INDUSTRIAL ENERGY SYSTEMS

ENERGY CONVERSION SYSTEM

ELFIE MECHAUSSIE
ADVANCED ENERGETICS | 2021

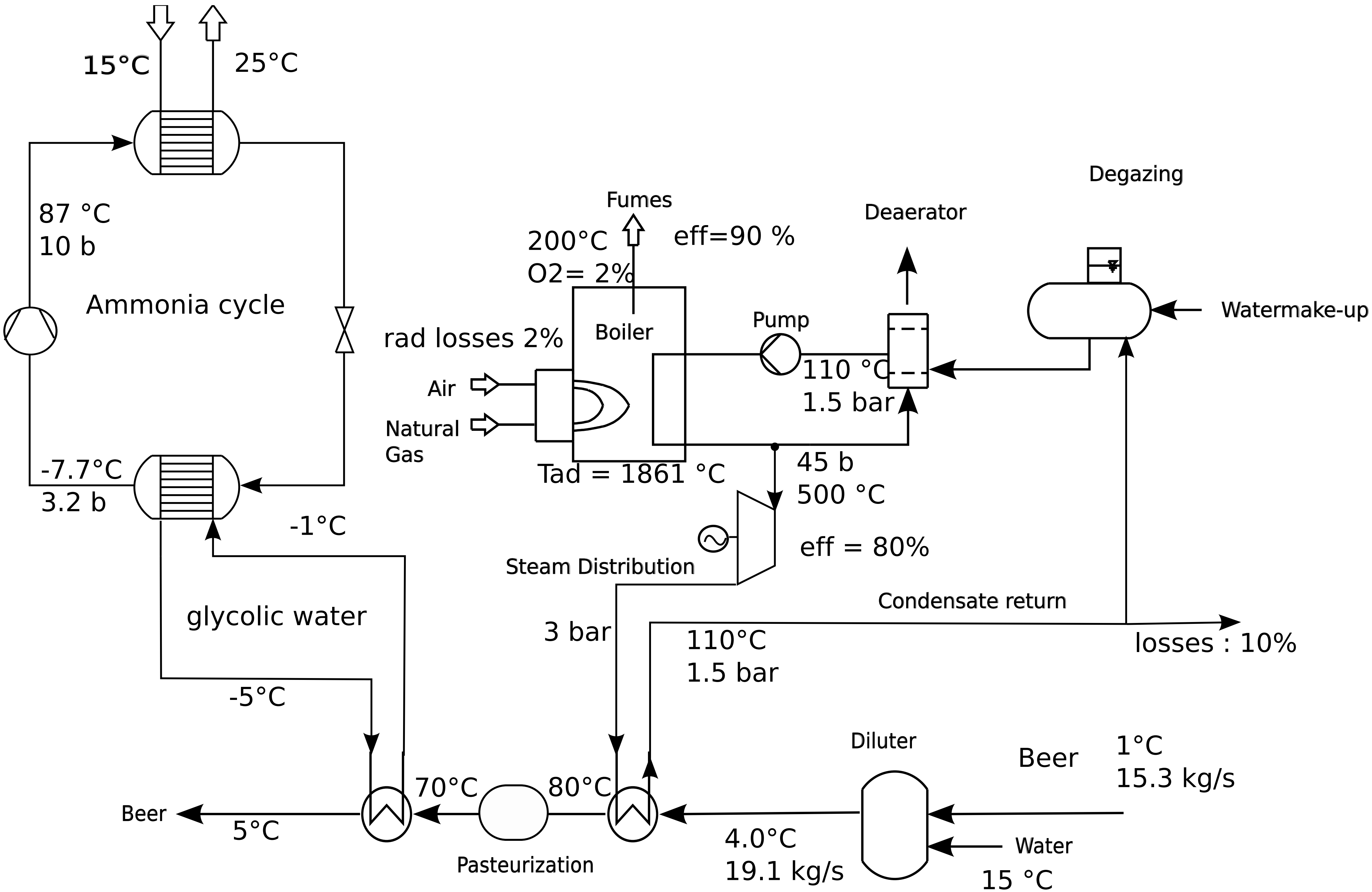
EPFL

TODAY'S PLANNING

- How to analyse the energy consumption of an industrial system?
  - close balances: energy, mass, atomic
  - identify and quantify losses
  - calculate energy bill
- How to improve the system's efficiency?
  - locate losses
  - propose improvement options

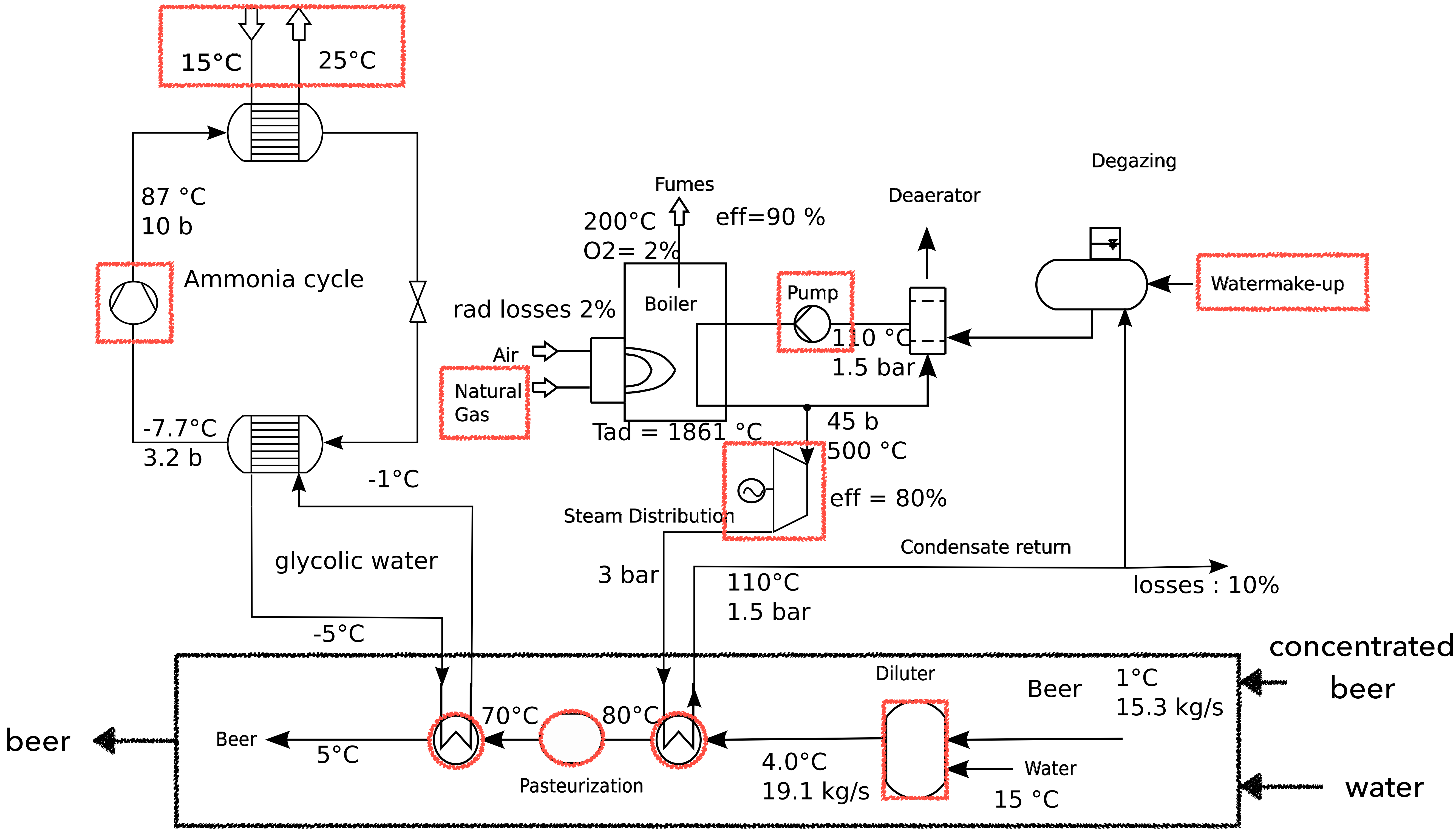
SYSTEM UNDER STUDY

BEER PASTEURISATION



WHERE IS ENERGY ENTERING THE SYSTEM?

BEER PASTEURISATION

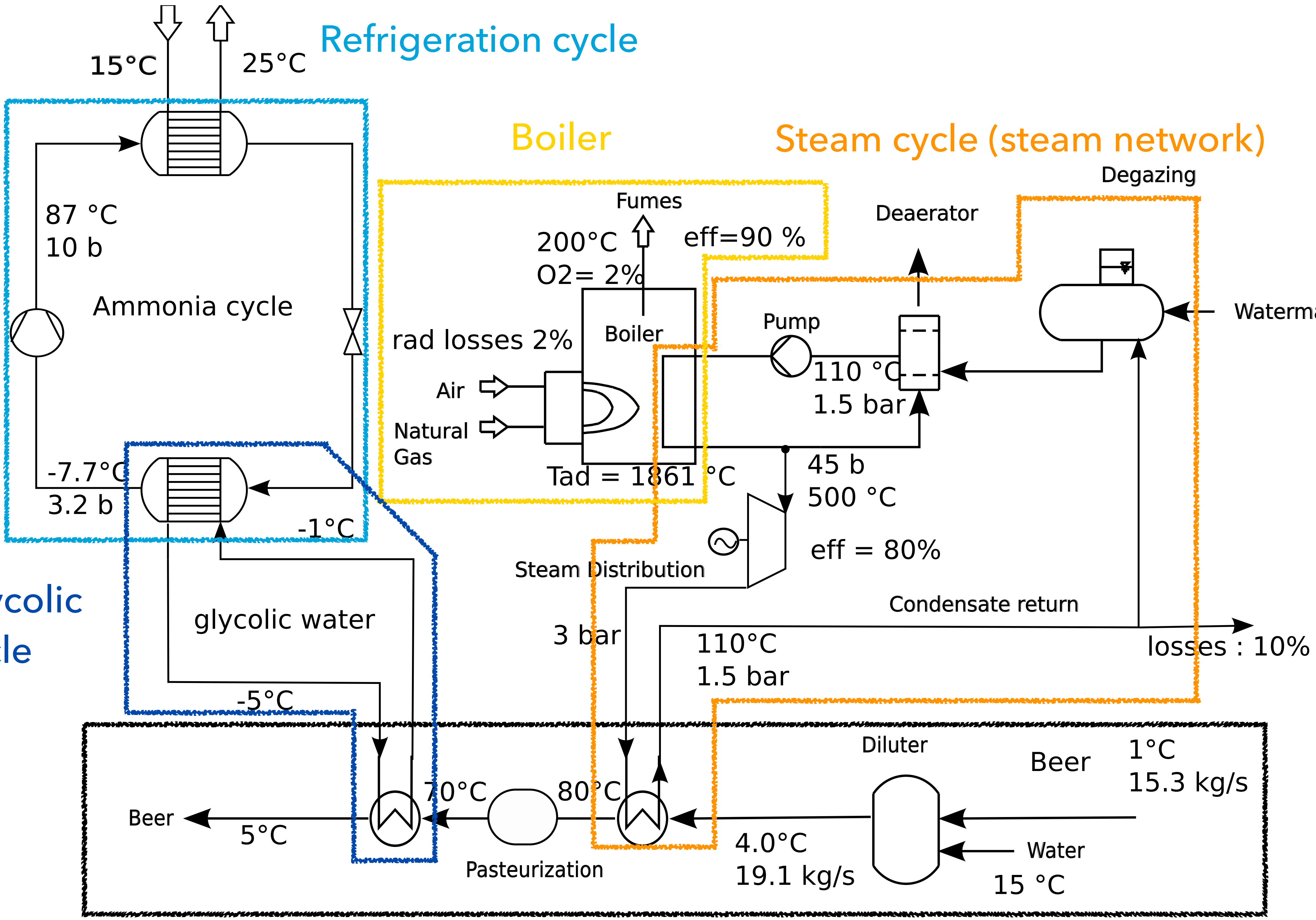


Process unit operation (Beer pasteurisation)

ENERGY CONVERSION

SYSTEM UNDER STUDY

BEER PASTEURISATION

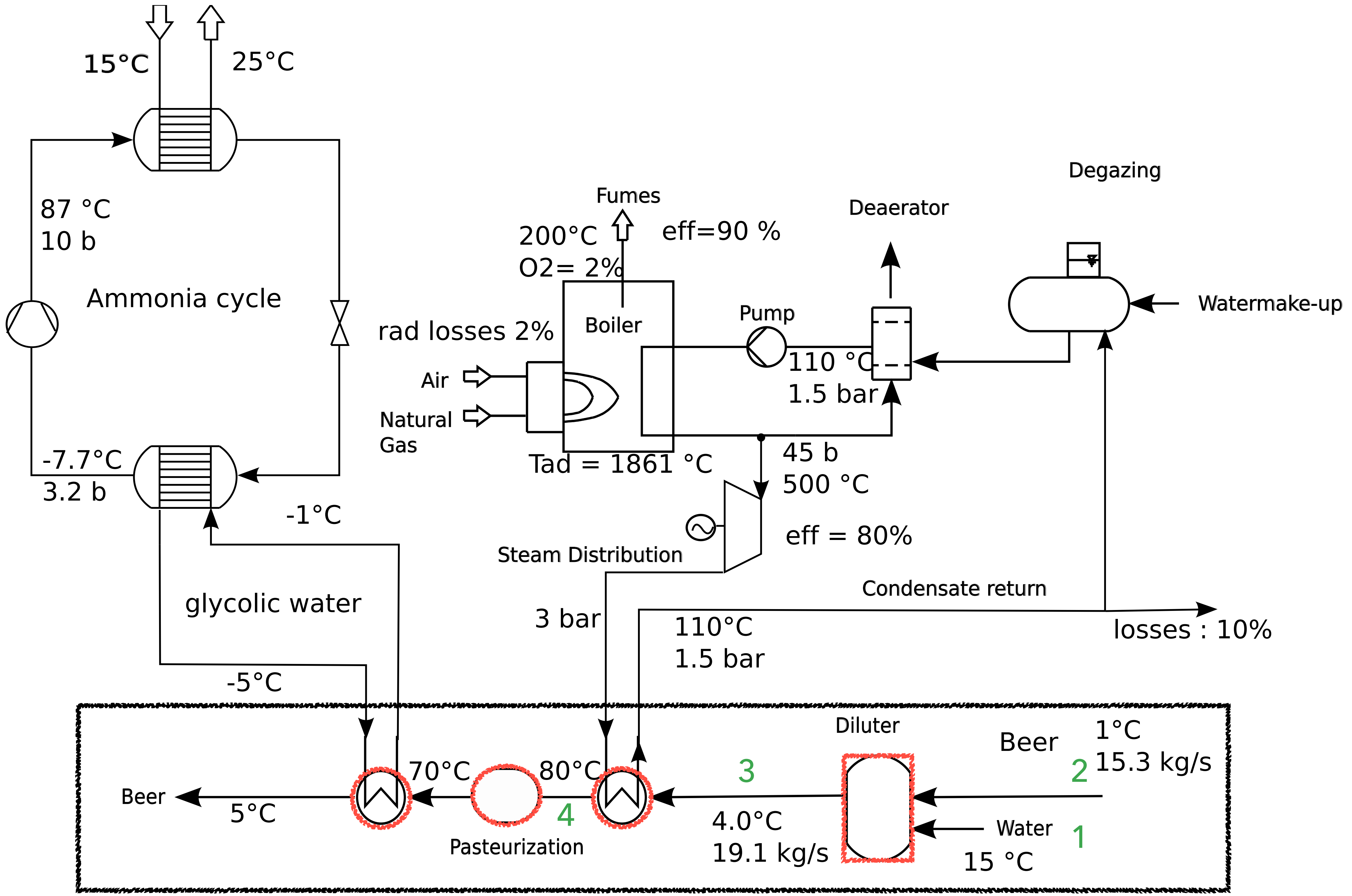


Process unit operation (Beer pasteurisation)

UTILITIES

- Resources:
  - natural gas, coal, electricity, waste fuels, cooling water
- Distributed energy: utilities in between the process and the final energy source/sink
  - hot: steam, hot oil, hot water
  - cold: glycolic water, hot water
- energy conversion units: boilers, cogeneration units
- distribution system: networks

PROCESS UNIT OPERATION

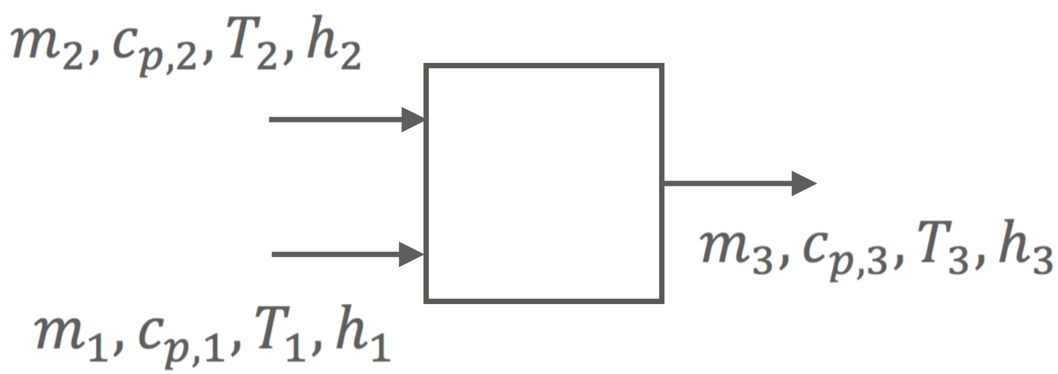


Process unit operation (Beer pasteurisation)

PROCESS UNITS (BEER PASTEURISATION)

IDENTIFYING ENERGY REQUIREMENTS

- Mixers/splitters



- mass balance:

$$\dot{m}_3 = \dot{m}_1 + \dot{m}_2$$

$$\dot{m}_3 \cdot x_{c,3} = \dot{m}_1 \cdot x_{c,1} + \dot{m}_2 \cdot x_{c,2} \quad \forall c \in n_c$$

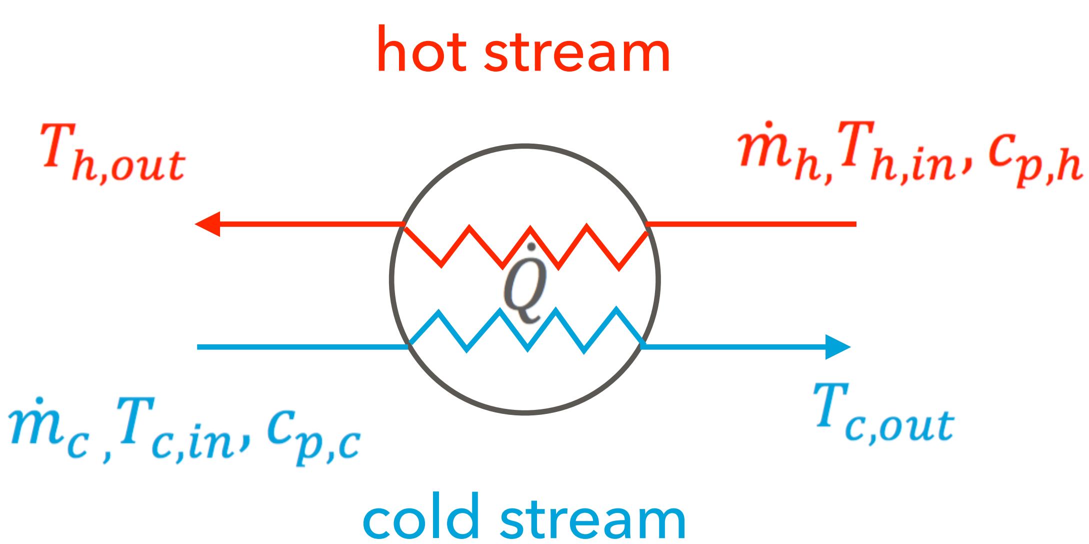
- heat balance (non isothermal mixing):

$$cp_i = \sum_{c=1}^{n_{c,i}} x_{c,i} \cdot cp_c$$

$$\dot{m}_3 \cdot h_3 = \dot{m}_1 \cdot h_1 + \dot{m}_2 \cdot h_2$$

$$\dot{m}_3 \cdot cp_3 \cdot (T_3 - T_{ref}) = \dot{m}_1 \cdot cp_1 \cdot (T_1 - T_{ref}) + \dot{m}_2 \cdot cp_2 \cdot (T_2 - T_{ref})$$

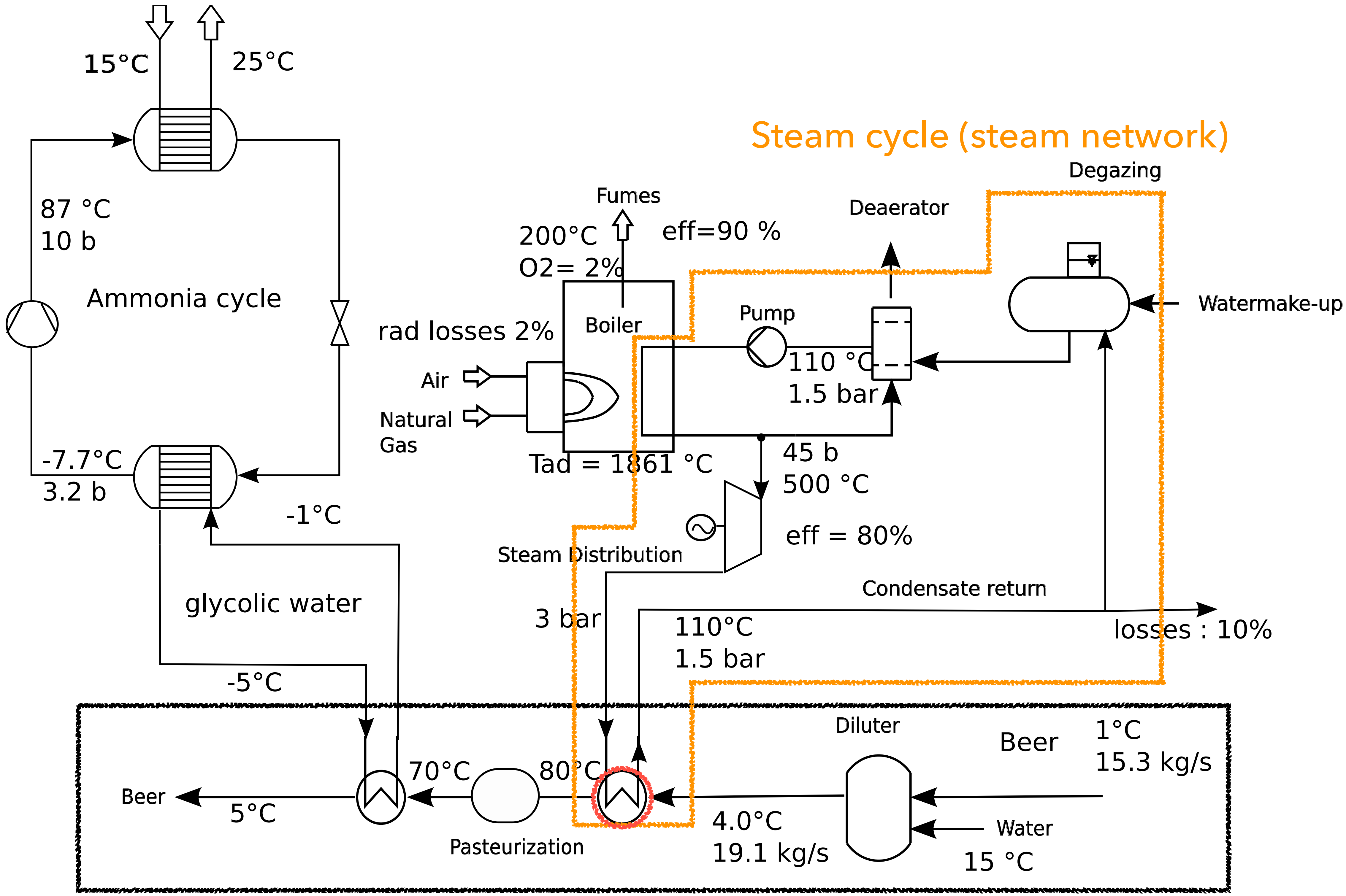
- Heat exchangers



$$\dot{Q} = \dot{m}_c \cdot c_{p,c} \cdot (T_{c,out} - T_{c,in}) = \dot{m}_h \cdot c_{p,h} \cdot (T_{h,in} - T_{h,out})$$

$$\dot{Q} = \dot{m}_c \cdot (h_{out} - h_{in}) = \dot{m}_h \cdot (h_{in} - h_{out})$$

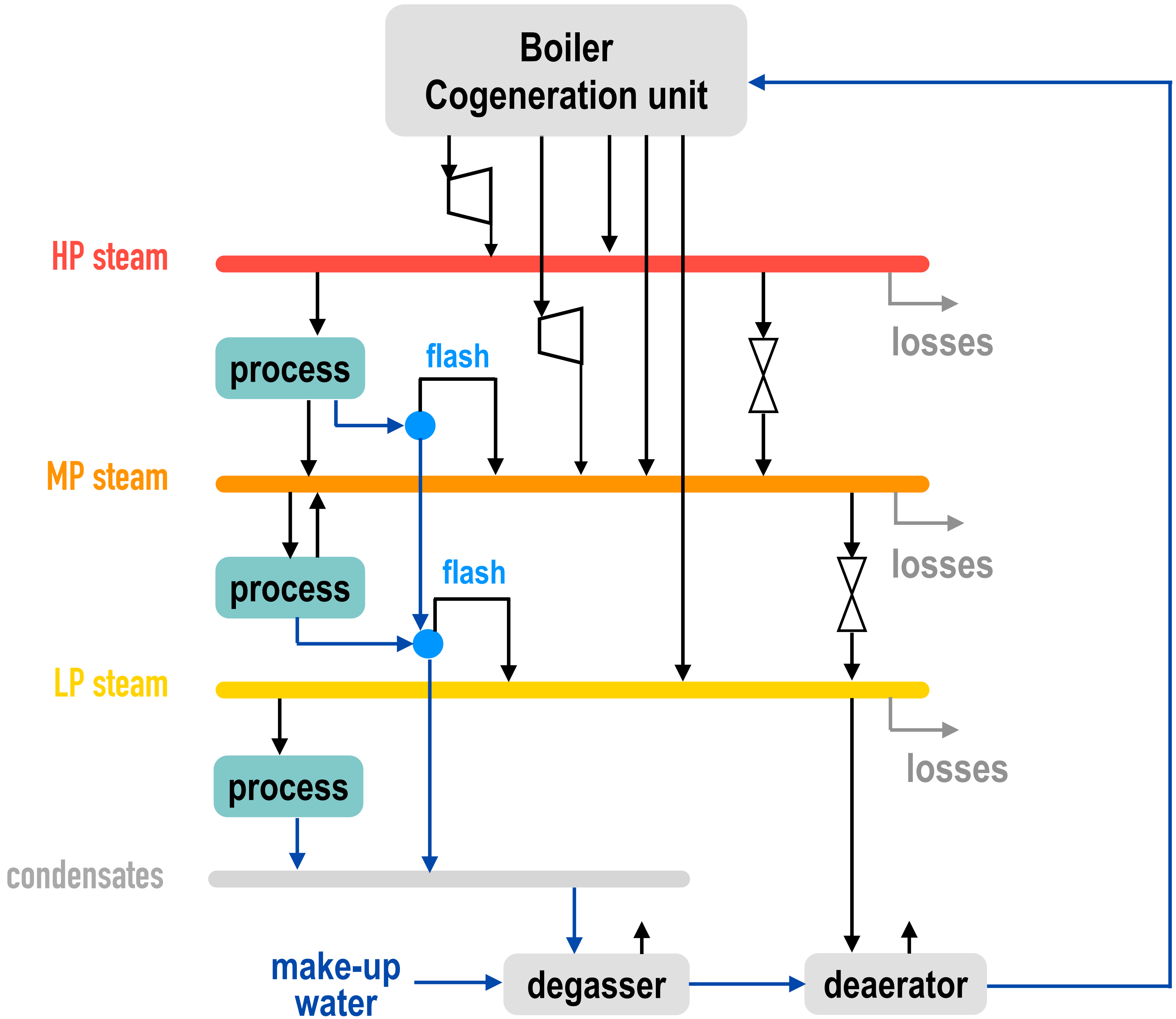
STEAM NETWORK



Process unit operation (Beer pasteurisation)

STEAM NETWORK

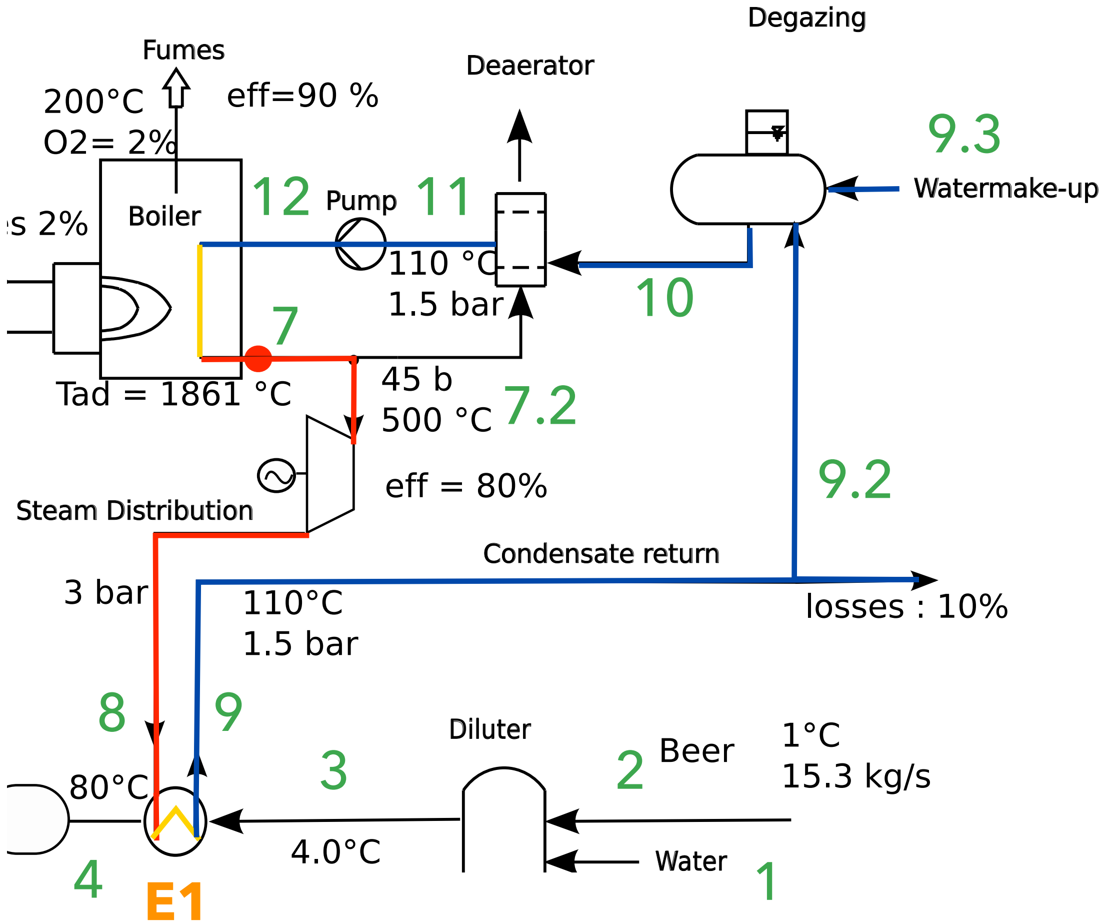
GENERAL ARCHITECTURE

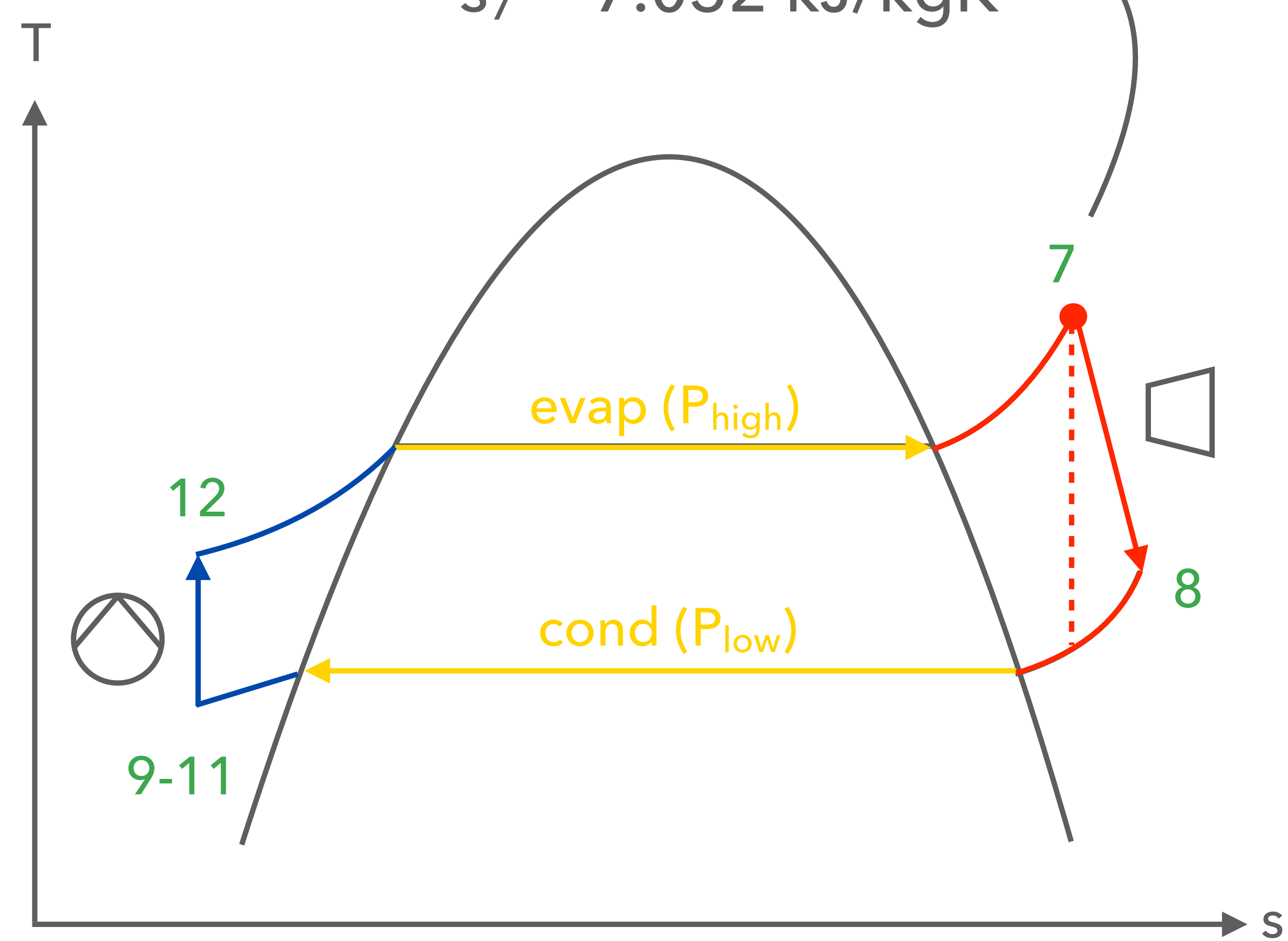


STEAM CYCLE

T-S DIAGRAM OF WATER

- *MiniRefprop:* $h(T,P)$ $s(T,P)$



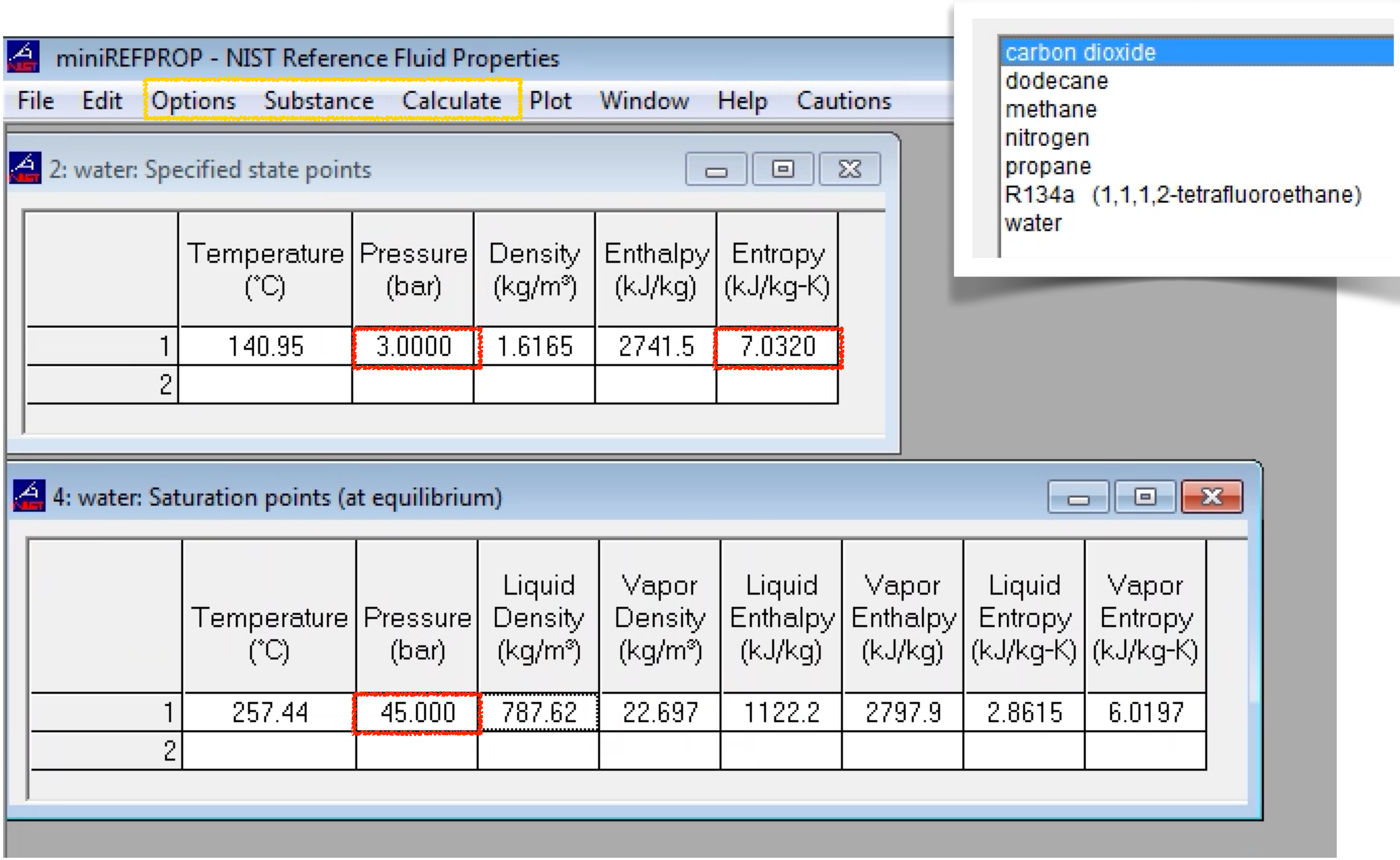


- turbine isentropic efficiency: $$\eta_{is,T} = \frac{h_7 - h_8}{h_7 - h_{8,is}}$$

- turbine/pump: $$\dot{W}_P = (h_{12} - h_{11}) \qquad \dot{W}_T = (h_7 - h_8)$$

WATER PROPERTIES (+ OTHER FLUIDS)

STATE VARIABLES - MINIREFPROP



2: water: Specified state points

	Temperature (°C)	Pressure (bar)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/kg-K)
1	140.95	3.0000	1.6165	2741.5	7.0320
2					

4: water: Saturation points (at equilibrium)

	Temperature (°C)	Pressure (bar)	Liquid Density (kg/m³)	Vapor Density (kg/m³)	Liquid Enthalpy (kJ/kg)	Vapor Enthalpy (kJ/kg)	Liquid Entropy (kJ/kg-K)	Vapor Entropy (kJ/kg-K)
1	257.44	45.000	787.62	22.697	1122.2	2797.9	2.8615	6.0197
2								

WATER PROPERTIES

STATE VARIABLES - WEBSITE

http://www.peacesoftware.de/einigewerte/wasser_dampf_e.html

Calculation of thermodynamic properties of water

Pressure: 5 bar
Temperature: 60 Celsius

Compute

specific enthalpy :	251.55753600597	[kJ / kg]
specific entropy :	0.83096088836028	[kJ / kg K]

Calculation of thermodynamic properties of overheated steam (upper limit: 799 C, 1000 bar)

Pressure: 1 bar
Temperature: 150 Celsius

Compute

specific enthalpy :	2776.5918154499	[kJ / kg]
specific entropy :	7.614673430236	[kJ / kg K]

Calculation of thermodynamic properties of saturated steam

Pressure: 10 bar
or
Temperature: Celsius

specific enthalpy water :	762.68284433541	[kJ / kg]
specific enthalpy steam :	2777.1195376847	[kJ / kg]
specific entropy water :	2.1384313508991	[kJ / kg K]
specific entropy steam :	6.5849789963522	[kJ / kg K]
boiling temperature : (calculated)	179.88563239147	[Celsius]

WATER PROPERTIES

STATE VARIABLES - ROSMOSE

````
```{python use-coolprop, message=T}
from pyxosmose.state import State

state1 = State(pair='TP',fluid='Water',temperature=298,pressure=101325)
state1.StateCalc()
print(state1.__dict__)
```
````

specific enthalpy :	251.55753600597	[kJ / kg]
specific entropy :	0.83096088836028	[kJ / kg K]

````
```{python use-coolprop, message=T}
from pyxosmose.state import State

state1 = State(pair='TP',fluid='Water',temperature=423,pressure=101325)
state1.StateCalc()
print(state1.__dict__)
```
````

```
Python 3.8.8 (C:/Users/cterrier/Desktop/documents/ae-project-
reporting/venv/Scripts/python.exe)
Reticulate 1.25 REPL -- A Python interpreter in R.
Enter 'exit' or 'quit' to exit the REPL and return to R.
{'pair': 'TP', 'fluid': 'Water', 'temperature': 423, 'pressure': 101325,
'density': 0.523449293574313, 'cpmass': 1985.7445133408703, 'cvmass':
1496.585108926608, 'enthalpy': 2776207.7633732506, 'entropy': 7607.795928679631,
'vapfrac': -1.0}
```

specific enthalpy :	2776.5918154499	[kJ / kg]
specific entropy :	7.614673430236	[kJ / kg K]

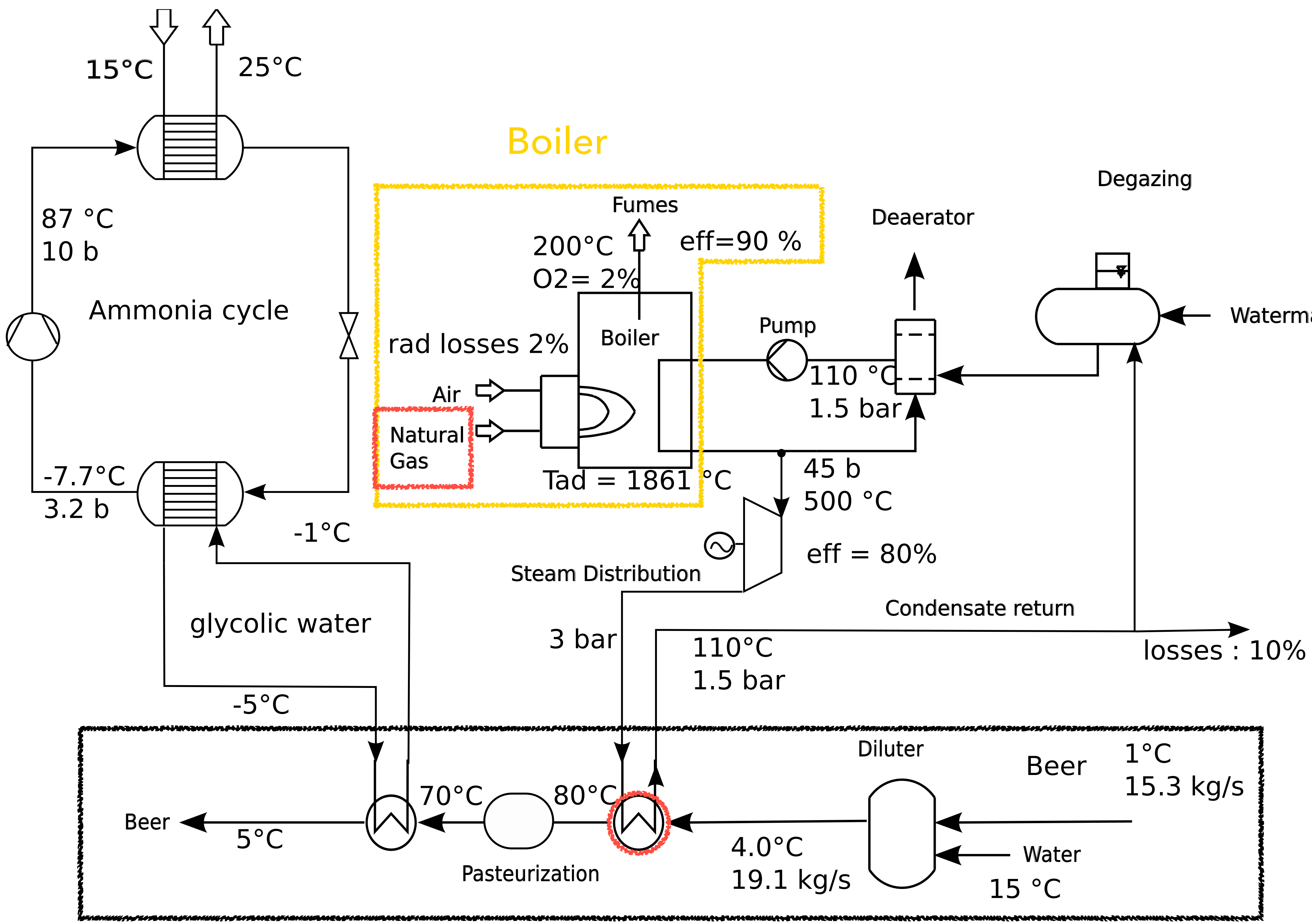
````
```{python use-coolprop-again, message=F}
from pyxosmose.state import State

state2 = State(pair='PQ',fluid='Water',pressure=1013250, vapfrac=1)
state2.StateCalc()
state2.cpmass
print(state2.__dict__)
```
````

```
-1.0
{'pair': 'PQ', 'fluid': 'Water', 'temperature': 453.60078378606056
1013250, 'density': 5.210070697253118, 'cpmass': -1.0, 'cvmass': -
2777606.1994804046, 'entropy': 6580.468121095475, 'vapfrac': 1.0}
```

specific enthalpy water :	762.68284433541	[kJ / kg]
specific enthalpy steam :	2777.1195376847	[kJ / kg]
specific entropy water :	2.1384313508991	[kJ / kg K]
specific entropy steam :	6.5849789963522	[kJ / kg K]
boiling temperature : (calculated)	179.88563239147	[Celsius]

BOILER



Process unit operation (Beer pasteurisation)

EQUATION

- general equation for HC stoichiometric combustion with O_2:

$$C_mH_n + (m + \frac{n}{4})O_2 \rightarrow mCO_2 + \frac{n}{2}\,H_2O$$

- Air: = O_2 21% and N_2 79% (molar%)
- excess O_2 in fumes –> excess air λ

$$CH_4 + 2\lambda\,O_2 + 7.52\lambda\,N_2 \rightarrow CO_2 + 2\,H_2O + 7.52\lambda\,N_2 + 2(\lambda - 1)\,O_2$$

$$\frac{2(\lambda - 1)}{1 + 2 + 7.52\lambda + 2(\lambda - 1)} = excess\ O_2\ (molar\%)$$

COMBUSTION

MOLAR QUANTITIES

- specific heat of fumes:

C_p's to be found in tables

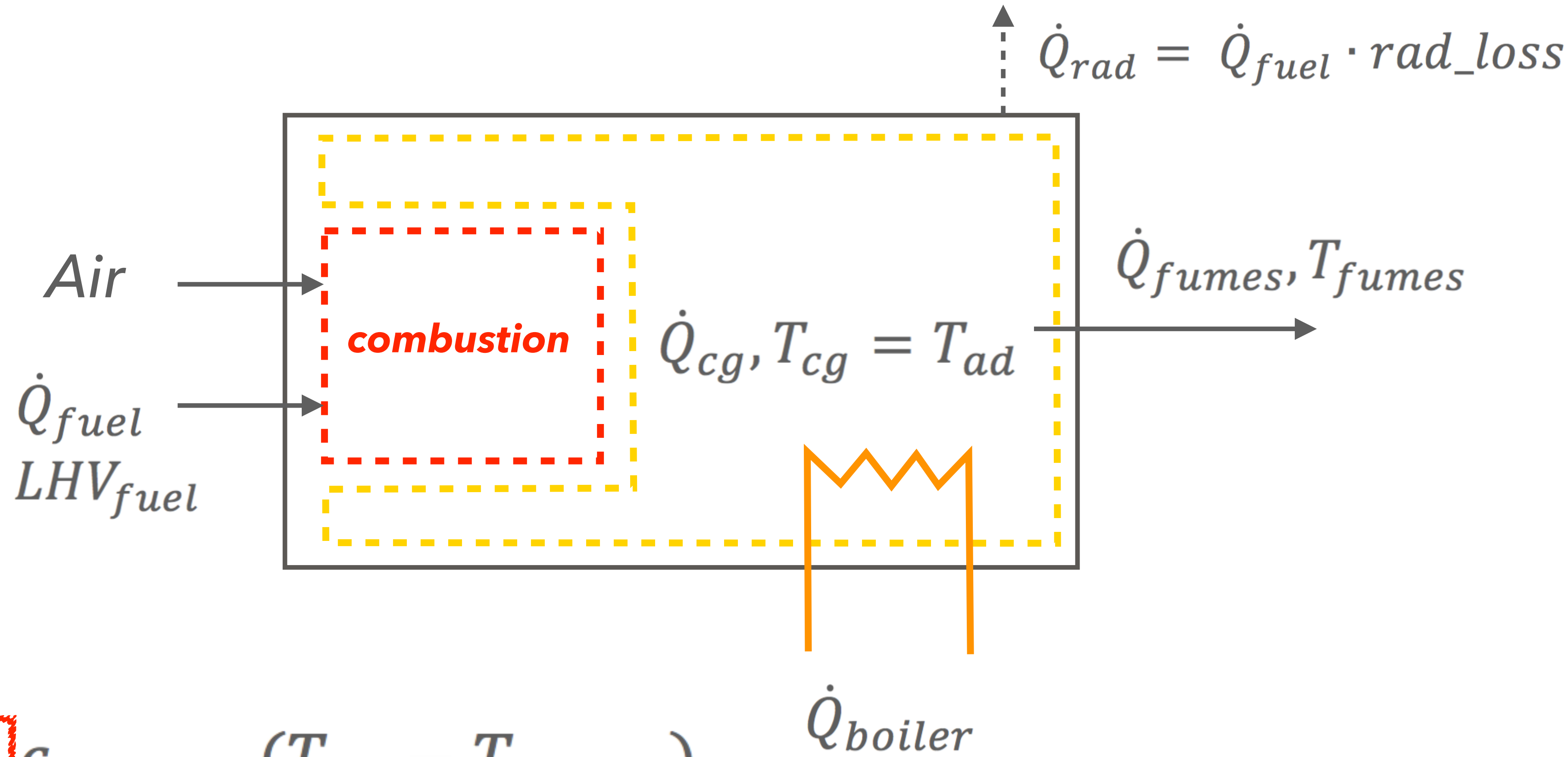
$$C_{p_{fumes}} = w_{CO_2} C_{p,CO_2} + w_{H_2O} C_{p,H_2O} + w_{N_2} C_{p,N_2} + w_{O_2} C_{p,O_2} \quad [kJ \cdot kg^{-1} \cdot K^{-1}]$$

$$w_{CO_2} = \frac{1 \cdot M_{CO_2}}{M_{CO_2} + 2 \cdot M_{H_2O} + 3.76 \cdot 2 \cdot \lambda \cdot M_{N_2} + 2(\lambda - 1) \cdot M_{O_2}} \quad [-]$$

$$w_{N_2} = \frac{7.52 \cdot \lambda \cdot M_{N_2}}{M_{CO_2} + 2 \cdot M_{H_2O} + 7.52 \cdot \lambda \cdot M_{N_2} + 2(\lambda - 1) \cdot M_{O_2}} \quad [-]$$

BOILER

ENERGY AND MASS BALANCES WITH T



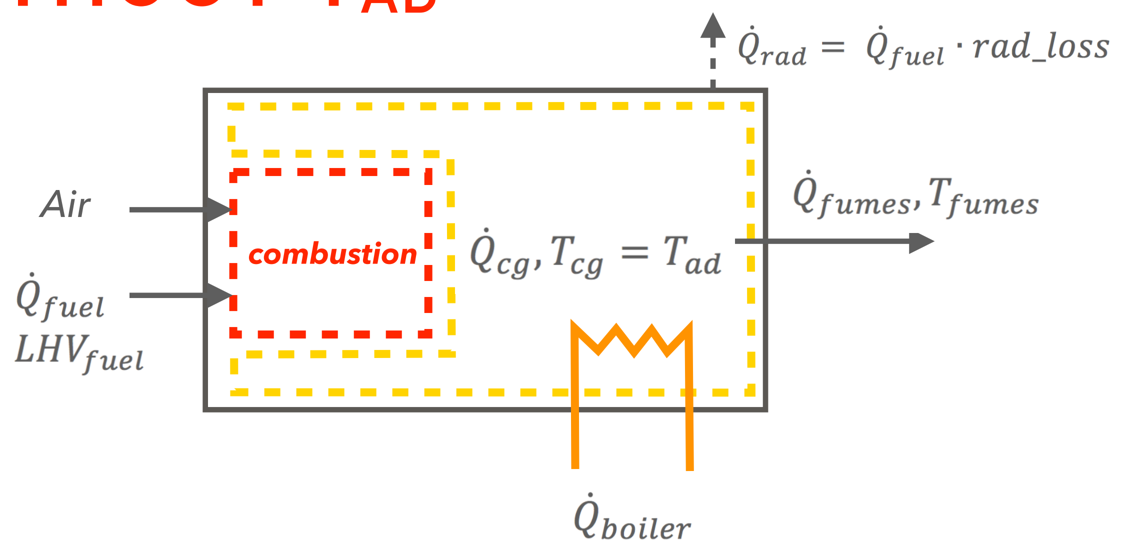
$$\dot{Q}_{boiler} = \boxed{\dot{m}_{fumes}} c_{p,fumes}(T_{ad} - T_{fumes})$$

$$\boxed{\dot{Q}_{fumes}} = \dot{m}_{fumes} C_{p,fumes}(T_{fumes} - T_{LHV,ref})$$

$$(\dot{Q}_{boiler} + \dot{Q}_{fumes}) = \eta_{comb,eff} \boxed{\dot{Q}_{fuel}} (1 - rad_{loss})$$

$$\dot{Q}_{fuel} = LHV_{fuel} \boxed{\dot{m}_{fuel}}$$

ENERGE AND MASS BALANCES WITHOUT T_{AD}



- Air-Fuel Ratio:

$$r_{air\ to\ fuel} = \frac{2\lambda M_{O_2} + 7.52\lambda M_{N_2}}{M_{CH_4}}$$

$$r_{fumes\ to\ fuel} = r_{air\ to\ fuel} + 1$$

$$\dot{m}_{fumes} = r_{fumes\ to\ fuel}\dot{m}_{fuel}$$

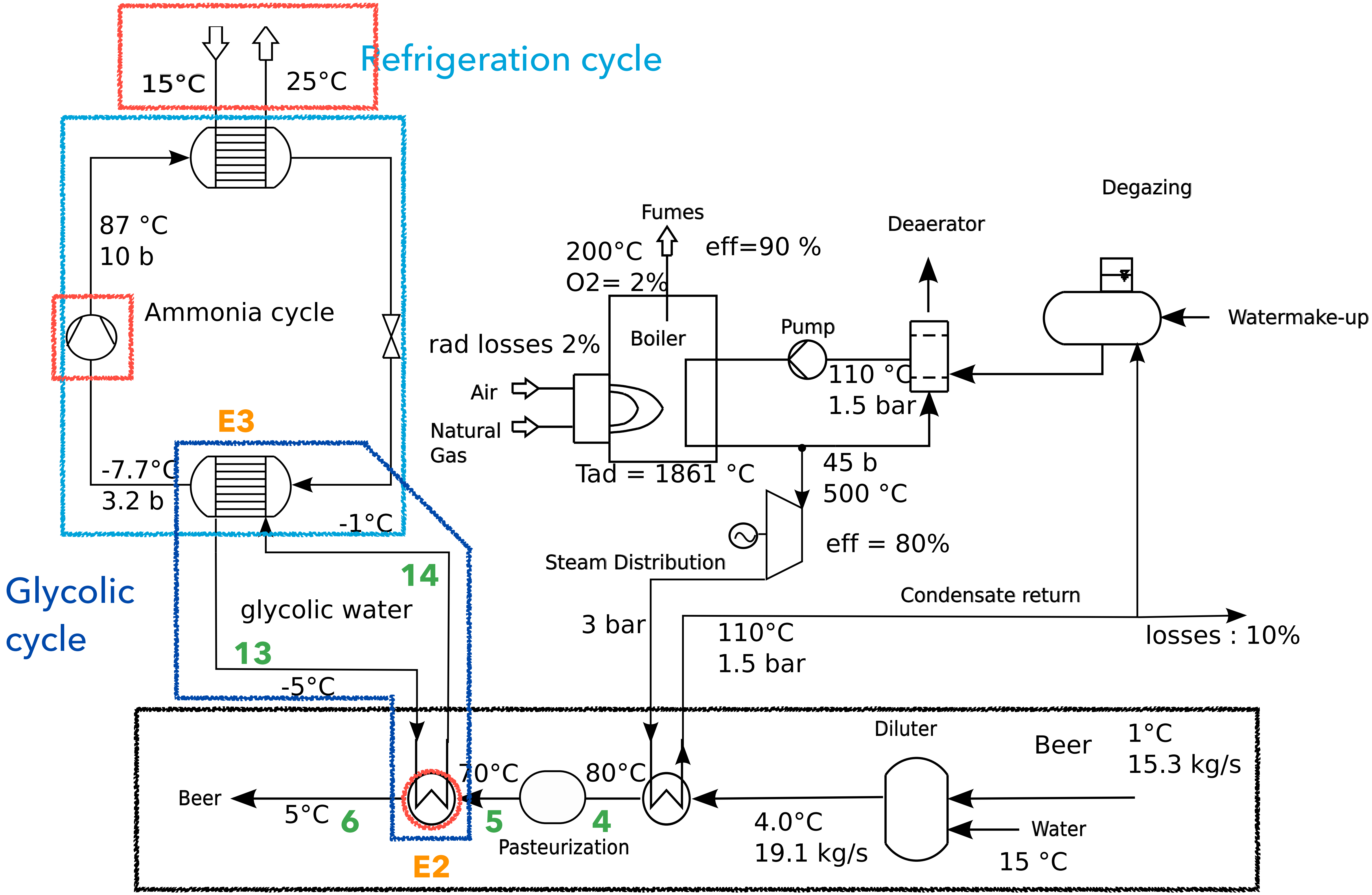
$$\dot{Q}_{fumes} = \dot{m}_{fumes} C_{p,fumes}(T_{fumes} - T_{LHV,ref})$$

$$(\dot{Q}_{boiler} + \dot{Q}_{fumes}) = \eta_{comb,eff}\dot{Q}_{fuel}(1 - rad_{loss})$$

$$\dot{Q}_{fuel} = LHV_{fuel}\dot{m}_{fuel}$$

- In exercise: 4 equations for 4 unknowns

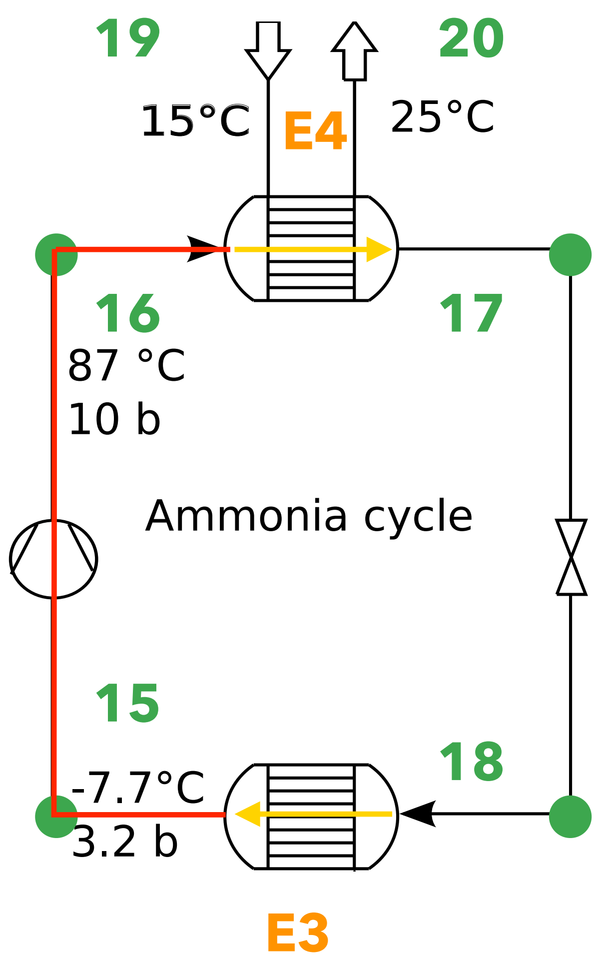
REFRIGERATION CYCLE

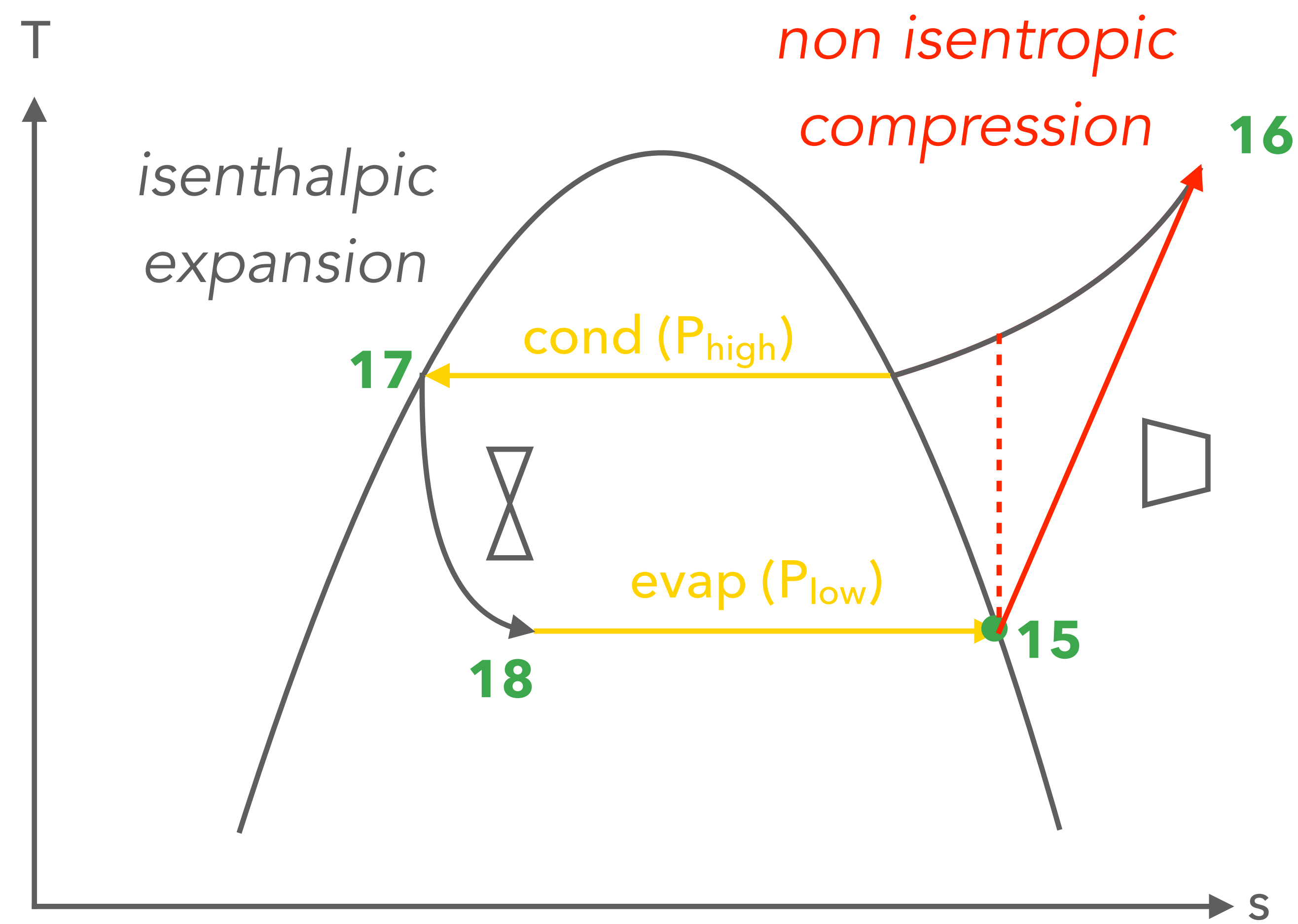


Process unit operation (Beer pasteurisation)

REFRIGERATION CYCLE

- *CoolPack: Ammonia = R717*





- compressor isentropic efficiency: $\eta_{is,c} = \frac{h_{16,is} - h_{15}}{h_{16} - h_{15}}$
- compressor: $\dot{W}_C = \dot{m}_{amm}(h_{16} - h_{15})$

ENERGY BILL

- Energy costs:

$$OC_{NG}[CHF/y] = \dot{Q}_{fuel}[kW] \cdot op_{time}[h/y] \cdot c_{NG}[CHF/kWh]$$

$$OC_{elec}[CHF/y] = (\dot{W}_{pump} + \dot{W}_{comp})[kW] \cdot op_{time}[h/y] \cdot c_{elec}[CHF/kWh]$$

$$OC_{w}[CHF/y] = \frac{\dot{m}_w[kg/s]}{\rho_w[kg/m^3]} \cdot op_{time}[s/y] \cdot c_w[CHF/m^3]$$

- Electricity sales income:

$$OI_{elec}[CHF/y] = \dot{W}_{turb}[kW] \cdot op_{time}[h/y] \cdot c_{elec}[CHF/kWh]$$

- Total energy bill:

$$OC_{tot}[CHF/y] = OC_{NG} + OC_{elec} + OC_{w} - OI_{elec}$$