Intro to Pinch Analysis

Pinch Analysis (PA) is a method for optimization of heat exchanger networks.

PA finds its typical applications when heat and cooling loads cover different temperature ranges.

The objective of PA is to minimize interactions with external heat or cooling resources: these are called "Hot Utilities" (HU) if they represent heat to be provided at high temperature, and "Cold Utilities" (CU) if heat must be removed from the system.

Minimization of interactions outside of the system Q_{hu} (external HU) and Q_{cu} (external CU) leads to the development of an internal heat recovery network which substitutes partially external loads.

Pinch Analysis and Exergy Analysis

PA determines a matching between Hot Streams (to be cooled) and Cold Streams (to be heated) which is effectively **minimizing the temperature difference inside heat exchangers**. This is also the condition which determines the lowest heat transfer **exergy destruction**.

However, PA does not deal explicitly with the **friction losses** encountred to produce the necessary flow conditions inside the heat exchanger. This can be a relevant issue when dealing with low-pressure gas streams and for fluids (liquids or two-phase) commonly encountered in the Oil&Gas or chemical industry. Under these conditions, a **trade-off bewteen heat transfer and fluid friction exergy destruction** is often determined.

An analysis of viscous flow effects can be anyway performed after optimizing the temperature profile with PA. To this end, reference books (*A. Bejan: Entropy Generation through Heat and Fluid Flow*) and advanced methodologies are available.

PA: Open Problems

Chemical production plants typically have diversified needs for process heating (HU= Hot Utility) – applied to “Cold streams” or cooling (CU = Cold Utility) applied to “Hot Streams”.

Q_{hu} (external HU) is often provided by steam or heat generators using fossil fuels, while Q_{cu} (external CU) is dealt using cooling equipment (e.g.: condensers, cooling towers, refrigeration units).

This is called an **Open Problem**, because the purpose of PA is to effectively minimize Q_{hu} and Q_{cu} and to provide thus a direct economy in terms of fuel, heat release to the environment, or electricity.

PA: Closed Problems (Ex. CCGT)

Other situations lead to **Closed Problems**, that is, conditions where the heat recovery from a stream is blocked by external constraints, as can be also for the heat to be released to the environment (sensible heat and exergy loss).

This is for example the case of **HRSGs for CCGTs**, where the gas flow rate and inlet/outlet temperature conditions are blocked.

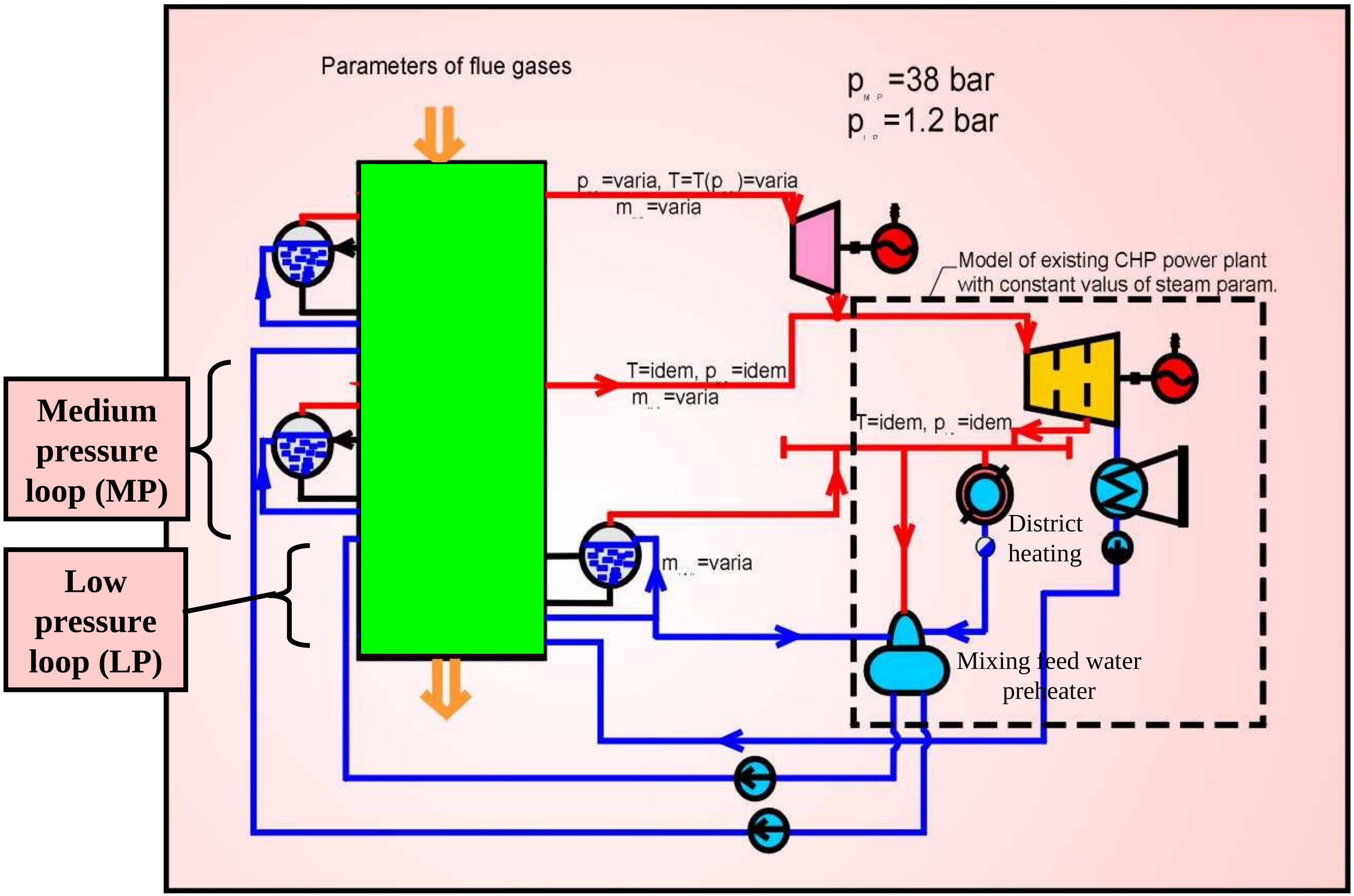
In the case of an **unfired HRSG**, $Q_{hu} = 0$ and Q_{cu} is constrained (usually because of corrosion or environmental concern connected to the release of a cold plume = lower limit to stack temperature).

The purpose of PA becomes here to determine the **minimum surface** of the heat transfer tube bundles in order to produce the required conditions (pressure/temperature, flow rates) for the water/steam circuit.

In some cases (e.g., Aero-derivative GTs with high pressure ratio) it can be useful to consider a **Fired HRSG**, in order to solve pinch problems in the high-temperature section; then, Q_{hu} # 0 (should be minimized) while Q_{cu} is still constrained (stack temperature).

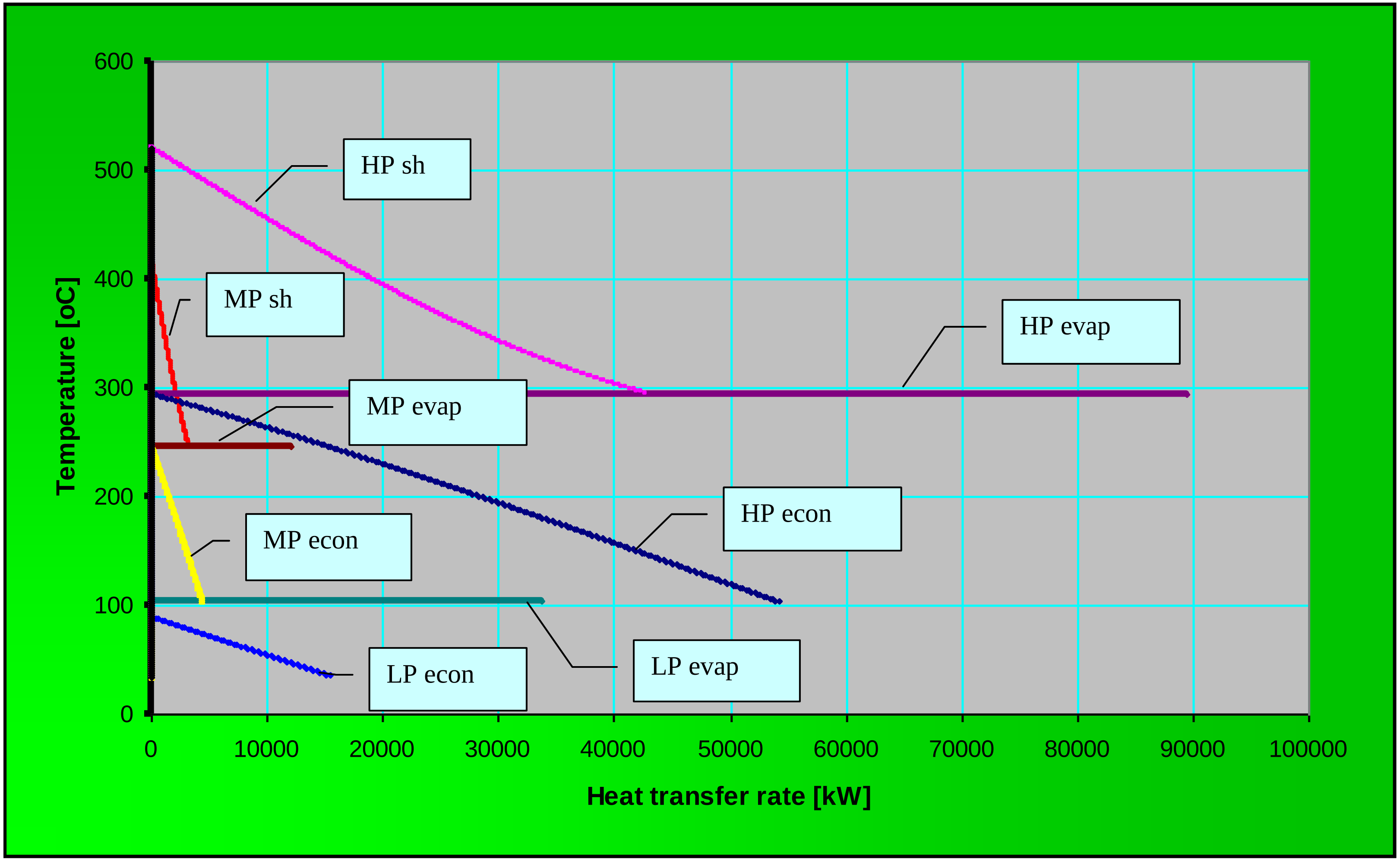
Optimization of Heat Recovery Steam Generators

- multi pressure - pinch analysis



Optimization of Heat Recovery Steam Generators

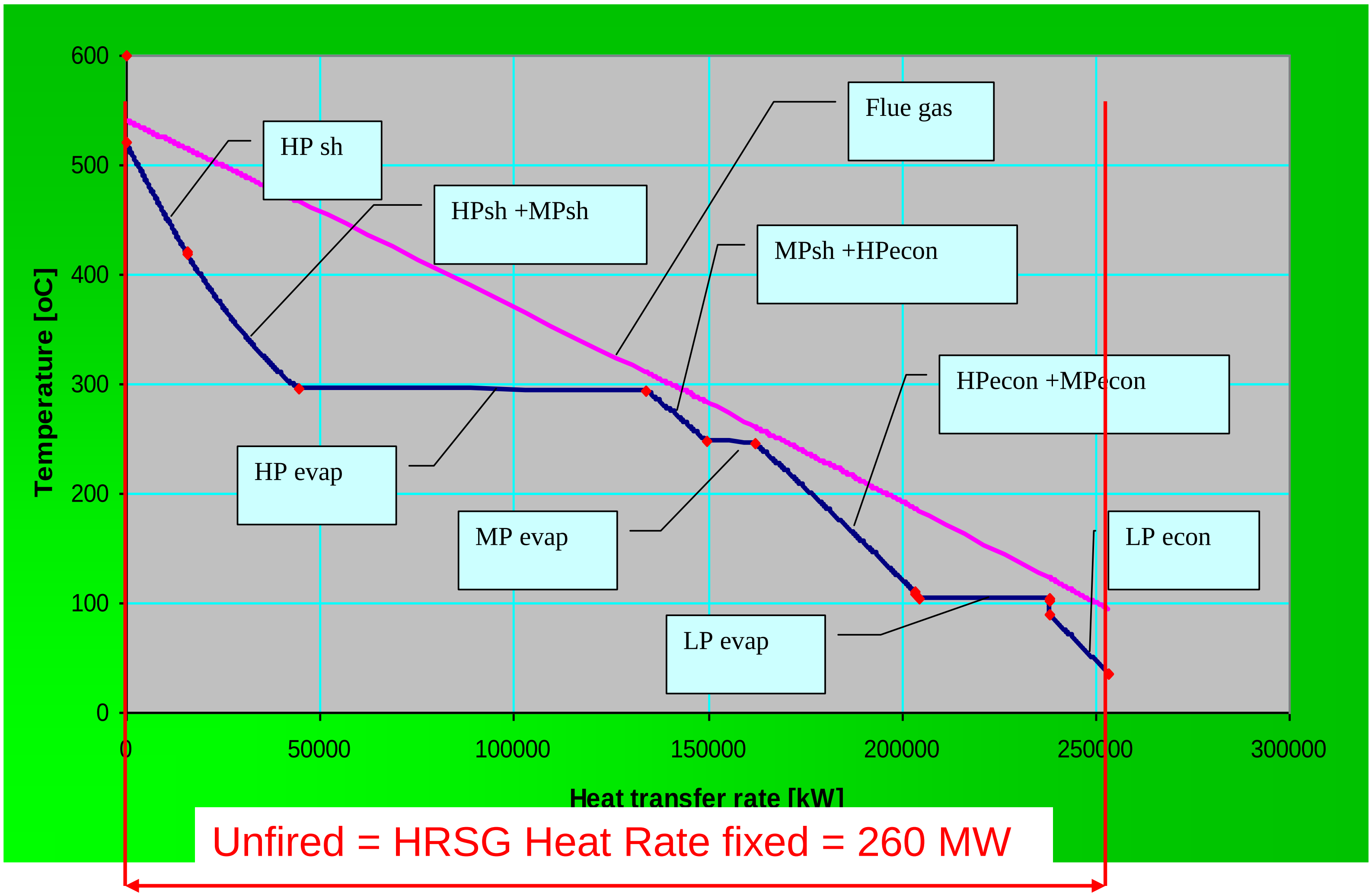
- Cold streams inventory (steam/water)



Multi-pressure HRSG for CCGT

Optimization of Heat Recovery Steam Generators

- Composite curves: Hot (gas) and Cold (Steam/Water)



PA: Closed Problems (CCGT Unfired; Geothermal)

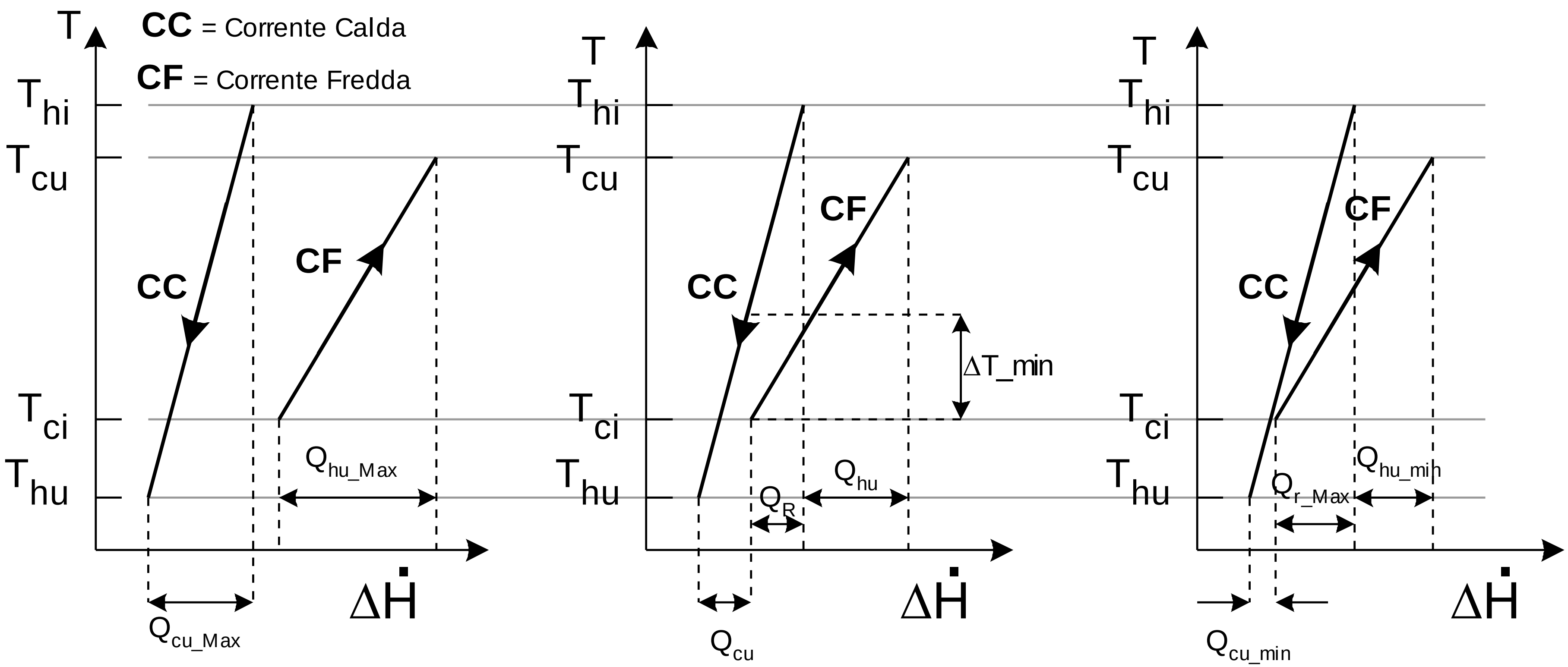
In complex Unfired HRSGs for CCGTs (3-pressure level with 1 or 2 reheats, possibly including process heat production) more than 15 tube bundles can be necessary, and often a series/parallel branching is determined.

PA leads to the solution minimizing heat transfer surface and, thus, the **production cost of the HRSG**. This represents a major issue both for the market competitiveness of equipment suppliers, and for the conservation of resources (see LCA section).

A similar situation occurs in **Geothermal Power Plants**, where constraints are determined by the production well specs (flow rate, temperature) and by conditions for reservoir reinjection (temperature, in order to avoid scaling and/or preserve the long-term operability of the reservoir). However, the heat transfer network is generally simpler at the present level of development of Geothermal Plants, even if combined heat and power units represent a promising field for application of PA.

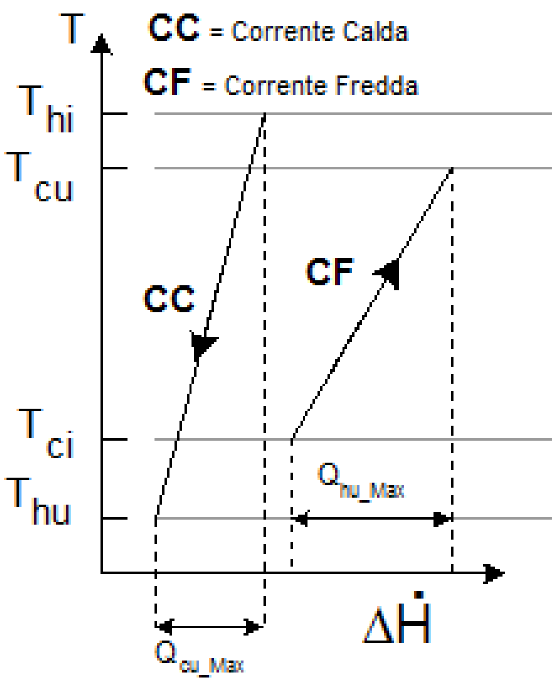
PA Basics: Temperature-Enthalpy (Heat Rate) Diagrams

Temperature-Enthalpy (or Heat Rate, kW) diagrams are the core of the PA methodology. The following pictures represent the basic situation potentially occurring with two streams (one cold CF and one hot CC):

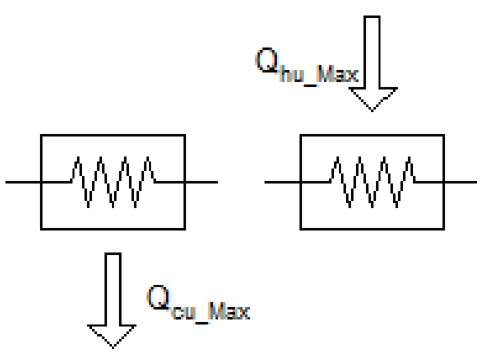


A = Disaccoppiamento Totale B = Accoppiamento Reale C = Massimo accoppiamento

PA Core: Temperature-Enthalpy Diagrams



A = Disaccoppiamento Totale



Starting conditions (Trivial solution)

The cooling load (cooling the hot stream CC) is provided by external removal of Q_{cu_Max}.

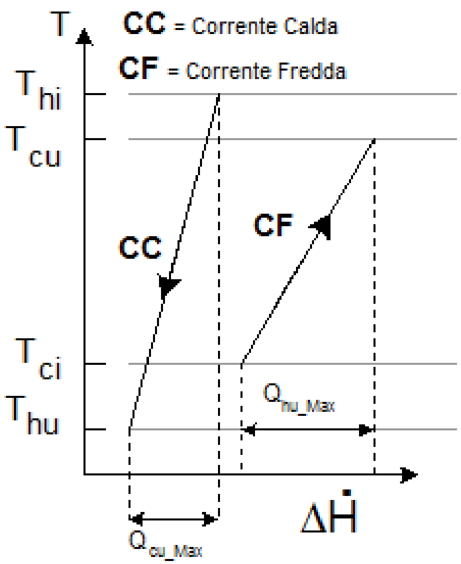
Heat is also supplied externally (e.g.: combustion) in order to heat the cold stream CF with a heat rate Q_{hu_Max}.

These heat or cooling rate loads represent large running and capital costs for the plant.

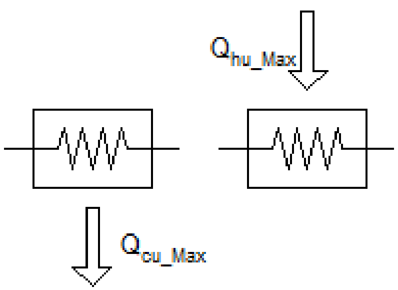
The different slopes of the CC and CF curves are determined by different

Heat Capacities $\boldsymbol{C = m\, c_p}$

Case A: No Process Integration



A = Disaccoppiamento Totale



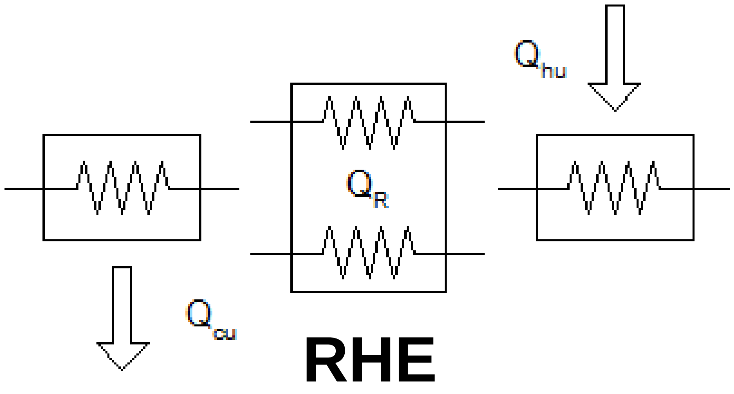
Evaluation of external Hot and Cold Utilities:

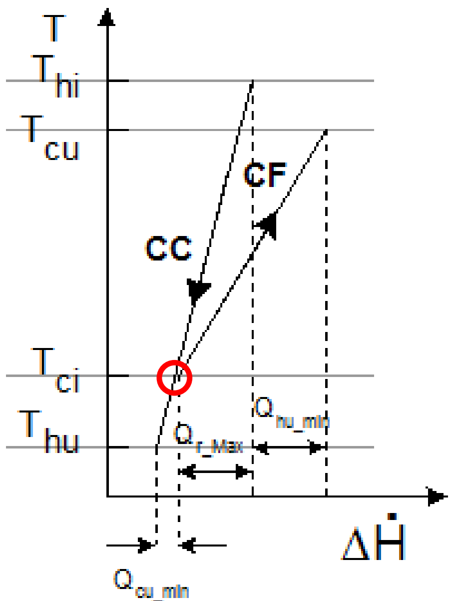
$$Q_{hu\_max} = Q_h = m_c\,(h_{cu} - h_{ci}) = m_c\,c_{pc}\,(T_{cu} - T_{ci}) = (\Delta H)_c$$

$$Q_{cu\_max} = Q_c = m_h\,(h_{hi} - h_{hu}) = m_h\,c_{ph}\,(T_{hi} - T_{hu}) = (\Delta H)_h$$

*Heat Capacities **C***

PA Basics: Temperature-Enthalpy Diagrams – with RHE





C = Massimo accoppiamento

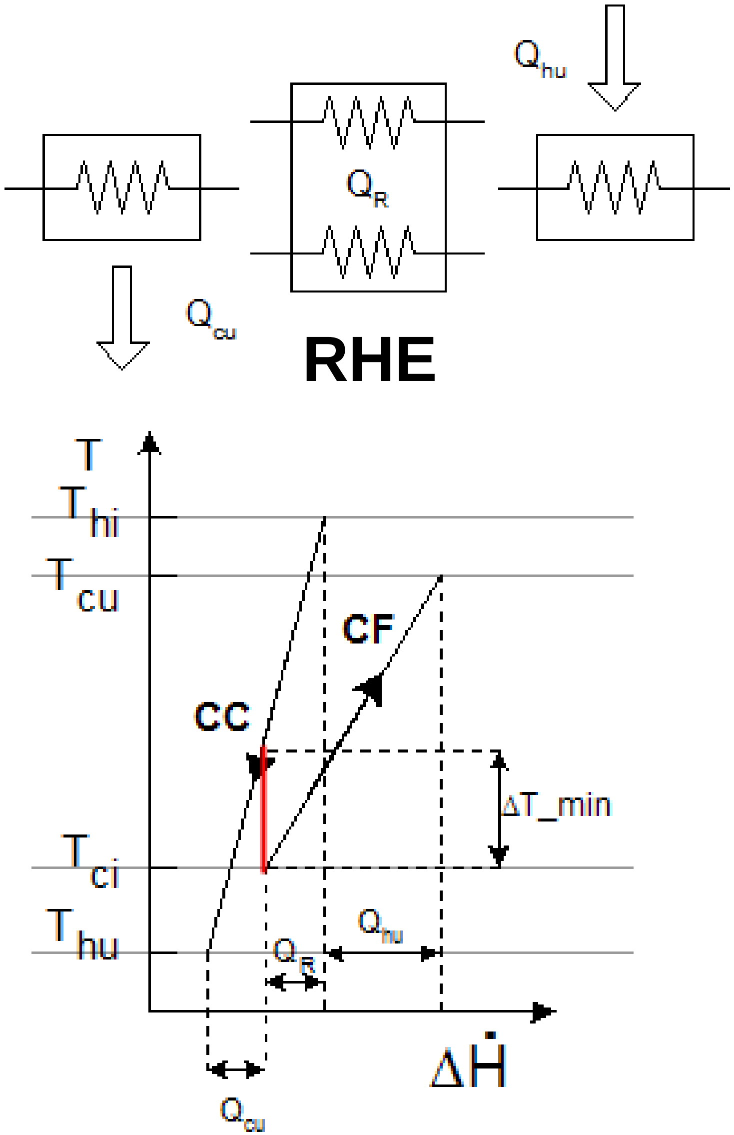
Introducing a **Regenerative Heat Exchanger (RHE)** allows to reduce considerably the heat and cooling loads.

The figure below shows that Q_{cu_Min} and Q_{hu_Min} are reached when the CC and CF streams achieve a **Pinch Condition**, that is, a local point where the temperatures of the two streams (CC and CF) are the same.

Under this condition, the RHE heat duty Q_R is maximized. Q_{cu} and Q_{hu} are minimized (external heat interactions).

Reaching Pinch conditions involves the use of an **HRE of infinite surface** – which is not a viable solution.

PA : Temperature-Enthalpy Diagrams – Real RHE case



B = Accoppiamento Reale

In the **real case**, the Regenerative Heat Exchanger (HRE) works with a finite temperature difference $\Delta T_{pp} = \Delta T_{min}$ at the pinch point.

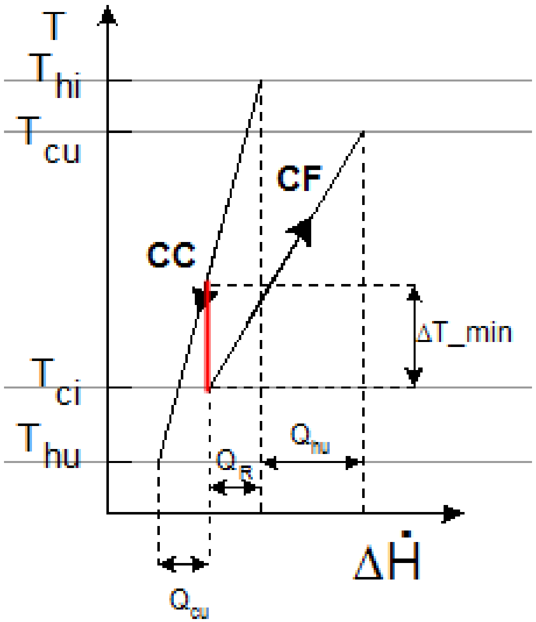
ΔT_{pp} is a design variable (ΔT_{min}), reflecting the limit to the investment which is allowed for heat transfer enhancement.

Q_{cu} and Q_{hu} lie between the minimum and maximum value determined before.

$0 < Q_R < Q_{R\ Max}$

In this specific case $C_c > C_h$ and the pinch takes place at the Cold Side of the HRE.

A Focus on Heat Capacities



B = Accoppiamento Reale

Heat Capacities represent a key issue in PA.

Streams with **small heat capacities** appear nearly **vertical**: large temperature variations are produced with limited heat rates.

Streams with **large heat capacities** appear nearly **horizontal**: large heat rates are needed to produce a small variation of temperature.

The **mismatch** between the **heat capacities** of **hot and cold streams** represents a limit to heat transfer performance, and is reflected by a large production of irreversibility (or, by an extensive rate of exergy destruction).

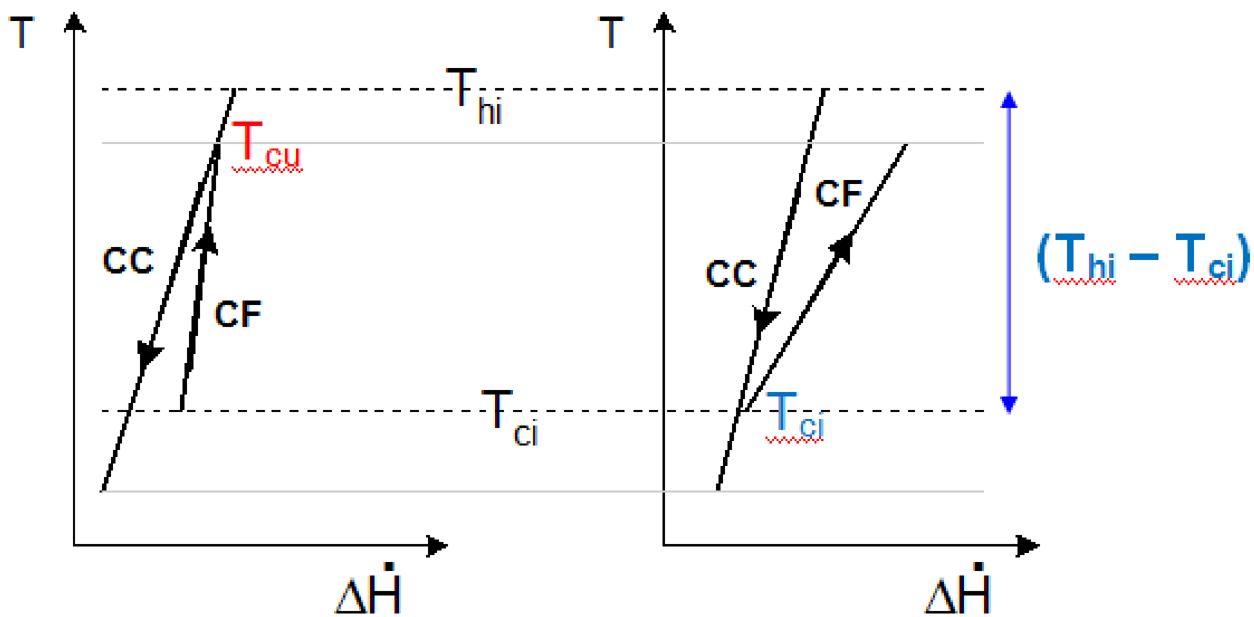
Locating the Pinch

The Location of the Pinch depends on the values of the heat capacities of the hot and cold streams, ($C = m\ c_p$):

a) if $\mathbf{m_h\ c_{ph} > m_c c_{pc}}$ the pinch is located at $\mathbf{T_{cu}}$, on the **hot side** of the HRE (Figure A)

b) if $\mathbf{m_c\ c_{pc} > m_h\ c_{ph}}$ the pinch is located at $\mathbf{T_{ci}}$, on the **cold side** of the HRE (Figure A)

c) if the heat capacities of the hot and cold streams are the same, the two curves evolve in parallel; in the limit case (∞ surface) the temperature difference between the cold and hot streams becomes zero everywhere.



(a) $m_h\ c_{ph} > m_c\ c_{pc}$ (b) $m_c\ c_{pc} > m_h\ c_{ph}$

Maximum Recoverable Heat – Limits to Regeneration

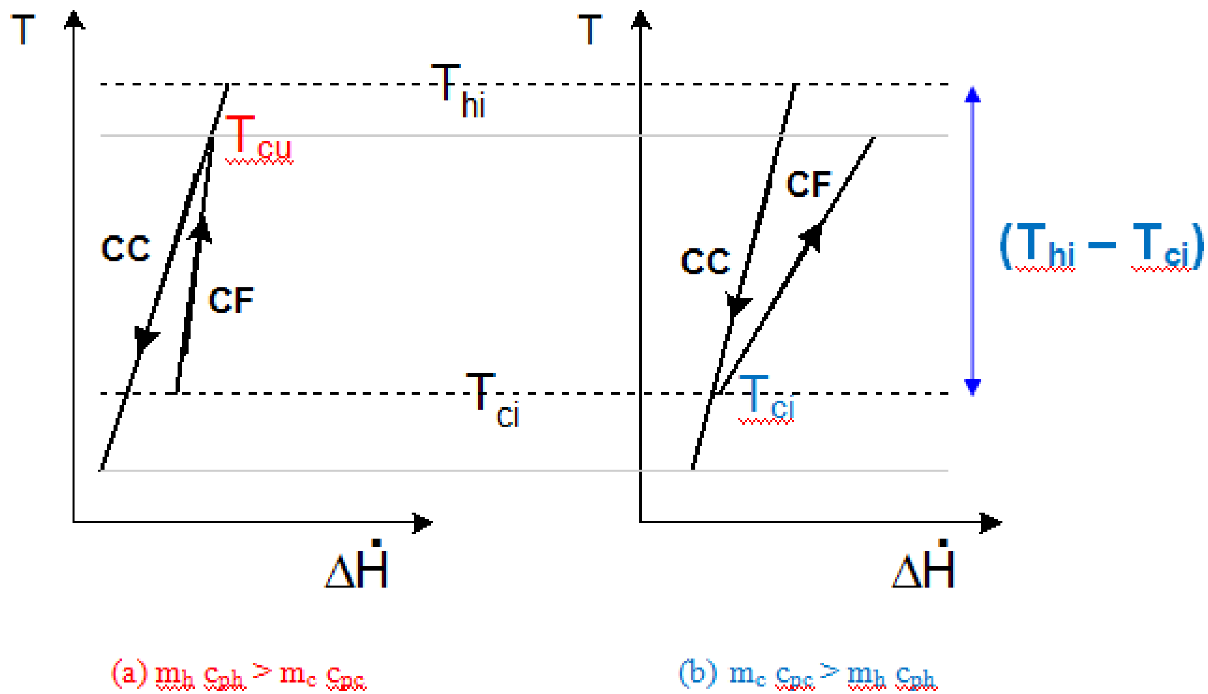
The Maximum Recoverable heat is given by:

$$Q_{R\_max} = (m\,c_p)_{min}\,(T_{hi} - T_{ci})$$

The Hot Stream cannot be cooled below T_{ci} interacting with the Cold Stream.

The Cold Stream cannot be heated beyond T_{hi} interacting with the Hot Stream.

In order to achieve Q_{R_max}, curve contact is required at the Pinch: that is, infinite surface.



<u>Fundamental Assumptions</u>:

- Constant heat capacity of all streams
- Perfect insulation
- Absence of structural conduction effects from hot to cold side

Graphical Approach to PA - Fundamentals

Pinch analysis becomes an interesting tool when more than 2 streams (1 Hot and 1 Cold) are involved.

The following example (taken from Bejan, Tsatsaronis e Moran (1996) deals with 2 Hots Streams and 2 Cold Streams and introduces the graphical interpretation (construction of the **Composite Curve**).

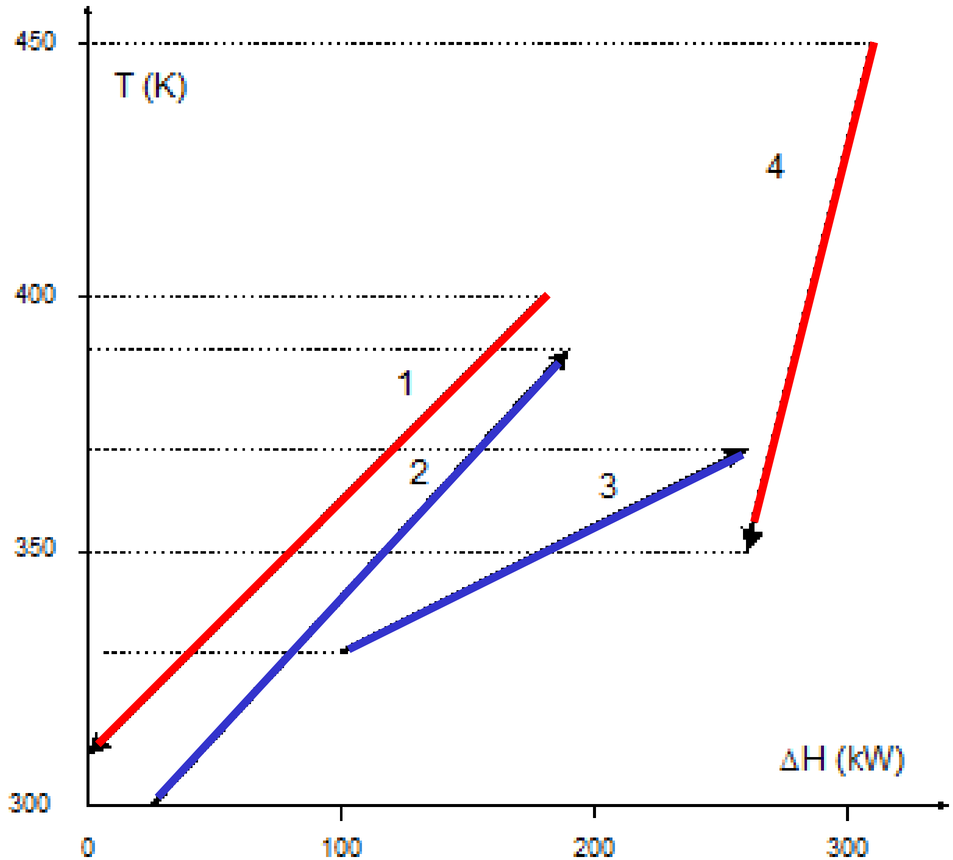
Stream ID	T_i[K]	T_u [K]	m c_p [kW/K]	ΔH [kW]
1 - h	400	310	2.0	180
2 – c	300	390	1.8	162
3 – c	330	370	4.0	160
4 - h	450	350	1.0	100

h = hot stream to be cooled (hot) c = cold stream to be heated (cold)

A) Separate Plotting of Hot and Cold Streams

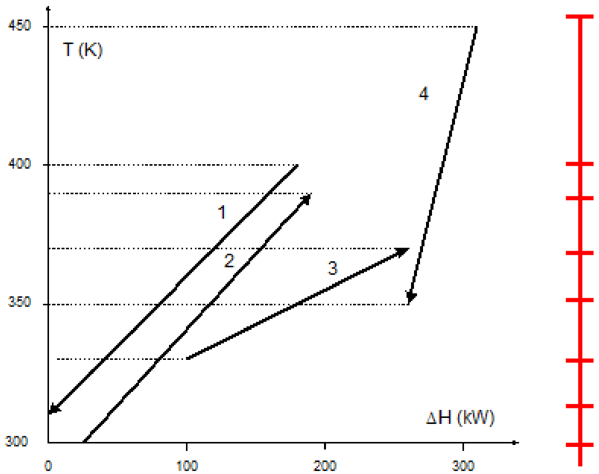
Stream ID	T_i[K]	T_u [K]	m c_p [kW/K]	ΔH [kW]
1 - h	400	310	2.0	180
2 – c	300	390	1.8	162
3 – c	330	370	4.0	160
4 - h	450	350	1.0	100

h = hot stream to be cooled (hot) c = cold stream to be heated (cold)



The origin of x axis for each stream can be displaced as is more convenient (avoid crossing)

B) Identifying Temperature Intervals for Hot and Cold Streams



The Analysis of this figure allows to identify **Temperature Intervals**.

It is better to separate Hot and Cold streams, determining 3 intervals for the hot streams and 3 intervals for the Cold streams. (**6 intervals total**).

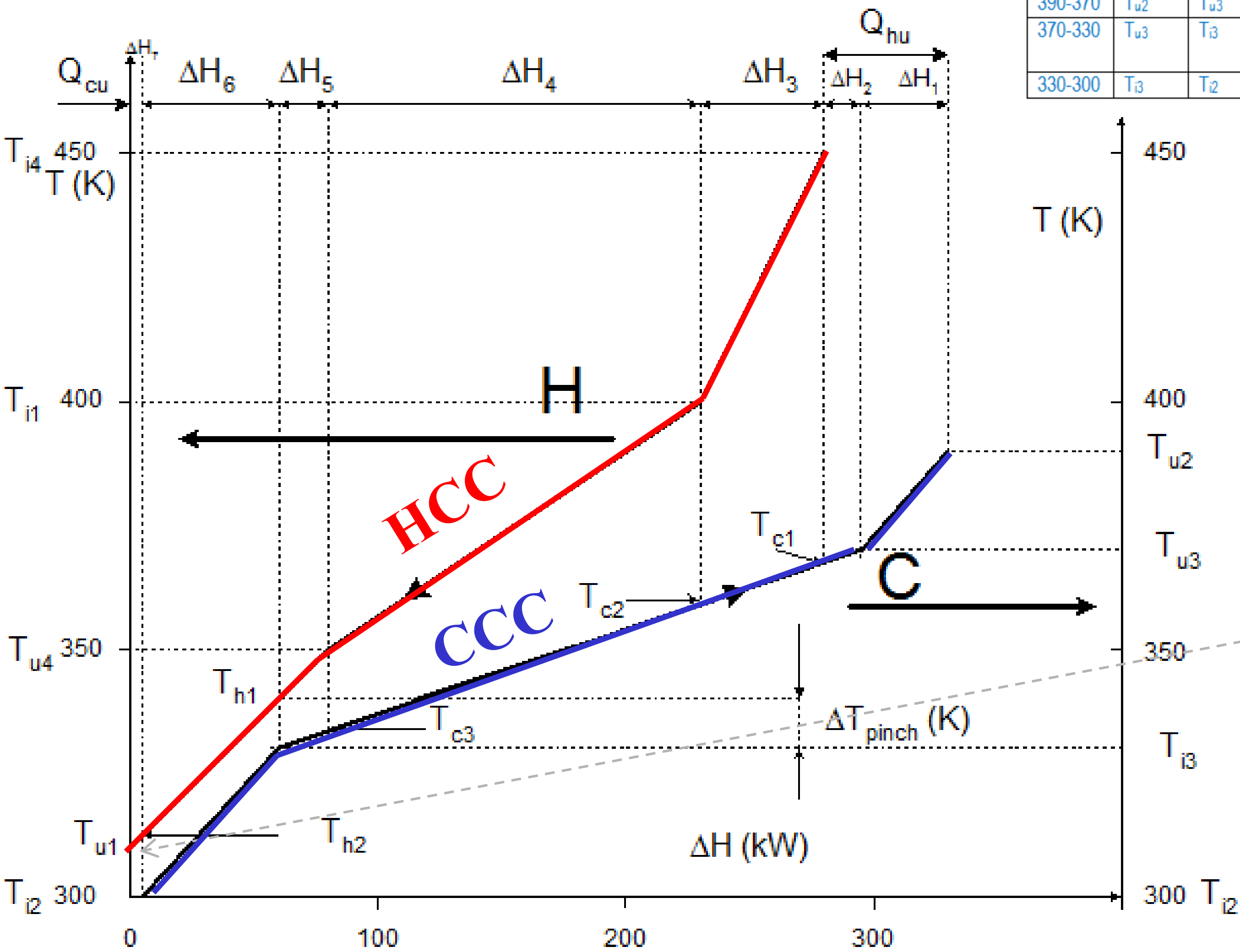
The results are summarized in the following table:

Temp. Interval	High Value	Low Value	Streams	Heat Rate, formal	m c_p (kW/K)	Heat Rate, kW	Graph Id. Of Heat Rate (Composite Curve)
450-400	T_{i4}	T_{i1}	4H	$m_4\ c_{p4}$ (450-400)	1	50	ΔH_3
400-350	T_{i1}	T_{u4}	4H, 1H	($m_4\ c_{p4}$ + $m_1\ c_{p1}$) (400-350)	3	150	ΔH_4
350-310	T_{u4}	T_{u1}	1H	$m_1\ c_{p1}$ (350-310)	2	80	$\Delta H_5+\Delta H_6+Q_{cu}$
390-370	T_{u2}	T_{u3}	2C	$m_2\ c_{p2}$ (390-370)	1,8	36	ΔH_1
370-330	T_{u3}	T_{i3}	2C, 3C	($m_2\ c_{p2}$ + $m_3\ c_{p3}$) (370-330)	5,8	232	$\Delta H_2+\Delta H_3+\Delta H_4+\Delta H_5$
330-300	T_{i3}	T_{i2}	2C	$m_2\ c_{p2}$ (330-300)	1,8	54	ΔH_6

B) Graphical building of the Composite Curve (CC)

The Table allows to draw the **Hot and Cold Composite Curves**, representing T on the Y axis and Heat Rates on the X axis.

Temp. Interval	High Value	Low Value	Streams	Heat Rate, formal	m c_p (kW/K)	Heat Rate, kW	Graph Id. Of Heat Rate (Composite Curve)
450-400	T_{i4}	T_{i1}	4H	$m_4\ c_{p4}$ (450-400)	1	50	ΔH_3
400-350	T_{i1}	T_{u4}	4H, 1H	$(m_4\ c_{p4} + m_1\ c_{p1})$ (400-350)	3	150	ΔH_4
350-310	T_{u4}	T_{u1}	1H	$m_1\ c_{p1}$ (350-310)	2	80	$\Delta H_5+\Delta H_6+Q_{cu}$
390-370	T_{u2}	T_{u3}	2C	$m_2\ c_{p2}$ (390-370)	1,8	36	ΔH_1
370-330	T_{u3}	T_{i3}	2C, 3C	$(m_2\ c_{p2} + m_3\ c_{p3})$ (370-330)	5,8	232	$\Delta H_2+\Delta H_3+\Delta H_4+\Delta H_5$
330-300	T_{i3}	T_{i2}	2C	$m_2\ c_{p2}$ (330-300)	1,8	54	ΔH_6

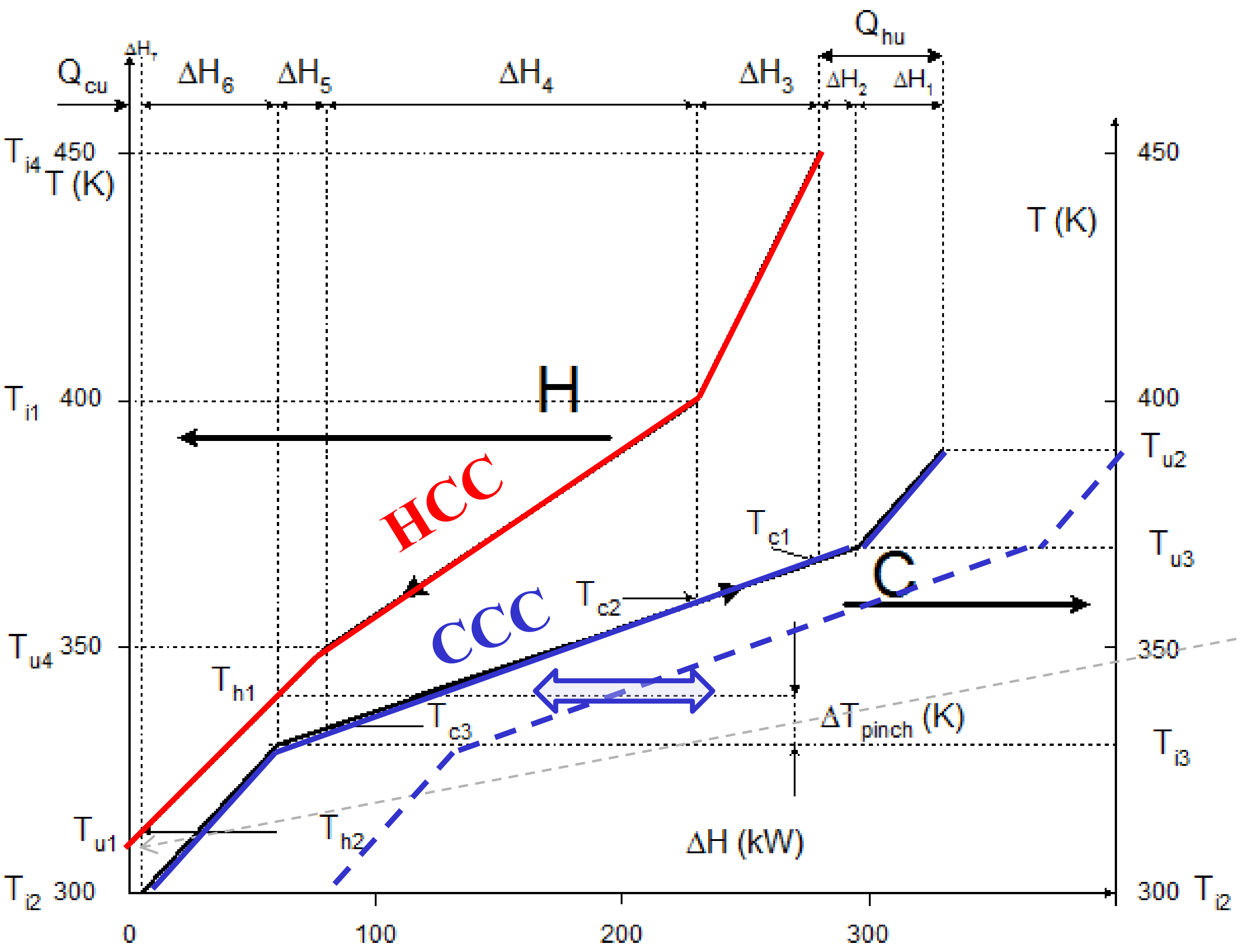


The origin of the X axis can be set arbitrarily.

It is convenient to set it at the cold end of the **Hot Composite Curve HCC**.

The **Cold Composite Curve CCC** is shifted horizontally to adjust the desired temperature difference at the Pinch

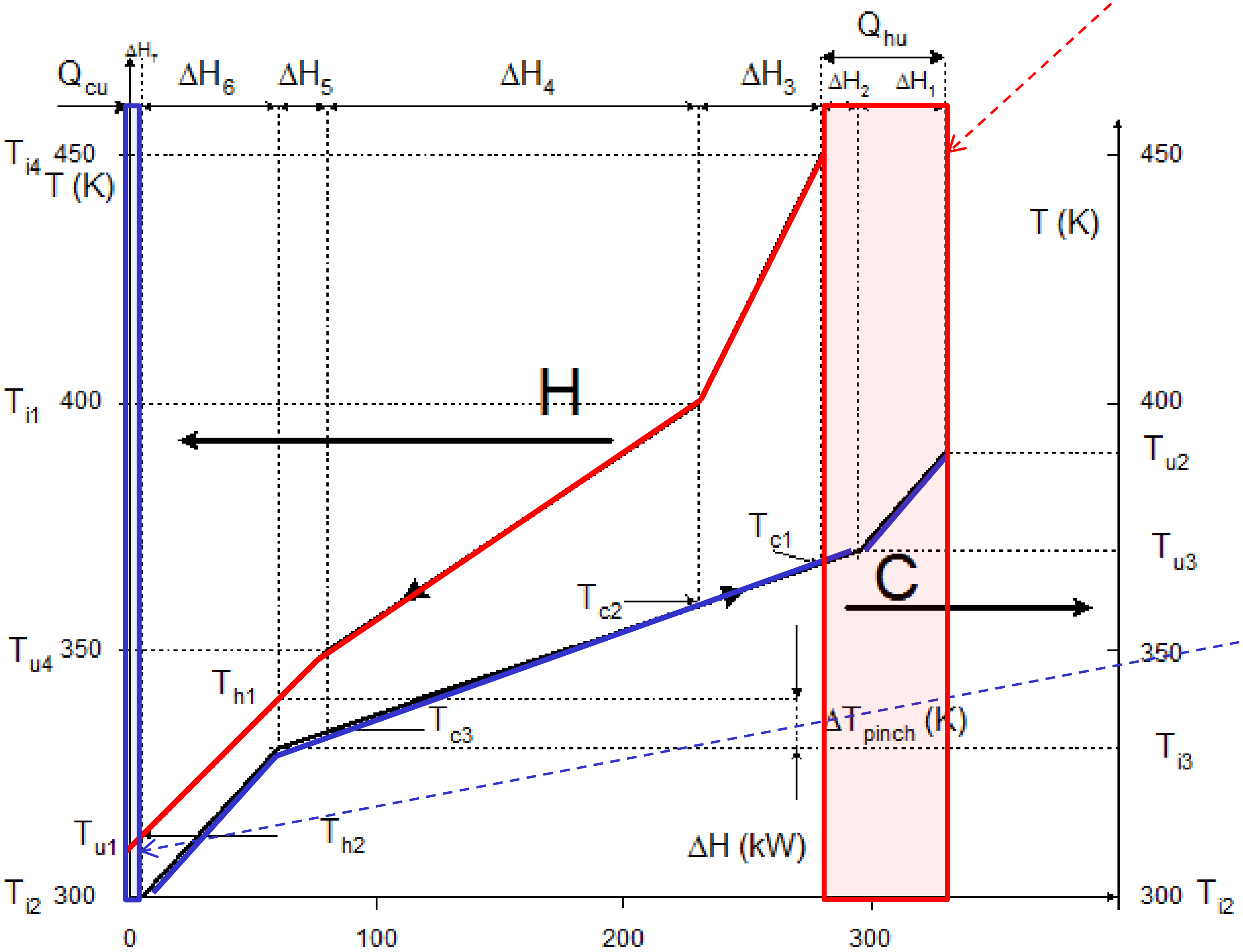
B) Shifting the Cold Composite Curve to adjust the Pinch



Shifting the **Cold Composite Curve CCC** from left to right allows to adjust the Pinch Temperature difference at the desired value (10 °C in the present case, solid blue line).

C) Visual representation of Q_{hu} and Q_{cu}

Heat/Cooling loads = X axis



Q_{hu} is represented by the uncovered x segment of the Cold Composite Curve at the right side of the diagram.

Q_{cu} is represented by the uncovered x segment of the Hot Composite Curve at the left side of the diagram.

D) Analytical solution of the Composite Curve

The graphical representation of the CC is very effective, but in order to represent it on a plot one needs to determine some unknowns, so that quantitative results can be produced.

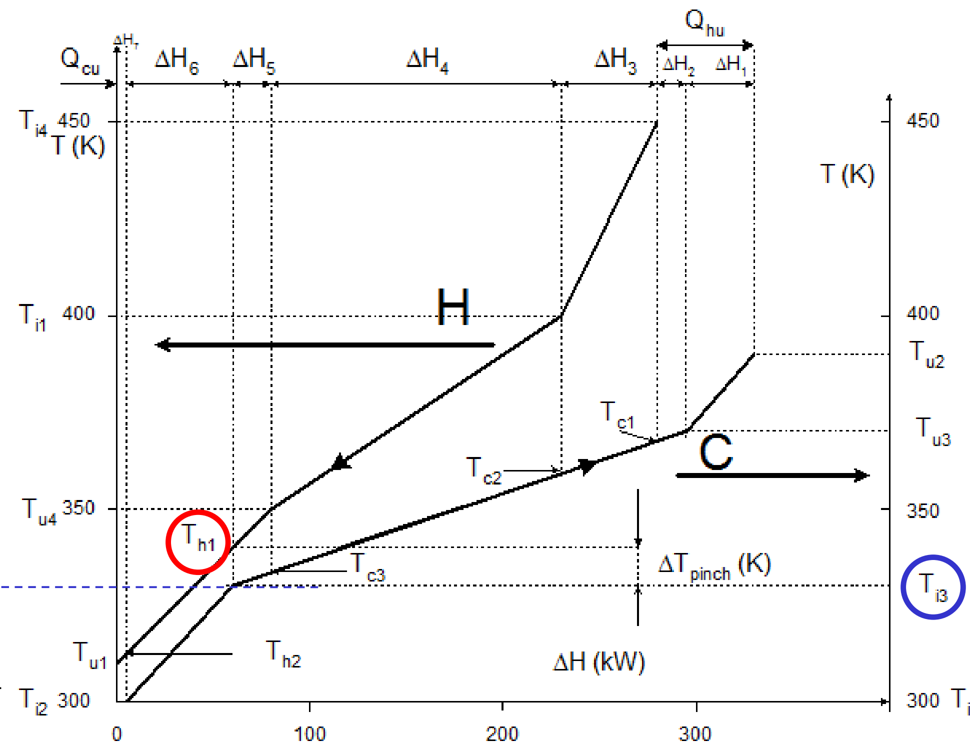
This must be applied both on the Y axis (Temperatures) and X axis (heat exchanger Heat Rates).

The solution always starts from the Pinch and requires the local application of energy balances (direct or indirect).

Visual inspection of the plot, and application of the heat capacity rules allow to easily **identify the Pinch** at **point i3 (inlet, stream n. 3, CCC)**:

$\mathbf{T_{pinch} = T_{i3} = 330\ K}$

$T_{h1} = T_{pinch} + \Delta T_{pinch} = 330 + 10 = 340\ K$

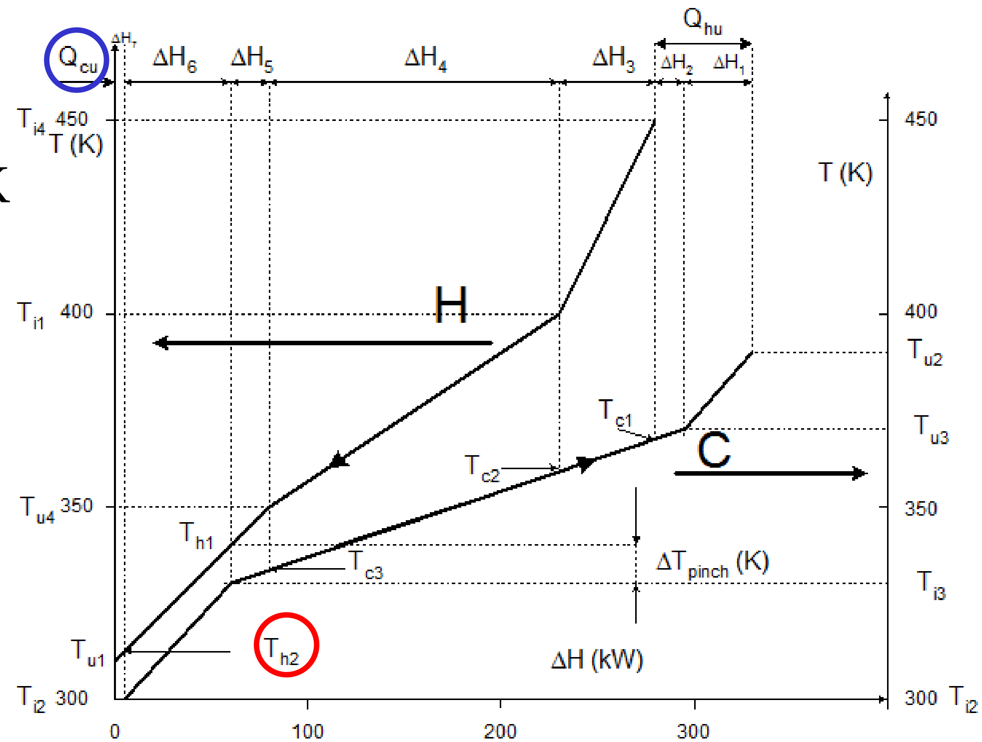


D) …. Proceeding Left and Right of the Pinch….

a) Left of the Pinch:

$T_{h2} = T_{h1} - \Delta H_6/(m_1\ c_{p1}) = 340 – 54/2 = 313$ K

$\mathbf{Q_{cu} = (m_1\ c_{p1}) * (T_{h2} – T_{u1}) = 6\ kW}$



b) Right of the Pinch:

$\Delta H_5 = 80 - \Delta H_6 - Q_{cu} = 80 - 54 – 6 = 20$ kW

$\Delta H_2 = 232 – (\Delta H_3 + \Delta H_4 + \Delta H_5) = 232 – (50 + 150 + 20) = 12$ kW

$\mathbf{Q_{hu} = \Delta H_1 + \Delta H_2 = 36 + 12 = 48\ kW}$

Other ΔH known, see original streams table.

……………………………………………………………………

D) …. still Right of the Pinch….

c) … Right of the Pinch (Cold Composite Curve):

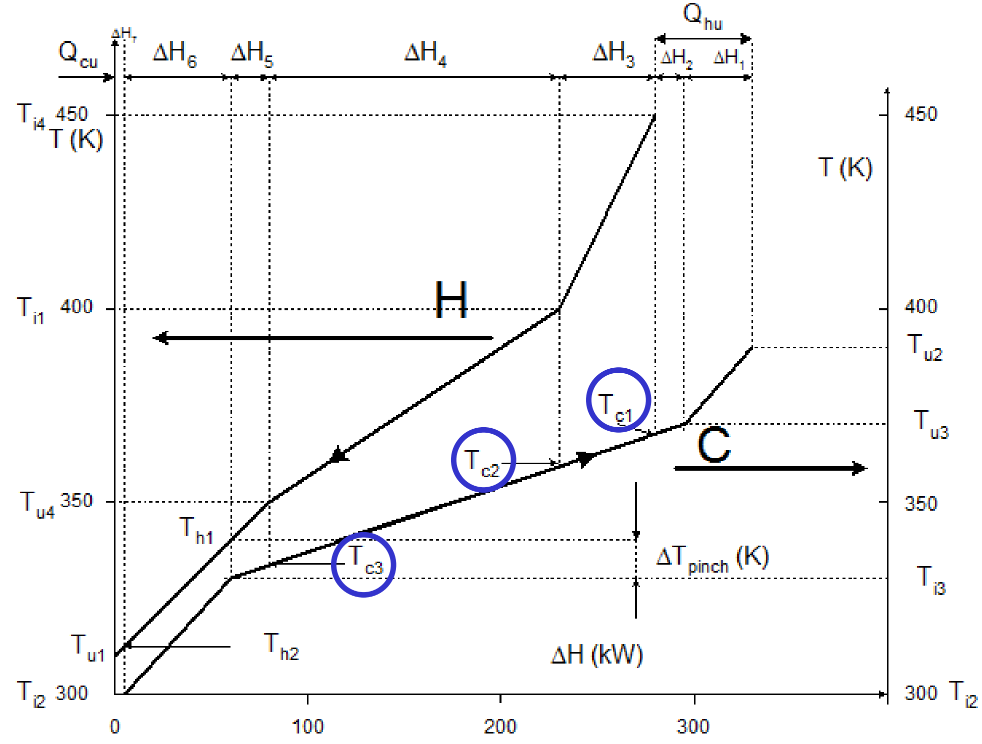
$\mathbf{T_{c3}} = T_{pinch} + \Delta H_5/(m_2\, c_{p2} + m_3\, c_{p3}) = 330 + 20/5{,}8 = 333{,}45$ K

$\mathbf{T_{c2}} = T_{pinch} + (\Delta H_4 + \Delta H_5)/(m_2\, c_{p2} + m_3\, c_{p3}) = 330 + (150+20)/5{,}8 = 359{,}31$ K

$\mathbf{T_{c1}} = T_{pinch} + (\Delta H_3 + \Delta H_4 + \Delta H_5)/(m_2\, c_{p2} + m_3\, c_{p3}) = 330 + (50+150+20)/5{,}8 = 367{,}93$ K

Once all temperatures are known on the HCC and CCC, one can calculate the log-mean temperature difference across the local section of the RHE:

$$\Delta T_{ml} = \frac{[(T_{hH} - T_{cH}) - (T_{hL} - T_{cL})]}{ln[(T_{hH} - T_{cH})/(T_{hL} - T_{cL})]}$$



E) Representing Composite Curve results in a Table

	Heat Rate, formal	KW	T_{hH} (K)	T_{hL} (K)	T_{cH} (K)	T_{cL} (K)	ΔT_{ml} (K)	S (m^2)
Q_{hu} 48 kW	$\Delta H_1 = m_2\ c_{p2}\ (T_{u2} - T_{u3})$	36	---	---	390	370		
	$\Delta H_2 = (m_2\ c_{p2} + m_3\ c_{p3})\ *(T_{u3} - T_{c1})$	12	---	---	370	T_{c1} = 367,93		
ΔH_3	$(m_4\ c_{p4})\ (T_{i4} - T_{i1})$	50	450	400	T_{c1} = 367,93	T_{c2} = 359,31	58,97	1,70
ΔH_4	$(m_4\ c_{p4} + m_1\ c_{p1})\ (T_{i1} - T_{u4})$	150	400	350	T_{c2} = 359,31	T_{c3} = 333,45	26,84	11,18
ΔH_5	$(m_1\ c_{p1})\ (T_{u4} - T_{h1})$	20	350	T_{h1} = 340	T_{c3} = 333,45	330	13,00	3,08
ΔH_6	$(m_1\ c_{p1})\ (T_{h1} - T_{h2})$	54	T_{h1} = 340	T_{h2} = 313	330	300	11,43	9,45
$Q_{cu} = \Delta H_7$ 6 kW	$(m_1\ c_{p1})\ *\ (T_{h2} - T_{u1})$	6	T_{h2} = 313	310	---	---		

…from the Heat Rate and the ΔT_{ml}, it is possible – assuming a value for the overall heat transfer coefficient, K = 0,500 kW/(m^2°C) in this example – to evaluate the **surface** needed for each section of the RHE ….

F) Proposing solutions for Q_{hu} and Q_{cu}

The external Heating and Cooling duties have been successfully identified.

Now, it is possible to say that to provide the 48 kW of Q_{hu}, it could be recommended to chose a **heat source** slightly higher than 368-370 K, and having a heat capacity of about 48/22 = 2,2 kW/K.

	Heat Rate, formal	KW	T_{hH} (K)	T_{hL} (K)	T_{cH} (K)	T_{cL} (K)	ΔT_{ml} (K)	S (m^2)
Q_{hu} 48 kW	$\Delta H_1 = m_2 c_{p2} (T_{u2} - T_{u3})$	36	---	---	390	370		
	$\Delta H_2 = (m_2 c_{p2} + m_3 c_{p3}) * (T_{u3} - T_{c1})$	12	---	---	370	T_{c1} = 367,93		
ΔH_3	$(m_4 c_{p4}) (T_{i4} - T_{i1})$	50	450	400	T_{c1} = 367,93	T_{c2} = 359,31	58,97	1,70
ΔH_4	$(m_4 c_{p4} + m_1 c_{p1}) (T_{i1} - T_{u4})$	150	400	350	T_{c2} = 359,31	T_{c3} = 333,45	26,84	11,18
ΔH_5	$(m_1 c_{p1}) (T_{u4} - T_{h1})$	20	350	T_{h1} = 340	T_{c3} = 333,45	330	13,00	3,08
ΔH_6	$(m_1 c_{p1}) (T_{h1} - T_{h2})$	54	T_{h1} = 340	T_{h2} = 313	330	300	11,43	9,45
$Q_{cu} = \Delta H_7$ 6 kW	$(m_1 c_{p1}) * (T_{h2} - T_{u1})$	6	T_{h2} = 313	310	---	---		

The Cold Utility Q_{cu} = 6 kW, on the other hand, should be best provided by a **cooling stream** having a heat capacity of 6/3 = 2 kW/K, at temperatures just below 313 – 310 K.

Solutions for Q_{hu} and Q_{cu}

A **trivial solution** for Q_{hu} is a **combustion system** or **heat generator**.
This heat is potentially generated at very high temperature, and its use is not recommended from the thermodynamics/exergy point of view.

Possible solutions for Q_{hu} (including CHP, beneficial in industrial plants):

- Gas turbine exhausts (large flow rates and heat capacity)
- Reciprocating engine exhaust (small flow rate and heat capacity)
- Use of condensing steam extractions (infinite heat capacity)
- Use of heat pumps to upgrade heat available below the pinch (if possible; heat capacity adptable)

... + Temperature range matching...!

Possible solutions for Q_{cu}:

- Direct cooling with liquid water stream (adjustable heat capacity, limits to temperature difference)
- Cooling towers (large heat capacity)
- Absorption (large heat capacity) or refrigeration units (small heat capacity)

Programming Approach to PA - Fundamentals

Pinch Analysis can be programmed instead of using a graphical solution. The programming rules were set by Bodo Linnhoff in his early works.

Data:

- Number of hot streams (CC) to be cooled N_h
- Number of cold streams (CF) to be heated N_c
- For each stream (Hot or Cold): flow rate, specific heat, Inlet Temperature T_i, Outlet Temperature T_u
- Design Pinch Temperature difference ΔT_{min}
- Approximate values of the overall heat transfer coefficient

Programming Approach to PA - Fundamentals

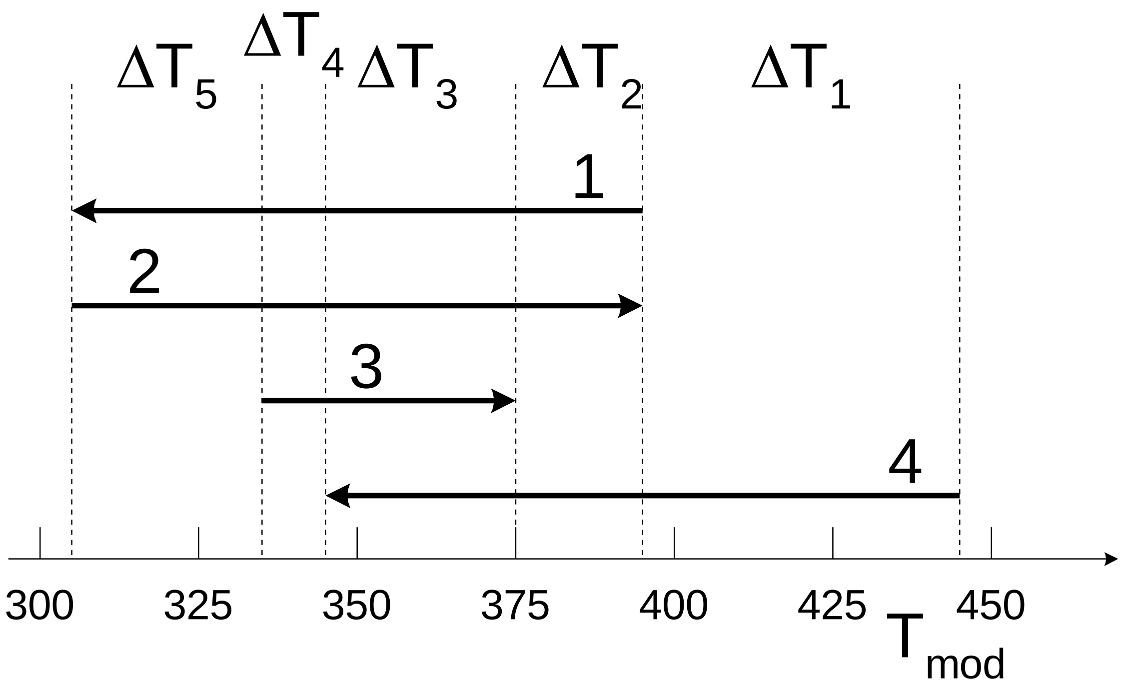
Outputs:

- Composite Curve with recommended solution for Regenerative Heat Trasnfer Section
- Hot Utility $Q_{hu,min}$ for the given Pinch ΔT_{min}
- Cold Utility $Q_{cu,min}$ for the given Pinch ΔT_{min}
- Heat Rate for each section of the RHE network
- ΔT_{ml} for each section of the RHE network
- Approximate surface for each section of the RHE network
- Grand Composite Curve (new)

Programming Approach to PA - Fundamentals

Programming steps:

- Calculate the **Heat Capacities** for each hot and cold stream $m\, c_p$ and the **Heat Rates** $(mc_p)\,(T_u - T_i)$
- Reduce the temperature of all hot streams of $\Delta T_{min}/2$
- Increase the temperature of all cold streams of $\Delta T_{min}/2$
- Build a vector diagram of Modified Temperatures T_{mod}, allowing to identify a set of relevant Temperature Intervals.

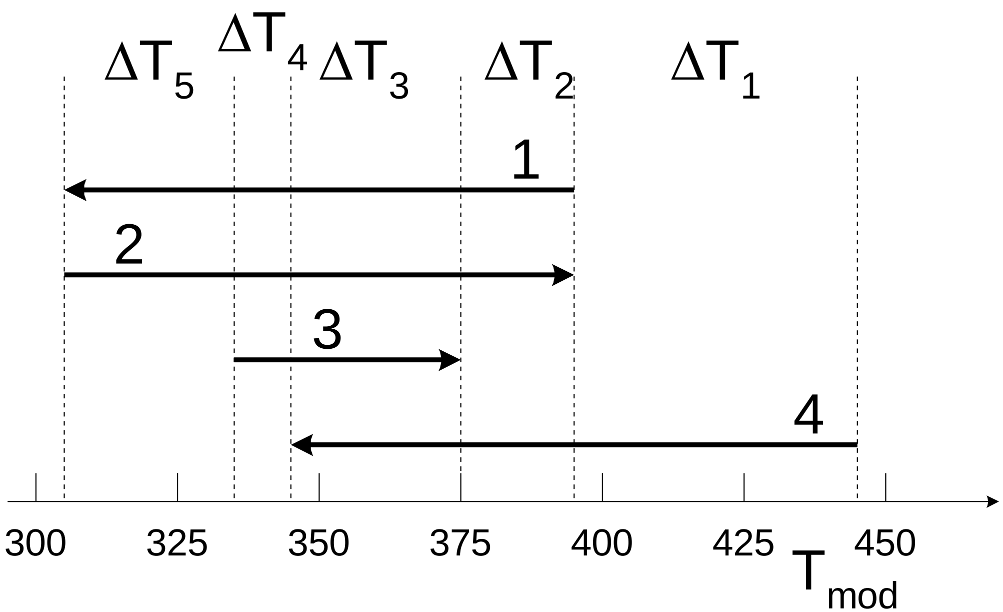


Programming Approach to PA - Fundamentals

Programming steps (2):

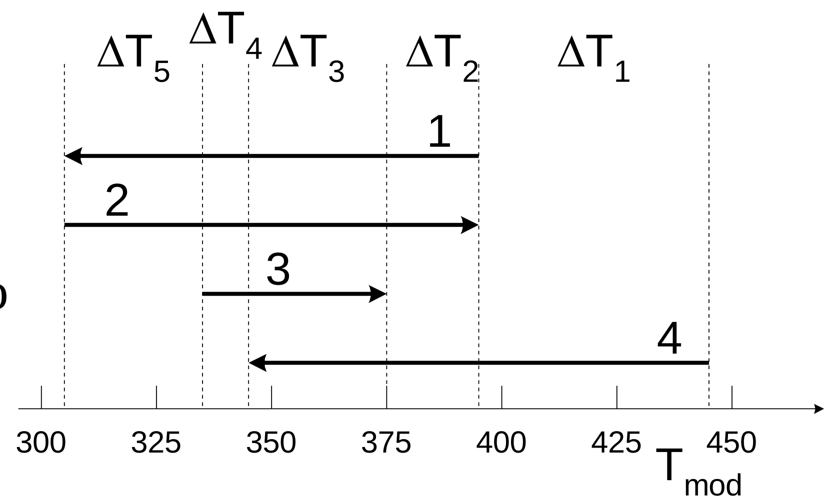
Starting from the highest temperature interval, calculate the heat to be transferred on that interval:

$$Q_i = \left\lfloor \sum_{cold} (m\,c_p)_{cold} - \sum_{hot} (m\,c_p)_{hot} \right\rfloor \Delta T_i$$



Programming Approach to PA - Fundamentals

$$Q_i = \left[\sum_{cold} \left(m\, c_p\right)_{cold} - \sum_{hot} \left(m\, c_p\right)_{hot}\right] \Delta T_i$$



A negative value of $\mathbf{Q_i}$ implies that there is an excess of energy available from the hot streams in the reference interval ΔT_i ; this excess heat can be used to heat cold streams at lower temperature.

The designer should propose a use for this excess heat (transfer to external users of heat, space heating, sanitary water,…).

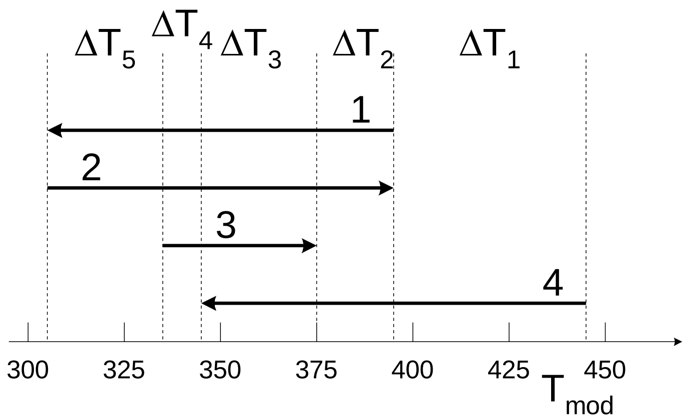
Recovery of low-grade heat becomes critical below the pinch.

A Positive value of $\mathbf{Q_i}$ implies that there is an energy defect on the hot streams side in the reference interval ΔT_i ; this energy defect should be if possible satisfied recovering heat available at higher temperature; otherwise, one should propose a correct external heat integration Q_{hu} : exhaust of an IC engine or Gas Turbine, or connection to other nearby processes generating hot sensible heat effluents.

A smart solution could be a Heat Pump able to upgrade heat available at low temperature at the higher temperature level where it is needed (also possible across the pinch).

Programming Approach to PA - Example - 1

$$Q_i = \left[\sum_{cold} (m\, c_p)_{cold} - \sum_{hot} (m\, c_p)_{hot}\right] \Delta T_i$$



1. The following table shows in the **first three columns** the calculation steps applied to the example at study:

Column 1	Column 2	Column 3	Column 4	Column 5
ΔT#	$T_{up/low}$ K	Q_i kW	Σ Q_i kW	Σ Q_i* kW
			0	-48
1	445/395	-50	-50	-98
2	395/375	-24	-74	-122
3	375/345	84	+10	-38
4	345/**335**	38	**+48**	0
5	335/305	-6	+42	**-6**

2. **Column 4** is calculated with the following formula:

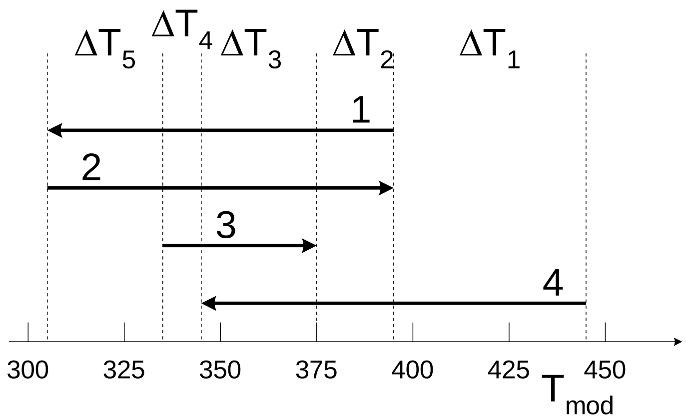
$$\Sigma Q_i = \sum_{j=1}^{i} Q_i$$

Taking care of the signs of heat fluxes in Column 3.

3. The largest value in **Column 4** identifies the result for $\mathbf{Q_{hu}}$.

Programming Approach to PA - Example - 2

Column 1	Column 2	Column 3	Column 4	Column 5
ΔT#	$T_{up/low}$ K	Q_i kW	ΣQ_i kW	ΣQ_i^* kW
			0	-48
1	445/395	-50	-50	-98
2	395/375	-24	-74	-122
3	375/345	84	+10	-38
4	345/**335**	38	**+48**	0
5	335/305	-6	+42	**-6**



4. **Column 5** is calculated subtracting Q_{hu} from all values in Column 4.

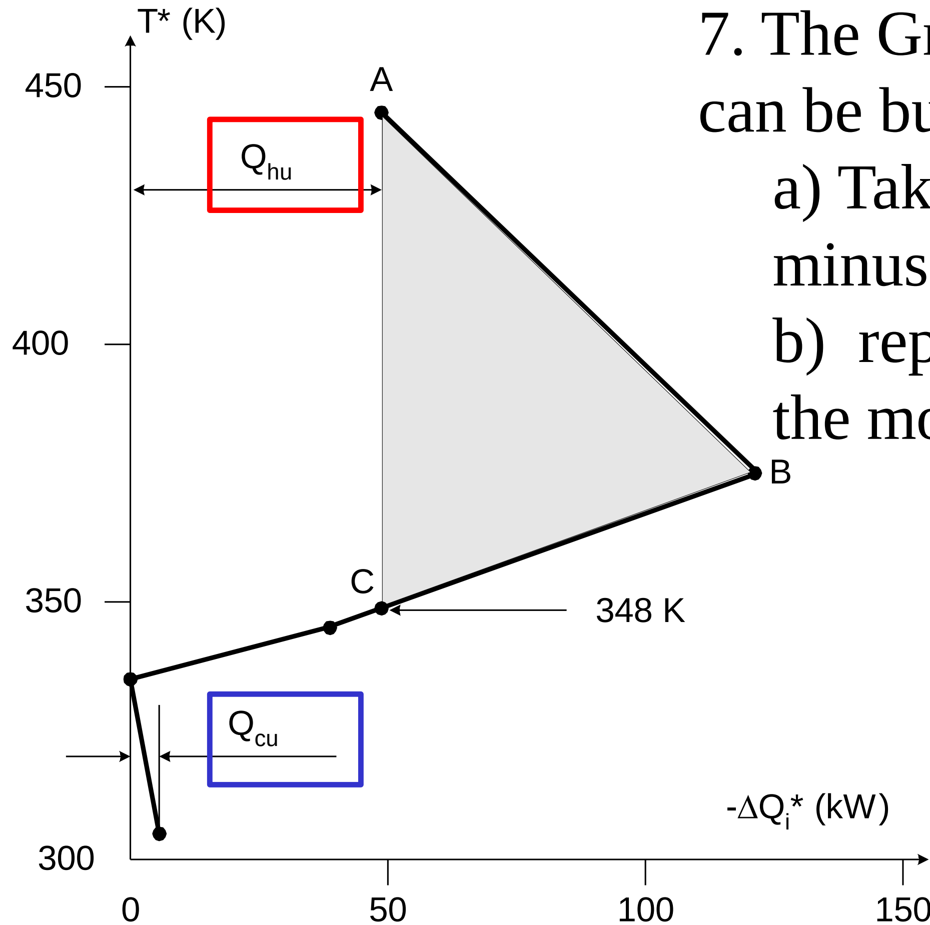
$$\Delta Q_i^* = \sum_{j=1}^{i} Q_i - Q_{hu}$$

5. The value in the last cell of Column 4 identifies the result for $\mathbf{Q_{cu}}$.

6. The lower temperature in the interval for which $\mathbf{\Sigma Q_i^* = 0}$ is called the **Average Pinch Temperature** (**335 K** in this example). Of course ± 5 K should be added/subtracted to get the real HCC or CCC temperature values.

PA - The Grand Composite Curve

Column 2	Column 5
$T_{up/low}$ K	ΣQ_i^* kW
	-48
445/395	-98
395/375	-122
375/345	-38
345/**335**	0
335/305	**-6**



7. The Grand Composite Curve can be built:

a) Taking on the x-axis the minus value of **ΣQ_i***

b) reporting on the y axis the modified Temperature

The **shaded area** represents the possibility of internal covering the needs of heating load for the cold streams using heat recovery from the hot streams. The **Pinch Temperature** is clearly identified by the Temperature condition when **$-\Sigma Q_i^* = 0$.**

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