Heat recovery

Optimal DTmin value at the process level

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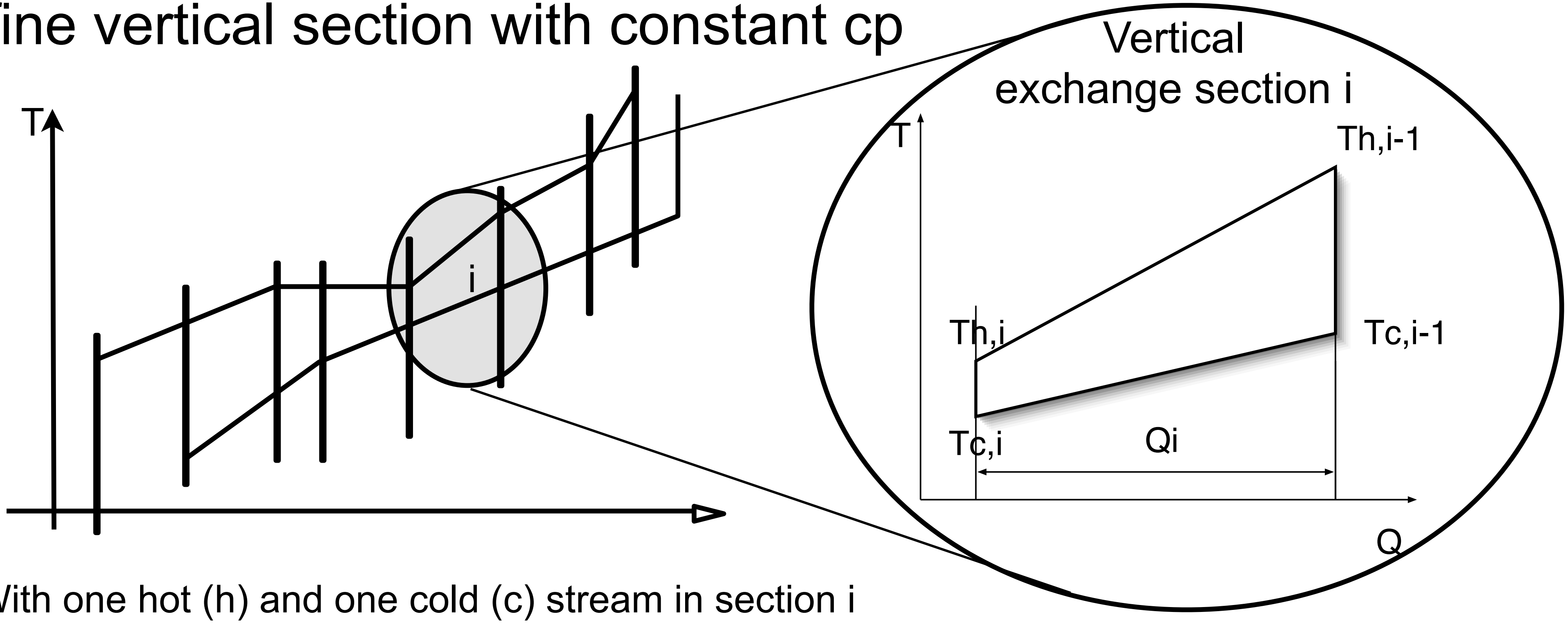
- What about the energy-capital trade-off ?
  - Cost of Energy [CHF/year]
    - Hot Utility :
      $[CHF/year] : \dot{Q}_{MER_{HU}}[kW] \cdot c_{HU}[CHF/kWh] \cdot t_{op}[h/year]$
    - Cold Utility :
      $[CHF/year] : \dot{Q}_{MER_{CU}}[kW] \cdot c_{CU}[CHF/kWh] \cdot t_{op}[h/year]$
    - Refrigeration :
      $[CHF/year] : \dot{Q}_{MER_{RU}}[kW] \cdot c_{RU}[CHF/kWh] \cdot t_{op}[h/year]$
  - Investment : [CHF/year]
    $$[CHF/year] : \frac{1}{\tau}[1/year] \cdot \sum_{e=1}^{n_{htx}} (I(A_e(\Delta T_{min}))[CHF])$$
  - ? ΔT_{min} ?

Estimating heat exchanger network cost

Define vertical section with constant cp



With one hot (h) and one cold (c) stream in section i

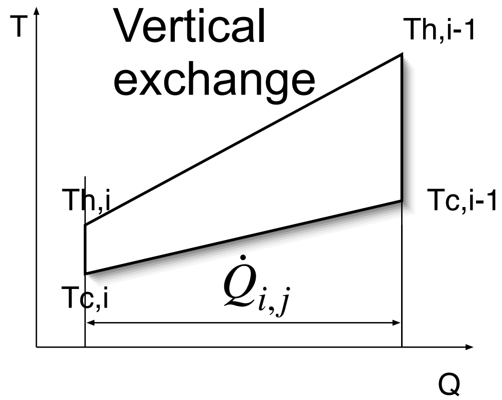
$$A_{h,ci} = \frac{(Q_{h,c})_i}{(U_{h,c})_i * \Delta(T_{lm})_i} = \left(\frac{1}{h_{i,h}} + \frac{1}{h_{i,c}}\right) * \frac{Q_i}{\Delta(T_{lm})_i}$$

With

$$(\Delta T_{lm})_i = \frac{(T_{h,i} - T_{c,i}) - (T_{h,i-1} - T_{c,i-1})}{ln(\frac{T_{h_i} - T_{c,i}}{T_{h,i-1} - T_{c,i-1}})}$$

The hot and cold composites are considered as an overall hot stream to be cooled down and a cold stream to be heated up. The heat recovery is therefore considered as a counter current heat exchanger made of fluids with linear segments (constant cp is the condition to apply the logarithmic mean formula). The linear segments define zones with constant cp (by defining vertical lines). In each vertical section, the log mean temperature difference can be calculated.

Vertical section with several streams



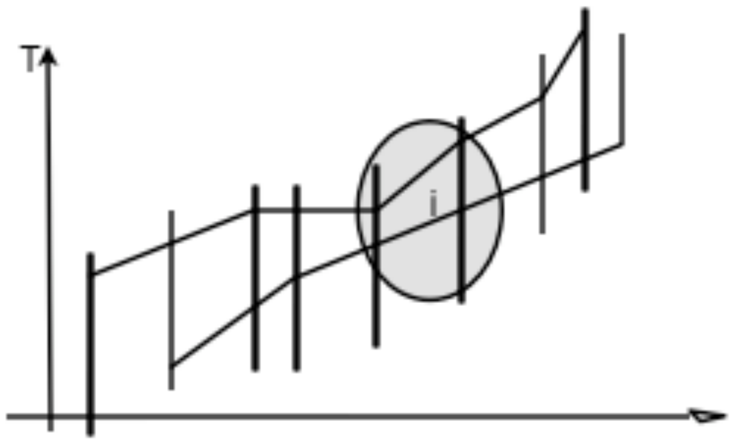
$$A_i = \frac{1}{(\Delta T_{lm})_i} * (\sum_{j=1}^{(n_{streams})_i} * \left(\frac{\dot{Q}_{i,j}}{h_{i,j}}\right))$$

With

$$(\Delta T_{lm})_i = \frac{(T_{h,i} - T_{c,i}) - (T_{h,i-1} - T_{c,i-1})}{ln(\frac{T_{h_i} - T_{c,i}}{T_{h,i-1} - T_{c,i-1}})}$$

when several streams are in the same vertical section, they see the log mean temperature difference. The area is therefore a sum c the contributions of each of the streams in the vertical section. The sum concern the ratio heat load over film heat transfer coefficier of the corresponding stream j in section i.

Total heat exchange area



$$A_{total} = \sum_{i=1}^{n_{vertical\ exchanges}} A_i$$

$$A_{total} = \sum_{i=1}^{n_{vertical\ exchanges}} \frac{1}{(\Delta T_{lm})_i} * \left(\sum_{j=1}^{(n_{streams})_i} \left(\frac{\dot{Q}_{i,j}}{h_{i,j}}\right) \right)$$

Total investment

$$[CHF/year] : \frac{1}{\tau}[1/year] \cdot \sum_{e=1}^{n_{htx}} (I(A_e(\Delta T_{min}))[CHF])$$

$$A_{total} = \sum_{i=1}^{n_{vertical\ exchanges}} A_i$$

What is the cost of the heat exchangers ? => we need the number of heat exchangers and we need the area of the heat exchangers, if possible before calculating the heat exchanger network.

Minimum number of units : from graph theory

Pinch point = two independent sub-systems

Number of Independent sub-systems above the pinch point

Number of Independent sub-systems below the pinch point

$$U_{\min,MER} = (N_{above} - 1 - S_{above}) + (N_{below} - 1 - S_{below})$$

Number of streams above the pinch point

Number of streams below the pinch point

$$U_{\min,MER} = (N_{total} + N_{utility} - 1) + (N_{pinch} - 1) - (S_{above} + S_{below})$$

Number of Independent sub-systems below and above the pinch point

Total number of streams, including the utilities

Number of streams crossing the pinch point

Estimating the investments

Cost of 1 heat exchanger

$$I(A) = a + b\,(A)^{c}$$

c: **0,6 - 0,8**

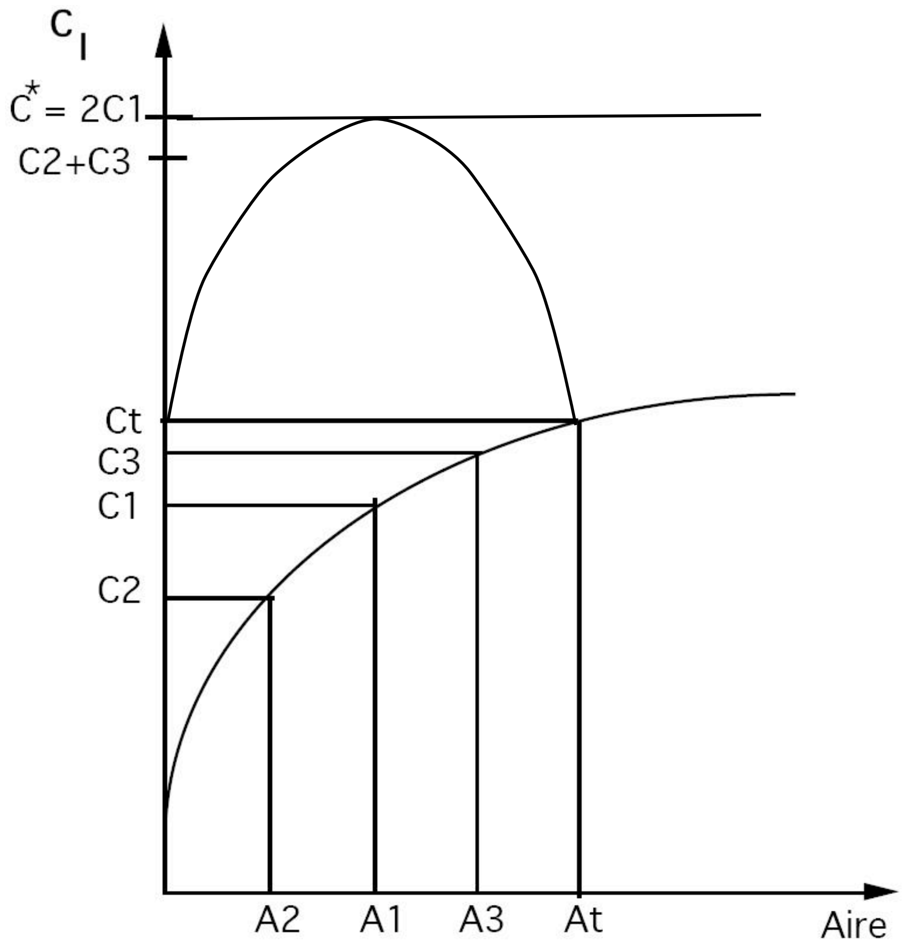
A: **Heat exchange area**

$$A = \frac{\sum_i A_i}{U_{\min,mer}} = \frac{\sum_{i=1}^{nb_{T\,inter}} \sum_{j=1}^{nbstreams_i} \frac{\dot{Q}_i}{h_{j,i} * (\Delta T_{\ln})_i}}{(N_{total} + N_{utility} - 1) + (N_{pinch} - 1) - (S_{above} + S_{below})}$$

$$\sum_{e=1}^{n_{htx}} (a + b(A_e(\Delta T_{min}))^c)[CHF]) \simeq U_{min,MER} \cdot (a + b(\frac{A_{tot}}{U_{min,MER}})^c)[CHF]$$

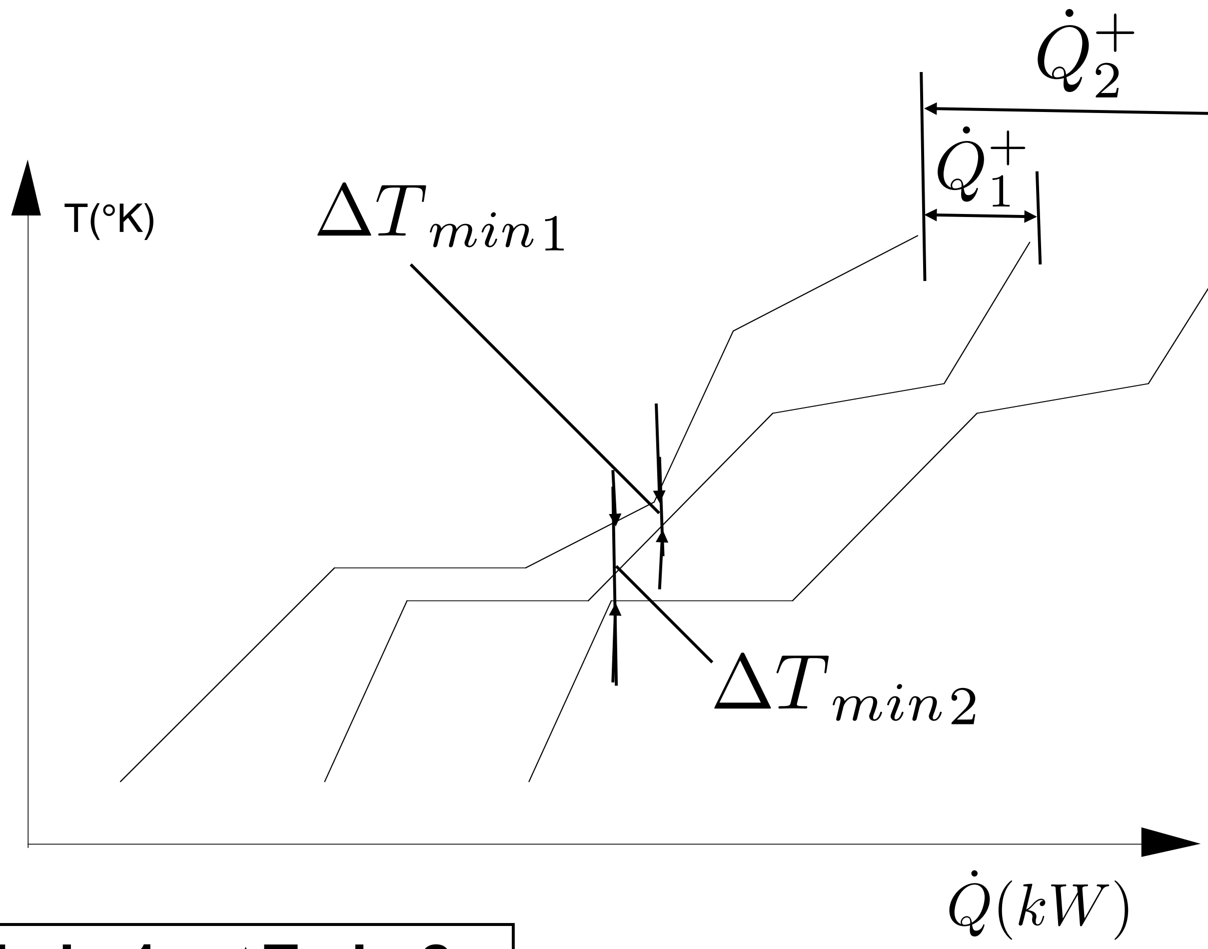
we assume an equal repartition of the total area between the minimum number of heat exchangers

Cost estimation : over estimation



by assuming an equal repartition of the area over all the heat exchangers, we will overestimate the heat exchangers total cost.

Influence of ΔTmin

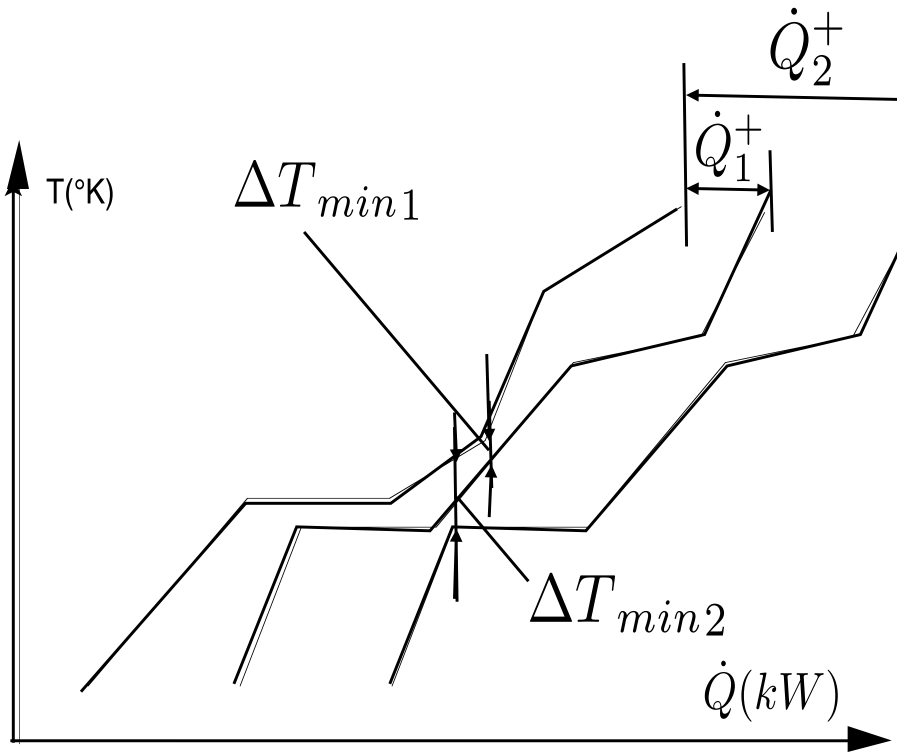


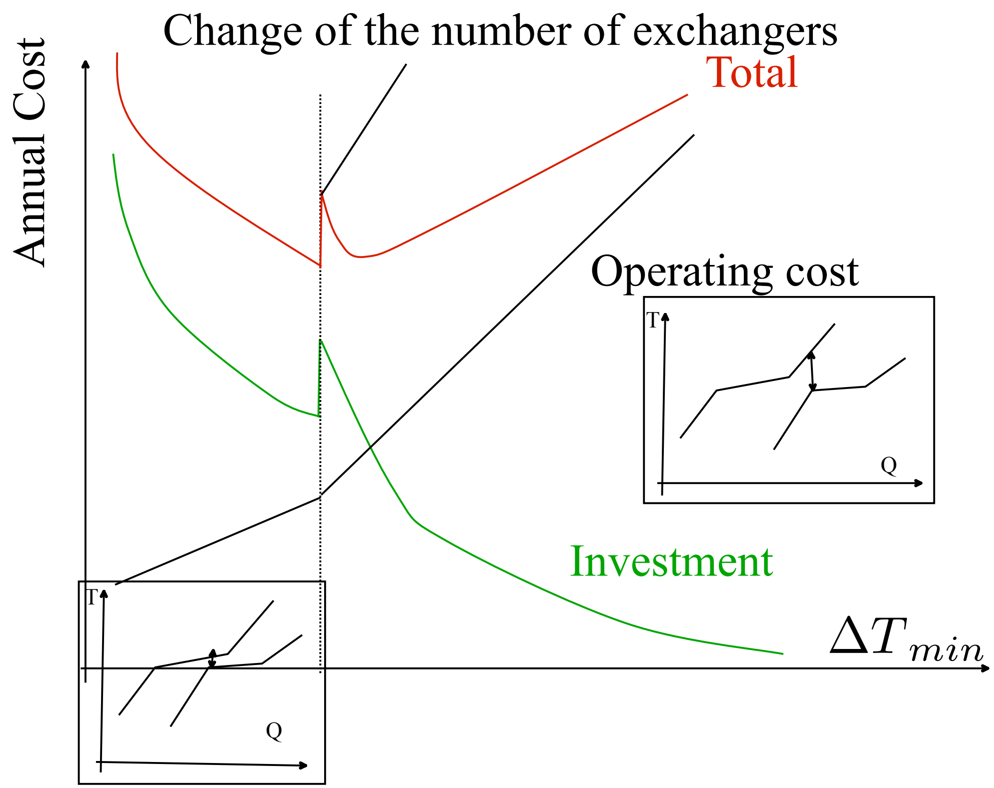
ΔTmin 1 < ΔTmin 2

- Q1 < Q2 -> Operating costs
- ≠ pinch points-> ≠ number of units & ≠ streams at the pinch point
- A1 > A2 -> Investments

Changing the value of the ΔTmin we may change the position of the pinch point. Some heat exchange might become impossible for for a bigger temperature difference. When the pinch point is changing the number of streams crossing the pinch is going to change and therefore the number of heat exchangers. At the same time the total area is changing but can be distributed over more or less heat exchangers.

Variation of the ΔTmin value





Therefore both the heat recovery and the capital cost curves will have discontinuities or jumps.

Fluid dependent ΔTmin value

The ΔTmin is related to the type of fluids

Heat exchange:

Temperature difference

$$\dot{Q}_{ex} = U_{ex} A_{ex} \Delta T_{lm}$$

$$\frac{1}{U_{ex}} = \frac{1}{\alpha_{cold}} + \frac{e}{\lambda} + \frac{1}{\alpha_{hot}}$$

If A and Q are constant

If U increases : ΔT decreases

If U decreases : ΔT increases

=> ΔTmin is related to the streams involved

-> to the film heat transfer coefficient

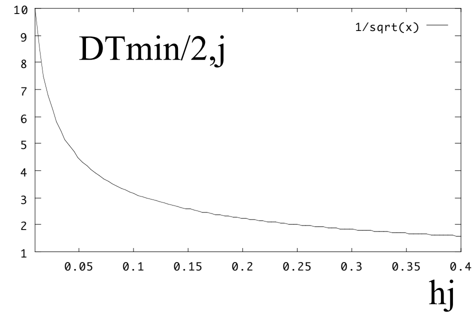
ΔT ≥ ΔTmin/2,h + ΔTmin/2,c

As the heat exchange area depends on the heat transfer film coefficient, it makes sense to consider different values of the ΔTmin when streams have different heat film transfer coefficient.
SO one can associate a contribution to the ΔTmin that is associated to each stream.

DTmin as a function of heat transfer

Remaining parameter => 1 DOF

$$\Delta Tmin/2_j = K_{\Delta Tmin} \cdot (\frac{Q_j}{h_j})^{\frac{c}{c+1}}$$



Liquid State : $2 \cdot K_{\Delta Tmin}$

Fluid phase change :$1 \cdot K_{\Delta Tmin}$

Gas State :$5 \cdot K_{\Delta Tmin}$

Convective heat transfer coefficient

c is the cost exponent in the heat exchanger cost estimation formula

Table 1: Typical values for the $\Delta T_{min}/2$ as a function of the heat transfer film coefficient

Type	Heat transfer coefficient $W/m^2/C$	$\Delta T_{min}/2$
Gas stream	60	15
Liquid stream	560	5
Condensing stream	1600	3
Vaporizing stream	3600	2

In reality, not only the film transfer coefficient defines the area but also the heat load (smaller heat exchangers would have higher specific cost (CHF/m2) due to the heat load. Therefore the ΔTmin/2 contribution can be associated to the ratio heat per heat transfe coefficient. The exponent comes from the optimum value considering the trade-off between capital and savings.
Note that there is still one unknown ($K_{\Delta Tmin}$) that will be used to calculate the overall ΔTmin value.

Streams dependent ΔTmin

$$T_h^* = T_h - \Delta T_{min}/2_h \quad \forall h \in \{hot\, streams\}$$

$$T_c^* = T_c + \Delta T_{min}/2_c \quad \forall c \in \{cold\, streams\}$$

$$\min_{R_r} \dot{Q}^+ = R_{n_r+1}$$

subject to heat balance of the temperature intervals :

$$\begin{aligned} R_r =& R_{r+1} \\ &+ \sum_{h_r \in \{\text{hot streams in interval } r\}} \dot{M}_{h_r} c_{p_{h_r}} (T_{r+1}^* - T_r^*) \\ &- \sum_{c_r \in \{\text{cold streams in interval } r\}} \dot{M}_{c_r} c_{p_{c_r}} (T_{r+1}^* - T_r^*) \end{aligned} \quad \forall r = 1, ..., n_r$$

and the heat cascade feasibility

$$R_r \geq 0 \quad \forall r = 1, ..., n_r + 1$$

With the new definition of the corrected temperatures, the calculation of the heat cascade and the pinch point location remains identical.

ΔTmin value analysis

$$\forall K_{\Delta Tmin} \in \{K^{min}_{\Delta Tmin}..K^{max}_{\Delta Tmin} \text{ by } \delta\}$$

Cost estimation of the system

Operation : Energy cost by heat cascade

Investments :

- minimum number of units
- estimated area
- equal repartition

Total cost = Operating +1/τ* investments

-> Pinch point changes

Streams concerned

New connections

-> Optimal value

has to be between the two pinch points that frame the optimal value

By changing the value of the $K_{\Delta Tmin}$ it is possible to calculate what is the best value of the $\Delta Tmin/2_j$

Conclusions

- Estimating the cost of heat exchange system
  - Vertical heat exchanges => overall area
    - Adapted for different heat transfer coefficient
  - Graph theory => minimum number of units
    - Pinch point divides system in sub-systems
  - Equi-repartition of area
    - overestimation of the investment cost
- DTmin optimisation
  - Stream dependent DTmin/2
  - Best pinch point location
- Starting point for
  - Heat exchanger network design
  - Heat exchanger network debugging

- <u>pinch design method</u>