Process integration
Heat exchanger network synthesis

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Heat exchanger network Investments
Identify the energy saving heat exchanges

Utilities Cost of Energy
Satisfy the energy requirement

Improve the MER: onion structure

Chemical processes: the onion structure

Reaction
Separation
Utilities
Heat exchanger network

Energy
Minimum Energy Requirements

Cost of Energy
Satisfy the energy requirement

Investments
Identify the energy saving heat exchanges
The process utilities

- Energy
- Raw materials
- Intermediate Utilities: Thermodynamic cycles, Rankine, refrigeration, steam networks
- Process
- Products and by-products
- Waste
- Export

Utilities:
- Raw Utilities: Hot (fuels), Cold (Cooling Water, electricity)

Notes:
- Waste
- Raw materials
- Process
- Products and by-products
- Export

Diagram shows the flow of energy and materials through different stages of a process.
Engineering work method

From Goals & Constraints to Solutions ...

Goals & Constraints

Analyse

Problem definition

Generate

Results

Evaluate

New problems - New goals

Solutions
Utility integration

Hot utility : above the pinch point

Hot utility at low T !

Cold utility below the pinch point

DH= 60 kW

DH= 2.5 kW

DH= -82.5 kW

DH= 75 kW

DH= -15 kW

Cold utility at higher T !

Hot utility : above the pinch point

DH= 60 kW

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Cold utility at higher T !
Utility integration

Counter current analogy
- Hot utility - cold process

 GCC = cold stream

Counter current analogy
- Hot process - cold utility

 GCC = hot stream

Self sufficient zones
Exchange process -> process

Heat sink

Heat-source

T(°C)

H(kW)

H
Q
P
T

120

140

160

180

200

H
Q

220

240

260

280

300

320

340

360

400

420

440

460

480

500

520
Multiple utilities

Identify the temperature levels

T (°C)

Qh min

Q1

Q2

T1

T2

T3

PINCH

H (kW)
Multiple utilities

Use of multiple utilities for different levels

-> Cost of Energy instead of Energy
Utilities

- Gas turbine
- Fuels
- Gas engines
- Enriched air
- Preheating
- Steam
- Liquid Fuel
- Natural gas
- PSA
- VSA
- Membrane
- Cryogenic
- Temperature
- Pressure
- Turbine
- Heat pumps
- Organic Rankine Cycles
- Water
- Air
- Refrigerant
- Pressure
- Compressor
- Refrigeration
Utility definition

Type of utility (e.g. : combustion)

Outlet conditions
(environment, operation)

inlet conditions
(fuel type, combustion, operation)

3 characteristics:
- H-T diagram (from GCC analysis)
- Cost as a function of flowrate
- Flowrate : to be determined to satisfy the requirements at Minimum Costs.
Utilities definitions

For the same MER !!!

Utility 1 : $C_1 = \text{cost 1} \times \text{flow 1}$

Utility 2 : $C_2 = \text{cost 2} \times \text{flow 2}$

Different utility heat loads

Energy available or excess
Energy balance of a temperature interval

- Integrating heat producers and consumers
  - Sharing energy by counter current heat exchange
    Excess of energy from the upper intervals

For each utility stream
- Unknown flowrate -> \( f_j \) : Continuous variable
- Use YES/NO ? -> \( y_j \) : Integer variable 1/0
Optimalisation

- **Minimum cost of energy requirement (MCER)**
- **Mixed Integer Linear Programming (MILP)**

\[
\min_{R_i, f_j, y_j} \quad \text{Cost} = \sum_{j=1}^{nu} (C_1 j y_j + C_2 j f_j)
\]

Submit to:

- **Heat balance** 
  \[
  R_{i+1} + \sum_{j=1}^{n_c} f_j q_{ji} - \sum_{j=1}^{n_f} f_j q_{ji} - R_i = 0
  \]

- **Utility** 
  \[
  f_{\min_j} y_j \leq f_j \leq f_{\max_j} y_j
  \]

- **2nd principle ideal HEN model**
  \[
  R_i \geq 0; R_1 = 0; R_{n_i+1} = 0
  \]
  \[
  y_j \in \{0, 1\}
  \]
Combined mechanical power production

- Linear constraints

Mechanical power consumption

\[
\sum_{w=1}^{\text{nu}} w_w f_w w + \text{Wel} - \text{Wp} = 0
\]  
Process requirement

\[
\sum_{w=1}^{\text{nu}} w_w f_w w + \text{Wel} - \text{Welv} - \text{Wp} = 0
\]  
Electricity import

Production from the utilities (\(W_w > 0\))

- Export of electricity

\[
\sum_{w=1}^{\text{nu}} w_w f_w w + \text{Wel} - \text{Welv} = 0
\]  

Electricity export

- Operating cost

\[
\text{Cost} = \sum_{w=1}^{\text{Welv}} (C_1 w_w y_w + C_2 w f_w) + \text{Cel Wel} - \text{Celv Welv}
\]  
buy

sell
Use of integer variables

- 1 integer variable for each flowrate
  - \( y_j = 0 \): the utility \( j \) is not used
  - \( y_j = 1 \): the utility \( j \) is used

Linear constraint:

\[
\begin{align*}
& f_{\text{min},j} y_j \leq f_j \leq f_{\text{max},j} y_j \\
& \text{if } y_j = 0 \Rightarrow f_{\text{min},j} 0 \leq f_j \leq f_{\text{max},j} 0 \\
& \Rightarrow 0 \leq f_j \leq 0 \Rightarrow f_j = 0 \\
& \text{if } y_j = 1 \Rightarrow f_{\text{min},j} \leq f_j \leq f_{\text{max},j}
\end{align*}
\]

Linear cost:

\[
\begin{align*}
\text{Cost}_j &= C_{1j} y_j + C_{2j} f_j \\
& \text{if } y_j = 0 \Rightarrow \text{Cost}_j = C_{1j} 0 + C_{2j} 0 = 0 \\
& \text{if } y_j = 1 \Rightarrow \text{Cost}_j = C_{1j} + C_{2j} f_j
\end{align*}
\]
Results: balanced hot and cold composite curves

Multiple pinch points
optimal use of the cheapest utility

- Combustion
- Exothermal reactor
- Steam production
- Steam consumption
- Water cooling
- Air cooling
Balanced Grand composite curve

Understand the results?
Evaluate: the Integrated Composite Curves

Sub-set B: complement

\[ RB_k = R_{ref} + \sum_{r=k}^{n_k} \left( \sum_{w=1}^{n_B} f_w q_{wr} + \sum_{i=1}^{n_A} Q_{ir} \right) \]

Sub-set A

\[ RA_k = R_{ref} - \sum_{r=k}^{n_k} \left( \sum_{w=1}^{n_Bw} f_w q_{wr} + \sum_{i=1}^{n_A} Q_{ir} \right) - n_{k+1} \]

Hot and cold streams

\[ RB_{kp} = 0 \Rightarrow R_{ref} = - \sum_{r=kp}^{n_k} \left( \sum_{w=1}^{n_Bw} f_w q_{wr} + \sum_{i=1}^{n_A} Q_{ir} \right) \]

\[ T \]

\[ Q \]
ICC for utility system integration

T (K)

Process
Utility system

Furnace
air cooling
water
fridge

Q (kW)
ICC for the integration of the fumes

Excess of heat in the fumes
ICC for refrigeration cycle integration

T (K)

Q (kW)

"process"
"Fridge system"
ICC of the steam network

- Energy supplement
- Steam production
- Steam cons.
- Mechanical production

Other systems
Steam network
Heat exchanger placement audit

Systematic drawing of the ICC of the existing heat exchangers

Heat exchange through the pinch point

Penalty

MER

Existing Heat Exchanger

Rest of the process of remaining problem
Heat exchanger placement audit

Heat exchanger below the pinch point

Heat exchanger

Penalty of heat exchanger

Overall process

Remaining

MER

T(K)

Q(kW)

FM_07/2000
Conclusions

Method for targeting Minimum Cost of Energy Requirements

✔ Analyse
  ◆ using composite curves

✔ Generate
  ◆ using Mixed Integer Linear Programming

✔ Evaluate
  ◆ using a new graphical representation: the Integrated Composite Curves
  ◆ Better Understanding of the Integration of the components of the system
    ◆ processes - utilities - steam network - heat exchangers
  ◆ Support to the engineer’s creativity
HEN synthesis: Introduction

Chemical processes: the onion structure

- Heat exchanger network
- Utilities
- Separation
- Reaction

List of streams
Investments
Heat exchangers network synthesis

Goals

Find a heat exchangers network that satisfies:
- the MER and MCER
- Minimum number of units or minimum of HTX modifications
- Minimum investment
- Other criteria
- Best return on investment

In other words ...

- Which hot stream with which cold stream ?
- What is the heat exchanged ?
- What is the structure : serial or //, ...
Heat exchanger network synthesis

Knowing ...

- Target
  - list of streams
  - utility streams flow
  - DTmin
  - Hot and cold streams matching constraints

Generate

- Heat exchanger network
  - Heat exchanger network structure
    - hot and cold streams in a heat exchanger
    - heat load
    - // or serie
  - Heat exchanger characteristic
    - type and rating
  - Optimisation
    - flowrates
    - area and investment

Evaluate

- Solutions
  - benefit / investment
  - detailed calculations
    - rating
    - simulation
    - operating conditions
Synthesis: methods

- **Heuristic**
  - Pinch design method
    - sequential
    - Based on pinch location
    - Sub-systems
    - Feasibility rules
    - Heuristic rules
      - tick-off
      - driving force
    - work method
      - loops
      - energy relaxation

- **Optimal ?**

- **Mathematical programming**
  - Heat load distribution
    - with and without MER and DTmin
    - multiple solutions
    - Y/N integer variables
  - Superstructures
    - MINLP
    - unimodality ?

- **Poor interaction of the engineer**
Heat exchangers network representation

Grid representation:
- Streams = horizontals
- Heat exchange = verticals

Corrected temperatures
Actual temperatures

Pinch exchangers
Pinch design method: feasibility rules

**Numbers of streams**

For pinch exchangers:

**Above the pinch point:**
- Number of hot: ?
- Number of cold: ?

**Below the pinch point:**
- Number of cold: ?
- Number of hot: ?

**Cp rule**

For pinch exchangers:

**Above the pinch point:**
- Cp hot: ?
- Cp cold: ?

**Below the pinch point:**
- Cp cold: ?
- Cp hot: ?
Pinch Design Method: heuristic rules

Goals:
- Above the pinch point: cool down the hot streams without cold utilities.
- Below the pinch point: heat up the cold streams without hot utilities.

Start with pinch exchangers

Rules

1 - Order the streams by decreasing $C_p$

   -> exchange first between the highest $C_p$

2 - The heat load is calculated to satisfy the heat load of one of the two stream involved: "tick-off"

3 - Place the utilities at the end of the streams
Pinch Design Method: Remaining problem analysis

Initial problem:
Hot stream: Tic -> Toc
Cold stream: Tif -> Tof

Remaining problem
Hot streams: Tic -> T2
: T1 -> Toc
Cold streams: Tif -> T4
: T3 -> Tof

Place a heat exchanger

New target
The synthesis algorithm

{k} ordered list of Key streams with decreasing Cp at the pinch point
{k-1} the other streams

Key streams:
Above the pinch point: hot streams
Below the pinch point: cold streams
Pinch Design method: Loops

$X_2 = \min(Q_2, Q_3, Q_4, Q_5)$

Suppress a heat exchanger!
Is the DTmin verified or acceptable?
Pinch design method: Energy relaxation

Path following from hot utility to cold utility

X such that DTmin is verified

If not => Energy Penalty !!!
Drawbacks of the simplified algorithm:

- multiple solutions
- combinatorial problem
- sequential

Use of mathematical programming:

Heat load distribution:
- which streams exchange heat
- How much
- minimize the number of connections
- satisfies DTmin and MER

Remaining problem: find the HEN structure
Heat load distribution

Hot stream i

Cold streams j

Hot stream i in temperature interval k

\[ \sum_{j=1}^{nc} Q_{ikj} = Q_{ik} \quad i = 1, \ldots, nh \quad k = k1, \ldots, k2 \]

Cold stream j in and above temperature interval k

\[ \sum_{j=1}^{nc} \sum_{r=k}^{k2} Q_{irj} - y_{ij} \max_{ij} = 0 \quad j = 1, \ldots, nc \quad k = k1, \ldots, k2 \]

Connection between i et j (integer variable)

\[ \sum_{r=k1}^{k2} Q_{irj} - y_{ij} \max_{ij} = 0 \quad j = 1, \ldots, nc \quad i = 1, \ldots, nh \]
Heat load distribution

**MILP formulation**

Minimize the number of connections

\[
\text{Min} \sum_{i=1}^{nh} \sum_{j=1}^{nc} y_{ij} Q_{ikj} \quad \text{subject to:} \quad \begin{align*}
\sum_{j=1}^{nc} Q_{ikj} &= Q_{ik} \quad \text{for } i = 1, \ldots, nh; \quad k = k_1, \ldots, k_2 \\
\sum_{j=1}^{nc} Q_{irj} - \sum_{j=1}^{nc} Q_{jr} &= 0 \quad \text{for } j = 1, \ldots, nc; \quad k = k_1, \ldots, k_2 \\
Q_{irj} - y_{ij} Q_{\text{max}ij} &= 0 \quad \text{for } j = 1, \ldots, nc; \quad i = 1, \ldots, nh
\end{align*}
\]
The synthesis method

Calculate the heat load distribution for each section

  Multiple solutions using integer cuts
  Heuristic rules or user

-> screening and choice of the appropriate solution

Define the HEN structure

  Apply feasibility rules and heuristics of pinch design method
  Splits and serial exchanges

Optimise the HEN

  Total cost criteria
  no DTmin nor MER fixed
Heat exchanger network retrofit

• Goals
  – Reach the MER but …
  – Reuse existing system
    • reuse existing heat exchangers
    • keep it in place if possible
    • disconnect a minimum (minimise piping)
    • increase area if necessary
  – Minimise process modifications
  – Minimise investment
    • equipment
    • operation
  – Trade-off Energy - Capital - Operation
Heat exchange network retrofit

1) Identify penalty exchangers

2) disconnect but remember ...

[Diagram showing heat exchange network retrofit with penalty exchanger identification and disconnection process]
Heat Exchanger network retrofit

• 1°) Identify exchanger creating penalty
• 2°) Eliminate these exchangers but remember of their position
• 3°) Using the pinch design method, complete the network by utilising where possible the existing exchanger.
  – The eliminated exchangers can be reused
    • in an other place
    • if possible keep their place unless for one of the stream.
    • existing exchangers can be by-passed to allow better exchange somewhere else.
• 4°) Try to restore the existing area to decrease the investment
  – The MER can be relaxed for this step to reuse the existing heat exchangers
    • heat sent through the loops
    • heat sent through down stream path.
Optimize the heat exchangers network

**NLP problem**

\[
\text{Min} \sum_{i=1}^{\text{nunit}} (C_{1i} + C_{2i} f_i) + \sum_{i=1}^{\text{nunit}} (a_i + b_i A_{c_i}^f)
\]

**Constraints**

Heat and mass balances
Rating equations
Specifications:

\[
F(X) = 0
\]

Bounds and limits

\[
G(X) \leq 0
\]

\(X\): State variables: pressure, temperature, area, heat exchanged, ...

Off course forget DTmin and MER constraints
Restricted matches constraints

• Why?
  – Safety - product quality
  – Topology
  – Site scale and processes independence

• Existing approaches
  – Cerda et al. (1983) - Papoulias and Grossmann (1983)
    • Energy target with constraints using large scale LP
  – Floudas - Grossmann and others
    • HEN superstructure together with energy target
  – Pinch technology
    • Restricted matches during the HEN synthesis
Restricted matches: our goals

• Targeting the **Minimum Cost Energy Requirement** taking into account the restricted matches
  – Energy penalty of the constraints?
  – Cost of the energy penalty?
  – Solve site scale problems
  – Find technological solutions to minimise the cost penalty of the restricted matches
    • choice of the heat transfer fluids

• Before the HEN synthesis task
  – Start HEN synthesis with the complete list of streams
The heat cascade a LP formulation

minimise \[ R_{n_{k+1}} \]
\[ R_k \]

Heat balance of a temperature interval
\[ R_{k+1} + \sum_{i=1}^{n_h} f_i q_{ik} - R_k - \sum_{j=1}^{n_c} f_j q_{jk} = 0 \]
\[ k=1, \ldots n_k \]
\[ R_k \geq 0 \]
\[ k=1, \ldots n_{k+1} \]

\( (R^*_k, T_k) \) the MER heat cascade
(Grand composite curve)
The constraints

Heat balance of a temperature interval
\[ R_{k+1} + \sum_{i=1}^{n_h} f_i q_{ik} - R_k - \sum_{j=1}^{n_c} f_j q_{jk} = 0 \quad \text{for} \quad k=1,...,n_k \quad (1) \]

Heat balance of a hot stream \( i \) in a restricted match
\[ \sum_{j=1}^{n_{ca}} Q_{ij} + R_i - f_i q_{ik} - R_{i,k+1} = 0 \quad \text{for} \quad k=1,...,n_k, \quad i=1,...,n_h \quad (R1) \]

Heat cascade of the cold stream \( j \)
\[ \sum_{i=1}^{n_h} Q_{ijk} - f_j q_{jk} = 0 \quad \text{for} \quad k=1,...,n_k, \quad j=1,...,n_c \quad (R2) \]

Overall heat cascade
\[ \sum_{i=1}^{n_h} R_i = R_k \quad \text{for} \quad k=1,...,n_k \quad (R3) \]

Accepted Matches

New variables

\( R_{ik} \geq 0 \quad \text{for} \quad k=1,...,n_k, \quad i=1,...,n_h \)
\( R_{ik+1} = 0 \) when \( k < k_i \)
\( Q_{ijk} \geq 0 \quad \text{for} \quad k=1,...,n_k, \quad i=1,...,n_h, \quad j=1,...,n_c \)
Compute the energy penalty

- Target the Minimum Cost Energy Requirement without constraints
  - Optimal heat cascade: $R^*_k$
  - Fix the flowrates
  - Add the restricted matches constraints
  - Solve the problem (P1)

\[
\begin{align*}
\text{minimise} & \quad R_{nk+1} \\
R_{ik}, Q_{jk}, R_k
\end{align*}
\]

$R_{nk+1} - R^*_{nk+1}$ is the energy penalty

- if penalty is acceptable goto HEN Synthesis
- if not choose the heat transfer fluid
Choose the heat transfer fluid

- **Ro** = \( \sum \frac{n_h}{R_{ik}} \)
- **nh**
- **Restricted matches cascade**

**Grand composite curve**

- **Energy penalty** 6810 kJ
- **MER** 4807 kJ
- **R hot** 5250 kJ
- **R cold** 1560 kJ
- **Heat sink**
- **Process pinch point**
- **Heat source**
Heat transfer fluid characteristics

- Process: Hot streams
  - Heat transfer fluid: cold stream
  - Heat transfer fluid hot stream
  - Process: Cold streams

<table>
<thead>
<tr>
<th>Conditions to be satisfied by the heat transfer fluid</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) All the $R_k$ must be positive (definition of the MER);</td>
</tr>
<tr>
<td>2) $R_{n_{k+1}} = R'<em>{n</em>{k+1}}$ (no energy penalty is due to the use of the intermediate stream);</td>
</tr>
<tr>
<td>3) $R_{0k} = R_k$ for all $k = 1, ..., n_k$ (the intermediate fluids solve the restricted matches constraints)</td>
</tr>
</tbody>
</table>
Choose the heat transfer fluid

Above the pinch point

1. **Cold stream**
2. **Add cold stream**
3. **Hot stream**

**RMC**
- Rhot: 5250 kJ

**Process GCC**
- MER: 4807 kJ

**New GCC**
- MER: 10057 kJ

Heat to cold stream
Heat from hot stream
Choose the heat transfer fluid

Place the heat transfer fluid between Red and Blue lines

Energy penalty if 1.5 b steam is used

Cold streams

Hot streams

Rcold 1560 kJ

Rhot 5250 kJ

Q(kJ)

T(K)

12 b

6 b

1.5 b

27.5 b

6 b

1.5 b steam is used
Steam network and restricted matches

Process 1

Cooling system

C

Process 2

fuel
Target the minimum cost of energy requirement

- Add the heat transfer fluids
  - Hot and cold streams
  - Unknown flowrate
- Use the MILP model
  - Heat cascade
  - Mechanical power balance
  - EMO models
    - Energy technologies
    - Heat transfer fluids or steam network
    - Restricted matches constraints
- Objective function: Minimum Cost of Energy
  - Fuels - Electricity - CHP - Investments

SYNTHESES
with complete list of streams
Heat exchanger network synthesis

Any Questions?