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Biodiesel production process intensification using a rotor-stator type generator of hydrodynamic cavitation

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ABSTRACT

Triglyceride transesterification for biodiesel production is a model reaction which is used to compare the conversion efficiency, yield, reaction time, energy consumption, scalability and cost estimation of different reactor technology and energy source. This work describes an efficient, fast and cost-effective procedure for biodiesel preparation using a rotating generator of hydrodynamic cavitation (HC). The base-catalyzed transesterification (methanol/sodium hydroxide) has been carried out using refined and bleached palm oil and waste vegetable cooking oil. The novel HC unit is a continuous rotor-stator type reactor in which reagents are directly fed into the controlled cavitation chamber. The high-speed rotation of the reactor creates micron-sized droplets of the immiscible reacting mixture leading to outstanding mass and heat transfer and enhancing the kinetics of the transesterification reaction which completes much more quickly than traditional methods. All the biodiesel samples obtained respect the ASTM standard and present fatty acid methyl ester contents of >99% m/m in both feedstocks. The electrical energy consumption of the HC reactor is 0.030 kW h per L of produced crude biodiesel, making this innovative technology really quite competitive. The reactor can be easily scaled-up, from producing a few hundred to thousands of liters of biodiesel per hour while avoiding the risk of orifices clogging with oil impurities, which may occur in conventional HC reactors. Furthermore it requires minimal installation space due to its compact design, which enhances overall security.

1. Introduction

A huge gap currently exists between classic production processes and the most recent generation of enabling technologies which provide process intensification, higher efficiency and sustainability. Over the last few years, chemists and chemical engineers have found that sonochemical methods furnish attractive solutions to bottle necks in chemical processes [1]. Sonochemical effects arise from the action of ultrasound (US) waves and/or hydrodynamic cavitation (HC). The use of sound energy and in a liquid flow can result in significant gains in process intensification by generating cavitational events inside reactors. When a liquid passes through a constriction, it undergoes a sudden increase in its velocity of liquid at the expense of local pressure. If this local pressure falls below the vapour pressure, a number of cavities will be generated and subsequently collapse, while pressure is recovered downstream of the mechanical constriction.

Several authors have studied reactors since the early 1990s in order to optimize cavitation distribution [2–4]. The last decade has seen the chemistry of flowing systems become more prominent as a method of carrying out chemical reactions, which can range from the lab scale up to kilogram-scale processes [5,6]. Flow reactors stand out above their classic batch sonochemical process counterparts thanks to their greater efficiency, flexibility and lower energy consumption [7].

The aim of this work is to draw attention to a new means of generating HC, using rotation generators, and their easily operated applications in loop and flow through modes [8]. The reduced energy consumption, environmental and economical impact of this type of reactor mean that it is well suited to industrial scale up and biodiesel production in particular. Most commercial oil transesterification technologies that use cavitation are currently based on acoustic cavitation (US), which is simpler to implement than HC, but also less energy efficient. Cavitation in US reactors (horns and baths) occurs in a confined region around the vibrating surface meaning that there are evident limitations to its operational scale up. Lab scale HC, on the other hand, is either generated by

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multiple-hole orifice plates or simple Venturi restrictions that require high power pumps because of the considerable pressure losses caused by the restrictions. An innovative design has been presented by Kumar and Pandit [9], who used a high-speed homogenizer consisting of an impeller inside a cage-like stator with numerous slots where cavitation generates. Another rotor and stator based design has been presented by Badve et al. [10]. In this set up, a rotor presents a solid cylinder with indentations on its surface meaning that cavity regions are established inside the indentations due to high speed rotation. A similar design with two counter spinning rotors has also been presented by Petkovšek et al. [8], which, like all the other machines presented, needs an extra pump for operation. This means that the cavitation generator causes extra pressure losses in the existing system. The same Authors have very recently improved the system making it more energy efficient thanks to an extremely compact generator and pump [11]. This device has been outstanding in waste water treatment [12]. This work tests a novel commercial unit (patent pending) that was designed by E-PIC S.r.l. (Turin, Italy). It is characterized by rotor-stator apparatus equipped with a three-phase, 7.5 kW electric engine, while absorbed power is constantly monitored (Fig. 1).

A concerned effort has been made to search out new highly efficient reactors that produce biodiesel while saving time and energy. Inefficient mass transfer is one of the main limitations in biphasic heterogeneous reactions, such as transesterification. Although many types of vigorous mixing have been investigated to address this requirement, most of them suffer from high energy demands [13–15]. Optimal mass/heat transfer is doubtless the key to enhancing biodiesel production while cavitational effects may also play a significant role. The two main routes to acoustic cavitation are high-intensity ultrasound and HC (passage of liquid at high flow rates through a constriction), although rotating HC generators are the most recent innovation.

With the aim of reducing energy consumption in biodiesel production, we have thoroughly investigated the effect of cavitation on the transesterification reaction of triglycerides over the last few years [16]. We have also investigated combinations of different enabling technologies both in batch and in flow processes [17–19]. Hybrid processes for biodiesel production that function upon a combination of sonochemical reactors and other intensification techniques have been thoroughly reviewed [20] as have continuous flow technologies [21]. In 2005 Gogate and Pandit described HC as a technology for the future [22], and one year later, a Chinese group from the Zhejiang University of Technology compared US and HC conditions for biodiesel production [23]. The techniques displayed similar enhancement effects in the transesterification reaction of soybean oil, both giving shorter reaction times and lower energy consumption than the conventional mechanical stirring method. Several authors have confirmed these results [24,25] and have highlighted HC's easier scale-up compared to US methods. The micro level turbulence created by HC may be able to overcome the mass transfer limitations of a triphasic reaction such as transesterification. With the best of our knowledge we could not find previous applications of rotor-stator type HC reactors for biodiesel production, however the commercially available SPR BD reactors equipped with a spinning rotor (a drum with hundreds of holes) from Hydro Dynamics, Inc. (USA) are successfully used in this field [26].

The high cost of vegetable oils and the ethical issues that surround competition with the food industry for oil crops means that much attention has been focussed on non-edible oils and used frying oils which are a renewable source [27–29].

The recycling of waste cooking oil (WCO) that had been used for frying has been investigated under HC conditions [30–33]. HC has also been used as a pre-treatment for residual algal biomass's conversion into cheap feedstock for yeast cells that produce lipids [34].

This work highlights the potential industrial applications of a rotating generator of HC for biodiesel production even with waste unfiltered cooking oil feedstock.

2. Material and methods

2.1. Material

Transesterification reactions were carried out using two different feedstocks; refined and bleached palm oil, purchased from

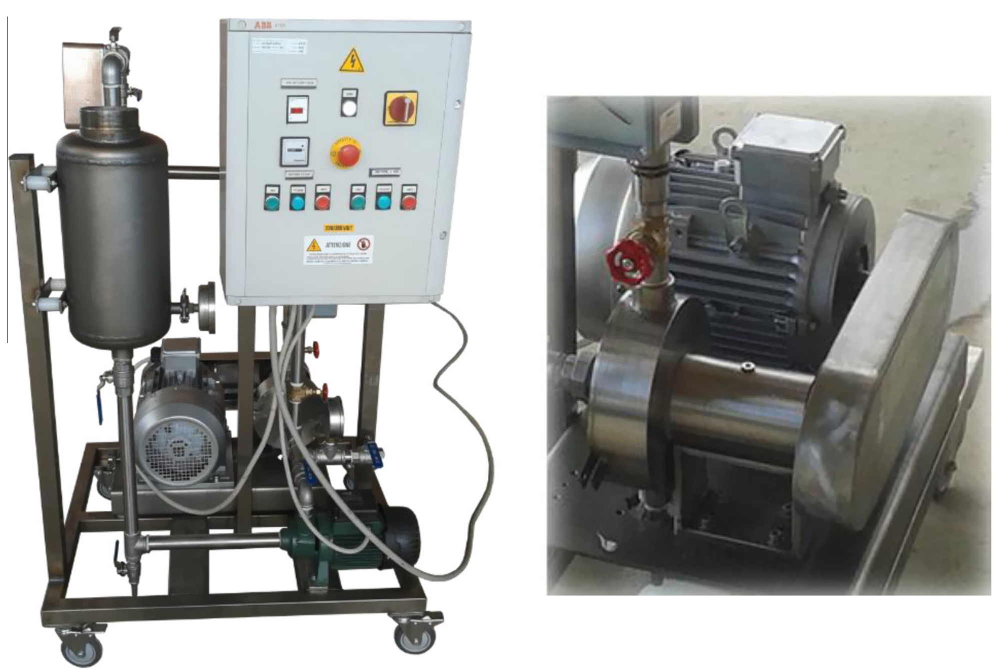

Fig. 1. Rotor-stator generator of HC.