Monitoring of Mixing Process by Visualization of Stirred Bio-diesel Production Reactor Using Electrical Capacitance Tomography

Syed F.A. Bukhari[a] and Adesoji A. Adesina[b]
[a]Department of Computer Engineering, Sir Syed University of Engineering & Technology,
University Road, Karachi-75300, PAKISTAN
[b]Reactor Engineering & Technology Group, School of Chemical Engineering,
The University of New South Wales, Sydney, NSW 2052, AUSTRALIA

Abstract - *Biodiesel are long chain fatty acid alkyl esters produced from the alcoholysis of triglycerides (or esterification of free fatty acids) in stirred vats. Non-edible (or waste cooking) oil and bioethanol are used as reactants in the second generation biodiesel technologies. As a result, complex multiphase (oil-aqueous-solid) mixing is inevitable (where the solid phase is the suspended catalyst particles). In order to improve production performance, this study deals with the non-invasive measurement of the phase hold-up and mixing attributes via electrical capacitance tomography (ECT).*

Keywords Biodiesel, electrical capacitance tomography, multiphase mixing, phase hold-up

1 Introduction

In a recent study, it has been shown that the world's oil resources are expected to meet the global demand until next few decades only [1]. According to World Energy Outlook (WEO) 2007, oil and gas supplies will reach 61 million barrels per day by 2030. On the other hand, in 2006 the forecast about available reserves of oil and gas are 1300 billion barrels and 6100 trillion cubic feet respectively. This alarming fossil fuel depletion rate has triggered the world to start research and development for alternate renewable energy sources. Bio-energy (e.g. biodiesel) is considered to be one of the potential renewable energy sources. The concept of biodiesel is not new as Rudolf Diesel invented a diesel engine running on vegetable oil in the year 1900 [2]. Biodiesel is considered superior to conventional diesel based on degree of pollution, sulphur content, aromatic content and flash point [3].

Nowadays, the most popular and commonly used methodology for second generation biodiesel production is transesterification. Conventionally homogeneous base catalyst under mild heating condition (50–60 °C) was used for biodiesel production. The transesterification processes are affected by main factors such as, reaction temperature, alcohol/oil molar ratio, type and concentration of catalyst as well as purity of reactants [4]. The cost of production of biodiesel can be reduced by using waste cooking oil as raw material since it is cheaper than virgin vegetable oils [5]. An increase in food consumption with the rise of world's population has created significant disposal problems for waste edible oils. For example, in USA waste cooking oil per year is about 4.5-11.3 million litres and in Japan it is $4x10^5$-$6x10^5$ tons [6]. Because waste cooking oil and bio ethanol (with alumina as catalyst) are used as reactants for the production of biodiesel therefore complex multiphase (oil-aqueous-solid) mixing phenomena is involved. It is essential to monitor the process of biodiesel production for the improvement of industrial performance. This study deals with the non-invasive measurement of the phase hold-up and mixing attributes via electrical capacitance tomography (ECT).

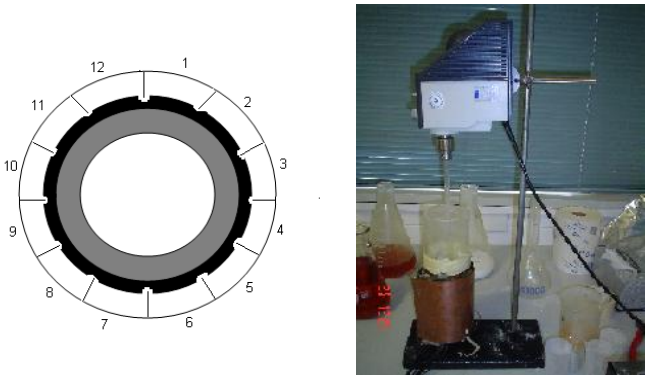
2 ECT System

ECT has been used effectively for monitoring of mixing processes in the past [7] [8]. In a conventional ECT system, the sensor takes the form of an array of electrodes placed around an insulating pipe and surrounded by a grounded screen. The data acquisition unit measures the capacitance of all possible electrode pairs, thus producing total measurements of n(n-1)/2, where n is the number of electrodes. In this work, the ECT system is used for non-invasive monitoring of phase hold-up and mixing attributes. Experimental work was carried out in a mechanically-agitated 2L reactor containing oil-ethanol-alumina mixture in various ratios. This reactor was fitted with an external 12-electrode copper belt sensor tightly wrapped around its acrylic glass wall (Fig. 1). All measurements were taken and analysed on the dual-mode M3000 module ECT system. A glass stirrer was used with speed up to 1300 rpm. The solid alumina (catalyst) was loaded in an amount of 0-100 grams/litre.

3 Eclectic data analysis approach

There are two main approaches for data analysis in process tomography: (1) raw measurement data analysis and

(2) visualisation of 2D or 3D images. Many algorithms have been developed for visualisation of ECT images but still quantitative errors exist associated with the image reconstruction techniques [7]. It has been shown that useful information about phase distribution can be obtained using raw data [9].



(a) Cross-sectional view (b) ECT sensor with stirrer

Fig. 1: ECT sensor test set-up

The Maxwell model can be applied to ECT measurements for calculation of dispersed phase hold up [10] [11] [12] which can be expressed in terms of measured capacitance (C_m) and high and low capacitance readings at calibration (C_h, C_l) by the following equation.

$$\text{Maxwell model: } \varepsilon_d = \frac{2C_l + C_h - 2C_m - C_m k}{C_m - k + 2(C_l - C_h)} \qquad (1)$$

In above equation, k is the high to low permittivity ratio (C_h / C_l) and ε_d is the dispersed phase hold up. Banisi *et al.* [13] have shown that Maxwell's two phase model (Equation 1) can be modified for the three phase system (Equation 2). In this work this modified version has been used with the following assumptions.

1) Oil-ethanol (liquid-liquid) mixture has been treated as a continuous phase.
2) Solid particles of alumina are assumed to have a porous nature.

$$\varepsilon_g = \varepsilon_{s'} = \frac{1 - k_m / k_s}{1 + 0.5 k_m / k_s} \qquad (2)$$

Where

k_m Measured permittivity of mixture
k_s Permittivity of alumina (solid)
$\varepsilon_{s'}$ Gas holdup

The estimation of $\varepsilon_{s'}$ requires two permittivity measurements, that of the liquid-liquid phase alone and that of the liquid-gas mixture (or dispersion).

The pressure difference between two vertically spaced points is given by

$$\frac{P_B - P_A}{L} = g(\rho_g \varepsilon_g + \rho_l \varepsilon_l + \rho_s \varepsilon_s) \qquad (3)$$

Where

ρ_i Density of i (gas, liquid, solid) in g/cm^3
ε_i Holdup of i
g Acceleration due to gravity in cm/s^2
L Vertical distance between two points in cm

Since $\rho_g <\ \rho_s, \rho_l$, it is assumed that $\rho_g = 0$ and substituting ε_l for ε_s and ε_g using global volume balance equation, i.e. $\varepsilon_s + \varepsilon_g + \varepsilon_l = 1$. Equation (2) can be re-arranged to give ε_s

$$\varepsilon_s = \frac{\Delta P / L - g\rho_l(1 - \varepsilon_g)}{g(\rho_s - \rho_l)} \qquad (4)$$

where $\Delta P = P_B - P_A$, since in this work pressure is assumed constant so $\Delta P = 0.$

4 Experimental data analysis and discussion

In this research, experiments were conducted in both 2-phase (oil-ethanol, alumina-oil and alumina-ethanol) and 3-phase (oil-ethanol-alumina) systems. An eclectic approach to the treatment of the raw dispersed phase data permitted the decoupling of oil phase hold-up and solid hold-up. The permittivity for ethanol, alumina and oil are 24.3, 9 and 3 respectively. The normalised measured values of permittivity for the mixture are shown in Fig. 2.

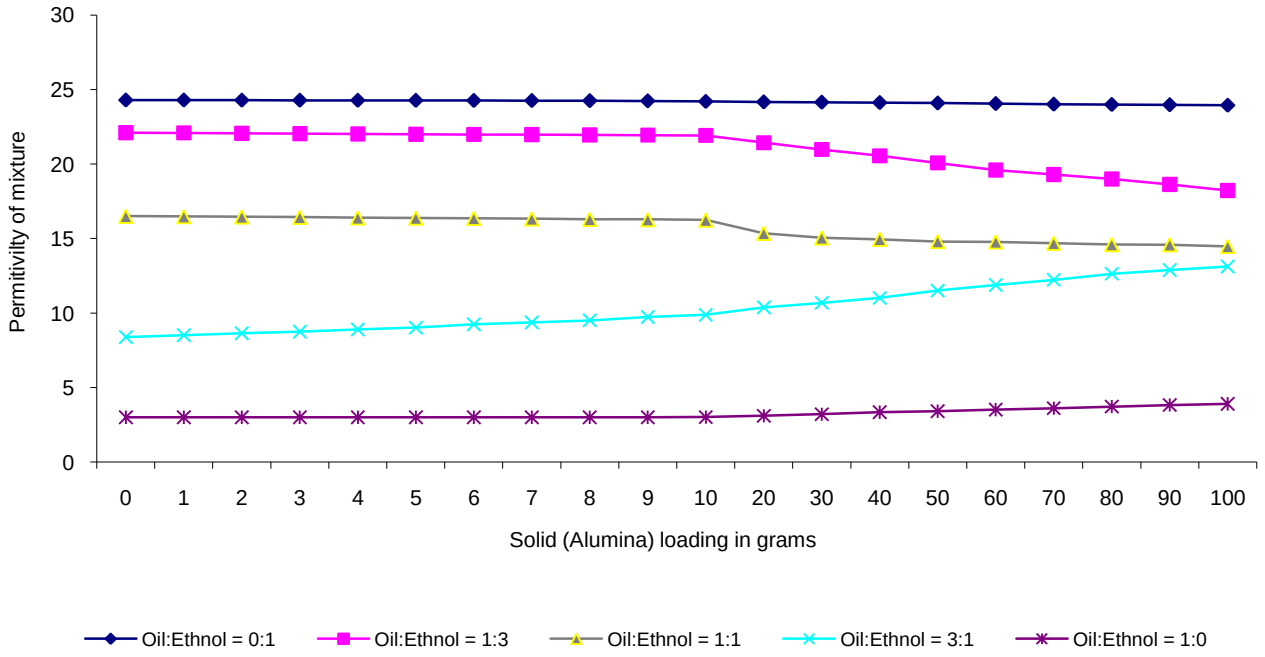


Fig. 2: Measured permittivity values for oil and ethanol mixture for different alumina loading

In the first case, oil:ethanol ratio was 0:1 and the observed change of permittivity was from 24.30 to 23.95 respectively on addition of alumina from 0 gram to 100 gram (in 20 steps). The reason for this decrease in permittivity was due to the addition of low permittivity material, i.e. alumina to high permittivity material, i.e. ethanol. The experiment was then performed for oil:ethanol ratio of 1:3. Here the permittivity was changed from 22.11 to 18.23 on addition of alumina similar to the previous case. The decrease in permittivity of the mixture was again dominated by alumina particles. The third experiment was performed on oil:ethanol ratio of 1:1. In this set of readings, the change of permittivity was from 16.50 to 14.48. The next experimental data were obtained for oil:ethanol ratios of 3:1 and 1:0 respectively. The change of permittivity values were from 8.39 to 13.13 and from 3.00 to 3.53 for oil:ethanol ratios of 3:1 and 1:0 respectively. The values of mixture permittivity were increased because mixture was dominated by oil having lower permittivity than alumina. Fig. 3-5 show effect on dispersed phase hold-up for different oil:ethanol ratios. These values are calculated using Maxwell model for three phases.

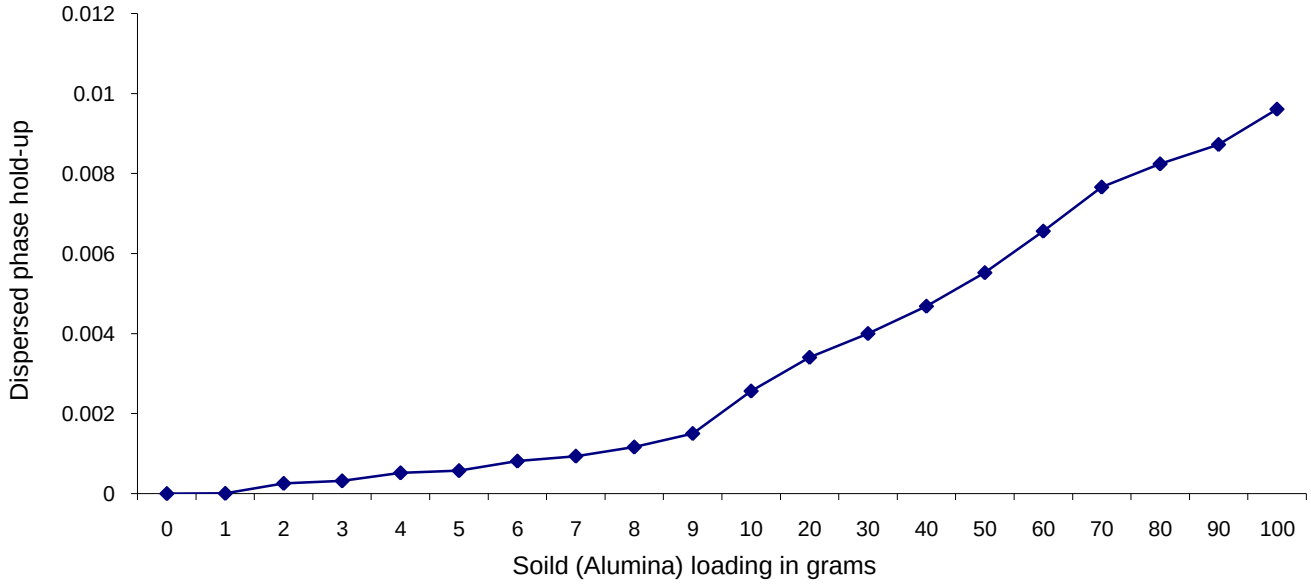


Fig. 3: Dispersed phase hold-up for oil:ethanol = 0:1 mixture for different alumina loading

Another set of experimental data were obtained with alumina loading at 20 grams/litre in different oil:ethanol ratios. The results are given in Fig.6, which show that the dispersed phase hold-up increased monotonically with solid loading, w, for all oil-ethanol ratios. In particular, the dispersed phase hold-up increased with increasing oil composition in the liquid phase suggesting that oil was dispersed as droplets in the continuous ethanol phase. This dependency was captured by the power-law relation:

$$\phi_{d/e} - \phi_{o/e} = aw^n \quad (5)$$

where, $\phi_{d/e}$ and $\phi_{o/e}$ are the dispersed phase hold-up and oil phase hold-up respectively (with ethanol as the continuous phase). Interestingly, both a and n are functions of the oil phase volume fraction, x_{oil}.

The effect of different stirring speeds on phase hold up with solid loading at 50 grams/litre was also observed. The results are shown in Fig. 7, which also reveals that the phase hold-up is strongly correlated with the impeller Reynolds number, Re_I. Indeed, as the oil volume fraction increased, the curves rose sharply suggesting that mixing would be better with very low oil:ethanol ratio. Incidentally, the transesterification reaction rate is favoured by ethanol:oil volume ratio greater than 6.

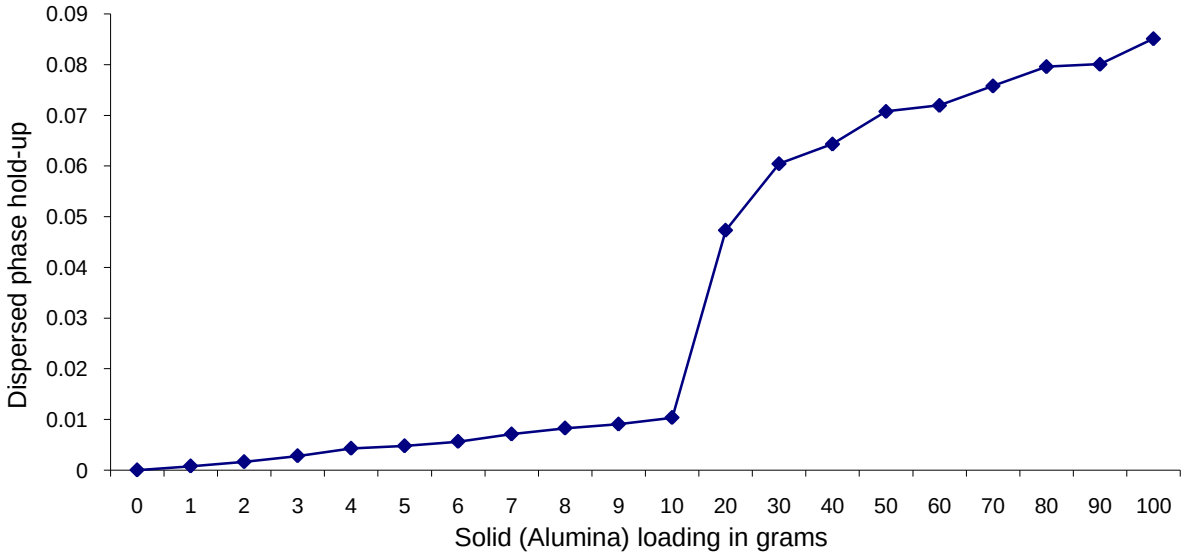


Fig. 4: Dispersed phase hold-up for oil:ethanol = 1:1 mixture for different alumina loading

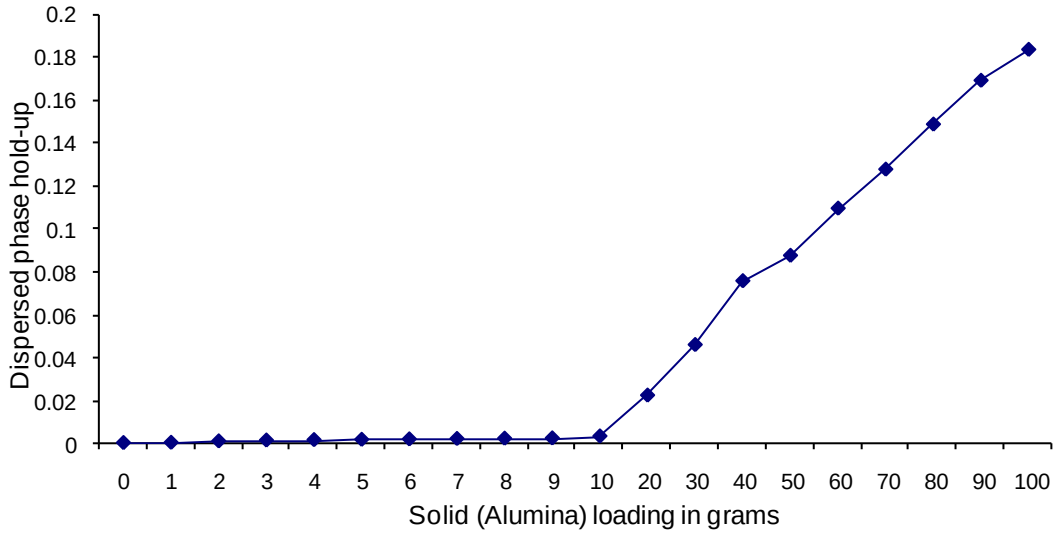


Fig. 5: Dispersed phase hold-up for oil:ethanol = 1:0 mixture for different alumina loading

5. Conclusions

In this work, an ECT-based system has been used to monitor the mixing and phase hold-up characteristics of a stirred bio-diesel production reactor. Experiments were conducted for different oil and ethanol ratios with different loading of alumina. Calculations were performed using Maxwell model for three phases. It was observed that the dispersed phase hold-up increases monotonically with solid loading for all oil-ethanol ratios. For the cases having high oil composition, it was noted that oil was dispersed as droplets in continuous ethanol phase. The experiments showed that ECT was also effective for sensing very low amount of alumina, i.e. in the range of 1 gram/litre.

6 References

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