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Total Site Utility Systems Optimisation for Milk Powder Production

Timothy G. Walmsley*[a], Martin J. Atkins[a], Michael R.W. Walmsley[a], James R. Neale[a], Matthias Philipp[b], Gregor Schumm[b], Ron-Hendrik Peesel[b]

[a]Energy Research Centre, School of Engineering, University of Waikato, Private Bag 3105, Hamilton, New Zealand
[b]Universität Kassel, Dep. Umweltgerechte Produkte und Prozesse, Kurt-Wolters-Straße 3, 34125 Kassel, Germany
timgw@waikato.ac.nz

This study applies the Total Site Heat Integration method, in conjunction with a detailed process and utility model, to investigate three methods to increase the energy efficiency of the utility supply system for milk powder production. Sequentially explored opportunities are: (1) increasing boiler efficiency through condensing economisers, (2) waste heat recovery from the chiller unit, and (3) Combined Heat and Power (CHP) for electricity production. The basis for the analysis is the anticipated future milk powder process design, which incorporates results from recent studies that have focused on improving the process design and integration of the heat treatment and evaporator systems and recovering heat from the spray dryer exhaust, which show a combined specific fuel consumption reduction of 29.6 % and a relatively small increase in electricity use of 4.5 %. To maximise boiler efficiency, the study concludes that a condensing economiser for the flue gas can be indirectly matched with heating fluidised bed air flows through the boiler condensate system, which results in specific fuel use reduction of 227 MJ/t_p. Chiller waste heat can be upgraded and integrated as a heat source to replace the equivalent specific fuel use of 101 MJ/t_p through integration with the site low temperature hot water loop. By designing the steam system to maximise electricity generation in a new turbine, results show that 51 % of the site's electricity demand may be satisfied by CHP. The combined effect of implementing these three utility systems opportunities is a specific fuel use of 3,868 MJ/t_p, of which 530 MJ/t_p result from electricity production, and a specific grid electricity demand of 113.4 kWh/t_p.

1. Introduction

Conversion of raw milk into powdered milk is an energy intensive process requiring steam heating, chilling and electrical utilities. The milk powder process has four main processing steps: milk separation, heat treatment, evaporation, and spray drying. Over the past four decades, there has been significant progress in the energy efficiency of milk powder plants. Specific fuel consumptions have decreased from about 12,000 MJ/t_p of powder to between 5,000 – 6,000 MJ/t_p, while the specific electricity uses are in the order of 150 to 400 kWh/t_p (Ramírez et al., 2006). The absolute fuel and electricity use and split depends on the installed technology, the degree of heat integration, the scale of production, and the utility system efficiency.
Significant improvements to the energy efficiency of the heat treatment, evaporation and spray dryer process through process redesign and additional heat recovery have been reported in literature. Using the appropriate placement principle for a heat pump, Walmsley et al. (2016) demonstrated the optimal use of vapour recompression technology in the process and network design of the combined heat treatment and evaporation systems. The result was a dramatic 78 % reduction in steam use at the expense of a 16 % increase in electricity. For spray dryer systems, exhaust heat recovery presents another significant opportunity to increase energy efficiency. Walmsley et al. (2015b) developed a dryer exhaust heat recovery model, which included economic calculations and fouling predictions, and found that a 14 % reduction in steam through heat recovery was economic for the given site. Beyond these two opportunities, there are more prospects to reduce energy use in milk powder production.

Total Site Heat Integration (TSHI) provides a graphical method for the selection, design, and optimisation of utility systems (Klemeš, 2013). With respect to milk powder factories, TSHI may be applied to target the minimum boiler flue gas temperature (thus maximising boiler efficiency) and Combined Heat and Power (CHP) production for a site. Even though the milk powder process can have a low Pinch Temperature, very few sites in New Zealand have steam boilers equipped with condensing economisers. Likewise, out of the 82 NZ dairy processing sites, only four use CHP technology – NZ Heat Plant Database cited in (Walmsley et al., 2015a). Given the low uptake, it is valuable to explore options for maximising CHP as a means for improving and developing a more attractive business case. Such options include raising the initial steam pressure, the addition of new steam pressure levels to improve the overall heat and powder cascade (Sun et al., 2013), and the complete design optimisation of a new CHP system (Manesh et al., 2012).

Another area in the utility system that can contribute to energy cost reduction is waste heat recovery from chiller units. In most instances this opportunity requires an additional compressor unit to increase the pressure of the chiller's condenser, thereby upgrading its heat so that it may be integrated to fulfil process heat demands. TSHI can aid the selection of the condenser pressure and identify the method for its integration, either direct with process stream and/or via the hot water utility network, using the appropriate placement principle for heat pumps (Yang et al., 2014).

The aim of this paper is to investigate methods to increase the energy efficiency of utility supply operations that are required for milk powder factories given the proposed future designs of the heat treatment, evaporation, and spray dryer processes. In particular the three investigated energy reduction opportunities for the milk powder plant utility system are: (1) increasing boiler efficiency through condensing economisers, (2) waste heat recovery from the chiller unit, and (3) Combined Heat and Powder (CHP) for electricity production.

2. Methods

2.1 Milk powder plant model

A comprehensive heat and mass balance process and utility model of a milk powder factory has been implemented in an Excel^{TM} spreadsheet and validated against industrial data from NZ's current milk powder plant design as well as an anticipated future plant design. Model results are based on a plant capacity of 30 t_p/h, which can be modified for other desired capacities. The model plant without modification has a specific fuel consumption of 5,200 MJ/t_p and an electrical use of 210 kWh/t_p. These are applied as a comparative baseline for the future plant design and the utility optimisation opportunities. The future plant design incorporates a redesigned evaporation system (Walmsley et al., 2016) and dryer exhaust heat recovery (Walmsley et al., 2015b).

2.2 Steam boiler and back pressure steam turbine model

The natural gas steam boiler model, including a deaerator, blowdown vessel and feed water pump, was modelled using Excel Add-in JSteam^{TM} (www.inverseproblem.co.nz). TSHI techniques are applied to maximise boiler efficiency. The composite curve of boiler flue gas (initially at 140 °C), after generating steam and preheating combustion air using a standard economiser, is shifted and pinched against the Total Site Source Profile to target the minimum flue gas temperature, which leads to maximising boiler efficiency.

For CHP, the back pressure steam turbine model estimated performance using the M-P turbine model (Medina-Flores and Picón-Núñez, 2010), which is the best available empirical correlation for single and multiple extraction turbines. Where a turbine (or steam drive) rating falls below the M-P turbine model's lower limit, the model estimates work assuming an isentropic efficiency of 65 %.

2.3 Ammonia chiller model

The chiller model uses the vapour compression cycle with ammonia as the working fluid, a compressor efficiency of 53 %, a condenser pressure of 2,000 kPa, and a Co-efficient of Performance (COP) of 2.3. Thermophysical properties are called from REFPROP^{TM} (http://www.nist.gov/srd/nist23.cfm). The combined chiller/heat pump unit uses a higher condenser pressure (2,600 kPa) that has a saturation temperature of 60 °C. The COP of this unit is 1.8 for chilling and 2.8 for heating. Since the process requires a chiller, it's useful to understand the performance of expending additional electricity to upgrade the condenser heat. The marginal COP* for heating in the combined system may be defined by:

$$COP_H^* = \frac{Q_{H(HP)} - Q_{rej.}}{W_{HP} - W_{LP}} \tag{1}$$

Where subscripts HP refers to a high pressure condenser, LP refers to a low pressure condenser, and rej refers to rejected heat. If all the condenser heat is able to heat process streams (i.e. the rejected heat is zero), then the marginal COP of heating is 13.4.

3. Envisaging future energy efficiency opportunities for the utility system

This section explores three energy efficiency opportunities in the utility system for the future milk powder process design (1.0), as previously described.

3.1 Maximising boiler energy efficiency through condensing economisers

Standard industrial steam boilers for milk powder production operate at 40 bar (250 °C saturated) and are fitted with an economiser. The economiser preheats pressurised boiler feed water before it enters the main evaporation tubes. Depending on the boiler design the flue gas enters the economiser at up to 350 °C and leaves above the acid dew point at 140 °C. An additional condensing economiser can be installed to capture more flue gas heat. There is also a water dew point, which for a natural gas boiler (as considered in this study) is about 60 °C while a coal fired boiler is 40 °C. Extracting additional heat, both sensible and latent (if useful), maximises boiler efficiency and minimises fuel use.

Two sinks within the boiler plant to match with the flue gas in a condensing economiser are the combined condensate return / make-up water flow and the combustion air inlet. The condensate returns from servicing the process at 85 °C, and once combined with the make-up water, the temperature decreases to 68 °C for the current process design and 82 °C for the future design. This difference in temperature is due to current plant design having a lower condensate return percent compared to the expected percent in the future design (74 % to 94 %). The future process design uses less direct steam injection and therefore has a higher condensate return percentage. Matching the combined water flow with the flue gas has a maximum duty of 69 MJ/t_p. Preheating the combustion is another option, but is undesirable due to poor heat transfer coefficients of gas to gas heat exchange. Further sink options beyond the boiler system may be found using TSHI techniques.

The source profile of the Total Site Profiles together with targeted steam and hot water utility profiles may be pinched with the shifted boiler flue gas flow using a ΔT_{cont} of 12.5 °C. Figure 1 plots these source, sink and utility profiles for the future process design. The targeted final flue gas temperature is 58.4 °C and the additional heat extraction from the flue gas is 180 MJ/t_p. The target is influenced by the hot water utility temperature selection. The additional heat extraction from the flue gas has the knock on effect of reducing boiler fuel consumption to meet the process heat demand, which in turns means the flue gas flow rate slightly decreases. As a result the process and utility model becomes an important tool to capture these superimposing effects.

The hot water utility system, as shown in Figure 1, is one sink option for the condensing economiser. This option would require additional piping from the boiler house to the processing buildings. At present the boiler supplies the process with only two steam pressure levels (using a let-down valve) and returns hot condensate in a separate line. Another sink option that requires minimal additional piping between the boiler and process locations is to return cold condensate (35 °C) by placing the heat in a process sink. For the future process design, the Fluidised Bed air flows may be matched with the hot condensate flows to achieve a duty of 232 MJ/t_p. The cold condensate, combined with a small amount of make-up water, then extracts an additional 197 MJ/t_p in a condensing economiser. The overall result is a specific fuel reduction of 227 MJ/t_p, which is actually greater than the initial integration target.

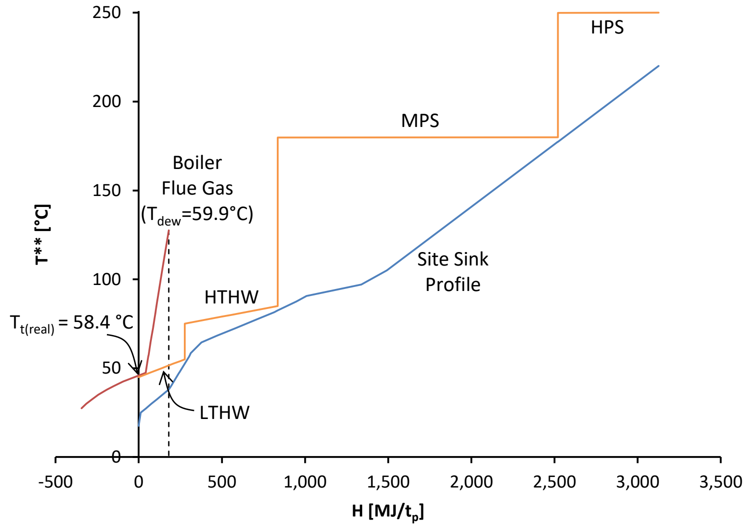

Figure 1: Target for the minimum boiler flue gas temperature by pinching the flue gas profile with the site hot water utility system

3.2 Chiller waste heat upgrading and recovery

The chiller system is an essential utility supply operation of chilled water for process cooling. The condenser is normally air-cooled in a closed loop. With ammonia as the working fluid, the condenser operates at 2.0 MPa, which is a saturation temperature of 49 °C. By increasing the compression to 2.6 MPa, the saturation temperature increases to 60 °C and the heat may be integrated into the LTHW, which has a supply temperature of 55 °C. This can be achieved by installing a second compression stage.

Figure 2 presents how a combine chiller/heat pump system appropriately integrates with the Site Source and Sink Profiles. The Site Sink Profile excludes the portion of heat demand for the Fluidised Bed air streams that is satisfied indirectly through the condensate system using the boiler flue gas. The target boiler heat displacement is 85 MJ/t_p and its integration results in a specific fuel reduction of 101 MJ/t_p. Electrical use increases by 1.8 kWh/t_p, which is a marginal COP_H of 13. In the future plant design, the LTHW system is used to heat HVAC air flows and direct use water applications such as process cleaning, tanker washing, and lactose powder reconstitution.

At some existing dairy factories there is a substantial amount of waste heat, not just from the chiller unit, rejected at about 40 °C. Future work will look at both the integration of heat pumps using chiller and other waste heat, as well as the internal design of the heat pump cycle to match process demand profiles while maximising its COP.

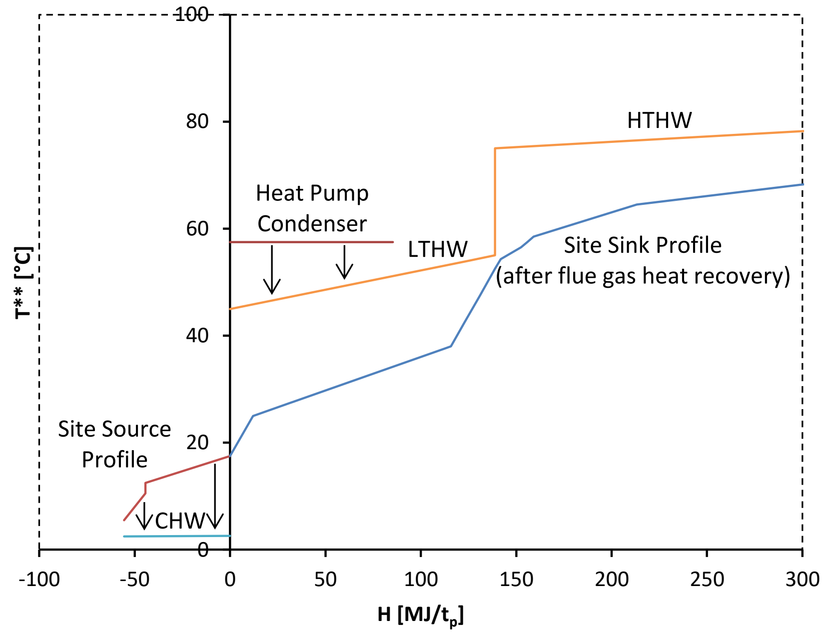

Figure 2: Combined chiller (through chilled water) and heat pump condenser integration with Total Site Profiles. Note: axes are zoomed; only a portion of the Total Site Profiles is shown

3.3 Combined heat and power

The final investigated opportunity within the utility system is CHP using a back pressure steam turbine for electricity production. Using the existing two steam levels and a turbine to drop the required steam from 40 bar to 10 bar for the MPS demand gives an electricity production of 46.4 kWh/t_p, which for a production rate of 30 t_p/h is a 1.4 MW turbine, at an isentropic efficiency of 67 %. A turbine installation for only 1.4 MW of electricity generation struggles to find economic justification. Alternatively, plant equipment such as fans may be driven by steam turbines instead of electric motors.

CHP can be increased by adding a VHPS level with superheat and an LPS level. The LPS level requires additional piping to go from the boiler house to the process building. Figure 3 presents the enhanced CHP system using the Total Site Profiles. These changes to the steam system increases electricity production by 133 % to 108.1 kWh/t_p. In this case self-generation of electricity reduce grid draw by 49 %.

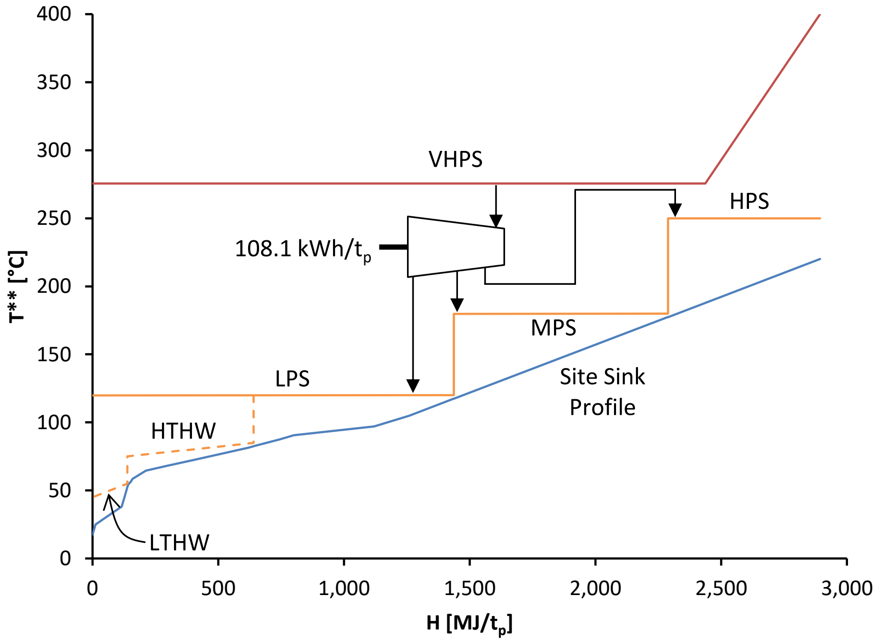

Figure 3: Combined heat and power system using Total Site Profiles.

Table 1: Specific energy use of major processing units in future generations of milk powder plants excluding (1.0) and including (2.0) utility systems optimisation opportunities.

Zone	Major Equipment	Thermal Energy Use [MJ/t_p]		Electrical Use [kWh/t_p]	
		1.0	2.0	1.0	2.0
Milk Separation	Cream pasteurisation	11	11	-	-
	Process pumps	-	-	13.1	13.1
Heat Treatment & Evaporators	Heat treatment	208	210	9.7	9.7
	MVR and TVR units	-	-	93.9	93.9
	Process pumps	-	-	2.6	2.6
Spray Dryer	Air heaters	2,610	2,377	-	-
	Feed heater and pump	131	131	7.8	7.8
	Process fans	-	-	46.4	46.4
	Product handling	10	10	22.1	22.1
Utility Services	CIP	74	74	-	-
	HVAC	83	83	7.3	7.3
	Chiller unit	-	-	6.7	8.5
	Compressed air unit	-	-	6.8	6.8
	Boiler pump and fan	-	-	3.3	3.2
	Thermal losses	537	441	-	-
	Electricity generation	-	530	-	108.1
Totals	Excluding CHP	3,663	3,338	219.9	221.6
	Including CHP	-	3,868	-	113.4

4. Comparison of energy use for current and future milk powder plant designs

The milk powder plant model has been applied to calculate thermal and electrical energy demand for three designs: the current plant design, the future process design (Design 1.0), and the future optimised process and utility design (2.0). Table 1 compares the thermal and electrical energy for the two future designs, broken down into processing zone and major plant equipment. The figures are presented as specific energy per tonne of milk powder produced.

The future process design, which includes improvements to the heat treatment, evaporator and spray dryer process, achieves an overall specific fuel reduction of 29.6 %. A key element of the new designs is the increased use of Mechanical Vapour Recompression technology in the evaporator process. This is the main driver for electricity use increasing by 4.5 %. The air heaters contributes 55 % of thermal energy demand in the current process design and 71 % in the future process design. As Table 1 shows, the reduction in process heat demand has the natural consequence of reducing boiler thermal losses since less steam is required.
Implementing a condensing economiser in the boiler system and upgrading chiller waste heat further reduces fuel use by 6.3 %, which is an overall reduction of 35.9% compared to the current plant design. CHP uses an extra 530 MJ/t_p of fuel (15.9 % increase compared to the fuel use in design 1.0) to efficiently generate electricity, which lowers the site's grid draw. In the 2.0 design, CHP provides 51 % of the total electricity requirement.

5. Conclusions

Maximum boiler efficiency for milk powder production is achieved by installing a condensing economiser for the flue gas to indirectly heat fluidised bed air flows through the boiler condensate system. This is best achieved by matching the hot condensate return flows to heat the fluidised bed air and then returning the cold condensate to the boiler to be reheated in the condensing economiser prior to deaeration. As a result specific fuel use decreases by 227 MJ/t_p. Chiller waste heat can be integrated as a heat source with a marginal COP of 13 by expending more electricity to increase the pressure of the condenser. The condenser may replace the equivalent specific fuel use of 101 MJ/t_p through integration with the site low temperature hot water loop. By designing the steam system to maximise electricity generation in a new turbine, results show that 51 % of the site's electricity demand may be satisfied by CHP. The combined effect of implementing these three utility systems opportunities is a specific fuel use of 3,868 MJ/t_p, of which 530 MJ/t_p results from electricity production, and a specific grid electricity demand of 113.4 kWh/t_p. Future work will extend the search to longer-term energy efficiency opportunities in the processing system as well as performing a cost-benefit analysis. Without CHP, the new specific fuel use is 3,338 MJ/t_p, which is a 35.9 % reduction from the current plant design, and the increased electricity use is 221.6 kWh/t_p, which is a 4.5 % increase. Future work will extend the search to longer-term energy efficiency opportunities in the processing system as well as performing a detailed cost-benefit analysis.

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