Increasing Plate Heat Exchanger Thermal Duty: An Industrial Case Study

Method for Improving Heat Recovery Loops

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Talk Outline

• Introduction
• Integrating semi-continuous processes
• Heat Recovery Loop & Thermal Storage
• HRL Design Methodology
• HRL Storage Temperature selection
• HRL HX Area Targeting
• Conclusions
Introduction

• Large semi-continuous multi-plant sites are difficult to integrate
Introduction

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Introduction

• Large semi-continuous multi-plant sites are difficult to integrate
Large Multi-Plant Dairy Processing Site

Mt Taranaki, New Zealand

Whareroa Dairy Factory
Site Layout
Site Layout – Multiple Plants
Large Dairy Factory – multiple plants

Plants 4, 5, 6

- Cheese
- Casein
- Whey

Plant 1

Raw Milk → Milk Treatment

Milk → Evaporators

Spray Dryer A
2 t/h

Spray Dryer B
10 t/h

Spray Dryer C
23 t/h

Cream → Evaporators

AMF / Butter

Cream Products

Evaporators

Powder

Plant 2

Plant 3

THREE Milk powder plants

Plants 4, 5, 6
Large Dairy Factory – multiple plants

- 8 million litres (peak) per day

- 8 Plants
  - Anhydrous Milk Fat (AMF) / butter plant
  - Cheese, Casein, Whey
  - THREE milk powder plants

- Semi continuous plants
  - Regular cleaning required
  - Product changes (start-up, shut down)
  - Variable milk supply over season

- Inter-plant integration opportunity
How semi-continuous are the plants?
Milk to Factory for Processing

% Max Site Production

Weeks

Winter Spring Summer Autumn Winter

Aug Oct June
Annual Operating Schedule

Plants
- Cream Products
- AMF/Butter
- Dryer C
- Dryer B
- Dryer A

Operating Conditions
- A = 6 Weeks
- B = 8 Weeks
- C = 12 Weeks
- D = 13 Weeks

Dryer A
Dryer B
Dryer C
AMF/Butter
Cream Products

2 week variability
2 Week Operation of Dryer B

Dryer State

- CIP
- Product
- Warm
- Water
- Offline

Day

RUNNING

Not producing product
Unsteady plant operation

• Streams can be unsteady in both Temp and Flow
• Unsteady due to many factors
  • Production Rate Changes & Variations
  • Regular Cleaning
  • Multiple Plants
Total Site Integration

- **Interplant integration** (Previous work: Bagajewicz and Rodera, 2000, 2002; Krummenacher and Favrat, 2001)
  - Direct
  - Indirect

- **High Pinch Temperature Applications**
  - Use steam belt system for indirect heat exchange between sources and sinks.
  - Surplus can be used for power generation.
  - Deficit met with utility.

- **Low Pinch Temperature Applications**
  - Food & Beverage
  - Pulp & Paper
  - Heat Recovery Loop
Heat Recovery Loop

- **Stratified Tank**
- **Heat Sources**
- **Heat Sinks**
- **Pipe Bridge**
Indirect Heat Transfer + Thermal Storage

Heat Recovery Loop

Hot water

COLD process stream

Hot

Stratified storage tank

HOT process stream

Cold water

Hot

Cold
Dairy Case Study - Heat Recovery Loop

COLD Streams Heated (Sinks)

HOT Streams Cooled (Sources)

Hot & cold water loop temperatures?
Stratified Tank
Pipe Bridge & Heat Exchangers
Heat Recovery Loop

- Low Temperature Applications
  - <100 - 150 °C
- Indirect Heat Transfer
- Non-Continuous or Variable Rate
- Heat Sources / Heat Sinks
- Thermal Storage
  - Single Stratified Tank
  - Multiple Tanks
- Distribution System
- Control System
Thermal Storage – Stratified Tank

• Used for storage of thermal energy
  • e.g. Hot Water, Chilled Water

• Usually operated in a charge – hold – discharge cycle

• Exploits a density difference of the fluid to create stratification

• Can be very large ~15,000 m³

• Thermocline reduces effective storage
Thermal Storage – Stratified Tank

Increasing Thermocline Size
Decreasing Storage Capacity

Temperature

\( T_{\text{cold}} \)  \( T_{\text{hot}} \)

40°C

20°C

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Two Tanks vs. Single Stratified Tank

• Why not have 2 tanks?

Single Stratified Tank

Two Individual Tanks

Fixed Volume System
Eliminate Thermocline Problem
BUT need 2x amount of tank volume
Designing a Heat Recovery Loop

• Selection of $T_{\text{hot}}$ and $T_{\text{cold}}$
• Selection of Sources & Sinks
• Availability and Variability of Streams
  • Availability – When is the stream “on”? 
  • Variability – What is the variability in $T_s$, $mc_p$?
• Sizing of Thermal Storage
  • Optimal Heat Recovery
  • Optimise Life Cycle Cost
• System Control
  • HX Trimming
  • Load Balancing
HRL Design Methodology

Data Extraction

- Integrate zones or areas
- Determine most common production state
- Extract and screen stream data

HRL Initial Design

- Draw CC using shifted temps
- Select number of HST
- Shift CC until pinch occurs
- Remove streams with no HR
- Remove storage pinch stream

Dynamic Modelling

- Generate more options
- Decide HST Temps for best option
- Design HRL network

- Combine & relax networks for various production states
- Estimate HR as function of storage size
- Estimate costs / economics
Integrate each plant (zone) & identify heat sources & heat sinks
Extract stream data
Average versus Peak Design Heat Flows
## Extract Stream & Screen Data

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A = 60% time, B = 40% time
HRL Design Methodology

1. Integrate zones or areas
2. Determine most common production state
3. Extract and screen stream data
4. Draw CC using shifted temps
5. Select number of HST
6. Shift CC until pinch occurs
7. Remove streams with no HR
8. Generate more options (Yes/No)
9. Decide HST Temps for best option
10. Design HRL network (Yes/No Any other production states?)
11. Combine & relax networks for various production states
12. Estimate HR as function of storage size
13. Estimate costs / economics
Inter-plant process Composite Curves

![Composite Curves Diagram]

- $Q_R = 0 \text{ kW}$
- $Q_{c,\text{max}} = 179 \text{ kW}$
- $Q_{h,\text{max}} = 238 \text{ kW}$
Two Tank Case – Selecting Storage Temp

- Tank 1
- Tank 2

Q_R = 24 kW

H1 not on HRL

HST 1

HST 2

Example HRL System

Diagram showing temperature changes and energy inputs for two tanks.
Two Tank Case – Selecting Storage Temp

![Diagram](image-url)

- **Tank 1**
- **Tank 2**

- **Limiting TS for hot HST**

- **$Q_R = 30 \text{ kW}$**

- **Diagram Description:**
  - The diagram illustrates the relationship between storage temperature ($T^*$) and energy difference ($\Delta H$) for two tanks.
  - The limiting temperature for hot HST is indicated.
  - Points A, B, C, and D are marked on the graph, showing the transitions between different operational states.
  - Tank 1 and Tank 2 are depicted with specific temperature ranges.
Two Tank Case – Selecting Storage Temp

![Diagram showing two tanks and heat transfer curves]

- **Tank 1**
- **Tank 2**

- **$Q_R = 47 \text{ kW}$**

- Points A, B, C, D

- C3 not on HRL

- Graph shows heat transfer rates against temperature and power difference.
Two Tank Case – Selecting Storage Temp

![Diagram showing Two Tank Case with Tank 1 and Tank 2 highlighted.](image-url)
Two Tank Case – Selecting Storage Temp

- $Q_R = 89 \text{ kW}$
- $mc_{p,\text{min}} = 8.9 \text{ kW/°C}$

![Graph showing Two Tank Case with Tank 1 and Tank 2 highlighted]
Selection of Streams & Storage Temp.

Streams included on HRL

- H3, H4, C1
- H1, H3, H4, C1
- H1, H3, H4, C1, C3
- H1, H2, H3, H4, C1, C3

HST temperature (°C)

Q_R (kW)

- Hot min/max
- Cold min/max
Multi Tank Cases – Selecting Storage Temp

1. $Q_r = 89 \text{ kW}$
   - 3 tank HRL system
   - 3 Tanks

2. $Q_r = 115 \text{ kW}$
   - 3 tank HRL system
   - 3 Tanks

3. $Q_r = 148 \text{ kW}$
   - 4 tank HRL System
   - 4 Tanks

4. $Q_{r, \text{max}} = 150 \text{ kW}$
   - 5 tank HRL system
   - 5 Tanks
HRL Design Methodology

**HRL Network & HX Area Design**

Design flow rates used

1. **Integrate zones or areas**
2. **Determine most common production state**
3. **Extract and screen stream data**

**HRL Design Flow Rates Used**

1. **Draw CC using shifted temps**
2. **Select number of HST**
3. **Shift CC until pinch occurs**
4. **Remove streams with no HR**
   - **Generate more options**: Yes
      - **Decide HST Temps for best option**
   - **No**
   - **Combine & relax networks for various production states**
5. **Remove storage pinch stream**
6. **Design HRL network**
   - **Yes**
     - **Any other production states?**: No
   - **No**
7. **Estimate HR as function of storage size**
8. **Estimate costs / economics**
HRL Heat Exchange Network – State A

Hot Streams (4 Sources)

Cold Streams (3 Sinks)

Ave CP
H1 (0.85 kW/K°C)
H2 (9.00 kW/K°C)
H3 (0.26 kW/K°C)
H4 (0.53 kW/K°C)

Cold Streams
C1 (0.85 kW/K°C)
C2 (1.80 kW/K°C)
C3 (3.38 kW/K°C)

HOT STREAMS

COLD STREAMS

THREE STORAGE TANKS

HST 3 115°C
HST 2 95°C
HST 1 85°C

HX units = 9
U = 1 kW/m²·K°C
Σ A = 35.0 m²
Σ CP = 8.4 kW/K°C
Ave. Q_R = 115 kW

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HRL Heat Exchange Network – State B

**HOT STREAMS (3 Sources)**

- **H2** (9.00 kW/°C) to 100 kW
- **H3** (0.26 kW/°C) to 165 kW
- **H4** (0.53 kW/°C) to 165 kW

**COLD STREAM (1 Sink)**

- **C2** (1.80 kW/°C) to 70 kW

**TWO STORAGE TANKS**

- **HST 3** (150°C)
- **HST 2** (135°C)

**HX units = 3**

- **U = 1 kW/m²°C**
- **Σ A = 24.0 m²**
- **Σ CP = 1.3 kW/°C**
- **Ave. Q_R = 20 kW**

**Ave CP**

- **H2** (9.00 kW/°C)
- **H3** (0.26 kW/°C)
- **H4** (0.53 kW/°C)

**HE Area**
HRL Heat Exchange Network – State A + B

**HOT STREAMS (3 Sources)**

- H1 (0.85 kW/°C) 135
- H2 (9.00 kW/°C) 100
- H3 (0.26 kW/°C) 165
- H4 (0.53 kW/°C) 165

**State B**

- HST 3
  - A: 115°C
  - B: 150°C
- HST 2
  - A: 95°C
  - B: 135°C
- HST 1
  - A: 85°C

**COLD STREAM (1 Sink)**

- C1 (0.85 kW/°C) 25
- C2 (1.80 kW/°C) 130
- C3 (3.38 kW/°C) 80

**HX units = 7**

- $U = 1 \text{ kW/m}^2 \text{ °C}$
- $\Sigma A = 46.0 \text{ m}^2$
- Ave. $Q_R = 74 \text{ kW}$

**Ave CP**

- H1 (0.85 kW/°C)
- H2 (9.00 kW/°C)
- H3 (0.26 kW/°C)
- H4 (0.53 kW/°C)

**HE Area**

- 15
- 95
- 125
- 125
HRL Design Methodology

Integrate zones or areas

Determine most common production state

Extract and screen stream data

Draw CC using shifted temps

Select number of HST

Shift CC until pinch occurs

Remove streams with no HR

Generate more options

Yes

No

Decide HST Temps for best option

Design HRL network

Yes

Any other production states?

No

Dynamic Modelling

Combine & relax networks for various production states

Estimate HR as function of storage size

Estimate costs / economics
Spreadsheet Optimisation Tool

<table>
<thead>
<tr>
<th>HRL Input</th>
<th>Results</th>
<th>Cost</th>
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<td>150 m²</td>
<td>Q_H 6878 kW</td>
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<tr>
<td>V_i</td>
<td>75 m²</td>
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<td>TT Cold</td>
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<td>T_F 48 °C</td>
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<td>19.4 °C</td>
<td>T_F 9.4 °C</td>
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<td>Cycle 2880 min</td>
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<tr>
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<td>ΔT_min</td>
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<td>ΔT_max</td>
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<td>Darcy</td>
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Solve Temps

Storage temperature (°C) vs Time (mins)

Hot storage (m³)

Cold storage (m³)

Utility Use

Heat Recovery

Hot IN

Cold IN

Real time tank

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<tr>
<th>Time (min)</th>
<th>CP Pro</th>
<th>T1 Pro</th>
<th>T2 Pro</th>
<th>ΔQ</th>
<th>Cp Loop</th>
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Storage Levels & Annual Heat Recovery

(a) Storage levels over time for HST1, HST2, and HST3.

(b) Yearly average heat recovery Q_r vs. total oil storage volume.

State A+B
Cost optimisation of storage tank size

Minimum cost
3 HSTs of 25 m³

Total cost
Storage cost
Utility cost

Cost [$/y]

Total oil storage volume [m³]

0 25 50 75 100 125 150
Case Study: Area Targeting of HRL
# Extract Stream & Screen Data

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<thead>
<tr>
<th>Stream</th>
<th>$T_s$ [°C]</th>
<th>$T_t$ [°C]</th>
<th>$CP$ [kW/°C]</th>
<th>$Q$ [kW]</th>
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<td>H1</td>
<td>43</td>
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<td>H2</td>
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<td>C3</td>
<td>16</td>
<td>55</td>
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Inter-plant process Composite Curves

\[ Q_c = 648 \text{ kW} \]
\[ Q_h = 758 \text{ kW} \]
Maximum heat recovery using HRL

\[ Q_r = 366 \text{ kW} \]

\[ Q_c = 281 \text{ kW} \]

\[ Q_h = 392 \text{ kW} \]

**TWO STORAGE TANKS**
Apparent versus actual HX driving force

![Diagram showing hot and cold process streams with energy exchanges.](image)

[Diagram legend: H1, H2, H3 for hot process streams; C1, C2, C3 for cold process streams. Graph showing temperature difference and actual/ apparent driving force.]
Area Targeting Methods

• $dT_{\text{min}}$ method
  • Provides insight to the design
  • Defines the storage temperature levels and loop flow rate
  • Areas and HR result from $dT_{\text{min}}$ choice (1 DoF)

• Global area optimisation for average state
  • 6 heat exchanger areas and 2 storage temperatures
  • 8 DoF

• Global area optimisation with constant NTU or LMTD
  • 1 NTU or LMTD and 2 storage temperatures
  • 3 DoF
HR versus Total Area

Indirect heat recovery limit

Design method

- \( \Delta T_{\text{min}} \)
- Global
- NTU
- LMTD

\( Q_r \ [\text{kW}] \)

\( A \ [\text{m}^2] \)
HX Area Design Method

\[ \Delta T_{\text{min}} = 5 \, ^\circ C \]

- LMTD method
- ΔT_{\text{min}} method
- NTU method

Additional area vs. \( Q_r \) [kW]
Conclusions

• Stream and storage temperature selection is important
• Need to Optimise Heat Recovery / Area Trade-off to Maximise Savings
• $dT_{min}$ method is effective and simple to apply
• Global optimisation of areas and temp selection can improve HR savings (same area) by 5%
• Dynamic modelling provides effective means for sizing storage capacity and predicting actual HR
Thank You

Questions?