Work and Heat Exchange Networks (WHENs) for PI in Sub-Ambient Processes

by

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T. Gundersen
Some Process Integration Events

- IEA Workshop, Gothenburg, 28-29 January 1992
- IEA Expert Meeting, Berlin, October 1993
- IEA Implementing Agreement on PI, 1995-2002
- Nordic Energy Research Program on PI, 1995-2002
- Conference PI’99, Copenhagen, March 1999
- Jubilee Conference on PI, Gothenburg, March 2013
- IEA Expert Workshop on PI and its Role for Greenhouse Gas Mitigation in Industry, Berlin, April 2017
- Annual Conferences on PI
  - PRES from Prague 1998 to Tianjin 2017
- PI Related Sessions on various Conferences
  - ESCAPE, FOCAPD, PSE, AIChE, etc.
The IEA Definition of Process Integration

"Systematic and General Methods for Designing Integrated Production Systems, ranging from Individual Processes to Total Sites, with special emphasis on the Efficient Use of Energy and reducing Environmental Effects"

From an Expert Meeting in Berlin, October 1993

IEA Expert Workshop
The Role of Process Integration for Greenhouse Gas Mitigation in Industry

Time: Tuesday April 4, 09.00-Wednesday April 5, 16.30
Outline of the Presentation

- PI Extensions by using Analogies
- Work Exchange Networks (WENs)
  - Flow Work & Shaft Work
- Combined Work & Heat Integration
  - Work and Heat Exchange Networks (WHENs)
  - (i) Focus on Work – (ii) Focus on Heat (*this talk*)
  - Work & Heat – Different Qualities – *Exergy* as Objective
- Important Sub-ambient Processes
  - Natural Gas Liquefaction (LNG)
  - Air Separation Units (ASUs)
- Appropriate Placement of Compressors & Expanders
- A Novel WHEN Methodology
- A Sub-ambient Example
- Future Research
PI Expansions through the Use of Analogies

Flow Work Exchanger

1967

HEN / Heat Pinch 1971-78
MEN / Mass Pinch 1989
Water Pinch 1994
Hydrogen Pinch 1999
Oxygen Pinch 1999
CO₂ Emission Pinch 2007

WEN – Work Exchange Network

Developments in WENs

- Work Exchange Networks
  - Pressure Integration
    - Flow Work
      - Direct Exchange
        - Flow Work Exchanger
      - Indirect Exchange
        - Expander / Compressor
  - Work/Power Integration
    - Shaft Work
HENs and WENs
Important Differences

Flow Work Exchanger
Direct

Heat Exchanger

Expander / Compressor
Indirect

The Pressure-Work Diagram shows Crossover, i.e. no $\Delta p \geq \Delta p_{\text{min}}$ and no Pressure Pinch

$\Delta T \geq \Delta T_{\text{min}}$ between hot and cold Composite Curves, and there is a Heat Pinch

Expander: $p_{E,\text{out}} < p_{E,\text{in}}$

Compressor: $p_{C,\text{out}} > p_{C,\text{in}}$

No $\Delta p \geq \Delta p_{\text{min}}$ between expanded and compressed gas and no Pressure Pinch
Combined HENs and WENs

Different Approaches

Work Exchange Networks + Heat Exchange Networks

Work and Heat Exchange Networks (WHENs)

WHEN
Focus on Work Integration
Accounting for Heat Effects

WHEN
Focus on Heat Integration
Accounting for Heating & Cooling produced by Compression & Expansion

This Presentation
Given a set of process streams with supply and target states ($T$ and $p$), as well as utilities for power, heating and cooling; design a Work and Heat Exchange Network consisting of heat transfer equipment such as heat exchangers, evaporators and condensers, as well as pressure changing equipment such as compressors, expanders, pumps and valves, in such a way that Exergy consumption or Total Annual Cost is minimized.

Applicable Above and Below Ambient Temperature
Process Integration in Sub-ambient Processes

- Prejudice: Already tightly Integrated
  - Limited Scope for Improvements
    - Cold end of Ethylene Plants
    - Air Separation Units (see later slides)
    - Natural Gas Liquefaction – LNG
    - Hydrogen Liquefaction (not this talk)

![Composite Curves](image)

![Cold End of Ethylene Plant](image)
Objective:

Minimize Shaftwork subject to 2 Constraints by varying 2 Pressures and 5-6 Flows of Refrigerant Components

$\Delta T_{\text{min}}$ vs. $UA_{\text{max}}$ in Sub-ambient Design: PRICO
Results from the Optimization

<table>
<thead>
<tr>
<th>$\Delta T_{\text{min}}$ as Specification</th>
<th>$UA_{\text{max}}$ as Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T_{\text{min}}$</td>
<td>$UA$</td>
</tr>
<tr>
<td>(K)</td>
<td>(MW/K)</td>
</tr>
<tr>
<td>1</td>
<td>3.101</td>
</tr>
<tr>
<td>2</td>
<td>1.658</td>
</tr>
<tr>
<td>3</td>
<td>1.110</td>
</tr>
<tr>
<td>4</td>
<td>0.812</td>
</tr>
<tr>
<td>5</td>
<td>0.632</td>
</tr>
</tbody>
</table>

$UA_{\text{max}}$ is a better Specification than $\Delta T_{\text{min}}$ and it is all related to Exergy
Comparing 4 Design Specifications

C1: $\Delta T \geq \Delta T_{\text{min}}$
C2: $\Delta T \geq k \cdot T_H$
C3: $\Delta T \geq \Delta T_{\text{LM}}$
C4: $UA \leq UA_{\text{max}}$

<table>
<thead>
<tr>
<th>$\Delta T_{\text{min}}$ (K)</th>
<th>$UA$ (MW/K)</th>
<th>$C1$ (MJ/kmol)</th>
<th>$C2$ (MJ/kmol)</th>
<th>$C3$ (MJ/kmol)</th>
<th>$C4$ (MJ/kmol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>59.2</td>
<td>14.2</td>
<td>14.3</td>
<td>14.1</td>
<td>14.0</td>
</tr>
<tr>
<td>2</td>
<td>31.5</td>
<td>15.6</td>
<td>15.4</td>
<td>15.2</td>
<td>15.0</td>
</tr>
<tr>
<td>3</td>
<td>20.2</td>
<td>16.9</td>
<td>16.5</td>
<td>16.3</td>
<td>15.9</td>
</tr>
<tr>
<td>4</td>
<td>14.8</td>
<td>18.3</td>
<td>17.6</td>
<td>17.3</td>
<td>16.8</td>
</tr>
<tr>
<td>5</td>
<td>11.4</td>
<td>19.6</td>
<td>18.8</td>
<td>18.2</td>
<td>17.6</td>
</tr>
</tbody>
</table>

Comparing 4 Design Specifications

C1: $\Delta T \geq \Delta T_{\text{min}}$
C2: $\Delta T \geq k \cdot T_H$
C3: $\Delta T \geq \Delta T_{\text{LM}}$
C4: $UA \leq UA_{\text{max}}$
Using Exergy Analysis to improve ASUs

Linde’s Classical Coupled Column Design

- Our “need”: O₂ Product: 95 mole%, 1.2 bar, gas phase, N₂ vented
- Shaftwork: 0.199 kWh/kgO₂ vs. Theoretical Minimum: 0.049 kWh/kgO₂

Distribution of Exergy Losses

AU1: The main air compressor
AU2: The pre-purification unit
AU3: The main heat exchanger
AU4: The air distillation system
AU5: The tail N2 turbine
AU6: The waste N2

Largest Sources of Exergy Losses

- Main Air Compressor (38.4%)
  - Compression Process itself
  - Interstage Coolers

- Distillation System (28.2%)
  - LP Column
Recuperative Vapor Recompression Cycle (RVRC)

Fu C., Gundersen T. and Eimer D., “Air Separation”, GB Patent, Application number GB1112988.9, July 2011

Single Column, Distributed Reboiling, Heat Pumping (RVRC)
Of course, we used the Column Grand Composite Curve.
The Appropriate Placement Concept

- Heat Pumps & Heat Engines (H/U)
  - Townsend and Linnhoff, 1983
- Distillation Columns (S)
  - Linnhoff, Dunford and Smith, 1983
- Evaporators (S)
  - Smith and Linnhoff, 1988
- Reactors (R)
  - Glavič, Kravanja and Homšak, 1988
- Basis for Correct Integration
  - “Plus/Minus” Principle
  - Pinch Decomposition
Q: What about Compressors & Expanders?

- Aspelund, Berstad and Gundersen, 2007
  - Compressors provide Heat – should be placed above Pinch
  - Expanders provide Cooling – should be placed below Pinch
  - This is in Conflict with Industrial Practice

- Gundersen, Berstad and Aspelund, 2009
  - Compression & Expansion should start at the Pinch

- Fu and Gundersen, 2015a,b,c,d
  - The Pinch point(s) will change
  - A Need to improve our Insight
Motivation for Pressure Manipulations and WHENs

- Use of Compression Heat and Expansion Cooling
  - Sacrifice modest amounts of Work to make significant savings in Thermal Energy (Heating and Cooling)

- WHEN Research has strong Relations to
  - Heat Pumping and Refrigeration Cycles
  - “Self-Heat Recuperation”

- Challenges in WHENs compared to HENs:
  - Thermodynamic Path ($T$ vs. $H$) is unknown
  - Shape of CCs and GCC will change
  - Pinch Point(s) and Utility Demand may (will) change
  - Stream Identity (hot/cold) may (will) temporarily change
Pinch Location Methods

- Our Insight is based on the Heat Recovery Pinch Concept
  - Decomposition into Heat Surplus & Deficit Regions
  - Appropriate Placement of Compressors & Expanders requires Pinch Point(s)

- Variable Temperatures
  - Heat Cascade without fixed Temperature Intervals
  - Need Pinch Location Method


Our Terminology (above Ambient)

"Hot Utility Expansion"  ➔ Case A

"Pinch Expansion"  ➔ Case B

"Ambient Expansion"  ➔ Case C

"Ambient Compression"  ➔ Case D

"Pinch Compression"  ➔ Case E
The Complete Picture (above & below Ambient)

- No Expansion at $T_{CU}$
- No Compression at $T_{HU}$

*10.04.2017 T. Gundersen Slide no. 24*
Physical Explanation – Expanders above Ambient

2 important Variables:
- $Q_{\text{exp,PI}}$ vs. $Q_{\text{C,min}}$
- $T_{\text{exp,HU}}$ vs. $T_{\text{PI}}$ and $T_0$

Case I (covered by Theorem 1):
- $Q_{\text{exp,PI}} \leq Q_{\text{C,min}}$ and $T_{\text{exp,HU}} > T_0$
- Use Pinch Expansion only

Case II (covered by Theorem 2):
- $Q_{\text{exp,PI}} > Q_{\text{C,min}}$ and $T_{\text{exp,HU}} \geq T_{\text{PI}}$
- Max Expansion at $T_{\text{PI}}$, then at $T_{\text{HU}}$ or $T_0$

Case III (covered by Theorem 3):
- $Q_{\text{exp,PI}} > Q_{\text{C,min}}$ and $T_0 < T_{\text{exp,HU}} < T_{\text{PI}}$
- Increase Expansion at $T_{\text{HU}}$, reduce at $T_{\text{PI}}$

Case IV (covered by Theorem 4):
- $T_{\text{exp,HU}} < T_0$
- Expansion at $T_{\text{HU}}$ only

$Q_{\text{exp,PI}} = mCp \cdot (T_{\text{PI}} - T_{\text{exp,PI}})$
A Design Procedure for Appropriate Placement of Compressors & Expanders in HENs: Here above Ambient

Theorem 1

Theorem 2

Theorem 3

Theorem 4

Iterative (Loops) & Graphical (GCC) based on 4 Theorems
## The Complete Picture – Symmetric of course 😊

<table>
<thead>
<tr>
<th>Theorem</th>
<th>Expansion Above</th>
<th>Compression Above</th>
<th>Expansion Below</th>
<th>Compression Below</th>
</tr>
</thead>
</table>
| 1       | $Q_{\text{exp,PI}} \leq Q_{\text{C,min}}$  
          $T_{\text{exp,HU}} > T_0$  
          $\Rightarrow$ Use Pinch Expansion | $Q_{\text{comp,PI}} \leq Q_{\text{H,min}}$  
          $T_{\text{comp,0}} < T_{\text{HU}}$  
          $\Rightarrow$ Use Pinch Compression | $Q_{\text{exp,PI}} \leq Q_{\text{C,min}}$  
          $T_{\text{exp,0}} > T_{\text{CU}}$  
          $\Rightarrow$ Use Pinch Expansion | $Q_{\text{comp,PI}} \leq Q_{\text{H,min}}$  
          $T_{\text{comp,CU}} < T_0$  
          $\Rightarrow$ Use Pinch Compression |
| 2       | $Q_{\text{exp,PI}} > Q_{\text{C,min}}$  
          $T_{\text{exp,HU}} \geq T_{\text{PI}}$  
          $\Rightarrow$ Split and maximize Pinch Expansion, then exp. at $T_{\text{HU}}$ or $T_0$ | $Q_{\text{comp,PI}} > Q_{\text{H,min}}$  
          $T_{\text{comp,0}} \leq T_{\text{PI}}$  
          $\Rightarrow$ Split and maximize Pinch Compression | $Q_{\text{exp,PI}} > Q_{\text{C,min}}$  
          $T_{\text{exp,0}} \geq T_{\text{PI}}$  
          $\Rightarrow$ Split and maximize Pinch Expansion | $Q_{\text{comp,PI}} > Q_{\text{H,min}}$  
          $T_{\text{comp,CU}} \leq T_{\text{PI}}$  
          $\Rightarrow$ Split and maximize Pinch Compression,  
          then comp. at $T_{\text{CU}}$ or $T_0$ |
| 3       | $Q_{\text{exp,PI}} > Q_{\text{C,min}}$  
          $T_0 < T_{\text{exp,HU}} < T_{\text{PI}}$  
          $\Rightarrow$ Increase HU Expansion & reduce Pinch Expansion | $Q_{\text{comp,PI}} > Q_{\text{H,min}}$  
          $T_{\text{PI}} < T_{\text{comp,0}} < T_{\text{HU}}$  
          $\Rightarrow$ Increase Ambient Compression & reduce Pinch Compression | $Q_{\text{exp,PI}} > Q_{\text{C,min}}$  
          $T_{\text{CU}} < T_{\text{exp,0}} < T_{\text{PI}}$  
          $\Rightarrow$ Increase Ambient Expansion & reduce Pinch Expansion | $Q_{\text{comp,PI}} > Q_{\text{H,min}}$  
          $T_{\text{PI}} < T_{\text{comp,0}} < T_0$  
          $\Rightarrow$ Increase CU Compression & reduce Pinch Compression |
| 4       | $T_{\text{exp,HU}} \leq T_0$  
          $\Rightarrow$ Use HU Expansion | $T_{\text{comp,0}} \geq T_{\text{HU}}$  
          $\Rightarrow$ Use Ambient Compression | $T_{\text{exp,0}} \leq T_{\text{CU}}$  
          $\Rightarrow$ Use Ambient Expansion | $T_{\text{comp,CU}} \geq T_0$  
          $\Rightarrow$ Use CU Compression |

10.04.2017  
T. Gundersen  
Slide no. 27
Example – Illustrating the Procedure

<table>
<thead>
<tr>
<th>Stream</th>
<th>$T_s$, K</th>
<th>$T_i$, K</th>
<th>$mc_p$, kW/K</th>
<th>$\Delta H$, kW</th>
<th>$p_s$, bar</th>
<th>$p_i$, bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
<td>288</td>
<td>124</td>
<td>2</td>
<td>328</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>H2</td>
<td>252</td>
<td>168</td>
<td>4</td>
<td>336</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>C1</td>
<td>138</td>
<td>284</td>
<td>3</td>
<td>438</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>C2</td>
<td>198</td>
<td>235</td>
<td>7</td>
<td>259</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Hot utility</td>
<td>288</td>
<td>288</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Cold utility</td>
<td>120</td>
<td>120</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

\[ T_{HU} = 288 \text{ K}, \quad T_{CU} = 120 \text{ K}, \quad \Delta T_{\min} = 4 \text{ K} \]

2 Streams subject to Pressure Manipulation:

H1 is expanded and C1 is compressed

“Experimental” Setup for Illustrative Example

- Assumptions:
  - Supply/Target States \((p,T)\) for Streams are given
  - Compression and Expansion of only one Stream
  - Only one “hot” \((288 \text{ K})\) and one cold Utility \((120 \text{ K})\)
  - Polytropic Efficiency \(\eta_{\text{poly}}\) is constant
  - Ideal Gas with constant \(\kappa = c_p/c_v\)

- Parameters used in the Calculations
  - \(\eta_{\text{poly}} = 1.0\), \(\Delta T_{\text{min}} = 4 \text{ K}\), \(T_0 = 288 \text{ K}\) and \(\kappa = 1.4\)

- Objective is to minimize Exergy Consumption
  - Work is assumed to be pure Exergy
  - Exergy of Hot Utility is neglected \((T_{\text{HU}} = T_0 = 288 \text{ K})\)
  - Exergy of Cold Utility from Carnot Equation:

\[
Ex = Q_{\text{CU}} \cdot \left(\frac{T_0}{T_{\text{CU}}} - 1\right)
\]
## Example – Illustrating the Procedure

Case O: Without Compression and Expansion  
Case I: Compression/Expansion at Supply Temperatures  
Case II: CU Compression (C1) & Ambient Expansion (H1)  
Case III: Pinch Compression and Expansion  
**Case IV: Using the novel Design Procedure**

<table>
<thead>
<tr>
<th>Cases</th>
<th>O</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot utility demand, kW</td>
<td>145</td>
<td>300.2</td>
<td>300.2</td>
<td>47.6</td>
<td>9.6</td>
</tr>
<tr>
<td>Cold utility demand, kW</td>
<td>112</td>
<td>202.6</td>
<td>193.6</td>
<td>36.0</td>
<td>13.0</td>
</tr>
<tr>
<td>Pinch temperature, K</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>140</td>
<td>140;200;250</td>
</tr>
<tr>
<td>Compression work, kW</td>
<td>-</td>
<td>90.6</td>
<td>81.6</td>
<td>130.2</td>
<td>135.5</td>
</tr>
<tr>
<td>Expansion work, kW</td>
<td>-</td>
<td>155.2</td>
<td>155.2</td>
<td>108.8</td>
<td>99.1</td>
</tr>
<tr>
<td>Exergy consumption, kW</td>
<td>-</td>
<td>219.0</td>
<td>197.4</td>
<td>71.8</td>
<td>54.6</td>
</tr>
</tbody>
</table>

**Lesson to learn:** Previous “Insight” was not Rigorous
Case III – Pinch Compression and Expansion

1 Compressor, 1 Expander, 7 HEs, Exergy Consumption: 71.8 kW
Case IV – Compression and Expansion by Procedure

2 Compressors, 2 Expanders, 10 HEs, Exergy Consumption: 54.6 kW

Remember Loops & Paths?
### Summary for the Illustrative Example

<table>
<thead>
<tr>
<th>Property</th>
<th>Case I</th>
<th>Case II</th>
<th>Case III</th>
<th>Case IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exergy Consumption (kW)</td>
<td>219.0</td>
<td>197.4</td>
<td>71.8</td>
<td>54.6</td>
</tr>
<tr>
<td># of Pinch Points</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td># of Compressors</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td># of Expanders</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td># of Heat Exchangers</td>
<td>7</td>
<td>8</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td># of Stream Splits</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

#### Some Observations
- The Design Procedure should primarily be regarded as a Targeting Exercise – it aims for the “ultimate”
- The Procedure (Case IV) results in new Pinch Points when maximizing Pinch Compression and Expansion
- The Result is considerable Complexity (Units & Stream Splits)
- Using only Pinch Compression and Expansion (Case III) at the original Pinch seems to be the best option in **this** Example
Future Research in WHENs

- Increase the Industrial Realism for our Procedure
  - Multiple Hot and Cold Utilities
  - Constant and Non-constant Temperature Utilities
  - Ability to treat Streams as Utilities
  - Multi-Stage Compression and Expansion
  - Exergy for Targeting – TAC for Design & Optimization

- Our Main Objectives for Future Research
  - Increased **Insight** for more Complex Cases
  - Move from Exergy to **TAC** (Total Annual Cost)
  - Establish a “Rich” but “Efficient” **Superstructure**
  - Build **MINLP** Models subject to Global Optimization
Superstructures and MINLP Models for WHENs


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Slide no. 35

Worked for Offshore LNG Process but not rich enough for general WHENs
NTNU/SINTEF Research Program: **HighEFF**

Centre for an **Energy Efficient and Competitive Industry for the Future**

Budget: 419 MNOK ≈ 49 MUSD ≈ 46 M€
8 years: 2017 – 2024, 20 PhDs and 3 Post.docs