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Practical Heat Integration Analysis In The Process Industries

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Abstract: Energy is of ever increasing importance given rising world-wide population and the demand for resources of nations as they strive to maintain or modernise their economies. Clearly a mix of the right resources, technologies and practices is needed to meet the energy and environmental demands being placed on the available resources. A key component of the mix is to improve the energy efficiency of the industrial sector. In the process industries, process integration strategies involving thermal systems provide a means to reduce energy use and environmental emissions. The objective of this paper is to focus from a practical perspective on two integration analysis strategies for industrial processes based on the pinch analysis method. The first includes the integration of an energy conversion unit (ECU) into an industrial process involving mechanical vapour recompression (MVR). The second analysis describes integration strategies for batch processes across multiple time slices. Both methods are accomplished using the PinCH engineering tool.

Keywords: Batch Process, Heat Integration, Heat Exchanger Network, Optimisation, Pinch Analysis.

1. Introduction

The importance of energy in today's society is increasing given rising world-wide population and the associated demand for resources. Modern as well as developing nations need a substantial amount of energy to maintain or improve the standard of living of their citizens upon which a stable societal framework can prosper. To achieve this, it is required to have access to energy sources to ensure continued economic growth and innovation of these nations in addition to maintaining a balance with the ecology. Therefore, a major environmental and economic goal in today's world is to find the right mix of technologies and practices to help meet present and future energy demands and at the same time minimise pollution. A major component in this mix is improved energy efficiency. In the process industries, process integration strategies involving thermal systems provide an effective means to reduce energy use and environmental emissions.

A well-established method of process integration is called pinch analysis. This analysis method provides a systematic procedure for determining the minimum thermal energy requirement for industrial systems. The method helps decompose the complex problem of energy system design into smaller sub-systems to help the design engineer better understand how to minimise or, respectively, optimise the energy requirements. The method distinguishes between avoidable and un-avoidable losses and provides the

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necessary incentive to the design engineer to find the correct set of measures to meet the minimum energy needs for the industrial process being analysed.

The goal of this contribution is to focus on two common heat integration challenges commonly found in the process industries that illustrate the use of the pinch analysis method in the corresponding assessment. The approach maintains a practical perspective on how the method can be applied to these common yet challenging energy integration problems. The first case study involves the application of an energy conversion unit (ECU). A common application area is the dairy industry where energy costs in the milk drying process can account for up to 25% of the direct manufacturing costs [1]. The process contains the energy intensive multiple effect evaporator and spray drying unit operations. Careful design and optimization of such operations are critical to help minimise energy use in the dairy industry. As a result, this process has been selected as a case study for integration of a mechanical vapour recompression (MVR) unit.

A second area of analysis focuses on an integration strategy for batch processes. Batch processes are characterised by their time dependent, non-continuous mode of operation necessitated by the need for specific product requirements of high-value at a low production rate often found in specialty chemicals, fine chemicals and pharmaceuticals industries [2]. Nevertheless, batch process energy integration is important as estimates of 50% of all industrial and chemical production processes operate in a batch mode [3] with the scope of between 30 to 50% possible savings based on experience with integrating batch processes [4]. However, heat integration analysis of batch processes has been neither applied nor researched as much when compared to continuous processes [5, 6]. The challenges are great as the complexity of batch analysis is higher as compared to continuous operation, yet the potential is equally great as batch processes have been typically ignored from an energy recovery perspective enabling the possibility for easy saving opportunities to be implemented [2].

One approach to heat integration within batch processes is to use direct heat transfer. The use of direct heat exchange is a preferred and effective approach in batch processes under the correct conditions and scheduling [6]. However, the time dependence of the individual streams within the process requires careful analysis and design to identify the opportunities for heat transfer. Given this premise of using direct heat exchange in batch processes as a heat integration strategy, the requirement to determine a cost optimal heat exchanger network (HEN) with the flexibility to operate across the different time periods becomes apparent. This optimization can be realised through the maximization of the common heat exchanger area used over all time periods leading to a lower overall area and hence capital cost requirement.

This paper focuses on the application of these two integration strategies. In addition, the PinCH engineering tool [7] has been used as a basis for the implementation and results.

2. PinCH Engineering Tool

To help promote the use of the pinch analysis method, a software tool called PinCH (CH stands for the Latin name “Confoederatio Helvetica”, i.e. Switzerland) has been developed to provide a sound basis for the application and support of the pinch method. The two Competence Centers Thermal Energy Systems & Process Engineering and Distributed Secure Software Systems from the Lucerne School of Engineering and Architecture worked together closely with the Swiss Federal Office of Energy (SFOE) and a team of industry experts to develop PinCH 1.0. The new software focuses on the support of the classical pinch analysis with the aim of providing user friendly tools to be used in the training of new engineers in the field of process integration and to support engineers already advanced in the application of pinch analysis.

The core of the software is centered around supporting the intensive calculations involved in pinch analysis ranging from the data extraction to detailed HEN design. During the first phase of development, ten major processing steps were identified that are typically done by the design engineer and are directly supported in the PinCH software [7]. They are as follows:

1. Extracting Stream Data
2. Creating Processes

3. Assigning Streams to Processes
4. Setting Economic Data (Global and Utility Stream Specific)
5. Creating an Operating Cases Schedule
6. Creating a Target Group
7. Calculating a Target Result (e.g. Separate Design or Time Average Model (TAM) Design)
8. Calculating Target Results Based on Variations of ΔTmin Values or other parameters (e.g. economic data and scheduling data)
9. Adding Energy Conversion Units
10. Creating HEN Designs for Specific Target Results

Each of these steps is managed within PinCH through the use of graphical user interface object visualizers. The key features include the ability to create complex plant design scenarios for the analysis of single continuous, multiple base case and single product batch processes. Once standard targeting calculations are complete detailed HEN grid diagrams can be created to produce minimum energy or relaxed designs. In addition, several ECU operations (heat pump, MVR, thermal vapour recompression and engine) can be integrated into the targeting and HEN design stages for assessment.

3. Energy Conversion Unit Integration

3.1 Milk Powder Production

A particular energy intensive operation in a dairy process is the manufacturing of milk powder [1, 8]. The first step in a typical process involves the concentration of a skim milk feed stream in an evaporator system. Following this concentration step, the product is then dried into its powder form in a spray dryer coupled with a fluidized bed finisher. A simplified flowsheet is shown in figure 1.

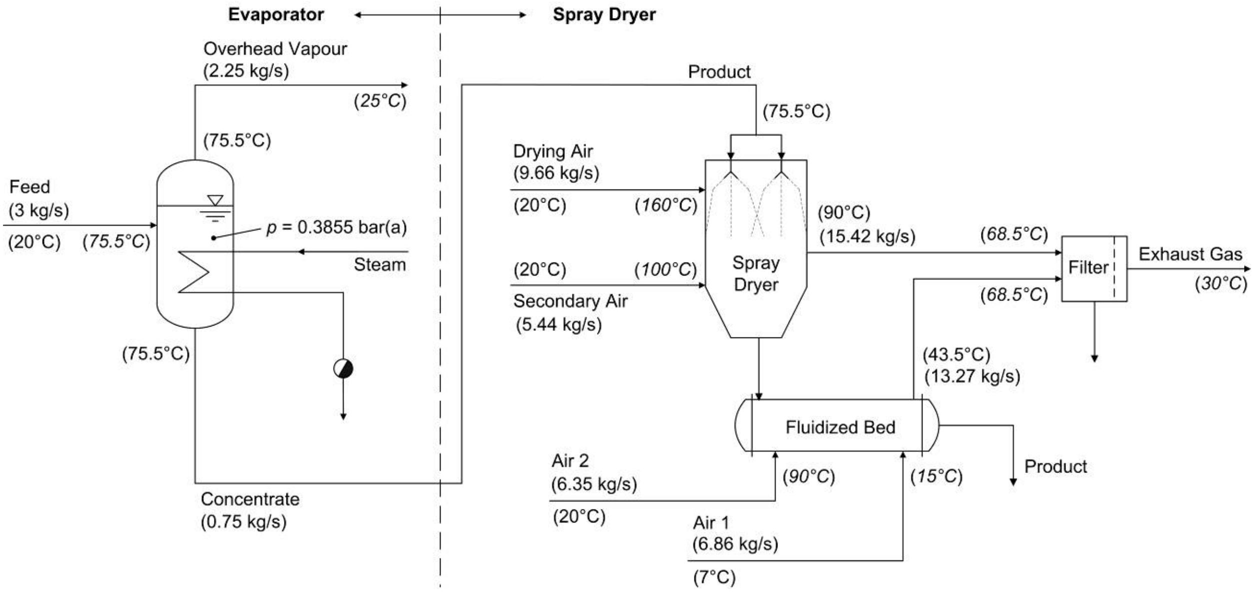

Figure 1: Simplified milk powder process flowsheet (process requirement outlet temperatures shown in *italics*).

Process analysis of the above flowsheet can be done using the PinCH engineering tool. Figure 2 shows the resulting composite curves and cost curve based on the given process requirements.

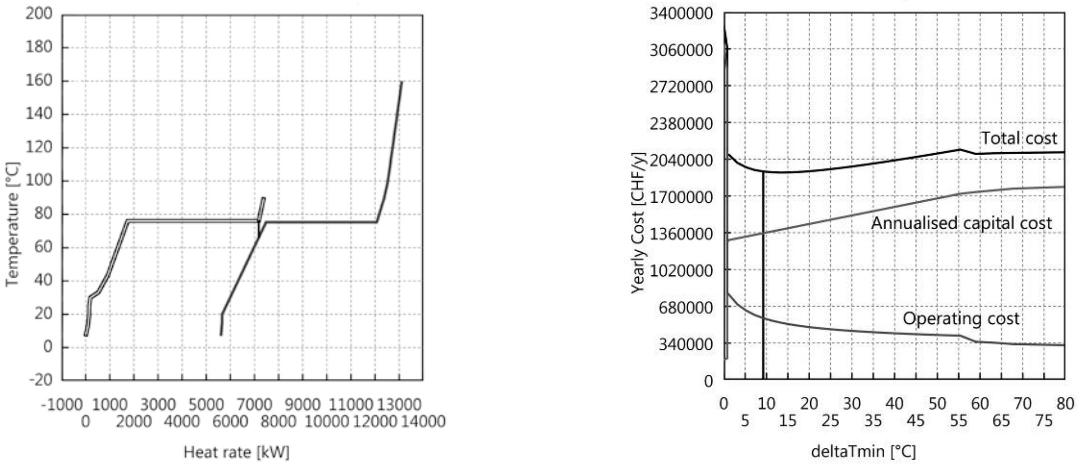

Figure 2: Left – Simplified milk powder process composite curves. Right - Simplified milk powder process cost curve.

Most modern day evaporator systems have been optimised from a unit operation perspective by adding additional evaporator effects in series in order to take advantage of heat recovery using the overhead vapour to heat the next lower temperature effect. In industry having between 3 to 7 effects in series is common [9]. However, for the purpose of clearly illustrating the integration of an MVR unit, a single effect has been assumed for this example.

With this representation, the composite curve and grand composite curve (GCC) of the evaporator simplify to clearly show how the data is extracted based on the corresponding heat duty received by the effect and the heat duty available from the overhead vapour stream (Fig. 3). Correspondingly the GCC shows the residual requirement for heating and cooling when accounting for the process minimum temperature difference (ΔTmin) in each stream. As a result, the upper line is the heat duty to evaporate the vapour while the lower line is the heat duty available in the vapour overhead. The temperature difference between the two horizontal evaporation and condensation segments shown on the GCC correspond to the process ΔTmin, since boiling point elevation of the skim milk has been ignored. The temperature difference would be greater if the boiling point elevation was included [10].

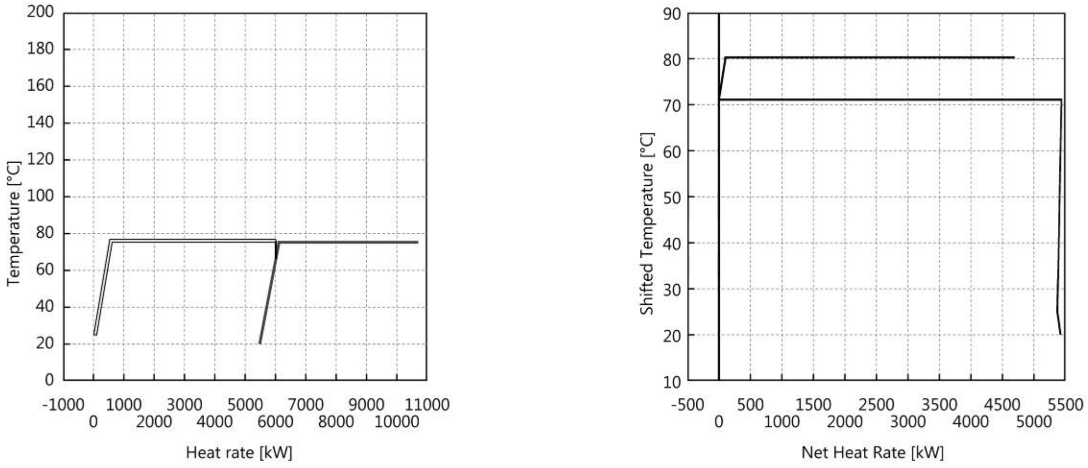

Figure 3: Left – Evaporator Composite Curves. Right - Evaporator Grand Composite Curve.

3.2 Mechanical Vapour Recompression Integration

An MVR provides the ability to upgrade a vapour stream from a lower temperature to higher temperature level using a compressor. In essence, an MVR is a heat pump operating as an open cycle. The PinCH tool provides the ability to integrate an MVR into the particular process that contains a water vapour overhead stream. In order to accomplish this, the overhead vapour stream is replaced with an *upgraded* and *reduced* flowrate stream in the internal stream population used to create the composite curves (Fig. 4).

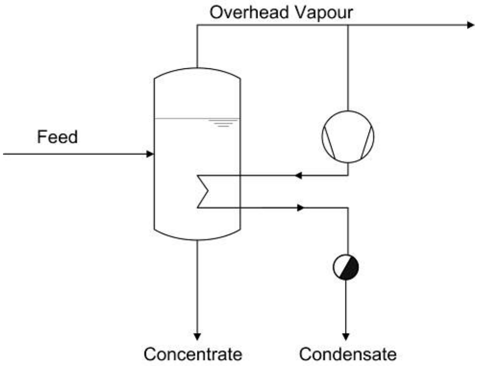

Figure 4: Mechanical vapour recompression integration in a single evaporator effect.

The upgraded stream compressor outlet conditions are calculated internally based on the user defined input conditions that allows the complete solution of process states using the equation of state model according to Lee and Kesler [11]. For this example, the following data in Table 1 are used to achieve a required temperature lift of about 10 K. This temperature lift is relative to the condensation temperature of the upgraded stream leaving the compressor. For design purposes, it is most common to work in terms of the condensation temperature as this temperature is the point at which the most energy is transferred to the fluid within the evaporator.

Table 1: MVR conditions and economic parameters for a single evaporator effect example.

Parameter		**Remarks**
Condensation temperature	85.5 °C	Compressor outlet stream
Mass flow waste heat stream	1.8 kg/s	Portion of overhead vapour to be upgraded
Isentropic efficiency	0.8	
Drive efficiency	0.9	Mechanical and electrical losses
Heat rate of selected waste stream	5950 kW	Total duty of overhead vapour process requirement

a	0	Fixed investment cost component
C_b	157’000 CHF	Base cost
Q_b	250 kW	Quantity base unit of measure – electrical power
m	0.46	Equipment type degression factor
f_m	1	Materials of construction factor
f_p	1	Pressure factor
f_T	1	Temperature factor
f_I	3	Installation factor
Index	500	Cost Index (CE Plant Cost Index)
Index (Base)	391	Cost Index (base values CE Plant Cost Index)

The overall effect of integrating the MVR results in an overlap of a portion of the overhead vapour stream and the required evaporation stream within the evaporator. Clearly the greater the overlap the more energy recovery possible and corresponding reduction in required hot and cold utility targets as shown in figure 5.

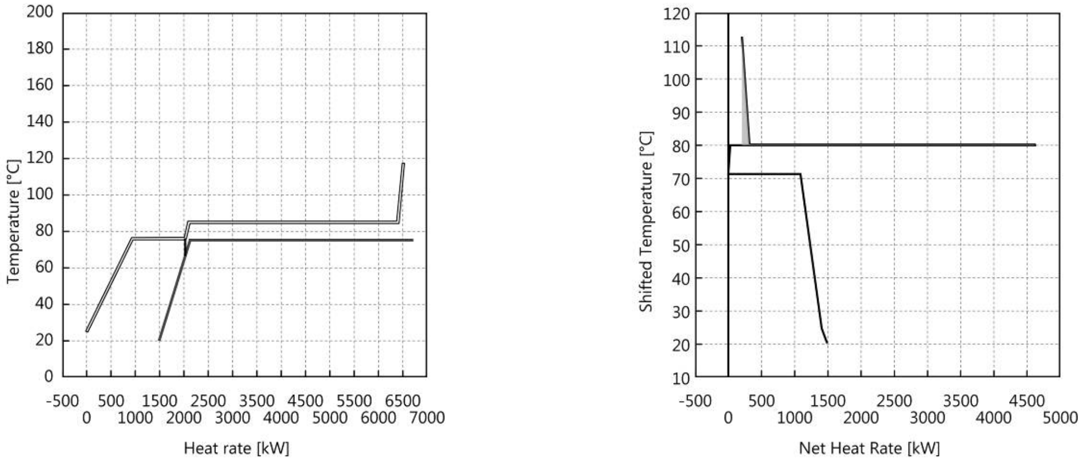

Figure 5: Left – New evaporator composite curve with MVR integrated. Right – New evaporator grand composite curve with MVR integrated.

In this example approximately 165 kW of electrical power is able to upgrade 1.8 kg/s of overhead vapour to provide approximately 4300 kW of condensation duty at 85.5C. This performance comes at a cost, however, as the following standard compressor investment cost calculation (1) [12] leads to a value of approximately 500’000 CHF and an additional operating cost of 39’000 CHF/y (assuming 0.12 CHF/kWh and 2000h operation time).

$$C = \left[\left(a + C_b \left(\frac{Q}{Q_b} \right)^m \right) \cdot f_m \cdot f_p \cdot f_T \cdot f_I \cdot \left(\frac{\text{Index}}{\text{Index}(\text{Base})} \right) \right] \tag{1}$$

Nevertheless, the integration of an MVR provides a convenient method to take a low grade thermal stream and upgrade it. If more effects are included, each effect’s overhead vapour stream and evaporation stream must be included in the composite curve. By selecting a specific overhead stream of a lower temperature effect, the PinCH tool can calculate the associated conditions exiting the compressor for the required condensation temperature to be used in a higher temperature effect and new composite curves can then be calculated.

4. Direct Heat Integration in Batch Processes

4.1 Batch Process Characteristics

A batch processes’ time dependent nature presents unique challenges in the evaluation of energy integration possibilities. In order to apply the pinch analysis technique to a batch process the process time structure can be divided into time slices that represent the time intervals in which specific streams exist at the same time [13]. Once a stream is no longer active or a new stream comes into existence then a new time slice is considered. By carefully assessing the boundaries where streams start and end it is possible to segment in time the entire batch process into periods where streams can exchange heat directly with each other. As a result, within each of these time slices an individual pinch temperature plus composite curves can be determined. This type of analysis is commonly called the time slice model (TSM).

Further challenges arise in the assessment of batch processes related to the nature of the scheduling of each batch. In the above discussion it is inherently assumed that a cyclic pattern exists for the batch process that allows for the derivation of a repeating set of time slices. However, challenges arise in many operations whereby the processes operate in a non-regular manner characterised by changes in yearly production and short term somewhat random on/off cycles such as for cleaning [14]. Additional challenges in finding a repeated schedule is due to complexity that arises when batch processes are operated in a multipurpose configuration [3].

4.2 Heat Integration Flexibility–Capital–Energy Tradeoff

Even though many challenges face those assessing a batch process from an energy perspective it is still important to assess the process TSM. For many batch processes the possibility still exists to isolate and simplify the process schedule and identify opportunities for direct heat exchange. For such processes a natural priority exists in developing the heat integration opportunities whereby the first priority is direct heat exchange followed by indirect heat exchange methods and lastly utility system. However, if a process is non-regular and lacking in a consistent repetitive cycle then indirect methods and utility system methods are necessary. This is often the case for cross plant integration in the food and beverage industry [14].

Given a batch process with an identified repeatable sequence, the question arises how to design a HEN that is robust and flexible enough to handle the different time slices. Several prominent authors have looked at the challenge of flexibility in continuous processes [15, 16] that provide practical and intuitive methods to aid the design engineer in developing a HEN to meet the changing conditions. An additional method for handling this multiple period or multiple base case (MBC) flexibility problem was to determine how to fully optimise the design of flexible HENs and ensure a global minimum in cost [17]. The approach relies on the basics of pinch analysis, yet extends it with the concept of design types that describe the constraints a company is limited to in terms of the flexibility they have in changing the HEN. The design types include conventional, resequence and repipe. The conventional type is the most restrictive form and limits the placement of exchangers to the order they have been placed. However, resequence is more flexible and allows changing the order in which a stream comes in contact with particular heat exchangers. The most flexible and optimistic case is the repipe design which allows complete changing of the order of heat exchangers as well as which streams flow in which pipes. These design types form the constraints used in determining a cost optimal MBC HEN by treating flexibility as an optimization variable at first and not afterwards. Therefore, a better balancing or tradeoff between capital-energy-flexibility can be found

The application of this optimization technique to batch processes is the next step. Batch process time slice intervals are very similar to the MBC operating cases concept which allows for the application of the MBC supertargeting algorithms to be applied to the batch process time slices [18]. This approach includes several extensions. Streams in a batch process are highly dependent on their location and must be checked for validity of heat transfer based on this parameter. In addition, many batch processes operate in parallel trains with duplicates of the unit operation vessels used in producing a particular batch product. Accounting for this duplication in the energy analysis is critical for properly assessing the benefits of direct energy integration in such circumstances. The methods for batch and multiple base case processes are now being implemented in the second version of the PinCH engineering tool.

4.3 Separate Design Analysis

The separate design type is an additional TSM analysis. This type is calculated by assuming the individual intervals are completely independent from all the other intervals. No consideration of overlapping common area is considered and the HENs are treated as being separate from each other. This approach sets an upper limit of area and cost for the batch process HENs and also provides insight into how scheduling changes could be used to reduce complexity and increase opportunities for direct heat exchange. In this study, an example process EP1 as given elsewhere [18] has been selected to test this methodology. The stream data are given in table 2.

Table 2: Example process EP1 stream data [18].

Name	Tin (°C)	Tout (°C)	MC_p (kW/K)	Start (min)	Stop (min)	Alpha W/m^2K)
C1	25	100	1	0	102	1000
C2	130	180	3	48	120	1000
C3	80	105	5	39	120	1000
H1	135	15	1.1	9	102	1000
H2	100	95	20	48	102	1000
H3	165	125	3.5	39	48	1000
H2	165	125	3.5	102	120	1000

The results can be calculated for each time slice and summed together to give the targeting result based on 2000 batches in a year (Table 3). As a result, this overall target result becomes the basis upon which to compare the results from other design types such as resequence or conventional design. The implementation of such design types optimization is presently still in progress and will be completed as future work.

Table 3: Separate design type targeting results for example process EP1.

Variable		Remarks
Total Annual Cost	51.8 kCHF/y	Annualised capital cost plus operating cost
Total Surface Area	90.4 m^2	Combined area over all time slices
Number of Units	20	Combined number of units over all time slices
Total Hot Utility	391.5 MWh/y	Combined hot utility over all time slices
Total Cold Utility	154.2 MWh/y	Combined cold utility over all time slices

5. Conclusions

The study has determined and tested a case study that demonstrates the analysis approach for integrating a mechanical vapour recompression (MVR) unit operation within a process containing an evaporator. In addition, the analysis approach for a batch process using the separate design type was shown. The use of conventional, resequence and repipe design type assumptions was elaborated in how to determine a cost optimal heat exchanger network (HEN) through the maximizing of the common area over all time slices during the targeting stage. Finally, the PinCH software has shown to successfully support the analysis of an energy conversion unit (ECU) integration and separate design type batch analysis for direct heat integration studies. Future work is to include the final implementation of resequence and conventional optimization methods in PinCH.

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