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Heat integration of biochemical ethanol production from straw – A case study

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HIGHLIGHTS

- We perform heat integration of ethanol production from straw.
- In pinch analysis distillation and evaporation design are examined in detail.
- Via pinch analysis the design is improved and the utility targets reduced by 15%.
- For the improved design an efficient heat exchanger network was obtained.
- For this network 50% of residual materials suffice to provide process heat.

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ABSTRACT

Ethanol produced from lignocellulosic biomass is a desired, renewable fuel that can help to reduce our dependence on oil. In order to achieve the commercial deployment of this fuel good economic and environmental performance are mandatory. Both these targets are tackled by the efficient use of process heat. This work deals with the heat integration of the biochemical production of ethanol from straw. Process simulation and pinch analysis are applied to investigate a base case design of the production process. The energy intensive unit operations distillation and evaporation are in the focus of this pinch analysis. Pressure and heat load modifications of these sections are applied to improve the process design. For this improved process design a heat exchanger network is synthesized. Energy stream and pinch analysis revealed that process residues easily suffice to provide the investigated process with heat. The design modifications of the distillation and evaporation sections lead to increased heat integration. Consequently, a 15% reduction of the utility targets compared to the base case is obtained in the improved design. The heat exchanger network for the improved design is simple, yet the increase in utility consumption compared to the utility targets is quite modest. As a result, in the network only 51% of waste biomass suffice to provide the process with heat. The exceeding biomass can be used for the recovery of energy or material by-products, which highlights the need for efficient polygeneration concepts.

1. Introduction

It is widely accepted that bioethanol from lignocellulosic feedstock should play an important role in the energy system of the future. This consensus, based on several appealing features of the fuel and the technology, is expressed in policies in both, the EU and the US [1–3]. Bioethanol is a renewable fuel that reduces our dependence on oil, has very good combustion properties and can be applied to the existing car fleet when blended at low concentrations [4]. The greenhouse gas mitigation potential of lignocellulosic ethanol is high compared to both, fossil fuels and bioethanol from starchy crops [5,6]. Ultimately, the food vs. fuel debate can be avoided, when lignocellulosic waste materials are used for the production of bioethanol.

At present, the technology is limited to the demonstration scale. For commercial production lignocellulosic ethanol has to be economically feasible and environmentally friendly. A common strategy to achieve this goal is to provide process heat by burning the lignin-rich process residues and thereby avoid the use of external, fossil fuels [7–10]. Another way to reach this goal is to increase the process efficiency by means of process integration. For this task, pinch technology can be employed in different ways.

A first strategy is to use pinch technology to improve the core process design. Using this approach, Fujimoto et al. [11] found that a heat pump can significantly improve the process efficiency of a lignocellulosic ethanol production process based on concentrated acid hydrolysis. Another strategy to increase process efficiency by means of pinch technology is to optimize the CHP or polygeneration system associated with utility allocation. Zhang et al. [12] used this approach to investigate different polygeneration options for a lignocellulosic ethanol process employing two-stage dilute acid

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hydrolysis and significantly improved process efficiency. Ultimately, Morandin et al. [13] combined the two strategies and used pinch analysis for parameter optimization of the core process as well as for validation of different CHP systems. For a process producing ethanol and sugar from sugarcane parameter optimization resulted in a heat demand reduction of one third. In addition, the net power output of the associated CHP system was maximized.

1.1. Aim and scope of the paper

In this work we aim to thermally integrate the biochemical production process of ethanol from straw using pinch analysis and heat exchanger network synthesis. The process under consideration is made up of the unit operations steam pretreatment, on-site enzyme and yeast production and simultaneous saccharification and co-fermentation (SSCF) of C5 and C6 sugars to convert straw to ethanol. The ethanol product is recovered and purified by means of distillation and pressure swing adsorption. The stillage from distillation is treated using solid–liquid separation, multi-stage evaporation and superheated steam drying of solid residues.

We start our work with a base case flowsheet model of the process and aim to (i) find options to improve this base case design and (ii) create a fully integrated flowhsheet model of the improved process design. Thereto we apply pinch analysis and heat exchanger network synthesis. As a result of this procedure, a heat exchanger network and the utility requirement of the fully integrated production process are obtained. The mass balances for the process can be closed and general conclusions about the technology can be drawn. Future work will be dedicated to further process analysis (e.g. exergy analysis, economic evaluation or life cycle analysis).

2. Methodology

The methodology followed in this work is schematized in Fig. 1. First, a flowsheet model of the base case design for the production process is developed. From this flowsheet model, data is extracted for pinch analysis. The pinch analysis focuses on the energy intensive downstream unit operations distillation and evaporation. Following a well-established procedure [14], these unit operations are analyzed separately from the background process. The findings from this pinch analysis allow us to derive modifications of the process design. These modifications concern the above mentioned unit operations distillation and evaporation and include a change of (i) the number of stages in these unit operations, (ii) the temperature level of the stages and (iii) the heat load of the stages. These design modifications aim at increased heat integration and are implemented to create a flowsheet model of the thus obtained improved process design. Again, data extraction and pinch analysis are performed for the improved design in order to assess the proposed design modifications. Thereto the utility targets of the base case design and the improved design are compared. To complete this heat integration study, a heat exchanger network is developed for the improved process design.

2.1. Flowsheet simulations

Steady state flowsheet simulations are performed using the equation oriented software “IPSEpro”. The software was developed for simulation of power plants [15]. Hence, detailed property data and unit operations are available for power plant computations only. For simulation of the process considered in this work a suitable model library was developed [16]. Due to “IPSEpro’s” equation oriented solving approach input and output information can be exchanged arbitrarily and complex flowsheets including recycle streams converge quickly. For heat integration, thermal process data obtained from simulations with IPSEpro is extracted, exported to Microsoft Excel and from there imported to the pinch analysis and heat exchanger network software described in Sections 2.2 and 2.3.

2.2. Pinch analysis

Pinch analysis is a powerful methodology to determine options for process heat recovery. In this work it is carried out using the pinch analysis module of the software “TVTHENS”. “TVTHENS” was developed at the Vienna University of Technology using the computational software program “Mathematica”. After data extraction (see Section 3.1) and energy stream investigation according to [14,17], thermal data of the cold streams needing heating and hot streams needing cooling are entered into “TVTHENS” via Microsoft Excel. Based on these data and a specified minimum temperature difference $\Delta T_{\min}$ of 10 °C that is applied in pinch analysis throughout this work, composite curves and grand composite curves representing the minimum heating and cooling demands are constructed by a graphical approach introduced by Salama [18]. For streams without phase change constant heat capacities are assumed. To deal with isothermal streams involved in the process, it is assumed that these streams have 1 °C temperature difference during phase

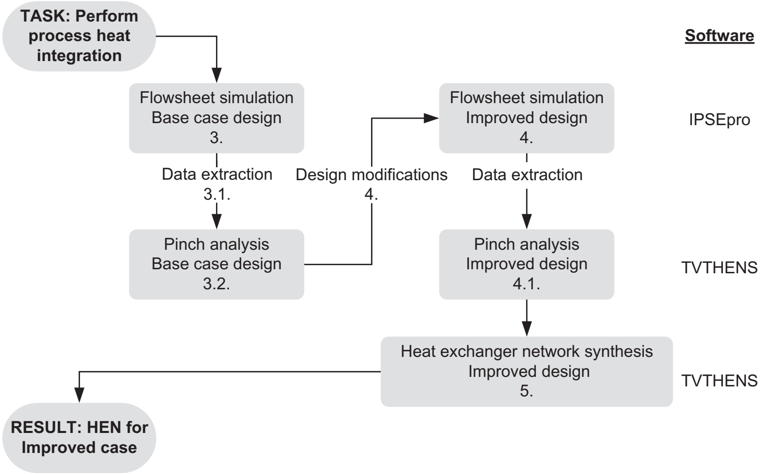

Fig. 1. Methodological workflow and simulation tools used. The numbers indicate the respective sections of the text. HEN: Heat exchanger network. Numerals stand for the respective sections of the text.