UNIVERSITY of OTAGO
Te Whare Wānanga o Otāgo
NEW ZEALAND

Industrial Heat Pump Drying Processes

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Outline

- Three types of heat pumps: vapour compression heat pumps (VCHP), absorption heat pumps (AHP), and heat transformers (HT)
- Application of heat pumps to timber drying processes
- Potentials of heat pumps for milk powder spry drying processes

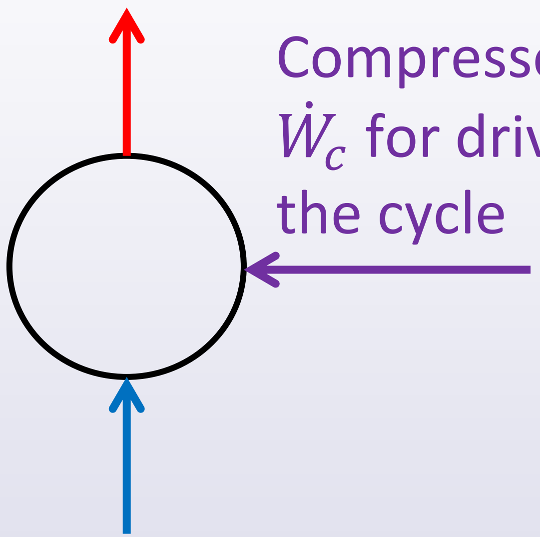
Overview

- Significant amounts of low to medium temperature heat energy, generated by burning high-emissions fuels, are used by industrial drying processes in NZ.
- All the energy used for drying products is discharged from dryers to the environment as low grade heat contained in humid air streams.
- Heat pump drying (HPD) technology is an energy efficient and cost-effective way to recover lost energy and thus to reduce carbon emissions.

Vapour Compression Heat Pump Cycle

High temperature heat $\dot{Q}_H$ at T_H for heating processes

Compressor power $\dot{W}_c$ for driving the cycle



Low temperature heat $\dot{Q}_L$ at T_L (e.g., process waste heat)

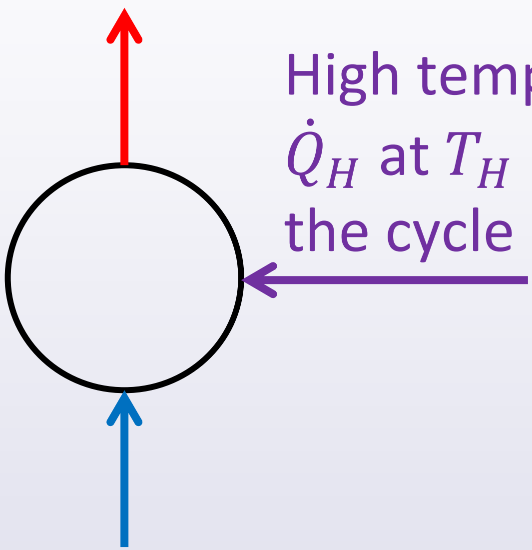
$$T_H > T_L$$

$$\mathrm{COP} = \frac{\dot{Q}_H}{\dot{W}_c} = 3.0 \sim 7.0$$

Working fluids: e.g., R134a, CO2, ammonia and water

Absorption Heat Pump Cycle

Intermediate temperature heat
$\dot{Q}_I$ at T_I for heating processes



High temperature heat
$\dot{Q}_H$ at T_H for driving the cycle

$$T_H > T_I > T_L$$

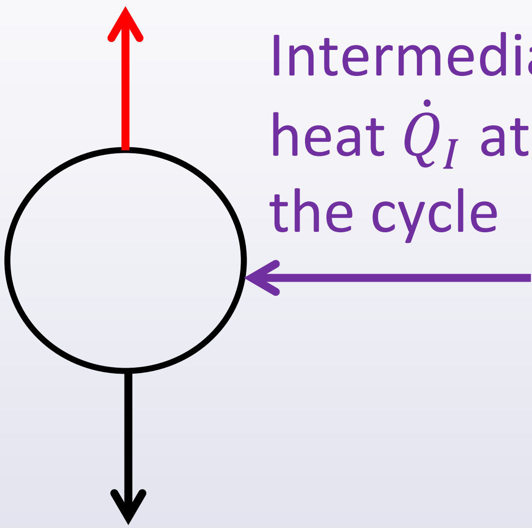
$$\mathrm{COP} = \frac{\dot{Q}_I}{\dot{Q}_H} = 1.2\sim2.5$$

Low temperature heat $\dot{Q}_L$ at T_L
(e.g., process waste heat)

Working fluids: e.g., water and lithium bromide (LiBr); ammonia and water

Heat Transformer Cycle

High temperature heat $\dot{Q}_H$ at T_H for heating processes



Intermediate temperature heat $\dot{Q}_I$ at T_I for driving the cycle

Low temperature heat $\dot{Q}_L$ rejected to heat sink at T_L

$$T_H > T_I > T_L$$

$$\mathrm{COP} = \frac{\dot{Q}_H}{\dot{Q}_I} = 0.4{\sim}0.5$$

From the thermodynamic principles, the lower T_L is, the higher T_H is.

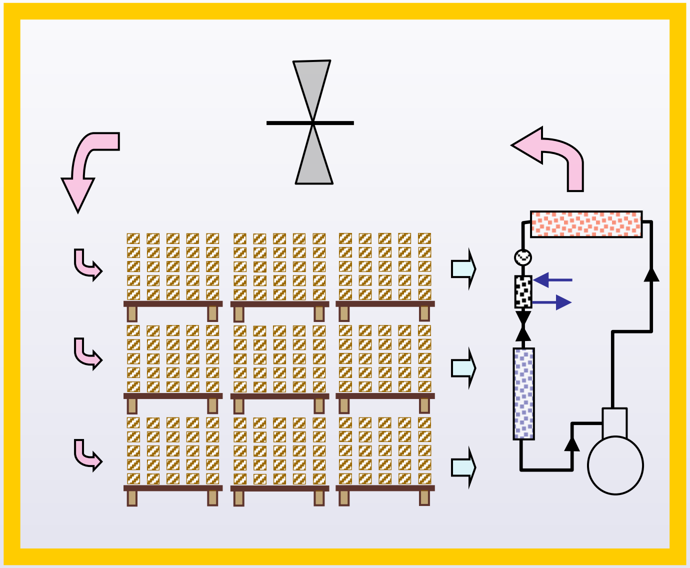
Working fluids: e.g. water and lithium bromide (LiBr); ammonia and water

Heat Pump Timber Drying

- Drying costs and timber quality are under constant pressure
- Wood waste is not as easy to come by
- Carbon price will be further increased
- Change is needed

Team for HP timber drying programme: Murray Burnett (Dunedin Heat Pumps Ltd), Gerry Carrington (team leader, Delta S Company; Otago University), Eric Scharpf (Delta S Company), Zhifa Sun (Delta S Company; Otago University).

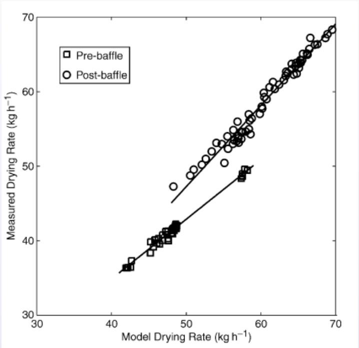
Otago (Delta S) Heat Pump Timber Drying System

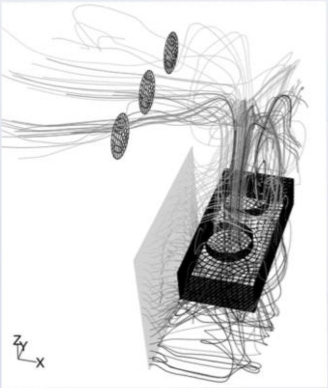


Schematic diagram of Delta S heat pump timber dryer

Delta S reverse airflow heat pump module (a vapour compression system with R134a as the refrigerant)

Design of Otago (Delta S) Heat Pump Timber Driers





- Modelled and validated air flow, internal and external heat and moisture transfer, and drying rate
- Integrated design matches heat pump and airflow to timber behavior
- Advanced controls and drying schedules make operation simple and clear

Performance of Otago (Delta S) Heat Pump Timber Driers

- More than 6 tons of water can be pulled out per day
- Full reverse airflow capability for even drying
- Sterilization and optional spray reconditioning

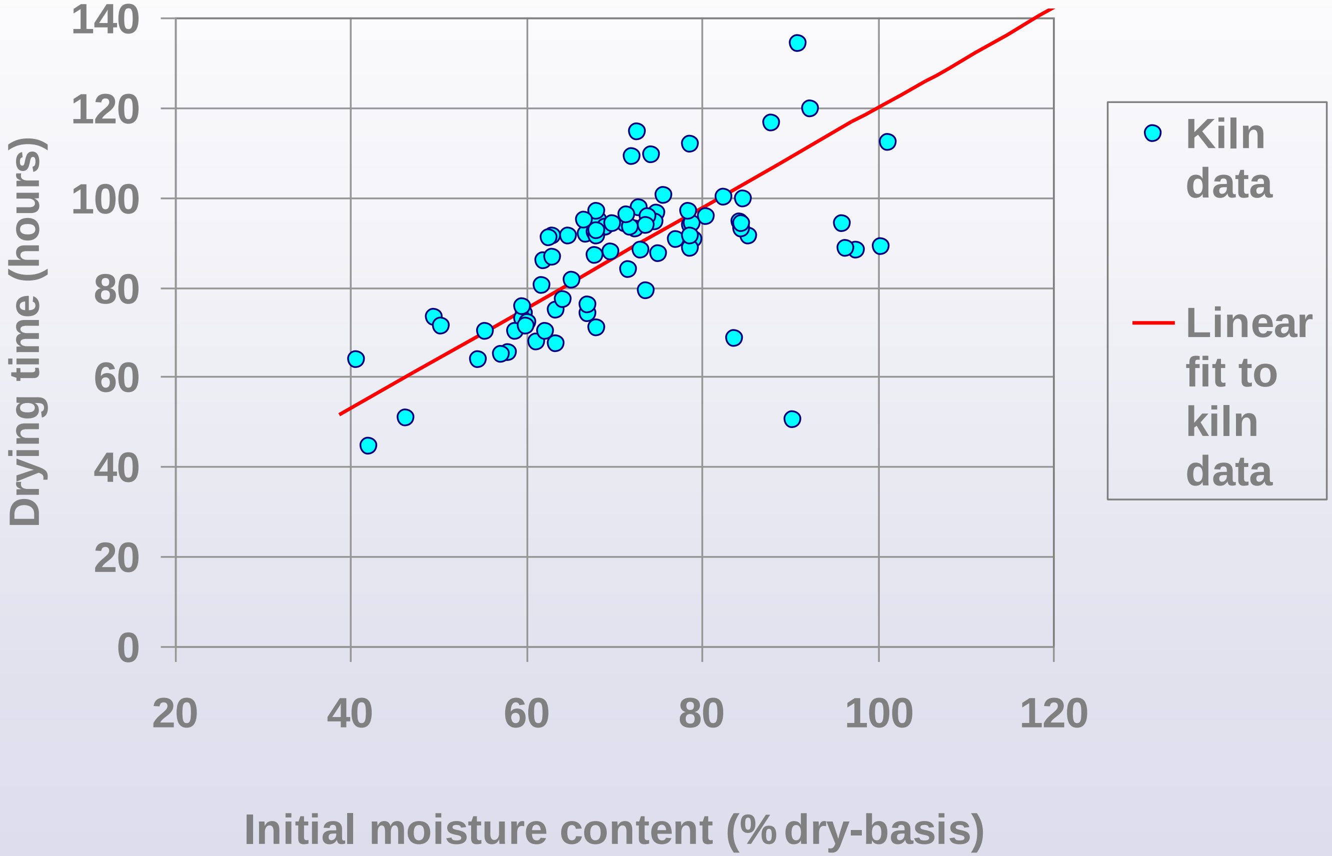
Quality and Costs

- Lower operating temperature improves quality of dried *P. radiata*: lighter timber colour, negligible kiln brown stain, negligible internal checks
- Heat pumps' high efficiency makes electricity cheaper than fuel
- Low capital cost heat pump driers mean the cost per cu-m of dry timber meets or beats "faster" heat and vent systems
- No boiler system needed and thus no CO_2 emissions (depending on fuel types)

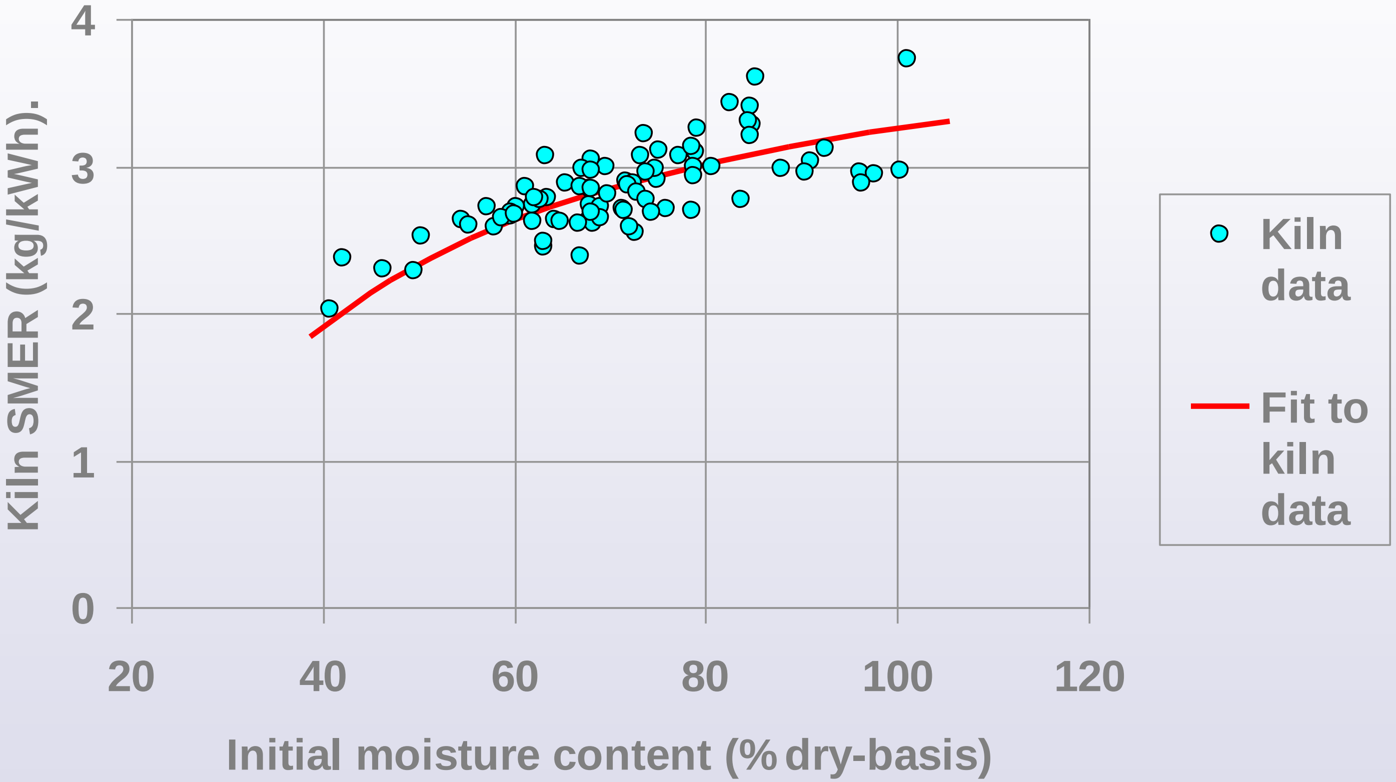
Demonstration Site

- Croft Poles & Timber Ltd, Whangarei since 2003
- Independent commercial operation focussed on production performance
- Producing approx 4700 m^3 of 20% mc radiata pine per year
- Performance monitored in detail for 16 months
- The operational performance of the HPD covering a period of 10 years was reviewed in a paper by the team (Drying Technology, 33: 455–465, 2015)

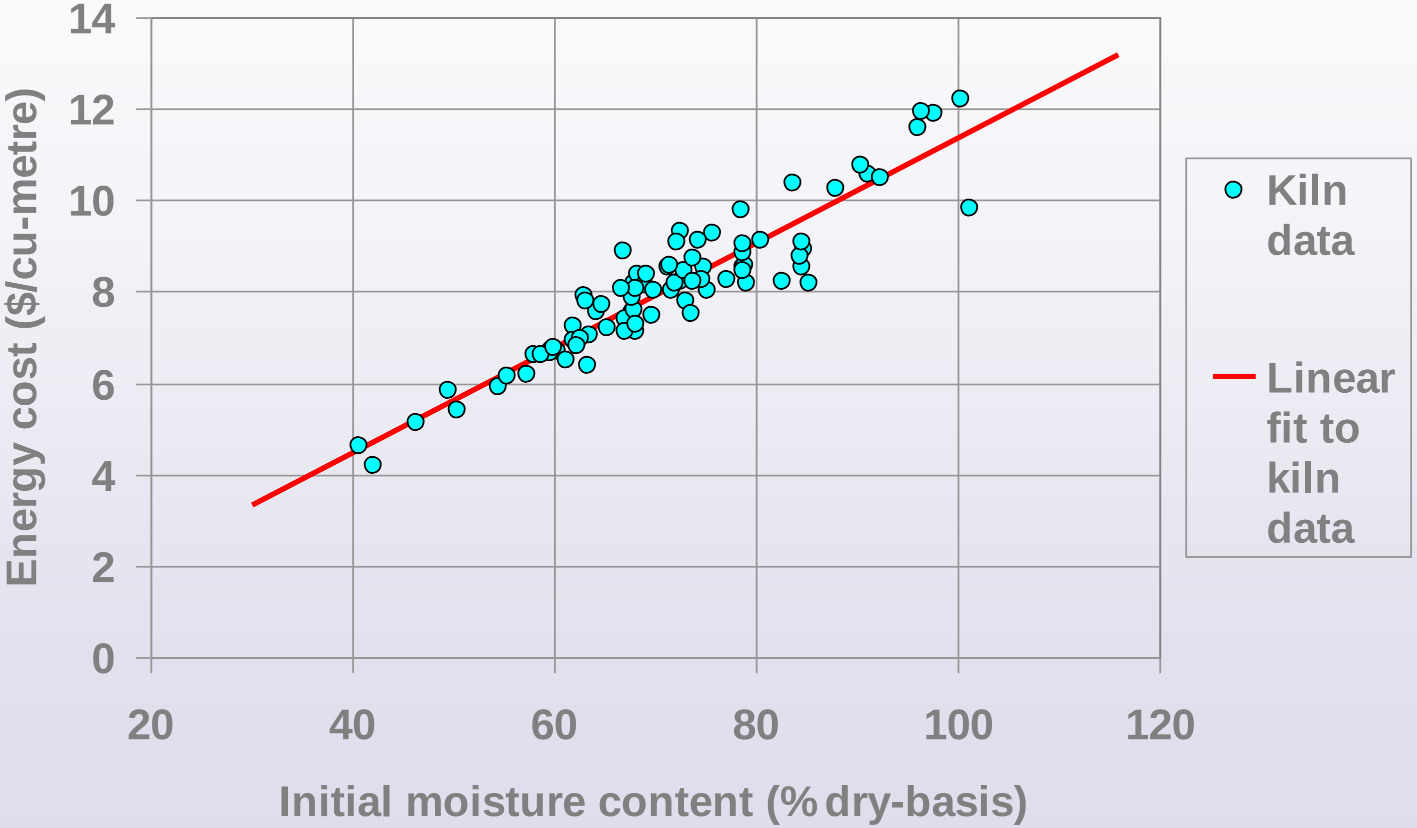
Drying Time


140
120
100
80
60
40
20
0
Drying time (hours)
20
40
60
80
100
120
Initial moisture content (% dry-basis)
Kiln data
Linear fit to kiln data

Kiln Efficiency

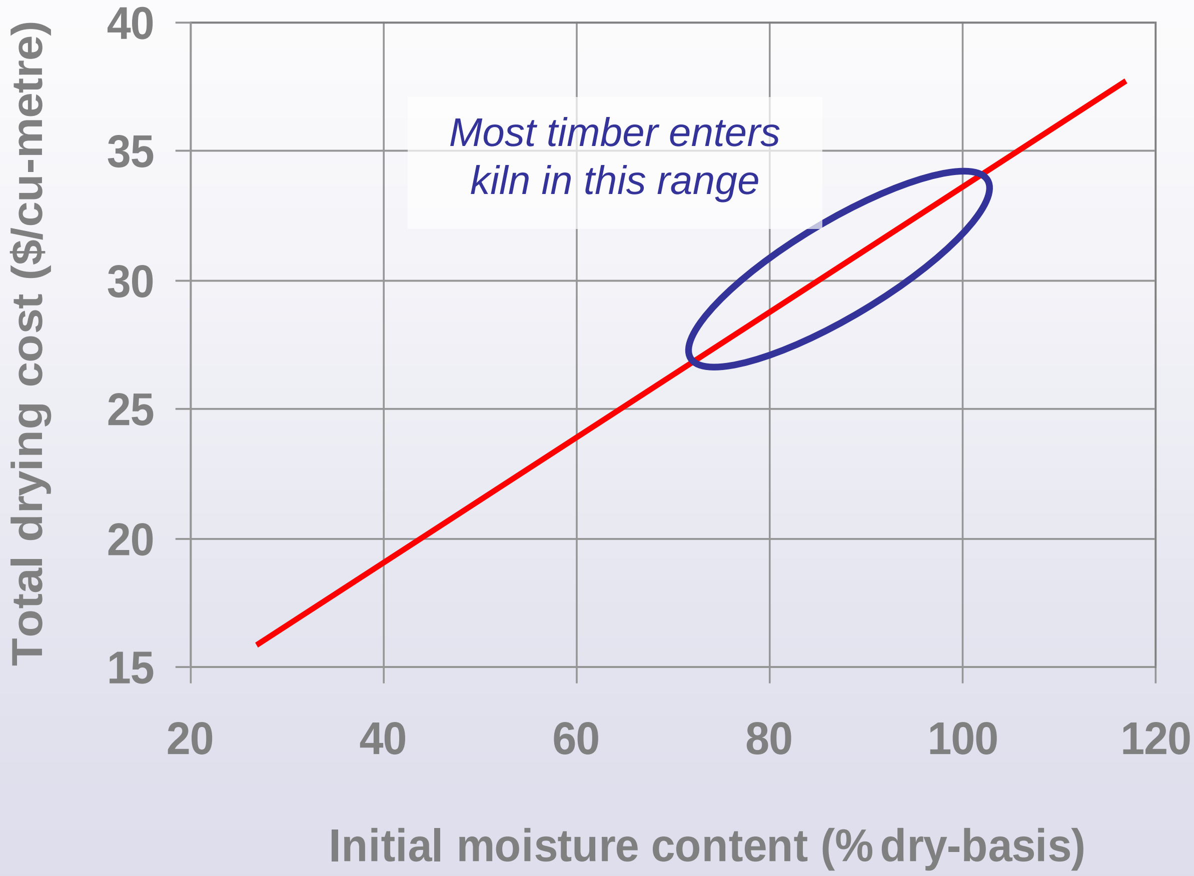


Energy Cost



14
12
10
8
6
4
2
0
Energy cost ($/cu-metre)
20
40
60
80
100
120
Initial moisture content (% dry-basis)
Kiln data
Linear fit to kiln data

Total Drying Cost

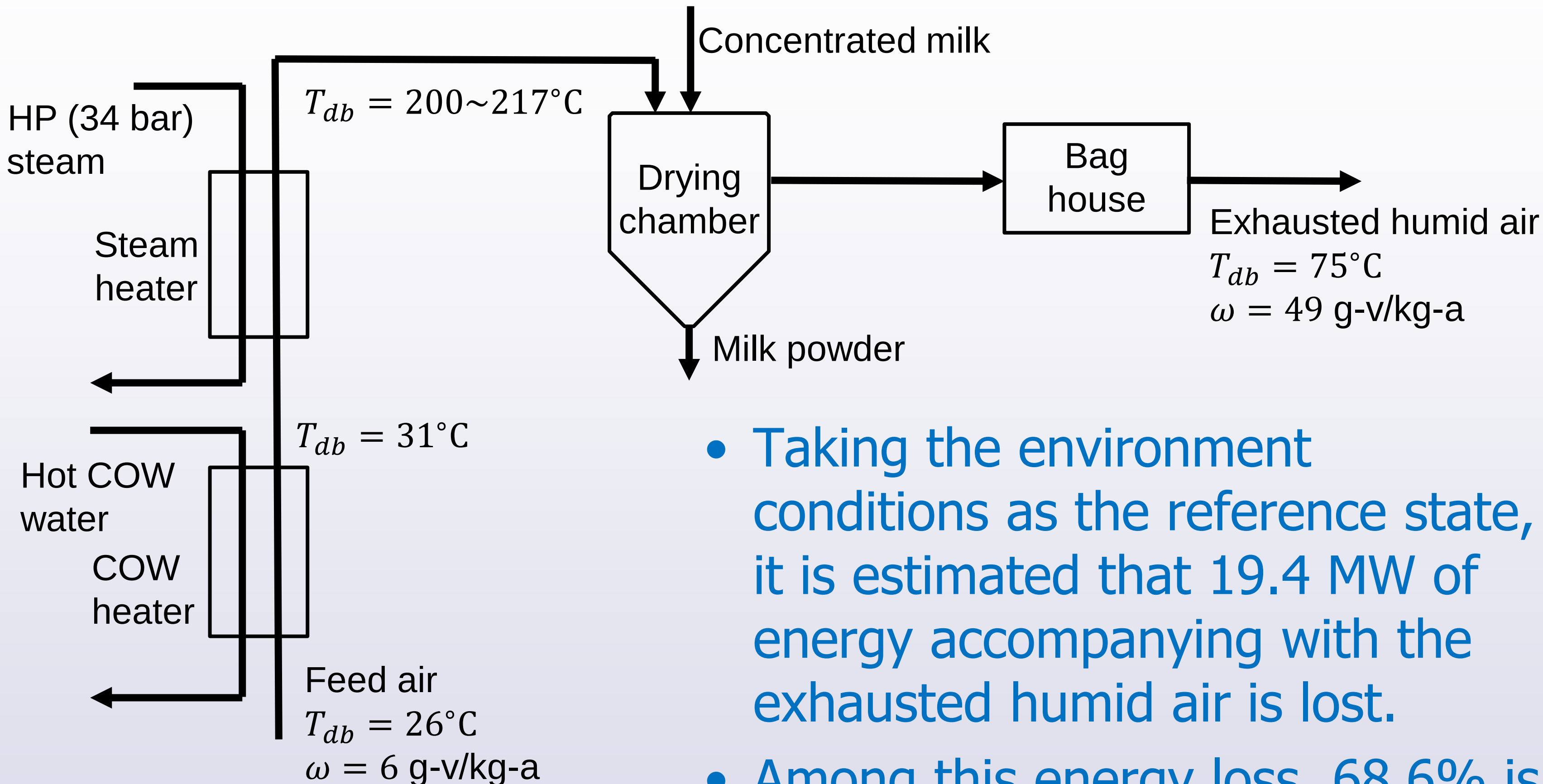


Potentials of Heat Pumps for Milk Powder Drying

- Among the specific processes requiring process heat in the dairy manufacturing sector, milk powder spray drying is the most energy-intensive dairy manufacturing process [1].
- Significant amounts of low quality energy exhausted from spray dryers is lost to the environment.
- It is necessary to develop technologies to recover this lost energy and reduce carbon emission.

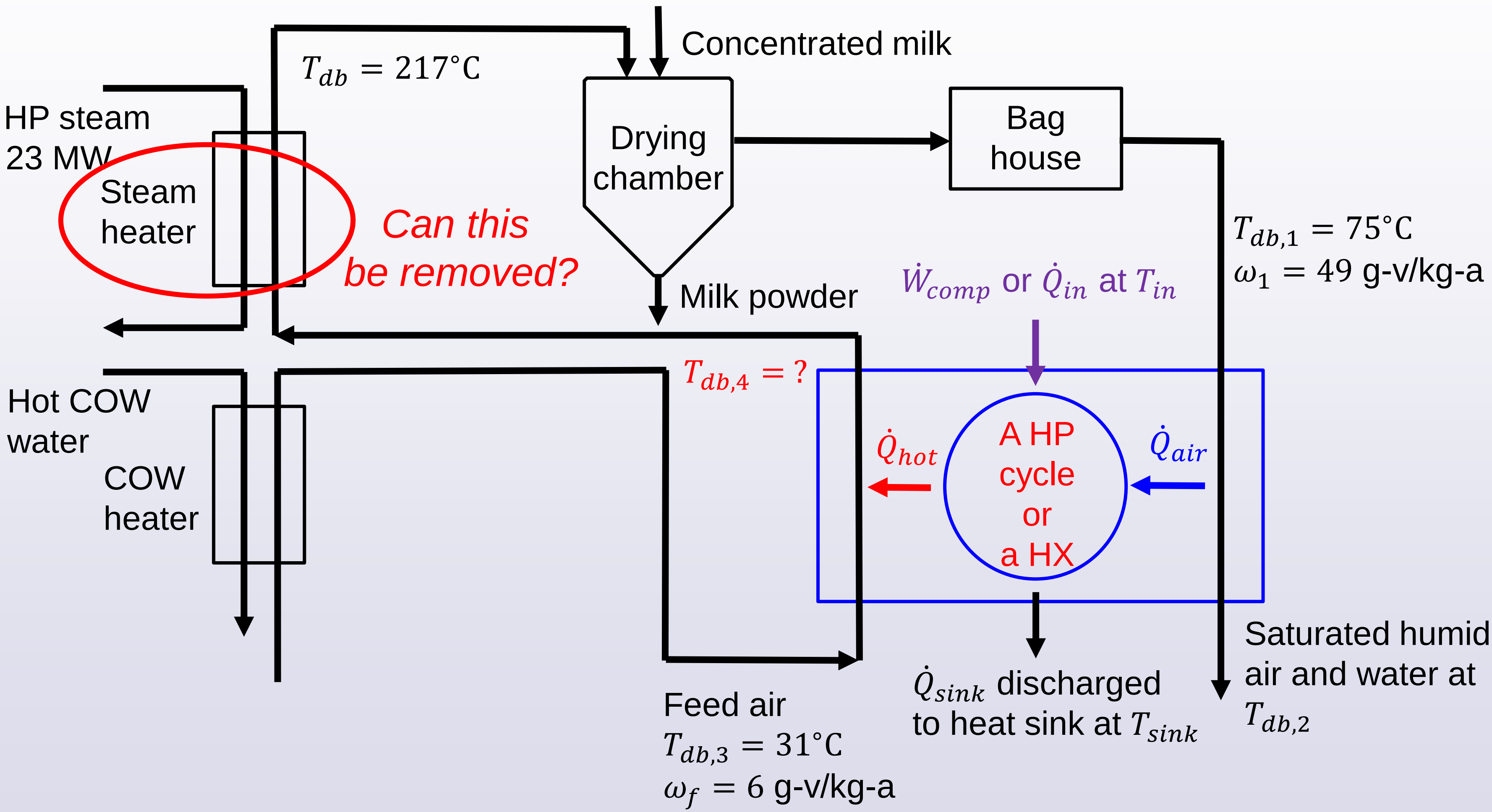
1. Dairy Manufacturing – Process Heat and Greenhouse Gas Emissions, Fact Sheet, Process Heat in New Zealand

Operation of a Milk Powder Spray Dryer

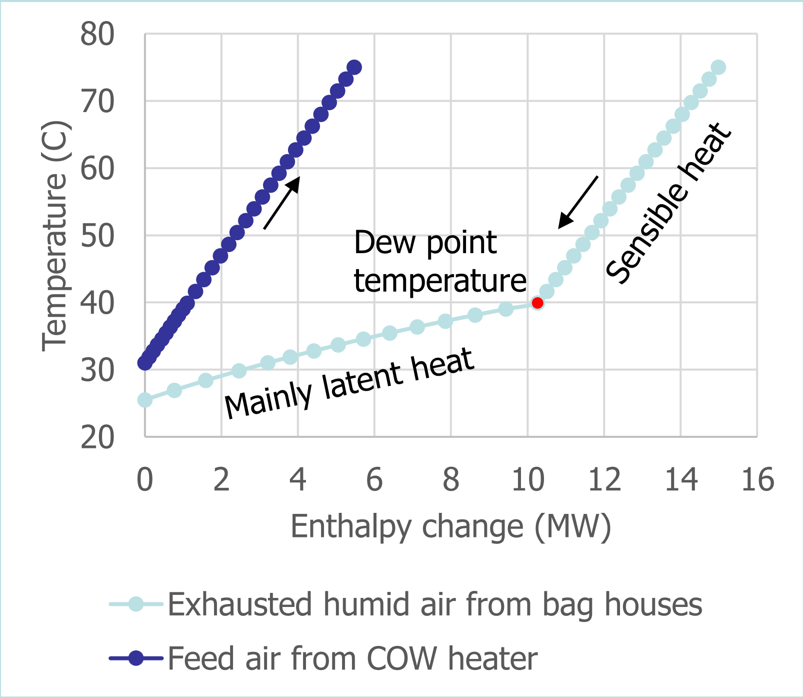


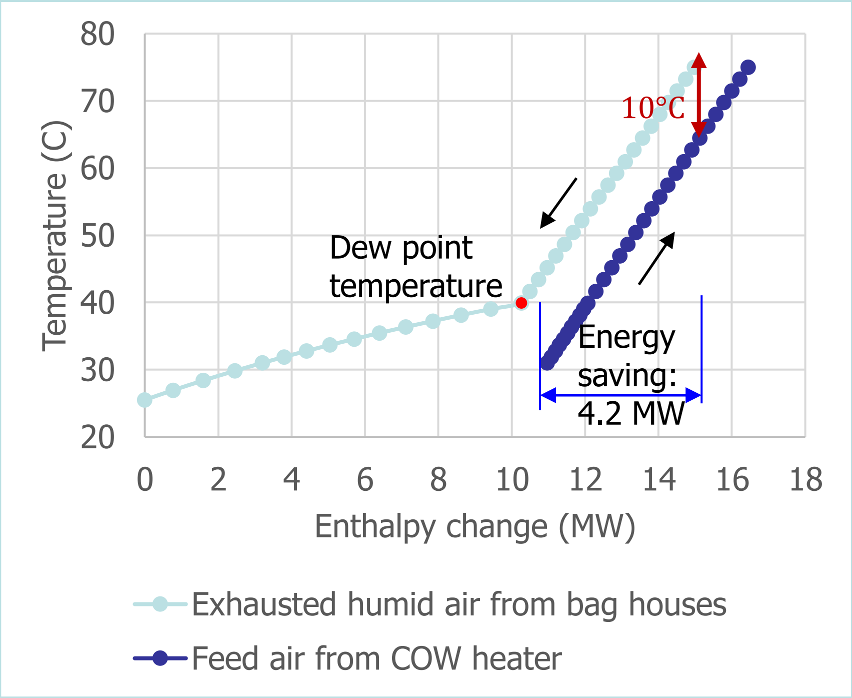
- Taking the environment conditions as the reference state, it is estimated that 19.4 MW of energy accompanying with the exhausted humid air is lost.
- Among this energy loss, 68.6% is attributed to the latent heat of moisture contained in the exhausted humid air.

Modified Spray Dryer Energy Systems

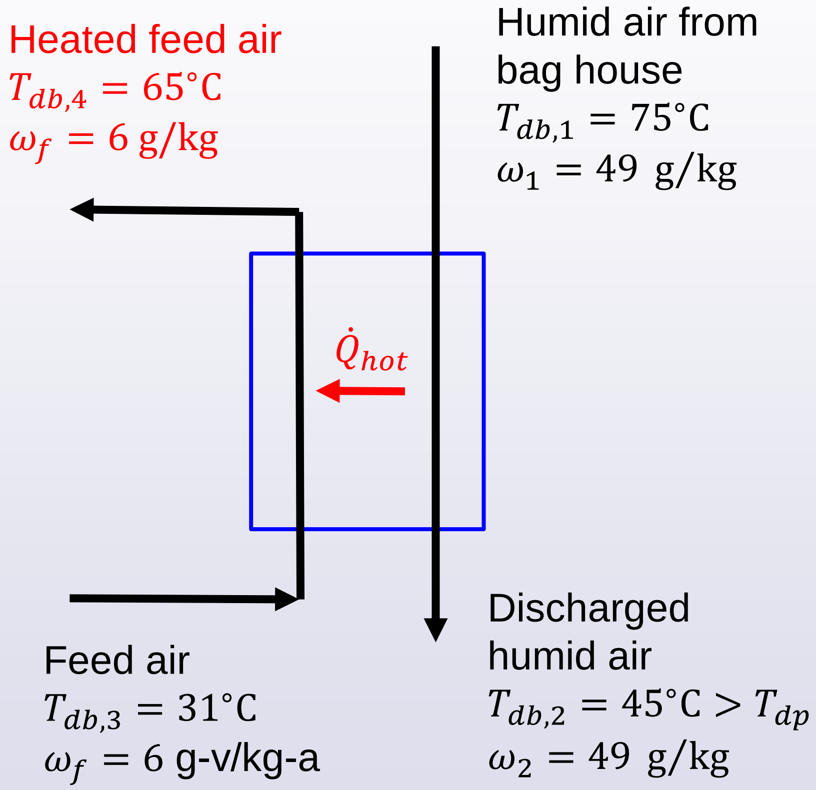


A Simple Heat Exchanger: Pinch Analysis





A Simple Heat Exchanger: Results



- Energy recovery from the most air stream: $\dot{Q}_{hot} = 4.2$ **MW** (19.4 MW lost without energy recovery)
- Heated air temperature: $\mathbf{65°C < 217°C}$ at the dryer inlet using the HP steam heater. HP steam heaters are required.
- 15 MW contained in the humid air stream is lost. Heat pumps may be used to recover this energy loss.

Initial Theoretical Investigations

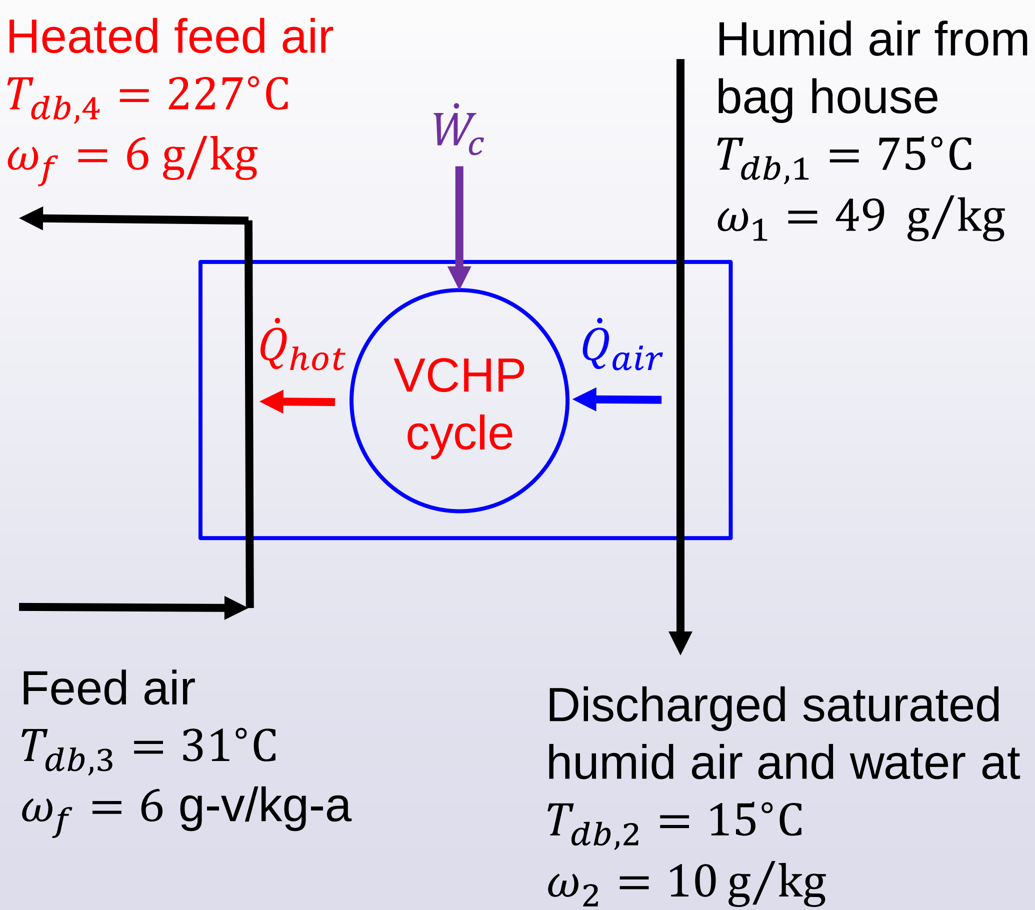
- It is assumed that the heat pump cycles are ideal cycles without irreversibilities.
- For the AHP and HT, it is assumed that there exists a suitable heat sink to discharge heat from the cycles. The heat sink may be cold air from a cooling tower with a temperature of 15°C corresponding to the wet-bulb temperature of local air conditions. In fact, the cooled liquid milk at 5~7°C could be a heat sink.
- For the AHP and HT, electrical power required for driving pumps are ignored.
- It is also assumed that the humid air exhausted from the bag houses can be cooled to the heat sink temperature of 15°C.

Thermodynamic Heat Pump Models

The following laws of thermodynamics are used to theoretically analyse the potentials of the heat pumps for recovering lost energy from spray dryers:

- The mass conservation law
- The first law of thermodynamics
- The second law of thermodynamics

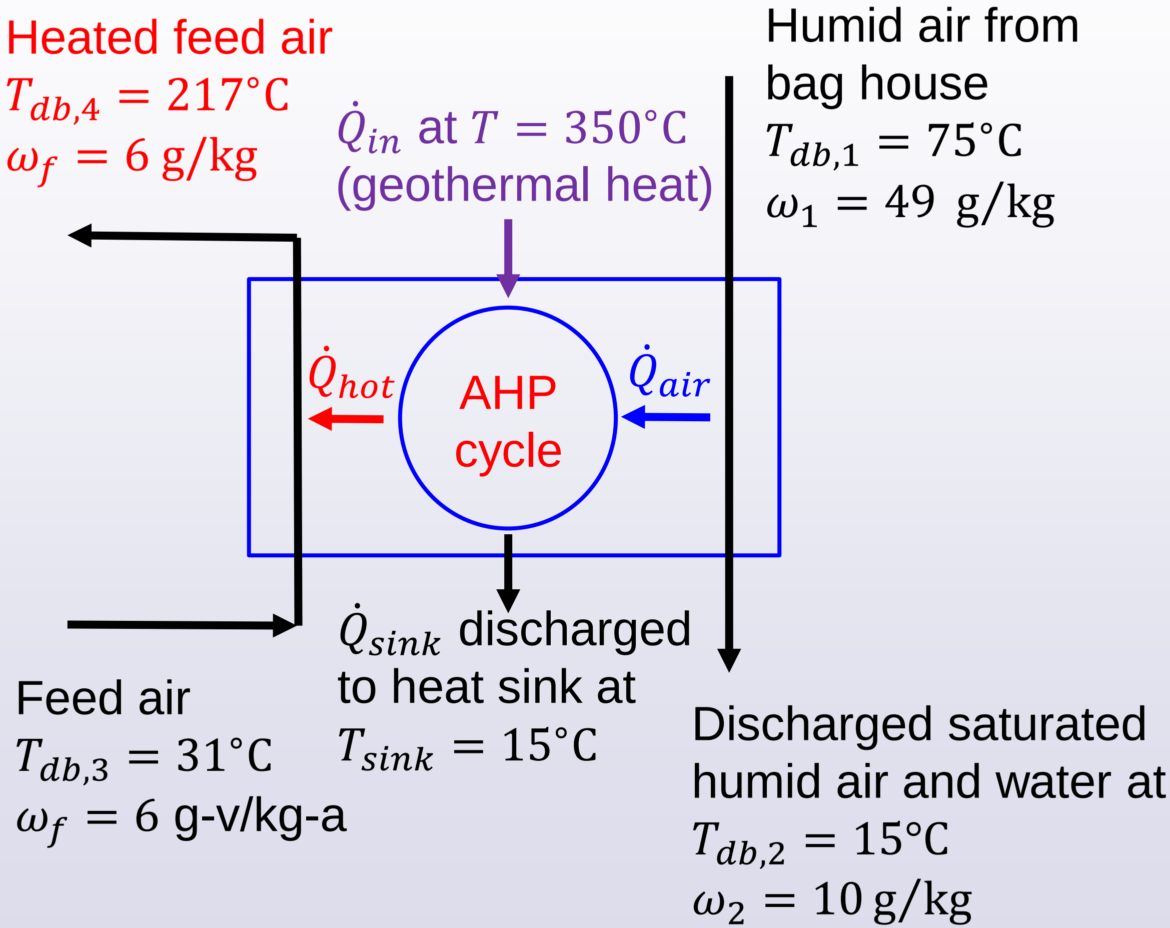
Vapour Compression Heat Pump



- Energy recovery from the most air stream: $\dot{Q}_{air} = 19.6$ MW
- Power of compressor: $\dot{W}_c = 5.6$ MW

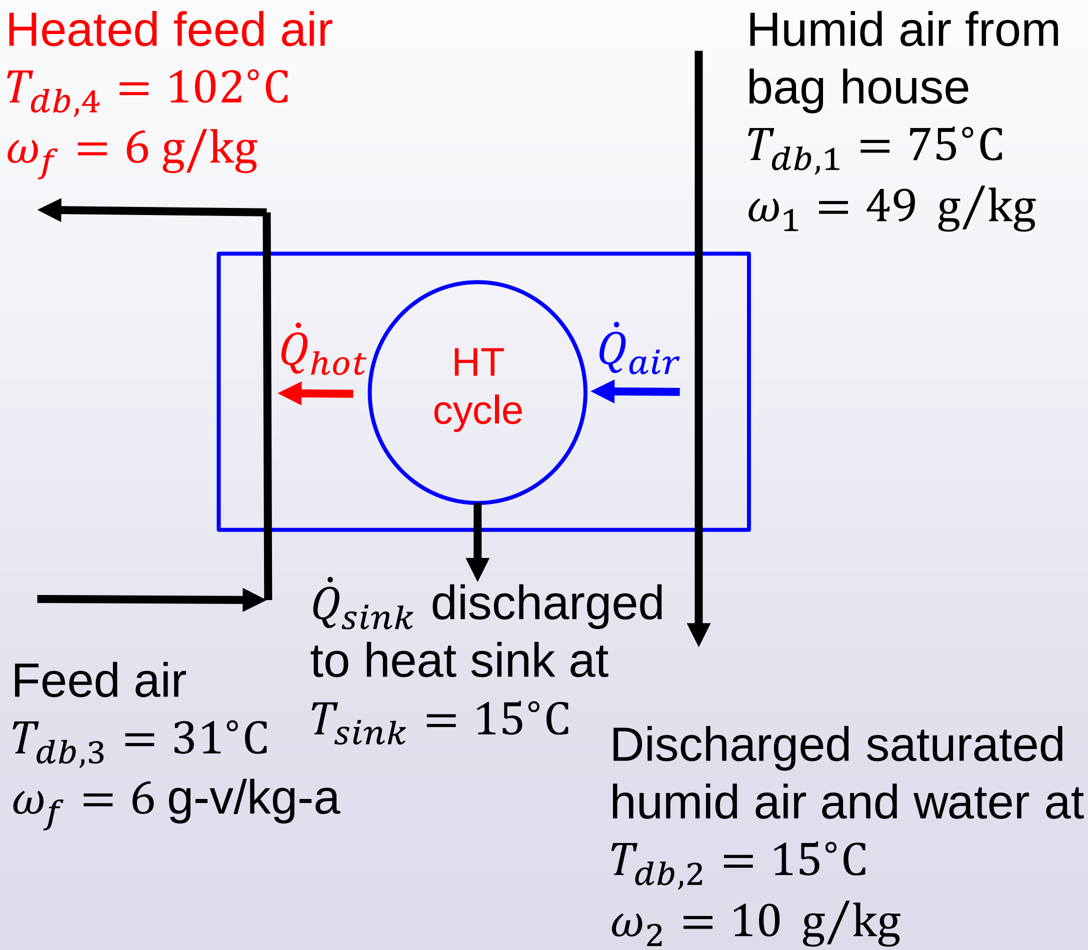
  For comparison: the capacity of the Clyde Dam is 464 MW
- Energy provided to the feed air: $\dot{Q}_{hot} = 25.2$ MW
- Heated air temperature: $227°C > 217°C$ achieved using the HP steam heater
- Theoretical $\text{COP} = \dot{Q}_{hot}/\dot{W}_{comp} = 4.5$

Absorption Heat Pump



- Energy recovery from the most air stream: $\dot{Q}_{air} = 19.6\ \mathrm{MW}$
- Heat supply: $\dot{Q}_{in} = 9.2\ \mathrm{MW}$
- Energy provided to the feed air: $\dot{Q}_{hot} = 23.3\ \mathrm{MW}$
- Heated air temperature: $217°\mathrm{C} = 217°\mathrm{C}$ achieved using the HP steam heater
- Theoretical $\mathrm{COP} = \dot{Q}_{hot}/\dot{Q}_{in} = 2.5$

Heat Transformer



- Energy recovery from the most air stream: $\dot{Q}_{air} = 19.6\ \mathrm{MW}$
- Energy provided to the feed air: $\dot{Q}_{hot} = 8.8\ \mathrm{MW}$
- Heated air temperature: $102°\mathrm{C} < 217°\mathrm{C}$ achieved using the HP steam heater.
- Theoretical $\mathrm{COP} = \dot{Q}_{hot}/\dot{Q}_{air} = 0.45$
- Boilers are still needed. However, no external high quality heat or electrical power is required to drive the cycle.

Potentials of Energy Saving and CO_2 Emission Reduction per Operation Season

	Thermal energy of HP steam saving[a] (TJ/season)	CO_2 emission reduction[b] (k-tonne)
VCHP	612	58
AHP	612	58
HT	380	36

a. Based on the operation season from 1 August to 31 May.
b. Based on the the emission factor for sub-bituminous coal of 0.095 tonne-CO_2/GJ_{th} (Lignite and climate change, Parliamentary Commissioner for the environment, 2010).

Challenges

- High temperature heat pumps need to be developed
  - Reverse Rankine cycles, cascade and transcritical operation
  - Natural refrigerants: water ($T_c = 373.9°C$) and ammonia ($T_c = 132.4°C$), which have no influence on ozone layer and less green house gas emissions
- Optimum integration of the heat pump systems with the spray dryers to minimize both internal and external irreversibilities
- Fouling on heat transfer surfaces could be formed by milk powder particulates contained in the humid air stream
- Is renewable electricity sufficient and is geothermal or high T waste heat available on site, to drive HP cycles?
- Capital cost for high temperature heat pumps

Conclusions

- Industrial dryers are facing challenges
- Change is needed
- Heat pumps offer a powerful option
- High temperature heat pump technology is necessary to be developed and integrated with dryers
- We are keen to establish collaborations to develop industrial high temperature heat pumps

Acknowledgements

- Heat pump timber drying:
  - NZ Foundation for R S & T
  - Croft Poles & Timber Ltd
  - A. Firth, L. Jakobsen, S. Shannon, M. van der Pal, Q. Sun
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  - Engineers and operators of the milk powder plant
  - S. Thornton and M. Mason

Thank you