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Process design and probabilistic economic risk analysis of bio-diesel production

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ABSTRACT

Process design and economic risk analysis were performed for a biodiesel production plant having an annual production capacity of 45,000 tonne of biodiesel using inedible Jatropha oil as the biomass feedstock. Five major economic factors associated with the cost were computed and analyzed. These included total capital investment, fixed cost, variable cost, annual operating cost and total cost. Probabilistic cost estimation was performed to analyze the variability in the cost data. Among all other cost elements, raw material cost was found to be the most significant variable affecting the economic viability of biodiesel production system. Probabilistic risk estimation showed that, even using the published cost data, the estimated total risk was 50% uncertain. The study also showed that by incorporating environmental benefits of biodiesel burning, the benefit to risk ratio increased.

Keywords: Process economics; Economic risk analysis; Cost uncertainty; Probabilistic cost; Probabilistic revenue; Environmental friendly fuel

1. Introduction

Biodiesel is an environmentally friendly biofuel for diesel engines and is an alternative to conventional petroleum based diesel fuels. On a large industrial scale, it is produced by a chemical reaction of feedstock (edible vegetable oil or inedible oils or animal fats) with an alcohol (methanol or ethanol) in the presence of a catalyst (alkaline, acidic or enzymatic). The reaction is called transesterification. Stoichiometrically, one mole of triglyceride (feedstock) reacts with three moles of methanol (alcohol) to form three moles of fatty acid methyl ester (FAME), known as biodiesel. The reaction produces glycerol, which is generally considered as a by-product of a transesterification reaction. The process of biodiesel production has much been studied by various researchers (Kumar et al., 2011; Hawash et al., 2011; Raja et al., 2011; Banković-Ilić et al., 2012).

Currently, the high cost of biodiesel production remains a big hurdle to its large-scale commercialization. Therefore, the economic assessment of biodiesel production has been a central focus of recent research. Various economic studies of biodiesel production have been performed using different technologies, raw materials and production capacities (Zhang et al., 2003a; West et al., 2008; Cynthia and Teong, 2011).

Zhang et al. (2003b) assessed the economics of four different biodiesel plants using different raw materials. Haas et al. (2006) developed a computer model to estimate operational and capital cost of a biodiesel production facility. Kasteren and Nisworo (2007) studied the economics of biodiesel production at three plants operating at different capacities. You et al. (2008) reported the economic analysis of biodiesel production using soybean oil as raw material. Lopes et al. (2013) performed the economic feasibility of biodiesel using Macauba oil as raw material in Brazil. Nagarajan et al. (2013) studied the cost of biodiesel production using algae as a raw material. Most of these studies used the static cost data published on web-sites or by government departments.

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Previous economic assessments of biodiesel production were based on cost data reported in open literature. None explain how reliable their cost data are and how much uncertainty is present in their cost data. The uncertainty present in the cost data greatly influences the accuracy of the total cost of biodiesel production. A few researchers have reported that the accuracy of their cost estimation was within a range of +30% to −20% (Zhang et al., 2003b; West et al., 2008). Since their estimated cost is millions of dollars and may be even 1% uncertainty in it, the actual cost may exceed the expected cost value. This may result in a huge cost escalation and the project may become uneconomical. Moreover, their project profitability criteria do not account for uncertainties present in the estimated cost data. The presence of uncertainty in the cost data significantly affects the accuracy of the results of economic analysis. Generally, there are uncertainties present in both the estimated cost and the estimated revenue data. Therefore, it is important to include a probabilistic analysis in any techno-economic study of biodiesel processes.

The present study performs an economic analysis of a biodiesel plant with an annual production capacity of 45,000 tonne of biodiesel from Jatropha oil using a homogeneous base catalyzed process. This work develops a risk analysis methodology and the technique developed is demonstrated on a biodiesel case. This study deals with the uncertainties present in the estimated cost and the estimated revenue. A probabilistic cost–benefit analysis is also conducted to address the potential economic risk and the results provide an accurate indication of the return period over the period of investment.

2. Probabilistic economic risk analysis methodology

2.1. Basis and scope of calculations

The economic and probabilistic economic analyses were based on the following assumptions. (1) The process is based on a production capacity of 45,000 tonne/year biodiesel. (2) Including the maintenance and breakdown schedules, the plant operates 8000 h/year. (3) The cost of oil includes the cost of extracting the oil from Jatropha *curcas* seeds and the oil does not contain any impurities and is free from water content. (4) All costs, revenue and profit data are shown in US $ and the respective values are valid for the year 2013. One Australian dollar is taken as equivalent to US $0.94. The prices of the equipment were updated to year 2013 from year 2001 using Chemical Engineering Plant Cost Index (CEPCI, 2014). The index for year 2001 was 394.3 and for year 2013 was 567.3. (5) The asset depreciation and plant decommissioning are not considered in this analysis. (6) The prices of biodiesel and other products are retail prices. Both the prices of biodiesel and mineral diesel exclude transportation, excise tax and distribution cost. (7) Only positive percentile values are studied for probabilistic analysis. (8) Being less in cost value as compared to the rest of the equipments, the equipment risk analysis ignores the probabilistic curves for the splitter (S-206), gravity settler (S-202) and liquid–liquid extraction unit (S-204).

2.2. Methodology description

The methodology to perform this research is divided into two major steps.

1. *Process description and economic analysis*: The process flow diagram (PFD) for biodiesel manufacturing was selected and the fundamental material and energy balances were performed on a Microsoft Excel sheet. Process design was carried out using Aspen HYSYS version 7.3. The results of equipment sizes obtained from process design were used to estimate the capital costs and annual operating costs.
2. *Probabilistic risk analysis*: This step included the probabilistic risk analysis and the probabilistic cost–benefit analysis. Vagueness in cost and revenue of biodiesel production system were also incorporated into the study. The probabilistic cost–benefit analysis was conducted with and without the time domain. The methodology for the current research is sketched in Fig. 1.

2.2.1. Process description

The biodiesel production process, its reaction kinetics and the latest conversion techniques from different raw materials have already been much defined (Zhang et al., 2003a; West et al., 2008; Myint and El-Halwagi, 2009; Keera et al., 2011; Nasir et al., 2013; Yusuf and Kamarudin, 2013). The alkali-catalyzed biodiesel process was chosen to perform economic analysis. The raw material for producing biodiesel was Jatropha oil obtained from Jatropha *curcas* seeds. Jatropha oil is inedible and does not require any special kind of soil to grow its seeds. Moreover, it eliminates the debate between food resources and fuel for energy (Balat, 2011). The PFD of the biodiesel production process from Jatropha oil shown in Fig. 2 was adopted from literature (Rahman et al., 2010; Abbaszaadeh et al., 2012). Chemical and physical properties of Jatropha oil and its FAME were extracted from literature (Kywe and Oo, 2009).

2.2.2. Process simulation and sizing

Before proceeding to the HYSYS simulation step, the following assumptions were made regarding different process parameters:

- Perfect mixing in the reactor was assumed.
- For the gravity settler, the separation efficiency was assumed to be 80%.
- The main reaction conversion was 95%.
- The reference temperature for energy balance was 25 °C.

The method for process simulation involved describing the chemical components, choosing the proper system of units, defining the stream conditions (temperature, pressure, flow rate, compositions of components in a stream) and selecting an appropriate thermodynamic model. Most of the components under study such as glycerol, methanol, hydrochloric acid, water and sodium hydroxide were available in the HYSYS library. Jatropha oil and its FAME were not present in the HYSYS library. Triolein ($C_{57}H_{104}O_6$) and methyl oleate ($C_{19}H_{36}O_2$) in Jatropha oil and its FAME had been chosen in previous research studies (Yusuf and Kamarudin, 2013) were used to represent Jatropha oil and its biodiesel in this study. The properties of methyl ester (methyl oleate) were present in the HYSYS component library. Triolein was defined in HYSYS using a 'hypo manager' tool. The enthalpies of the formation of oil and its respective methyl ester were taken from literature (Borghi et al., 2012; Lapuerta et al., 2010). Since there were highly polar components (glycerol and methanol) present in the system, the activity coefficients of the components were estimated using a universal quasi-chemical (UNIQUAC) model (Zhang et al., 2003a; Kasteren and