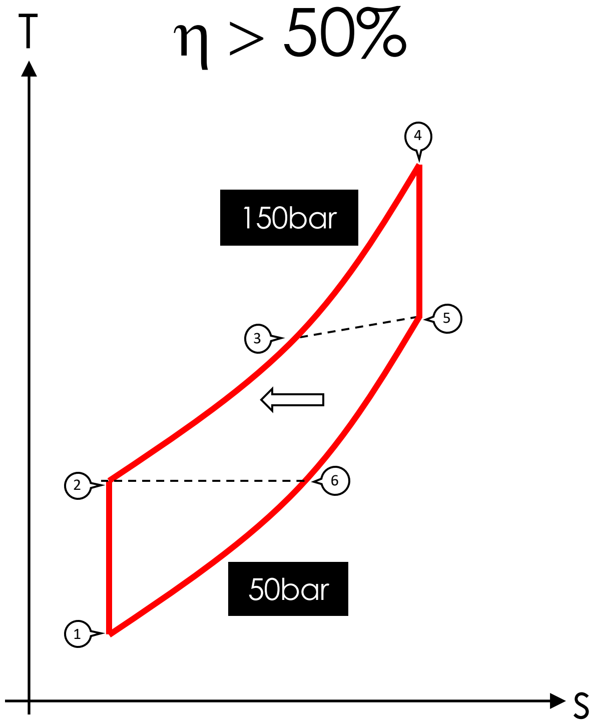
Design Optimization Possibilities



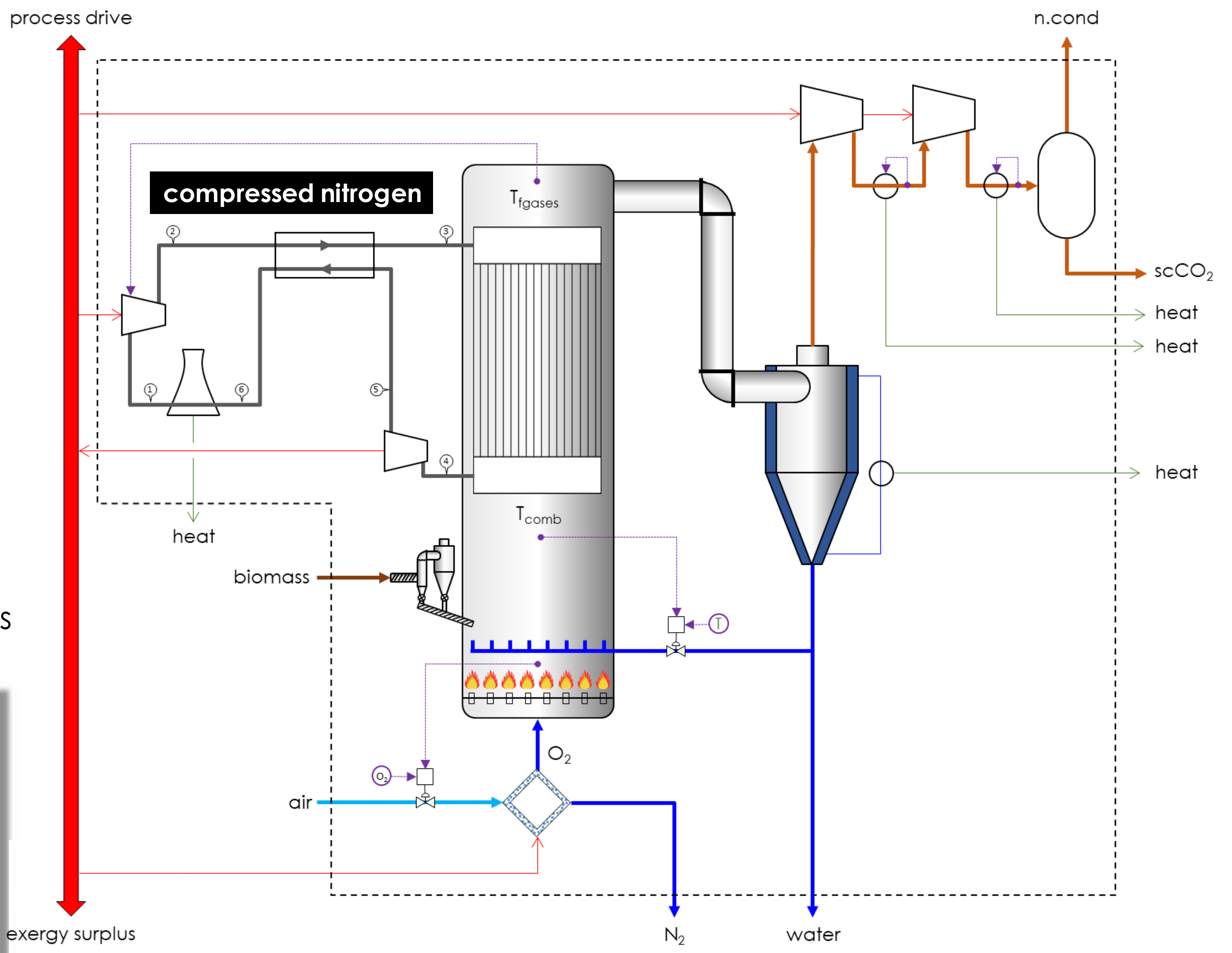
Rankine with reheat



Obs.: CAPEX ↑



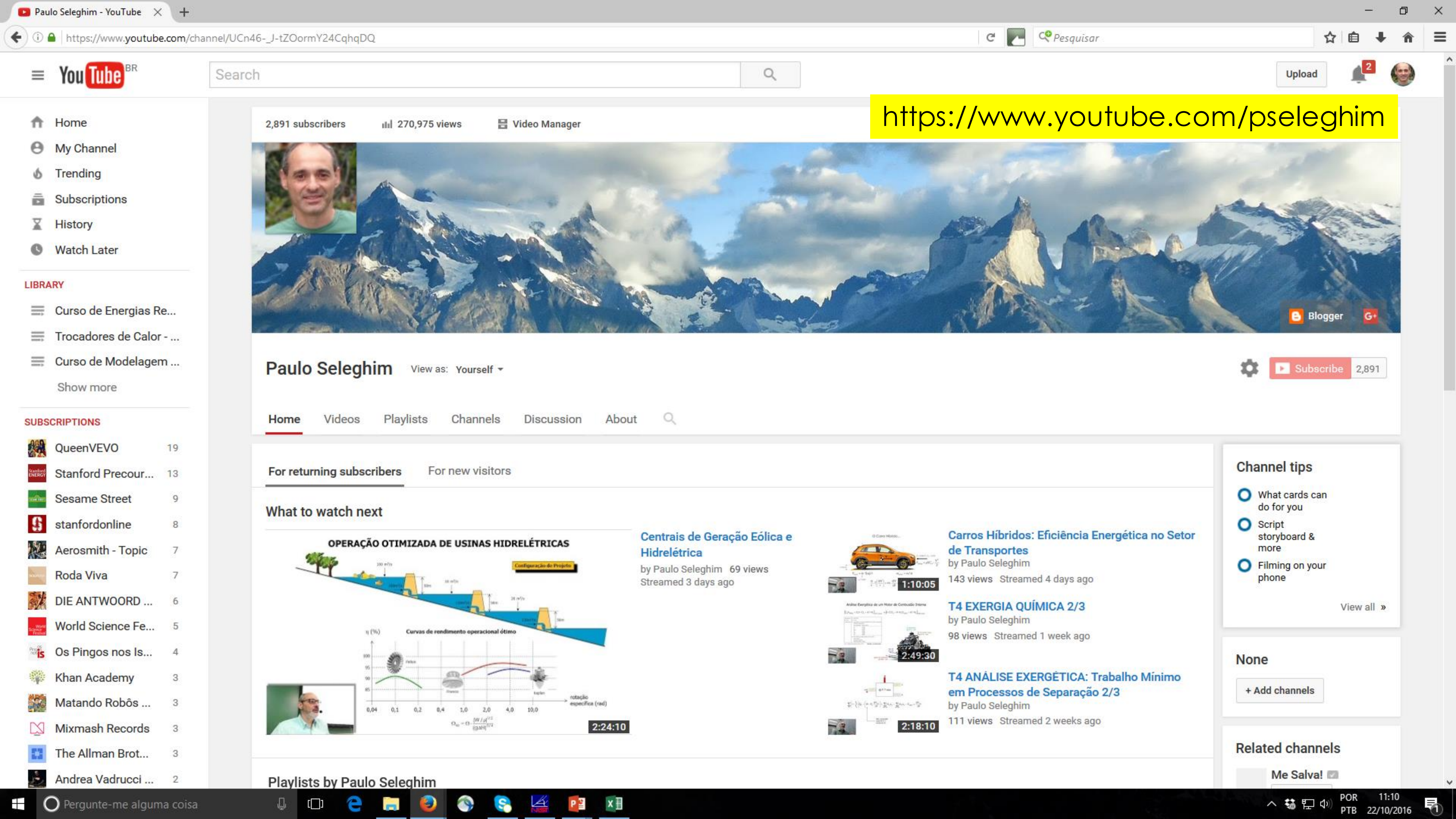
T
η > 50%
150bar
50bar
S



process drive
n.cond
compressed nitrogen
Tfgases
Tcomb
scCO2
heat
heat
heat
heat
biomass
air
O2
N2
water
exergy surplus

It is technically possible to capture atmospheric CO_2 and transform it to $scCO_2$ suitable for geological storage:

Sun Powered CCS Machines...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