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Biodiesel Production using Reactive Distillation: A Comparative Simulation Study

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Abstract

Biodiesel is one of the most prominent biofuels in the market, recent trends indicate a worldwide production growth to replace crude-based diesel as transportation fuel. In this work, two reactive distillation processes with their corresponding downstream separation units are simulated: the first involves alkali whereas the second includes heterogeneous catalyst. The processes yield a high purity biodiesel product. Aspen Plus v8.4 was used as the process simulation tool in the present work. Comparison between the two production processes were made in terms of the annual production costs and economic indicators such as Return-On-Investment (ROI) and payback period. The simulation results show that the heterogeneous-catalyzed process is more economically advantageous than the alkali-catalyzed process for biodiesel production due to a much higher ROI, lower payback period, and lower annual cost per unit of biodiesel produced.

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1. Introduction

In recent years, biodiesel has emerged as a popular alternative to the standard crude-based diesel fuel. Biofuels have turned out to be a promising renewable fuel option. There are several advantages for the use of biodiesel fuels: 1) it can be derived from a domestic renewable source (e.g., vegetable oil), 2) it reduces the net carbon dioxide (the most common greenhouse gas) emissions by 78% on a lifecycle basis when compared to crude-based diesel fuel, 3) it is biodegradable and non-toxic therefore it is a more environmentally friendly fuel, and 4) it has also been found to have dramatic improvements on engine exhaust emissions [1]. Biodiesel or the mono-alkyl ester of long chain fatty acids is formed from a transesterification reaction between the vegetable oil (which is composed of several triglycerides) and a

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low molecular weight alcohol (e.g., methanol). The reaction products include a complex mixture of fatty acid methyl esters (FAME which is essentially biodiesel) and glycerol as by-product. The reaction typically requires a catalyst that can be a homogeneous alkali, a homogeneous acid, or a heterogeneous alkali. Also, in cases where the reaction is in supercritical conditions there is no need for a catalyst. A process simulation approach has been typically used to model biodiesel production using different catalysts (i.e., alkali, acid or heterogeneous alkali), feedstock (pure vegetable oil or waste cooking oil), and reaction conditions (normal or supercritical) [1, 2]. The first step consists of simulating the transesterification reactor followed by downstream product purification steps. Another major development in the biodiesel production process consists of modelling the transesterification reaction using a reactive distillation column. During reactive distillation two processes take place within the same unit operation: 1) the transesterification reaction, and 2) the separation of the subsequent products. Following this type of process can potentially alleviate capital investment, operation costs, and provide a more effective separation. In prior simulation studies, the simulation of processes involving reactive distillation either using alkali catalyst [3] or heterogeneous catalyst [4] has been analyzed. Moreover, simulation studies have been performed on the reactive distillation column alone. These studies aimed to optimize the column's performance and maximize product (biodiesel) yield [5, 6]. However, a comprehensive comparison between the two processes (i.e., alkali and heterogeneous catalyst) involving reactive distillation with additional downstream processes is currently lacking in the literature to the best of the authors' knowledge. Thus, the present work aims to fulfil this gap.

The present work aims to find the more preferable reactive distillation and downstream separation process following a process simulation approach to obtain a pure biodiesel fuel 99 wt. %. The currently considered most efficient distillation models, i.e., alkali and heterogeneous catalysts, for biodiesel production were compared to determine the most cost-effective process. Pure soybean oil was used as process feedstock due to its low free fatty acids content (less than 0.3%); which prevents the need of a pre-treatment process [1]. The two processes are compared based on a detailed economic analysis.

2. Methodology

For the alkali catalysed simulation, the transesterification reaction pathway is described in equations (1)-(3):

$$TG + MeOH \rightarrow DG + ME \quad (1)$$

$$DG + MeOH \rightarrow MG + ME \quad (2)$$

$$MG + MeOH \rightarrow GL + ME \quad (3)$$

where [TG],[DG],[MG],[MeOH],[ME] and [GL] are the molar concentrations of Triglyceride, Diglyceride, Monoglyceride, Methanol, Methyl Ester and Glycerol, respectively [5]. The simulation software used was AspenTech AspenPlus^{TM}. The alcohol that reacts with the soybean oil is in excess, and the alcohol-to-oil mole ratio in the inlet is maintained at 6:1. In order to obtain simulation results that can be directly compared in terms of biodiesel production, the feed flow rates were set to be equal in both processes. For simulation purposes, the fluid package was set as UNIFAC for the Alkali-catalysed process, while the heterogeneous-catalysed process used the UNIQUAC fluid package in Aspen Plus. The kinetic parameters used to describe the transesterification reaction pathway in the heterogeneous-catalysed process were obtained from Gaurav et al. [4]; whereas for the alkali-catalysed process the parameters were taken from Mueanmas et al. [5]. A standard RADFRAC column was used for the reactive distillation unit in both processes. Moreover, since the purity of the biodiesel product is equal for both processes, it is necessary to compare these processes in terms of capital and operational costs as well as energy consumption rates for identifying the most cost-effective process. On this regard, the Aspen Plus v8.4 analysis option was used to estimate the costs (i.e., capital and operational) of the converged