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Heat Pump Integration by Pinch Analysis for Industrial Applications: A Review

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The aim of this paper is to review energy-efficient integration applications of vapour-compression heat pumps for various industries and processes based on the Grand Composite Curve (GCC) and to demonstrate its savings potential. A method was applied to directly deduce the integration parameters from the GCC by Coefficient of Performance (COP) curves. This approach has been applied to various case study data. Typical integration concepts are presented graphically and evaluated quantitatively using the COP. For a system efficient application, the heat pump must be integrated across the pinch. In particular, the food, paper, electroplating, metalworking and chemical industries are suited for heat pump integration with their unit operations of cooling, bathing and process heating, domestic hot water (DHW), drying and space heating. Their integration concepts show COPs from 2.2 to 5.8 with temperature lifts from 32.5 to 102 K and cover 23 to 100 % of the process heat demand and 28 to 82 % of the cooling demand.

1. Introduction

Increasing energy efficiency and the share of renewable energy are two significant ways to reduce greenhouse gas emissions in the framework of the global energy transition. First, with regard to the onion layer model, the potential for reducing process energy demand can be identified using Pinch Analysis methods (Kemp, 2007). After identifying the potential for increasing energy efficiency at process level through direct heat recovery, further energy savings are possible by Total Site Heat Integration (Klemeš, 2013) including heat recovery loops (Schlosser et al., 2018). The remaining heating and cooling demands can be simultaneously met through heat pumps (Seevers et al., 2018). Heat pump technology powered by renewable electricity can efficiently upgrade low-temperature surplus heat into high-quality thermal process heat, mitigating the emission of substantial greenhouse gases.

Arpagaus et al. (2018) showed in a market review that high temperature heat pumps (HTHP) are commercially available for various process specifications with respect to heat source and sink temperatures, thermal load, and efficiency. Furthermore, multi-temperature heat pumps are appropriate devices using multiple heat sources at different temperature levels to additionally increase system efficiency. Application examples of multi-temperature heat pump concepts include refrigeration, air-conditioning and water heating.

Due to the multitude of possible heat sources and sinks and their coupling in a manufacturing site, the identification of a suitable integration point of a heat pump is a challenging task. Pinch Analysis is a suitable method for the correct thermodynamic integration of heat pumps into industrial processes. Based on the temperature-load profile of the Grand Composite Curve (GCC) and the location of the Pinch Temperature, the integration of different heat pump concepts can be derived (Townsend and Linnhoff, 1983). Based on the state changes in the log(p)-h diagram of a heat pump cycle, suitable integration concepts ideally closely mirror the GCC profiles' charateristic shapes. Typical integration concepts can then apply to similar GCC in the same industry or process unit operation.

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The aim of this study is to review and identify sector- and process-specific integration concepts for heat pumps based on the evaluation of typical GCCs. In particular, the focus is on the evaluation of typical Pinch Temperatures of industrial processes in the food, paper, electroplating, metalworking, and chemical industries. By assessing the integration's efficiency (COP), the process-specific potential is quantified in terms of relative energy savings.

2. Targeting heat pump integration

Pinch Analysis provides a thermodynamic based lens to gain insights into heat flow constraints within processes and sites. By collecting stream data for heat flows and temperatures, Composite Curves – cumulative heat source and sink profiles – can help target practical levels of heat recovery and design an efficiency Heat Exchanger Network. Another important tool is the Grand Composite Curve (GCC), which expresses the net difference between source and sink profiles. The Pinch temperature(s) and utility targets for multiple temperature levels can be determined from the GCC.
The Pinch temperature plays an essential role in the appropriate integration of heat pumps, i.e. recover low-grade heat from below the Pinch and then providing heat above the Pinch. The shape of the GCC and the position of the Pinch explicitly determine the integration point and the design of the heat pump. For some industrial processes, typical GCC profiles can identify appropriate heat pump applications.
The premise for heat pump dimensioning is to integrate the heat as completely as possible into the process and to minimise the remaining demand. Technical, environmental and economic aspects need consideration as part of the design process. The COP range of industrial heat pumps is between 2.4 and 5.8 with a temperature lift from heat source to sink of 40 to 95 K (Arpagaus et al., 2018). From a compressor efficiency point of view, single-stage heat pumps should not exceed a temperature lift of about 50 K. Eq(1) assesses the environmental and economic feasibility of heat pump integrations.

$$COP_{real} > \max\left\{\frac{GEF}{EF_{fuel}/\eta_{boiler}},\ \frac{p_{el}}{p_{fuel}/\eta_{boiler}}\right\} \tag{1}$$

Where GEF is the Grid Emissions Factor, EF_{fuel} is the emissions factor of the fuel, η_{boiler} is the overall boiler system efficiency, p_{el} is the price of electricity and p_{fuel} is the fuel price.
Figure 1 presents the approach for dimensioning a heat pump for a given GCC. It assumes that the heat exchanger network fully exploits its realistic heat recovery potential. Otherwise, the potential for a heat pump may increase further. The first step is to analyse available heat sinks and sources in the processes for the integration of a heat pump. Figure 1a displays the average heat load of all sink and source streams at the corresponding temperature levels of a metal processing plant (Wellig and Grüninger, 2014). Often the target temperature of the heat sink process ($T_{t,Sink}$) is decisive. Thereupon, it must be checked whether the heat demand can be completely covered by heat pumping the available heat ($\dot{Q}_{a,Sink}$) to the target sink temperature. In this case, the condensing capacity ($\dot{Q}_{Cond,HP}$) at $T_{t,Sink}$ and corresponding condenser temperature ($T_{Cond,HP}$) can be read from the GCC (red line on Figure 1a).
The corresponding evaporation capacity ($\dot{Q}_{Evap,HP}$) accounts for a real COP (COP_{Real}) according to Eq(2) and Eq(3). The quality grade ζ_{HP} (also known as the 2nd Law efficiency) describes heat pump efficiency as a function of the evaporation temperature ($T_{Evap,HP}$) and temperature lift (ΔT_{Lift}). These parameters determine the choice of refrigerant and the selection and connection of hydraulic components. Most experimental ζ_{HP} data of industrial heat pumps range between 40 and 60 % (Arpagaus et al., 2018). The current review of applications applies ζ_{HP} = 0.55 (Becker, 2012).

$$COP_{Real} = \zeta_{HP} \cdot COP_{Carnot} = \zeta_{HP} \cdot \frac{T_{Cond,HP}}{T_{Cond,HP} - T_{Evap,HP}} = \zeta_{HP} \cdot \frac{T_{Cond,HP}}{\Delta T_{Lift}} \tag{2}$$

$$\dot{Q}_{Evap,HP} = \dot{Q}_{Cond,HP} - P_{el} = \dot{Q}_{Cond,HP} \cdot \left(1 - \frac{1}{COP_{Real}}\right) \tag{3}$$

The choice of the evaporation temperature ($T_{Evap,HP}$) and the correlated evaporation capacity ($\dot{Q}_{Evap,HP}$) is determined by the COP curve (Stampfli et al., 2018). If the evaporation capacities are calculated for the shifted temperatures from the Pinch Temperature to the coldest source temperature according to Eq(4), they form the COP curve (green line in Figure 1a).

$$\dot{Q}_{Evap,HP} = \dot{Q}_{Cond,HP} \cdot \left(1 - \frac{T_{Cond,HP} - (T_{t,Source} - 5/4 \cdot \Delta T_{HEX})}{\zeta_{HP} \cdot T_{Cond,HP}}\right) \tag{4}$$

Figure 1b indicates two heat transfers: (1) between process stream and heat recovery loop (HRL), a closed-circuit coupled loop, and (2) between the heat pump and HRL. To ensure a sufficient driving temperature gradient, an exchanger-specific temperature difference (ΔT_{HEX}) is selected. A value of $\Delta T_{HEX} = 5$ K is chosen, which is often a good trade-off between the investment and energy costs (Becker, 2012). Condensation ($T_{Cond,HP}$) and evaporation ($T_{Eva,HP}$) temperatures are defined by Eq(5) and Eq(6) according to the GCC (Figure 1b) containing the two heat transfers.

$$T_{Cond,HP} = T_{t,Sink} + 5/4 \cdot \Delta T_{HEX} \tag{5}$$

$$T_{Evap,HP} = T_{t,Source} - 5/4 \cdot \Delta T_{HEX} \tag{6}$$

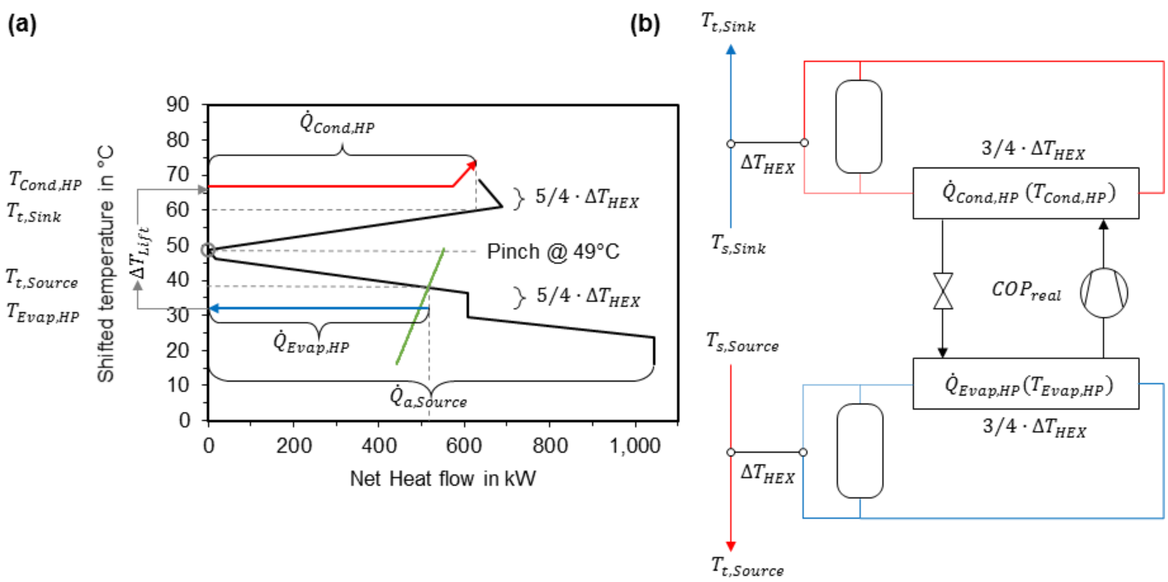

Figure 1: (a) Dimensioning of a heat pump by GCC and COP curve for a metal processing (data adapted from (Wellig and Grüninger, 2014). (b) Schematic illustration of the corresponding heat pump parameters

The intersection point of the GCC (black line) and COP (green line) curves defines the required evaporation load. From $T_{t,Source}$ minus $5/4 \cdot \Delta T_{HEX}$, the required $T_{Evap,HP}$ can be targeted. The shift of $5/4 \cdot \Delta T_{HEX}$ results from the following logic. Firstly, a full ΔT_{HEX} must be ensured for heat transfer between the process stream and HRL. Secondly, for the latent heat transfer from the evaporator (or condenser) to the HRL, a smaller exchanger minimum temperature difference, equivalent to $3/4 \cdot \Delta T_{HEX}$, is applied due to its higher heat transfer coefficient (Stampfli et al., 2018). Since the process streams are already shifted by 1/2$\cdot$ ΔT_{HEX} in the GCC, the total remaining required temperature shift is 5/4$\cdot$ ΔT_{HEX} to fully account for the two heat exchangers.
If the heat source is insufficient, the condenser capacity is determined by the COP curves as a function of the available heat capacity $\dot{Q}_{a,Source}$ at a fixed evaporator temperature using the same logic as Eq(4).

$$\dot{Q}_{Cond,HP} = \dot{Q}_{Evap,HP} \left(1 - \frac{1}{\zeta_{HP}} \cdot \left(\frac{T_{t,Sink} + 5/4 \cdot \Delta T_{HEX}}{T_{t,Sink} + 5/4 \cdot \Delta T_{HEX} - T_{Evap,HP}}\right)^{-1}\right)^{-1} \tag{7}$$

Within an industrial sector, the GCCs can be similar due to the same unit operations. In this paper, several GCCs of the same industry are compared and a representative mean GCC was extracted. In this way, typical integration concepts can be derived from the characteristic shape of the GCC and the position of the Pinch temperature. Furthermore, the relative savings potential ($q_{sav,i}$) of the remaining heating and cooling demand after exhausting the heat recovery potential can be quantified by the ratio from covered heat demand ($\dot{Q}_{i,HP}$) and available heat ($\dot{Q}_{a,i}$) according to Eq(8).

$$q_{sav,i} = \dot{Q}_{i,HP}/\dot{Q}_{a,i} \tag{8}$$

3. Application to six industrial case studies

A typical integration concept for heat pumps in a metal processing plant has been shown in Figure 1. Due to their functional sequence of heat sources (e.g. manufacturing of parts) and heat sinks (e.g. washing of parts and space heating) in a production line, metal processing companies (Figure 1a) are suitable for the use of conventional electrical closed vapour-compression cycle heat pumps (CCCel) (Seevers et al., 2018).
Figure 2a and b illustrate two examples of meat-processing plants using CO2 heat pumps (Fritzson and Berntsson, 2006; Philipp et al., 2018). Meat processes often have a high heating demand for DHW along a large temperature glide of more than 20 K, as well as a large amount of chilled water. In such applications, CO_2 heat pumps are suitable for heating over a temperature glide due to their transcritical operation (Nekså, 2002). At this point, the Lorentz COP for a transcritical cycle is determined in conjunction with Eq(3) to obtain the COP curve.

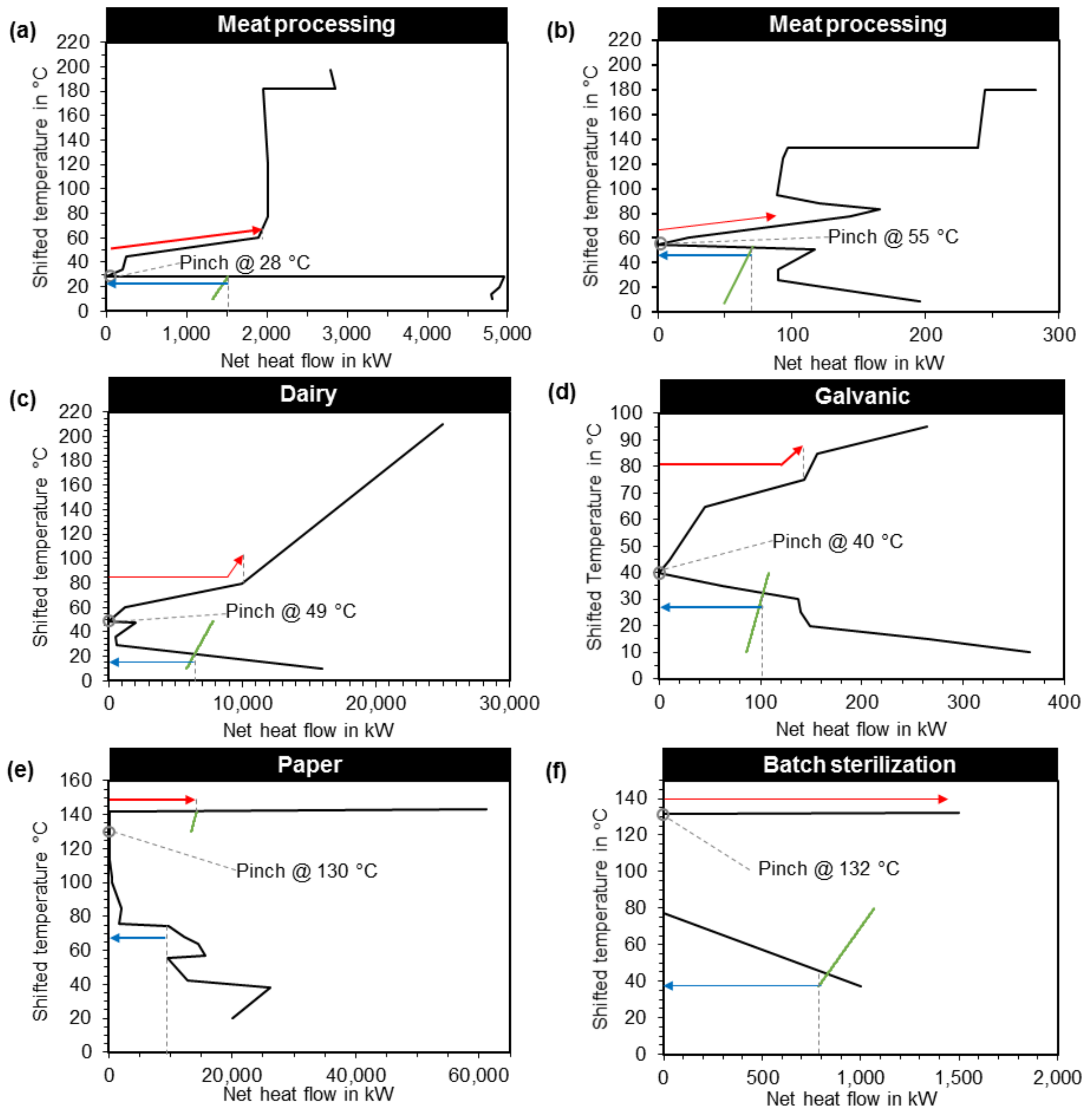

Figure 2: GCC-specific HP integration in (a, b) meat-processing plants with CO_2 heat pumps (Fritzson and Berntsson, 2006; Philipp et al., 2018), (c) dairy site (Atkins et al., 2011), (d) galvanic process (Cu/Ni/Cr coating), (e) paper machine (Axelsson and Berntsson, 2005), and (f) batch sterilisation process (Peesel et al., 2016).

Figure 2c and d further illustrate integration concepts for a dairy processing site (Atkins et al., 2011) and a galvanic process (Cu/Ni/Cr coating). In the food industry, especially in dairy processing, ammonia chillers traditionally provide the required cooling demand. If a heat pump circuit or a second compressor stage (2-staged CCC_{el}) increased the temperature level of the rejected condenser load, the heat can be used for DHW or process

heat instead of being dissipated to the environment (Kapustenko et al., 2008). The examples also show the synergies between reducing cooling efforts and at the same time providing useful heat. Electroplating and metal processing can use heat pumps for both heating and cooling as part of necessary processing steps. Considering the double impact of heating and cooling savings, it improves the suitability of the integration concepts further.
Figure 2e shows the heat pump integration possibility for a paper machine (Axelsson and Berntsson, 2005) according to Eq(7), and Figure 2f for a batch sterilisation process (Peesel et al., 2016). The principle of utilising the latent evaporation enthalpy of humid air by a heat pump during drying of, for example, paper (Haasteren, 2017) can be transferred to other drying applications, such as drying of wood or malt.
Processes with higher temperature requirements (see Figure 2f) can be achieved by multi-temperature heat pumps, e.g. by combining conventional heat pumps with mechanical vapour recompression (MVR). Since the heat pump should always be integrated across the pinch, HTHP are suitable for high Pinch Temperatures or large temperature lifts. Electrically driven compression heat pumps are commercially available today, operating at condensing temperatures of up to about 130 to 165 °C. However, integration in drying and sterilisation processes show limitations in terms of the COP. Suitability must be assessed on a case-by-case basis using the present GEF of the electricity grid and the electricity/gas price ratio in relation to Eq(1).
Six unit operation sinks can be identified among the application examples with particular potential for the integration of heat pumps, such as: DHW (Figure 2a and c), bath heating (Figure 2d), washing processes (Figure 1a), drying (Figure 2e), process treatment (Figure 2f) and space heating (Figure 1a).
Table 1 summarises the application examples and shows the calculated relative heating and cooling saving potentials ($q_{sav,i}$) according to Eq(8), as well as the efficiency assessment (Eq(2)) of heat pump integration for different industries and their unit operations. The saving potentials range between 28 and 100%. Due to the static optimization character of the Pinch Analysis, non-continuities are not considered. This often requires the use of thermal storages, as indicated in Figure 1b.

Table 1: Relative heating and cooling saving potentials for different industries and unit operations calculated based on typical heat pump integration concepts (according to application data shown in Figure 1a and 2).

Industry	Unit operation		Heat pump	Pinch	ΔT_{Lift}	$\mathrm{COP_{real}}$	$q_{sav,heat}$	$q_{sav,cool}$
	Heat sink	Heat source	Type	°C	K	-	%	%
Galvanic	Bath heating	Bath cooling	CCC_{el}	40	55	3.5	54	28
Food (Meat)	DHW	Cooling	CO_2	28	37	4.9	68	31
Paper	Drying	Humid air	CCC_{el}	130	80.5	2.9	23	47
Metal	Washing	Cooling	CCC_{el}	49	35	5.4	100	50
Food, Medical	(Batch) sterilisation	Cooling	MVR	132	100.7	2.2	100	82
Food (Dairy)	Milk treatment, DHW	Cooling	2-staged CCC_{el}	49	70	2.8	40	40
Chemical	Extraction	Cooling	CCC_{el}	45	32.5	5.8	40	28

4. Directions for future research

New heat pump technologies from HTHP to open cycle mechanical vapour compression systems have recently entered the commercial market with much more still under development. Advances include the development of new high-temperature refrigerants, improved compressor performance, and a new Joule-cycle based heat pump; all of which focus on the heat pump cycle. More attention should be directed to identifying synergies with specific industrial implementations beyond energetic performance, such as improved safety, maintenance and reliability, and distributed energy production.
Process Integration plays a critical role in defining the most suitable applications of these novel technologies to harness their full potentials. Where heat pumps can entirely replace a conventional boiler plant, the heat pump displaces both energy and capital investment costs. This is particularly important when boilers come to the end of their life and companies must invest in a new utility system. For a better comparison to conventional energy supply systems, an allocation method should assess the particular effort for heating and cooling as it is standard for the evaluation of CHP systems. Building a knowledge base of both technological advances in heat pump performance as well as industrial heat demand profiles is critical in rapidly progressing implementation. The current paper provides the basis for increased awareness among stakeholders of the energy-efficient integration of technical heat pump concepts in accordance with the Pinch Analysis principles. For a holistic evaluation of the various integration concepts, future work should also consider energy storage for non-continuous processes and the under-utilised heat recovery potential. In addition, the efficiency assessment by the quality grade should be extended as a function of the source temperature and temperature difference.

5. Conclusions

This work reviewed and evaluated heat pump integration concepts for industrial applications based on the GCC. The presented method enables the direct derivation of heat pump integration parameters from the GCC (i.e. pinch temperature, temperature lift, COP, savings potential). The graphical visualisation provides planners and engineers a tool to discuss the integration of a heat pump into processes. Appropriate integration concepts for heat pumps are processes with both heating and cooling utility demands. Suitability depends on the existing environmental and economic framework conditions of the local electricity grid and the COP. Against this background, the food, paper, electroplating, metalworking and chemical industries all have promise for efficient heat pump integration. COPs for these applications range from 2.2 to 5.8 with temperature lifts of 32.5 to 102 K and cover 23 to 100 % of the heating demand and 28 to 82 % of the cooling demand. A fundamental premise for system efficiency is the integration across the Pinch and after all the heat recovery potential has been tapped. HTHP are suitable for high Pinch temperatures or high temperature lifts.

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