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Review

Fuel ethanol production: Process design trends and integration opportunities

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Abstract

Current fuel ethanol research and development deals with process engineering trends for improving biotechnological production of ethanol. In this work, the key role that process design plays during the development of cost-effective technologies is recognized through the analysis of major trends in process synthesis, modeling, simulation and optimization related to ethanol production. Main directions in techno-economical evaluation of fuel ethanol processes are described as well as some prospecting configurations. The most promising alternatives for compensating ethanol production costs by the generation of valuable co-products are analyzed. Opportunities for integration of fuel ethanol production processes and their implications are underlined. Main ways of process intensification through reaction–reaction, reaction–separation and separation–separation processes are analyzed in the case of bioethanol production. Some examples of energy integration during ethanol production are also highlighted. Finally, some concluding considerations on current and future research tendencies in fuel ethanol production regarding process design and integration are presented.

Keywords: Fuel ethanol; Process design; Process synthesis; Process integration; Co-products

1. Introduction

Ethanol is one of the most important renewable fuels contributing to the reduction of negative environmental impacts generated by the worldwide utilization of fossil fuels. However, the production of ethanol is a complicated process. The transformation of such biological resources as energy-rich crops (like sugar cane or corn) or lignocellulosic biomass requires the conditioning or pretreatment of the feedstocks for fermenting organisms to convert them into ethanol. Then, aqueous solutions of ethanol should be concentrated for obtaining hydrous ethanol. This product has to be dehydrated in order to be utilized as an oxygenate for gasoline, the trade form in which ethanol is mostly employed in the transportation sector. The complexity of this process partly explains why fuel ethanol has not played a leading role in comparison to cheaper oil derived fuels. Only in the last years due to rising environmental concerns and to the periodic crises in some of the larger oil exporting countries, has bioethanol become a viable and realistic alternative in the energy market.

Therefore, the development of cost-effective technologies for fuel ethanol production is a priority for many research centers, universities and private firms, and even for different governments. Due to the large amount of existing and not completely developed technologies for the production of ethanol (especially from lignocellulosic biomass), the application of process engineering tools is required. Process engineering applied to the production of fuel ethanol includes the design of new innovative process configurations aimed at reducing ethanol production costs. Through process design, product diversification for ethanol production processes can be achieved implying the improvement of their costs structure thanks to co-product

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credits. On the other hand, the development of environmentally friendly technologies for bioethanol production can be carried out utilizing different design approaches.

In addition, process synthesis, as a tool of process design, allows the formulation and assessment of many technological flowsheets for finding those ones with improved performance indicators (e.g. techno-economical and environmental indexes). In this way, the impact of specific technologies over the global process and the production costs can be elucidated. Process optimization is another crucial tool employed within the framework of process design. Optimization plays a decisive role not only during the experimentation, but also during the design steps. Particularly, in the case of ethanol produced from lignocellulosic biomass, production costs were reduced during the 80s, but there has been a little drop in the projected costs since 1991 based on the technologies developed for the US Department of Energy. It is believed that some technologies have reached their inherent limits and other less expensive alternatives could replace them. Consequently, advanced models for optimization of ethanol production costs utilizing a systemic approach that permits the identification of opportunities for overcoming the technological barriers should be developed (National Academy of Science, 1999). Other issues related to process engineering as process modeling and simulation underlie the successful design of alternative process configurations for ethanol production. This is particularly true in the case of continuous ethanolic fermentations where dynamic analysis is the key for an appropriate design of such processes.

One of the most important approaches for the design of more intensive and cost-effective process configurations is process integration. Process integration looks for the integration of all operations involved in the production of fuel ethanol. This can be achieved through the development of integrated bioprocesses that combine different steps into one single unit. Thus, reaction–separation integration by removing ethanol from the zone where the biotransformation takes place, offers several opportunities for increasing product yield and consequently reducing product costs. Other forms of integration may significantly decrease energetic costs of specific flowsheet configurations for ethanol production. Process integration is gaining more and more interest due to the advantages related to its application in the case of ethanol production: reduction of energy costs, decrease in the size and number of process units, intensification of the biological and downstream processes.

Very valuable and interesting reviews have been published on the theme of fuel ethanol production especially from lignocellulosic biomass (Chandrakant and Bisaria, 1998; Lee, 1997; Lin and Tanaka, 2006; Lynd, 1996; Wyman, 1994) or covering some key related issues like the cellulose utilization (Béguin and Aubert, 1994; Lynd et al., 2002; Zhang and Lynd, 2004). However, the analysis of integration features of the overall process for fuel ethanol production from different feedstocks has not been the main objective of these reviews. In addition, various process design issues have not always been sufficiently highlighted in order to get a comprehensive picture of the role that process engineering can play for improving fuel ethanol production processes. This paper attempts to achieve this aim. Therefore, the objective of this work is to review the state of the art in bioethanol production from a process engineering point of view, and explore integration as an important avenue for process improvement in the production of this liquid biofuel.

2. Trends in process design for fuel ethanol production

The design of cost-effective processes for fuel ethanol production implies the selection of the most appropriate feedstocks, and the selection and definition of a suitable process configuration making possible the conversion of raw materials into the end product meeting given specifications. The task of defining a proper configuration of the process requires the generation and assessment of many process flowsheets for finding those ones with improved performance indicators. This step of process design is called process synthesis. During process analysis, the structure of the synthesized flowsheets is established in order to improve the process through a more detailed insight of it. In both steps, process modeling and simulation play a significant role although with different level of detail (basically, short-cut models for synthesis and rigorous models for analysis). In this work, the importance of the feedstock as a key factor in the economy of ethanol production processes is highlighted. Process synthesis features for bioethanol production are also examined considering different trends utilized for reducing production costs. In addition, some aspects involving process analysis methodologies are stressed in order to show how they may contribute to the design of successful technologies in the case of fuel ethanol production.

2.1. Evaluation of feedstocks

Bioethanol can be produced from raw materials containing fermentable sugars as sugar cane and beet that are rich in sucrose. In addition, bioethanol may also be produced from some polysaccharides that can be hydrolyzed for obtaining sugars convertible into ethyl alcohol. Starch contained in grains is the major polymer used for ethanol production. Lignocellulosic biomass (a complex comprised of several polysaccharides) is the most promising feedstock considering its great availability and low cost, but the large-scale commercial production of fuel ethanol from lignocellulosic materials has still not been implemented. For designing fuel ethanol production processes, the assessment of the utilization of different feedstocks (i.e. sucrose containing, starchy materials, lignocellulosic biomass) is required considering the big share of raw materials in ethanol costs. In the present review, some trends in the evaluation of feedstocks for process design in the case of bioethanol production are highlighted below.