

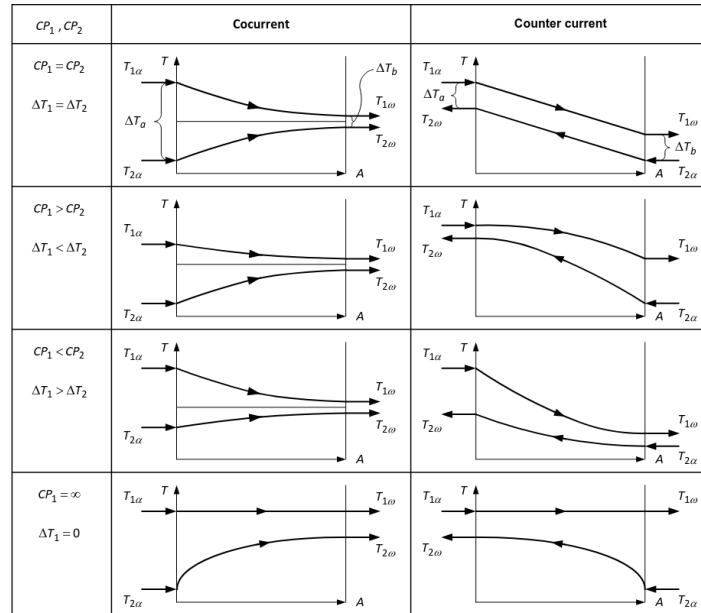
I. Fundamentals of Energy and Processes

Heat exchanger Energy balance

$$\dot{Q} = \dot{m}c_p\Delta\vartheta = CP\Delta\vartheta, \quad \dot{Q} = \phi$$

$$\dot{m}_1c_{p1}\Delta\vartheta_1 = \dot{m}_2c_{p2}\Delta\vartheta_2 \iff CP_1\Delta\vartheta_1 = CP_2\Delta\vartheta_2$$

Average temperature difference



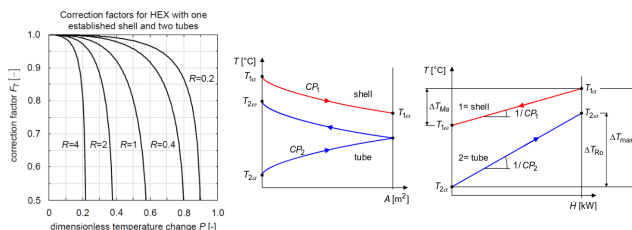
Logarithmic mean temperature difference (LMTD)

$$\Delta T_m = \frac{\Delta T_a - \Delta T_b}{\ln \frac{\Delta T_a}{\Delta T_b}}$$

$$\Delta T_a = |\vartheta_{1,a} - \vartheta_{2,a}| \quad ; \quad \Delta T_b = |\vartheta_{1,b} - \vartheta_{2,b}|$$

Corrected mean temperature heat flow

$$\dot{Q} = kA\Delta T_m \cdot F_T, \quad \text{with } 0 < F_T < 1$$



Co-current vs countercurrent flow heat exchanger

$$\dot{Q} = kA_{co}\Delta T_{m,co} = kA_{count}\Delta T_{m,count}$$

$$\frac{A_{co}}{A_{count}} = \frac{\Delta T_{m,count}}{\Delta T_{m,co}}$$

$$\frac{A_{co}}{A_{count}} = \frac{\dot{Q}_{co}}{\dot{Q}_{count}} \cdot \frac{\Delta T_{m,count}}{\Delta T_{m,co}}, \quad \text{if } \dot{Q}_1 \neq \dot{Q}_2$$

Heat capacity rate ratio (Capacity ratio)

It measures the relative ability of stream 1 vs. stream 2 to carry heat per kelvin:

$$CP_1 (\vartheta_{1,\alpha} - \vartheta_{1,\omega}) = CP_2 (\vartheta_{2\omega} - \vartheta_{2,\alpha})$$

$$R_1 = \frac{CP_1}{CP_2} = \frac{\vartheta_{2,\omega} - \vartheta_{2,\alpha}}{\vartheta_{1,\alpha} - \vartheta_{1,\omega}} = \frac{\Delta\vartheta_2}{\Delta\vartheta_1}$$

T,H diagram

Cold and Hot streams

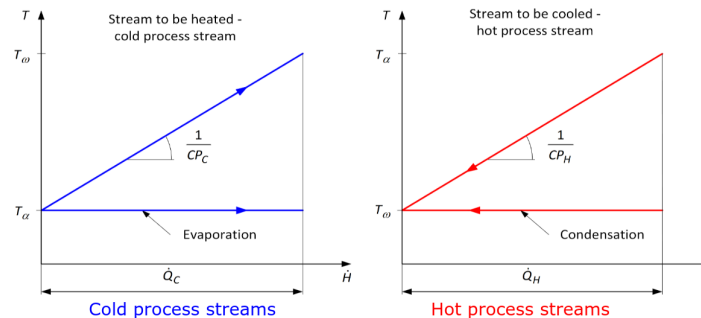
The process is extracted into material streams that must be heated (heating need) or cooled (cooling need):

Cold streams

- Heating needed (heat sink):
- Warming of milk for pasteurisation
 - Heating a heat transfer oil
 - Preparation of hot water
 - Evaporation of fruit juice

Hot streams

- Cooling needed (heat source)
- Cooling of a salt solution
 - Cooling a polymer melt
 - Cooling water from air compressors
 - Chiller refrigerant
 - Flue gas

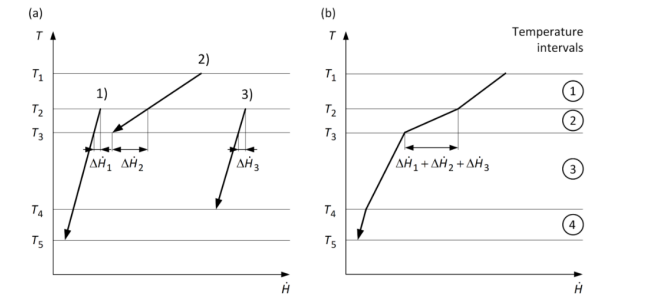


Slope of the streams

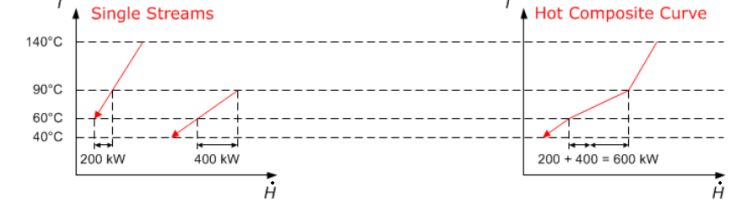
$$\frac{\Delta T}{\Delta \dot{H}} \iff \frac{\Delta T_1}{CP_1 \cdot \Delta T_1} = \frac{1}{CP_1} \iff \frac{\Delta T_2}{CP_2 \cdot \Delta T_2} = \frac{1}{CP_2}$$

Composite curve

$$\frac{1}{CP_n} = \frac{\Delta T_n}{\Delta \dot{H}_n} = \frac{\Delta T_n}{\sum_i CP_i \Delta T_n} = \frac{1}{\sum_i CP_i}$$



Streams to be Cooled (Hot Streams):



Streams to be Heated (Cold Streams):



II. Energy and Cost Targets

ΔT_{min}	HR Potential	Required Utilities	HEX Area	Investments Costs	Energy Costs
decreases	increases	decreases	increases	increases	decreases
increases	decreases	increases	decreases	decreases	increases

Cost targets

Calculation of Annual Total Costs (Annualized Total Costs)

$$C_{tot} = AC_{inv} + C_{Op}$$

Annuity factor

$$A = \frac{Z(1+Z)^n}{(1+Z)^n - 1}$$

Z = interest rate

n = Depreciation/Amortisation period

Investment costs

$$C_{Inv} = C_{HEN} + C_{ECU} + C_{Ind}$$

HEN = Heat exchanger network cost

ECUs = Energy conversion units

Ind = Independent (eg. control integration)

Capital costs for heat exchanger network (HEN)

$$C_{HEN} = \sum C_{HEX} = \sum \left(a + C_b \left(\frac{Q}{Q_b} \right)^m \right)$$

C_{HEX}	Capital cost of heat exchanger (HEX)
a	Base cost
C_b	Cost of reference heat exchanger
Q_b	Heat transfer area of reference heat exchanger
m	Degression exponent
Q	Area of HEX to be costed

Q refers to quantity (in this case, Area for the HEX costs)

Annual operating costs

$$C_{Op} = C_{En} + C_M + C_{Per}$$

Maintenance costs

$$C_M = C_{Inv} f_M$$

Personnel costs

$$C_{Per} = C_{Inv} f_{Per}$$

Annual energy costs

Annual energy costs are the sum of the annual hot and cold utility costs and the energy costs of the ECUs.

$$C_{En} = C_{HU} + C_{CU} + C_{En,ECU}$$

Hot utility costs

$$C_{HU} = \dot{Q}_{HU} \tau c_{HU}$$

Cold utility costs

$$C_{CU} = \dot{Q}_{CU} \tau c_{CU}$$

$\dot{Q}_{HU/CU}$	Hot/cold utility requirements (heat flow rate)
$C_{HU/CU}$	Annual energy cost of hot/cold utility
τ	Annual operating hours
$c_{HU/CU}$	Specific energy cost of hot/cold utility

Energy costs of energy conversion units (ECUs)

$$C_{En,ECU} = \sum E_{ECU} c_{En}$$

$C_{En,ECU}$	Annual energy cost of ECUs
E_{ECU}	Annual energy requirement of an ECU
c_{En}	Specific cost of the energy supplied to an ECU

Heat exchanger network cost target

Assuming an equal distribution of the total heat transfer area among the required heat exchangers:

$$C_{HEN,Target} = N_{Units,Target} \left(a + C_b \left(\frac{A_{HEN,Target}}{N_{Units,Target} Q_b} \right)^m \right)$$

Single-stream heat transfer area target

$$A_{HEN,Target} = \frac{\dot{Q}}{\Delta T_m} \left(\frac{1}{\alpha_h} + \frac{1}{\alpha_c} \right)$$

Heat transfer area target (Uniform Bath Formula)

$$A_{HEN,Target} = \sum_{k=1}^K \frac{1}{\Delta T_{m,k}} \left[\sum_{i=1}^I \frac{\dot{Q}_{i,k}}{\alpha_i} + \sum_{j=1}^J \frac{\dot{Q}_{j,k}}{\alpha_j} \right]$$

k, K	Enthalpy interval index k through K
i, j	Hot and cold stream indices within interval k
I, J	Number of hot and cold streams within interval k
α_i, α_j	Heat transfer coefficients of hot and cold streams
$\dot{Q}_{i,k}, \dot{Q}_{j,k}$	Heat flow rates of the streams within interval k
$\Delta T_{m,k}$	Mean temperature difference within interval k
$A_{HEN,Target}$	Target total heat transfer area of the HEN

Number of heat exchangers

$$N_{Units,Target} = [S_{above} - 1] + [S_{below} - 1]$$

$N_{Units,Target}$	Target number of heat exchangers
S_{above}	Number of streams including utilities above the pinch
S_{below}	Number of streams including utilities below the pinch

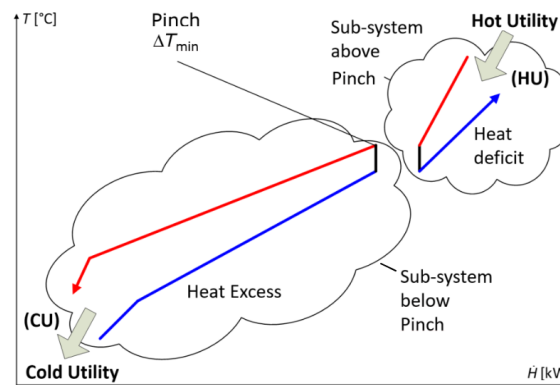
Energy targets**Three main pinch rules**

1. No heat transfer through the pinch
2. No external heating below the pinch
3. No external cooling above the pinch

Characteristics of the pinch point

The pinch divides the total system into two subsystems with:

- Heat deficit above the pinch
- Heat excess below the pinch.

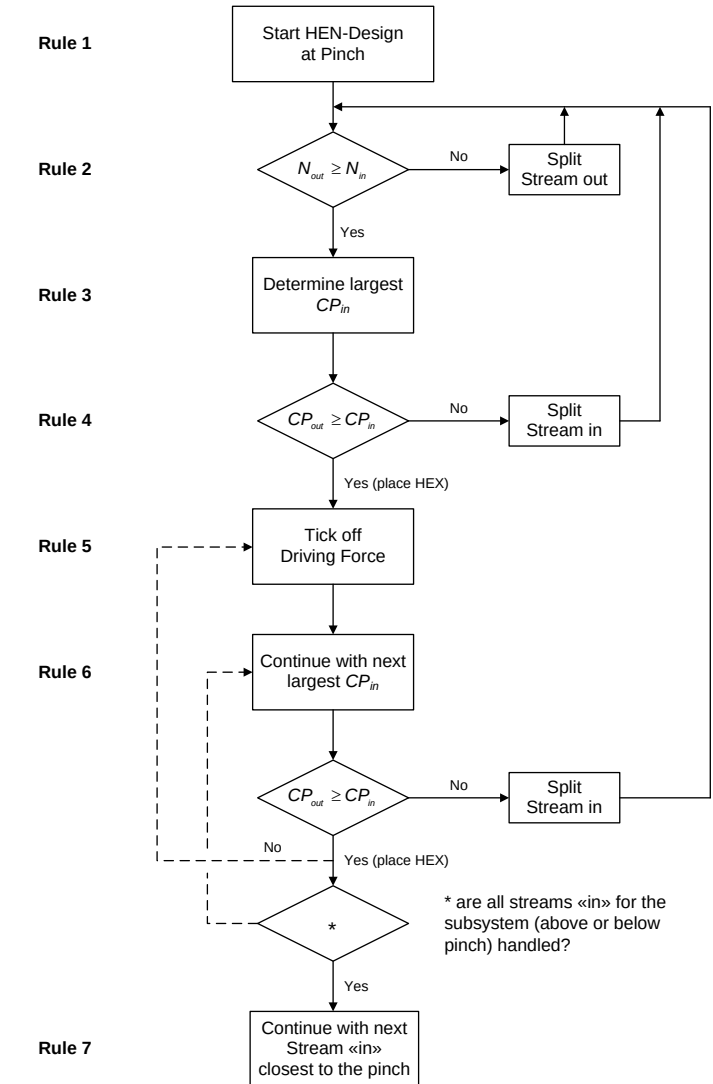
**III. Heat Exchanger Network (HEN)**

MER = Maximum Energy Recovery (for HR)

MER = Minimum Energy Requirement (for CU/HU)

Inwards = Stream that is approaching the PT

Outwards = Stream temperature that is leaving the PT

Rules for the design of HENs

These design rules help to achieve the targets.

1. Start from the pinch and progress outwards
2. Number rule: $N_{\text{out}} \geq N_{\text{in}}$: every stream which heads in the direction of the pinch has a match partner in a HEX
3. Begin with the largest CP_{in} : stream which heads in the direction of the pinch with the largest CP_{in}
4. CP rule: $CP_{\text{out}} \geq CP_{\text{in}}$: no HEX less than ΔT_{min}
5. HEX Optimization:
 - a) **"Tick Off Rule"**: minimize the number of HEX and/or
 - b) **"Driving Force Plot"**: minimize the area of the HEN
6. Continue with the largest CP_{in} at the Pinch
7. If all HEXs at the Pinch are set, then proceed with the stream closest to the Pinch that leads to the Pinch