Example of optimisation and heat integration on a basis of ethanol plants

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By means of the process simulation tool IPSEPro and pinch analysis, the authors identified and evaluated strategies for energy saving and heat transport in ethanol plants with a production target below 10.000 t/a. It is shown, that with the standard set-up the integration of the basic ethanol plant has little potential for heat integration. By increasing the pressure in a rectification column of the distillation process more transferable energy is available which is followed by a reduction of 27 % and 24 % in heating and cooling duty of the plant.

To decide whether process steam or hot water is the optimal heat transfer medium for the small-scale ethanol process, the complete heat exchanger network was balanced to both cases. The comparison led to the conclusion, that in this case the heat is best transported by steam. This is due to a higher heat conductivity that concludes in a lower demand for the heat exchangers area for all examined units.

Key words: heat integration, pinch analysis, process simulation, ethanol

Nomenclature

A – total surface area of conductive surface [m^2]
F – correction factor for log. mean temperature difference
k – overall heat transfer coefficient [W · m^{-2} · K^{-1}]
m – mass flow [kg · s^{-1}]
NTU – number of transfer units
ε – dimensionless temperature difference
Q – heat flow [W]
R – ratio of heat capacity flow
T – temperature [°C]
S/L – ratio of steam to hot water operated heat exchanger surface area
$\dot{W}$ – heat capacity flow [W · K^{-1}]

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Indices

ε_{G} – gas hold-up [–]
$'$ – cold stream
i – inner
j, k – indices
cc – counter current

1. Introduction

The major production of ethanol for the transport sector is facilitated in plants with a yearly output > 100.000 t. Although the capacity of such plants allows advanced energy integration techniques, the internationally obtained substrate deteriorates the sustainable process index (SPI). Embedded in a regional concept the production capacity drops below 10.000 t/a dehydrate ethanol, but the impact on the environment is massively reduced [1]. Ethanol plants of this size are found in the beverage industry with the focus on high quality spirits over energy concerns. This needs to be addressed when refurbishing the process from spirits to fuel for transportation.

1.1 Ethanol process

Starting point for the ethanol process (Fig. 1) is the milling of the substrate. The range of substrates as of today is limited to corn and grain with a high starch content as well as sugar cane [2]. The production of cellulose-based ethanol is still in the development phase and therefore not considered in this paper [3]. The starch flour is mixed with hot water to obtain a mash temperature of 90 °C. In this temperature range the enzymes that facilitate the digestion of starch to mono-saccharides have their highest activity. The temperature range of the fermentation process is between 35 to 40 °C. The yeast takes about 3 days to convert most of the sugar into ethanol and carbon dioxid. The beer is then processed in a two-step distillation process. The first distillation column (beer column) facilitates the separation of the ethanol water mixture from the slurry. This step is followed by a rectification step that further concentrates the ethanol to 95.1 % w/w. To dehydrate the water a vapour permeation unit is installed. The final concentration of alcohol is 99.7 % w/w.

To evaluate the potential for optimising the ethanol process with respect to energy concerns the paper deals with two distinct cases.

1.2 Heat integration

The object of the first task is to analyse the heat distribution system within the ethanol plant. As mentioned before, the process has several sinks and sources of heat at various qualities and quantities. The result of this analysis will then be used to derive a heat exchanger network to distribute the energy as economic as possible within the system. The size of the heat exchanger and the specific

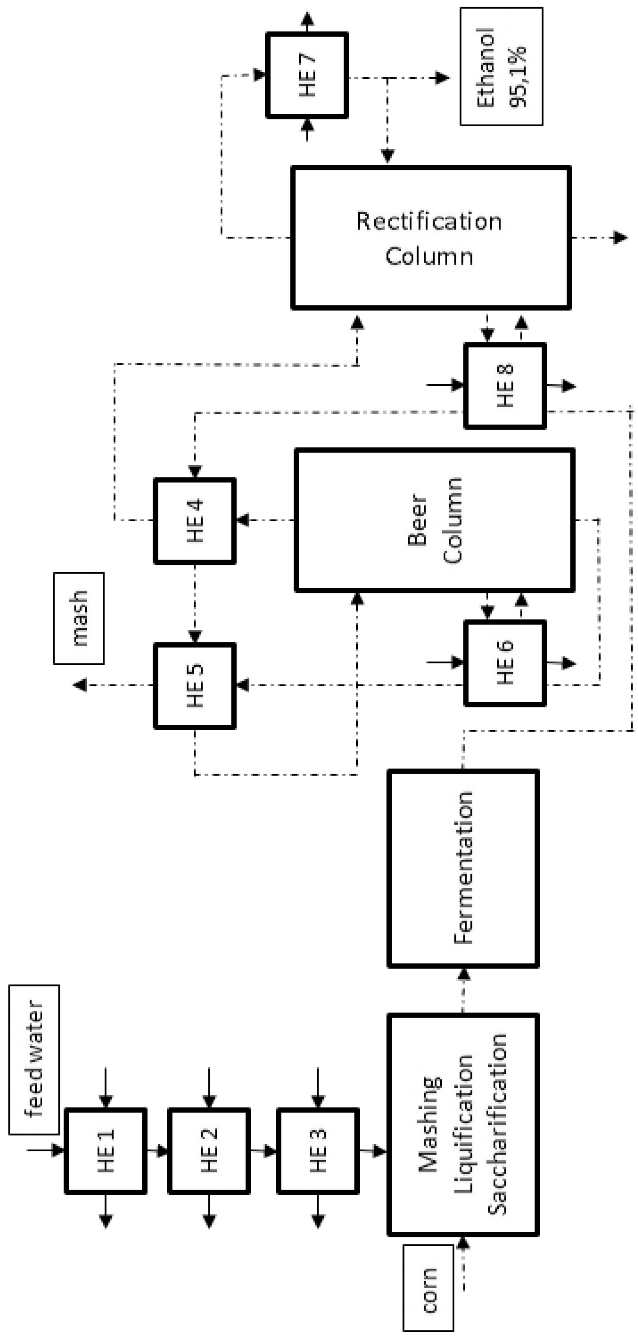

Fig. 1. Ethanol process including heat exchanger (HE).

attributes of the heat transfer medium lead to the decision for the most economic set-up for process heat supply in an ethanol process of small scale.

1.3 Pressurized rectification column

To further optimise the process, simulations are conducted regarding the set-up of the rectification column. The potential of the rectification column operated at 4 bar absolute in comparison to atmospheric pressure is examined. The corresponding significant reduction of energy consumption might be outweighed by the additional investment costs. This measure is standard in mid-sized and large facilities where more expensive procedures can be implemented.

2. Simulation and calculation

2.1 Process simulation

To obtain process parameters and verify the calculated data, IPSEpro, a process simulation tool was utilized. Based on a library of process units for ethanol production developed earlier the process was simulated.

2.2 Pinch analysis

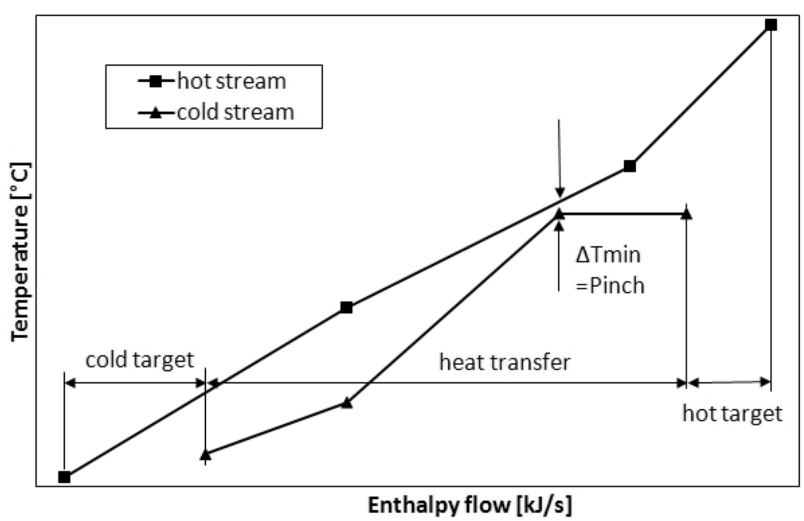

Fig. 2. Pinch analysis by composite curves.

The first step for an efficient integration of heat fluxes is the pinch analysis, which is a method for process integration and a support tool for the design of heat exchanger networks. First, all the heat sources (flue gas and cooling cycle of the gas engine, gas combustion chamber) and sinks (distillation columns, fermenter, ...) of the process are identified. The data required for the plot can be derived directly from the simulation data. To visualize the energy flows, a composite curve is drawn (Fig. 2). This temperature over heat load plot shows the hot streams (hot composite curve) in relation to the cold streams (cold composite curve) with the pinch temperature established at the point of closest approach of both curves ($\Delta T_{\min}$).

$$\dot{Q} = \left(\sum_j \dot{W}'_j - \sum_j \dot{W}_j \right) \Delta T_k. \tag{1}$$

The plot can be divided in three sections. The cold target that specifies the minimal required cooling duty of the process, the overlapping region that allows actual heat transfer by the heat exchange network and the hot target that is the minimal required heating duty of the process.

2.3 Heat exchanger sizing

Based on the pinch analysis a network of heat exchanger is designed to recover process heat and thereby reduce the heating and cooling duty at the same time. The primary selection criterion for the type of heat exchanger is the applicability in the ethanol facility. Especially liquids loaded with organic matter demand for thorough design. Common types found in these plants are tube in tube, shell in tube, plate and spiral heat exchangers. Based on the specific task, economy, serviceability and performance, the type is chosen (Fig. 3).

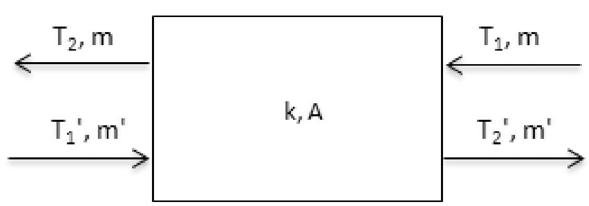

Fig. 3. Schematic depiction of a heat exchanger.

2.4 Design parameter

In regard to economic design of the units, a minimal temperature difference of the streams of 10–15 °C should be achieved. To prepare for potential fouling, and therefore loss of heat transfer capacity, heat exchangers loaded with mash and distillation slurry are designed with an excess charge of 10 °C that result in at least 25 °C temperature difference between the cold and the hot medium. The velocity of the media in the heat exchangers should be in the range of 0.7–1.3 $\mathrm{m \cdot s^{-1}}$.

2.5 Equations

The calculation of the heat exchangers is based on the method described by Roetzel and Spang [4, 5]. The applicability and the reliable results make this technique faster and more convenient over the "cell method" described by Gaddis and Schlnder [4], as long as an analytical solution for the type is provided.

The dimensionless temperature difference for hot and cold stream:

$$\varepsilon = \frac{T_1 - T_2}{T_1 - T_1'}, \qquad \varepsilon' = \frac{T_2' - T_1'}{T_1 - T_1'} \tag{2}$$

for $0 \le \varepsilon \le 1$.
Number of transfer units for hot and cold stream:

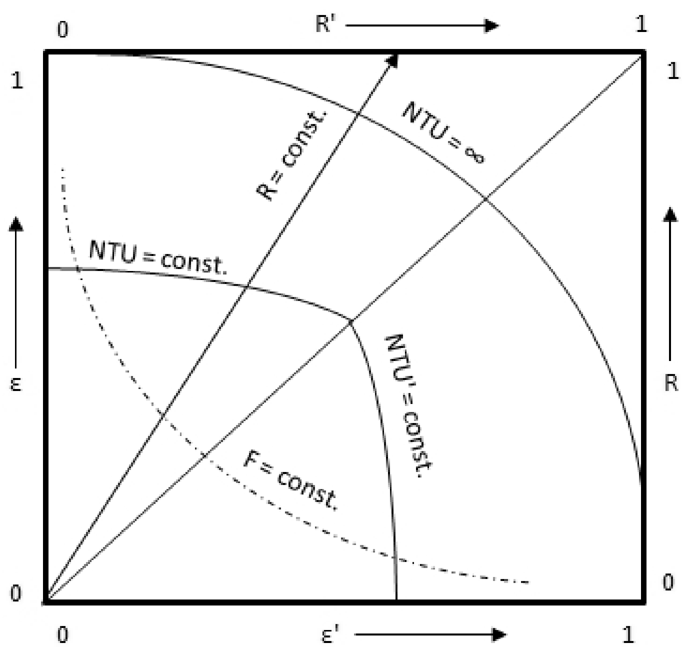

Fig. 4. Schematic depiction of the diagram.

$$NTU = \frac{kA}{\dot{W}}, \qquad NTU' = \frac{kA}{\dot{W}'} \tag{3}$$

for $0 \leq NTU \leq \infty$.
Ratio R of heat capacity flows:

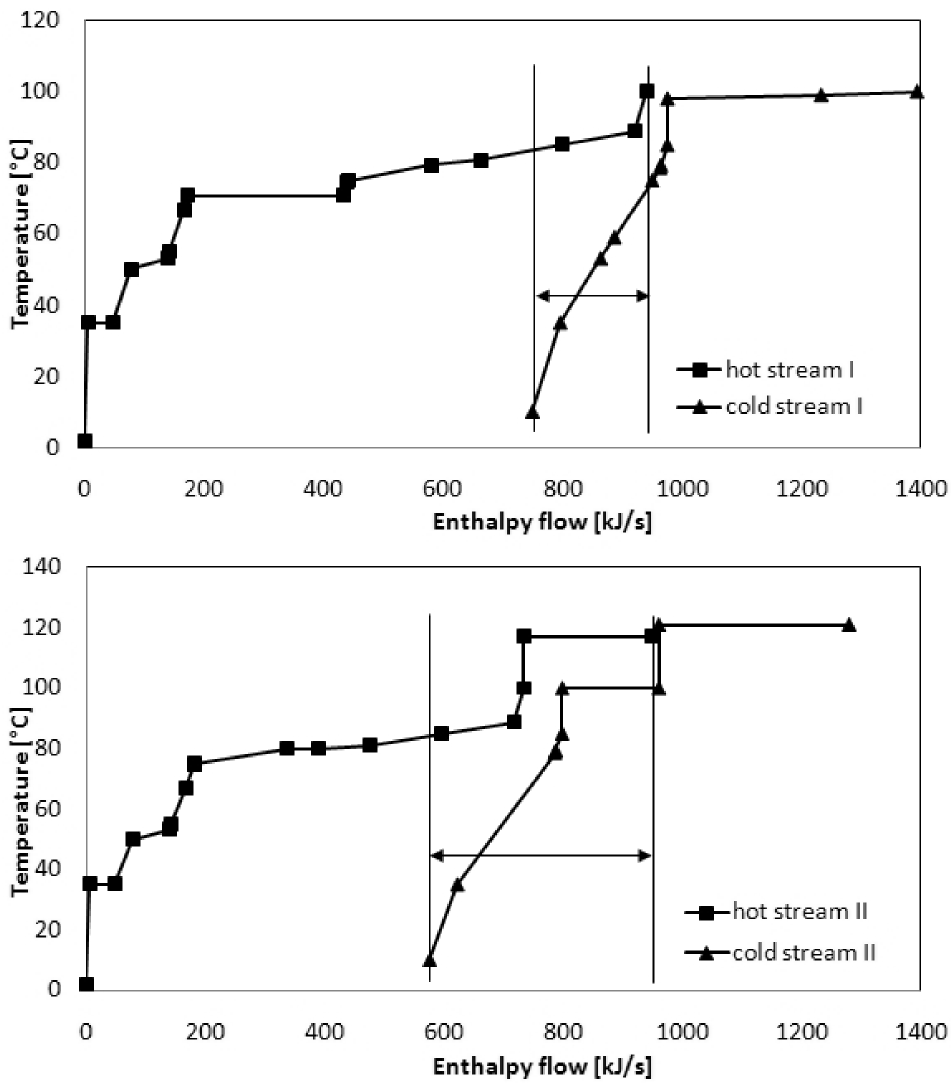

Fig. 5. Pinch analysis of ethanol plant without (I) and with pressurized rectification column (II).

$$\frac{\varepsilon}{\varepsilon'} = \frac{NTU}{NTU'} = \frac{1}{R} = R' = \frac{W'}{W} \tag{4}$$

for $0 \leq R \leq \infty$.

The correction factor for log. mean temperature difference F:

$$F = \frac{NTU_{\mathrm{iG}}}{NTU_{\mathrm{i}}}. \tag{5}$$

This set of formulas lay down the basis for the graphical solution of the problem. Figure 4 shows a schematic of the diagram and its components. For the most common heat exchanger types this diagram can be found in the literature [4].

3. Results

3.1 Pinch analysis

The results of the pinch analysis of the basic ethanol plant (I) as well as the design with pressurized rectification column (II) are shown in Fig. 5. The cold target of (I) amounts to 749 kW, the hot target to 451 kW. This graph is characteristic for fermentation processes combined with distillation processes. The requirement of high quality heat for distillation and a considerable amount of low temperature streams from the fermentation process reduce the potential energy transfer to only 192 kW. This amounts to 30 % of the heating duty and 20 % of the cooling duty.

The pinch analysis of the modified distillation process demonstrates the impact of this measure on the entire system. There are two immediate effects: 1) The head product of the rectification column – that is partially condensed and looped back into the same column – is now available as high quality heat source (248 kW). 2) Additional utilities for cooling of this process stream can be spared. This frees up further resources. The cold target is reduced from former 749 kW to 575 kW, the hot target from former 451 kW to 333 kW. This is due to an increased overlapping region (373 kW instead of 192 kW). Of the absolute duty for cooling and heating, 52 % of the cooling duty and 40 % of the heating duty can be provided by means of heat integration.

3.2 Heat exchanger dimensioning

The integration of the ethanol plant requires eight heat exchange units (Table 1). For the examination of the heat transfer agent only three units have to be adapted (HE3, HE6 and HE8). The version (a) is heated by hot water (150 °C, 5 bar) and (b) by process steam (152 °C, 5 bar). Based on the calculation of the efficiency as well as on economic considerations, the type of the heat exchanger

Table 1. Steam and hot water heat exchanger for small-scale ethanol plant

	Label	Hot stream	Cold stream	Type
Feed water preheat	HE1	motor cooling II	feed water	tube in tube
Feed water preheat	HE2	motor cooling I	feed water	tube in tube
Feed water preheat	HE3a	hot water	feed water	tube in tube
	HE3b	process steam	feed water	tube in tube
Distiller wash cooling	HE4	distiller's wash	mash	tube in tube
Dephlegmator	HE5	head beer column	mash	tube in tube
Sump HE beer column	HE6a	hot water	mash	shell and tube
	HE6b	process steam	mash	shell and tube
Rectification condenser	HE7	head rectification	cooling water	tube in tube
Sump HE rectification column	HE8a	hot water	sump product	shell and tube
	HE8b	process steam	sump product	shell and tube

Table 2. Results of heat exchanger calculation

Label	Q	T_1	T_2	T_1'	T_2'	m	m'	A	S/L	k
	[kW]	[°C]	[°C]	[°C]	[°C]	$[\mathrm{kg \cdot s^{-1}}]$	$[\mathrm{kg \cdot s^{-1}}]$	$[\mathrm{m^2}]$	[%]	$[\mathrm{W \cdot m^{-2} \cdot K^{-1}}]$
HE1	46.9	53.0	30.0	10.0	40.0	0.485	0.374	2.0		1456
HE2	62.5	90.0	50.0	40.0	80.0	0.374	0.374	4.6		1368
HE3a	26.1	110.0	90.0	80.0	97.0	0.309	0.374	**1.7**		1300
HE3b	15.7	152.0	152.0	80.0	90.0	0.007	0.374	**0.1**	5	2617
HE4	40.6	100.0	75.0	55.0	78.0	0.398	0.444	1.4		1450
HE5	34.4	81.0	79.0	35.0	55.0	0.075	0.444	0.7		2998
HE6a	140.0	150.0	110.0	78.0	100.0	0.820	0.473	**5.9**		917
HE6b	140.0	152.0	152.0	78.0	100.0	0.066	0.478	**1.3**	22	2076
HE7	248.1	78.0	78.0	57.0	67.0	0.274	5.933	7.8		1198
HE8a	250.0	150.0	110.0	78.0	99.0	1.465	0.233	**10.5**		910
HE8b	250.0	152.0	152.0	78.0	99.0	0.119	0.233	**2.3**	22	2064

was selected. Except HE6 and HE8 all units are designed as tube in tube heat exchangers. The advantage of this set-up is the simple design that allows a modular concept. In case the area in contact with the liquid is blocked by impurities and therefore the heat transfer falls below a defined threshold, the unit is easily disassembled and cleaned or replaced. The heat exchangers in the distillations columns sumps are traditionally designed as shell in tube.

The results of the heat exchanger calculation are summarized in Table 2. When steam is used as heat transfer medium, the required area for heat transfer is reduced to 22 % compared to the scenario hot water. It should be noted that

HE3b has a lower temperature target (T2′ = 90 °C instead of 97 °C with HE3a). This is due to process specific requirements.

4. Discussion

The simulation and analysis of an ethanol process highlights the possibilities and limits of heat integration. Only 30 % of the required heat can be provided by steam that needs to release heat. The remaining energy has to be supplied by an additional source. A possible measure to improve the process is to increase the pressure of the rectification column and therefore to increase the operating temperature. This way, the heat of condensation at the rectification columns head stream is released at an elevated temperature, which is ideal for integration with the remaining process.

This modification improves the process in several areas. The integrability of the system is greatly improved. The hot target is reduced by 27 % and the cold target by 24 % compared to the original system. This has a direct impact on the utilities for cooling and heating that can be saved but have to be of higher quality.

The calculation of the heat exchanger network in regard to the optimal heat transfer medium is decidedly in favour of steam over hot water. The size of the heat exchangers transfer area is only 22 % with the steam than with hot water. Further steam has advantages in regard to automation and controlling and requires no pumping.

5. Conclusion

A method for optimisation of an ethanol of different process scenarios pinch analysis as based for heat integration and benchmark for the process performance and heat exchanger design as decision tool for the selection of a heat transfer medium led to a good understanding of the process what is the basis of every efficient optimisation strategy.

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