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Hybrid-Heating-Systems for Optimized Integration of Low-Temperature-Heat and Renewable Energy

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The food and beverage industries are significant industrial producers of green-house gas (GHG) emissions. Reductions can be achieved by increased energy efficiency and the use of renewable energy to replace fossil fuel use. The main efficiency method within this industries is the use of low temperature heat (LTH), i.e. below 100 °C. Sources for LTH include heat recovery from process flows, heat rejection from utility operations (i.e. chillers, combined heat and power (CHP), condensing economisers), and renewable energy (i.e. solar thermal). A hybrid heating system (H^2S) has been developed that can retrofit steam heater designs for the integration of LTH. Two different systems have been found, for adapting direct and indirect steam heaters, either installing an extra hot water heater or using the indirect hot water loop for the integration. In both systems the existing steam heater remains a part of the system for individual back-up. The set-up and the control algorithm of the H^2S allow installing a 37 % smaller hot water grid than a common design with one central back-up heater. Investigations using a comprehensive model of a whey separation and drying plant showed that implementing a piston engine CHP unit combined with the H^2S reduce the energy costs by 42 % and the GHG emissions by 33 %.

1. Introduction

Capture of low temperature heat (LTH), i.e. below 100 °C, from waste heat and renewable energy sources provide an opportunity in the food and beverage industries, including whey powder production, to increase in energy and emissions efficiency. The specific energy consumption (SEC) of dried whey powders reaches up to 15.5 MJ/kg (Feitz et al., 2007). This shows that drying of whey products is a highly energy intensive process where the reduction of energy costs and green-house gas emissions (GHG) play an important role. The drying of whey products is similar to the milk powder production using heat treatment (e.g. pasteurization), evaporators, spray dryers and fluidised beds for the concentration (Walmsley et al., 2016). Membrane filtration for protein concentration and demineralisation as well as crystallisation of lactose are commonly used for separation and pre-concentration distinguishing the whey process from the milk process. The degree of heat recovery within these plant sections is high and total site heat integration is possible through the hot water utility system for dairy factories (Walmsley et al., 2015).

A high potential for increased energy efficiency, emission reduction and cost savings is a change in heat supply from gas or coal fired steam boilers to combined heat and power (CHP) and heat pumps (Philipp et al., 2016). The heat and electricity profile of drying plants allow the use of CHP, where most technologies, with the exception of some fuel cell systems, generate more heat than electricity. Fuel cell systems might have interesting electricity to heat ratios and high temperature heat outputs but are still too expensive. The typical size of drying plants with an electrical consumption below 7 MW prefers packaged CHP units using piston-engines over gas turbines, because electrical output is higher and investment costs are lower. The motor block and lubricating cooling cycle of an engine CHP requires a hot water based utility loop with sufficient

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sinks to match the duty. The same change in the infrastructure of heat supply needs to be carried out for heat pumps. Because many process streams have target temperatures below 80 °C, this is possible.
The aim of the paper is to show where and how to integrate, backup and control waste hot water for optimizing LTH utility and flexible heat supply with hybrid heating systems (H^2S). The scope includes the design of control algorithms for the H^2S and the cost-benefit of the individual back-up that the hybrid heating provides. The benefits are shown by numerical simulations on a semi-continuous whey processing plant programmed with comprehensive MATLAB models embedded in Simulink and event based StateFlow controls.

2. Methods

Total Site Heat Integration (Klemeš, 2013) has been applied to the case study to determine the amount of hot water utility needed by the processes that may be satisfied by waste and/or renewable heat. Economic modelling is employed to determine the amount of recovery that minimises payback time for the extra piping costs. The whey powder process has been modelled, including dynamics and control, using MATLAB in conjunction with Simulink and StateFlow. In this case the source of hot water is from piston-engine CHP. Comparison to industrial data validated the fidelity of the model. For all energy cost calculations, industrial OECD prices are applied: 104.8 USD/MWh for electricity and 30.6 USD/MWh (IEA, 2016). The ratio of electricity to gas prices has a high influence on the economic results of heat pumps and CHPs.

3. Total Site Integration of whey powder plant

Figure 1 shows the Total Site Profiles (TSP) of the whey separation and drying process. The process is divided into 9 zones of semi-continuous operating processes. The TSP showed only 8 % more potential than the zonal integration target. An extra utility loop for inter-process heat recovery will be investigated in future works. Figure 1 shows the potential of a hot water utility stream.

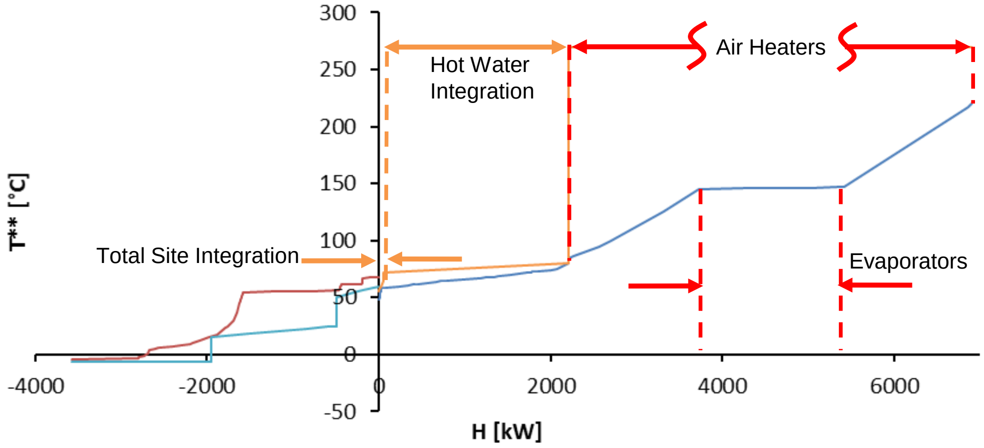

Figure 1: Total Site Profiles for the whey separation and drying process.

In dairy systems, the recovered heat is relatively high in the area between 30 to 60 °C. Hot Water must therefore be integrated above the hot pinch of 58 °C. Besides the Clean-In-Place (CIP), the thermal treatment at 72 – 74 °C is one of the main possible sinks. The flow temperature of the HW-loop needs to be greater than 74 °C to completely provide the duty. All temperature sinks above 74 °C relate to air heating except for the direct steam use in the evaporators. Heat recovery from flue gas and drying air already lift the incoming air to above 50 °C, which means there is limited potential for its use as a sink for additional LTH. To show the integration of two promising technologies, heat pumps and CHP (Figure 2), the utility heat profiles are compared with the Total Site Profiles of the wet processes, i.e. filtration thermal treatment, CIP, crystallization, evaporators and preheating of the spray drying feed, but it excludes the dryer heating section.
The hot water potential in the wet area derives from the heat treatment at the evaporators (EHT), the spray dryer pre-heaters (SPH) and CIP. Table 1 summarises results from a simulation where all possible HW sinks are integrated. Due to cleaning cycles and different product lines, the HW demand is highly variable from a low of 3.8 kg/s to a peak of 175 kg/s. Low and high peaks can be smoothed using a storage tank. Besides the sizing of the storage and the required utility duty, a grid has to be installed that is designed to meet the required mass flow.

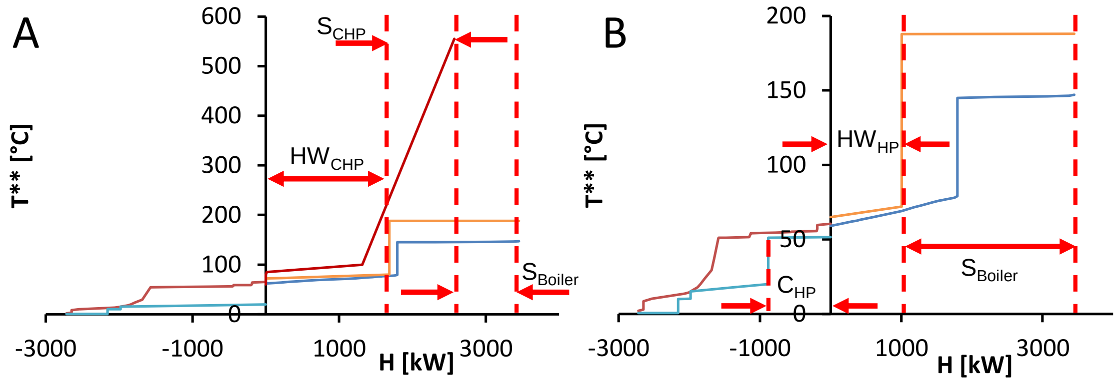

Figure 2: Total Site Profiles for wet processes of the whey powder process. System A: piston-engine CHP integration. System B: Heat Pump integration.

Table 1: Extreme and average simulation values of a 100 % HW integration.

HW flow @ 76 °C	HW Duty (kW)	Mass Flow HW (kg/s)	T HW return (°C)
Minimum	68.9	3.8	53.8
Maximum	6,275	175.2	72.4
Average	2,028	53.7	66.3

Figure 4 shows how the sizing of HW systems based on payback time as calculated from energy cost savings and piping cost estimates using different HW mass flowrates with the optimized pipe diameter (Peters and Timmerhaus, 1991). To reach 100 % of HW integration, the utility doesn't need to be much bigger than for 90 % but the HW grid needs to be sized for a mass flow of up to 175 kg/s. The economical optimum for HW integration using a heat pump is 79 % and using CHP 91 %.
To understand how it will still be possible to connect all HW sinks to the grid to maximize the CHP benefits, the status quo and the retrofitting to H^2S are explained in the next section.

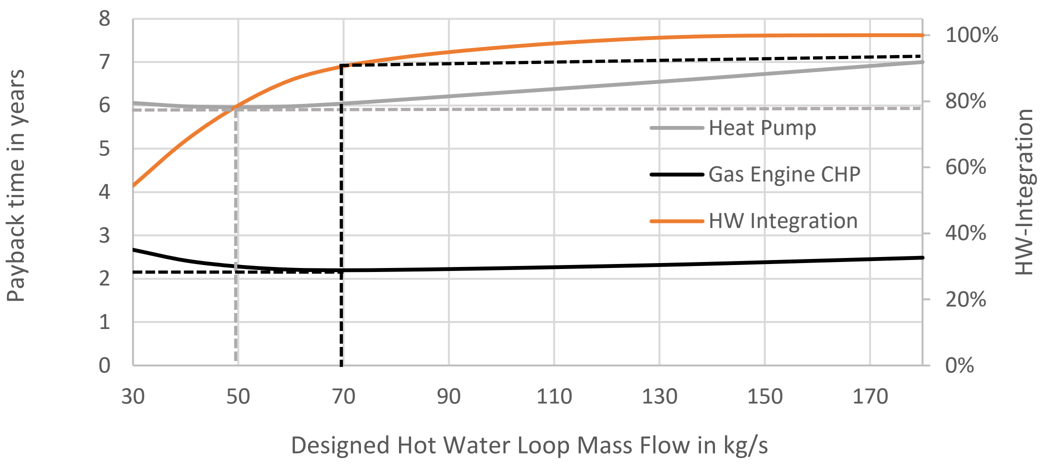

Figure 4: Correlation of designed HW-loop (incl. storage and CHP size adjusting), payback time, and the corresponding HW integration fulfilment.

4. Hot water integration

Except for the CIP and the EHT, the heat is supplied by indirect heaters with an isolated hot water loop as shown in Figure 3, which illustrates a pasteurization plant. The heat is transferred from steam to an isolated hot water loop via the water heater as to protect the heat-sensitive product from overheating.

The CIP mediums – hot water, caustic and acid – are stored in tanks, which are held at a target temperature by circulating them through heaters as shown in Figure 4A.

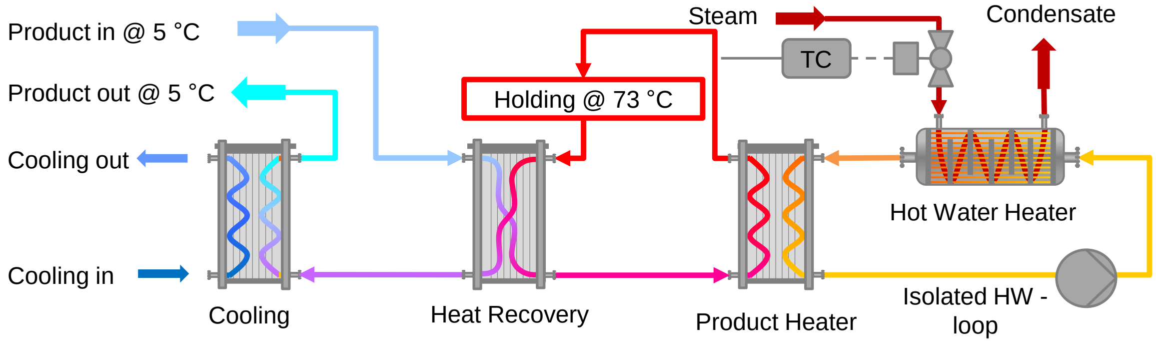

Figure 3: Pasteurization plant with heat recovery, heating and cooling section.

Evaporators appear in various different designs, depending on the number of effects, the type of vapour recompression and the product's constraints. The EHT heat demand profile has therefore various characteristics, ranging from direct steam injection to hot water loops. Evaporators operate at vacuum pressures allowing different methods for handling steam as the heat transfer medium. Figure 4B represents a common way to reuse vapour from the product for the EHT using thermal vapour recompression (TVR). If the use of excess vapour is not applicable, due to more efficient use elsewhere or the lack of availability, hot water loops or steam heaters, connected to the vacuum pump, are used. Analysis showed that two out of three evaporators target the integration of hot water.

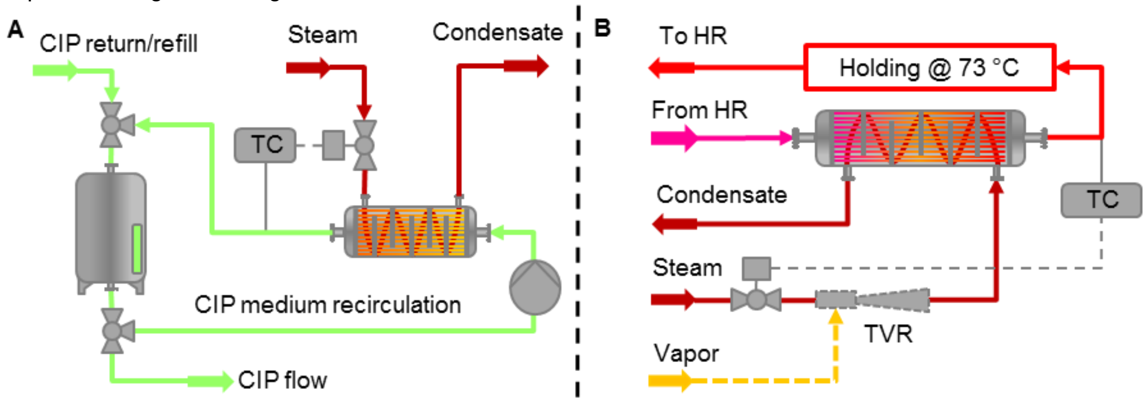

Figure 4: (A) CIP station; (B) Thermal treatment of evaporator feed, optional with TVR.

5. Retrofitting existing indirect heating systems

The aim of the retrofit is to integrate as much hot water as possible by maintaining the process control and the product safety at low investment costs. The existing steam infrastructure is used to back-up the hot water source individually for each heating system, to avoid heating the whole utility stream. To integrate the highest amount of hot water, complete and partial contribution to the product's duty needs to be realized. The ability for partial LTH and HTH supply and its control forms the so called hybrid heating system (H^2S). Figure 5 shows two options for H^2S, with an additional heat exchanger (System B) and the direct integration into isolated HW-loops (System A). In System B, the steam is either supplied directly like in CIP or used in a TVR like in EHT. In System A, hot water is piped in to the HW-loop with three-way valves (TWV). Both systems have the same HW return temperature, therefore the same thermodynamic criteria for the integration, and steam supply for redundancy. Differences appear in equipment costs, space requirements, control, maintenance and hygienic design, which are mostly determined and negatively influenced by the extra heat exchanger in System B. System B will be used for CIP and ETH, because the original Heater is designed for steam use. System A is preferably applied to pasteurization and SPH where an extra heat exchanger can be avoided.

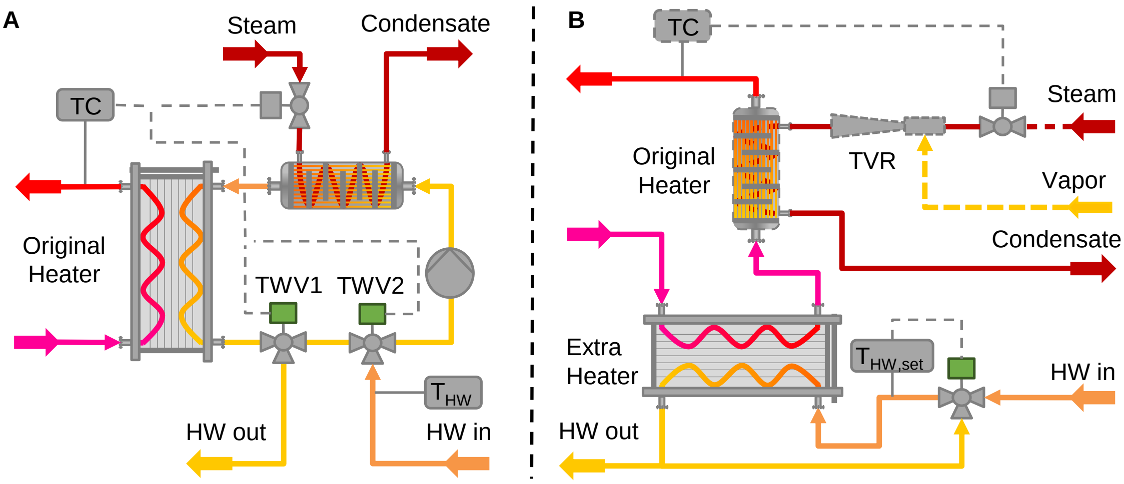

Figure 5: Hybrid Heating Systems. System A: HW-Integration into isolated HW-loop with three-way valves; System B: HW-Integration with additional Heat Exchanger.

6. Hybrid heating systems control

The primary target is to reach the product's set-point temperature regardless of temperature/flow variability in process or utility streams. Secondary is a holistic maximisation of recovered hot water integration. Under certain circumstances steam use can be favoured to a degree to ensure controllability. Low overall steam demand for example, as may occur during stand-by or small workload on evaporators, can cause a surplus of steam from the CHP or the boiler, even at the minimum loads, which is needed to avoid purging and long response delays.

Figure 6 shows how the control of individual hybrid heaters can be connected and steadily compared to a holistic optimization algorithm. The ratio of hot water to the heating duty, called the energy recipe (ER), can be calculated from the process criteria (ER_{in}) and based on the comparison between supply and demand (ER_{ex}). ER_{in} is calculated from the workload, which is derived from the production recipe (set temperature $T_{P,o,set}$ and mass flow $\dot{m}_{P,,set}$) the inlet temperature $T_{P,in}$ and the hot water temperature T_{HW}. Each H^2S calculates its own ER_{in} and compares it to the ER_{ex}, while setting the actuators to target the ER with the lowest value. This guarantees, that hot water is only used if the temperature and capacity are high enough and steam is used when there is a surplus.

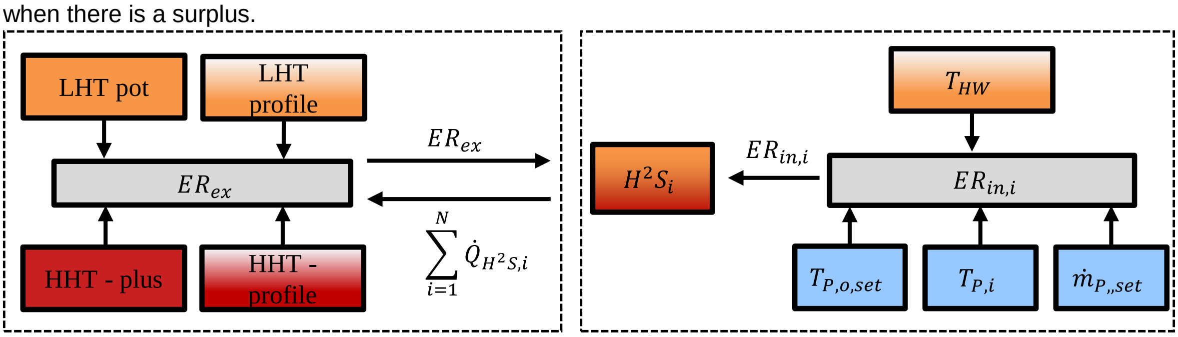

Figure 6: General functions and parameters for determining the degree of hot water integration.

The control algorithm implemented with comprehensive MATLAB models embedded with Simulink and event based StateFlow controls. For the hot water supply, an engine CHP unit with hot water storage was implemented. Figure 7A shows how the control adapted the mass flow using a cumulative chart for one week. The integration of hot water allowed to install a 3.5 MW_{el} piston-engine CHP with an exhaust steam generator. The produced electricity reduces electricity draw from the grid and the recovered heat reduces the duty on the boiler, as shown in Figure 7B.

A 92 % HW-integration was achieved by the controlled use of the H^2S. The targeted optimum mass flow of 70 kg/s was not reached at all times, due to sudden peaks from CIP demand, but was lowered in the critical region. Pipe sizing for 70 kg/s can deliver higher flows at the expense of increased pressure drop and pumping power. Further reduction of mass flow can be achieved by higher hot water temperatures, especially with the System presented in figure 5A. Comparing the maximum mass flow of 175 kg/s to the new maximum of 110 kg/s the sizing of the affordable hot water grid is 37 % smaller. The H^2S helped to reach an 85 % utilisation of the CHP without shut downs of the boiler or the CHP. Changing the energy demand to hybrid consumption with a matching supply from a CHP unit reduced energy costs by 1,745,432 USD/y and GHG emissions by 9,003 t CO_2-e/y. Further investigations will be carried out on heat pump systems, where the supply is also dependent on the availability of waste heat. Future work will also report on a H^2S unit that was installed in the laboratories of the University of Kassel and is currently being tested.

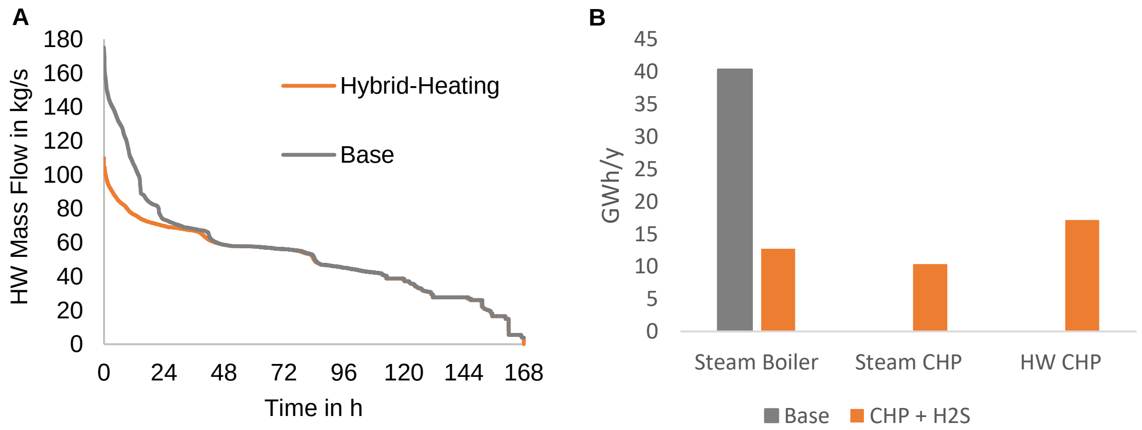

Figure 7: Results from the simulation. (A) Cumulative HW mass flows for the H^2S compared to demand; (B) Comparison between steam supply only (Base) and the integration of a CHP unit and the H^2S.

7. Conclusion

The use of hybrid heating systems, where heat is preferably supplied by recovered hot water and backed up with steam is a possible retrofit on the demand side for hot water integration. The Benefit of this system is a reduction in utility sizing and a high flexibility for the use of available heat sources. Applying the hybrid heating algorithm to a simulation of a whey separation and drying process, 92 % of the HW potential was served from a CHP unit, saving 42 % energy costs and 33% GHG emissions. The concept of the hybrid heating system applies beyond whey processing plants to most low temperature processes in the Food and Beverage industry.

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