Heat Integration - Introduction

• Sub-Topics
  ▪ Design of Heat Exchanger Networks
  ▪ Selection of Utilities
    ➢ Consumption and Production
  ▪ “Correct” Integration
    ➢ Distillation and Evaporation
    ➢ Heat Pumps
    ➢ Turbines (Heat Engines)
  ▪ Heat and Power Considerations

• Project Applications
  ▪ New Design (“grassroot”)
  ▪ Reconstruction (“retrofit”)

T. Gundersen
$Q_h = Q_c = Q$

$\Delta T_{LM} = ??$

$Q_h = \Delta H_h = mCp_h \cdot (T_{h,in} - T_{h,out})$

$Q_c = \Delta H_c = mCp_c \cdot (T_{c,out} - T_{c,in})$

$Q = (A \cdot U) \cdot \Delta T_{LM}$

**Pure Countercurrent Heat Exchanger**
## WS-1: Heat Integration

<table>
<thead>
<tr>
<th>Stream</th>
<th>$T_s$</th>
<th>$T_t$</th>
<th>$mCp$</th>
<th>$\Delta H$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>°C</td>
<td>°C</td>
<td>kW/°C</td>
<td>kW</td>
</tr>
<tr>
<td>H1</td>
<td>300</td>
<td>100</td>
<td>1.5</td>
<td>300</td>
</tr>
<tr>
<td>H2</td>
<td>200</td>
<td>100</td>
<td>5.0</td>
<td>500</td>
</tr>
<tr>
<td>C1</td>
<td>50</td>
<td>250</td>
<td>4.0</td>
<td>800</td>
</tr>
<tr>
<td>Steam</td>
<td>280</td>
<td>280</td>
<td>(var)</td>
<td></td>
</tr>
<tr>
<td>Cooling Water</td>
<td>15</td>
<td>20</td>
<td>(var)</td>
<td></td>
</tr>
</tbody>
</table>

**Specification:**

$\Delta T_{\text{min}} = 20^\circ\text{C}$

**Find:**

$Q_{H,\text{min}}, Q_{C,\text{min}}, T_{\text{pinch}}, U_{\text{min}}, U_{\text{min,MER}}$

and Network

**Notice:**

1. H1 and H2 provide as much heat as C1 needs (800 kW)
2. $T_s (\text{C1}) < T_t (\text{H1,H2}) - 20^\circ\text{C}$ & $T_s (\text{H1}) > T_t (\text{C1}) + 20^\circ\text{C}$
More Solutions

Question:
1) Minimum Energy?
2) Which Network?
### Summary for WS-1

<table>
<thead>
<tr>
<th>Design</th>
<th>$Q_H = Q_C$ (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>280</td>
</tr>
<tr>
<td>B</td>
<td>280</td>
</tr>
<tr>
<td>C</td>
<td>380</td>
</tr>
<tr>
<td>D</td>
<td>142.5</td>
</tr>
<tr>
<td>E</td>
<td>See later . . .</td>
</tr>
<tr>
<td>F</td>
<td>Around 149 (optimal split)</td>
</tr>
<tr>
<td>X</td>
<td>Any better ???:</td>
</tr>
</tbody>
</table>

We need Best Performance Targets!!
Phases in the Design of Heat Exchanger Networks

- **Data Extraction** (assume R/S given)
- **Performance Targets**
  - Energy, Area, Units / Shells
  - Total Annual Cost (gives value for $\Delta T_{\text{min}}$)
- **Process Modifications** (change R/S ?)
- **Design of Network** (minimum energy)
  - Decomposition at the Pinch
  - Qualitative and Quantitative Tools
- **Optimization** (given the basic structure)
  - Heat Load Loops & Paths and Stream Splits
Illustrating Example

Process, Energy and System

Heat Integration – Introduction

T. Gundersen

Heat 8
Phase 1: Data Extraction

- Time consuming (80%) and Critical Phase
- New Design: Material / Energy Balances
- Retrofit: Various Sources of Data
  - Measurements (that are often incorrect)
  - Simulations (M+E balances ➔ Consistent)
  - Design Basis (original, but was it updated?)
- Should keep Degrees of Freedom open
- Practical Limitations must be included, but Cost Effects should be evaluated before such Constraints are accepted
Necessary Data (1)

- **Process Streams**
  - Flowrates \( m \) kg/s, tons/h
  - Specific Heat Capacity \( Cp \) kJ/kg°C
  - Supply Temperature \( Ts \) °C
  - Target Temperature \( Tt \) °C
  - Heat of Vaporization \( \Delta H_{vap} \) kJ/kg
  - Film Heat Transfer Coeffs. \( h \) kW/m² °C

- **Utility Systems**
  - Temperature(s) and Specific Heat Content
  - Price per Energy Unit (Amount)
Necessary Data (2)

- **Cost Data for Heat Exchangers**
  - Relation between Area and Purchase Price
  - Example: $Cost = a + b \times (A)^c$

- **Economical Data**
  - Number of Operating Hours per year
  - Specification on required Payback Time
  - Installation Factors
  - Maximum Investment (for Retrofit Projects)
  - Minimum allowed Approach Temperature ($\Delta T_{min}$), possibly based on Pre-optimization
## Data Extraction for the Example

<table>
<thead>
<tr>
<th>Stream</th>
<th>ID</th>
<th>$T_s$ °C</th>
<th>$T_i$ °C</th>
<th>$mC_p$ kW/°C</th>
<th>$\Delta H$ kW</th>
<th>$h$ kW/m²°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor outlet</td>
<td>H1</td>
<td>270</td>
<td>160</td>
<td>18</td>
<td>1980</td>
<td>0.5</td>
</tr>
<tr>
<td>Product</td>
<td>H2</td>
<td>220</td>
<td>60</td>
<td>22</td>
<td>3520</td>
<td>0.5</td>
</tr>
<tr>
<td>Feed Stream</td>
<td>C1</td>
<td>50</td>
<td>210</td>
<td>20</td>
<td>3200</td>
<td>0.5</td>
</tr>
<tr>
<td>Recycle</td>
<td>C2</td>
<td>160</td>
<td>210</td>
<td>50</td>
<td>2500</td>
<td>0.5</td>
</tr>
<tr>
<td>Reboiler</td>
<td>C3</td>
<td>220</td>
<td>220</td>
<td></td>
<td>2000</td>
<td>1.0</td>
</tr>
<tr>
<td>Condenser</td>
<td>H3</td>
<td>130</td>
<td>130</td>
<td></td>
<td>2000</td>
<td>1.0</td>
</tr>
<tr>
<td>HP Steam</td>
<td>HP</td>
<td>250</td>
<td>250</td>
<td>(≈ 40 bar)</td>
<td>(var.)</td>
<td>2.5</td>
</tr>
<tr>
<td>MP Steam</td>
<td>MP</td>
<td>200</td>
<td>200</td>
<td>(≈ 15 bar)</td>
<td>(var.)</td>
<td>2.5</td>
</tr>
<tr>
<td>LP Steam</td>
<td>LP</td>
<td>150</td>
<td>150</td>
<td>(≈ 5 bar)</td>
<td>(var.)</td>
<td>2.5</td>
</tr>
<tr>
<td>Cooling Water</td>
<td>CW</td>
<td>15</td>
<td>20</td>
<td></td>
<td>(var.)</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Phase 2: Targeting

• **Basis:**
  - Minimum Approach Temperature: \( \Delta T_{\text{min}} \)

• **Results:**
  - Minimum External Heating: \( Q_{H,\text{min}} \)
  - Minimum External Cooling: \( Q_{C,\text{min}} \)
  - Minimum Number of Units: \( U_{\text{min}} \)
  - Minimum Heat Transfer Area (total): \( A_{\text{min}} \)

• **Pre–Optimization:** Near optimal \( \Delta T_{\text{min}} \)
  - \( Q_{H,\text{min}}, Q_{C,\text{min}}, U_{\text{min}}, A_{\text{min}} = f(\Delta T_{\text{min}}) \)
  - \( TAC = f(Q_{H,\text{min}}, Q_{C,\text{min}}, U_{\text{min}}, A_{\text{min}}) = f(\Delta T_{\text{min}}) \)
Composite Curves

Stream | $T_s$ | $T_t$ | $mC_p$ | $\Delta H$
---|---|---|---|---
H1 | 270 | 160 | 18 | 1980
H2 | 220 | 60 | 22 | 3520

Heat Integration – Targeting

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Composite Curves for the Example

\[ \Delta T (\, ^\circ C) \]

\[ Q_{H,min} \]

\[ Q_{Recovery} \]

\[ \Delta T_{min} \]

\[ Q_{C,min} \]

Note: The Column Reboiler / Condenser are not included
Trade-off: Area vs. Energy

\[ T (\degree C) \]

\[ H (kW) \]

\[ Q_{H,\text{min}} \]

\[ Q_{C,\text{min}} \]

\[ +\delta \]
Pinch Point and Decomposition

$Q_{C,\text{min}} + \delta$

$Q_{H,\text{min}} + \delta$

Surplus

Deficit

$T (\degree \text{C})$

$H (\text{kW})$

Heat Integration – Targeting

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Heat 17
Summary of Targeting by Graphical Methods

- Provides an Overview and Understanding
- Identifies Key Information about the Heat Recovery Problem, such as:
  - Minimum External Heating, $Q_{H,\text{min}}$
  - Minimum External Cooling, $Q_{C,\text{min}}$
  - The Process Pinch Point (Bottleneck)
- More Graphical Diagrams later
- Time consuming and subject to Errors
$\Delta T_{min} = 20^\circ C$
Pinch Point changes with $\Delta T_{\text{min}}$
Pinch Point Candidates

Pinch Candidates (○) are the Supply Temperatures of Streams or Stream "Segments"

Total $mCP$ is then increasing

$T$ (°C)

$H$ (kW)
Motivating Example – Remember?

Heat Integration – Targeting

\[ \sum (H) = 1722 \quad \text{6 units} \]
\[ \sum (C) = 654 \]
(a) Design as usual

Area = 629 m\(^2\)

\[ \sum (H) = 1068 \quad \text{4 units} \]
\[ \sum (C) = 0 \]
(b) Design with targets

Area = 533 m\(^2\)
The Actual Flowsheet & Data Extraction

Focus: Thermal Energy and the Energy Balance

First: Checking the Mass Balance:

Symbol: \[
\text{kg/s}
\]

(1) \[ 1.089 + 1.614 = 2.703 \text{ (OK)} \]

(2) \[ 6.931 + 2.703 = 9.634 \text{ (OK)} \]

(3) \[ 7.841 + 0.179 + 1.614 = 9.634 \text{ (OK)} \]
## Simple Data Extraction

### Process Integration for the Efficient Use of Energy

<table>
<thead>
<tr>
<th>Str.</th>
<th>Ts (ºC)</th>
<th>Tt (ºC)</th>
<th>ΔH (kW)</th>
<th>mCp (kW/ºC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>200</td>
<td>2233</td>
<td>11.451</td>
</tr>
<tr>
<td>2</td>
<td>40</td>
<td>200</td>
<td>413</td>
<td>2.581</td>
</tr>
<tr>
<td>3</td>
<td>35</td>
<td>126</td>
<td>992</td>
<td>10.901</td>
</tr>
<tr>
<td>4</td>
<td>200</td>
<td>35</td>
<td>2570</td>
<td>15.576</td>
</tr>
</tbody>
</table>

PRO_PI1: $\Delta T_{\text{min}} = 10^\circ\text{C}$ $\Rightarrow Q_{H,\text{min}} = 1068$ kW and $Q_{C,\text{min}} = 0$ kW
PRO_PI1: $\Delta T_{\text{min}} = 22^\circ\text{C} \Rightarrow Q_{H,\text{min}} = 1068\ kW$ and $Q_{C,\text{min}} = 0\ kW$

$\Delta T_{\text{min}} = 23^\circ\text{C} \Rightarrow Q_{H,\text{min}} = 1083\ kW$ and $Q_{C,\text{min}} = 15\ kW$

$\Delta T_{\text{thrsh}} = 22.1^\circ\text{C} \Rightarrow$ Threshold Process becomes Pinched
Q: What about Phase changes & $C_p = C_p(T)$?

$Q_1 = \Delta H_1^I = \Delta H_4^I = ??$

$Q_{II} = \Delta H_1^{II} + \Delta H_2^{II} = \Delta H_4^{II}$

$Q_{III} = \Delta H_3^{III} = \Delta H_4^{III} = 992 \text{ kW}$

$Q_{H1} = \Delta H_1^{H1} = 1652 \text{ kW}$

$Q_{H2} = \Delta H_1^{H2} + \Delta H_2^{H2} = 70 \text{ kW}$

$Q_C = \Delta H_4^C = 654 \text{ kW}$

$mCp_{4}^{III} = \frac{992}{153 - 128} = 39.68 \text{ kW/°C}$

$mCp_{4}^{"tot"} = \frac{2570}{200 - 35} = 15.576 \text{ kW/°C}$

Q: Can we solve this Puzzle?
Heat Integration – Targeting

Simple
Q (kW)

Detailed
Q (kW)

Heat 28
$\Delta T_{\text{thrsh}} = 10.5^\circ C \quad \Rightarrow \quad \text{Threshold Process becomes Pinched}$
Lessons learned from the Example

• **Data Extraction** is a Critical Activity
  ▪ We have to solve a “Puzzle”
  ▪ Plant Data are often missing or incorrect
  ▪ Collecting and ”Processing” Data is Time consuming (80% of Conceptual Studies)
  ▪ Remember: ”Garbage in means Garbage out”

• **Energy Targeting** is much Simpler

• Next: Heat Exchanger **Network Synthesis** (Design & Optimization) is manageable
Fewest Number of Units

\[ U_{min} = (N-1) \]

\[ N = \text{Number of Streams and Utilities} \]
\[ N = n_H + n_C + n_{util} = 2 + 2 + 2 = 6 \]

\[ L = \text{Loops} \]
\[ S = \text{Subnetwork} \]
\[ U = \text{Units} \]

Euler’s Rule:
\[ U = N + L - S \]

Assume: \( L = 0, S = 1 \)
Maximum Energy Recovery requires Decomposition at Pinch Point(s)

\[ U_{min, MER} = (N-1)_{\text{above}} + (N-1)_{\text{below}} \]