Fuel 235 (2019) 100–112

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

Multi-objective exergetic and technical optimization of a piezoelectric ultrasonic reactor applied to synthesize biodiesel from waste cooking oil (WCO) using soft computing techniques

Mortaza Aghbashlo[a,*], Soleiman Hosseinpour[a,*], Meisam Tabatabaei[b,c,*], Mohamad Mojarab Soufiyan[a]

[a] *Department of Mechanical Engineering of Agricultural Machinery, Faculty of Agricultural Engineering and Technology, College of Agriculture and Natural Resources, University of Tehran, Karaj, Iran*
[b] *Microbial Biotechnology and Biosafety Department, Agricultural Biotechnology Research Institute of Iran (ABRII), P.O. Box: 31535-1897, Karaj, Iran*
[c] *Biofuel Research Team (BRTeam), Karaj, Iran*

ARTICLE INFO

Keywords:
Biodiesel production
Exergy analysis
Multi-objective optimization
Piezoelectric ultrasonic reactor
Soft computing techniques
Waste cooking oil

ABSTRACT

This work was devoted to optimizing the operating conditions of a low-energy consumption, high frequency piezoelectric ultrasonic reactor used for biodiesel production from waste cooking oil (WCO). The optimization was conducted on the basis of exergetic and technical constraints using a consolidated combination of soft computing techniques. Transesterification temperature, residence time, methanol/oil molar ratio were input variables, while functional exergy efficiency (FEE), universal exergy efficiency (UEE), normalized exergy destruction (NED), and conversion efficiency (CE) were considered as output parameters. Four independent ANFIS models were first developed to map the outputs as a function of the inputs. The developed ANFIS models were then introduced to a hybridized optimization paradigm obtained by consolidating the elitist non-dominated sorting genetic algorithm (NSGA-II) and linear interdependent fuzzy multi-objective optimization (ALIFMO) approaches. The optimization was set to maximize the FEE and UEE and to minimize the NED, while satisfying the ASTM standard on CE (i.e., biodiesel content > 96.5%). All the developed ANFIS models excellently estimated the outputs with an $R^2 \approx 1.0$. The transesterification temperature of 60 °C, residence time of 10 min, and methanol/oil molar ratio of 6.20 were selected as the best operating conditions among the spectrum of the solutions suggested by the developed approach.

1. Introduction

The world's current energy demand is largely met by unsustainable and non-renewable energy resources such as coal, oil, and gas [1]. It is obvious that fossil fuels reserves will not last forever and, therefore, mankind cannot sustainably live on these finite energy resources. The conventional fuels have also proven to be one of the main contributors to the environmental problems faced by mankind today. These issues have spurred interest in further developing and utilizing biofuels as renewable energy carriers [2,3]. Among biofuels, biodiesel has received much attention worldwide as one of the very first renewable transportation fuels became known to the public. Biodiesel obtained from vegetable and animal oils is not only potentially carbon-neutral and biodegradable, but also is physicochemically very similar to mineral diesel facilitating its straightforward substitution [4,5]. However, production of cost-effective and eco-benign biodiesel from food- and feed-grade oils is very challenging [6,7]. Some environmental and humanitarian groups increasingly highlight the concern that biodiesel production from food and feed commodities could jeopardize global food security and environmental sustainability due to food price hikes and massive deforestation. To address these issues, research attempts have been propelled towards waste-oriented low-cost oils and fats such as waste cooking oil (WCO) for biodiesel production [8].

Global biodiesel production is largely based on vegetable oils/animal fats transesterification using a light alcohol in the presence of a catalyst *via* mechanical agitation [9–11]. The use of mechanically-assisted reactors in biodiesel production has several disadvantages such as long processing time and high energy utilization resulted from poor diffusion of the reactants. Ultrasound irradiation could overcome this issue by increasing the interfacial surface area between alcohol and oil,

* Corresponding authors at: Biofuel Research Team (BRTeam), Karaj, Iran (M. Tabatabaei).
E-mail addresses: maghbashlo@ut.ac.ir (M. Aghbashlo), shosseinpour@ut.ac.ir (S. Hosseinpour), meisam_tabatabaei@abrii.ac.ir (M. Tabatabaei).

https://doi.org/10.1016/j.fuel.2018.07.095
Received 3 April 2018; Received in revised form 16 June 2018; Accepted 20 July 2018

thereby leading to higher biodiesel yield within a shorter processing time compared with the conventional stirred reactors. Accordingly, much research has been reported on the use of ultrasound technology for accelerating the transesterification process [12–19].

Although promising results have been reported in the literature on the acceleration of biodiesel synthesis using ultrasound technology, the process must be modeled and optimized in order to simultaneously meet the ASTM standards and sustainability criteria. It is well-documented that the sustainability of thermodynamic systems like biofuel synthesizing units could be best evaluated using exergy analysis [20,21]. Exergy is regarded as the maximum extractable useful work from a given thermodynamic system on which it completely equilibrates with its surroundings reversibly [22–24]. Exergy approach could be used to optimize the use of natural resources and mitigate the negative environmental consequences of all engineering processes [25,26]. Using exergy-based methods, the difference between theoretically possible and actually produced works, i.e., exergy destruction or irreversibility can be accurately identified [27–29]. A thorough literature review manifests that a large number of research attempts have been conducted using exergy and its advanced extensions for measuring and optimizing thermodynamic and environmental viability of various biofuel production processes [30]. Overall, exergy-based analyses can assist in identifying the most thermodynamically-efficient and environmentally-benign technologies among an array of options emerged for the production of a given biofuel.

Despite the fact that exergy-based methods seem to be promising approaches for optimization and improving various biodiesel production process, implementing such surveys is not straightforward without having an accurate modeling system and existence of various incompatible objectives. Modeling exergetic and technical aspects of ultrasound-assisted biodiesel production process is very difficult using the conventional physical and mathematical approaches. This could be attributed to the several nonlinear and complex phenomena involved in the process like sound waves propagation and dissipation, transesterification reaction, heat and mass transfer, and emulsification. Fortunately, elaborated combinations of artificial neural networks (ANN) and fuzzy systems like adaptive neuro-fuzzy inference system (ANFIS) are capable of dealing with uncertainty and complexity in ill-structured complex engineering processes [31].

Once objective functions are developed for such complex processes using an appropriate modeling method, an advanced algorithm will still be required to find the optimum operating conditions by taking into account exergetic and technical constraints. This could be addressed by consolidating fuzzy systems and evolutionary algorithms. In this context, in the present study, the elitist non-dominated sorting genetic algorithm (NSGA-II) was consolidated with additive linear interdependent fuzzy multi-objective optimization (ALIFMO) system in nested form in order to avoid local optima. Subsequently, the operating variables of a low-energy consumption, high frequency piezo-based ultrasonic reactor used for biodiesel production from WCO were optimized based on exergetic and technical parameters through the application of ALIFMO-NSGA-II combination. More specifically, the ANFIS approach was first used to develop objective functions as a function of the three exogenous variables. The objectives were functional exergy efficiency (FEE), universal exergy efficiency (UEE), normalized exergy destruction (NED), and conversion efficiency (CE), while transesterification temperature, residence time, and methanol/oil molar ratio were input variables. The developed ANFIS models were then concurrently fed into the ALIFMO-NSGA-II approach in order to identify the optimum operation conditions of the reactor by maximizing the FEE and UEE and minimizing the NED, while satisfying the ASTM standard concerning the CE (i.e., biodiesel content > 96.5%).

2. Materials and methods

In the current survey, the selection of the optimum operating conditions of a low-energy consumption, high frequency piezoelectric ultrasonic reactor applied for biodiesel synthesis from WCO with respect to the exergetic and technical constraints were conducted in four successive steps: (i) compilation of the required exergetic and technical data for training and testing phases, (ii) selection of the best-performing ANFIS models for estimating exergetic and technical parameters, (iii) interfacing the developed ANFIS models with the ALIFMO-NSGA-II approach, and (iv) selection of optimal operational variables by maximizing the FEE and UEE, minimizing the NED, and complying with the ASTM biodiesel yield (i.e., CE higher than 96.5%).

2.1. Data compilation

The required database for developing and evaluating ANFIS models were obtained from our previous publication on the sustainability evaluation of a piezo-based ultrasound-assisted biodiesel production process using exergy concept [32]. Detailed information on WCO pretreatment, reactor design and development, biodiesel production experiments, gas chromatography (GC) analysis, and exergetic computations were comprehensively presented in previous publications [32]. A brief explanation of the above-mentioned steps is represented in the following subsections.

2.1.1. Materials preparation, reactor development, and biodiesel production and analysis

WCO was obtained from a restaurant in Karaj, Iran, with a free fatty acid content of about 1%. The oil contained 50.57% Linoleic acid, 33.94% Oleic acid, and 15.48% Palmitic acid. Food debris was eliminated from WCO by filtrating through a normal sieve, followed by removing the water present. Sodium methoxide was prepared by blending 1 wt% potassium hydroxide and methanol for 2 min by a magnetic stirrer. The obtained slurry was then gradually mixed with WCO in the reactor. A low-energy consumption (31 W), high frequency (1.7 MHz) cylindrically-shaped piezoelectric ultrasonic reactor was used to intensify the transesterification process (Fig. 1). Experiments were conducted at three levels of transesterification temperature (40–60 °C), residence time (6–10 min), and methanol/oil molar ratio (4:1–8:1). Sonication was started on which the reactants heated to a desired temperature.

Immediately after finishing each experiment, the products of the transesterification process were drained from the reactor. In order to cease spontaneous transesterification process, the resultant mixture was

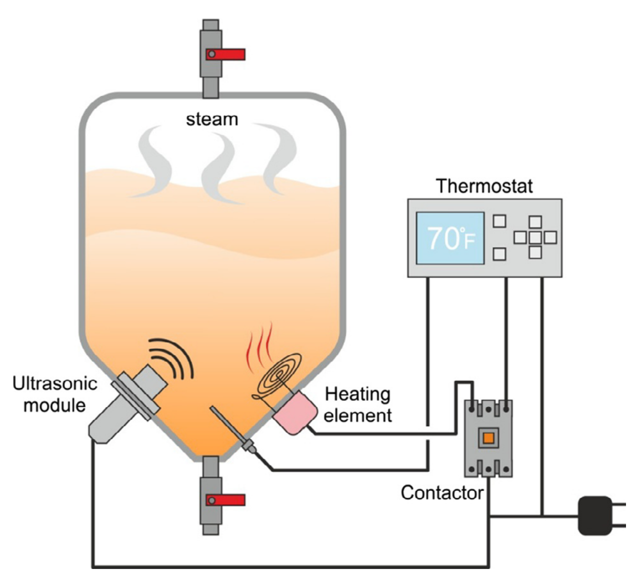

Fig. 1. A schematic representation of the developed piezoelectric ultrasonic reactor.