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Energy Procedia 156 (2019) 452–457

Energy Procedia

www.elsevier.com/locate/procedia

2018 5th International Conference on Power and Energy Systems Engineering, CPESE 2018, 19–21 September 2018, Nagoya, Japan

Technological Progress in Biodiesel Production: An Overview on Different Types of Reactors

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Abstract

Nowadays, research on biodiesel focuses on enhancing the conversion and production yield to fulfill the demand. Utilization of new feedstocks, development of highly efficient catalysts, determination of effective and economical reaction approaches, and application of process system engineering tools are efforts for the optimization purposes. This paper reviews the technological progress of reactors used for biodiesel production. The first part gives an overview of previous findings available in the literature. Many factors affecting the production yield of biodiesel have been reviewed such as reaction time, agitator rotational speed, temperature, types of catalyst, catalyst concentration, the molar ratio of oil and alcohol, types of solvent, and types of feedstock. However, the review of different types of reactors used for the biodiesel production is still lacking. The appropriate selection of reactor type is necessary to enhance the product yield and the productivity. Thus, the second part of this paper aims at compiling the information on various reactors. The description of key operating conditions and process design, relevant integrated reaction and separation techniques, recent achievement and progress, and challenges for future development are highlighted. This review provides the basis for exploitation and selection of reactor to enhance optimization, scale-up development, and implementation in industrial-scale biodiesel production.

Keywords: biodiesel production; process design; process operation; types of reactors

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1876-6102
10.1016/j.egypro.2018.11.086

1. Introduction to biodiesel

Recently, the sustainability of energy and fuel supply claims attention of the global community due to the limited amount of petroleum [1]. Energy and fuel play a vital role, especially in the transportation sector. An average consumption of energy in the transportation industry is raised by 1.1% per year, and only this sector will account for 63% of the increment of total world liquid fuel usage from 2010 to 2040 [2, 3, 4]. The progress of this sector has increased the release of toxins such as hydrocarbon, nitrogen oxides, carbon monoxides, and carbon dioxides, which could affect the air quality and cause global warming [3, 5].

The urgency of cleaner energy sources for the transportation sector has been highlighted. For this strategy, biodiesel can be used since it is feasible cleaner energy worldwide and recommended as an alternative fuel in various fields particularly in the transportation sector [6, 7, 8]. Biodiesel is becoming more attractive due to the sustainability issues of current energy usage and supply. It is well established that biodiesel is widely used as a mix or substitute for petro-diesel, applicable to existing engines, and easily produced from prevalent bio-resources. Therefore, it presents many benefits to the environment, society, and economy [9, 10, 11]. Biodiesel also offers numerous advantages over petro-diesel such as non-toxicity, biodegradability, lesser air pollutants per net energy (reduction of greenhouse gases (GHG) by 41%), lower sulfur and aromatic content, more safety (higher flash point), and better lubrication [2, 3, 7, 11, 12]. The increment of biodiesel production could initiate the reduction in the dependence on petroleum fuels, boost and diversify the energy and fuel supplies, promote the development of rural economies, and diminish the emission of GHG [11, 13]. Thus, this natural energy source not only offers an alternative for the transportation fuel but also preserves the environment [7, 11].

Table 1: Factors affecting transesterification process [2, 9, 10]

Factors		Advantages	Disadvantages
Types of feedstock	Edible oils/fats (palm, soybean, sunflower, rapeseed, etc.).	Renewable, sustainable, high-energy security and content.	Competition with food supply.
	Non-edible oils/fats (*Jatropha curcas*, castor, animal waste, sludge, microbes, etc.).	Relatively cheap, abundant in amount, eliminates environmental pollution.	High free fatty acids, contaminant, and water content could lead to the soap formation and extensive separation.
Types of solvent	Alcohol (ethanol, methanol, etc.).	Great polarity, cheap in price.	Sometime could cause miscibility problem and mass transfer limitation.
	Others (co-solvent, deep eutectic solvent, etc.)	Reduce miscibility problem.	High cost.
Types of catalyst	Homogenous (NaOH, KOH, H_2SO_4, H_3PO_4, etc.).	Well known reaction route, operate at mild temperature.	Extensive neutralization process, large wastewater generation, equipment corrosion.
	Heterogenous (solid acid/base, zeolites, polymer, activated carbon, etc.).	Simplify the downstream process, reduce waste generation.	Long reaction times, recovery and reusability issues, high viscosity increases the mass transfer resistance.
	Others (enzyme, ionic liquid, whole cell, etc.).	Environmental-friendly.	Expensive cost, low stability, recovery and reusability issues.
	Non-catalytic (supercritical condition).	Short reaction time.	High requirement (oil/alcohol ratio, temperature, pressure), high production cost.

Nowadays, the utilization of new feedstocks, development of highly efficient catalysts, and determination of effective and economical reaction approaches have attracted numerous attentions amongst the researcher to enhance the production yield and achieve the industrial-scale capacity. In addition, application of process system engineering (PSE) tools to the systematic process design has been proposed due to the involvement of complex chemical reactions in the biodiesel production [14]. In this respect, modeling, simulation, and optimization which provide various benefits and chances to determine the optimum production parameters with the lowest costs especially during the initial process selection and design are developed.

Several processes have been exploited to convert various types of oils and fats into biodiesel such as direct use and blending, transesterification, microemulsion, and pyrolysis [4, 9, 11, 15]. Among these, transesterification is the most common process because of high conversion rate with relatively low production cost, mild reaction conditions, product properties similar to petro-diesel, and applicability to industrial-scale production [5, 16]. The main factors that affect the transesterification process and the production rate are types of feedstock, solvent, and catalyst as summarized in Table 1; other factors are reaction time, rotational speed, temperature, catalyst concentration, and the oil/alcohol molar ratio [17]. However, a complete understanding of biodiesel production using different types of reactors is still lacking in scientific literature.

In closing the aforementioned problem, this paper offers an overview on the technological progress in producing biodiesel using different types of reactors. It is highly beneficial in providing basic guidelines for the design and operation of biodiesel production process. In general, it is evidenced that there are many different reactor technologies that can be used for biodiesel production.

2. Biodiesel production using different types of reactors

In the initial era of biodiesel production, batch reactor was widely employed. However, it has disadvantages such as large reactor volume, extensive separation process, and high labor costs [18]. In addition, the major restraint of batch reactor is often related to the mass transfer limitation between oil and solvent [5]. To overcome these problems, various types of continuous reactors were designed through optimizing the use of solvent, catalyst, and energy, as well as simplifying the recovery stages by integrated and in-situ separation techniques. In comparison with batch reactor, continuous reactor offers better performance in improving heat and mass transfer, reduce the production cost, provide a uniform quality of the final product, and support industrial-scale production [19, 20].

2.1. Continuous stirred tank reactor (CSTR)

In CSTR, the reactor configuration is developed so that the reactant can be pumped continuously and efficiently into the reactor. In the beginning, the reactor is loaded with reaction materials, and then an adequate agitation process lasts until the reaction process is completed. The main parameters in CSTR are in-out flowrate and agitation speed, which affect the residence time, mass transfer rate, and mixing efficiency [21]. Intensive mixing is required to guarantee high uniformity of products, which resulted in high energy consumption. Thus, various attempts have been conducted using other types of continuous reactors to replace the mechanical agitator and reduce the energy usage. To date, CSTR has been widely used in the industrial-scale biodiesel production due to the sufficient technical knowledge and deep understanding of the operation of CSTR.

2.2. Fixed bed reactor (FBR)

FBR is a cylindrical tube filled with catalyst pellets packed in a static bed, while oil and solvent flow through the bed and are converted into biodiesel. The use of heterogeneous catalyst in FBR simplifies the recovery steps because no separation process between the product and the catalyst is required. FBR also enhances the heterogeneous catalytic reaction due to the slow deactivation and longer durability of the catalyst. Consequently, the production cost can be reduced. The main parameters in FBR are bed height, feed flowrate, residence time, molar ratio, and catalyst size and amount. Although FBR reduces the reaction time and increases the contact between reactant and catalyst as compared to other heterogeneous catalytic reactors, a higher molar ratio is needed. Moreover, the resulting glycerol (by-product) remains at the bottom of the reactor and adsorbs on the surface of the catalyst. Thus, it decreases the catalytic efficiency and requires an additional removal process [22].

2.3. Bubble column reactor (BCR)

Typically, an intensive mechanical agitation has been utilized to improve the mass transfer between oil and solvent. However, it also possesses negative effect when bio-catalyst (enzyme) is used because the mechanical agitation could break down the enzyme carrier and deactivate the catalytic activity. In BCR, vigorous agitation is achieved when gas is dispersed through a sparger that produces bubbles in a vertical cylindrical column [23, 24]. It has been reported that, in a highly viscous and solvent-free system, agitation by gas bubbling reduces wear and tear on the enzyme and provides longer durability [23]. However, the major challenges for BCR usage in biodiesel production are the requirement for uniform bubble size distribution (effect of bubbles coalescence and breakup) and gas holdup profiles, which are affected by many critical parameters such as column diameter and height, sparger geometry, liquid phase viscosity, and gas velocity [24]. The difficulty of optimizing these parameters is the main limitation in application of BCR to the large-scale production.

2.4. Microchannel reactor (MCR)

MCR is typically used in the down-scaling approach to reduce the materials consumption; it is composed of channels whose diameters range from sub-micrometer to sub-millimeter [25]. The advantages of MCR are short reaction time, high surface area to volume ratio, perfect mixing, and effective mass and heat transfer with safer operating conditions. The key parameters involved are length and number of channels, nozzle diameter, the configuration of fluid junctions, and flow motion (such as Y-shape, T-shape, cross-shape, a zig-zag shape, spiral-shape, etc.) [25]. In addition, MCR with micromixer is introduced to achieve higher fluid mixing and oil conversion by inducing the occurrence of the change in flow direction, disturbance in the boundary layer, and formation of the vortex [26]. The most challenging and unsolved problem of MCR is the scale-up or numbering-up to achieve industrial-scale capacity, which makes this technology inapplicable for biodiesel production in the near future [27].

2.5. Membrane reactor (MR)

MR is proven to intensify the production process using a very broad range of feedstocks. At the same operational conditions with CSTR, MR achieved 30% higher conversion rate [12]. MR is capable of recovering the product continuously during the process hence improves its purity and minimizes the wastewater generation. MR involves the exploitation of immiscibility between the oil and alcohol with in-situ separation process by formation of an emulsion with dispersed oil droplets in the continuous alcohol-rich phase [28]. This allows efficient transesterification at the surface of the oil droplets [28]. Therefore, maintaining the equilibrium of two liquid phases is crucial and requires careful consideration of the type of membrane, membrane pore size, residence time, and alcohol recycle and flux [29]. Moreover, further research is needed to fully utilize the unique characteristics of the membranes such as high selectivity/conversion, high surface area per unit volume, ability to recover the target products, and capacity to control the contact between components [17, 18]. Critical attention also must be paid to the effects of stability and fouling of the membrane [17]. Although better product separation via MR can simplify the downstream equipment, it does not change the overall capital cost significantly [5].

2.6. Reactive distillation column (RDC)

In RDC, fatty acid is fed to the top of the column and alcohol is fed to the bottom as vapor, while the resultant biodiesel is pumped from the bottom and water by-product is distilled from the top. Thus, RDC is a combination or integration of the reaction and separation processes in one column, which simplifies and eliminates the extensive downstream process that is required when CSTR is used [30]. RDC also reduces the reaction time, eliminates the excess alcohol requirement, minimizes the use of catalyst, can shift the reaction equilibrium (product and reactant are separated), eliminates side reactions, and generates less waste [19, 31]. The main parameters of RDC are the column size, the number of stages (reactive, rectifying, and stripping), molar reflux ratio, reboiler duty, the molar ratio of reactant, feed conditions (ratio, flowrate, and location), temperature, and pressure [29]. Various configurations of RDC such as dual-RDC, thermally coupled-RDC, dividing-wall-RDC, etc. have been tested for biodiesel production and show 6 to 10 times higher yield than batch and other continuous reactors. Also, reactive absorption and in-situ reactive extraction set-up are developed to achieve higher conversion without thermal degradation of the product at a considerable reduction in energy usage and cost [10, 18].

2.7. Other types of reactors

Another approach to efficiently replace the mechanical agitation is the use of ultrasound, microwave, and hydrodynamic, which generate cavitation of liquids. The cavitation of liquids causes two immiscible liquids to emulsify by the generated shockwaves which disrupt the phase boundaries. As a result, a better mixing, liquid-liquid mass transfer, and miscibility could be achieved. It was found that these reactors make the reaction time shorter (10 to 40 min) than the mechanical agitation method, enhance the mixing efficiency, reduce approximately 50% of the oil and alcohol molar ratio, and decrease the glycerol concentration [6, 31, 32, 33]. The performance of these reactors is affected by various parameters including the diameter ratio of probe to the reactor, reactor height and width, penetration depth of the probe, wave frequency and intensity, and liquids properties [34]. Although these reactors provide an advantage in processing time, the production volume is still limited because only batch reactor is available [6, 35]. This technology also requires a large amount of catalyst which leads to the higher amount of soap formation, extensive recovery process, and generating large amounts of wastewater. Therefore, it is potentially to increase the purification cost and thus deter the viability of the technology in industrial-scale.

3. Future directions, recommendations, and conclusions

Various continuous reactors used in biodiesel production possess numerous advantages over batch reactors; they improve the conversion rate by overcoming the mass and heat transfer problems, eliminate the conventional catalyst-related and waste-related issues, and are suitable for wide ranges of feedstocks. Nowadays further technological advancement is required to realize the large-scale production. However, detailed reaction mechanisms and kinetics in various types of reactors have not yet been revealed, and the proposed technologies have been at the research and development stage. Hence, comprehensive experimental works and application of process system engineering (PSE) tools can enhance the knowledge and ensure the feasibility of industrial-scale production [14]. Finally, this paper will strengthen the understanding of various types of reactors and could be used as a guide for the reactor selection to improve the yield and achieve cost-effective biodiesel production.

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