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Te Whare Wānanga o Waikato

Spray Dryer Exhaust Heat Recovery

A Techno-economic Assessment Model

Tim Walmsley, M Walmsley, M Atkins, J Neale

PRES 2014



Outline

Research Motive/Context

Overarching Goal

Review of Progress

Exhaust Heat Recovery Modelling

Conclusions

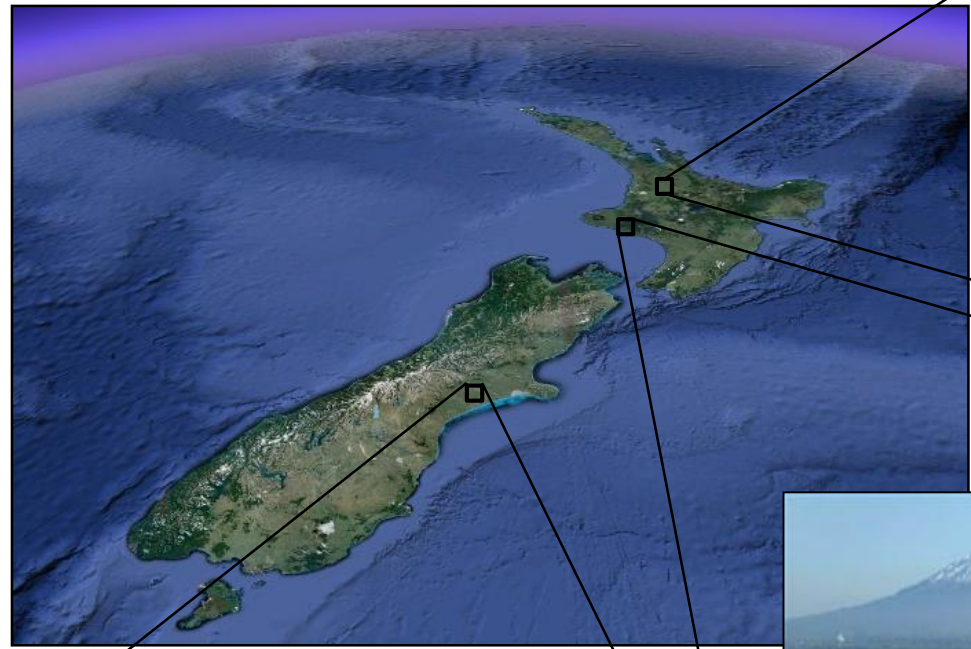




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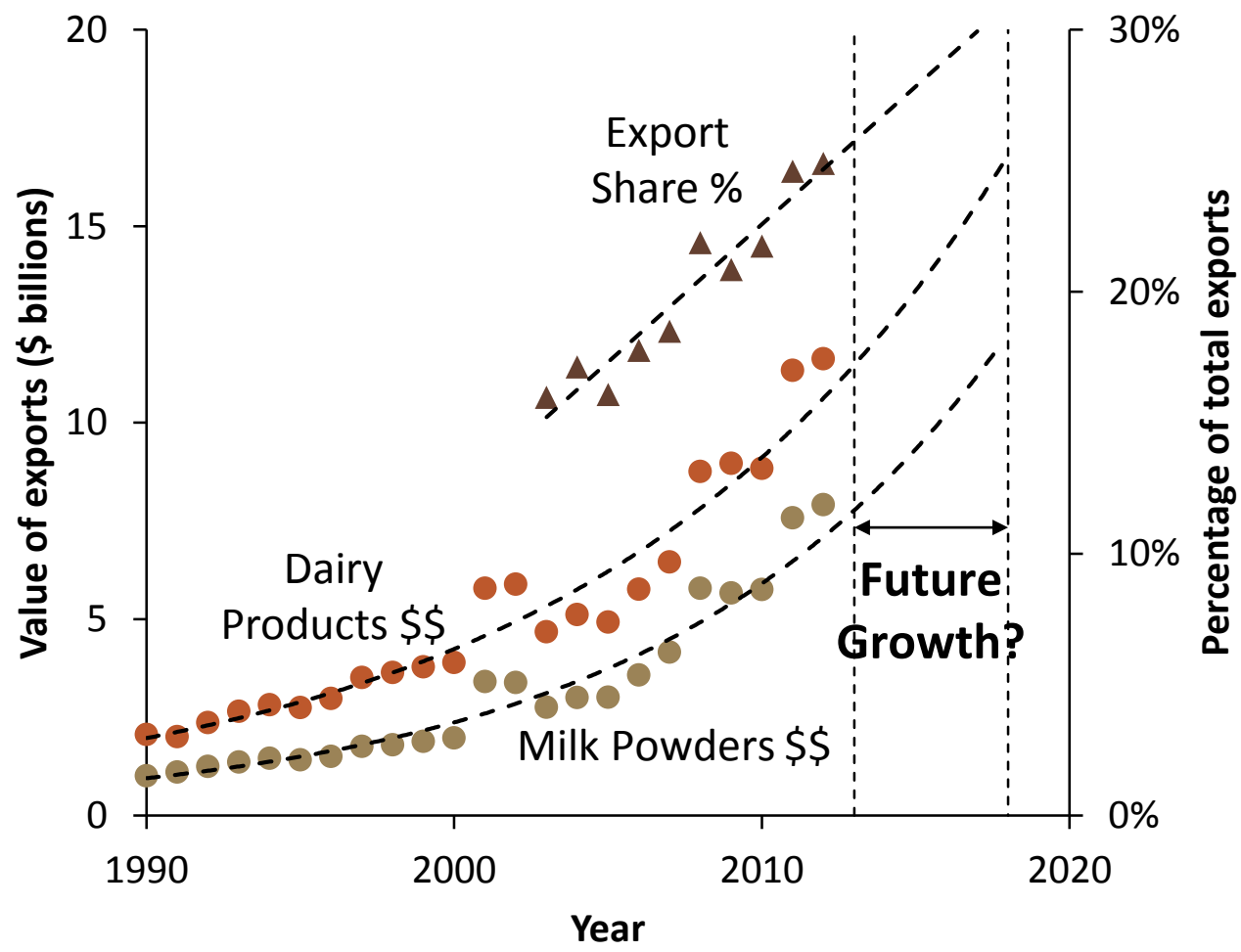
Dairy



Cows

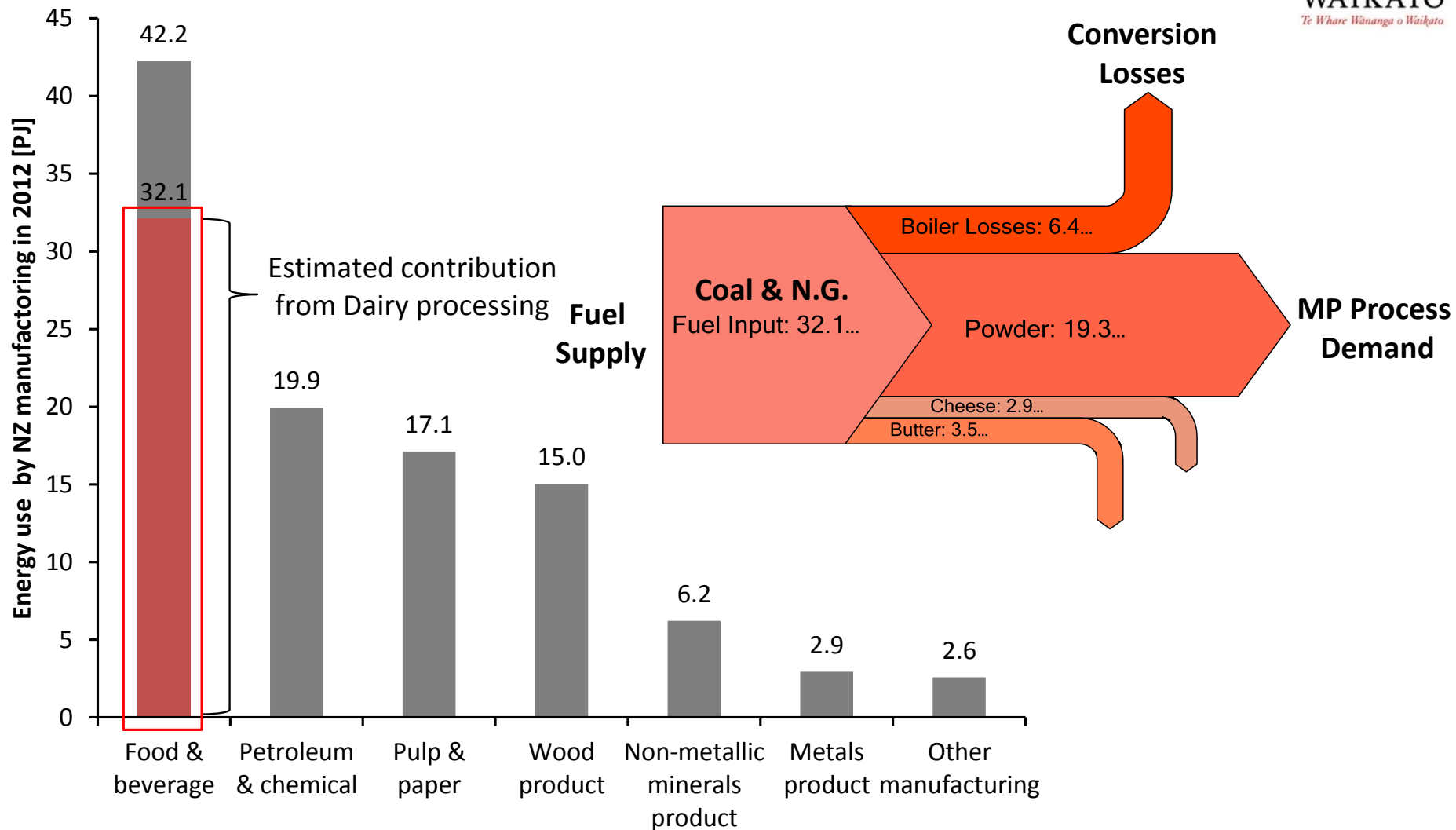


NZ Dairy Performance



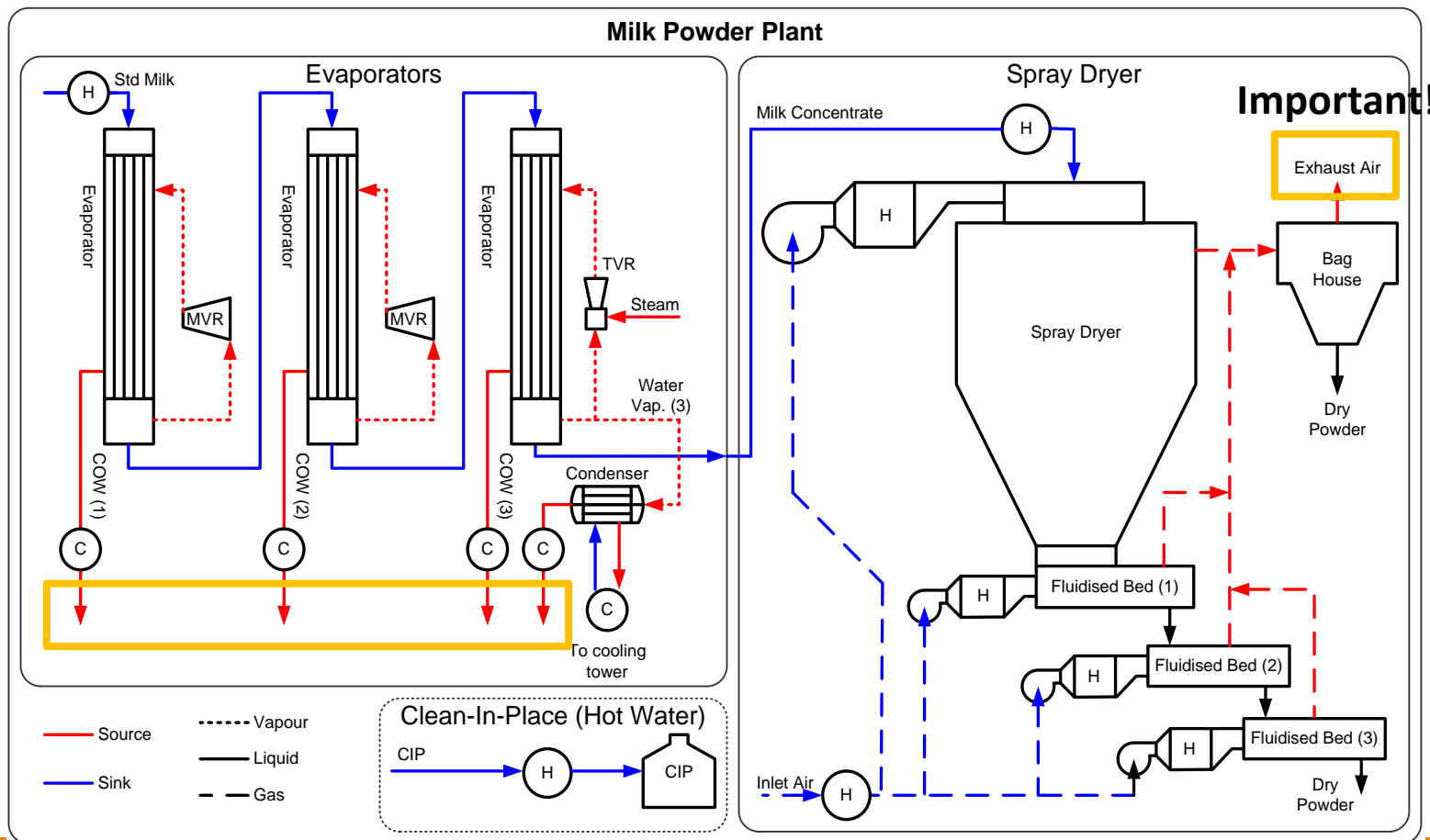


NZ Manufacturing Process Heat Use 2012



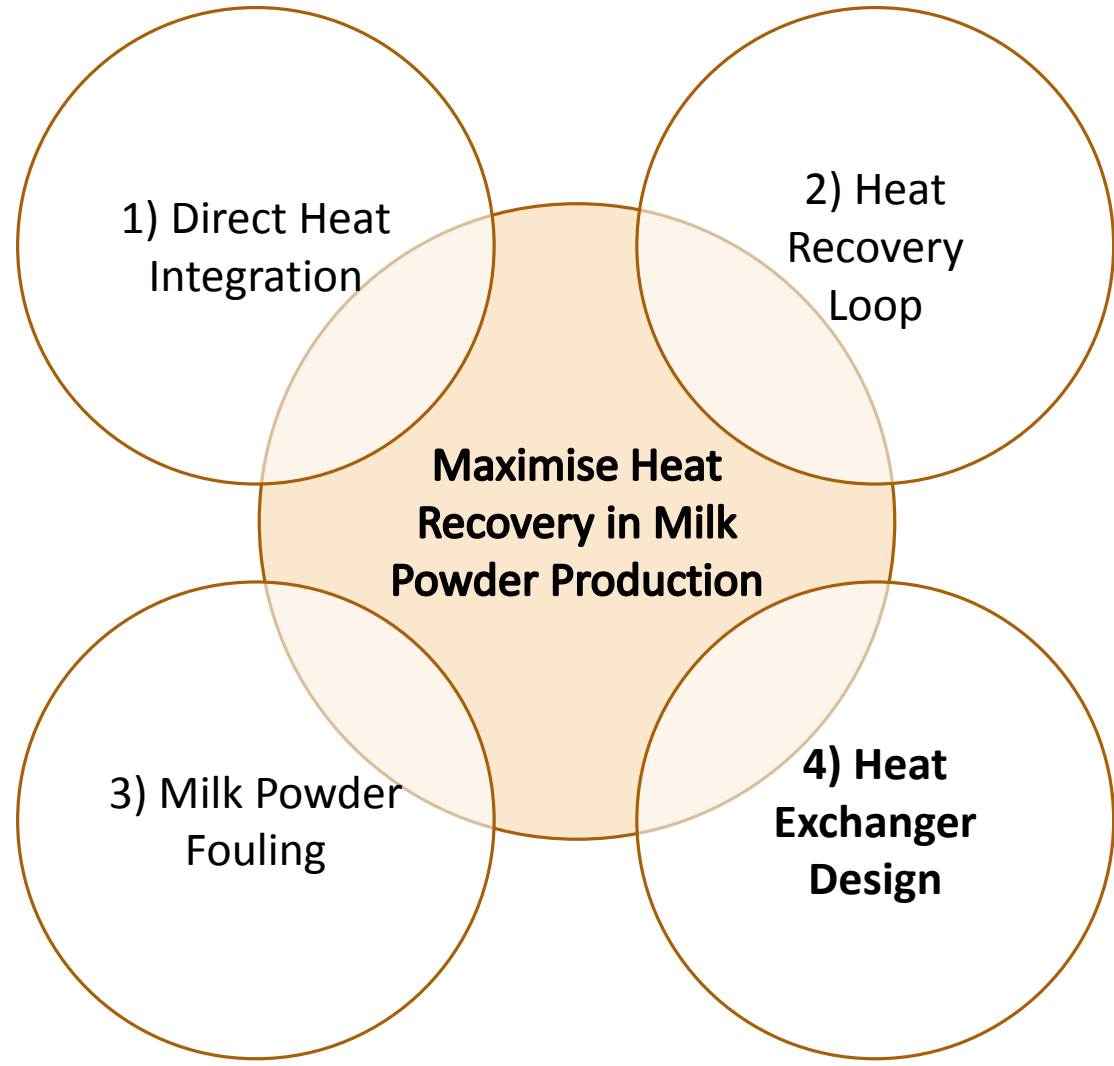
Milk Powder Production Utility Demands

Aim: To Investigate How to Maximise Economic Heat Recovery in Milk Powder Production?



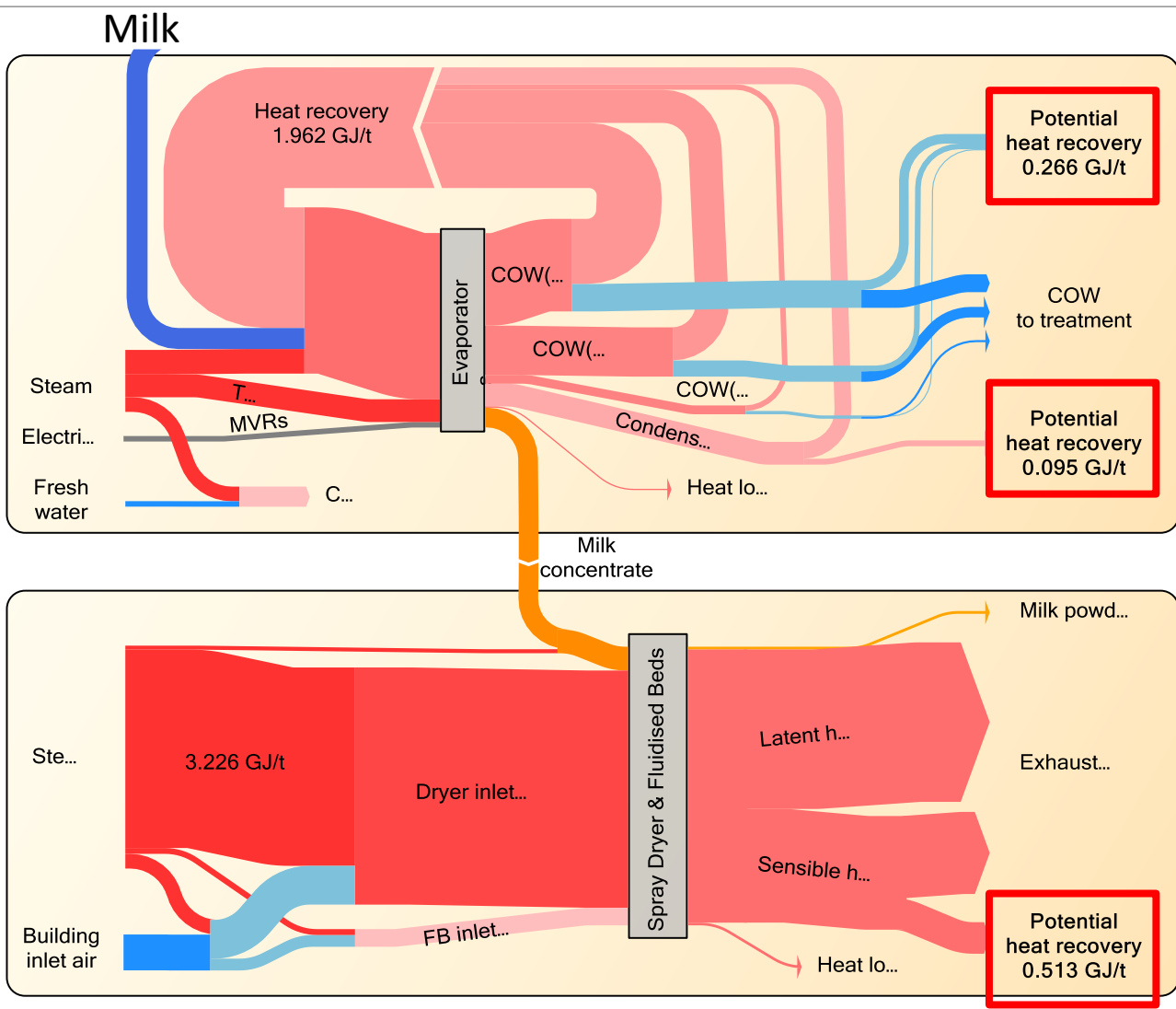


Progress to Achieving the Research Goal





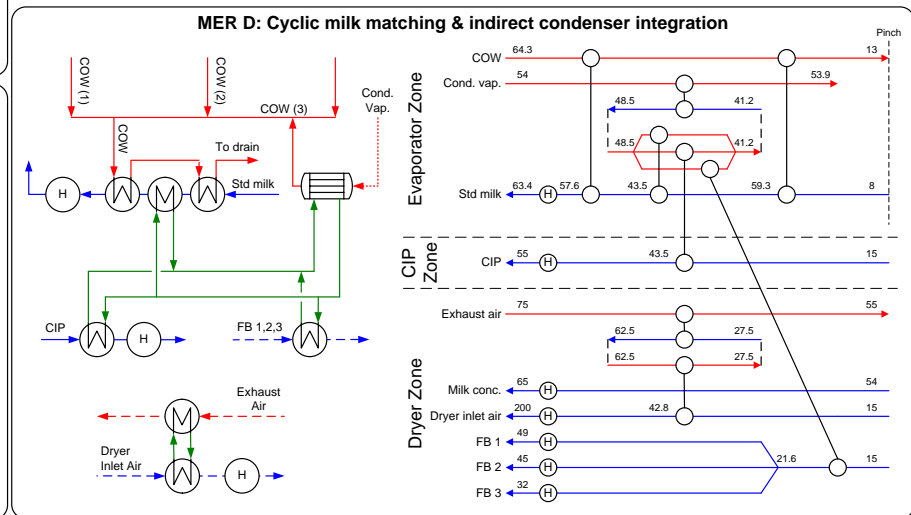
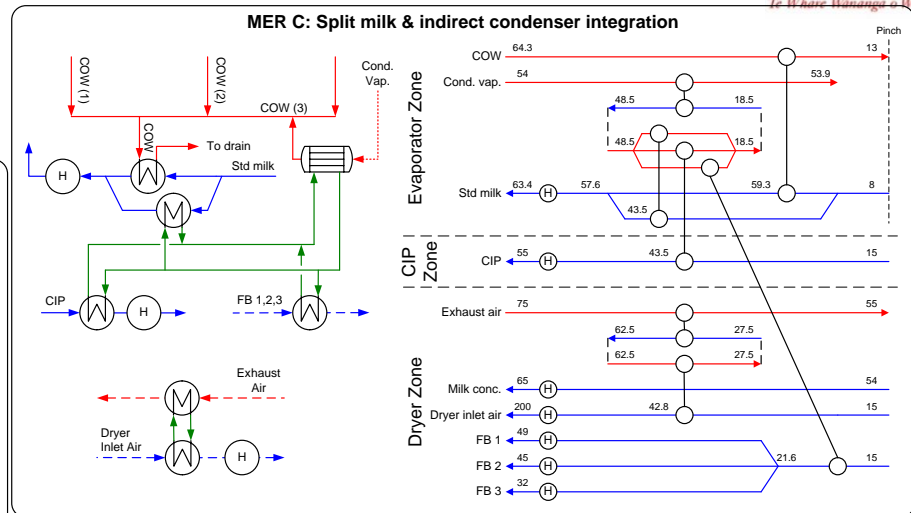
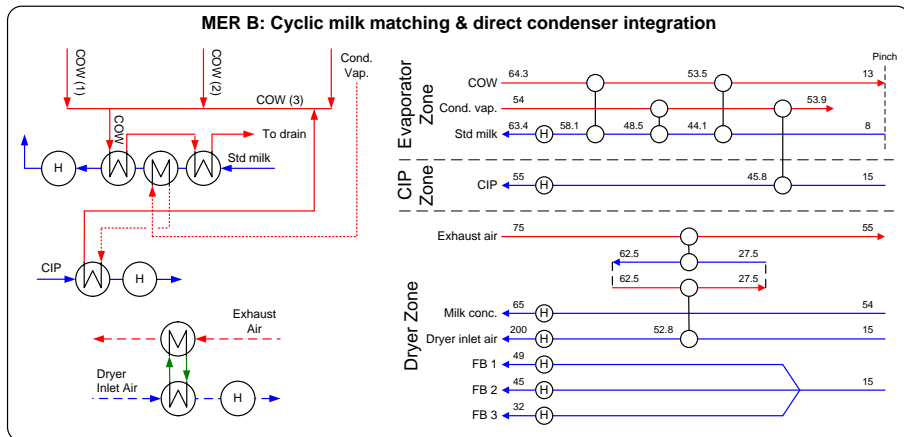
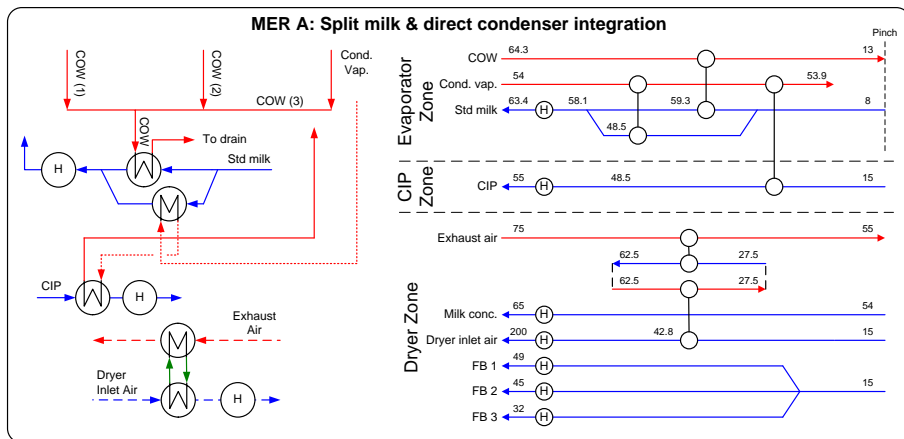
(1a) PDM Heat Integration Schemes (PRES'12)



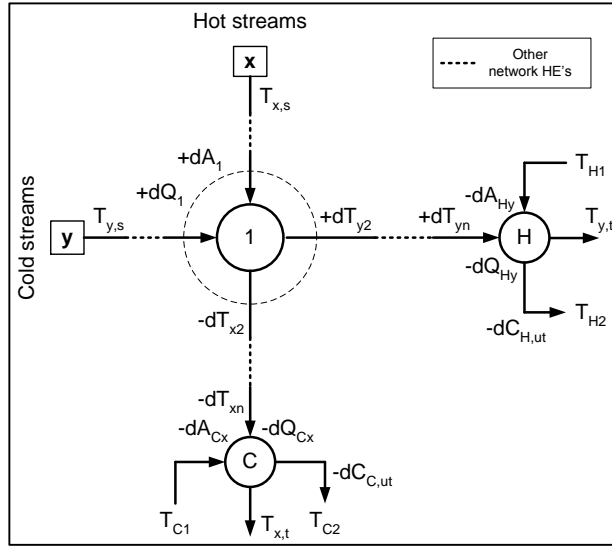


(1a) PDM Heat Integration Schemes (PRES'12)

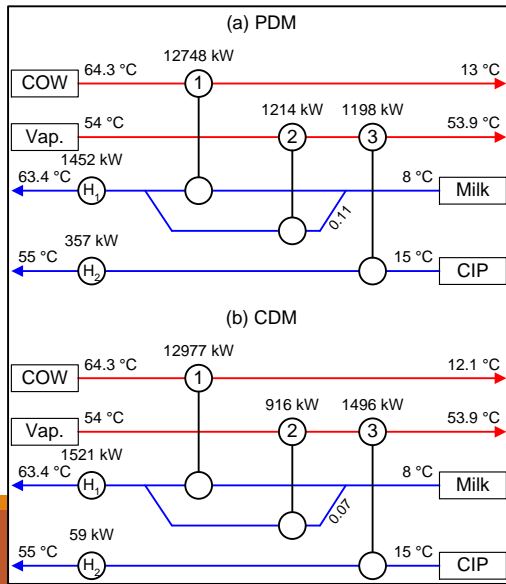
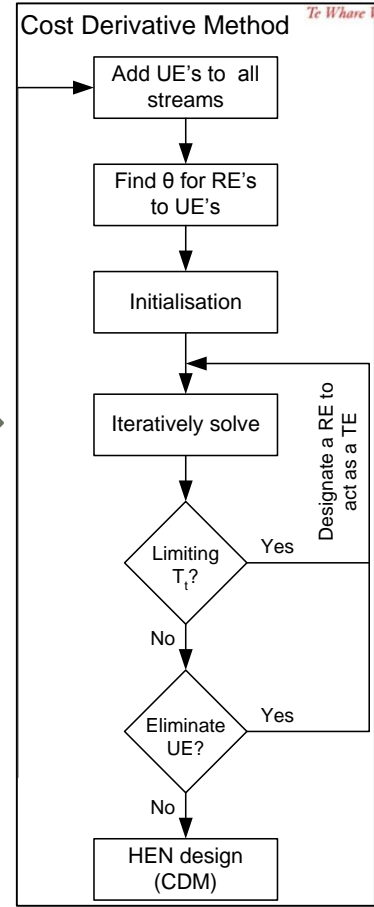
9 % Cost reduction,
30% Heat Recovery (HR) improvement



(1b) The Cost Derivative Method (PRES'13)



$$\frac{dTC}{dA_1} = \frac{dCC_1}{dA_1} + \sum \frac{dCC_{ut(i)}}{dA_1} - \sum \frac{dS_{ut(i)}}{dA_1}$$

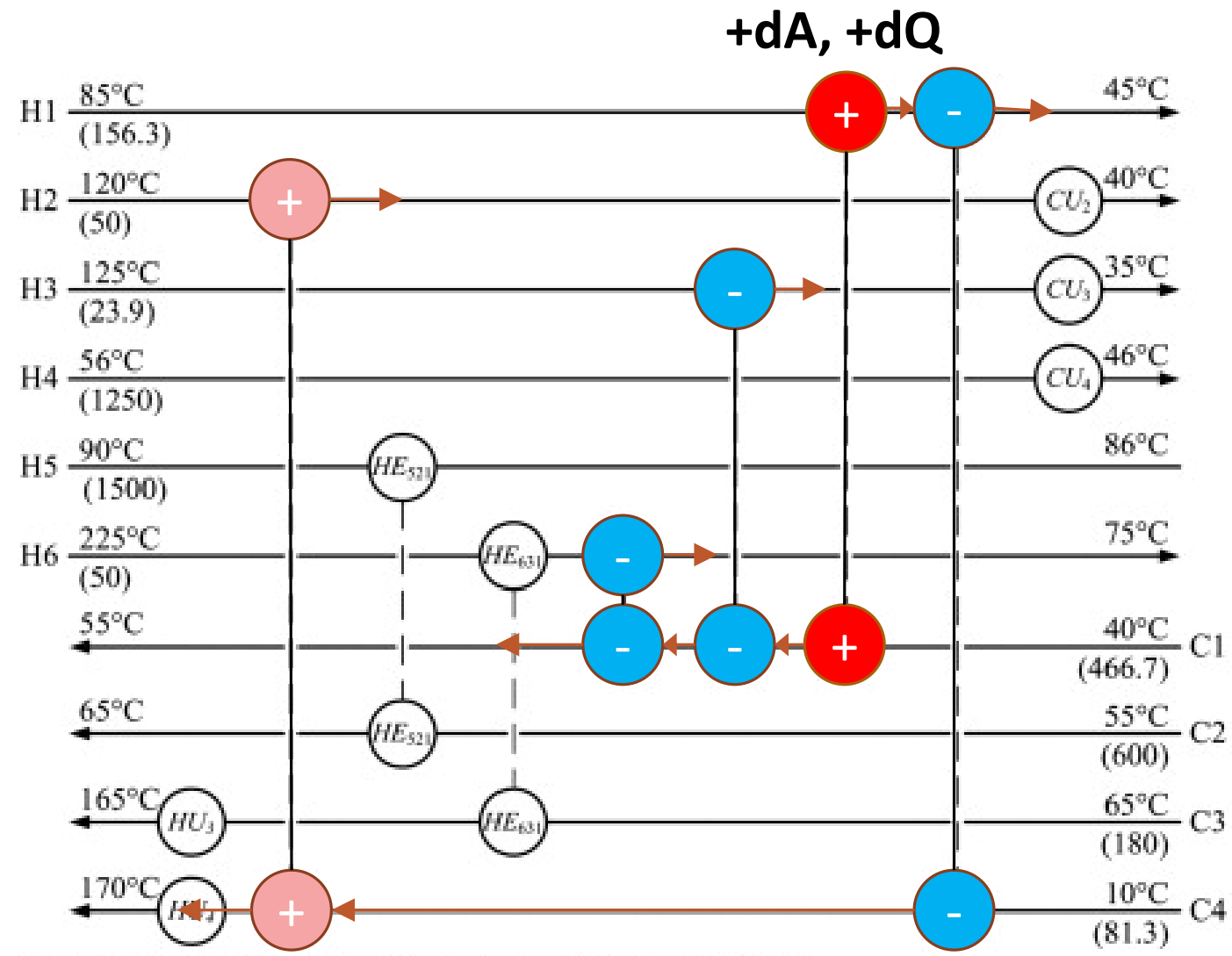


5 % Cost reduction

Stream Name	m ³ /h	T _{in} °C	T _{out} °C	Q _h kW	C* °C	NTU	ε	h kW/m ² °C	U °C	CC S/y	TC S/y	de/dNTU	dQ/dA	φ	θ	ds/dA	dC/dA		
100 H1 (1)	18.0	270.0	196.8	180.0	1338	0.360	2.3	0.841	0.500	0.25	166.57	38.905	38.905	0.11	2.4	220	0.33	174	174
101 C2 (2)	50.0	183.0	209.3	210.0	662	0.900	1.9	0.671	0.500	0.25	133.77	33.097	33.097	0.06	0.8	220	1.00	181	181
102 H1 (2)	20.0	142.0	175.1	210.0	1150	0.440	2.8	0.871	0.500	0.25	245.70	52.156	52.156	0.08	1.2	220	0.62	169	169
104 H2 (1)	50.0	180.0	183.0	210.0	662	0.900	3.1	0.781	0.500	0.25	247.31	52.458	52.458	0.06	1.9	220	0.40	169	169
106 H2 (2)	22.0	167.7	84.1	60.0	686	0.629	0.6	0.466	0.500	0.42	30.34	12.492	139.634	152.127					
107 C1 (1)	20.0	50.0	142.0	210.0	33	0.654	0.0	0.025	2.500	0.42	1.97	4.878	6.338	11.416					
108 H1	698.2	250.0	248.0	0	0.000	0.0	0.000	0.500	0.33	0.00	0	0	0						
109 C1 (3)	20.0	175.1	210.0	0	0.000	0.0	0.000	0.500	0.33	0.00	0	0	0						
110 HU	32.7	250.0	248.0	0	0.000	0.0	0.000	0.500	0.33	0.00	0	0	0						
111 C1 (3)	50.0	209.3	210.0	0	0.000	0.0	0.000	0.500	0.33	0.00	0	0	0						
112 H1 (3)	18.0	180.0	180.0	0	0.000	0.0	0.000	0.500	0.33	0.00	0	0	0						
113 CU	0.0	15.0	20.0	0	0.000	0.0	0.000	0.500	0.33	29.49	12.295	10.617	22.912						
114 H2 (3)	22.0	84.1	60.0	531	0.207	0.4	0.349	0.500	0.33	29.49	12.295	10.617	22.912						
115 CU	106.2	15.0	20.0	0	0.000	0.0	0.000	0.500	0.33	0.00	0	0	0						



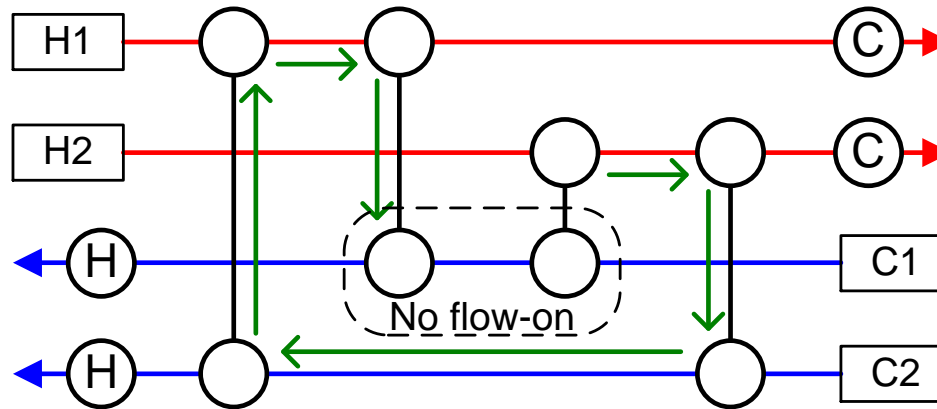
(1b) The Cost Derivative Method (PRES'13)



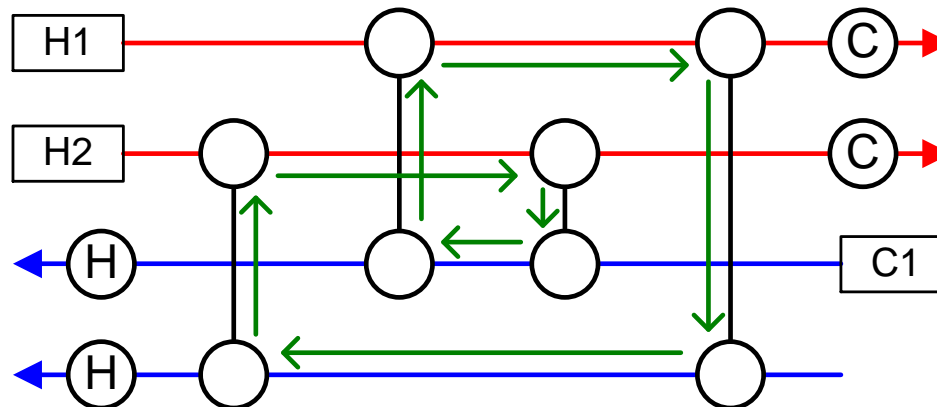
* The numbers within the brackets are heat content flows (kW/°C)

(1b) The Cost Derivative Method (PRES'13)

(a) Non-self-interacting open loop

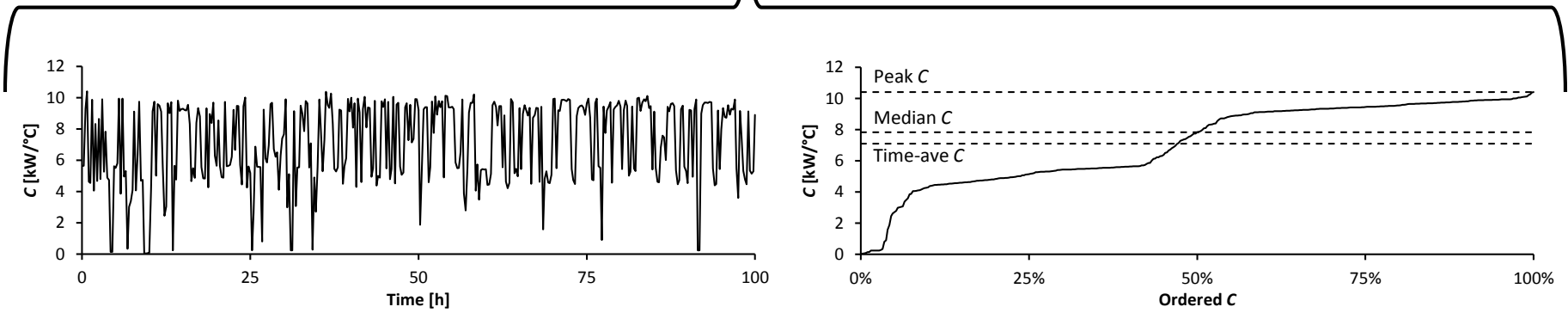
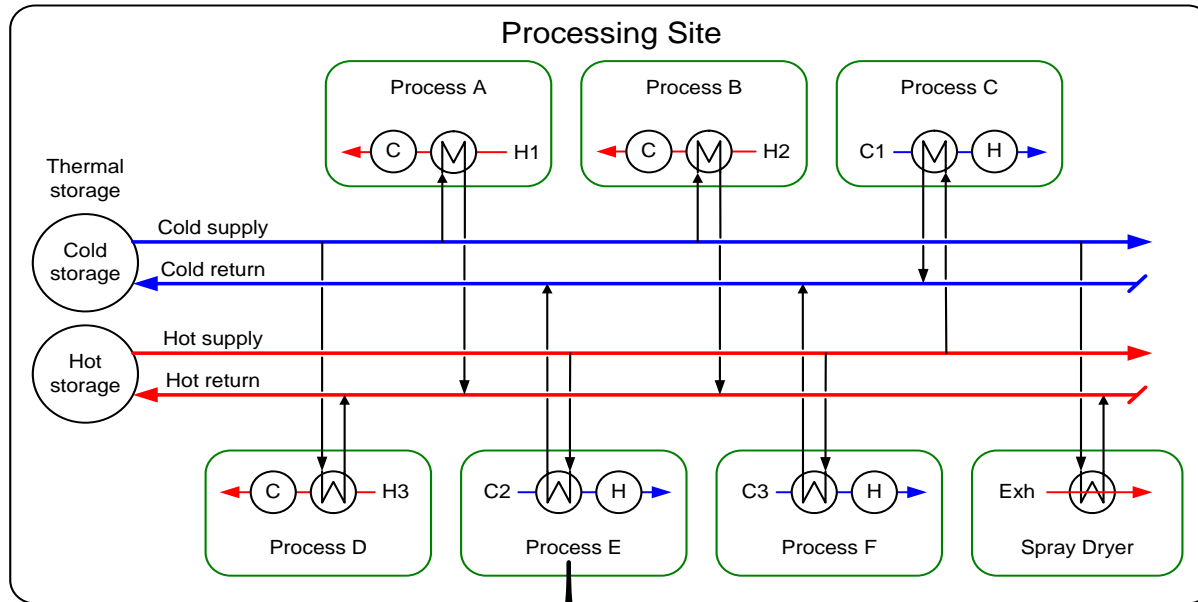


(b) Self-interacting closed loop



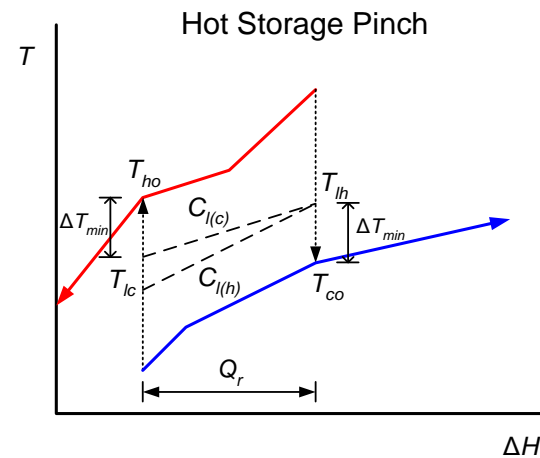
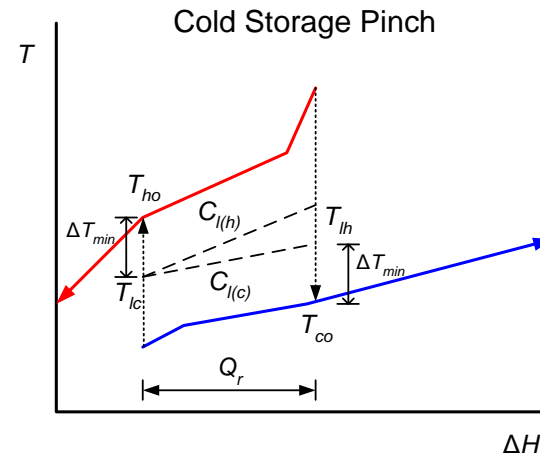
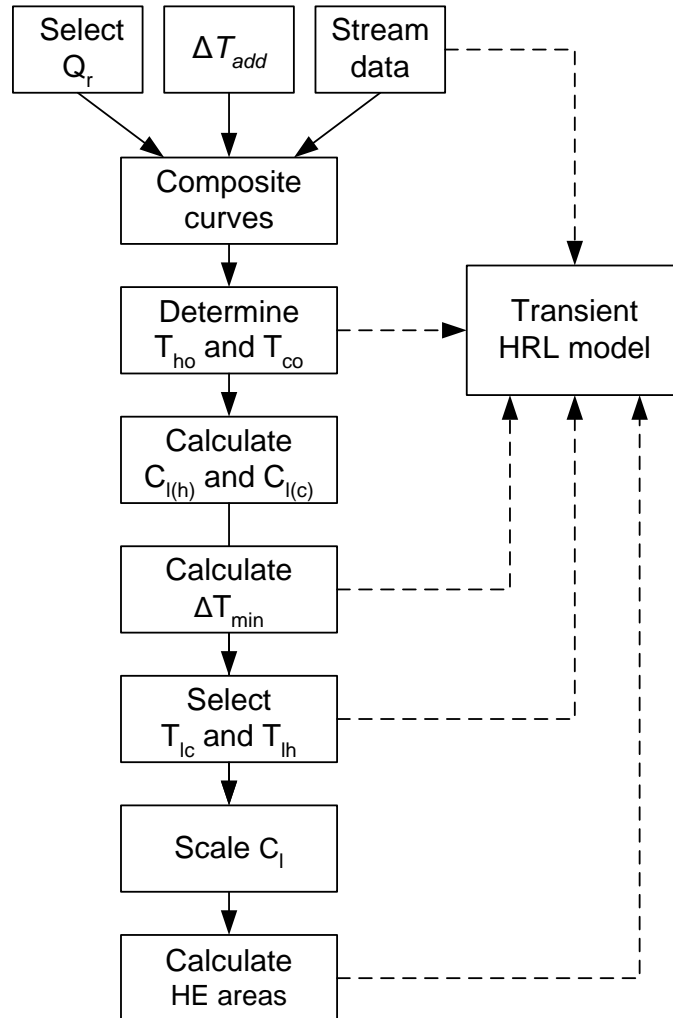


(2) New Heat Recovery Loop Design Method for Improved Inter-plant Heat Integration (PRES'13)



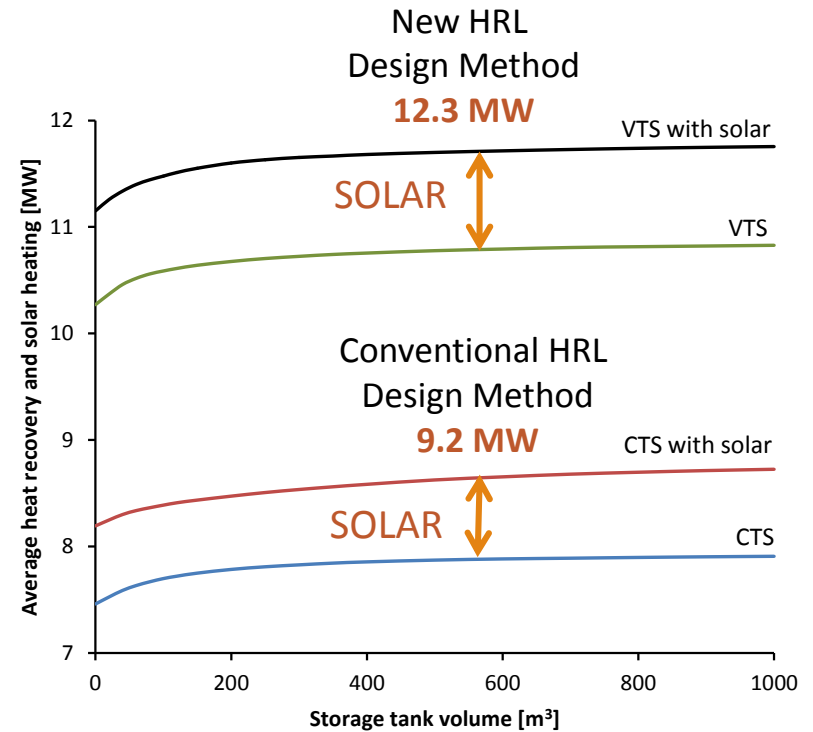
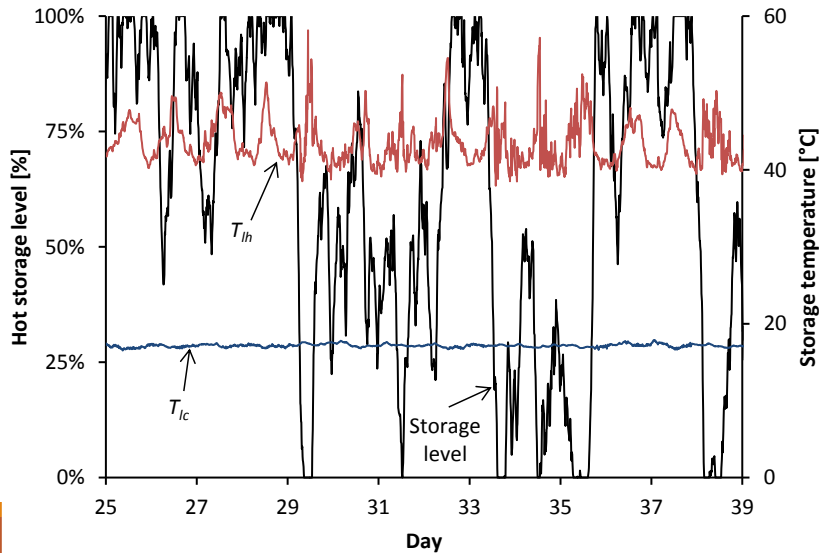
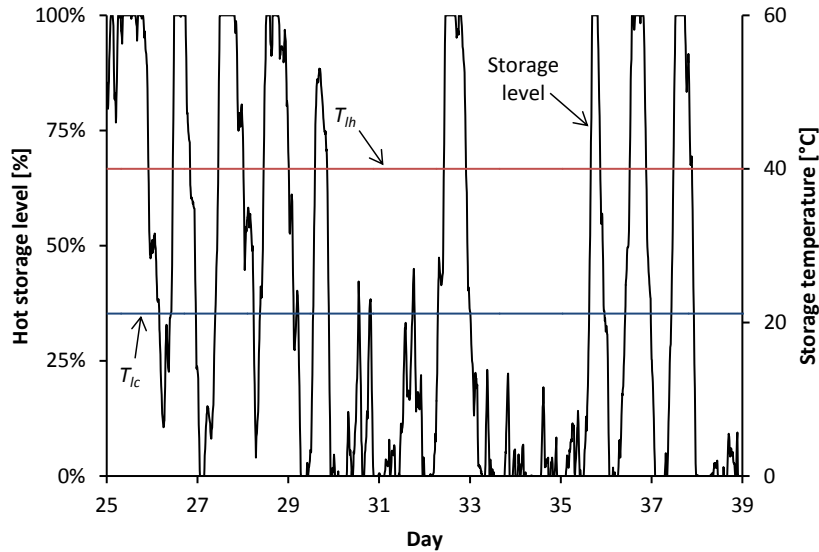


(2) New Heat Recovery Loop Design Method for Improved Inter-plant Heat Integration (PRES'13)

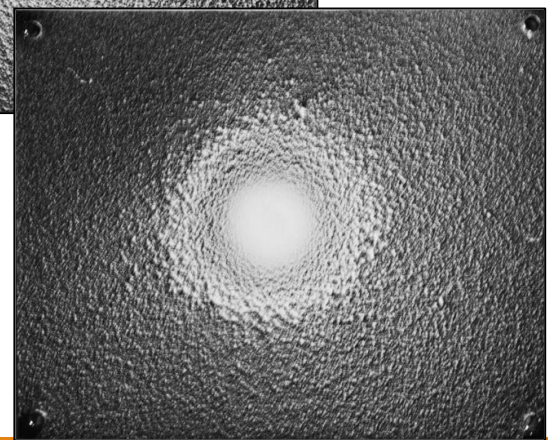
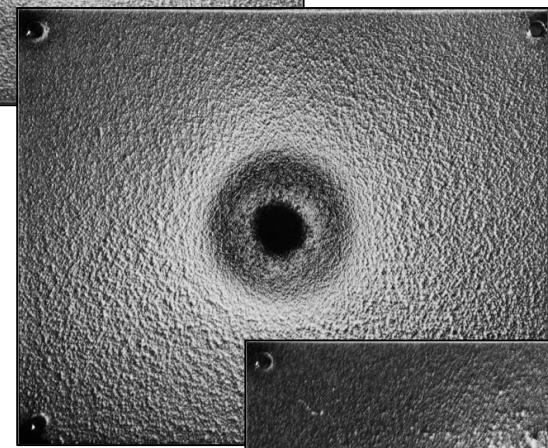
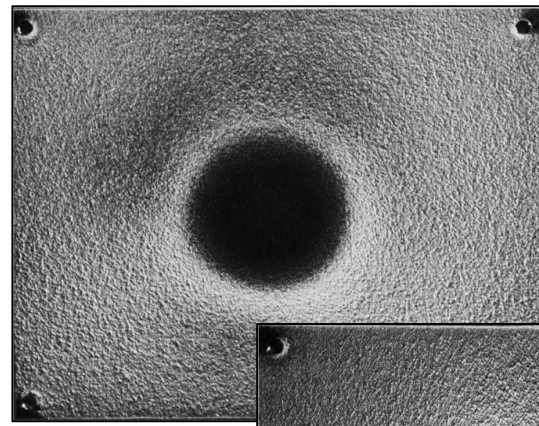
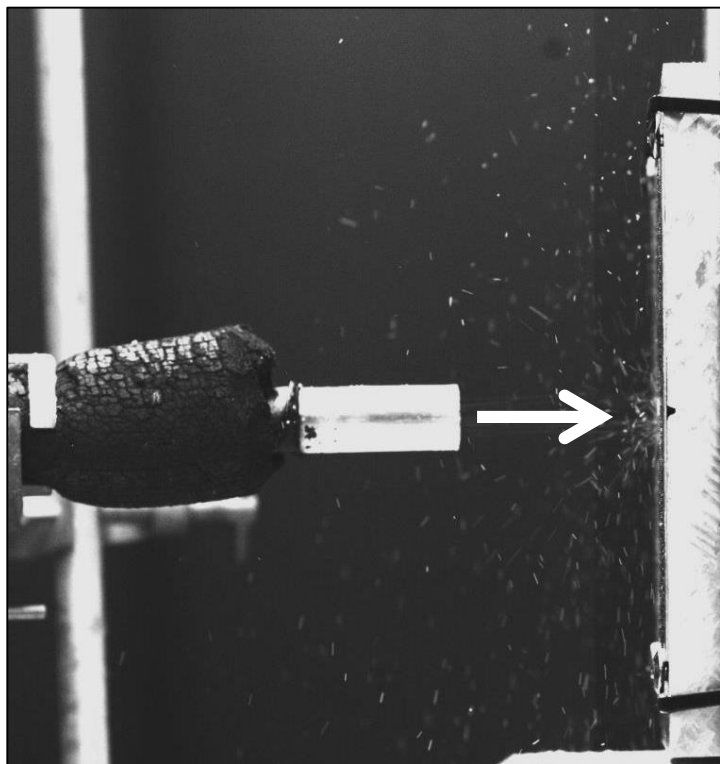




(2) New Heat Recovery Loop Design Method for Improved Inter-plant Heat Integration (PRES'13)



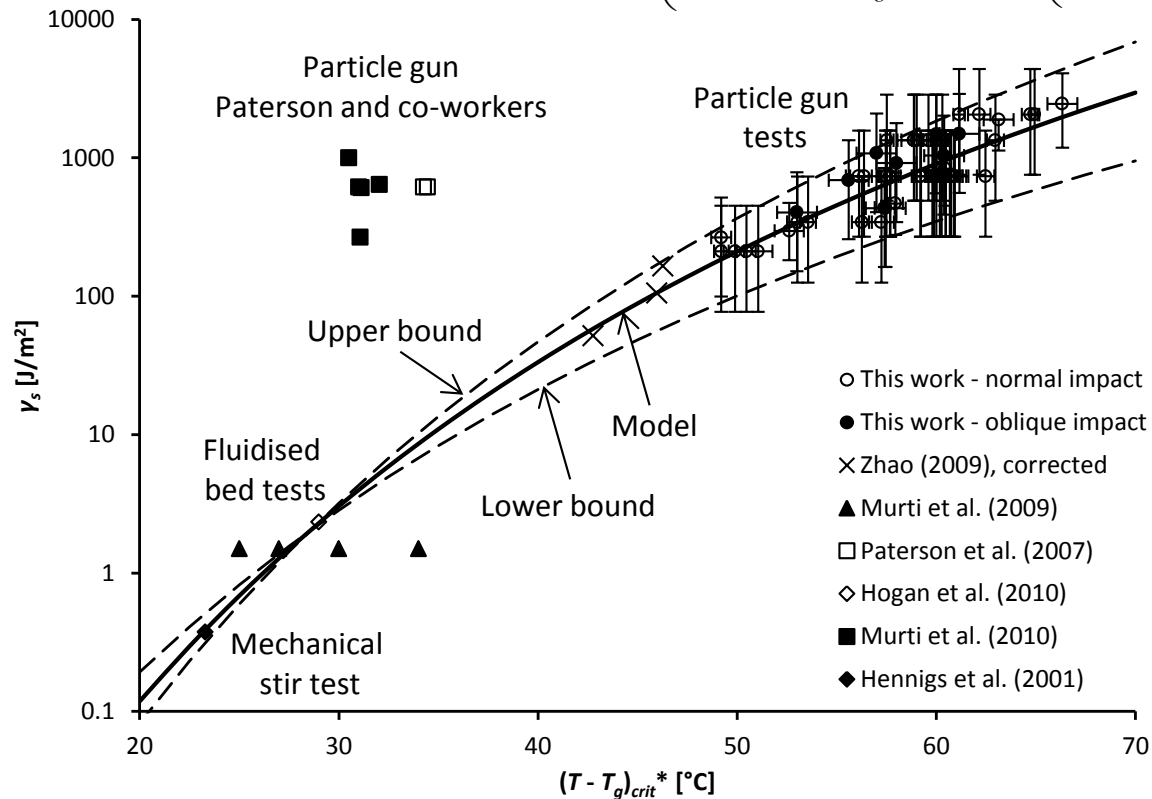
(3) Milk Powder Fouling of Flat Plates



(3) Milk Powder Fouling Model

SMP Deposition model

$$(T - T_g)_{crit}^* = \frac{D_2 \log \left(\frac{0.2442 r \rho^{3/5} v_n^{6/5} Y^{*2/5}}{a \gamma_g} \left(1 + \sqrt{1 + \frac{Y^* B^2}{4G^*} \tan^2(\Theta_n)} \right) \right)}{D_1 - \log \left(\frac{0.2442 r \rho^{3/5} v_n^{6/5} Y^{*2/5}}{a \gamma_g} \left(1 + \sqrt{1 + \frac{Y^* B^2}{4G^*} \tan^2(\Theta_n)} \right) \right)}$$



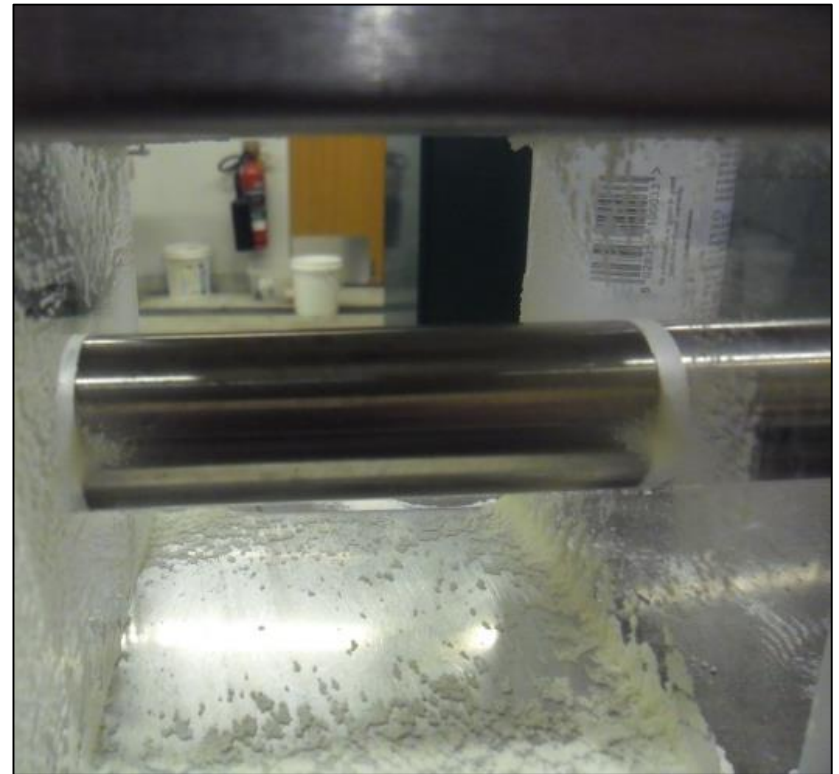


(3) Milk Powder Fouling of Tubes

Front



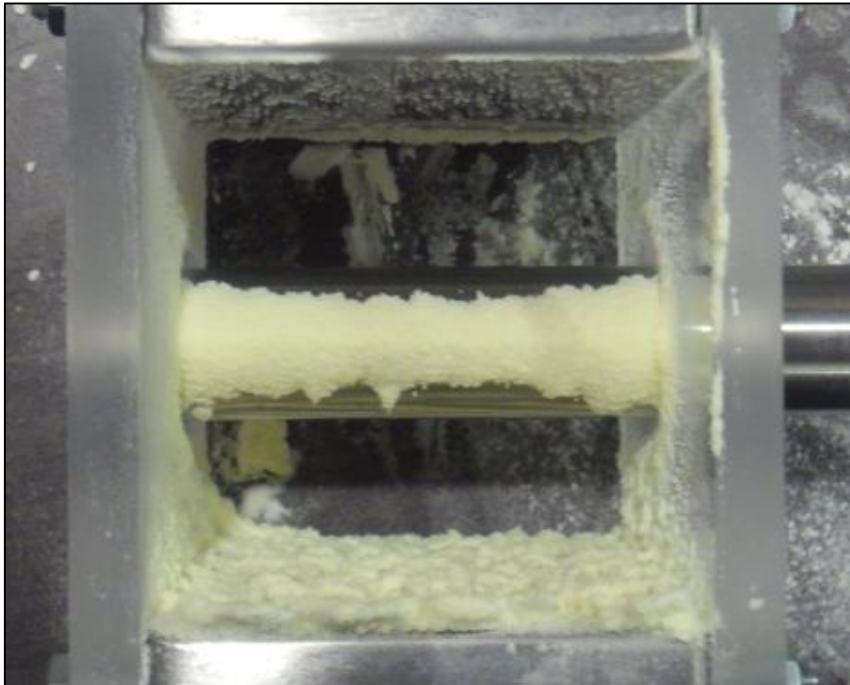
Back





(3) Milk Powder Fouling of Tubes

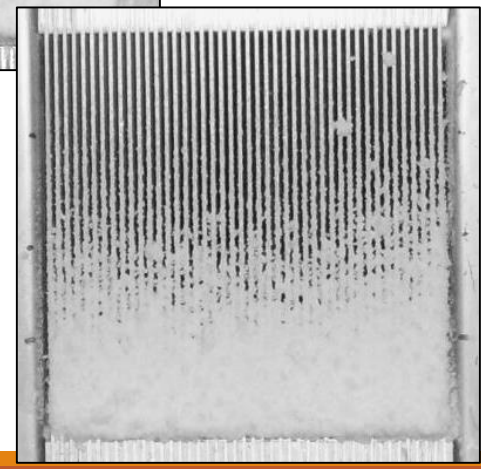
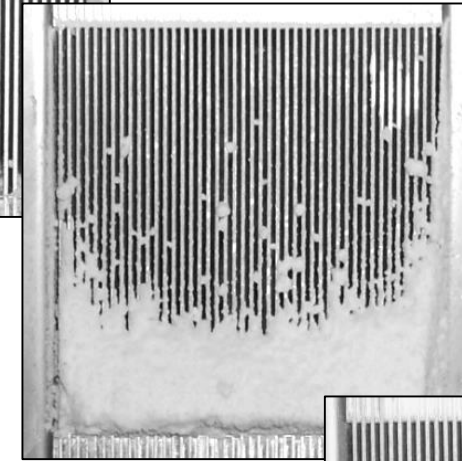
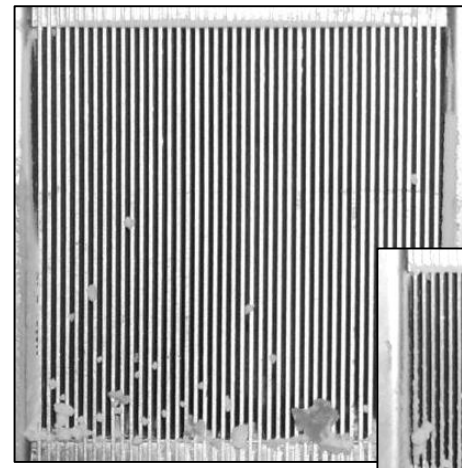
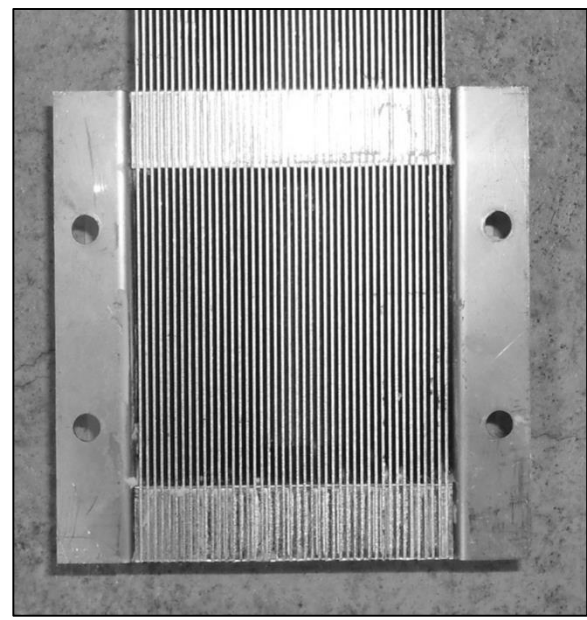
Round Tube



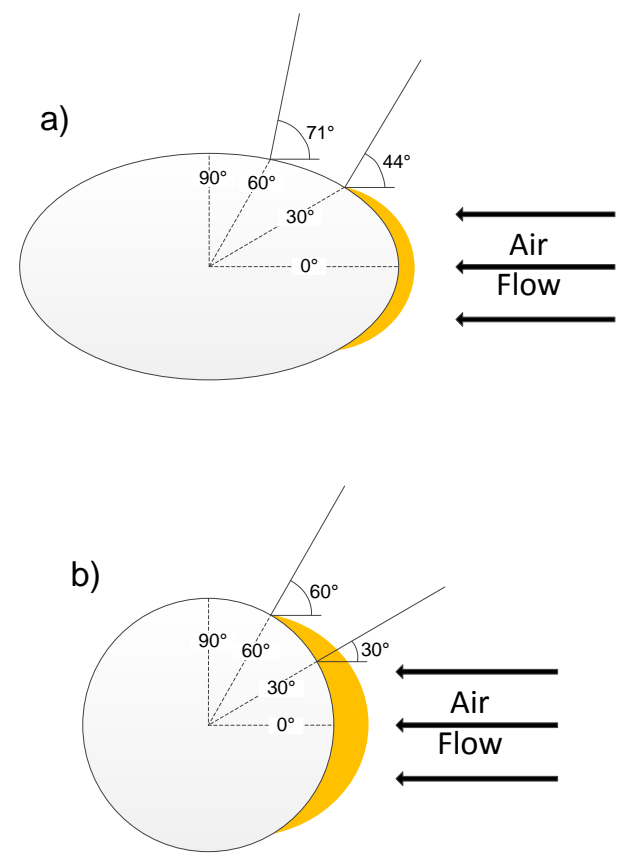
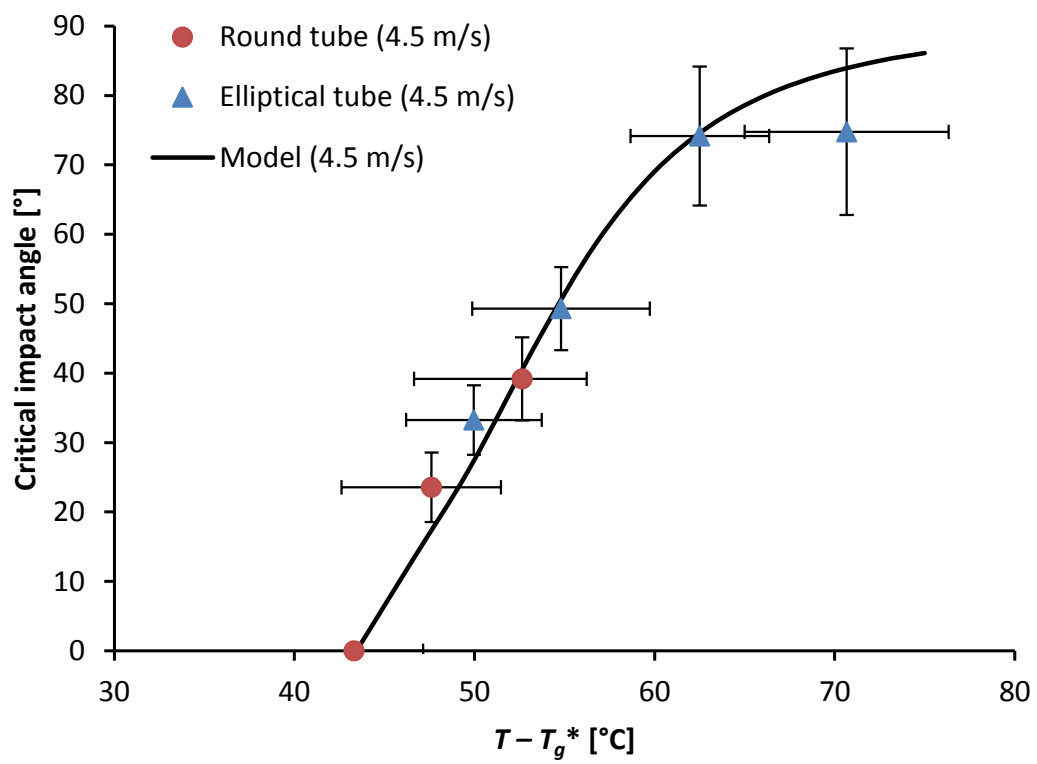
Elliptical Tube



(3) Milk Powder Fouling of Fins

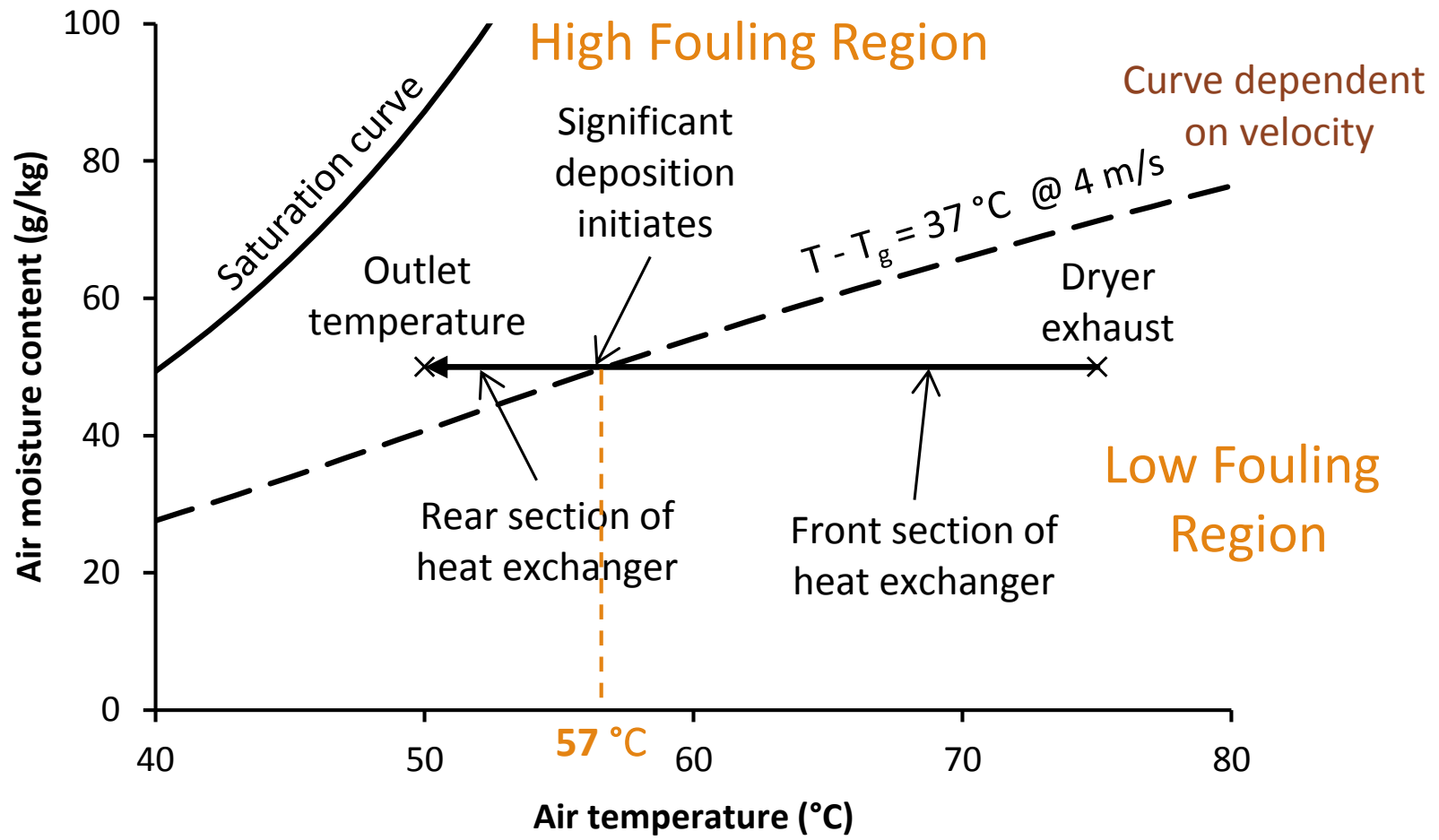


(3) Model Validation for Tube Fouling





(3) Application of Fouling Results

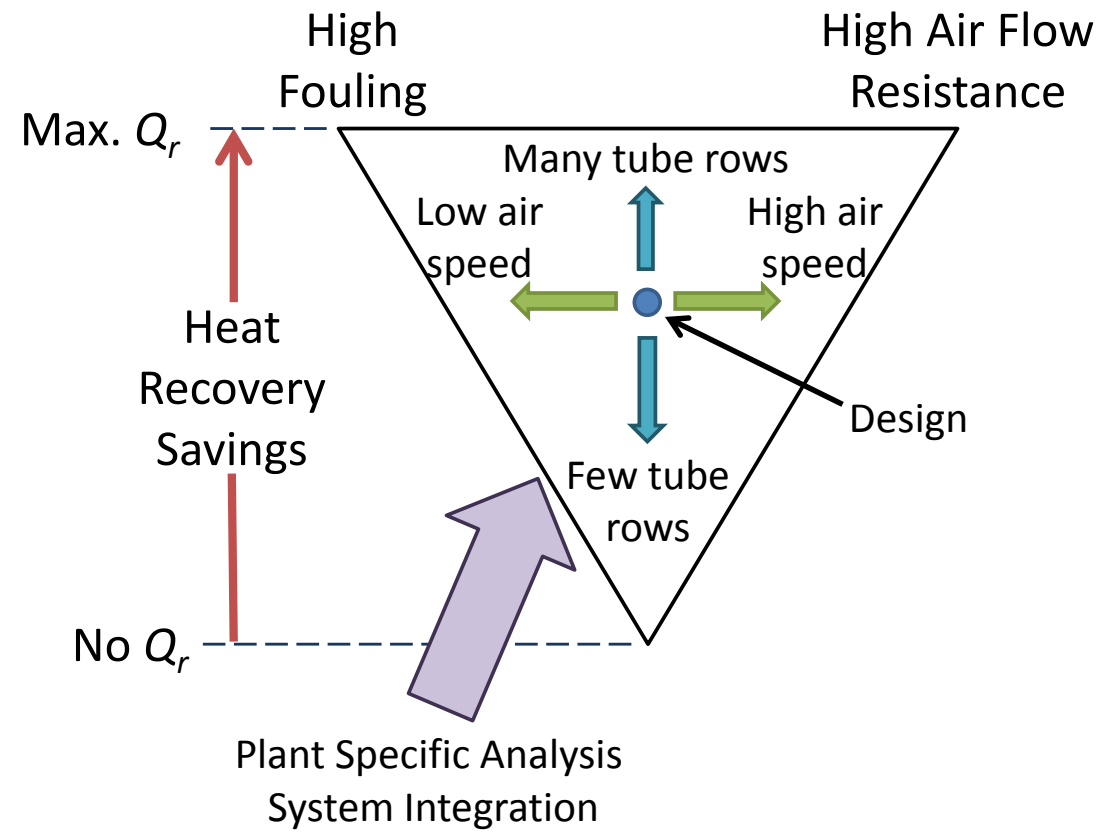




(4) Exhaust Heat Exchanger Design Problem

Design Parameters

- Air Velocity (HX Face Size)
- Tube Diameter
- Tube Spacing
 - Transverse, Longitudinal
- Fin Dimensions
 - Height, Pitch, Thickness
- Number of passes
- Loop flow rate





Spreadsheet Optimisation Model

Indirect Multi-pass Liquid Coupled Loop Finned Tube Heat Exchanger System Model

User Defined Design Parameters	
Exh. HX	Inlet HX
Air Mass Flow Rate	153 117 kg/s
Temperature In	75.0 15.0 °C
Abs Humidity	48.0 10.0 g/kg
Face Velocity	10.0 4.0 m/s
Tube Type	10 8
Tube Rows	12 12
Number of Passes	6 6
Loop Flow Rate	Optimum kg/s
Target Inlet Temp	200 °C
Steam Price	\$ 30 /t
Electricity Price	\$ 120 /GWh
$\eta_{pump/fan}$	0.60
Cost for Cleaning	\$ 5,000 /wash
Production Hours	5000 h/y
Utility Price Rise	5% /y
Discount Rate	15% /y
Accounting Period	10 y
Cost Factor	3.5

Heat Exchange Temperatures						
Stream Name	T _{in} °C	RH _{in}	T _{out} °C	RH _{out}	mC _p kW/°C	Q kW
Exhaust Heat Exchanger CF-9.05-314J (C)						
Exhaust Air	75.0	18.7%	54.8	46.3%	167.8	3397
Water (Cold)	23.8		53.5		143.7	-3397
T _{LM}	23.2 °C		ΔT _{LM}	215 °C		3397
Inlet Heat Exchanger CF-9.05-314J (A)						
Water (Hot)	53.5		23.8		143.7	3397
Inlet Air	15.0	33.6%	43.3	18.1%	120.0	-3397
T _{LM}	12.4 °C		ΔT _{LM}	10.2 °C		3397

Cost/Benefit		
Estimated Savings	3397	kW
Steam Savings	\$764,342	/y
Inlet Air Heat Req.	22,192	kW
%Main Air Heater Duty	15.3%	
Electrical Power	283	kW
Electrical Cost	\$169,879	/y
Cleaning Cost	\$ 37,092	/y
Profit	\$ 557,371	/y
HX Cost A	\$ 607,115	/y
HX Cost B	\$ 2,444,656	/y
Pump & Fan Cost	\$ 66,725	/y
Total Capital Cost	\$2,511,381	
Payback	4.51	y
Net Present Value	\$ 984,619	
IRR	20%	

Fouling and Cleaning Parameters		
Concentration	3.5	mg/m ³
Run time	672	h
Time Step	6.0	h
Wash Length	2.0	h
Start Clean?	TRUE	
Optimum Clean?	FALSE	
Foul Resistance	0.0	m ² C/kW
Time	0	h
Heat Recovered	0	kWh
Total Foulant	0	kg
Q _{res}	3369	kW

Exhaust Tube Type	CF-9.05-314J (C)
Inlet Tube Type	CF-9.05-314J (A)

Calculation Summary	
Depth (m)	0.53 0.53
A _{exh,lm} (m ²)	290 759
A _{inlet,lm} (m ²)	1742 4556
Re _{exh}	74164 34091
Re _{in}	10312 2699
ΔP _{exh} (Pa)	746 505
ΔP _{inlet} (kPa)	37.0 10.7
(mC _p) _{exh}	143.7 120.0
(mC _p) _{in}	167.8 143.7
(mC _p) [*]	0.856 0.835
Q _{exh} (kW)	6489 4617
U _{exh} (W/°C)	84 61
NTU _{exh}	0.17 0.39
ε _{exh}	0.147 0.283
N	6 6
ε _{inlet}	1.02 2.33
ε	0.524 0.736
Q (kW)	3397 3397
ε _{exh}	0.472
Q _{exh} (kW)	7197
Solution Converged	

Solve and Record

Run Macro

Clear Results

Row **0**



User-Defined Inputs

Coupled HX System Design

- Face size (i.e. air velocity)
- Tube & fin dimensions
- Pass arrangement
- Pump, piping & Buffer tank
- Fan

Fluid Flow Specifications

- Exhaust air temperature, flow rate, humidity
- Inlet air temperature, flow rate, humidity
- Intermediate fluid (loop) flow rate

Economic Parameters

- Steam & electricity price
- Capital cost formula
- Discount rate
- Price inflation
- Production hours per annum
- Cost to clean

Fouling & Cleaning Parameters

- Powder concentration
- Particle size distribution
- Run length
- Wash length
- Model time step



Spreadsheet Optimisation Model

Indirect Multi-pass Liquid Coupled Loop Finned Tube Heat Exchanger System Model

User Defined Design Parameters			
	Exh. HX	Inlet HX	
Air Mass Flow Rate	153	117	kg/s
Temperature In	75.0	15.0	°C
Abs Humidity	48.0	10.0	g/kg
Face Velocity	10.0	4.0	m/s
Tube Type	10	8	
Tube Rows	12	12	
Number of Passes	6	6	
Loop Flow Rate	Optimum		kg/s
Target Inlet Temp	200		°C
Steam Price	\$ 30		/t
Electricity Price	\$ 120		/GWh
$\eta_{pump/fan}$	0.60		
Cost for Cleaning	\$ 5,000		/wash
Production Hours	5000		/y
Utility Price Rise	5%		/y
Discount Rate	15%		/y
Accounting Period	10		y
Cost Factor	3.5		

Heat Exchange Temperatures					
Stream Name	T _{in} °C	RH _{in}	T _{out} °C	RH _{out}	Q kW
Exhaust Heat Exchanger CF-9.05-3/4J (C)					
Exhaust Air	75.0	18.7%	54.8	46.3%	167.8
Water (Cold)	23.8		53.5		143.7
T _{in}	23.2	°C	ΔT _{in}	21.5	°C
Inlet Heat Exchanger CF-9.05-3/4J (A)					
Water (Hot)	53.5		23.8		143.7
Inlet Air	15.0	33.6%	43.3	18.1%	120.0
T _{in}	12.4	°C	ΔT _{in}	10.2	°C

Cost/Benefit	
Estimated Savings	3397 kW
Steam Savings	\$764,342 /y
Inlet Air Heat Req.	22,192 kW
%Main Air Heater Duty	15.3%
Electrical Power	283 kW
Electrical Cost	\$163,879 /y
Cleaning Cost	\$ 37,052 /y
Profit	\$ 557,371 /y
HX Cost A	\$ 607,115 /y
HX Cost B	\$ 2,444,656 /y
Pump & Fan Cost	\$ 66,725 /y
Total Capital Cost	\$2,511,381
Payback	4.51 y
Net Present Value	\$ 984,619
IRR	20%

Fouling and Cleaning Parameters		
Concentration	3.5	mg/m ³
Run time	672	h
Time Step	6.0	h
Wash Length	2.0	h
Start Clean?	TRUE	
Optimum Clean?	FALSE	
Foul Resistance	0.0	m ² Ck/W
Time	0	h
Heat Recovered	0	kWh
Total Fouling	0	kg
Q _{eff}	3369	kW

Calculation Summary	
	Exh. HX
Depth (m)	0.53
A _{exh,exh} (m ²)	290
A _{exh,inl} (m ²)	1742
Re _{exh}	74164
Re _{inl}	10312
ΔP _{exh} (Pa)	746
ΔP _{inl} (Pa)	37.0
(m _c) _{exh}	143.7
(m _c) _{inl}	167.8
(m _c) [*]	0.856
Q _{exh} (kW)	6489
U _{exh} (W/C)	84
NTU _{exh}	0.17
s _{exh}	0.147
N _{exh}	6
INTU _{exh}	1.02
s _{exh}	0.524
Q (kW)	3397
s _{inl}	0.472
Q _{inl} (kW)	7197

Solution Converged

Solve and Record

Run Macro

Clear Results

Net Present Value (Millions) vs Effectiveness

HX Duty (kW) vs Time (hr)

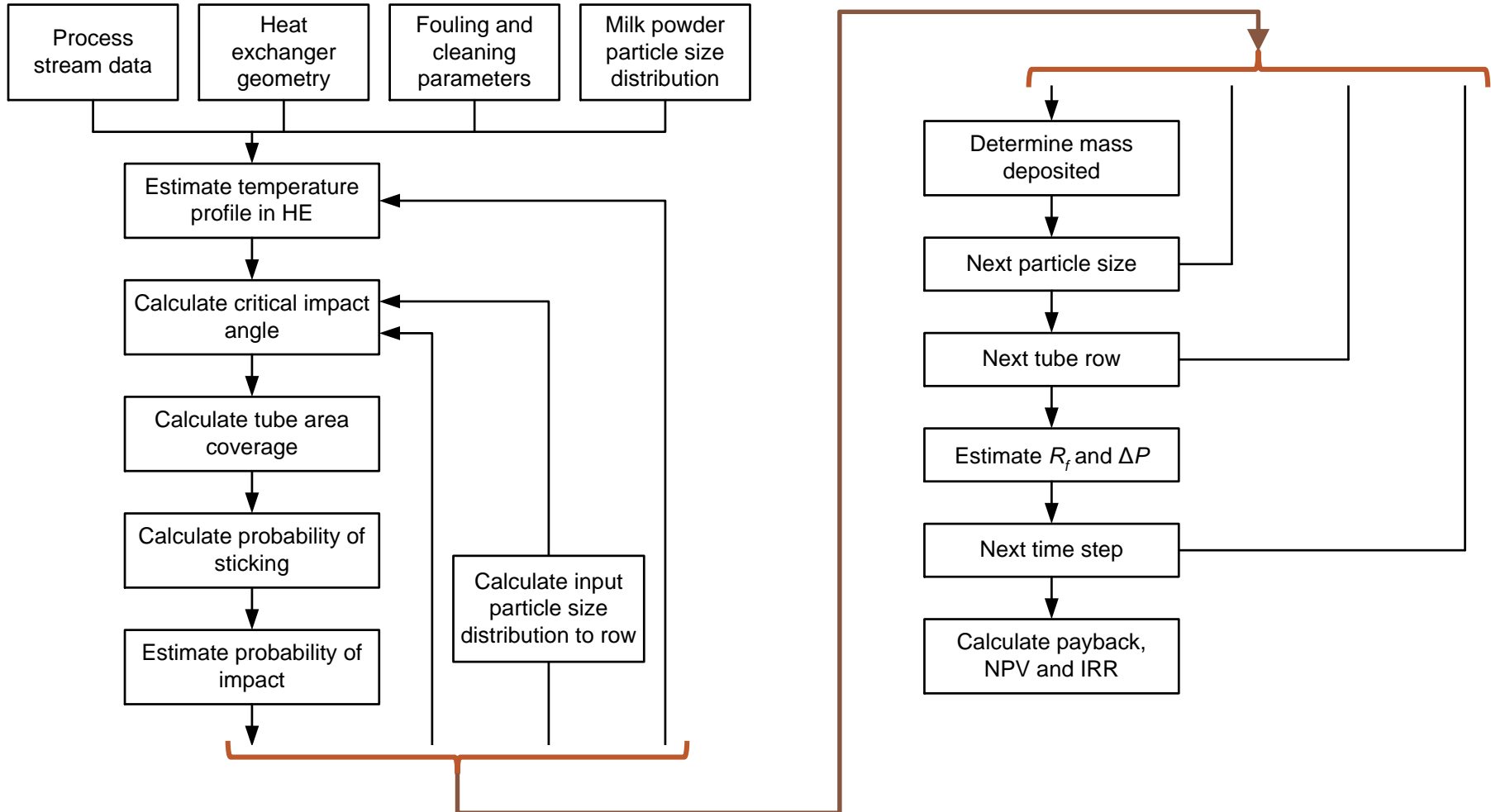
Fouling HT Resistance (m²Ck/W) vs Time (hr)

Input Parameters

Heat Exchanger	Parameters	Start	Last	Step	<input type="checkbox"/> Optimum loop?
<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="checkbox"/> Solve IRR?
<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="button" value="MODEL FOULING"/>
<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="button" value="RUN"/> <input type="button" value="EXIT"/>



Fouling Prediction Model





Key Model Outputs

Average heat exchanger duty

Temperature profiles within a heat exchanger

Fouling over time

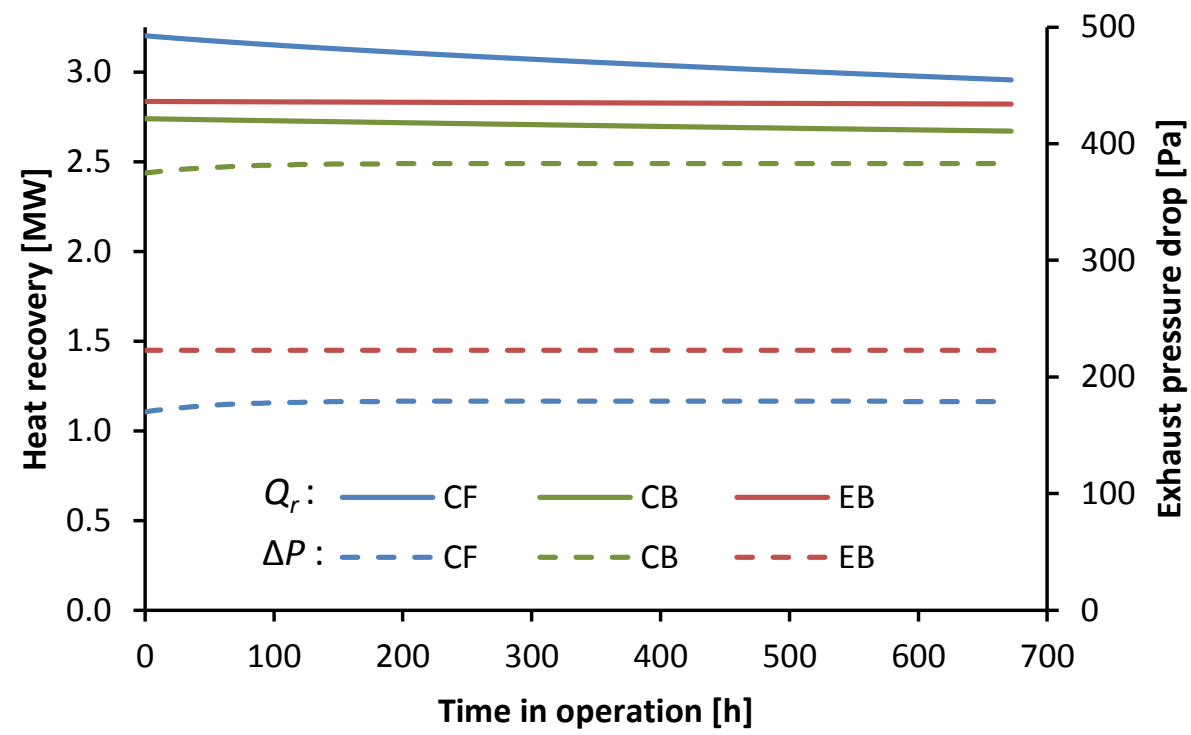
- Mass deposited
- Thermal and hydraulic resistance over time
- Duty over time

Cost estimations

Economic Indicators (NPV, IRR, Payback)



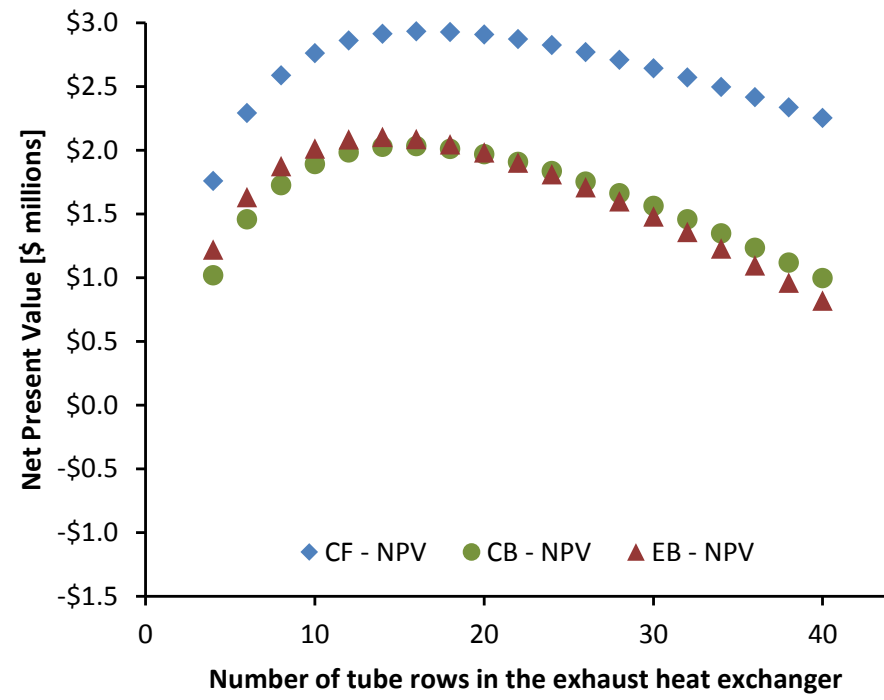
Fouling Model Results



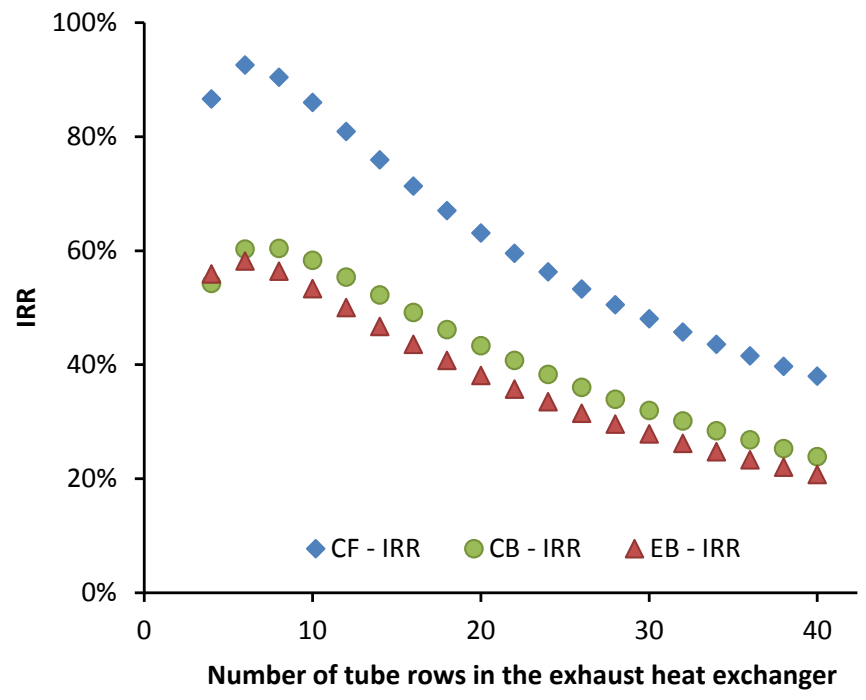


Effect of Number of Tube Rows

NPV

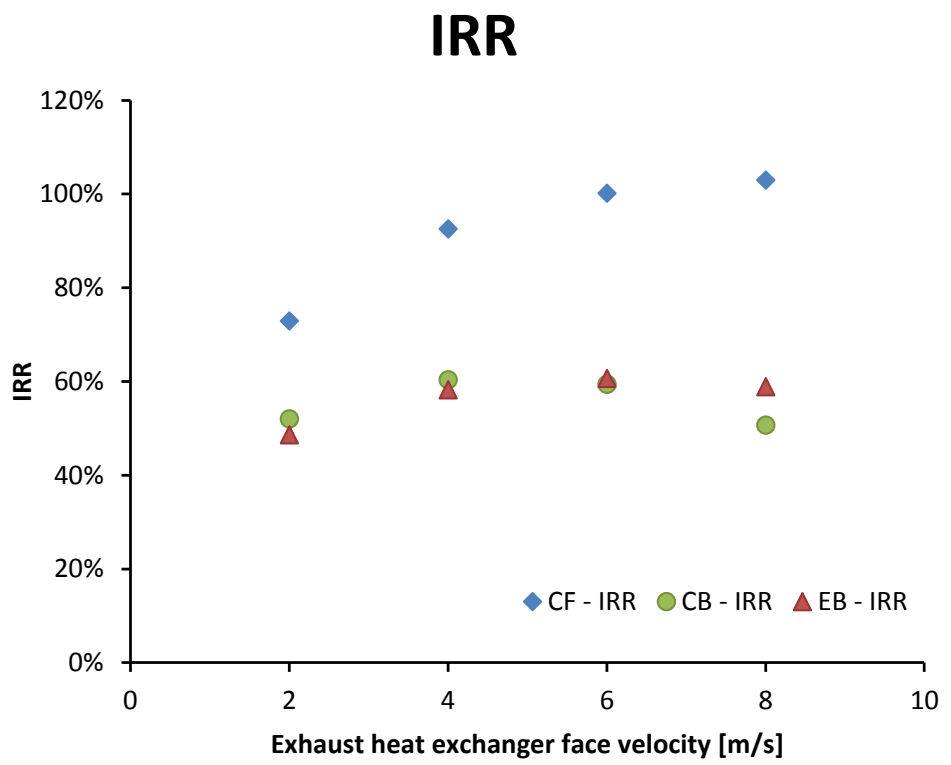
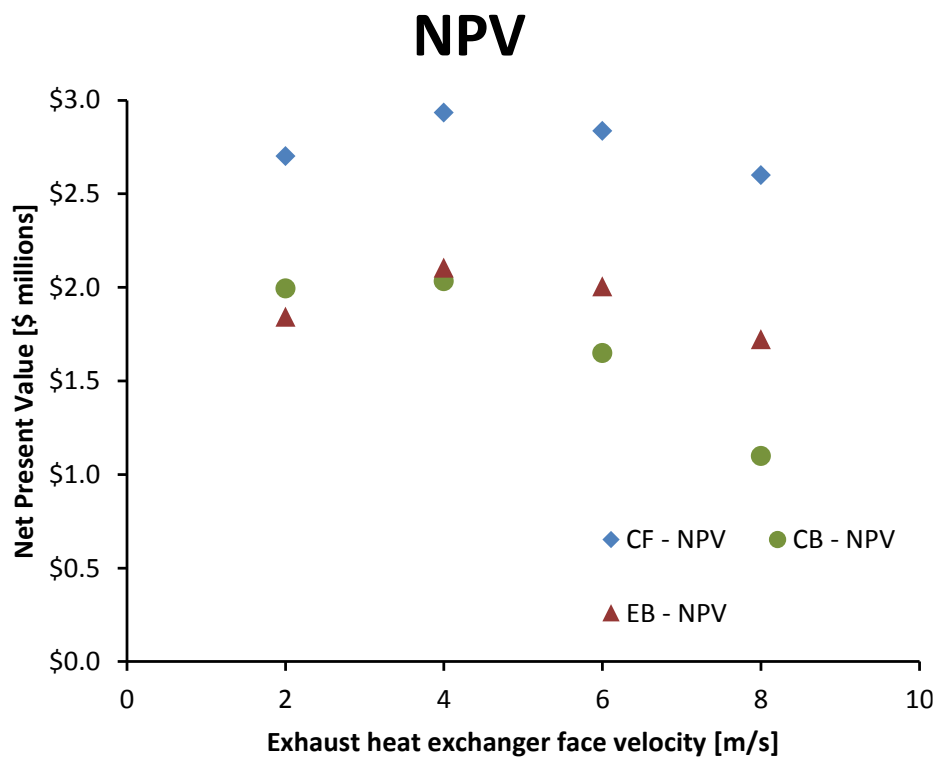


IRR





Effect of Exhaust Air Velocity





Site Specific Factors Affecting Economics

- Inlet air temperature (outside 15°C or inside 33°C)
- Inlet air absolute humidity (outside or inside)
- Exhaust air temperature (+5° → +25% HR)
- Bag filters (low powder conc.)
- Inlet and exhaust fan capacity (reduce cost by ~25%)
- Existing pre-heaters using utility
- Existing heat recovery to dryer inlet air

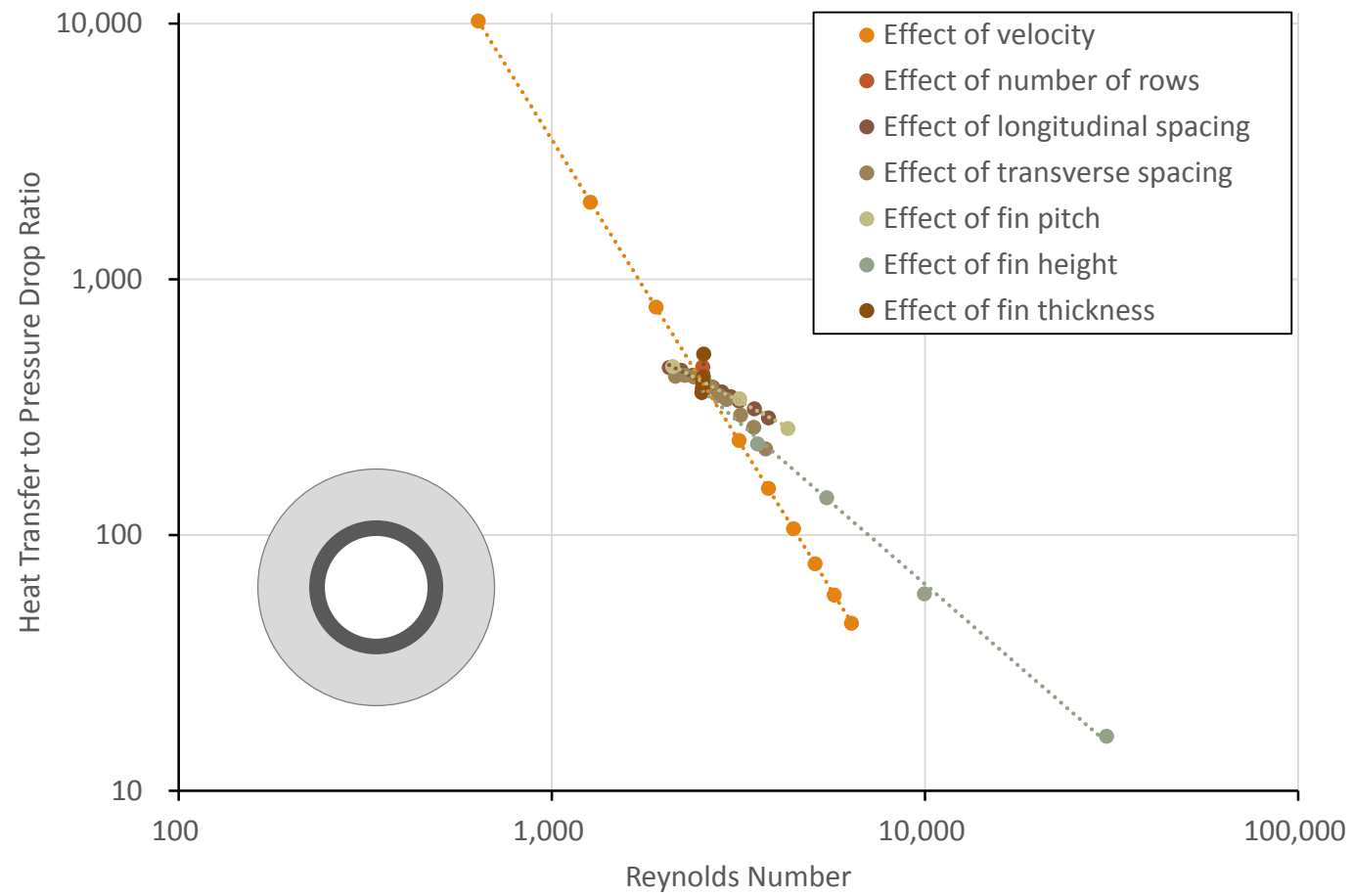


Site Specific Factors Affecting Economics

- Re-usable existing ducting (reduce cost by ~20%)
- Operating and production hours
- Price of energy (varies by 30 – 50%)
- Space
- Inlet air heater bottleneck
- Good attitude to change



Present Work: Design Optimisation





Overall Conclusions

- New Zealand milk powder plants can economically increase HR by ~20 %; exhaust heat recovery (HR) is the single largest opportunity
- Exhaust HR can play an integral part in supplying heat to neighbouring plants via HRLs
- For SMP, a final exhaust air temperature above 55 °C can minimise particulate fouling problems
- Exhaust HR is economic for good sites (payback time of ~1.6 years, NPV of NZ\$2.9 million and IRR of 71 %)
- Site selection is important



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Te Whare Wānanga o Waikato

Thesis Link & Any Questions?

Heat Integrated Milk Powder Production

By Tim Walmsley

<http://hdl.handle.net/10289/8767>

