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PRELIMINARY DESIGN OF OSCILLATORY FLOW BIODIESEL REACTOR FOR CONTINUOUS BIODIESEL PRODUCTION FROM JATROPHA TRIGLYCERIDES

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Abstract

The concept of a continuous process in producing biodiesel from jatropha oil by using an Oscillatory Flow Biodiesel Reactor (OFBR) is discussed in this paper. It has been recognized that the batch stirred reactor is a primary mode used in the synthesis of biodiesel. However, pulsatile flow has been extensively researcehed and the fundamental principles have been successfully developed upon which its hydrodynamics are based. Oscillatory flow biodiesel reactor offers precise control of mixing by means of the baffle geometry and pulsation which facilitates to continuous operation, giving plug flow residence time distribution with high turbulence and enhanced mass and heat transfer. In conjunction with the concept of reactor design, parameters such as reactor dimensions, the hydrodynamic studies and physical properties of reactants must be considered prior to the design work initiated recently. The OFBR reactor design involves the use of simulation software, ASPEN PLUS and the reactor design fundamentals. Following this, the design parameters shall be applied in fabricating the OFBR for laboratory scale biodiesel production.

Keywords: Jatropha, OFBR (Oscillatory Flow Biodiesel Reactor), biodiesel, reactor design.

1.Introduction

Biodiesel is composed of long-chain fatty acids with an alcohol attached, often derived from vegetable oils. It is produced through the reaction of a vegetable oil with methyl alcohol or ethyl alcohol in the presence of catalyst [1]. Chemically, biodiesel is called methyl ester if the alcohol used is methanol.

Nomenclatures

a_c	Tube cross sectional area, m^2
C_o	Standard orifice coefficient
D	Tube internal diameter, m
d_o	Baffle orifice diameter, m
L	Baffle spacing, m
ℓ	Eddy mixing length, m
m_t	Total number of baffles
Q	Volumetric throughput, m^3/h
Re_n	Reynolds number based on net flow only
Re_o	Reynolds number based on oscillatory only
S	Fractional open area of baffle
St_r	Strouhal number
t	Mean residence time, s
u	Superficial tube velocity (based on net flow), m/s
V	Reactor (tube) volume, m^3
z	Total tube length, m
Greek Symbols	
ΔP	Total pressure drop due to frictional losses, Pa
ε_n	Energy dissipation for net flow, W/m^3
ε_v	Average energy dissipation per unit volume, W/m^3
μ	Fluid viscosity, N.s/m^2
ζ	Pressure enhancement ratio
ρ	Fluid density, kg/m^3
χ_o	Amplitude of oscillation (center-to-peak), mm
ψ	Velocity ratio
ω	Angular frequency of oscillation, 1/s

Jatropha triglyceride is produced from Jatropha curcas L. seeds through extraction process. The seeds of physical nut are a good source of oil, which can be used as a diesel substitute. They are also used in medicines, soap and cosmetic manufacture in various tropical countries [2].

The most common method for producing biodiesel is the one step or two-steps batch transesterification process. Batch processes have suffered several disadvantages compared to continuous processes because batch processes require larger reactor volume, resulting in higher capital investment [3]. Subsequently, continuous process in producing biodiesel from vegetable oils have been developed by some researchers to reduce a higher procurement cost and to enhance mixing of the reactants in order to improve the reaction rates [4-6].

The fundamental steps in oscillatory flow biodiesel reactor (OFBR) design calculation are baffle geometry, tube configuration and power dissipation [7]. In general, the geometric configuration of the reactor should be kept identical to lab scale devices, where the baffle orifice diameter is half the tube internal diameter.

2. Background

Oscillatory flow in baffled tubes has been studied for many years and much work have been done in areas related to fluid dynamics, heat and mass transfer and residence time distribution. Many advantages have been characterized for oscillatory flow mixing, such as efficient dispersion for immiscible fluids, uniform particle suspension, gas-in-liquid dispersions and multiphase mixing [8-9]. Recent researches have indicated that oscillatory flow in a baffled tube has significant potential for process and product enhancement in a wide range of application.

Continuous processing is achieved by superimposing an oscillatory flow on a steady throughput in a tubular reactor. Each inter-baffle zone is a unit stirred tank, and in a multi-pass configuration, a multiplicity of stirred tanks exists in series, allowing a close approach to plug flow RTD (Residence Time Distribution), even at low throughput rates. An operating advantage is that residence time can be fixed, but control over RTD and heat transfer is maintained [10].

Stonestreet and Harvey [7] reported that oscillatory flow reactor is a novel type of continuous reactor, in which tubes fitted with orifice plate baffles have an oscillatory motion superimposed upon the net flow of the process fluid. The interaction between the fluid and the baffles creates the oscillatory motion of the fluid that generates excellent mixing and enhanced transport rates, whilst maintaining a close approach to plug flow. Oscillatory motion in the tube is provided by an electrically or pneumatically driven piston or diaphragm to oscillate the fluid or to displace series of baffles [11].

3. Design Method for Oscillatory Flow Biodiesel Reactor (OFBR)

The geometric configuration is a proposed approach to design oscillatory flow biodiesel reactor (OFBR) by maintaining the dynamic similarity using various dimensionless groups, followed by the application of other empirical design correlations specific to oscillatory flows. Scaling up oscillatory flow reactor can be assured by keeping two geometric ratios constant such as the baffle spacing (L) which is expressed as a fixed ratio of the tube diameter, and the baffle orifice open area (S) as stated in the following equations:

$$L = 1.5\,D \tag{1}$$

$$S = d_o^2 / D^2 \tag{2}$$

In this matter, Stonestreet and Harvey [7] reported that the fractional open area of baffle is in the range 0.2-0.4, usually 0.25, such that the orifice diameter is half the tube diameter.

Some dimensionless numbers should be kept on the full scale as pilot or laboratory scale when oscillatory flow is concerned. The results of dimensionless number derivation are as shown in the following:

$$Re_n = \rho\, u\, D/\mu \tag{3}$$

$$Re_o = \chi_o \omega\, D\, \rho/\mu \tag{4}$$

$$St_r = D/4\pi\, \chi_o \tag{5}$$

Based on the selection of net Reynolds number Re_n, and oscillatory Reynolds number, Re_o values and the required mean residence time, the superficial velocity, the reactor length, volume, and the volumetric flow rate are given as:

$$u = \mu\, Re_n / D\rho \quad (6)$$

$$z = u\, t \quad (7)$$

$$V = z\, \pi\, D^2/4 \quad (8)$$

$$Q = V/t \quad (9)$$

In a continuous oscillatory flow reactor, the power dissipation is attained from both the steady flow and the oscillatory flow components. The pressure drop due to net flow through a baffle tube can be obtained by the standard equation for flow through an orifice modified to account for the summation of total number of identical baffles (m_t) [7]:

$$\Delta P = m_t \rho u^2 / 2C_o \left(1/S^2 - 1\right) \quad (10)$$

Overall power per unit volume or power density for net flow and oscillatory flow through baffled tube can be calculated with involving the density of fluid (ρ), angular frequency of oscillation (ω), amplitude of oscillation (χ_o) and eddy mixing length (ℓ) in the following equations:

$$\varepsilon_n = \Delta P a_c / V u = \Delta P u / z\zeta \quad (11)$$

$$\varepsilon_v = 3 m_t \rho \omega^3 \chi_o^2 l / Sz \quad (12)$$

In order to ensure that the selected configurations do not require an unfeasible large amount of energy to achieve the required mixing and flow rate, the power density for each of the tube sizes is evaluated. A useful way of assessing the configurations is to plot the power density against the length to diameter ratio as shown in Fig. 1.

4. Plug Flow Reactor (PFR)

A recent study has found that the velocity ratio is important in defining the residence time distribution performance in an oscillatory flow biodiesel reactor. The study recommended that the velocity ratio should be maintained in the range $2 \le \psi \le 6$ to ensure a close approach to plug flow [7]. Although the design is intended for plug flow reactor, there is a formal analogy with the batch reactor equations where it is assumed that there is no volume change during the reaction. In a similar problem, Butt [12] reported that the design equations for plug flow reactor are written for first order irreversible reaction. In this study, the plug flow reactor performance is calculated by utilizing the software, Aspen Plus.

Plug flow reactors in Aspen Plus simulation are based on the assumption that perfect mixing occurs in radial direction and no mixing occurs in the axial direction. It can only handle kinetic reaction, which means that a kinetic data for the reaction should be specified in order for the simulation to run. Other type of reactors in Aspen Plus such as 'R-Stoich' and 'R-Equil' do not require a kinetic data but simulate the reaction based on stoichiometry and equilibrium [13].

In this simulation, the plug flow reactor (PFR) is designed to handle 2 litre/hour of inlet flow with diameter of 0.05 m. This specification is similar to the oscillatory flow biodiesel reactor (OFBR) and thus comparisons can be made in terms of performance. Using this specification, the retention time (RTD) is varied in order to obtain the corresponding reactor length and conversion.

A set of simulation is done to observe the performance of plug flow reactor by varying the RTD while diameter remains constant. For each simulation, conversion of triglycerides as the reactant into products was calculated. This is taken as the performance of the reactor. The specifications of each simulation and the resulted conversions for both PFR and OFBR are listed in Tables 1 and 2. Meanwhile, the calculated specifications of oscillatory flow biodiesel reactor are shown in Table 3.

Table 1. Simulation Specifications and Corresponding Results (PFR).

RTD (min)	Length (m)	Conversion (%)
1	0.016	1.58
3	0.05	4.78
7	0.116	11.05
10	0.166	15.84
13	0.216	20.64
15	0.25	23.83
20	0.33	31.46
30	0.50	47.69
40	0.667	63.55
50	0.833	79.34
60	1.0	95.29
70	1.08	100.00

Table 2. Simulation Specifications and Corresponding Results (OFBR).

RTD (min)	Length (m)	Conversion (%)
1.25	0.07	8.21
2.59	0.13	16.46
4.04	0.20	24.63
5.62	0.27	32.87
7.33	0.33	41.05
9.19	0.40	49.28
11.24	0.47	57.46
13.49	0.53	65.70
16.00	0.60	73.87
18.79	0.67	82.05
21.95	0.73	90.29
25.55	0.80	98.46
29.15	0.87	100.00

Table 3. Specifications of Oscillatory Flow Biodiesel Reactor (OFBR).

Description	Design Value
Tube diameter (m)	0.05
Total tube length (m)	1.00
Number of tubes	2.00
Straight tube length (m)	0.40
Total volume (Liter)	2.00
Volumetric flow rate (Liter/s)	5.56×10^{-4}
Total number baffles	14.00
Baffle diameter (m)	0.049
Baffle orifice diameter (m)	0.025
Baffle spacing (m)	0.075
Baffle per insert	6.00
Specific power req. (W/m^3)	5.10
Frequency (Hz)	3.00
Amplitude (mm)	12.00
Mean residence time (s)	3600.00
z/D	20.40

The simulated result of a PFR shows that for a fix diameter of 0.05 m, by varying the RTD between the ranges of 1 minute to 65 minutes, the conversion of triglycerides into product is increased due to increase in length of the reactor. At RTD = 60 minutes, the projected conversion in a PFR is 95%. In order to obtain complete conversion, the PFR should be designed with length at least 1.1 m. However, an OFBR gives greater conversion at reduced residence time with the same diameter. It has been projected that the required length is approximately 0.8 metre. Therefore, it is expected that the design of an OFBR at RTD = 65 minutes with the same reactor dimensions would enhance the product conversion. The conversion of triglycerides in the designed plug flow reactor and the corresponding RTD is shown in Fig. 2.

Figure 1 shows that as the length of diameter ratio increases, the required power density is also increased. It clearly shows that the *z/D* ratio is smaller for the OFBR at similar power densities, indicating that, in general, an OFBR would be significantly shorter, typically by at least two orders of magnitude, thus reducing the cost incurred to fabricate and operate.

Figure 2 illustrates the trend of simulated conversion in the reactors namely the PFR and the OFBR. In the OFBR, the conversion of triglycerides into methyl ester increases with increase of RTD. It also indicates that the reaction has reached the plateau and the conversion is complete after 40 minutes. It clearly shows that the reaction could achieve 100% conversion at lower RTD with an OFBR when compared to a PFR. As a consequence, a long residence time with a relatively short tubular reactor can possibly be achieved using the oscillatory flow type biodiesel reactor. Furthermore, it is possible to control the performance of the device independently from the throughput using the amplitude and frequency of oscillation.

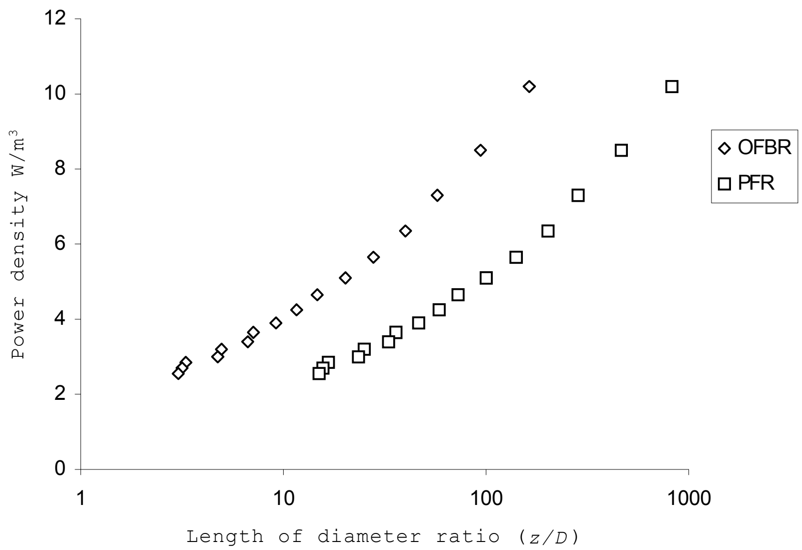

Fig. 1. Comparison of Power Density vs. *z/D* Behaviour for OFBR and PFR.

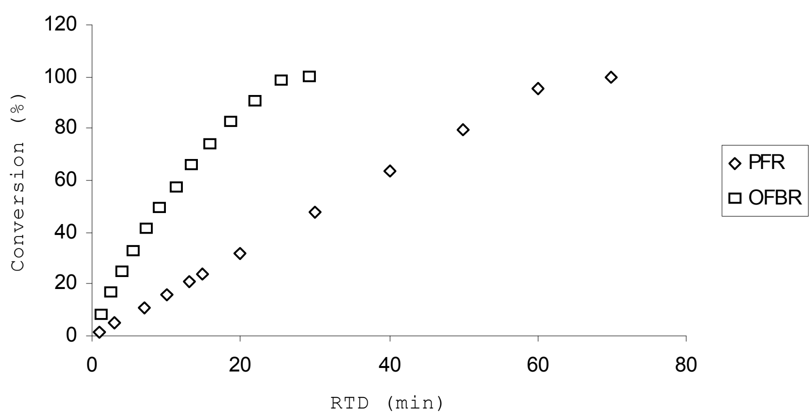

Fig. 2. Comparison of Conversion vs. RTD of Triglycerides in PFR and OFBR.

5. Conclusion

The design for continuous oscillatory flow reactor follows an appropriate methodology, based on the standard shell and tube heat exchanger. Other criteria employed to take into account are the effect of baffles and rate of reaction. Geometric configuration is achieved by maintaining the baffle spacing to diameter ratio and fractional open area of the baffle.

This study clearly illustrates the advantages of the oscillatory flow biodiesel reactor (OFBR) configuration over a plug flow reactor (PFR). In addition, the

OFBR has significantly lower power density than the PFR and if compared to an equivalent continuous reactor.

Oscillatory flow in baffled tubes has been shown to enhance process engineering properties such as mixing, heat transfer, homogeneous and heterogeneous phase mass transfer and most of all, the rate of reaction. The ASPEN PLUS simulation also indicated that complete conversion of triglyceride into methyl ester can be achieved at long residence time with a relatively compact tubular reactor.

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