Improving Energy Recovery in Heat Exchanger Network with Intensified Tube-side Heat Transfer

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Outline

1. Introduction
2. Intensified tube-side heat transfer
3. Optimization of retrofitting heat exchanger networks with intensified heat transfer
4. Case studies
5. Conclusions and future work
1. Introduction
Heat exchanger network (HEN)

- Models used for units in heat exchanger network (HEN) are very simple
- HEN design neglects the heat-exchanger details
- No account of pressure drops

\[ Q = U \times A \times \Delta T_{LM} \times FT \]

Specified overall U

- HEN design neglects the heat-exchanger details
- No account of pressure drops

Not suitable for many retrofit applications
Heat exchangers

- **Double pipe (DPHEX)**
  - two pairs of concentric pipes, counter flow
  - the simplest type

- **Shell and tube (STHEX)**
  - a bundle of tubes in a cylindrical shell, combining parallel and counter flows
  - the most widely used type in the chemical industries

- **Plate and frame (PFHEX)**
  - metal plates are used to separate and transfer heat between two fluids
  - the common typed in the food and pharmaceutical industries
Existing design methods for HEN retrofit

- Yee and Grossmann (1991): retrofit design
- Sorsak and Kravanjia (2004): different exchanger types
- Ponce-Ortega et al. (2008): phase changes

Limits:

- Lots of topology modifications
- Too many repiping works
- No account of STHEX geometry modifications
- STHEX models are not rigorous


HEN retrofit with intensified heat transfer

- Polley et al. (1992): potential analysis of heat recovery
- Zhu et al. (2000): network pinch approach
- Smith et al. (2009): structural modifications and cost-effective design

Limits:

- Large scale problems
- No pressure drop restrictions
- Heuristic rules


Research objectives

• Account for detailed performance of heat exchangers

• Implement intensified heat transfer techniques to suitable heat exchangers

• Allow new heat exchanger installation

• Maximize total energy saving with less network structure modifications
2. Intensified tube-side heat transfer
Intensified tube-side heat transfer

- **Twisted-tape inserts**, which cause spiral flow along the tube length to increase turbulence

- **Coiled wire inserts**, which consist of a helical coiled spring and function as non-integral roughness

- **hiTRAN®,** which consist of a wire mesh with different densities. They are usually used to improve the heat transfer coefficient for the laminar regime
Correlations of twisted-tape inserts


Laminar region

\[ Nu = 4.612 \left[ 6.413 \times 10^{-9} \left( Sw \Pr^{0.391} \right)^{3.385} \right]^{0.2} \left( \frac{\mu}{\mu_w} \right) \]

\[ (f \ Re)_{sw} = 15.767 \left( \frac{\pi}{\pi - \frac{2t}{D_i}} \right)^2 (1 + 10^{-6} Sw^{2.55})^{1/6} \]

Turbulent region

\[ Nu = 0.023 \Re^{0.8} \Pr^{0.4} \left( \frac{\pi}{\pi - \frac{4t}{D_i}} \right)^{0.8} \left( \frac{\pi + 2 - \frac{2t}{D_i}}{\pi - \frac{4t}{D_i}} \right)^{0.2} \left( \frac{\mu}{\mu_w} \right) \]

\[ f = \frac{0.079}{\Re^{0.25}} \left( \frac{\pi}{\pi - \frac{4t}{D_i}} \right)^{1.75} \left( \frac{\pi + 2 - \frac{2t}{D_i}}{\pi - \frac{4t}{D_i}} \right)^{1.25} (1 + 2.752 / y^{1.29}) \]

\[ Sw = \frac{\Re}{\sqrt{y}} \quad y = H / D_i \]

\[ \Re_{sw} = \rho v_s D_i / \mu \]

**H**: 180° twist pitch of twisted tape

**t**: thickness of tapes

**μ**: viscosity

**D_i**: tube inner diameter
Correlations of coil-wire inserts

**Laminar region**

\[
Nu_m = 1.65 \tan \alpha Re_{Dv}^{m} Pr^{0.35} \left( \frac{\mu}{\mu_w} \right)^{0.14} \quad Re_{Dv} = \frac{\rho v D_v}{\mu} \quad m = 0.25 (\tan \alpha)^{-0.38}
\]

\[
f = 16 / Re \quad Re = \frac{\rho v D_v}{\mu}
\]

**Turbulent region**

\[
Nu_a = 0.303 (\frac{e}{D_i})^{0.12} (\frac{p}{D_i})^{-0.377} Re^{0.72} Pr^{0.37}
\]

\[
f_a = 9.35 (\frac{p}{e})^{-1.16} Re^{-0.217}
\]

**Symbols:**
- \( \alpha \): insert angle
- \( D_v \): hydraulic diameter
- \( 4x(\text{free volume}/\text{wetted surface}) \)
- \( \mu \): viscosity
- \( D_i \): tube inner diameter
- \( e \): wire diameter
- \( p \): helical pitch


Correlations of hiTRAN®

**MAXHTC**: heat transfer coefficient for the highest density of hiTRAN;

**MINHTC**: heat transfer coefficient for the lowest density of hiTRAN

\[
Re = D_i \nu \rho / \mu \\
Pr = C_p \mu / k
\]

**MAXHTC** = \( f_1(k, D_i, Pr, Re) \)  \hspace{1cm} **MINHTC** = \( f_2(k, D_i, Pr, Re) \)

**MAXΔP**: pressure drop for the highest density of hiTRAN;

**MINΔP**: pressure drop for the lowest density of hiTRAN

\[
MAX\Delta P = f_3(n_p, L, \rho, \nu, D_i, Re) \\
MAX\Delta P = f_4(n_p, L, \rho, \nu, D_i, Re)
\]

\( f_1( ) \), \( f_2( ) \), \( f_3( ) \) and \( f_4( ) \): relative correlations for heat transfer coefficients and pressure drops

- \( k \): conductivity, \( D_i \): tube inner diameter, \( \nu \): tube-side velocity, \( \mu \): viscosity, \( \rho \): density, \( C_p \): specific heat, \( n_p \): tube passes, \( L \): tube length
3. HEN retrofit with intensified heat transfer
New model for HEN retrofit (MINLP)

Energy balance:
\[ F_h \times C_{ph} (T_h - T'_h) = F_c \times C_{pc} (T'_c - T_c) \]

Heat transfer:
\[ F_h \times C_{ph} (T_h - T'_h) = A \times U \times \ln \Delta T \times FT \]

Intensified heat transfer:
\[ U_{min} \leq U \leq U_{max} + M \times (1 - EEX) \]
\[ U_{initial} \leq U \leq U_{initial} + M \times EEX \]

LMTD:
\[ \ln \Delta T = \frac{(T_h - T'_c) - (T'_h - T_c)}{\ln[(T_h - T'_c)/(T'_h - T_c)]} \]

FT:
\[ R_{ex} = \frac{H_{ex} - H_{to}}{C_{to} - C_{ti}} \]
\[ P_{ex} = \frac{C_{to} - C_{ti}}{H_{ex} - C_{ti}} \]

\[ S_{ex} = \frac{\alpha_{ex} - 1}{\alpha_{ex} - R_{ex}} \]

\[ FT_{ex} = \frac{\sqrt{R_{ex}^2 + 1} \times \ln \left( \frac{1 - S_{ex}}{1 - R_{ex} \times S_{ex}} \right)}{(R_{ex} - 1) \times \ln \left( \frac{2 - S_{ex} \times \left( R_{ex} + 1 - \sqrt{R_{ex}^2 + 1} \right)}{2 - S_{ex} \times \left( R_{ex} + 1 + \sqrt{R_{ex}^2 + 1} \right)} \right)} \]

Objective: maximizing energy saving

\[ F_h / F_c: \] flow-rates of hot / cold streams,
\[ C_{ph} / C_{pc}: \] specific heats of hot / cold streams,
\[ T_h / T_c: \] inlet temperatures of hot / cold streams,
\[ T'_h / T'_c: \] outlet temperatures of hot / cold streams,
\[ U: \] overall heat transfer coefficient,
\[ A: \] heat transfer area,
\[ U_{min}: \] minimum heat transfer coefficient for enhancement,
\[ U_{max}: \] maximum heat transfer coefficient for enhancement,
\[ U_{initial}: \] heat transfer coefficient without enhancement,
\[ EEX: \] binary variable, 1 if enhancement is implemented,
\[ M: \] a sufficiently large positive number,
\[ ln\Delta T: \] logarithmic mean temperature,
\[ FT: \] ln \Delta T correction factor
Iterative linear model

Nonlinear equations:

\[ F_h \times C_{ph}(T_h - T'_h) = A \times U \times \ln \Delta T \times FT \]

Use initial temperatures

Calculate: \( \ln \Delta T' \) and \( FT' \)

\[ \ln \Delta T' = \frac{(T_h - T'_c) - (T'_h - T_c)}{\ln[(T_h - T'_c)/(T'_h - T_c)]} \]

\[ FT' = \sqrt{R^2 + 1} \times \ln \left( \frac{1 - S}{1 - R \times S} \right) \]

Linear equation:

\[ F_h \times C_{ph}(T_h - T'_h) = A \times U \times \ln \Delta T' \times FT' \]

Updated temperatures:

\((T_h, T'_h, T_c, T'_c)\)

Not converged?

Compare initial and updated temperatures

Optimize MILP model

MILP model
Optimization procedure

1. Assume an initial small value of energy saving ($QS'$)
   - Input initial values for variables
     - Linearize nonlinear terms in MINLP
       - MILP model of HEN retrofit
         - Solve the MILP problem
           - If the MILP problem is infeasible
             - Replace $LMTD'_{ex}$ and the initial value of variables
               - Obtain new values of variables
                 - Calculate variable differences
                   - If the above differences are small enough
                     - Obtain the new energy saving ($QS$)
                       - Gradually increase $QS'$ ($QS' > QS$)
             - Yes → Stop
           - No
             - Obtain the new energy saving ($QS$)
4. Case studies
Case study 1

Stream heat-flow capacity: $F_{Cp}$ (kW/K)

<table>
<thead>
<tr>
<th></th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>228.5</td>
<td>20.4</td>
<td>53.8</td>
<td>93.3</td>
<td>196.1</td>
</tr>
</tbody>
</table>
## Case study 1

### Heat transfer coefficients of exchangers in different tube geometries (kW/m²·K)

<table>
<thead>
<tr>
<th>EXs</th>
<th>Tube passes (no tube-side enhancement)</th>
<th>Tube passes (tube-side enhancement)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 (N)</td>
<td>2 (N)</td>
</tr>
<tr>
<td>1</td>
<td>0 ~ 0.51</td>
<td>0 ~ 1.00</td>
</tr>
<tr>
<td>2</td>
<td>0 ~ 0.10</td>
<td>0 ~ 0.20</td>
</tr>
<tr>
<td>3</td>
<td>0 ~ 0.15</td>
<td>0 ~ 0.30</td>
</tr>
<tr>
<td>4</td>
<td>0 ~ 0.08</td>
<td>0 ~ 0.16</td>
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</tbody>
</table>
Case study 1 (Retrofit)

The details for exchangers in initial and retrofit cases

<table>
<thead>
<tr>
<th>Case</th>
<th>Exchanger 1</th>
<th>Exchanger 2</th>
<th>Exchanger 3</th>
<th>Exchanger 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>U</td>
<td>TP</td>
<td>A</td>
</tr>
<tr>
<td>Initial</td>
<td>200</td>
<td>0.50</td>
<td>1(N)</td>
<td>150</td>
</tr>
<tr>
<td>Retrofit</td>
<td>200</td>
<td><strong>0.83</strong></td>
<td><strong>1(E)</strong></td>
<td>150</td>
</tr>
</tbody>
</table>
Case study 1

Conclusions:

- **Heat transfer coefficients** of exchangers increase through increasing tube passes and implementing tube inserts.
- **One tube pass** has to be used in very small temperature cross (when FT is infeasible).
- **Heat duty** reduces 11.36% (17.6 MW to 15.6 MW).
- **No changes** in network structure.
Case study 2

Stream heat-flow capacity: $F_{Cp}$ (kW/K)

<table>
<thead>
<tr>
<th></th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCp</td>
<td>228.5</td>
<td>20.4</td>
<td>53.8</td>
<td>93.3</td>
<td>196.1</td>
</tr>
</tbody>
</table>
Case study 2

Heat transfer coefficients of exchangers in different tube geometries (kW/m²·K)

<table>
<thead>
<tr>
<th>EXs</th>
<th>Tube passes (no tube-side enhancement)</th>
<th>Tube passes (tube-side enhancement)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 (N)  2 (N)  4 (N)  6 (N)</td>
<td>1 (E)  2 (E)  4 (E)  6 (E)</td>
</tr>
<tr>
<td>1</td>
<td>0 ~ 0.51  0 ~ 1.00  0 ~ 2.00  0 ~ 3.00</td>
<td>0.60 ~ 1.00  0.80 ~ 2.00  1.80 ~ 4.00  3.60 ~ 5.00</td>
</tr>
<tr>
<td>2</td>
<td>0 ~ 0.10  0 ~ 0.20  0 ~ 0.42  0 ~ 0.60</td>
<td>0.12 ~ 0.20  0.15 ~ 0.40  0.35 ~ 0.90  0.80 ~ 1.20</td>
</tr>
<tr>
<td>3</td>
<td>0 ~ 0.15  0 ~ 0.30  0 ~ 0.61  0 ~ 0.72</td>
<td>0.20 ~ 0.30  0.28 ~ 0.60  0.58 ~ 1.20  0.90 ~ 2.00</td>
</tr>
<tr>
<td>4</td>
<td>0 ~ 0.08  0 ~ 0.16  0 ~ 0.32  0 ~ 0.50</td>
<td>0.08 ~ 0.16  0.16 ~ 0.35  0.34 ~ 0.60  0.53 ~ 1.00</td>
</tr>
<tr>
<td>5</td>
<td>0 ~ 0.20  0 ~ 0.40  0 ~ 0.89  0 ~ 1.00</td>
<td>0.20 ~ 0.70  0.40 ~ 0.80  0.89 ~ 1.00  1.00 ~ 2.00</td>
</tr>
</tbody>
</table>
Case study 2 (Retrofit)

The details for exchangers in initial and retrofit cases

<table>
<thead>
<tr>
<th>Case</th>
<th>Exchanger 1</th>
<th>Exchanger 2</th>
<th>Exchanger 3</th>
<th>Exchanger 4</th>
<th>Exchanger 5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>U</td>
<td>TP</td>
<td>A</td>
<td>U</td>
</tr>
<tr>
<td>Initial</td>
<td>323</td>
<td>0.50</td>
<td>1(N)</td>
<td>962</td>
<td>0.10</td>
</tr>
<tr>
<td>Retrofit</td>
<td>323</td>
<td><strong>0.83</strong></td>
<td>1(E)</td>
<td>962</td>
<td>0.07</td>
</tr>
</tbody>
</table>
Case study 2

Conclusions:

- **Heat transfer coefficients** of exchangers increase through increasing tube passes and implementing tube inserts.
- **One tube pass** has to be used in very small temperature cross (when FT is infeasible).
- **Heat duty** reduces 8.06% (12.4 MW to 11.4 MW).
- **No changes** in network structure.
# Case study 3

## Stream data without utilities

<table>
<thead>
<tr>
<th>Stream</th>
<th>$F$ (kg/s)</th>
<th>$T$ (°C)</th>
<th>Maximum Pressure drop (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>125.91</td>
<td>33.5 → 95.6</td>
<td>600</td>
</tr>
<tr>
<td>C2</td>
<td>160.23</td>
<td>91.4 → 157.3</td>
<td>500</td>
</tr>
<tr>
<td>C3</td>
<td>153.69</td>
<td>151.1 → 351.9</td>
<td>900</td>
</tr>
<tr>
<td>H1</td>
<td>6.39</td>
<td>335.4 → 69.4</td>
<td>200</td>
</tr>
<tr>
<td>H2</td>
<td>73.11</td>
<td>253.2 → 116.1</td>
<td>300</td>
</tr>
<tr>
<td>H3</td>
<td>40.63</td>
<td>293.7 → 130.</td>
<td>300</td>
</tr>
<tr>
<td>H4</td>
<td>9.27</td>
<td>212.4 → 156.1</td>
<td>100</td>
</tr>
<tr>
<td>H5</td>
<td>9.27</td>
<td>212.7 → 61.7</td>
<td>400</td>
</tr>
<tr>
<td>H6</td>
<td>16.21</td>
<td>174.4 → 43.3</td>
<td>300</td>
</tr>
<tr>
<td>H7</td>
<td>20.12</td>
<td>134.5 → 74.2</td>
<td>100</td>
</tr>
<tr>
<td>H8</td>
<td>11.64</td>
<td>364.3 → 65.6</td>
<td>400</td>
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<tr>
<td>H9</td>
<td>63.45</td>
<td>290.4 → 210.9</td>
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<tr>
<td>H10</td>
<td>9.28</td>
<td>284.2 → 65.6</td>
<td>300</td>
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<tr>
<td>H11</td>
<td>9.58</td>
<td>240.1 → 57.8</td>
<td>200</td>
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<tr>
<td>H12</td>
<td>25.05</td>
<td>178.7 → 69.3</td>
<td>300</td>
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</tbody>
</table>
# Case study 3

## Exchanger data without utilities

<table>
<thead>
<tr>
<th>Exchanger</th>
<th>U (kW/m²·K)</th>
<th>Max enhanced U (kW/m²·K)</th>
<th>Area (m²)</th>
<th>ΔTln (°C)</th>
<th>Th (°C)</th>
<th>Tc (°C)</th>
<th>Cpₗh (J/kg·K)</th>
<th>Cpₗc (J/kg·K)</th>
<th>Tube-side Max ∆P (kPa)</th>
<th>Shell-side Max ∆P (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>139.75</td>
<td>209.63</td>
<td>167.6</td>
<td>48.3</td>
<td>117.2 → 61.7</td>
<td>33.5 → 40.8</td>
<td>2197.4</td>
<td>2450.1</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>626.92</td>
<td>940.38</td>
<td>89.9</td>
<td>73.1</td>
<td>174.4 → 76.7</td>
<td>33.5 → 59.9</td>
<td>2598.2</td>
<td>2474.6</td>
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<td>100</td>
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<tr>
<td>4</td>
<td>184.78</td>
<td>277.17</td>
<td>153.1</td>
<td>74.4</td>
<td>284.2 → 203.2</td>
<td>160.2 → 166</td>
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<td>2413.4</td>
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<td>100</td>
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<td>5</td>
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<td>857.34</td>
<td>79.5</td>
<td>123.9</td>
<td>212.4 → 156.1</td>
<td>50.5 → 68.2</td>
<td>2598.2</td>
<td>2531.3</td>
<td>100</td>
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<tr>
<td>6</td>
<td>203.56</td>
<td>305.34</td>
<td>635.1</td>
<td>46.9</td>
<td>175.4 → 89.0</td>
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<td>12</td>
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<td>126.30</td>
<td>225.4</td>
<td>46.8</td>
<td>157.2 → 117.2</td>
<td>86.6 → 89.2</td>
<td>2397.3</td>
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<td>13</td>
<td>62.81</td>
<td>94.22</td>
<td>380.8</td>
<td>89.6</td>
<td>226.7 → 147.2</td>
<td>33.5 → 95.6</td>
<td>2316.9</td>
<td>2681.6</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>16</td>
<td>673.27</td>
<td>1009.91</td>
<td>113.1</td>
<td>110.3</td>
<td>262.8 → 189.6</td>
<td>91.4 → 139.5</td>
<td>2824.1</td>
<td>2184.8</td>
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<td>100</td>
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<tr>
<td>17</td>
<td>128.37</td>
<td>192.56</td>
<td>191.1</td>
<td>121.8</td>
<td>335.4 → 147.2</td>
<td>91.4 → 108.9</td>
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<tr>
<td>18</td>
<td>187.66</td>
<td>281.49</td>
<td>188.9</td>
<td>39.2</td>
<td>203.2 → 141.6</td>
<td>124.4 → 128.4</td>
<td>2483.8</td>
<td>2189.3</td>
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<tr>
<td>20</td>
<td>321.4</td>
<td>482.10</td>
<td>1336.3</td>
<td>24.3</td>
<td>200.1 → 140.3</td>
<td>128.4 → 156.6</td>
<td>2390.4</td>
<td>2310.0</td>
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<td>100</td>
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<tr>
<td>21</td>
<td>52.71</td>
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<td>220.2</td>
<td>20.1</td>
<td>178.7 → 175.4</td>
<td>156.6 → 157.3</td>
<td>2831.6</td>
<td>2344.4</td>
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<td>100</td>
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<tr>
<td>22</td>
<td>75.18</td>
<td>112.77</td>
<td>768.5</td>
<td>23.1</td>
<td>212.7 → 157.2</td>
<td>151.1 → 154.8</td>
<td>2596.9</td>
<td>2343.3</td>
<td>100</td>
<td>100</td>
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<td>23</td>
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<td>214.55</td>
<td>390.9</td>
<td>35.7</td>
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<td>154.8 → 160.2</td>
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<td>2368.1</td>
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<td>100</td>
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<tr>
<td>24</td>
<td>219.1</td>
<td>328.65</td>
<td>1004.7</td>
<td>46</td>
<td>253.2 → 200.1</td>
<td>166 → 192.9</td>
<td>2601.4</td>
<td>2444.1</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>26</td>
<td>169.8</td>
<td>254.70</td>
<td>272.4</td>
<td>80.2</td>
<td>293.7 → 262.8</td>
<td>192.9 → 202.4</td>
<td>2965.2</td>
<td>2525.8</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>27</td>
<td>182.95</td>
<td>274.43</td>
<td>223.5</td>
<td>46.9</td>
<td>287.8 → 226.7</td>
<td>202.4 → 207.2</td>
<td>2577.3</td>
<td>2525.8</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>28</td>
<td>211.1</td>
<td>316.65</td>
<td>1003.3</td>
<td>44.1</td>
<td>290.4 → 238.4</td>
<td>207.2 → 230.4</td>
<td>2831.3</td>
<td>2608.7</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>29</td>
<td>126.44</td>
<td>189.66</td>
<td>227.1</td>
<td>87.8</td>
<td>364.3 → 287.8</td>
<td>230.4 → 236.7</td>
<td>2832.4</td>
<td>2633.6</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

**Objective** - Maximize overall energy saving in HEN!
## Case study 3

### Optimal solution when N exchangers can be enhanced

<table>
<thead>
<tr>
<th>N</th>
<th>Enhanced exchanger:</th>
<th>Energy saving (kW)</th>
<th>Energy saving (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>EX16 (849.67), EX20 (457.68), EX24 (328.53), EX28 (316.65)</td>
<td>4250</td>
<td>6.51</td>
</tr>
<tr>
<td>6</td>
<td>EX16 (1009.9), EX20 (468.73), EX24 (321.74), EX26 (253.15), EX28 (304.08), EX29 (189.64)</td>
<td>5500</td>
<td>8.43</td>
</tr>
<tr>
<td>8</td>
<td>EX4 (277.00), EX6 (211.13), EX16 (1009.56), EX20 (434.28), EX24 (328.65), EX26 (254.53), EX28 (316.65), EX29 (189.65)</td>
<td>6100</td>
<td>9.35</td>
</tr>
<tr>
<td>All</td>
<td>EX4 (272.97), EX6 (219.63), EX16 (1009.88), EX18 (190.20), EX20 (406.29), EX22 (82.19), EX23 (207.29), EX24 (328.65), EX26 (254.68), EX27 (257.87), EX28 (316.65), EX29 (189.65)</td>
<td>6400</td>
<td>9.81</td>
</tr>
</tbody>
</table>

Enhancing **eight** exchangers can obtain almost maximum energy saving!
Case study 3

Conclusions:

- **Overall heat transfer coefficients** of enhanced exchangers increase
- **No topology modifications** required
- Based on the new model, up to **9.81% reduction** of heat duty is achieved (65.27 MW to 58.87 MW)
5. Conclusions and future work
Conclusions

Retrofit of HEN with heat transfer enhancement

- Intensified heat transfer for exchangers
- Exact calculation for LMTD and FT
- Multiple tube passes
- Energy saving
- No network structure modification
- Low retrofitting costs
Future works

- Improving optimal model for HEN retrofit
  - More details for enhancements
  - Large scale problems
  - Minimizing retrofitting costs

- Build up optimal model for HEN design
  - Exchanger geometry details
  - Pressure drop constraints
  - Maximizing total profit
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