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Energy, Exergy and Advanced Exergy Analysis of a Milk Processing Factory

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Abstract:

Energy, exergy and advanced exergy methods are used in this study to analyse a milk processing facility which is one of the largest energy consumers within the food industry in Denmark. While a conventional energy analysis maps the energy flows of the system and suggests opportunities for process integration, an exergy analysis pinpoints the locations, causes and magnitudes of thermodynamic losses. The advanced exergy analysis further identifies the real potential for thermodynamic improvements of the system by splitting exergy destruction into its avoidable and unavoidable parts, which are related to technological limitations, and into its endogenous and exogenous parts, which illustrate the interactions between the different sub-systems. This analysis is based on actual factory data from one of Europe's largest dairy producers: the complete production line is modelled, and includes the production of milk, cream and milk powder. The results show the optimisation potential based on 1st and 2nd law analyses. An evaluation and comparison of the applicability of exergy methods, including advanced exergy methods, to the dairy industry is made. The comparison includes typical energy mappings conducted onsite, and discusses the benefits and challenges of applying advanced thermodynamic methods to industrial processes.

Keywords:

Energy Efficiency, Exergy Analysis, Advanced Exergy Analysis, Process Integration, Dairy Industry.

1. Introduction

Increasing the energy efficiency of the industrial sector has the potential to significantly reduce the greenhouse gas emissions associated with the consumption of fossil fuels and the operating costs associated with energy use. The production of dairy products is a major industrial sector in Denmark and Europe and represents one of the most energy-intensive industries within the food sector [1]. In Denmark, 20 % of the agricultural exports are dairy products and a total of 4.7 billion kg of raw milk are processed, resulting in export revenues of 1.8 billion Euro [2].

For the determination, quantification and prioritisation of possible energy savings in complex and large scale industrial processes, several scientific and engineering methods exist and are in continuous development. The potential for increasing the energy efficiency of the dairy production processes, which are already highly integrated, still exists. The aim of this paper is to identify this potential by applying and assessing different methods. The methods used are based on engineering evaluations, exergy and advanced exergy analysis, as well as pinch analysis.

In terms of exergy, some analyses of the dairy industry were conducted in the last decade. However, these studies primarily analysed the milk processing [3,4] or only the drying process [5]. Quijera et al. [3,6] use the pinch and exergy methods to evaluate and optimise the integration of solar thermal technologies for the production of cheese and yoghurt. An exergy analysis for the pasteurisation of milk was performed by Fang et al. [4], where the process was also optimised.

The usefulness of exergy as a tool for the dairy industry was discussed by Vidal et al. [7]. A milk powder production facility in New Zealand is analysed in this study to investigate the usefulness of exergy methods in the dairy industry. Based on component-wise product input/output states an exergy

analysis is conducted and the authors conclude that exergy might be useful to design and optimize different units of operations within dairy processes.

The exergy losses of flavoured yogurt production were determined by Sorgüvan and Özilgen [8], and the production of other ingredients than milk is also included from a cumulative exergy perspective.

Several exergy analyses were conducted for different systems within the food industry and a study by Trägårdh [9] uses exergy as a quality factor. Most relevant for this work are articles on drying and evaporation technologies. Marnoch et al. [10] perform an exergy analysis of broccoli drying, evaluating the impact of drying parameters on the exergy losses and destruction. A review of exergy analyses of drying processes is done in [11]. Dincer and Sahin [12] propose a new thermodynamic model for drying processes, based on exergy analysis. Evaporation in food processes is discussed in [13,14], for the production of citrus processing, analysing different evaporator configurations. Winchester [15] analyses the modelling and operation of falling film evaporators at the example of a dairy plant. A lot of the literature on evaporation with thermal and mechanical vapour recompression technologies focuses on sea water desalination. For instance [16] with an exergy analysis of thermal vapour recompression evaporators, suggestion new designs and operating parameters.

The exergy destruction occurring in a given component depends on its characteristics and is also impacted by the performance of the other components present in the system. The common exergy analysis has some barriers to show the real recoverable losses, which can be shown with an advanced exergy analysis [17,18]. The method of advanced exergy analysis is well-documented and has been applied to several systems, such as refrigeration machines [19] and combined cycle power plants [20]. The application of advanced and conventional exergy analyses to an industrial plant was conducted in one study [21,22] for the production of rubber. These analyses document the usefulness of carrying out an advanced exergy analyses, as the improvement priorities are being ranked.

The current study aims at comparing different methods for the analysis of inefficiencies and improvement potentials in industrial processes. The focus lies on the application of exergy and advanced exergy methods, while comparing the results to traditionally applied energy analyses, such as pinch analysis. The conclusions drawn from the different analyses are compared amongst each other, including a discussion of the applicability of the second law methods to industrial processes and pin pointing challenges occurring in its application.

The case study used in this work is a dairy processing line for which the main production units are shown schematically in Fig. 1. The raw milk is separated into skimmed milk and cream, both products are thermally treated (pasteurised). The cream leaves the process, whereby some of the milk is concentrated in reverse-osmosis (RO) unit. The remaining skim milk, retentate from the RO-unit and additives are mixed, thermally treated and homogenised, before entering the evaporator unit. A large fraction of the water is evaporated afterwards, the remaining moisture is removed in a spray dryer and several fluidised beds. In this study, the drying processes and the RO unit are not included for the advanced exergetic analysis. Both processes are modelled with heaters and coolers, already analysed in the other units.

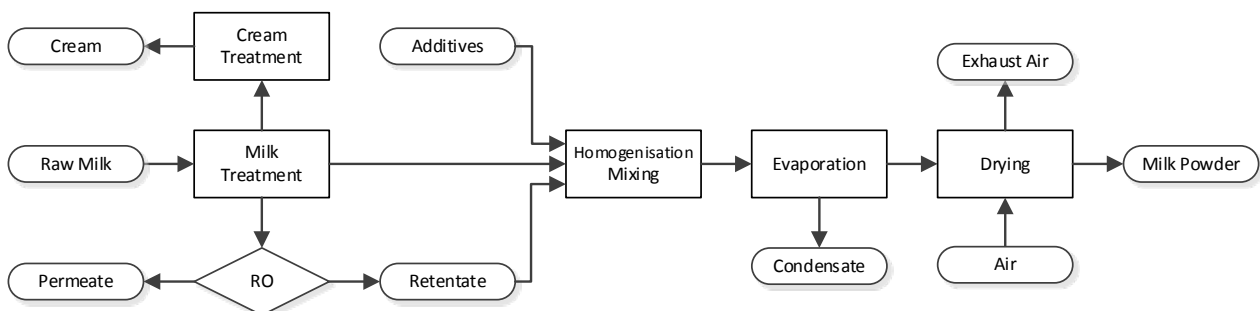


Fig. 1. Dairy processing line for the production of milk powder, with the main manufacturing units and materials.

In Section 2 the methods used in this study are introduced, as well as a more detailed description of the case study. Section 3 presents the results of the different analyses and a comparison of the methods. At the end in section 4 and 5 the results are discussed and put into perspective and conclusions are drawn.

2. Methods

The analysis of the dairy factory consists at first of a conventional energy mapping and analysis used within the consultancy sector, which is based on the first law of thermodynamic, using factory data and measurement. Secondly, the method for exergy and advanced exergy analysis is presented, which is further applied to the dairy model. At last, the pinch analysis is shown, as an advanced method for energy efficiency within the industry.

2.1 Case Study and System Modelling

The milk processing line used in the case study is part of several parallel production lines at the dairy factory and represents all major production steps. The processing line consists of five subsystems: (i) separation of raw milk into skimmed milk and cream, alongside with thermal treatment of the two products (pasteurisation); (ii) Reverse Osmosis unit for concentrating skim milk; (iii) Mixing unit, homogenisation and high temperature treatment; (iv) Preheating and evaporation of the mixture and (v) Spray drying line. Each subsection has fixed set points (temperature, pressure and dry matter content), and can be operated individually. The three first subsections are similar and are located in the same production unit, implying that the dairy factory can be split into three sections (separation and treatment, preheating and evaporation, drying).

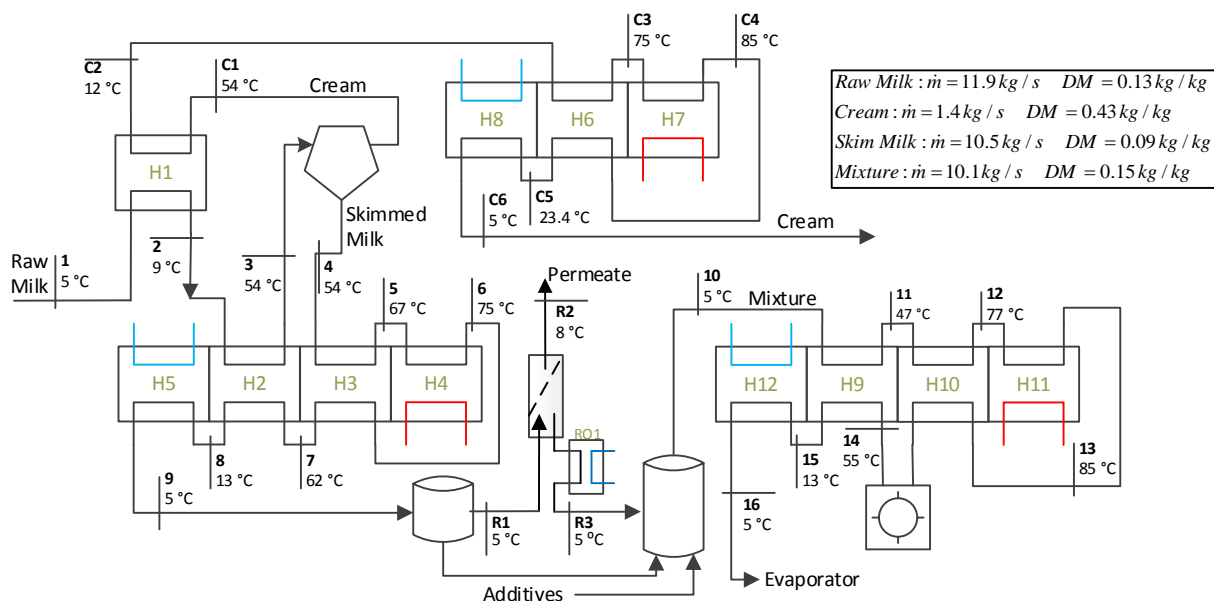


Fig. 2. Dairy processing line for the production of milk powder, with the main manufacturing units and materials.

The studied milk processing system is shown schematically in Figure 1, where the main components and states are shown. The incoming raw milk is heated to the separation temperature (3), where by means of a centrifuge the raw milk is separated into cream (C1) and skimmed milk (4). The skimmed milk is then pasteurised and cooled down in two steps, the first one being regenerative with the incoming milk and the second one with ice water. The cream is treated similarly in a parallel process. From the milk storage, the skimmed milk is either concentrated in a reverse osmosis process (R1) or directly pumped to the mixing unit. The RO unit consists of five membranes in series, after which a

cold utility regulates the temperature of the retentate. In the mixing unit the skim milked is mixed with the retentate from the RO system and different additives (e.g. vegetable fats, sugar, vitamins and minerals). The mixture (10) is heated and homogenised, and further cooled down.

In the evaporation section (Fig. 3) the mixture is heated to up to 85 °C in one regenerative step and one with externally supplied heat. The heated milk enters at first an evaporator with mechanical vapour recompression (E3) where most water is removed. The second step is an evaporator with thermal vapour recompression (E5) where the dry matter content is increased from 46 % to 55 %.

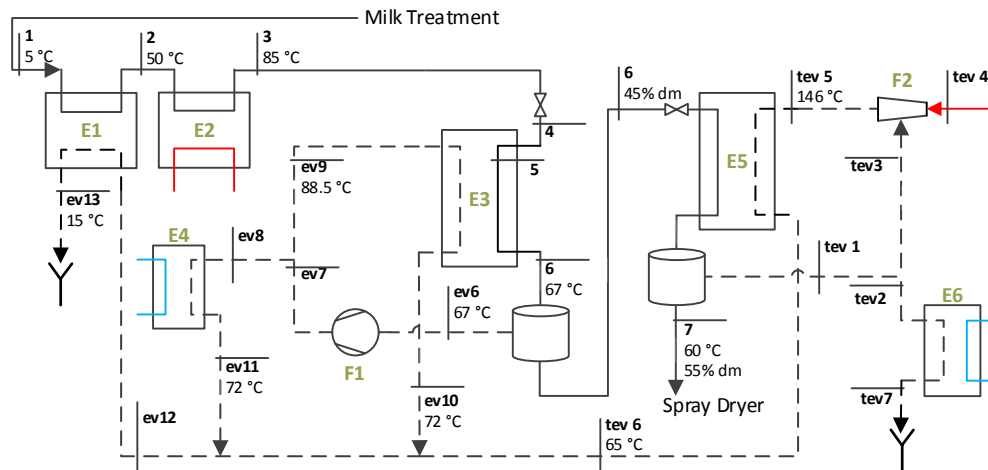


Fig. 3. Dairy processing line for the production of milk powder, with the main manufacturing units and materials.

The remaining water is removed in a drying system to achieve a drymatter content above 98 %, as shown in Fig. 4. After the concentrate is preheated to 72 °C, it is injected into a spray dryer, which has an internal fluidised bed at the bottom. The powder leaving the spray dryer is further treated in two external fluidised beds, of which the last one primarily cools the milk powder and supplies the correct consistency. The air for the spray dryer is heated with steam, and the air out of the system is treated in a cyclone, to recover powder carried out with the air, and a bag filter.

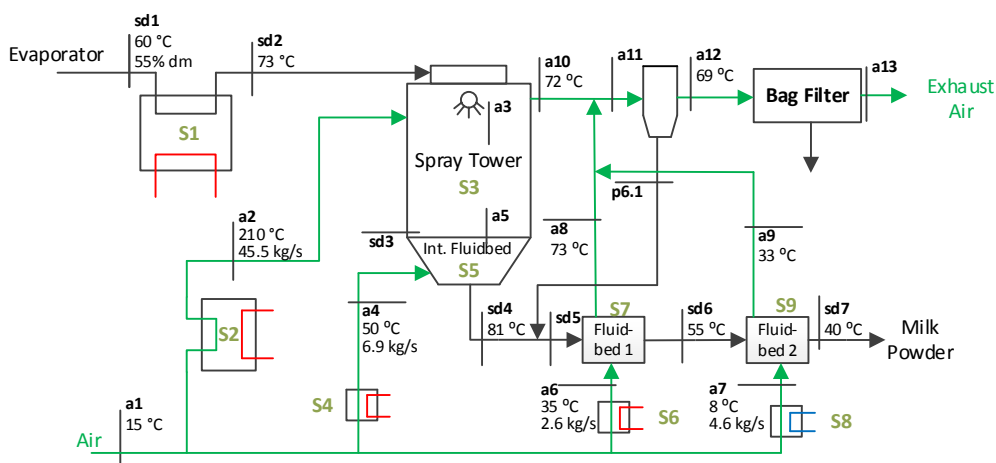


Fig. 4. Dairy processing line for the production of milk powder, with the main manufacturing units and materials.

The heating demand is covered by saturated steam at 25 bar supplied by a natural gas fired boiler and hot streams are cooled by ice water which has a supply temperature of 1 °C. The ice water is supplied by an ammonia refrigeration system.

The process modelling builds upon the real operation parameters and conditions of the production line, as found in process data and with on-site measurements. The following assumptions are taken. The processing line produces different products that are pasteurised at different temperature levels,

and they have varying dry matter contents after the mixing unit, depending on the milk additives. The input feed is modelled for simplicity as a representative mixture whose composition depends on the use of skimmed milk, retentate from the RO and a small portion of vegetable oils and sugars.

The number of evaporation steps in the MVR and TVR depends on the product mixture. Up to three steps can be implemented, and only one step is considered in this work. The heat losses from heat exchangers and other process components are neglected. Further, the states during start-up of the lines and cleaning in place (CIP) are not included.

The reader is referred to [23] for a detailed technical description of the technologies and processes used in the production of milk powder. An extensive description of the evaporation with vapour compression in single and multiple stages for salt water desalination is found in [24].

2.2 Energy Analysis

The energy analysis of the model is based on the 1st law of thermodynamics. For an open system, energy can be transferred in- and out of the system under study with streams of matter, heat and work. The present work does not consider changes in kinetic and potential energies, which implies that the energy balance in steady-state conditions, on a rate form, is as follows:

$$\sum_{in} \dot{H}_{in} - \sum_{out} \dot{H}_{out} + \sum_k \dot{Q}_k - \dot{W} = 0 \quad (1)$$

$$\sum_{in} h_{in} \dot{m}_{in} - \sum_{out} h_{out} \dot{m}_{out} + \sum_k \dot{Q}_k - \dot{W} = 0 \quad (2)$$

where:

- \dot{H} denotes the energy associated with a stream of matter;
- h the specific enthalpy of a material stream;
- \dot{m} the mass flowrate of the corresponding stream;
- the subscripts in and out the in- and outflowing streams;
- \dot{Q} and \dot{W} the heat and work rates exchanged with the surroundings.

2.3 Exergy Analysis

Unlike energy, exergy can be destroyed and accounts for the use of additional primary energy induced by the systems imperfections. It can be defined as 'the maximum useful work as the system is brought into complete thermodynamic equilibrium with the thermodynamic environment, while the system interacts with it only'. A system in thermal and mechanical equilibrium (same temperature and pressure) with the environment is called in 'environmental state' [25], while it is in 'dead state' if also in chemical equilibrium (same chemical species).

This thermodynamic concept builds on the first and second laws of thermodynamics, reflecting that all transformations are irreversible in nature and generate entropy. The exergy destruction is defined as the difference between the exergy inflowing and outflowing the system under study, and can thus be derived from the previous relations as:

$$\sum_{in} \dot{E}_{in} - \sum_{out} \dot{E}_{out} = \dot{E}_d \quad (3)$$

$$\sum_{in} e_{in} \dot{m}_{in} - \sum_{out} e_{out} \dot{m}_{out} + \sum_k \dot{E}_k^Q - \dot{E}^W = \dot{E}_d \quad (4)$$

where:

- \dot{E} denotes the exergy associated with a stream of matter, heat or work;
- e the specific exergy of a material stream;
- \dot{E}_k^Q and \dot{E}^W the heat and work exergy rates exchanged with the surroundings;
- \dot{E}_d the destroyed exergy.

The specific exergy of a flowing stream of matter consists of physical, chemical, kinetic and potential components. Excluding the kinetic and potential components, the specific exergy can be expressed as follows:

$$e = [(h - h_0) - T_0(s - s_0)] + \left[\sum_j (\mu_{j0} - \mu_{j00}) x_j \right] \quad (5)$$

The first term of the formula represents the physical exergy, which is the maximum useful work that can be extracted from the stream when brought to equilibrium with the environment. The second part, the chemical exergy, is the maximum available work that can be extracted from the stream when brought from the environmental state (denoted with the subscript 0) to the dead state (denoted with the subscript 00). There are no chemical reactions taking place within the system under study, and the changes of chemical exergy due to mixing and separation effects are negligible in comparison to the variations of physical exergy. Changes in chemical exergy are accordingly not considered in the present analysis asides the fuel conversion processes.

The exergy product $\dot{E}_{P,k}$ and fuel exergy $\dot{E}_{F,k}$ of the component k are defined based on the component function and are calculated from the inflowing and outflowing exergy streams. The exergy efficiency ε_k can therefore be defined using (6) and the exergy destruction ratio in (7).

$$\varepsilon_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}} \quad (6)$$

$$y_{D,k}^* = \frac{\dot{E}_{D,k}}{\dot{E}_{D,tot}} \quad (7)$$

The main system components are heat exchangers operating above the ambient conditions, and the product exergy is commonly defined as the increase of exergy related to the heating of the cold streams [25]. However, several heat exchangers operate across the ambient conditions, and their exergy products and fuels are thus not trivial. For these the product exergy is defined to be the increase of exergy of the cold stream from the environmental temperature to the final one, and the cooling of the hot stream from the environmental temperature to the final state.

2.4 Advanced Exergy Analysis

The real potential for optimising a given system cannot be assessed by a conventional exergy analysis, as this method disregards the mutual interdependencies of the system components and technological limitations [19,26]. These drawbacks can be addressed by conducting an advanced exergetic analysis, which divides the exergy destruction into its endogenous and exogenous parts, and into its unavoidable and avoidable fractions.

Unavoidable and avoidable exergy destruction take into account that some of the exergy destruction cannot be prevented because of physical and economic constraints (e.g. limitations on the maximum possible isentropic efficiency of a real compressor) [27]. The optimisation of the system should thus focus on reducing the avoidable part of the exergy destruction. The rate of exergy destruction is divided into two parts for the k th component, the avoidable part $\dot{E}_{D,k}^{AV}$ and the unavoidable one $\dot{E}_{D,k}^{UN}$.

$$\dot{E}_{D,k} = \dot{E}_{D,k}^{AV} + \dot{E}_{D,k}^{UN} \quad (8)$$

The unavoidable exergy destruction is defined as the remaining exergy destruction when the component of interest operates at its best thermodynamically possible and economically feasible limit. It is then scaled to the exergy product of the whole system using equation (9).

$$\dot{E}_{D,k}^{UN} = \dot{E}_{P,k} \left(\frac{\dot{E}_{D,k}}{\dot{E}_{P,k}} \right)^{UN} \quad (9)$$

Exogenous and endogenous exergy destruction are analogously split into two parts. The endogenous part of the exergy destruction $\dot{E}_{D,k}^{EN}$ of the k -th component is the exergy destruction of this component at its current efficiency when all the other system components operate in an ideal way. The exogenous part of the exergy destruction $\dot{E}_{D,k}^{EX}$ within the k -th component is related to the irreversibilities imposed on the component by the other components present in the system.

$$\dot{E}_{D,k} = \dot{E}_{D,k}^{EX} + \dot{E}_{D,k}^{EN} \quad (10)$$

$$\dot{E}_{D,k}^{EN} = \dot{E}_{P,k} \left(\frac{\dot{E}_{D,k}}{\dot{E}_{P,k}} \right)^{EN} \quad (11)$$

The real operating conditions shown in Table 1, are the ones currently found at the factory and are used here to reveal the real potential of improvement. Improvement opportunities of the system components are the avoidable conditions, which can be obtained with a technical and economic feasibility. In the last column, the theoretical conditions are found, expressing the thermodynamically ideal conditions. Depending on the fluids, heat exchangers are assigned minimum temperature differences. For ideal calculations, the minimum temperature difference is 0 °C. The hot utility supplies saturated steam at 25 bar, but a second pressure level of steam could be introduced, which is often found at 6 bar. Ideally, the steam would be delivered at the saturation temperature of the target temperature of the stream. For the steam ejector the real pressure ratio (PR) is changed to an unavoidable, close to the theoretical one. The latter one is defined as ratio of the saturation pressure at the condenser site and evaporator site at the minimal temperature difference.

Table 1. Real operating conditions and assumptions for unavoidable and theoretical conditions.

Component	Real	Unavoidable	Theoretical
Heat Exchanger Milk/ Milk	$\Delta T_{\min} = 8 \text{ K}$	$\Delta T_{\min} = 2 \text{ K}$	$\Delta T_{\min} = 0 \text{ K}$
Heat Exchanger Cream/ Milk	$\Delta T_{\min} = 7 \text{ K}$	$\Delta T_{\min} = 3 \text{ K}$	$\Delta T_{\min} = 0 \text{ K}$
Heat Exchanger Cream/ Cream	$\Delta T_{\min} = 10 \text{ K}$	$\Delta T_{\min} = 5 \text{ K}$	$\Delta T_{\min} = 0 \text{ K}$
Hot Utility Supply	$P_{\text{sat}} = 25 \text{ bar}$	$P_{\text{sat}} = 6 \text{ bar}$	$P_{\text{sat}} \text{ at } T_{\text{target}}$
Cold Utility Supply	$T_{\text{ice,water}} = 1^\circ\text{C}$	$T_{\text{ice,water}} = 3^\circ\text{C}$	$T_{\text{ice,water}} = T_{\text{target}}$
Evaporator	$\Delta T_{\min} = 5 \text{ K}$	$\Delta T_{\min} = 2 \text{ K}$	$\Delta T_{\min} = 0 \text{ K}$
Compressor	$\eta_{\text{is}} = 0.85$	$\eta_{\text{is}} = 0.95$	$\eta_{\text{is}} = 1.00$
Steam Ejector	$\text{PR} = 1.8$	$\text{PR} = 1.3$	$\text{PR} = 1.25$
Air Heater	$\Delta T_{\min} = 8 \text{ K}$	$\Delta T_{\min} = 8 \text{ K}$	$\Delta T_{\min} = 8 \text{ K}$

2.5 Pinch Analysis

Industrial processes such as dairy ones may present significant potentials for energy and fuel savings, which in turn would result in lower CO₂-emissions. Process integration techniques are powerful tools that aim at minimising the use of external energy utilities (e.g. heating by a boiler or cooling by a refrigeration cycle) by maximising internal heat recovery within the system of interest. The most well-known method is named pinch analysis and was developed by Linnhoff [28] in the 80's for designing heat exchanger networks in chemical processes. It was also applied to industrial sites such as refineries, as discussed in Smith [29] and Klemes [30], and has been applied to dairy factories before, where the heating demand is generally much higher than the cooling one, because of the significant drying needs. The pinch method can be subdivided into four steps: (i) data extraction (use of measurements to extract the appropriate data, and identify the heating and cooling demands with the corresponding temperatures and flows); (ii) definition of a minimum temperature difference, which sets the heat transfer driving force between two streams in a given heat exchanger (function of the film coefficients); (iii) evaluation of the maximum internal heat recovery and minimum utility demands (setting thermodynamic targets) and (iv) proposing system improvements by means of a re-design of the heat exchanger network (retrofit) or integration of processes such as cogeneration and heat pumping. In this work, the minimum and individual temperature difference is taken to be 1 °C,

2 °C and 4 °C for phase changing, liquid and gaseous streams, to account for the differences in film coefficients between different fluids and phases. In practice, the real temperature differences may even be smaller, as a result of large plate heat exchangers used in dairy industries.

3. Results

The analysis conducted by evaluating the heating demand over the most important utility consumers shows that the production line has cooling demand of 904 kW for product streams. The heating demand, excluding the energy required in the evaporators accumulates to 11,600 kW.

3.1 Pinch Analysis

A pinch analysis of the dairy factory illustrates the high degree of integration between the utilities and processes. The pinch point is located at 9 °C, meaning that the region above requires only external heating (about 29,700 kW), while the one below requires only external cooling (about 400 kW). The greatest heating demand is associated with the reduction of the water content in the milk products. In practice, these heating demands are satisfied by heat pumping of the evaporated water with a temperature lift smaller than 10 °C (MVR and TVR), which allows a close match of the temperature profiles of the heat and cold sides, at the expense of large equipment items. The remaining heating demand, which consists mainly of the heat required in the drying process, is satisfied by steam production at 25 bar, which corresponds to a saturation temperature of about 240 °C. The large temperature gap observed between the steam and process stream sides may be reduced by using steam at different production levels, which would be relevant if the saved high-pressure steam could be used elsewhere.

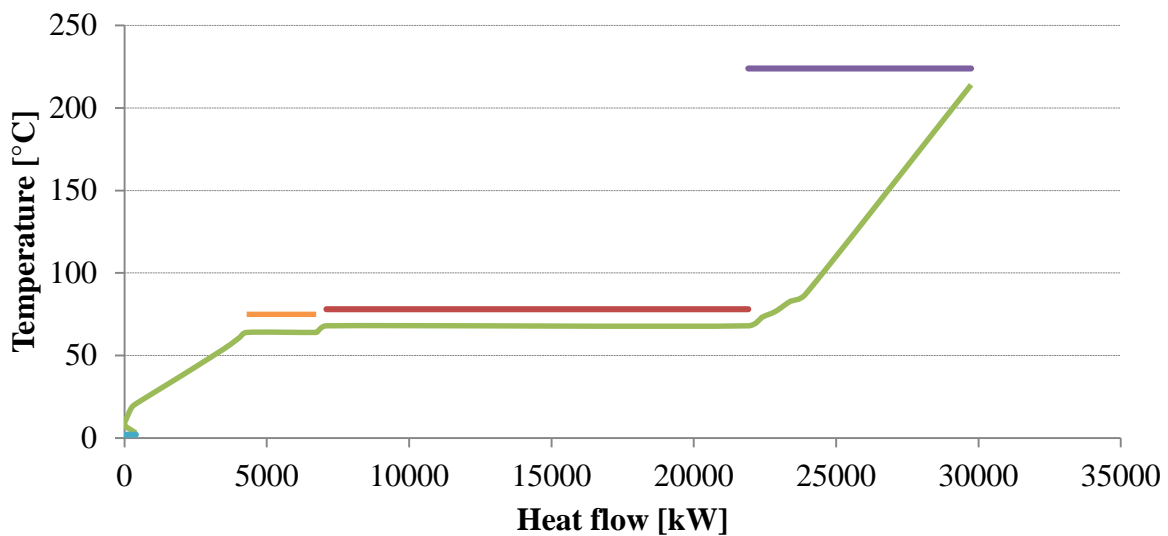


Fig. 5. Temperature heat profile of the dairy production line (green) and utility levels of steam (purple), evaporation (red and orange) and ice water (blue).

In theory, the external cooling demand is marginal and is satisfied by iced water produced by means of a refrigeration cycle. No self-sufficient pockets can be visualised in the overall temperature-heat profile of the dairy site, meaning that internal heat recovery is very limited, and that there is a priori no potential for cogeneration of heat and electricity from the process streams.

Additional heat pumping across the pinch point may not be an interesting option, as it would require a significant temperature lift to actually be relevant.

3.2 Exergetic Analysis

The results for the conventional and advanced exergy analysis of the first milk processing section are shown in Table 2. The highest rate of exergy destruction is found for the two heaters, H4 and H11. All heaters represent 50 % of the total exergy destruction, but only approximately one third of the avoidable part. The decomposition into the endogenous and exogenous parts shows that most of the irreversibilities taking place in the heaters are caused by other components (exogenous). Optimising the temperature difference in the regenerative preheater before the steam preheater will reduce the external utility required, theoretically eliminating the steam heater.

The first heat exchanger H1 has a very low exergy efficiency, as the product is only the cooling of cream from the environmental state to 12 °C (State C2). Thus this component has a high share of avoidable exergy destruction. In practice, the low exergy efficiency of the first heat exchanger is misleading, as also the preheating of the raw milk and cooling the cream to the environment could be seen as products. It might however be possible to reduce the exergy destruction by heating another cold stream above the environment, with the cream (C1).

Table 2. Conventional and advanced exergy analysis of the heat exchanger network for the milk treatment in section 1.

Component		$\dot{E}_{F,k}$	$\dot{E}_{P,k}$	$\dot{E}_{D,k}$	ε_k	$y^*_{D,k}$	$\dot{E}_{D,k}^{UN}$	$\dot{E}_{D,k}^{AV}$	$\dot{E}_{D,k}^{EN}$	$\dot{E}_{D,k}^{EX}$
		[kW]	[kW]	[kW]	[%]	[%]	[kW]	[kW]	[kW]	[kW]
H1	HEX	16.2	0.1	16.1	0.4	5.2	1.4	14.7	1.2	14.9
H2	HEX	147.9	112.5	35.4	76.1	11.5	28.0	7.4	34.0	1.4
H3	HEX	85.8	74.6	11.2	87.0	3.6	2.7	8.5	10.2	1.0
H4	HEX	134.8	55.0	79.8	40.8	25.8	55.0	24.8	0.0	79.8
H5	HEX	14.2	7.0	7.1	49.5	2.3	5.9	1.2	1.8	5.3
H6	HEX	33.4	25.6	7.8	76.7	2.5	3.6	4.1	7.8	0.0
H7	HEX	18.7	8.6	10.1	45.8	3.3	6.7	3.4	0.0	10.1
H8	HEX	1.8	0.7	1.1	40.3	0.4	0.9	0.2	1.1	0.0
H9	HEX	106.1	64.2	41.9	60.5	13.5	33.8	8.1	0.0	41.9
H10	HEX	190.9	166.4	24.5	87.2	7.9	5.4	19.0	24.5	0.0
H11	HEX	126.8	59.8	67.1	47.1	21.7	43.8	23.3	0.0	67.1
H12	HEX	13.7	6.6	7.2	47.9	2.3	6.0	1.2	1.4	5.8
Total		890.3	581.1	309.2	65.3	100.0	193.1	116.0		

Table 3 presents the results for the exergy analysis of the evaporator line. From the conventional exergy analysis, it is apparent that the heater and evaporators have the highest rate of exergy destruction. The heater and first heater also have a large share of avoidable exergy destruction. Though the absolute value of avoidable exergy destruction is comparably low, the compressor (F1) and first regenerative heat exchanger (E1) have a large fraction of avoidable exergy destruction. The splitting into endogenous and exogenous exergy destruction shows that the component E1 has a negative exogenous part. An ideal proceeding process, reduces the temperature of the condensate used for preheating. As a result, the milk is preheated to a lower temperature, reducing the exergy product over-proportionally due to the exergy product being only above the ambient conditions. Overall, most of the exergy destruction is endogenous. The compressor has a high share of exogenous exergy destruction, caused by the decrease in pressure within in an ideal evaporator and the reduced share of vapour to the condenser (E4).

The analysis of the spray drying line only includes heaters and coolers, for which the product side has specified set points, which cannot be modified. Therefore only the overall values are presented. For the spray drying section the total exergy destruction rate is found to be 1632 kW of which 1600

kW are unavoidable. The highest exergy destruction rate is in the air heat for the spray dryer, as this component has the highest mass flow rate. The same heater has no avoidable exergy destruction, as the utility supply is dimensioned after this component with the highest temperature requirement.

Table 3. Conventional and advanced exergy analysis of the components in the evaporator line in section 2.

Component		$\dot{E}_{F,k}$	$\dot{E}_{P,k}$	$\dot{E}_{D,k}$	ε_k	$y^*_{D,k}$	$\dot{E}_{D,k}^{UN}$	$\dot{E}_{D,k}^{AV}$	$\dot{E}_{D,k}^{EN}$	$\dot{E}_{D,k}^{EX}$
		[kW]	[kW]	[kW]	[%]	[%]	[kW]	[kW]	[kW]	[kW]
E1	HEX	150.8	76.6	74.2	50.8	7.2	30.2	44.0	83.3	-9.1
E2	HEX	552.0	213.7	338.4	38.7	33.0	236.9	101.5	320.9	17.5
E3	HEX	2533.0	2293.0	240.0	90.5	23.4	124.5	115.5	238.6	1.4
E4	HEX	106.7	28.0	78.7	26.3	7.7	70.9	7.8	68.9	9.8
E5	HEX	402.4	186.1	216.3	46.2	21.1	215.3	1.0	216.3	0
E6	HEX	115.7	37.2	78.4	32.2	7.6	70.0	8.4	93.1	0.0
F1	CM	276.4	243.2	33.2	88.0	3.2	10.2	23.0	19.7	13.5
F2	EJ	403.5	386.6	16.89	95.8	1.6	15.1	1.8	16.9	0.0
Total		4562.0	3471.4	1090.7	23.9	100.0	786.1	304.5		

4. Discussion

The analysis of the dairy factory using pinch analysis showed that the process used as a case study could be highly integrated with only minor cooling needs. The actual degree of integration of the factory is slightly lower than the theoretical one found. An economic analysis would be required to assess the practical saving potential based on pinch analysis.

Using the exergy methods to evaluate the heat exchanger network, it is shown that a combination of conventional and advanced analysis helps to find the real sources of inefficiency. The exergy analysis showed that steam heaters have the highest rate of exergy destruction, and that some of this destruction can be avoided by using steam at a lower pressure. The high share of exogenous exergy destruction however suggests that the focus of optimisation should be directed to other components first. The regenerative heat transfer should be increased before the utility is changed.

The choice of steam at different pressure levels, depending on the cold streams target temperature, increases the exergy efficiency of the component. However, the exergy destruction is moved from the production to the utility, where only slight efficiency increases are expected. If other utilities, than natural gas burners are used, for example heat pumps, a pressure level reduction will have a direct impact on the utility.

Using the advanced exergy analysis for a real production plant, where fixed set-points are found which have no thermodynamic meaning, e.g. heating a stream and cooling it again, makes it difficult to introduce the required degree of freedom to conduct the analysis. Tolerances of the set-points should be considered, e.g. if the homogenisation of the separation of milk and cream could occur at higher temperatures. An additional step would be to include the hot and cold utility, as they have interdependencies with the production units.

Research should include the reverse osmosis section, as well as sources of exergy destruction within in the spray dryer and fluidised-beds themselves, to obtain a full analysis of the process. The results can then be compared in more details to pinch and process analyses based on the first law of thermodynamics.

5. Conclusion

In this paper, a conventional and advanced exergy analysis, together with a pinch analysis, were conducted for a real industrial processing plant, which is a dairy processing line, producing cream and milk powder. The results of the pinch analysis suggest that the current plant is already highly integrated, and the utility demand consists mainly of the heating required in the water evaporation and drying processes. The existing plant has some further improvement potential which could be accessed through changes in the plant design.

The conventional second law analysis showed which components have the highest degree of exergy destruction. Steam heaters are the main source of irreversibility and the advanced exergy analysis showed the potential of reducing these irreversibilities by implementing different steam pressure levels. However, this measure would not reduce the exergy destruction taking place in the steam production process, implying that a change of the utility system is ultimately required to reduce the actual exergy destruction.

Dividing the exergy destruction into endogenous and exogenous parts, as part of the advanced exergy analysis, has shown to be challenging for the real processing plant. The desired degree of freedom for optimizing the plant is not available. Production set points fix many states of the process and their variations require expert knowledge of the production process. This leads to some uncertainties in the applicability of the results of this analysis.

Overall, the exergy and advanced exergy analyses, in particular the avoidable and unavoidable exergy destruction, can contribute to a better understanding of the real process and how to target process optimisations. This is especially useful if the process is to be redesigned or major components are about to be replaced. However, an advanced exergy analysis requires additional data and significant modelling effort in the cases of dairy factories. This additional work might not justify the additional in-depth knowledge obtained, in particular from a consultancy perspective.

Nomenclature

Letter symbols

\dot{E}	exergy rate, W
e	specific exergy, J/kg
\dot{H}	enthalpy rate, W
h	specific enthalpy, J/kg
\dot{m}	mass flow rate, kg/s
\dot{Q}	heat reate, W
s	specific entropy, J/(kg K)
T	temperature, °C
\dot{W}	power, W
y^*	exergy destruction ratio, -

Greek symbols

ε	exergy efficiency, -
η	energy efficiency, -
μ	chemical potential, -
χ	molar fraction, -

Subscripts and superscripts

in	inflow
0	environmental state

00	dead state
AV	avoidable
D	destruction
EN	endogenous
EX	exogenous
F	fuel
is	isentropic
k	component
min	minimum
out	outflow
P	product
sat	saturation
tot	total
UN	unavoidable

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