



Steam Cogeneration Heat Pumps for the Food, Dairy and Meat Industries

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Introduction

Steam cogeneration, or multi-temperature [1], heat pumps (SC-HTHPs) represent a transformative opportunity for decarbonising thermal energy supply in the food, meat, and dairy industries, sectors characterised by simultaneous heating and cooling demand [2,3]. Unlike traditional cogeneration systems, where fuel inputs generate both heat and power, a different design paradigm for industrial utility systems is emerging and inversely structured: electrical power flows into the system to upgrade heat (i.e., heat upgrade technologies), enabling efficient and flexible electrification of industrial steam services [4]. This “power-to-heat cogeneration” model redefines utility system design. Here, this study applies pinch analysis to investigate the potential integration of high-temperature heat pumps (HTHPs) as cogenerative utility systems, producing both steam and hot water utilities. Focus is given to simple heat pump cycles capable of significant subcooling.

Pinch analysis and its appropriate placement principle for heat pumps [5] provide a thermodynamically rigorous approach to determining where heat pumps should be located within a plant and across an industrial site. A key output of pinch analysis is the *Pinch Temperature* (or temperature range); above which process heating is needed and below which process cooling is needed. Engineers attempt to design systems to maximise heat recovery by avoiding *cross-pinch* heat transfer—i.e., sources at temperatures above the pinch transferring heat to sinks at temperatures below the pinch. After maximising heat recovery, heat pumps can be considered. Through detailed pinch analysis of representative food, meat and dairy processes, this study quantifies recoverable heat sources, viable temperature lifts, and achievable coefficients of performance using OpenPinch [6]—an open-source tool for conducting pinch analysis and the heat integration of heat pumps. The discussion then focuses on deducing principles and

patterns that guide the design and integration of heat pump systems to generalise the applicability of the ongoing research efforts.

Methods

The Open Pinch library in Python [6] embeds the core pinch analysis algorithms and advanced heat pump integration methods (under development) to enable systematic industrial application. Figure 1 provides an illustration of how pinch analysis through net load profiles, such as the Grand Composite Curve (GCC), can identify appropriate condenser and evaporator temperatures and lead to possible heat pump cycle system architectures. As an abstract principle, heat pumps aim to absorb heat at temperatures below the cold-side pinch temperature and release heat at temperatures above the hot-side pinch temperature. Next, net load profiles provide insight to both the temperature and duty of condensers and evaporators, as well as subcooling potential. The illustrative example shows the placement of two condensers and one subcooler for providing heating, (replacing e.g. fossil fuel fired boiler) and one evaporator for providing the cooling (replacing e.g. a cooling tower). A balance between complexity and performance must be struck when deciding the number of condensers (including gas coolers and subcoolers) and evaporators to target. From this point, concrete system architectures can be deduced, such as two simple vapour compression cycles. Other architectures are also possible, such as a cascade heat pump or a multi-temperature heat pump.

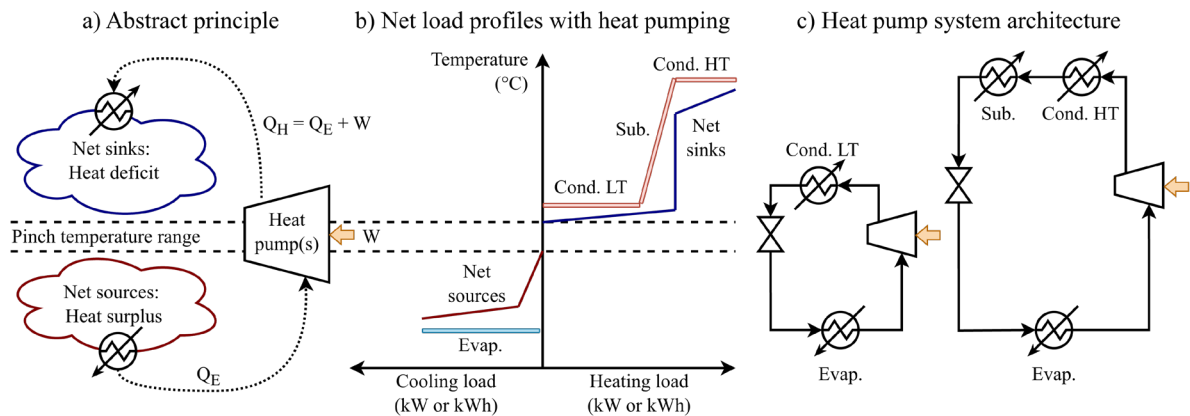


Figure 1: Appropriate heat pump integration as an abstract principle with its relationship to net load profiles from pinch analysis (e.g., the grand composite curve, total site profiles, etc.) and one possible heat pump system architecture.

Results

Chocolate Factory. This site involves 13 distinct processes (including an existing integrated refrigeration plant) that operate on various schedules. At the site-level, the net heating requirement is 1,331 kW and the net cooling requirement is 3,651 kW. Most processes are dominated by either heating or cooling. As a result, direct heat integration through conventional pinch analysis is less effective due to the need to exchange heat between processes. Instead, focus is given to site-level heat pump integration where heat can be transported using an intermediate energy carrier (i.e., existing utility lines), upgraded through the heat pump and potentially stored to enable source/sink timing differences. In this analysis, existing utility loads and temperatures are measured to provide the basis for integrating a heat pump. The refrigeration load appears as waste heat requiring cooling in the net load profiles. Results for this case study (Figure 2) show that single heat pumps with substantial subcooling generally achieves better total system COPs with R601A being the highest. For R601A, the condenser heat generates the low-pressure steam, LPS, while the subcooling creates hot water, HW. Medium pressure steam (MPS) is supplied external to the heat pump, e.g., by a boiler. The remaining cooling water load is sent to a

cooling tower. There are many other factors to consider, such as the volumetric heating capacity and safety of the system.

Figure 2: Net load profiles for site utilities of a Chocolate Factory, partly supplied by an optimised single R601A heat pump with subcooler and internal heat exchanger. Table insert – Heat pump cases investigated for supplying hot water (HW) and low-pressure steam (LPS) using cooling water (CW) as the source. Medium pressure steam (MPS) is supplied external to the heat pump, e.g., by a boiler. The remaining cooling water load is sent to a cooling tower.

Figure 3: Net load profiles for site utilities of a Dairy Factory, partly supplied by an optimised two heat pump system (R601 and Ammonia), each with subcoolers and an internal heat exchanger. Table insert – Heat pump cases investigated for supplying hot water (HW) and low-pressure steam (LPS) using cooling water (CW) as the source. High pressure steam (MPS) is supplied external to the heat pump, e.g., by a boiler. The remaining cooling water load is sent to a cooling tower.

Dairy Factory. This site has 10 processes with similar operating characteristics as the Chocolate factory. As a result, the same approach is taken with results in Figure 3. Results for this case study show that

two heat pumps with R601 and Ammonia would yield the highest system COP. A greater share of HW compared to LPS is needed for the Dairy Factory; as a result, the temperature matching between a single heat pump system and the utility supply loads is poorer than the two heat pump systems.

Meat Processing Factory. In this factory, there are four main processes. Rendering has significant heating and cooling needs (Figure 4–left) where spent process vapour (mainly water) could be recompressed and recycled within the process [7]. By applying mechanical vapour recompression, the spent gas acts as the refrigerant in an open heat pump cycle. Once this heat pump is applied, the site heating demand reduces to about one third of the initial requirement (Figure 4–right). Here, a single R600 heat pump could be optimised to generate low pressure steam and two grades of hot water.

Figure 4: Net load profiles for the Rendering process (with an MVR), left, and site utilities (after installing an MVR in Rendering), right, of a Meat Processing Factory. Utility generation is an optimised single heat pump system (R600) with subcooling and an internal heat exchanger.

Experimental heat pump system (ongoing work). Complementing the analytical work and as ongoing through 2026, an experimental 50 kW steam and hot water cogeneration heat pump test bed is under development at the University of Waikato, New Zealand. Designed to produce up to 1 – 3 bar steam and cogenerate 65 – 90 °C hot water, the facility will provide empirical data on performance, able to assess control strategies, and analyse demand-response operation under local climatic and industrial conditions. New Zealand currently has no steam generating heat pump at any scale; as a result, this is a first for the country and a significant milestone in the industrial decarbonisation journey of New Zealand.

Discussion

To summarise key learnings and generalise our ongoing research, we have synthesised three principles and four patterns to help guide practicing engineers in their analysis and formulation of heat pump integration and design solutions. The OpenPinch library focuses on implementing optimisation methods for achieving the first two principles and works with any defined heat pump architecture.

Principles. The principles of the appropriate heat integration and design of heat pumps are:

Principle 1 – Effective heat pumping upgrades heat at temperatures below the cold-side pinch temperature to temperatures above the hot-side pinch temperature. Pinch temperatures are driven by the potential for heat recovery within a process or site. Thus, to follow this principle, a design should

first maximise heat recovery; otherwise, it is likely that the heat pump has the system COP of an electric heater or that some or all the heat pumping could be achieved through direct heat recovery with much less cost.

Principle 2 – Efficient heat pump integration minimises the mean temperature lift for a given heat load target. This second requirement encourages close temperature matching between the heat pump condenser and evaporator and the process sink and source. Practical issues, such as distance and timing of source/sink, often stand in the way of achieving the ideal, and these issues needed to be treated as constraints in solution development.

Principle 3 – Efficient heat pump units minimise internal entropy generation. This final requirement addresses core heat pump decisions, including choice of refrigerant, compressor and heat pump type and configuration. Together, these decisions focus on maximising performance for defined heating and cooling loads and temperatures.

Patterns. Heat pump integration typically follows one of the following four patterns.

Pattern 1 – Direct process gas compression. If process gas cooling is needed below the pinch, it may be considered as the working fluid for an open cycle heat pump. Mechanical vapour (re)compression (MVC and MVR) technology, for example, can be applied to upgrade the gas temperature to above the pinch, providing useful heating to the process. This pattern is common in distillation columns/trains and evaporators.

Pattern 2 – Direct process heat supply. Here, a conventional heat pump with a suitable refrigerant supplies heating and cooling directly to process streams. It is normally localised to a specific plant within a site where sources and sinks operate synchronously. Heat storage potential relies on buffers and tanks for the process fluid where flow manipulation is constrained by production goals.

Pattern 3 – Dedicated hot water loops. In this integration pattern, dedicated water loops carry the heating and cooling duty from the heat pump to specific process streams, physically separating the heat pump and process. Like the previous two patterns, it is localised to a specific plant, avoids issues related to refrigerant leakage into sensitive project, and aims to minimise, or eliminate, any required heat storage to account for source and sink timing mismatch.

Pattern 4 – General site utility supply. This final pattern involves integrating the heat pump into the central utility system to generate general site hot water and steam. The main heat sources are cooling/refrigerated water loops, direct compression of existing refrigerant gas, as well as air and river water depending on the heat balance. This approach maximises the re-use of existing piping and auxiliary infrastructure because it is a like-for-like utility supply replacement of conventional boilers.

These patterns embed the classic capital investment-to-energy efficiency trade-off. The selection of the integration can also impact how the pinch analysis is carried out and the formulation of the stream data. For example, Pattern 1 requires detailed process stream data, whereas Pattern 4, at its simplest, only needs the utility temperature and flow data. This data requirement underpins the specific type of net load curve that the engineer relies on to define the pinch temperatures and formulate solutions.

Net load profiles. Pinch analysis and total site analysis are complimentary strategies for analysing processes, sites and districts (local areas). Both techniques use the same core targeting algorithms and yield net heating and cooling load profiles for different parts of a system: the grand composite curve, total site profiles, and the site utility grand composite curve, to name the most common [8]. These curves represent different basis for deciding the placement of one or more heat pumps. As a result, the heat integration pattern and the level of process/site data available influence the type of depth and breadth of

the analysis. It is recommended to investigate multiple approaches to ensure the best solution is found since the installation of a heat pump is a significant capital investment.

Site-specific factors. There are many additional integration challenges for heat pumps, including: operation, control and dynamics; space constraints; re-use of existing infrastructure; electrical supply and network connection; financial model and cost analysis; environmental impact; etc. These are case-specific issues that need thorough consideration when developing a full business case.

Conclusion

This study successfully demonstrated the application of the OpenPinch library to develop pinch-based solutions for the heat integration of heat pumps at chocolate, meat processing and dairy factories. The pinch-based analysis approach demonstrates a foundation for developing heat pump-centred industrial utility systems that are customised and enable decarbonisation through efficient and effective multiple utility cogeneration.

Acknowledgements

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