Pinch Analysis of an Industrial Milk Evaporator with Vapour Recompression Technologies

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Overview

1. Personal Introduction
2. Technical Topic Introduction
3. Dairy Processing Complications
4. Milk Evaporators with Vapour Recompression
5. Conclusions
New Zealand

Congratulations! You’ve made it over half-way to NZ from Europe.
New Zealand Geography – Many Mountains

75% of NZ is mountainous or hilly, numerous volcanoes and lakes
New Zealand’s Population
4.5 million people, with 1.2 million in Auckland
University of Waikato – Est. 1964
Our Team’s Research Philosophy

• Focus on meaningful research for industry

• Deliver engineering solutions

• Work with industrial producers & suppliers

• Influence industry best practice / standards
TECHNICAL TOPIC INTRODUCTION
New Zealand’s Major Industries

National Economy GDP approx. US$182 billion/yr

- Tourism #1 industry!!!
- Dairy, Meat, Wine & Fruit
- Forestry, Wood, Panels
- Pulp & Paper
- Agri-Biotechnology
- Aquaculture & fisheries
- Aluminium, Steel & Plastics
- Energy, Gas & Petrochemical
- Machinery & SS fabricators
- Electronics & Software
- Higher education
- Film production & arts
New Zealand Exports

Milk Powder >75%

Dairy, 23%
$12 Billion

Other, 18%
Petroleum, 4%
Wood, 6%
Metals, 12%
Meat, 13%
Other Agriculture, 18%

Pulp & Paper, 3%
Fish, 3%
Process Heat Use in NZ Dairy

Fuel Supply
Coal & N.G. Fuel Input: 32.1...
Boiler Losses: 6.4...
Powder: 19.3...
Cheese: 2.9...
Butter: 3.5...
Conversion Losses
MP Process Demand
Milk Powder Production
- The Largest Energy Sink

Multi-effect evaporators
Steam
Treated milk
Concentrated milk
Spray dryer & fluidised beds
Powdered milk

10% solids
52% solids
96% solids

Condensed water 64°C
Vapour 54°C
Warm, humid air 75°C
Highly Integrated Milk Treatment / Evaporator
New Zealand WMP/SMP Plants: Specific Fuel Use

Performance of NZ Milk Powder Plants

Current Best: Built 2014
Goal -30% <3.5 GJ/f/t

How can we “break” the 5.2 GJ/t_p barrier?
PINCH ANALYSIS & TOTAL SITE OF DAIRY PROCESSING: COMPLICATIONS
Seasonal, Variable Milk Supply

Oct - Nov

% Max Site Production

Weeks

Winter

Summer

Autumn

Winter

June

July

Winter

Spring
Semi-continuous Plant Operation

- Streams vary in both Temperature and Flowrate
- Unsteady due to many factors:
  - Production rate changes & variations
  - Regular cleaning
  - Multiple plants
Distance
Fouling, Hygiene, Product Quality

- Tight residence time, temperature and humidity control needed
Culture: Why Change?
Identifying Viable Industrial Solutions

• Problems:
  1. Variable milk supply, semi-continuous operation, distance
  2. Product quality
  3. Culture

• Solutions (not exhaustive):
  1. Prioritise direct integration within plants
     Indirect integration between plants
  2. Continuing dialogue with industry and suppliers
  3. Focus on industries’ needs (not your academic needs only)
INTEGRATION OF MILK EVAPORATOR SYSTEMS
Today’s Focus: Milk Evaporator System

- **Multi-effect evaporators**
  - Steam
  - **Treated milk**
    - 10% solids
  - **Concentrated milk**
    - 52% solids

- **Spray dryer & fluidised beds**
  - Steam
  - **Powdered milk**
    - 96% solids

- **Condensed water**
  - 64°C
- **Vapour**
  - 54°C
- **Warm, humid air**
  - 75 °C
General Analysis Methods / Concepts

• Develop mass and energy balance model of the milk powder plant for the latest builds (~30 t\textsubscript{p}/h plant)

• Apply Pinch Analysis / Total Site concepts to identify areas for energy savings
  • Minor impact on process – focus on energy recovery network
  • Major impact on process – what is possible for energy reduction?

• Questions needing answers
  • What are the process specific requirements? esp. product related requirements.
  • What other challenges will face implementation?
Pinch Concepts: Evaporator Integration
Traditional vs Vapour Recompression

(a) 4-effects above pinch

(b) 2-effects above pinch with TVR
Integrated Vapour Recompression Technologies

Mechanical vs Thermal

• More utility (enthalpy) input → more low grade “waste” heat out: Vapour flows (i.e. bleed, condenser), Condensate

• TVR adds 10 – 20 times more enthalpy than MVR
## Specific Cost Analysis of MVR and TVR

<table>
<thead>
<tr>
<th>Recompression Method</th>
<th>COP ($GJ_{evap} / GJ_{ut}$)</th>
<th>Cost$<em>{gross}$ ($/t</em>{evap}$)</th>
<th>Potential $q_{HR}$ ($GJ_h / t_{evap}$)</th>
<th>Cost$<em>{net(best)}$ ($/t</em>{evap}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-effect TVR</td>
<td>3.5</td>
<td>$4.19 /t_{evap}$</td>
<td>0.671</td>
<td>$0.00 /t_{evap}$</td>
</tr>
<tr>
<td>2-effect TVR</td>
<td>5.0</td>
<td>$2.94 /t_{evap}$</td>
<td>0.470</td>
<td>$0.00 /t_{evap}$</td>
</tr>
<tr>
<td>1-effect MVR</td>
<td>50.0</td>
<td>$0.91 /t_{evap}$</td>
<td>0.047</td>
<td>$0.62 /t_{evap}$</td>
</tr>
</tbody>
</table>
Current Evaporator HEN Design

Evaporation: 90% MVR effect / 10% TVR effect
Process Constraints for Milk Preheat

Milk Heat Treatment (before evaporators) significantly affects powder’s functional properties

• Constraints:
  • High thermophile growth, 45 – 65 °C
  • Heat exchanger fouling issues, 65 – 80 °C
  • Tight residence time at heat treatment temperatures > 80°C

• Industrial Solutions:
  • Direct vapour contact heaters
  • Duplicate heat exchangers – plate HX or shell & tube HX
Evaporator Plant: Composite Curves
-Internal Evaporation / Condensation Removed

MVR and TVR Utility Use
\[ Q_{ele,MVR} = 2.1 \text{ MW} \]
\[ Q_{h,TVR} = 2.8 \text{ MW} \]

\( \Delta T_{\text{min}} = 1 \text{ °C} \)
\( Q_{h,savings} = 0.6 \text{ MW} \)

Milk Flash
Vapour Bleed
Condenser
Current Set-up
Pinched with Current Set-up

\( Q_{\text{export}} = 1.6 \text{ MW} \)
Initial Pinch Analysis Results

• Additional heat recovery is constrained to 0.6 MW
  - Pinch Temperature = 80 °C
  - High temperature milk flash prevents more heat recovery
  - BUT, direct vapour contact >80 °C = process constraint

• What process changes can yield energy reduction?
  - Change evaporator pressures?
  - Change the way milk is preheated below 80 °C?
  - Change vapour upgrade technology?

• Let’s understand evaporators integrated with vapour recompression
Evaporator Plant: Grand Composite Curve

- \( Q_{h,\text{target}} = 3.5 \, \text{MW} \)
- \( Q_{c,\text{target}} = 4.8 \, \text{MW} \)
- \( Q_{\text{export}} = 1.6 \, \text{MW} \)
Evaporator Plant: Grand Composite Curve
-Excess Evaporation / Condensation Plotted

- Milk flash
- Vapour bleed (MVR)
- Condenser (TVR)

$q_{h,\text{target}} = 3.5 \text{ MW}$
$q_{c,\text{target}} = 4.8 \text{ MW}$
($q_{\text{export}} = 1.6 \text{ MW}$)
Evaporator Plant: Grand Composite Curve - Thermal Vapour Recompression

- Incorrect TVR placement
  - "Heat Pump"

- TVR Effect
  - TVR 1 DSI
  - TVR 2 DSI

- Upgraded Vapour

- MVR Effect

- $Q_{h, target} = 3.5 \text{ MW}$

- $Q_{c, target} = 4.8 \text{ MW}$
  - $(Q_{\text{export}} = 1.6 \text{ MW})$

- Replace with MVR effect
Evaporator Plant: Grand Composite Curve
-Other “Heat Pump” Application

Correct “Heat Pump” placement

Steam

$Q_{h,\text{target}} = 3.5 \text{ MW}$

$Q_{c,\text{target}} = 4.8 \text{ MW}$

($Q_{\text{export}} = 1.6 \text{ MW}$)

MVR Effect

TVR Effect

TVR 1 DSI

TVR 2 DSI

Upgraded Vapour

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How to Further Reduce Steam Use in the Evaporator Plant

1. Use TVR combined with Direct Steam Injection (DSI) for final milk pre-heat, >80 °C
   - Reduces net DSI steam usage

2. Integrated all effect(s) with MVR
   - Eliminates TVR effect
   - Thermal energy replaced by electricity in a cost effect way
   - Reduces emissions – highly renewable electricity in NZ

3. Optimise evaporator pressures / temperatures for improved heat recovery and product quality
1. TVR / DSI Milk Pre-heat System

- Energy efficient system design suggested by GCC
  - but requires more capital: energy-capital trade-off

- Steam reduction of 1.7 MW compared to evaporator current design
- Milk feed temperature to the evaporator decreases by 7°C, i.e. less flashing
2. Integrate All Effects using MVR

- MVR inputs less “enthalpy”, therefore less “waste” heat for preheating dryer airflows
  - Vapour bleed / condenser loads are significantly reduced

- Effective use of TVR requires:
  - Cascading of heat to low temperature sinks (currently dryer airflows)
  - But, other heat sources are available (dryer exhaust, refrigerator cond.)

- Simple: specific net cost of MVR is much lower TVR
  - Incorrect “placement” of a thermocompressor
  - Long-term operational energy costs outweigh capital savings
3. Optimise Evaporator Temperatures

- $T_{\text{evap}}$ of 1$^{\text{st}}$ effect is very important for heat recovery
  - The vapour bleed temperature from 1$^{\text{st}}$ effect defines a key “ceiling” for heat recovery in the milk pre-heat system
  - Current temperature of 1$^{\text{st}}$ effect is 65°C (tube-side); other plants successfully run at 68°C – better for heat recovery

- MVR work is minimised at higher $T_{\text{evap,sat}}$.
  - Upper temperature constraint, as above

$$W_{\text{comp}} \approx \dot{m}_{\text{evap}} \frac{k}{k-1} \left( \frac{RT_{\text{evap}}}{\eta_o} \right) \left( \frac{P_{\text{cond}}}{P_{\text{evap}}} \right)^{\frac{k-1}{k}} - 1$$
New Grand Composite Curves

Evaporator Effects Integrated with: Combination of MVR / TVR effects

A

\[ Q_{\text{vap}} = 1.7 \text{ MW} \quad Q_{h,\text{target}} = 2.3 \text{ MW} \]

\[ Q_{e,\text{ele}} = 0.3 \text{ MW} \]

B

\[ Q_{\text{vap}} = 3.0 \text{ MW} \quad Q_{h,\text{target}} = 0 \text{ MW} \]

\[ Q_{e,\text{ele}} = 0.3 \text{ MW} \]
New Grand Composite Curves

Evaporator Effects Integrated with:
Both MVR effects

\[ Q_{vap} = 2.2 \text{ MW} \]
\[ Q_{h,\text{target}} = 2.0 \text{ MW} \]
\[ Q_{c,\text{target}} = 0 \text{ MW} \]
New HEN Design using Pinch Concepts

- PHE (Duplicate) 14.5 MW
- Cow (3) To Cond. 35 t/h
  - Whole Milk 8 232 t/h
  - 13 218 t/h
  - 70 150 t/h

- Cow (2) From Cond. 239 t/h
  - 3.4 t/h

- MVR 1 Eff. 2.0 MW
  - 70 kW

- MVR 1 Eff. 3.7 t/h
  - 70 kW

- IP Steam 3.5 t/h
- HW84, 1.0 MW (1.5 t/h steam)

- CIP Water 1.3 MW

- Concentrate To Dryer
- TT 150 t/h
- 33 t/h
- 35 t/h

- Cow (3) To Cond.
- Cow (1) 3.7 t/h

- Cow (2) From Cond.
- 35 t/h

- Cow (1) To Cond.
- COW (1) To Cond.

- 183 t/h

- 70 kW
Impacts on the Site-wide Energy Balance

• Steam reduction of 6.4 MW (0.82 GJ/t), in exchange for 0.6 MW extra electricity
  • Net energy cost reduction, in trade-off with increased capital
  • Emissions reduction: New Zealand electricity is 80% from renewable energy sources

• Boiler makeup water substantially decreases
  • DSI in the evaporator plant decreases by 9.7 t/h
  • Higher per cent condensate return, higher boiler efficiency
Impacts on the Site-wide Energy Balance

• Dryer exhaust heat needed for minimum energy site
  • Direct integration with dryer inlet air: 4 MW of heat
  • Refrigeration heat recovery also possible; need increased refrigerator condenser temperature
  • Other intermittent sinks may also be viable with indirect integration: e.g. CIP water, milk recon., tank wash water, etc.

• Potential thermal energy consumption: <3.5 GJ$_f$/t
  • Approx. savings = MYR ~4 M (US$1 M) for 30t/h plant
So, Can we achieve our energy target? YES, its feasible, but more to be done

How can the SEC of Milk powder production “break” the ~5 GJ/t\textsubscript{p} barrier?

Current Best: Built 2014
Goal -30% <3.5 GJ\textsubscript{f}/t

Need dryer heat recovery

Performance of NZ Milk Powder Plants
Summary

• Industry and process constraints / information formulated from multiple sources

• GCC identifies appropriate use of heat pumps; includes evaporators with vapour recompression

• Identified thermal energy reduction of 6.4 MW (electricity up 0.6 MW) = net energy cost reduction
Thank You!

Questions?