

Heat Pump Integration in a Cheese Factory

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The aim of this work is to increase the efficiency of industrial processes by using pinch analysis and process design methods. The main goals are the reduction of energy consumption, of the corresponding operating costs and of CO₂ emissions. In this context heat pumps offer promising opportunities, when they are appropriately integrated into the process. Two different integration strategies can be applied: In a first approach, process modifications are not allowed whereas in a second approach it is possible to modify process units. It is shown that industrial and practical decisions have a big influence on the final choice of new equipments. The presented method is applied to a real case study in a cheese factory where both approaches are applied and compared. The results from the energy integration are analyzed and assessed with the practical feasibility of solutions.

1 Introduction

When studying the energy efficiency of an industrial process, the analysis of heat pump integration has to be considered as part of a complete methodology, beginning from the data collection and modeling of all process unit operations. In the food industry, most of the process operations are performed in batch mode. However, considering the temperature levels and the use of water as production support, the time average approach can be used to realize the process integration analysis. The use of pinch analysis techniques allows to identify heat recovery opportunities in the process while the grand composite curves shows the enthalpy temperature profile of the heat to be supplied to the process and of the heat excess to be evacuated by a cold utility. It allows also to identify opportunities for appropriate placements of utility systems such as heat pumping or refrigeration. Heat pump integration has been widely discussed in literature before 1990. For example, the rules for optimal placements of a heat pump in an industry process have been introduced by Linnhoff and Townsend (1983). Later, Wallin and Berntsson (1994) demonstrated that, characteristics of both, industrial process and heat pumps, must be taken into account. Kapustenko et al. (2008) analyzed heat pump integration based on selected streams of a cheese factory. Also Pavlas et al. (2010) analyzed heat pump integration for a gasification process. However both approaches are limited to ammonia refrigeration cycles. More generally, the potential of heat pumps is demonstrated by Becker et al. (2011). A mixed integer linear programming (MILP) formulation of the heat cascade is used to optimize simultaneously the flow rates in heat pumps and other utility systems. This paper analyzes two process integration options: First process modifications are not allowed and a newly

integrated heat pump cannot exchange directly with the process. In the second option, process modifications and direct heat pump process integration are possible. Saving potential becomes higher, but also the complexity of process configurations increases.

2 Example of cheese factory

The industrial process that is used for this analysis (Figure 1a) is a cheese factory with several pasteurization units that are used to remove bacteria from milk, cream or water. The evaporation unit, one of the main consumers, consists in 5 effects and one thermal vapour compression. Before entering the evaporation in the first effect, the whey is first preheated to reach predefined operating conditions that leads to a first evaporation. Then, the remaining liquid is sent to the second effect at a lower pressure, and the vapour boiled off in the first effect is recovered to provide heat to the second effect. The same principle is valid for the following effects. A part of the steam from the third effect is reused in the thermal vapour compression (TVR) driven by high pressure steam. The remaining heating and cooling requirements concern process units like forming, product refining, packaging or cold stores. The energy consumption is expressed in kWh per tons of product. Currently 2895 kWh/tprod of natural gas and 194 kWh/tprod of electricity are consumed.

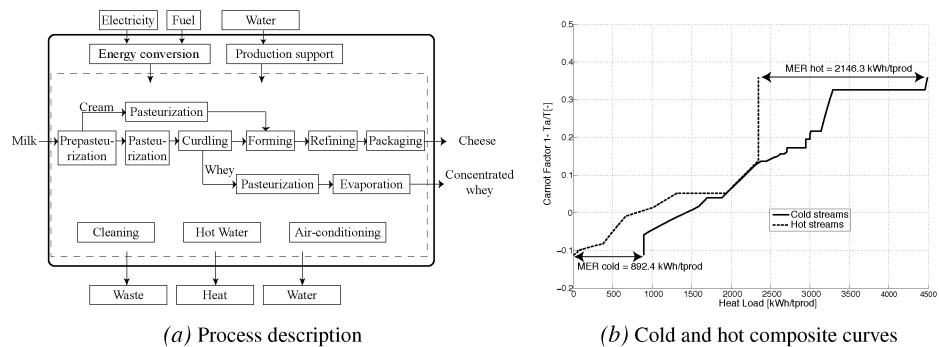


Figure 1: Process description and its hot and cold composite curves

3 Methodology - process integration

The analysis of process unit operations aims at defining the heating and cooling requirements to convert raw materials into products. In order to define heat recovery potentials, first the process hot and cold streams have to be defined. The streams of the evaporation units are modeled regarding the existing technology (5 effects with thermal vapour compression). The complete list of streams is reported in Table 1. Exergy losses can be visualized on Figure 1b, which shows the hot and cold Carnot composite curves. The process grand composite curve is presented in Figure 2a, while Figure 2b shows Case1, corresponding to the integrated current state of the process without heat pumping systems.

Table 1: Process streams, $\Delta T_{min/2}$ values: 2.5 °C (liquids), 1 °C (gases)

Unit	Name	Tin [°C]	Tout [°C]	Heat load [kWh/tp]	Unit	Name	Tin [°C]	Tout [°C]	Heat load [kWh/tp]
other	other_c1	100	190	367.8	pasto3	pasto3_c1	74	80	84.1
	other_h1	5	0.5	307		pasto3_c2	6	28	308.2
	other_h2	-0.3	-2.5	56.9	pasto4	pasto4_c1	69	75	32.1
evapo tech	evapo_c1	100	190	993.7		pasto4_c2	8.5	26	83.3
	evapo_h1	44	5	32.9	pasto5	pasto5_c1	66	76	54.2
	evapo_h2	44	25	198.1		proc6_c1	105	105	131
evapo_h3	44	44	627.8	proc6_c2		78	78	49.6	
pasto1	pasto1_c1	6	48	568.2	proc6_c3	95	95	49.6	
	pasto1_c2	48	75	344	proc7	proc7_c1	15	55	40.4
	pasto1_h1	75	4	904.6		proc8_c1	70	70	62.6
pasto2	pasto2_c1	79	85	5	proc9_c1	35	35	33.8	
	pasto2_h1	54	4	41.9	proc10_c1	32	25	175.5	
heat	heat_c1	35	35	153	CIP	clean_c1	85	85	238

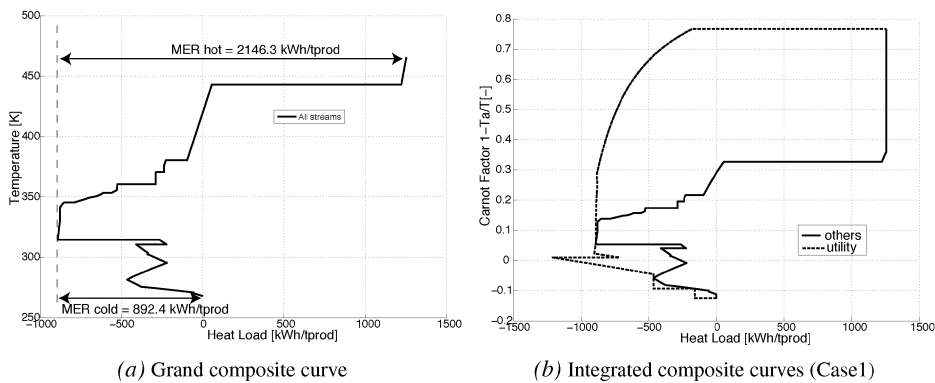


Figure 2: Grand composite curve of the process and integrated composite curve of the utility system using Carnot scale.

3.1 Heat pump integration option 1: No process modifications allowed

Heat pumps are used to valorize waste heat from the process below the pinch point by driving it above the pinch point with the help of mechanical power, reducing therefore hot and cold utility requirements. In the first approach, the process can not be modified. Thus, the direct heat exchange between a potential heat pump and the process is not allowed. The approach from Becker et al. (2010) is applied: two sub-systems (in this case the process and the heat pump) cannot exchange heat directly. A closed cycle heat pump using the refrigerant R245fa is considered. By analyzing the shape of the grand composite curve, appropriate operating conditions for the heat pump and the intermediate network can be estimated. Then, simultaneously the interdependent flow rates of the utility units, heat pumps and the heat distribution fluids are defined, in order to minimize the operating costs. The potential of a closed cycle heat pump without direct heat exchange is illustrated

in Figure 3a. The saving potential can be increased by minimizing the minimum temperature difference in the heat exchangers between the heat pump and the intermediate heat transfer fluids. The advantage of this approach is that only the investment costs related to the heat pump, heat exchangers and tubes for heat transfer have to be accounted without modifying the process itself. Also safety and product quality aspects are maintained. The results of this first approach are given in column "Case2" of Table 2.

3.2 Heat pump integration option 2: Process modifications allowed

In the second approach, process modifications are allowed. This leads to more heat pump integration opportunities. For example, operating pressures of the process can be modified to improve heat recovery, and mechanical vapour recompression (MVR) units can replace the thermal vapour compression unit. **Case3** replaces thermal vapour compression with mechanical vapour recompression. The layout and the pressure levels of the effects are kept. The steam leaving the third effect at about 61 °C is compressed mechanically to 75 °C. As the ΔT is less than 18 °C, a dynamic compressor (isentropic efficiency estimated to 0.7) is suitable and therefore selected (Figure 3b). In **Case4** all effects are realized in parallel and mechanical vapour recompression is integrated. The temperature difference for a mechanical vapour recompression is small (<10 °C). An isentropic efficiency for the compressor is estimated to 0.7 (Figure 3c). The pressure levels of the five effects are adapted, so that all effects evaporates at about 70 °C. In **Case5** the pressure of effects are modified and mechanical vapour recompressions are included: First the new temperature levels have to be defined. In order to keep the heat exchange surfaces of the effects (see Equation (1)) the temperature levels of effect 4 and 5 are reduced. The new temperature levels are 48 °C (effect 4) and 32 °C (effect5). Theoretically it could be possible to raise waste heat at 32 °C with a heat pump to satisfy a part of the heat demand in effect 1. However, high temperature lifts makes such heat pump integration not optimal. The use of a successive mechanical vapour recompressions between the different effects has therefore been preferred (Figure 3d). The temperature of effect 5 is quite low. If technologically it is not feasible, it could also be possible to raise the temperature levels of all effects.

$$Q = U * A * (T_{vap} - T_{prod}) \quad (1)$$

The results of Table 2 are compared to the current energy consumption of the process. The saving potential of a well integrated process without any supplementary heat pumps or MVR is about 15%. Heat pump or MVR integration will reduce the operating costs. In order to reduce the energy consumption, the effects can be modified (e.g. Case5). In Cases 2, 4 and 5, the heat pump or MVR can be integrated in the way that also heat from the condensation of the refrigeration cycle is used to heat up process streams. The 5 cases are compared regarding their estimated investment costs and related payback time (Table 3). To estimate the instantaneous power of heat pump or MVRs the mean value (heat load per tons of product) is multiplied by number of tons of products per year divided by the weekly total operating time of the evaporation unit. From selected quotations, the investment costs can be estimated related to the compressor power (\dot{E}_{hp} in [kW]) with Equation (2) (installation factor f supposed to be 1.5). In Case2, the process streams connected to

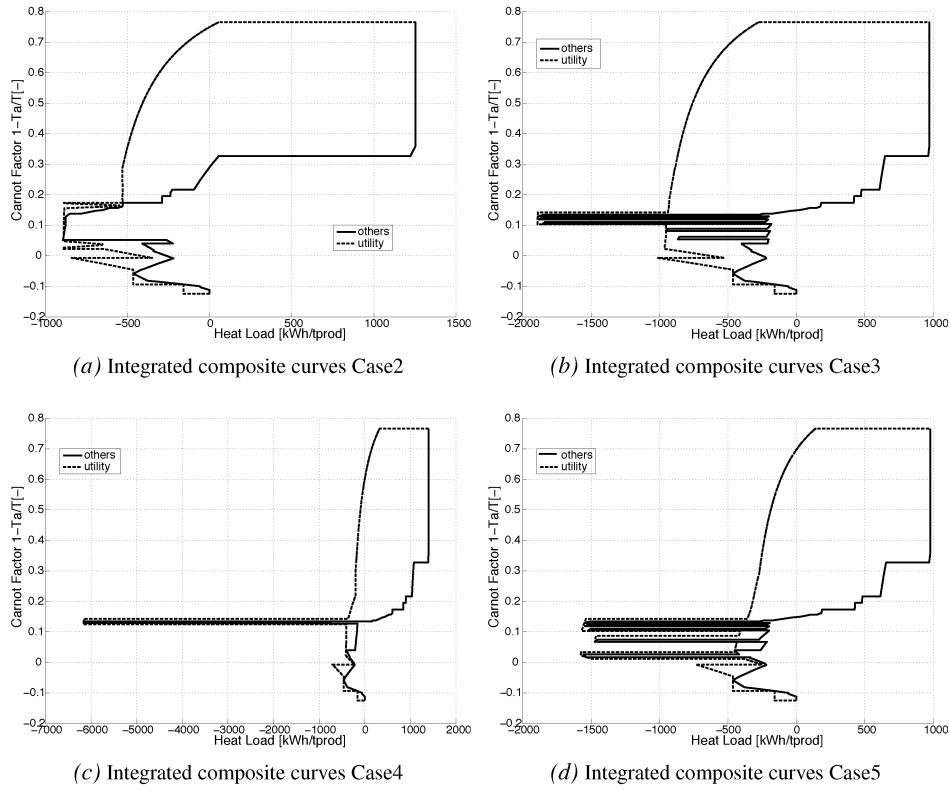


Figure 3: Comparison of composite curves

the heat pump are not simultaneous. Thus, the investment can not be calculated without considering heat storage. In Table 3, two extreme cases have been evaluated: "max" corresponds to the peak power required by the heat source, while "mean" assumes that the heat source is stored and progressively upgraded leading to a more constant operation of the heat pump. Supplementary investment costs for heat storage tanks are not included.

$$InvC = f \cdot 1500 \cdot 160^{0.1} \cdot \dot{E}_{hp}^{0.9} \quad [Euro] \quad (2)$$

4 Comparison of results & conclusions

In all cases, the installation of a closed cycle heat pump or a mechanical vapour recompression reduces operating costs and CO₂ emissions. The proper integration of heat pumps or MVRs changes the process pinch point location, allowing the heat recovery from the refrigeration cycle to preheat the process water and therefore leading to an even better integration and reduction of the mechanical power consumption. The investment costs are estimated and payback time can be roughly evaluated. However it has to be considered that the real investment costs depend strongly on a given case. Therefore the final decision has to be taken with concrete heat pump offers corresponding to the existing

facilities and installations of the company.

Table 2: Comparison of utility integration

	Unit	Case1	Case2	Case3	Case4	Case5
Operating Cost	[Euro/tprod]	107	96	97	93	75
Saving potential	[%]	-14.9	-23.6	-22.8	-26	-40.7
Fuel consumption	[kWh/tprod]	2582	2157	2245	1935	1513
Saving potential	[%]	-10.8	-25.5	-22.5	-33.1	-47.8
Electricity consumption	[kWh/tprod]	97	189	150	281	249
Saving potential	[%]	-50	-2.6	-22.6	44.8	28.4
Cooling water	[kWh/tprod]	934	682	996	449	495
CO2 emissions	[kg/tprod]	530	453	467	417	328
Saving potential	[%]	-12	-24.8	-22.5	-30.8	-45.5

Table 3: Technologies

	Case2	Case3	Case4	Case5
\dot{E}_{hp} [kW]	372 (max) 239 (mean)	241	698	297 + 136 + 152
$InvC$ [kEuro]	771.6 (max) 516.2 (mean)	519.9	1354.8	1285.1
Payback [Years]	3.6 (max) 2.4 (mean)	2.7	5.0	2.6

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