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Design and optimization of intensified biorefinery process for furfural production through a systematic procedure

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ABSTRACT

Furfural, which is used as a precursor for the production of many other industrial chemicals, has been identified as one of the major bio-based platform chemicals that can compete with petroleum-based chemicals. On the other hand, the current commercial furfural process has a low yield and is energy-intensive. Therefore, this study develops the biorefinery production process of furfural from lignocellulosic biomass using process heat integration and process intensification. In particular, a distillation unit of the furfural production process requires considerable energy, highlighting the need to improve energy efficiency, which is the motivation of this work. An integrated and intensified distillation sequence, including an innovative bottom dividing wall column with a decanter configuration (BDWC-D) was suggested to enhance the energy and cost efficiency of the furfural production process through a comprehensive and systematic procedure that combines process intensification with heat integration. The structures of the complex columns in all sequences were optimized using the optimization method-response surface methodology (RSM). All simulations were conducted using Aspen HYSYS. The results show the proposed sequence can reduce total annual cost and carbon footprint by 10.1% and 11.6%, respectively compared to the conventional sequence.

1. Introduction

Global climate change and the depletion of mineral resources are the major issues of the current petro-based economy. Consequently, the development of alternative renewable resources, particularly biomass, which is the most abundant feedstock on Earth, has been intensely promoted in recent years. The manufacturing facilities that produce biofuels, power and bio-chemicals from various biomass feedstock are called biorefineries [1]. Conceptually, this is analogous to a current petroleum refinery that produces fuels and chemicals from petroleum. In addition to effective biomass conversion technologies, separation and purification technologies, which account for about 20–50% of the total production costs of biorefineries [2], play a major role in the commercial implementation of biorefineries. Therefore, the great enhancements in separation and purification technologies can reduce the total production cost significantly and result in better environmental sustainability.

Furfural, which was listed as one of the top 30 potential chemicals from biomass by the US National Renewable Energy Laboratory (NREL) [3], is an important renewable lignocellulosic feedstock for producing fuels and chemicals. Furfural is used as an extractant for the refinement of lubricating oils, as a fungicide, nematocide and as a raw material (up to 65% of all furfural produced) for furfural alcohol production [4]. The first industrial production of furfural was constructed by the Quaker Oats company in 1921 and this process is still in use today [4]. Currently, the majority of furfural on the world market is produced in China by a large number of small producers with a capacity of few kilotons per year; whereas the largest furfural plant of 35 kilotons per year is located in the Dominican Republic [5].

Essentially, the traditional furfural process from biomass has two steps involving reaction and distillation units. At first, biomass is pretreated through a pretreatment stage and is then introduced to a reactor. Herein, the hydrolysis reactions occur and a vapor stream comprised of approximately 6% furfural, 4% by-products (acetic acid and methanol) and 90% water is produced [4]. This stream is then liquefied and fed to a series of distillation columns to achieve the desired products. The production technologies of furfural have shown few enhancements in the past, considering that the present production processes of furfural have a relatively low

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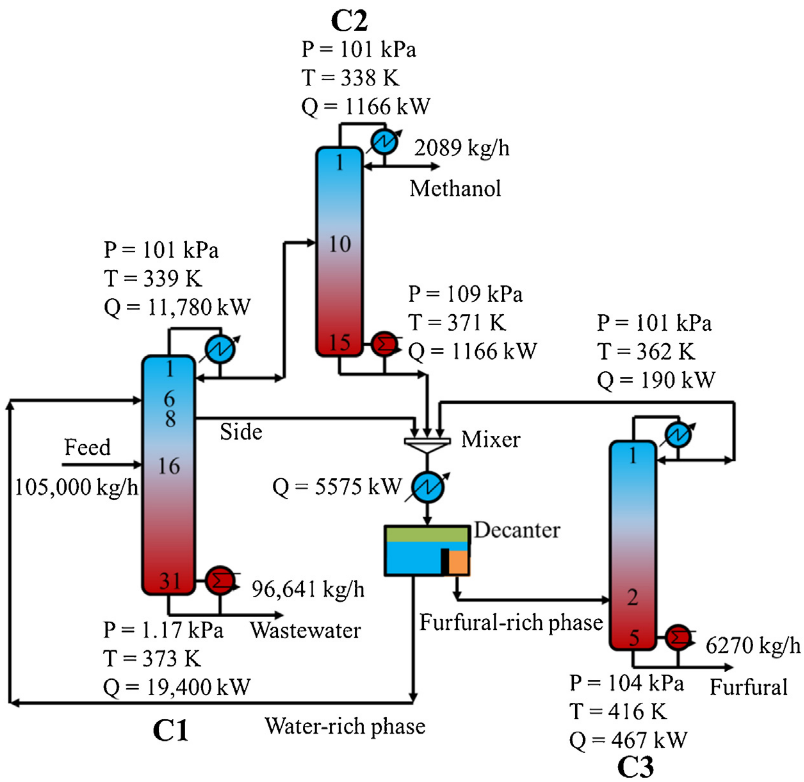

Fig. 1. Schematic diagram of the optimal conventional furfural process.

production yield (i.e., approximately 50% of the theoretical yield) and use inefficient technology [6]. Consequently, it is essential to develop a new production process of furfural to make this renewable alternative competitive with petroleum-based products.

Zeitsch presented a comprehensive overview of the traditional furfural production processes in industry, such as Quaker Oats, Escher Wyss, Rosenlew, Supratherm, Stake, Supray Yield, Voest-Alpine, and Chinese processes [4]. In recent times, several advanced processes of furfural have been studied extensively. Strong acid catalysts and salts are applied in the Vedernikovs process to improve the reaction efficiency [7]. Therefore, cellulose loss is reduced with a concomitant increase in furfural product yield. The CIMV production plant using organic acids to convert biomass (i.e., straw, bagasse, and wood) was launched 2010 in France to produce furfural along with whitened paper pulp and lignin [8]. Lignol Company constructed an advanced biorefinery pilot plant in British Columbia [6]. The advantage of this process is that many products can be produced from lignocellulosic biomass, such as ethanol, acetic acid, and furfural. The Suprayield process used a novel concept that furfural was removed from the reacting liquid phase [4]. As a result, furfural resinification, which is a reaction of furfural with itself, cannot occur and the furfural yield will be increased. This disruptive technology was then applied to several plants, such as the Proserpine sugar mill process in Queensland, and the furfural plant in Ankleshwar [6]. Recently, the innovative furfural production process from straw feedstock that uses a novel reactor, Multi Turbine Column, was reported [6]. In this process, the raw material was input from the top into the continuous turbine reactors and the steam rises up from the bottom. In addition, the furfural was removed continuously out of the reacting liquid, resulting in a high yield and low energy requirement.

Overall, most previous processes focused only on increasing the furfural yield of the reaction unit, whereas there is lack of concern in the energy-intensive distillation unit. Interestingly, de Jong et al. [9] considered both reaction and separation units for the production of furfural from pentoses. In their study, however, no detailed design was presented, only the simple heat integrated techniques, including vapor recompression and preheating were applied. The excessively high (499 K) temperature of a compressor output stream may also cause compressor overheating, which is currently the most serious problem of using compressor in industry [10]. To the best of the authors' knowledge, there is no study demonstrating the application of advanced intensified techniques, such as dividing wall columns on the furfural separation process.

Many techniques have been developed to improve the performance of the distillation system. Among them, process intensification (PI) and heat integration (HI) have been proven to be promising techniques in both academia and industry [11–15]. The primary benefit of process HI is to assess a system as a whole; thus, it can reduce the overall energy requirement by exchanging heat between the streams that need to be cooled and heated. Several examples of HI have been applied successfully, such as feed preheating, side reboiler, side condenser, and heat pump [16]. Interestingly, in the chemical and petro-refinery processes, PI has been applied widely to reduce the energy requirements and total cost of distillation processes [17–19]. A dividing wall column (DWC), which can allow reversible splits with no part of the separation being performed more than once, is one of the best examples of PI [20]. On the other hand, only a few studies of advanced PI and HI techniques have examined biorefinery processes, especially those processes using lignocellulosic biomass as feedstock.

The main disadvantages in many current commercial furfural production processes include intensive energy use, low capacity, and a lack of integrated/intensified designs. In this study, a novel integrated and intensified separation process, i.e., a bottom dividing wall column with a decanter (BDWC-D) configuration was developed to overcome these limitations. A comprehensive and systematic study using process intensification and heat integration was proposed to maximize process energy efficiency. All configurations were simulated rigorously by Aspen HYSYS and