IPESE
Industrial Process and Energy Systems Engineering

École Polytechnique Fédérale de Lausanne

Exercise 01: ΔTmin optimization Guidelines

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École Polytechnique Fédérale de Lausanne
ME451 – Advanced Energetics 2018/2019
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Exercise 01

General

FINAL GOAL:

- Calculate the energy bill of an industrial process
- Propose heat recovery options
- Optimize ΔTmin by minimizing total annual cost

Exercise 01

Process under study

Assumptions:

- No heat recovery possible during «Evaporation»
- Liquid water $c_p = 4.178$ kJ/kg/K $\rho = 996$ kg/m^3
- Refrigeration cycle COP = 4
- $\eta_{boiler} = 85$ %
- $\alpha_{cold} \approx \alpha_{hot} = 1000$ W/m^2/K

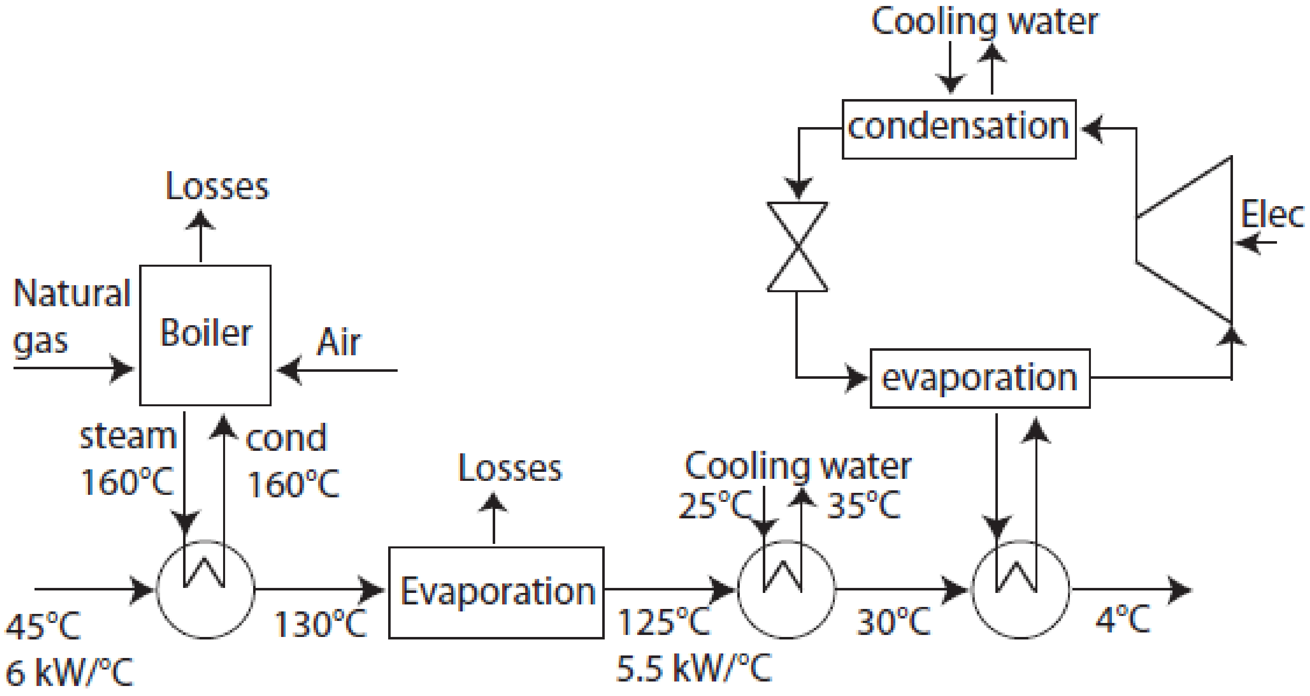
Resources costs:

- Natural gas: 0.09 CHF/kWh
- Water: 0.01 CHF/m^3
- Electricity: 0.15 CHF/kWh$_e$

Process operating data:

- Process operating time 8000 h/y
- Life time: 20 years

Investment cost functions

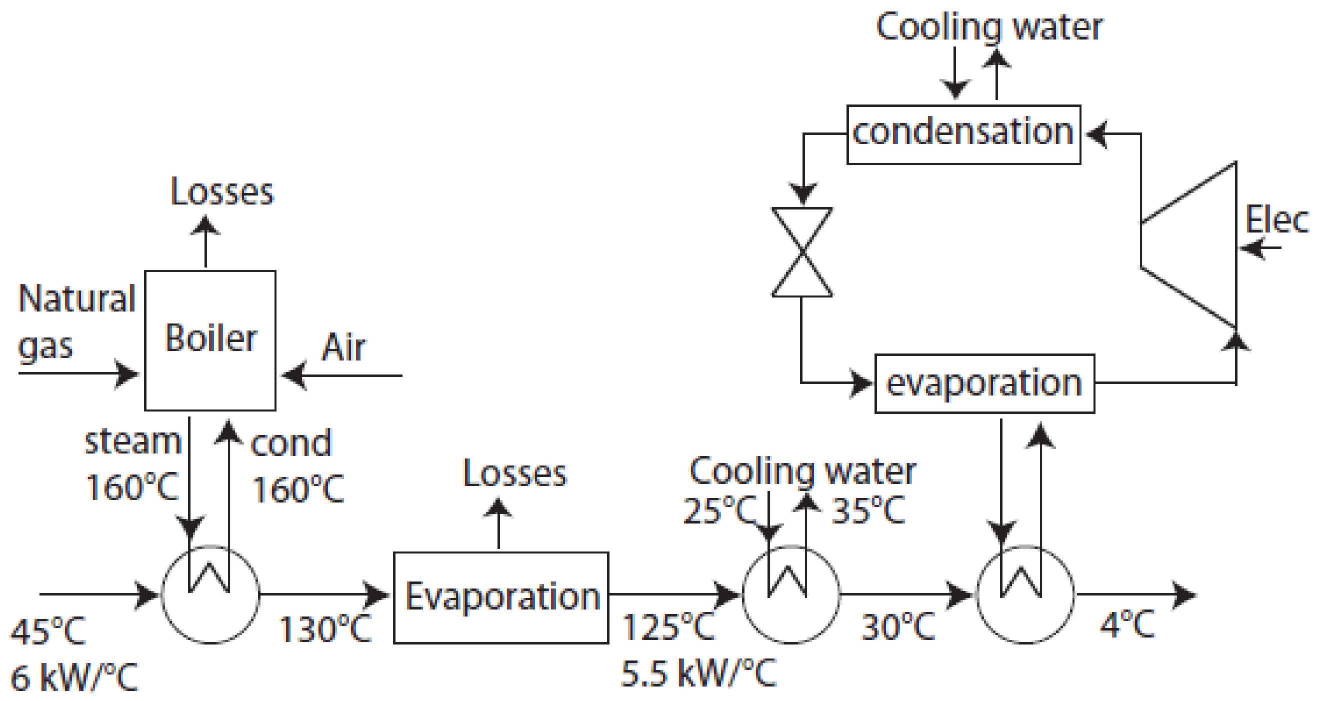


Exercise 01

Question 1

CALCULATE THE ACTUAL ENERGY BILL:

1. Identify the resources
2. Quantify the resources
3. Calculate the operating cost



Exercise 01

Question 1

CALCULATE THE ACTUAL ENERGY BILL:

1. Identify the resources
2. Quantify the resources

- **Natural gas**

$$\eta_{boiler} = \frac{\dot{Q}_{boiler}}{\dot{Q}_{NG}} \rightarrow \dot{Q}_{NG}$$

- **Cooling water**

$$\dot{Q}_{CW,cooler} = \dot{m}_{CW,cooler} c_{p,CW} \Delta T_{CW}$$

$$\dot{Q}_{evap} + \dot{E}^{+} - \dot{Q}_{cond} = 0$$

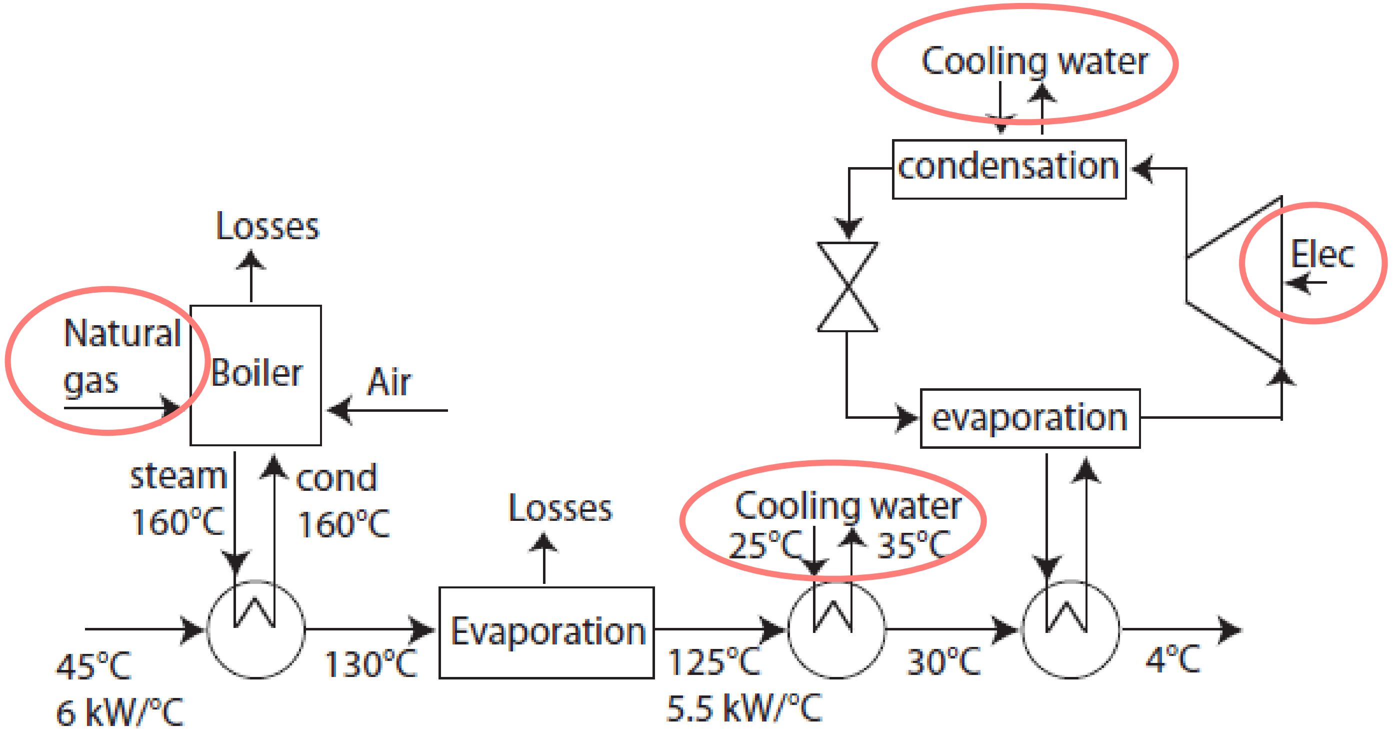
$$\text{COP} = \frac{\dot{Q}_{evap}}{\dot{E}^{+}}$$

$$\dot{Q}_{CW,cond} = \dot{Q}_{cond} = \dot{m}_{CW,cond} c_{p,CW} \Delta T_{CW}$$

$$\dot{m}_{CW,tot} = \dot{m}_{CW,cooler} + \dot{m}_{CW,cond}$$

- **Electricity**

$$\text{COP} = \frac{\dot{Q}_{evap}}{\dot{E}^{+}}$$



Exercise 01

Question 1

CALCULATE THE ACTUAL ENERGY BILL:

1. Identify the resources
2. Quantify the resources
3. Calculate the operating cost

- **Natural gas**

$$OC_{NG} = c_g \left[\frac{CHF}{kWh}\right] \cdot \dot{Q}_{NG}[kW] \cdot t_{op}\left[\frac{h}{y}\right] = \left[\frac{CHF}{y}\right]$$

- **Cooling water**

$$OC_{CW} = c_{CW}\left[\frac{CHF}{m^3}\right] \cdot \dot{m}_{CW,tot}\left[\frac{kg}{s}\right] \cdot \rho\left[\frac{m^3}{kg}\right] \cdot 3600\left[\frac{s}{h}\right] \cdot t_{op}\left[\frac{h}{y}\right] = \left[\frac{CHF}{y}\right]$$

- **Electricity**

$$OC_{elect} = c_e\left[\frac{CHF}{kWh_e}\right] \cdot \dot{E}^{+}[\mathrm{kW}] \cdot t_{op}\left[\frac{h}{y}\right] = \left[\frac{CHF}{y}\right]$$

Total energy bill:

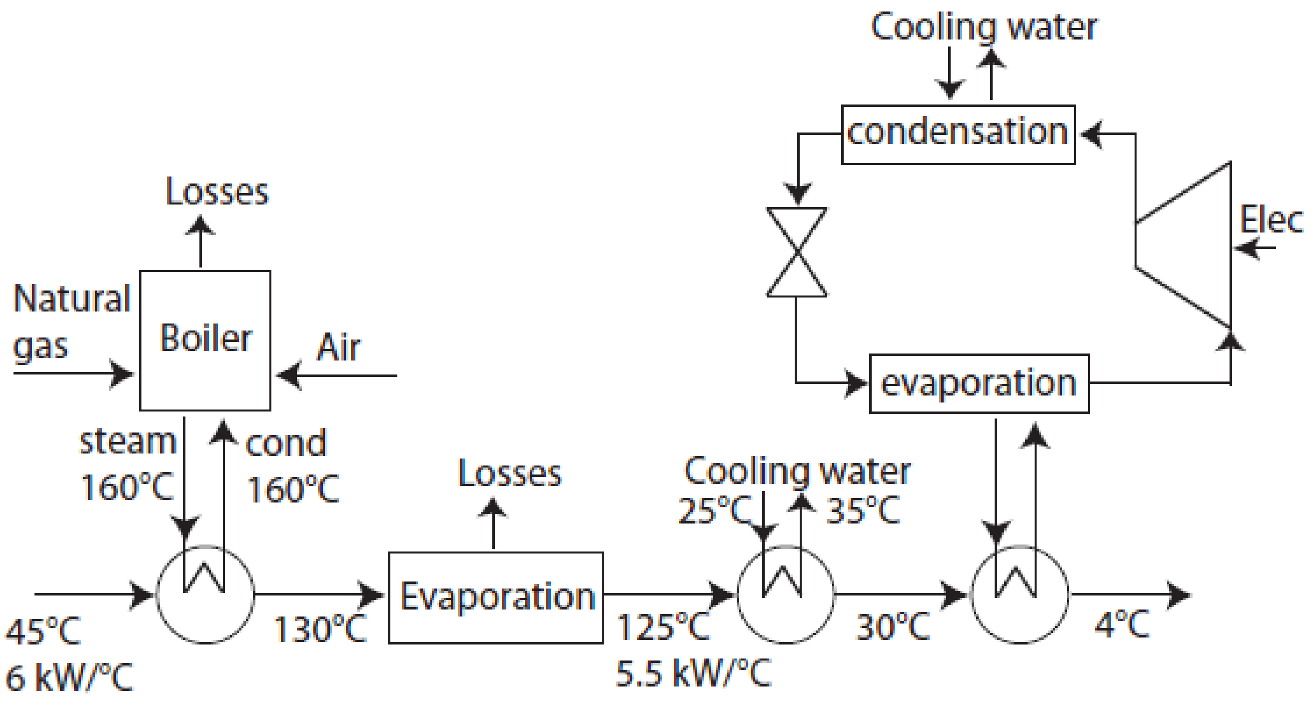
$$OC = OC_{NG} + OC_{CW} + OC_{elect}$$

Exercise 01

Question 2

HOW IS THE HEAT RECOVERY POSSIBLE?

1. Identify the heat recovery option(s)



Exercise 01

Question 2

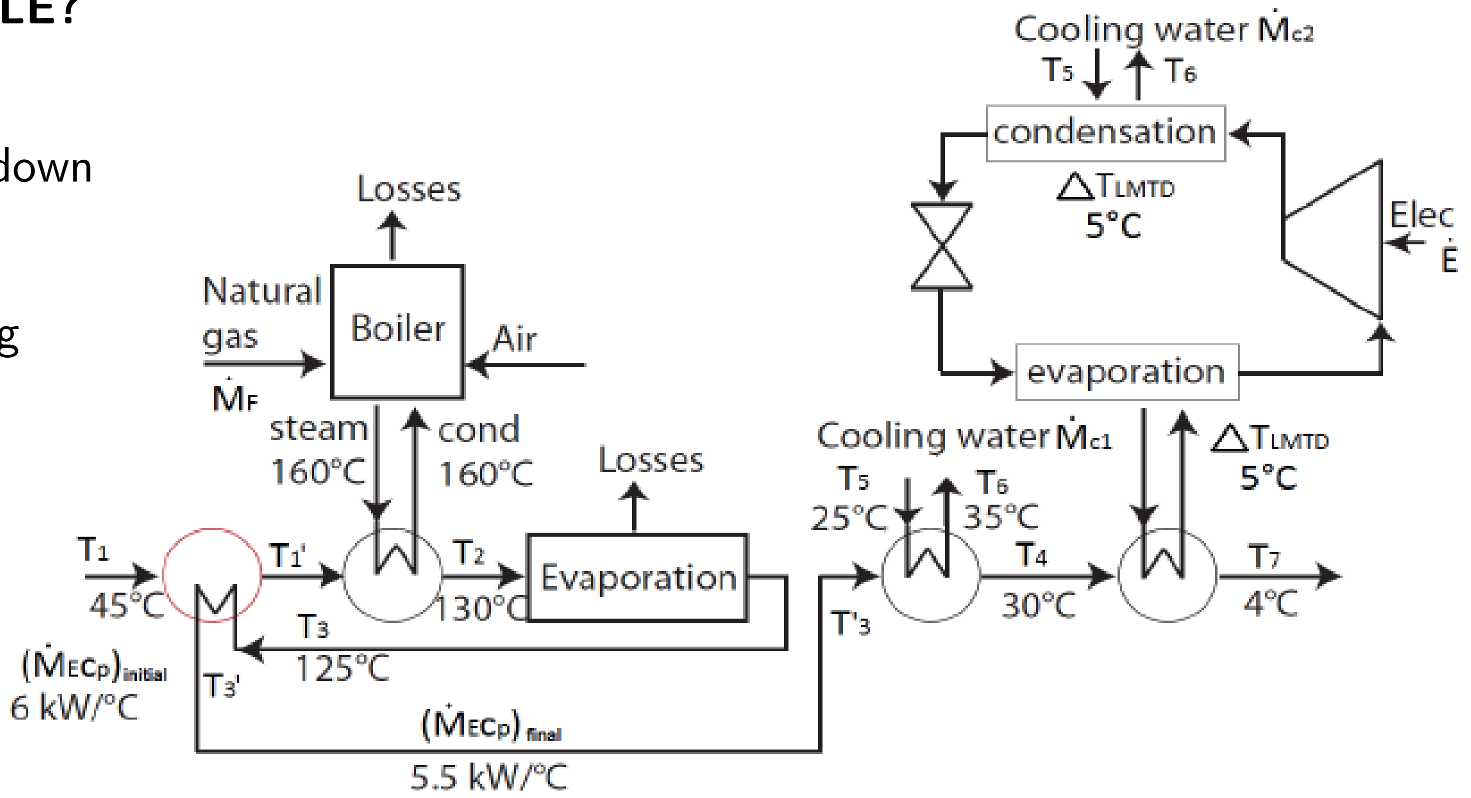
HOW IS THE HEAT RECOVERY POSSIBLE?

1. Idenfitiy the heat recovery option(s)

The fluid is heated up in the boiler and cooled down after the evaporator:

Preheat the fluid before the boiler by using the hot one before the cooler

$\dot{Q}_{boiler} \downarrow$ $\dot{Q}_{CW} \downarrow$ $\longrightarrow$ $OC \downarrow$



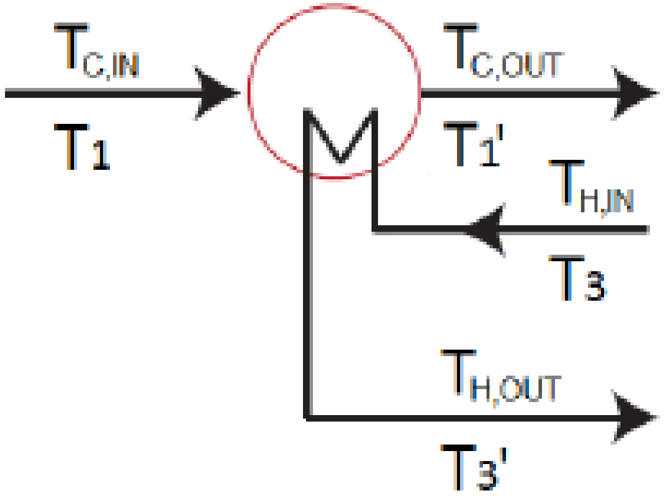
BUT

An additional heat exchanger has to be installed

$IC \uparrow$

WHAT IS THE OPTIMAL ΔTmin?

1. Express the investment cost of the HEX as a function of ΔTmin



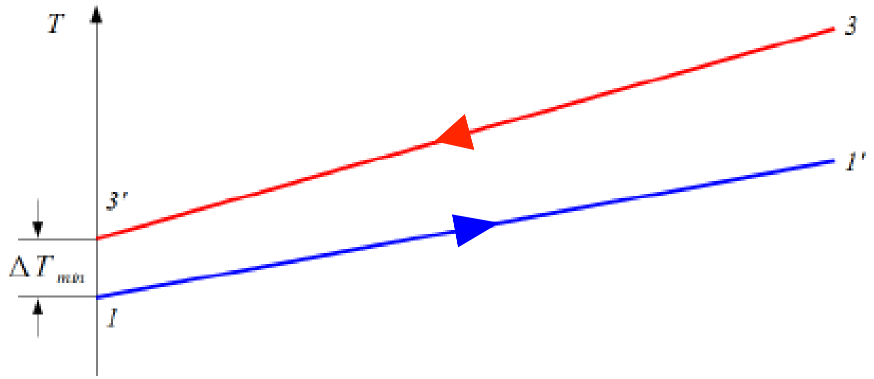
$C_{p,C} = 6\frac{kW}{°C} > C_{p,H} = 5.5\frac{kW}{°C}$ → ΔTmin at the inlet of the cold flow/outlet hot flow

$T_3 = 125\ °C\ ,\ T_1 = 45\ °C\ ,\ T_{3'} = T_1 + \Delta Tmin\ ,\ T_{1'} = T_1 + \frac{C_{p,H}(T_3 - T_{3'})}{C_{p,C}}$

$$LMTD = \frac{(T_3 - T_{1'}) - (T_{3'} - T_1)}{\ln\left(\frac{T_3 - T_{1'}}{T_{3'} - T_1}\right)}$$

$$A_{ex}(\Delta Tmin) = \frac{\dot{Q}_{ex}(\Delta Tmin)}{U \cdot LMTD(\Delta T_{\min})}$$

$$U = \frac{1}{\frac{1}{\alpha_{cold}} + \frac{s}{k} + \frac{1}{\alpha_{hot}}}$$



$$C_{P,ex}(\Delta Tmin) = \frac{I_t}{I_{t,ref}} 10^{k_1 + k_2 \log A_{ex}(\Delta Tmin) + k_3 (\log A_{ex}(\Delta Tmin))^2}$$

$$IC_{ex}(\Delta Tmin) = F_{BM_{ex}} \cdot C_{P,ex}(\Delta Tmin) \cdot \frac{i(1+i)^n}{(1+i)^n - 1}$$

Exercise 01

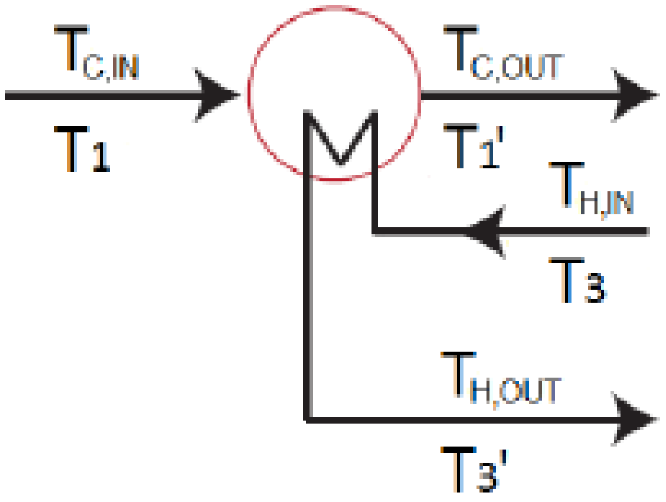
Question 3

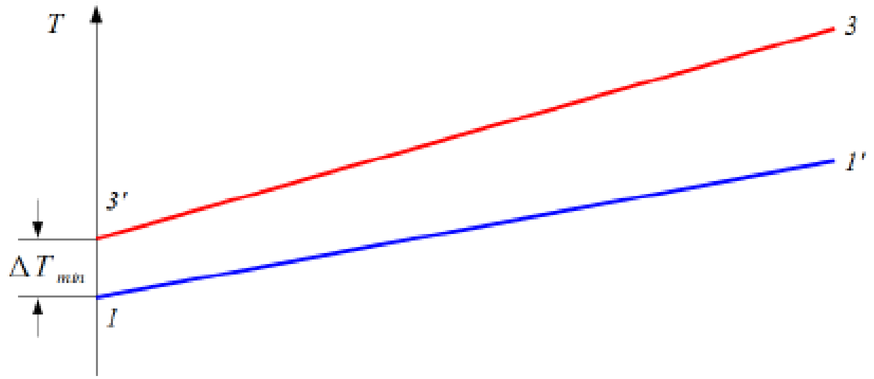
WHAT IS THE OPTIMAL ΔTmin?

1. **Express the investment cost of the HEX as a function of ΔTmin**
2. **Express the new operating cost as a function of ΔTmin**

The operating cost of the boiler and the cooling water is decreased

$$OC(\Delta Tmin) = OC_{NG}(\Delta Tmin) + OC_{CW}(\Delta Tmin) + OC_{elect}$$





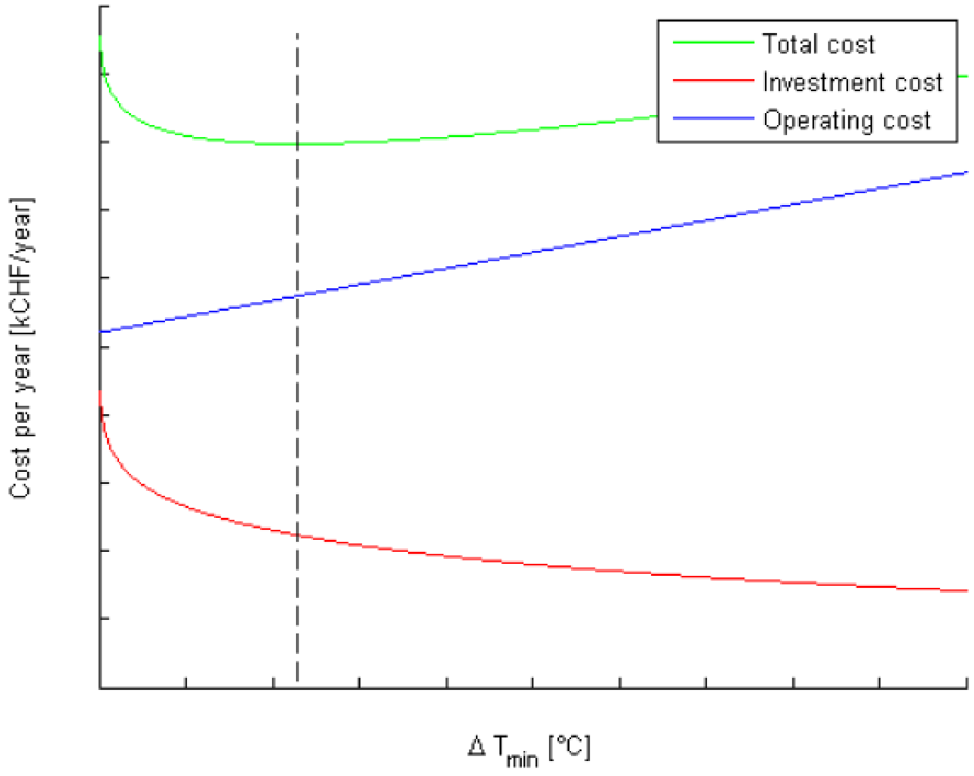
WHAT IS THE OPTIMAL ΔTmin?

1. **Express the investment cost of the HEX as a function of ΔTmin**
2. **Express the new operating cost as a function of ΔTmin**
3. **Find the optimum ΔTmin by minimizing the total annualized cost**

$$\min_{\Delta Tmin} TC(\Delta Tmin) = \{IC_{ex}(\Delta Tmin) + OC(\Delta Tmin)\}$$

The pay back time of the additional investment is:

$$t_{PayBack} = \frac{C_{BM_{ex}}}{OC - OC(\Delta Tmin_{opt})}$$



Exercise 01

Question 4

WHAT IS THE OPTIMAL ΔTmin TAKING INTO ACCOUNT ALL THE INVESTMENT COSTS?

1. **Express the investment cost of the boiler as a function of ΔTmin**
2. **Compute the investment cost of the refrigeneration cycle**
   - 1 compressor and 2 heat exchangers (consider a constant temperature difference = 5 °C for both)
3. **Find the optimum ΔTmin by minimizing the total annualized cost**

$$\min_{\Delta Tmin} TC(\Delta Tmin) = \{IC(\Delta Tmin) + OC(\Delta Tmin)\}$$

Is the optimum ΔTmin different wrt the previous case? Why?

Questions?

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