HDA Process

Heat → Reactor → Cool → Flash → Compressor → Recycle → Product → Stabilizer
Why Energy Integration?  
(ICI Experience)

20 case studies

In every case, there was a reduction in energy

In almost every case, the energy savings required less capital

Up to 60% energy savings, up to 25% capital savings, up to 15% lower product price

Why spend additional capital to waste energy?
Energy Integration

What are the minimum cooling and heating requirements?
What is the minimum number of heat exchangers required?
What are the main trade-offs?
An Example

For the two hot streams being cooled and the two cold streams being heated shown below, find the minimum heating and cooling requirements, as well as the minimum number of heat exchangers if $\Delta T_{\text{min}} = 10$ deg F.

<table>
<thead>
<tr>
<th>Stream</th>
<th>$T_1$ (F)</th>
<th>$T_2$ (F)</th>
<th>$FC_p$ (Btu/F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>250</td>
<td>120</td>
<td>1000</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
<td>100</td>
<td>4000</td>
</tr>
<tr>
<td>3</td>
<td>150</td>
<td>90</td>
<td>3000</td>
</tr>
<tr>
<td>4</td>
<td>190</td>
<td>130</td>
<td>6000</td>
</tr>
</tbody>
</table>
Net Energy Required
(First Law Calculation)

<table>
<thead>
<tr>
<th>Temperature Range</th>
<th>( \Delta T ) (deg F)</th>
<th>( F_{C_p} ) (Btu/F)</th>
<th>( Q_{\text{aval}} ) (MBtu/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250 F to 120 F</td>
<td>130</td>
<td>1000</td>
<td>130</td>
</tr>
<tr>
<td>200 F to 100 F</td>
<td>400</td>
<td>4000</td>
<td>400</td>
</tr>
<tr>
<td>150 F to 90 F</td>
<td>-180</td>
<td>3000</td>
<td>-180</td>
</tr>
<tr>
<td>190 F to 130 F</td>
<td>-360</td>
<td>6000</td>
<td>-360</td>
</tr>
</tbody>
</table>

Thus, 10 x10³ Btu/hr would have to be supplied from a hot utility if there were no requirement of \( \Delta T_{\text{min}} = 10 \) deg F.

**Question:** What are the minimum heating and cooling requirements?
Define hot and cold temperature scales shifted by 10 deg F and show streams

<table>
<thead>
<tr>
<th>$T_H$ (F)</th>
<th>$T_C$ (F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>240</td>
</tr>
<tr>
<td>220</td>
<td>210</td>
</tr>
<tr>
<td>190</td>
<td>180</td>
</tr>
<tr>
<td>160</td>
<td>150</td>
</tr>
<tr>
<td>130</td>
<td>120</td>
</tr>
<tr>
<td>100</td>
<td>90</td>
</tr>
</tbody>
</table>
Net Energy Required at Temperature Intervals

Draw in intervals by breaking at stream starting and ending points

<table>
<thead>
<tr>
<th>$T_H$ (F)</th>
<th>$T_C$ (F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>240</td>
</tr>
<tr>
<td>220</td>
<td>210</td>
</tr>
<tr>
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<td>150</td>
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<tr>
<td>130</td>
<td>120</td>
</tr>
<tr>
<td>100</td>
<td>90</td>
</tr>
</tbody>
</table>
Net Energy Required at Temperature Intervals

Compute net available Q for each interval

<table>
<thead>
<tr>
<th>FC_p</th>
<th>1000</th>
<th>4000</th>
<th>TH (F)</th>
<th>TC (F)</th>
<th>Q_{aval} (MBtu/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>250</td>
<td>240</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>220</td>
<td>210</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>190</td>
<td>180</td>
<td>-40</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>160</td>
<td>150</td>
<td>-80</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>130</td>
<td>120</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>100</td>
<td>90</td>
<td>20</td>
</tr>
</tbody>
</table>

Note: Sum of net heat available = -10 MBtu/hr
Same as first law
Cascade Diagram

We satisfy the net requirement for each interval from an external utility.

<table>
<thead>
<tr>
<th>$T_H$ (F)</th>
<th>$T_C$ (F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250 HOT</td>
<td>240 COLD</td>
</tr>
<tr>
<td>220 HOT</td>
<td>210 COLD</td>
</tr>
<tr>
<td>190 UTILITY $\Delta H = -40$</td>
<td>180 UTILITY</td>
</tr>
<tr>
<td>160 UTILITY $\Delta H = -80$</td>
<td>150 UTILITY</td>
</tr>
<tr>
<td>130 UTILITY $\Delta H = 40$</td>
<td>120 UTILITY</td>
</tr>
<tr>
<td>100 UTILITY $\Delta H = 20$</td>
<td>90 UTILITY</td>
</tr>
</tbody>
</table>

BUT ...
**Cascade Diagram**

We can always transfer excess heat from high temperature intervals to lower temperature intervals without violating \( \Delta T_{\text{min}} = 10 \text{ F} \)

<table>
<thead>
<tr>
<th>(T_H (\text{F}))</th>
<th>(T_C (\text{F}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>240</td>
</tr>
<tr>
<td>220</td>
<td>210</td>
</tr>
<tr>
<td>190</td>
<td>180</td>
</tr>
<tr>
<td>160</td>
<td>150</td>
</tr>
<tr>
<td>130</td>
<td>120</td>
</tr>
<tr>
<td>100</td>
<td>90</td>
</tr>
</tbody>
</table>

\(\Delta H = 50\)  \downarrow 50  \(\Delta H = -40\)  \downarrow 10  \(\Delta H = -80\)  \downarrow 40  \(\Delta H = 40\)  \downarrow 60
## Minimum Heating and Cooling

<table>
<thead>
<tr>
<th>$T_H$ (F)</th>
<th>$T_C$ (F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>240</td>
</tr>
<tr>
<td>220</td>
<td>210</td>
</tr>
<tr>
<td>190</td>
<td>180</td>
</tr>
<tr>
<td>160</td>
<td>150</td>
</tr>
<tr>
<td>130</td>
<td>120</td>
</tr>
<tr>
<td>100</td>
<td>90</td>
</tr>
</tbody>
</table>

Δ$H = 50$

Minimum heating = 70 MBtu/hr

Minimum cooling = 60 MBtu/hr

Net = 10 MBtu/hr of heating

Same as first law
Pinch Temperature

<table>
<thead>
<tr>
<th>$T_H$ (F)</th>
<th>$T_C$ (F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>240</td>
</tr>
<tr>
<td>220</td>
<td>210</td>
</tr>
<tr>
<td>190</td>
<td>180</td>
</tr>
<tr>
<td>160</td>
<td>150</td>
</tr>
<tr>
<td>130</td>
<td>120</td>
</tr>
<tr>
<td>100</td>
<td>90</td>
</tr>
</tbody>
</table>

The design problem can be decomposed into two separate problems:
1. A high temperature region where only heating is required
2. A low temperature region where only cooling is required
Relationship to First Law

Minimum Heat in = 70

\[ \text{HOT} \]

\[ \text{COLD} \]

Minimum Heat out = 60

\[ \text{Net} = -10 \]

Heat in = 70 + \( Q_E \)

\[ \text{HOT} \]

\[ \text{Heat out} = 60 + Q_E \]

\[ \text{Net} = -10 \]

If we put excess heat into the process, we must also remove this heat!
Excess Heating and Cooling

<table>
<thead>
<tr>
<th>( T_H ) (F)</th>
<th>HOT UTILITY</th>
<th>( \Delta H )</th>
<th>( T_C ) (F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td></td>
<td>( \Delta H = 50 )</td>
<td>240</td>
</tr>
<tr>
<td>220</td>
<td>( Q_E )</td>
<td>( \Delta H = -40 )</td>
<td>210</td>
</tr>
<tr>
<td>190</td>
<td>70</td>
<td>( \Delta H = -80 )</td>
<td>180</td>
</tr>
<tr>
<td>160</td>
<td>( 10 + Q_E )</td>
<td>( \Delta H = 40 )</td>
<td>150</td>
</tr>
<tr>
<td>130</td>
<td>( 40 + Q_E )</td>
<td>( \Delta H = 20 )</td>
<td>120</td>
</tr>
<tr>
<td>100</td>
<td>( 60 + Q_E )</td>
<td></td>
<td>90</td>
</tr>
</tbody>
</table>

Excess steam or furnace capacity requires excess cooling water.

Don’t transfer heat across the pinch!
Multiple Utilities

<table>
<thead>
<tr>
<th>$T_H$ (F)</th>
<th>$T_C$ (F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
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</tr>
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<td>210</td>
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<td>160</td>
<td>150</td>
</tr>
<tr>
<td>130</td>
<td>120</td>
</tr>
<tr>
<td>100</td>
<td>90</td>
</tr>
</tbody>
</table>

We prefer to add heat at the lowest possible temperature, and to remove heat at the highest possible temperature!

Multiple utilities correspond to multiple pinches.
T-H Diagram

Enthalpy, MBtu/hr

Cold
T-H Diagram

Enthalpy, MBtu/hr

250
230
210
190
170
150
130
90

Hot
Cold

ΔT_{\text{min}} = 10 \text{ F}

Q_{C,\text{min}} \quad Q_{H,\text{min}}
Limitation of the Procedure

We need to know

FC_p values of all streams
Inlet and outlet temperatures of all streams

BUT the design variables that fix the process flows must be determined from optimization which in turn depends on heat-exchanger network

Solution: Heat-exchanger network as function of the flows
Some iterations are needed
An Exercise

Given the following stream data below, find (assume $\Delta T_{\text{min}} = 10$ deg C)
- the minimum amount heat added
- the minimum amount of cooling
- the pinch temperature

<table>
<thead>
<tr>
<th>Stream</th>
<th>Temperature</th>
<th>Heat Flow Rate ($F_{C_p}$) (kW/C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>180 C → 60 C</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>150 C → 30 C</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>135 C ← 20 C</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>140 C ← 80 C</td>
<td>5</td>
</tr>
</tbody>
</table>
Minimum Number of Exchangers

From results of minimum heating and cooling estimates

Heat loads always balance as result of first law analysis

Number of exchangers \( (N_E) \) = Number of streams \( (N_S) \) + Number of Utilities \( (N_U) \) - 1

\[ N_E = 4 + 2 - 1 = 5 \]
Minimum Number of Exchangers

The previous solution is not always correct. Consider

Sources

- Hot Utility 230 MBtu/hr
- Stream 1 130 MBtu/hr
- Stream 2 400 MBtu/hr

Sinks

- Stream 3 180 MBtu/hr
- Stream 4 360 MBtu/hr
- Cold Utility 220 MBtu/hr

We see that if we have an exact matching between some streams, we need less exchanger

\[ N_E = N_S + N_U - N_P \]

\[ N_P = \text{number of independent subproblems} \]
Minimum Number of Exchangers

The previous solution is still not always correct. Consider

Sources

<table>
<thead>
<tr>
<th>Stream 1</th>
<th>Stream 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot Utility 130 MBtu/hr</td>
<td>Stream 2 400 MBtu/hr</td>
</tr>
<tr>
<td>Stream 3 180 MBtu/hr</td>
<td>Stream 4 360 MBtu/hr</td>
</tr>
</tbody>
</table>

Sinks

<table>
<thead>
<tr>
<th>Stream 3 180 MBtu/hr</th>
<th>Stream 4 360 MBtu/hr</th>
<th>Cold Utility 220 MBtu/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>70-Q_E</td>
<td>20-Q_E</td>
<td>340</td>
</tr>
<tr>
<td>110+Q_E</td>
<td></td>
<td>60</td>
</tr>
</tbody>
</table>

We see that there are now six exchangers and there is now a loop (i.e., HU -> S3 -> S1 -> S4 -> HU)

\[ N_E = N_S + N_U + N_L - N_P \]

\[ N_L = \text{number of loops} \]
Effect of Pinch Analysis

The pinch analysis indicates that we only use heat above the pinch and cooling below the pinch, so that the design problem can be decomposed into two subproblems.

Assume no loops & no exact matches

\[ N_E = N_S + N_U - 1 \]
\[ = 4 + 1 - 1 = 4 \]

\[ N_E = N_S + N_U - 1 \]
\[ = 3 + 1 - 1 = 3 \]

\( N_{\text{TOTAL}} = 7 \)
Effect of Pinch Analysis

Minimum Exchangers:  
$N = 5$

Pinch Analysis:  
$N = 7$  
(minimum energy)

A trade-off between capital cost (minimum exchangers) and utility costs (minimum energy)

We can decrease the number of exchangers if we transfer some heat across the pinch, but the energy usage increases
Design of Minimum-Energy HEN’s

Above the pinch: \( Q_{\text{tot}} = 70 \text{ MBtu/hr, heat added} \)
Above the pinch: \( Q_{\text{tot}} = 60 \text{ MBtu/hr, heat removed} \)
Design above the Pinch

Feasible Pinch Matches:
\[(\text{FC}_p)_{\text{HOT}} \leq (\text{FC}_p)_{\text{COLD}}\]

We can match stream 1 with either 3 or 4, and we can only match stream 2 with 4.
Design above the Pinch

Transfer the maximum amount of heat possible for each match to attempt to eliminate streams from the problem.
Transfer the remaining heat from stream 1 to stream 4.

<table>
<thead>
<tr>
<th>Q = 110-60</th>
<th>T_H (F)</th>
<th>T_C (F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 F</td>
<td>250</td>
<td>240</td>
</tr>
<tr>
<td>190</td>
<td>220</td>
<td>210</td>
</tr>
<tr>
<td>160</td>
<td>190</td>
<td>180</td>
</tr>
<tr>
<td>130</td>
<td>160</td>
<td>150</td>
</tr>
<tr>
<td>100</td>
<td>130</td>
<td>120</td>
</tr>
</tbody>
</table>

Q = 360-240
= 120

Q = 360-240
= 120

170 F
Remaining Heat Loads

\[ Q = 50 \]

\[
\begin{array}{ccc}
T_H (F) & T_C (F) \\
250 & 240 \\
220 & 210 \\
190 & 180 \\
160 & 150 \\
130 & 120 \\
100 & 90 \\
\end{array}
\]

Pinch
# Heat from Hot Utility

<table>
<thead>
<tr>
<th>$T_H$ (F)</th>
<th>$T_C$ (F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
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<td>210</td>
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<tr>
<td>190</td>
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<tr>
<td>160</td>
<td>150</td>
</tr>
<tr>
<td>130</td>
<td>120</td>
</tr>
<tr>
<td>100</td>
<td>90</td>
</tr>
</tbody>
</table>

Pinch

$H = 70$

178 F
1. Put in the matches at the pinch
2. Maximize the heat loads to eliminate streams
3. See what is left
Design above the Pinch
(Alternatives)

$T_H$ (F) $T_C$ (F)

- $Q = 60$
- $Q = 50$
- $Q = 240$
- $H = 70$

Pinch
Design below the Pinch

\[
\begin{array}{cccc}
& \text{$T_H$ (F)} & \text{$T_C$ (F)} \\
250 & 240 \\
220 & 210 \\
190 & 180 \\
160 & 150 \\
\end{array}
\]

Pinch

\[
\begin{array}{cccc}
\text{Q} = 20 & \text{Q} = 160 & \text{Q} = 120 \\
130 & 120 & \\
100 & 90 & \\
\end{array}
\]
Design below the Pinch
(One Alternative)

\[ \begin{array}{cc}
T_H (\text{F}) & T_C (\text{F}) \\
250 & 240 \\
220 & 210 \\
190 & 180 \\
160 & 150 \\
\end{array} \]

Pinch

\[ \begin{array}{cc}
C = 20 & \\
C = 40 \\
T = 120 \\
Q = 120 \\
\end{array} \]
A Complete Design

Total Number of Exchangers: 7
Remarks

Minimum approach temperature
So far, we have assumed a value of 10 deg F
Trade-off: Larger minimum approach temperature, smaller heat-exchanger area but larger minimum heating and cooling

Additional complexities
The design problem is not always as simple as the example considered
Stream splitting
Alternatives
Reducing the Number of Exchangers

The number of exchangers required for the overall process is always less than or equal to that for the minimum energy network.

The minimum energy network normally contains loops across the pinch.

These loops can be broken by transferring heat across the pinch, but we will introduce at least one violation of the specified $\Delta T_{\text{min}}$.

$\Delta T_{\text{min}}$ can be restored by shifting heat along a path, which increases energy consumption of the process.
Loops

A set of connections that starts from one stream and returns to the same stream.
Loops

A set of connections that starts from one stream and returns to the same stream.
Loops

A set of connections that starts from one stream and returns to the same stream.
Loops

A set of connections that starts from one stream and returns to the same stream.
Breaking Loops

Break the loop with exchanger with the small load
Remove the smallest heat load from loop
Breaking a loop across the pinch normally violates the 2nd law
\( Q = 60 \)

\( Q = 50 + 20 \)

\( Q = 240 - 20 \)

\( H = 70 \)

\( C = 40 + 20 \)

\( Q = 120 \)
BUT ...

Hot Stream: 200 F to 120 F
Cold Stream: 150 F to 130 F

Impossible according to 2nd Law!
Restoring $\Delta T_{\text{min}}$

Shift heat along a path, which is a connection between a cooler and a heater.

Thus, $1000(60+Q_E) = 3000(150-110)$

$Q_E = 60 \text{ MBtu/hr}$
Reducing Number of Exchangers

Total number of Exchangers: 6
Restoring $\Delta T_{\text{min}}$
(An Alternative Path)

But this path can’t restore $\Delta T_{\text{min}}$!
Breaking Another Loop

Q=10

Q=220

Q=120

Q=60

C = 120

H=130
Heat Engines

Efficiency: 100% 100% Standard Alone

Place Heat Engine either above or below the pinch (not across)!
Place heat pump across the pinch!
Distillation

Column as a heat engine

↓ Heat In ($Q_{Reb}$)

Column

↓ Heat Out ($Q_{Cond}$)

Column either above or below the pinch

$Q_{in}$

Energy Cascade

↓

$Q_{out}$

Energy Cascade

Energy Cascade

↓

$Q_{out}$

Column

$Q_{in}$

Energy Cascade

Energy Cascade

↓

$Q_{out}$

Column