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Methodology for Batch Heat Integration and Storage System Design for Ideal Integration of Solar Process Heat

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A newly developed algorithm for heat exchanger network design has been successfully tested in several case studies on its practical application potential. The combinatorial approach is based on an adapted time slice model and highlights the use of internal heat exchange, as well as exergetic considerations of heat exchangers. Results of a simple industrial case study are shown and outlook for future challenges are given.

1. Introduction

For the realization of the existing improvement potential on thermal energy in industry, demand side energy reduction via technological optimization and system optimization as well as the integration of renewable energy into the industrial thermal energy system need to be further stimulated. It has been shown by several authors that process integration is decisive prior to the selection of new energy supply technologies (Varbanov and Klemeš, 2010). The methodology developed by Schnitzer et al. (Schnitzer et al., 2007) and further elaborated by Brunner et al. (Brunner et al, 2008) to realize thermal energy supply in industry with minimal greenhouse gas emissions is based on a 3 step approach:

- Technological Optimization (measure to enhance energy efficiency)
- System Optimization (Pinch Analysis of a total production site)
- Integration of renewable energy (based on exergetic considerations)

Especially the integration of solar process heat into the industrial energy supply system has to be designed in an ideal way (Schnitzer et al., 2007; Atkins et al., 2010).
To reach the realization of the existing solar process heat potential, an algorithm for heat exchanger network design for heat integration of the total production site in low temperature industry sectors has been developed and is presented in the paper.

2. Methodology

The pinch analysis has proven itself as a strong tool for optimizing thermal energy management in production processes, for single processes or based on a total site approach. Especially when the pinch analysis is applied prior to designing new energy supply systems, it is decisive to consider all hot and cold streams of the total site under consideration. To design appropriate HEN networks it is recommended starting the project at the most constrained point, the pinch itself, and then work outwards. Since the

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early work by Linnhoff (Linnhoff and Hindmarsh, 1983), several authors have been working on continuous HEN design. Also for batch processes several strategies have been developed based on the pinch analysis: the TAM - Time Average Method- (Linhoff et al., 1988), time dependent heat cascade analysis approach for batch processes and time slice models for HEN design achieving maximum energy recovery (Kemp, 2007). The design of heat storage systems for indirect heat recovery has been tackled lately by a number of authors, based on batch mass exchange networks (Foo et al., 2008), based on a storage pinch approach (Krummenacher and Favrat, 2001) or optimizing the use of available storage sizes over MILP (Majozi, 2009).

For the ideal integration of solar process heat a combinatorial HEN design method has been developed that can be applied to continuous and batch processes. For batch processes the presented approach uses an adapted time slice model to calculate possible heat transfer over storages.

2.1 Heat exchanger selection algorithm

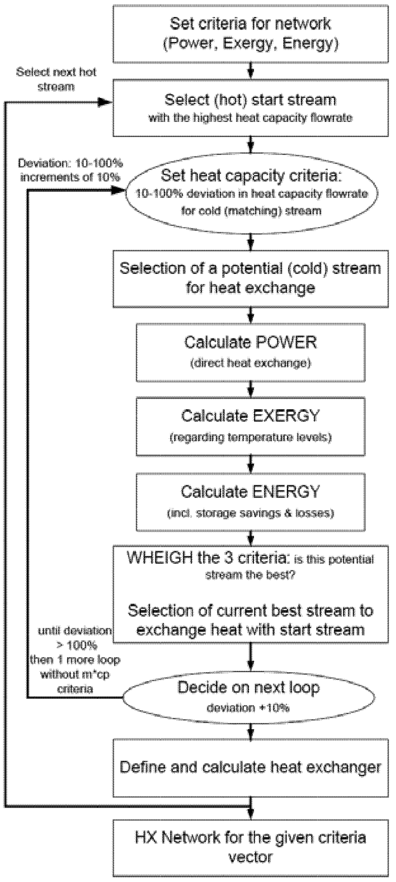

Figure 1: Algorithm for heat exchanger network design with batch processes

The main steps used in the developed heat exchanger network design algorithm are shown in Figure 1. Three criteria

- power of heat exchange
- transferable energy – if necessary over storage
- exergy

define the combination of different streams within the system in order to design the heat exchanger network. The weight of these criteria runs from 0-100. The best ranked heat exchanger network (based on its energy saving potential) is finally chosen.

2.2 Storage consideration

The algorithm works with an adapted time slice model to calculate the energy transferred over a heat exchanger when the processes are not running continuously. Storage calculations, so far limited to hot buffers, are an integral part of the heat exchanger network design to calculate the transferable energy.

Let's consider 2 hypothetical streams A and B, both running discontinuously. The operating schedules of the hot stream A (waste heat) and the cold stream B (energy demand) are presented in Figure 2. Streams A and B are either overlapping in certain intervals (creating intersections) or operating independently.

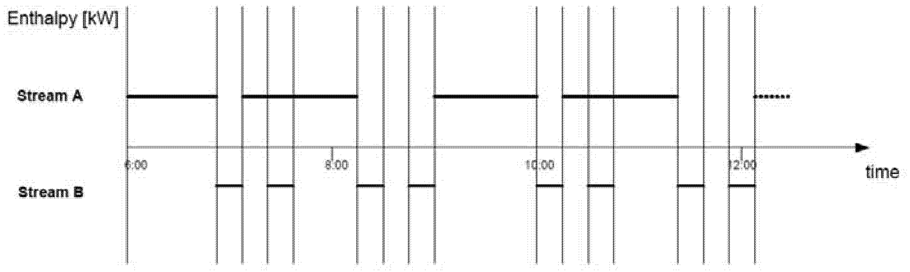

Figure 2: Group of "time slices" for hypothetical streams A and B

Each start point and/or end point of the operating schedule of these streams A and B, defines the start/end of one time section (time slice). For each time slice the available hot energy E_{hot} (from stream A) and the necessary heating demand E_{cold} (from stream B) can be calculated, based on the duration, the operation of the streams (which stream is operating in this time slice) and the respective enthalpy data of the streams. The difference of energy ΔE is calculated for each "time slice" according to:

$$\Delta E = \left|E_{hot}\right| - \left|E_{cold}\right| \tag{1}$$

This difference in energy within one time slice is positive, in case more (waste) heat is available in this time slice than the energy that is demanded. Over a certain time period (e.g. one typical production week), we can calculate when there is a heat surplus and when there is an energy demand. Also, the accumulated $\Delta E_{acc,\ week}$ is calculated, to see whether over a whole period there is energy surplus or deficiency.

For the calculation of the energy that can be possibly stored in a storage tank over a period Δt, two different cases can be defined:

1)$\Delta E_{acc,\Delta t} > 0$

2) $\Delta E_{acc,\Delta t} < 0$

For defining an estimated necessary storage tank, the maximum amount of energy that can sensibly be stored for later heat transfer has to be calculated for both cases. This maximum amount of storable heat is then converted to a storage tank size, calculated as a hot stream buffer. If the energy available is less than the demanded one (case 2), the heat storage possibility is defined by the maximum value of the accumulated energy $\Delta E_{acc,\ max}$ within the time period.

$$\Delta E_{storage} = \Delta E_{acc,\max} = \sum_{t1}^{t,\max} \Delta E_t \tag{2}$$

If the energy of the hot stream that is available within the period is higher than the energy demand of the cold stream (case 1), the minimum accumulated energy value (maximum accumulated energy demand) is decisive for the storage size.

A hot buffer volume is given by:

$$V = \frac{\Delta E_{storage}}{H} \frac{m_{hotstream}}{\rho_{hotstream}} \quad (3)$$

2.3 Multiple use of streams within HEN

With the approach shown above, we calculate the energy in each time slice that needs to be stored in a hot storage buffer to meet the requirements of the cold stream in its best possible way. At some time there might be a higher flow of the hot stream available than the amount that is stored. In this case, the storage would generate an overflow and the hot stream in this time is still available for other heat recovery.

Similarly, times can occur when the cold stream requirements are not met by the storage, so additional external utilities are required to meet the energy demand. In these times we have an energy demand that could be covered by an external utility or another source of waste heat. To consider these situations, both of these streams (surplus waste heat and additional energy demand) must be calculated for later consideration in the network.

2.4 Losses

In practice, energy storages in industrial sites generate considerable heat losses. A heat loss calculation is therefore integrated for estimating industrial storage systems (John, 2002). For each time slice, the actual temperature T is calculated from the mixture of the current storage temperature and hot stream input temperature.

3. Case Study

The approach has been tested and improved in several case studied in the food industry and the metal surface industry. In the galvanizing industries usually a large heat demand exists in the temperature range between 40-70 °C for surface treatment processes. Waste heat exists mainly from flue gases from dryers, or thermal post combustion systems. Energy streams from a simple case study, comprising a few surface treatment baths, driers and a thermal exhaust combustion system are shown in the grid diagrams in Figure 3 and Figure 4.

Currently the waste heat of the thermal post combustion (TPC) is used to preheat the incoming gas to 200 °C, and subsequently the heat is being used for heating one dryer at 120 °C and a hot water system at 80 °C that supplies all other low temperature (18-65 °C) processes. The thermodynamic proposal for heat exchange over the presented HEN algorithm shows that an extended preheating of the incoming gas to the TPC is sensible. The incoming gas can be preheated to 435 °C. Low temperature process energy demand for the remaining process baths and ventilation systems should be supplied by low temperature heat sources, such as waste heat from cooling machines or compressors or from solar thermal heat.

As dryer 1 is designed to be heated by an air-air system a practical realization could be an extension of the internal TPC heat exchanger and subsequent heating of the dryer (air to air heat exchange) to its target temperature (see Table 1). Due to the current inefficiencies of the thermal post combustion, estimated savings amount to 10 %.

Table 1: Heat exchanger network - practical realization

	Heat exchanger 1	Heat exchanger 2
Hot stream	Exhaust gas, TPC	Exhaust gas, TPC
Start Temperature (°C)	500	275
End Temperature (°C)	275	125
Cold stream	Incoming gas, TPC	Dryer for coated parts
Start Temperature (°C)	60	115
End Temperature (°C)	285	120
Transferred heat (kW)	**455**	**303**

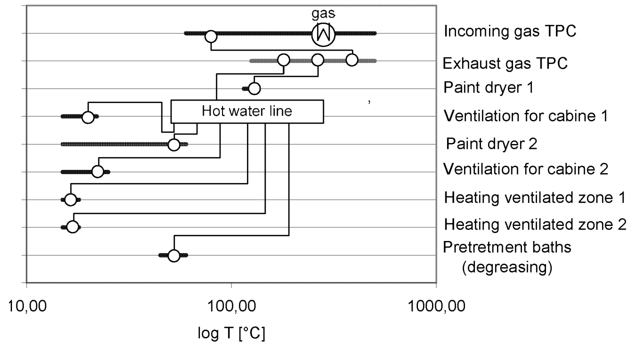

Figure 3: Initial heating system presented on a grid diagram

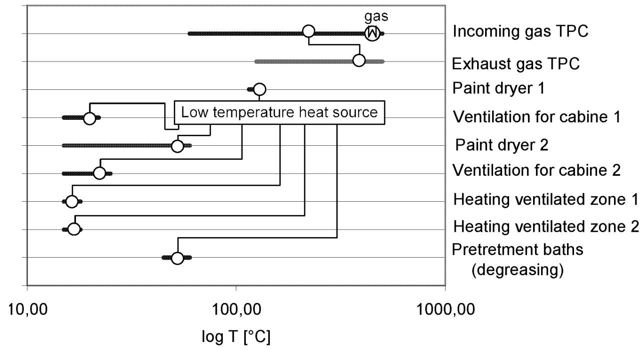

Figure 4: Proposed heating system presented on a grid diagram

4. Conclusions

A new algorithm for heat exchanger calculation has been developed and successfully applied. It is based on an adapted time slice model and, in case of batch processes, calculates heat exchanger systems including hot buffer calculations. The combinatorial approach highlights the use of internal heat exchange and sets heat exchangers according to exergetic considerations. Future developments will focus on using dynamic (real-time) data from processes for the pinch analysis and optimizing storage considerations over the integration of simulations of different storage concepts.

Nomenclature

ΔE	difference in energy availability & energy demand, kJ	$\Delta E_{storage}$	energy that defines the storage size, kJ
$\Delta E_{acc,\Delta t}$	accumulated ΔE over a certain time Δt, kJ	$\Delta E_{acc,max}$	maximum of accumulated ΔE over a certain time Δt, kJ
$V_{storage}$	Volume, m^3	H	heat exchanger power, kJ/s
m	mass flow of hot stream, kg/s	T	storage current temperature, K
ρ	density of hot stream, kg/m^3	t	storage time, s

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