Effect of surfactants on the lightning breakdown voltage of palm oil and coconut oil based Al$_2$O$_3$ nanofluids

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Abstract
In this paper, the effect of different types of surfactants on the lightning breakdown voltages of palm oil (PO) and coconut oil (CO) based aluminium oxide (Al$_2$O$_3$) nanofluids is investigated. Three different types of surfactants were used in this study known as cationic (cetyl trimethyl ammonium bromide (CTAB)), anionic (sodium dodecyl sulfate (SDS)) and non-ionic (oleic acid (OA)). The volume percentage concentrations of Al$_2$O$_3$ dispersed into PO and CO were varied from 0.001% to 0.05%. The ratio of surfactant to the nanoparticles was set to 50% from the volume concentration of nanoparticles which equivalent to 1:2. In total, two types of refined, bleached and deodorized palm oil (RBDPO) and one type of CO were examined for lightning breakdown voltage. The test was carried out based on needle-sphere electrodes configuration with 25 mm gap distance. The presence of Al$_2$O$_3$ improves both positive and negative lightning breakdown voltages of RBDPO and CO. Under the positive and negative polarities, the CTAB does provide further improvements on the lightning breakdown voltages of RBDPOA (1st type of samples) and CO at most of the volume of concentration of Al$_2$O$_3$. SDS and OA could also further improve the lightning breakdown voltage of CO at certain volume concentration of Al$_2$O$_3$. On the other hand, the lightning breakdown voltage of RBDPOB based Al$_2$O$_3$ nanofluid (2nd type of samples) does not further improve with the introduction of surfactants. At most of the volume concentration of Al$_2$O$_3$, the introduction of CTAB further increases the times to breakdown and decrease the average streamer velocities of RBDPOA under both polarities. The same finding is observed for CO under positive polarity with CTAB and SDS as well as under negative polarity in the presence of all surfactants. The streamer velocities and times to breakdown patterns of RBDPOB based Al$_2$O$_3$ nanofluid are inconsistent in the presence of all surfactants. It is found that RBDPO and CO based Al$_2$O$_3$ nanofluids have second mode of streamer whereby the streamer velocities are from 1 km s$^{-1}$ to 1.63 km s$^{-1}$ regardless with or without surfactants.
Keywords: Palm oil, coconut oil, lightning breakdown voltage, Al\textsubscript{2}O\textsubscript{3}, nanofluids

1. Introduction

In recent years, nanofluids have been extensively examined as possible alternative for dielectric insulating fluids applications. Several researches have proven that nanofluids possess good dielectric insulating capability as well as thermo physical properties such as thermal conductivity, thermal diffusivity and convective heat transfer coefficients [1–3]. It is known that the nanoparticle’s volume concentration, shape, size, surface contact area with insulating fluids could influence the enhancement of electrical breakdown properties of insulating fluids [4].

Several studies have been carried to examine the lightning breakdown voltages of either vegetable oil (VO) or mineral oil (MO) based nanofluids. Different types of nanoparticles have been considered such as magnetite (Fe\textsubscript{3}O\textsubscript{4}), silicone oxide (SiO\textsubscript{2}), titanium oxide (TiO\textsubscript{2}), copper (II) oxide (CuO), aluminium oxide (Al\textsubscript{2}O\textsubscript{3}), aluminium nitride (AlN), zirconium oxide (ZrO\textsubscript{2}) and zinc oxide (ZnO) [5–22]. Without surfactants, the effect of the nanoparticles on the lightning breakdown voltage improvements of dielectric insulating fluid is not consistent whereby it depends upon the properties of nanoparticles, polarities, testing configurations and types of oils. Under the non-uniform field, Fe\textsubscript{3}O\textsubscript{4} and SiO\textsubscript{2} could provide the highest improvement of positive lightning breakdown voltages of MO with 83% and 81% increments respectively [5, 6]. Similar positive effect on the positive lightning breakdown voltage of MO is found as the TiO\textsubscript{2} and ZrO\textsubscript{2} are introduced with 47% and 16% of improvements respectively [7–9]. Similarly, the positive lightning breakdown voltages of palm oil (PO), coconut oil (CO) and refined sunflower oil (RSO) show the improvement trends as ZnO, TiO\textsubscript{2} and CuO is introduced but the percentage of improvements are much lower ranging from 6% to 29% [10–12]. The improvement trend continue for quasi uniform field whereby the positive lightning breakdown voltages of PO and CO increase at much lower levels of 5% and 9% after introduction of TiO\textsubscript{2} [11]. Interestingly, Al\textsubscript{2}O\textsubscript{3} or ZnO could lead to negative effect on the positive lightning breakdown voltages of MO under non-uniform field whereby the percentages of decrements are 12% and 3% [14]. Under the non-uniform field, the negative lightning breakdown voltage of MO could also further decrease by 4% with the introduction of SiO\textsubscript{2} non-uniform field [5]. In fact, most of the negative lightning breakdown voltages of MO decrease with introduction of either Al\textsubscript{2}O\textsubscript{3}, ZnO, TiO\textsubscript{2} or Fe\textsubscript{3}O\textsubscript{4} with percentages of decrements ranging between 13% and 35% [13, 14]. Nevertheless, the case is not the same for VO. The negative lightning breakdown voltages of RSO increases by 20% with the introduction of ZnO [12]. Currently, there are limited studies on the effect of nanoparticles without surfactants on the chop time and time to breakdown of dielectric insulating fluids especially VO. Current knowledge show that the chop time and time to breakdown of MO increase with the introduction of nanoparticles such as Fe\textsubscript{3}O\textsubscript{4}, TiO\textsubscript{2} and Al\textsubscript{2}O\textsubscript{3} respectively [6, 8, 13]. The instability of nanoparticles in fluids has become one the main challenges for practical applications in transformers [23]. The introduction of surfactants is one of the approaches that can be implemented to mitigate the stability issue [3, 4]. Surfactants are long organic molecules that can be dispersed in a fluid at low concentration. It has the ability to adsorb on the solid, change the surface activity, modify the physical properties, reduce surface energy of nanoparticles, improve the electrostatic and high steric stabilities which can prevent agglomeration, minimize aggregation and improve dispersion behaviour of nanoparticles in dielectric insulating fluids [3, 4, 24–26]. Ionic surfactant (anionic and cationic) and non-ionic surfactants are the 2 types of surfactants mainly used in previous studies [11, 15–22]. Cetyl trimethyl ammonium bromide (CTAB), and oleic acid (OA) have been extensively considered in dielectric insulating fluids application [11, 15–22]. The improvements of the positive lightning breakdown voltages of dielectric insulating fluids are quite consistent in the presence of both nanoparticles and surfactants. Under non-uniform field, the combination of TiO\textsubscript{2} and OA provides the highest improvement of the positive lightning breakdown voltage for MO with 39% as the percentage of increment [15]. The combination of either Fe\textsubscript{3}O\textsubscript{4}, SiO\textsubscript{2} or AIN with OA also show the positive effect on MO with the positive lightning breakdown voltage increments ranging from 5% to 37% [17–21]. Fe\textsubscript{3}O\textsubscript{4} works well with OA and VO whereby 37% improvement of positive lightning breakdown voltage is found for rapeseed oil (RO) [16]. The introduction of TiO\textsubscript{2} and CTAB however, only provide small improvement on the positive lightning breakdown voltages of PO and CO based TiO\textsubscript{2} nanofluids with percentage of improvements of 6% and 8% respectively [11]. The impact of both nanoparticles and surfactants on the negative lightning breakdown voltage improvements of dielectric insulating fluids is quite inconsistent under non-uniform field. For MO, both SiO\textsubscript{2} and OA cause 7% reduction of negative lightning breakdown, while the combination of TiO\textsubscript{2}, AIN and Fe\textsubscript{3}O\textsubscript{4} with OA leads to further reduction ranging between 19% and 36% [15, 17]. Positive effect of Fe\textsubscript{3}O\textsubscript{4} and OA is observed on the negative lightning breakdown voltage of RO with the increment of 12% [16]. The latest knowledge show that the presence of surfactants such as OA could lead to the increment chop time of MO based TiO\textsubscript{2} nanofluid under positive polarity while under negative polarity, it decreases [15]. Meanwhile, the time to breakdown of RO maintain increase under both polarities in the presence of Fe\textsubscript{3}O\textsubscript{4} and OA [16]. On the other hand, the streamer velocities of VO increase by 21% and 14% under both polarities with addition of Fe\textsubscript{3}O\textsubscript{4} and OA [22].

In order to provide alternative to natural ester (rapeseed based), several efforts have been carried out to examine other
types of VO such as PO and CO. These oils are native products for south east asian countries and its exploration for the high voltage application could be beneficial to the local industries. These oils have similar chemical characteristics as natural ester, which also posses the ability to hinder the acceleration of insulation paper ageing through its water scavenging and hydrolytic mechanisms [27, 28]. Palm oils have additional advantage in term of good oxidation stability owing to its balance composition of carbon number [29, 30]. Most of the studies on lightning breakdown voltage of the dielectric insulating nanofluids are without surfactants. Since surfactants are one of the common materials used to maintain the suspension of nanoparticles in oils, it is important to examine its effect on the breakdown voltages, streamer velocities and times to breakdown for Refined, Bleached and Deodorized Palm Oil (RBDPO) and CO under different polarities. Limited information can be obtained on these parameters especially under non-uniform field.

The main contribution of the paper is to examine the effect of surfactants on the enhancement of lightning breakdown voltages for RBDPO and CO by Al$_2$O$_3$ under the non-uniform field. The nanoparticle tested is Al$_2$O$_3$ based on consideration in prior similar study, which can give the highest improvement on AC breakdown voltages of RBDPO and CO based nanofluids [31]. In total, 3 different types of surfactants have been examined which are cationic surfactant (CTAB), anionic surfactant (Sodium Dodecyl Sulfate (SDS)) and non-ionic surfactant (OA).

2. Materials and methods

2.1. Materials under test

Two samples of RBDPO Olein were examined in this study. In addition, virgin CO was also investigated. The RBDPO and CO were obtained from readily available oil food grade products in the market. The fatty acid composition and vitamin E/A of RBDPO and CO can be seen in table 1. The compositions of the fatty acids for all RBDPO and CO were determined by gas chromatography (GC) as per ISO 5508:1990 [32]. It is shown that both of the RBDPO consist mainly of oleic acid (mono-unsaturated) followed by palmitic acid (saturated) and linoleic acid (poly-unsaturated). CO is dominated by lauric and myristic acids (saturated). RBDPOA contains both vitamin A and E, while RBDPOB has only the vitamin E.

First, the oil samples were filtered 3 times by a membrane filter with a pore size of 0.2 µm. Next, the oil samples were dried in an air circulating oven at 85 °C for 48 h before tested for basic physiochemical and dielectric properties. The basic physiochemical and dielectric properties for both RBDPO are quite similar as shown in table 2. Among all the samples tested, CO has the highest dielectric dissipation factor and relative permittivity. The type of nanoparticle used in this study was insulative nanoparticle, Al$_2$O$_3$ whereby its properties can be seen in table 3. CTAB, SDS and OA were used as surfactants to attain suspension stability against sedimentation of Al$_2$O$_3$ in the oils. The appearance colour and form of CTAB and SDS are white and solid, while OA is liquid and colourless as shown in table 4. CTAB has the highest melting and flash points followed by SDS and OA.

2.2. Preparation of nanofluids

The synthesis procedure of RBDPO and CO based Al$_2$O$_3$ nanofluids were divided into 2 parts. The first part of the synthesis procedure for RBDPO and CO based Al$_2$O$_3$ nanofluids was carried out without surfactants as shown in figure 1. The RBDPO and CO were first individually dispersed with Al$_2$O$_3$, using a Fisher Scientific isostemp heated magnetic stirrer for 30 min at 800 rpm. Next, these nanofluids were dried in an air circulating oven for 2 d at 85 °C before tested for lightning breakdown voltage.

The second part of synthesis procedure was carried out with surfactants. First, a magnetic stirrer was used to suspend the surfactants, CTAB, SDS and OA individually into the respective oils for 30 min as shown in figure 2. The ratio of the surfactants to Al$_2$O$_3$ was set to 30% from the volume concentration of Al$_2$O$_3$ which equivalent to 1:2 ratio. The ratio was chosen to be optimum based on the previous study in [34]. Next, the Al$_2$O$_3$ was individually added into either RBDPO or CO of which the stirring time was kept for 30 min. In order to reduce the agglomeration time of nanofluids and surfactants, the sonication process was carried out based on TEFIC ultrasonic homogenizer–Model TF-650Y for 1 h. Next, these oils were dried for 48 h at 85 °C in an air circulating oven before tested for lightning breakdown voltage. The volume percentage concentrations of Al$_2$O$_3$ used in this study were 0.001%, 0.025%, 0.035% and 0.05%.
Table 1. Fatty acid composition and vitamin E/A content of all samples.

| Types of Fats | RBDPOA | RBDPOB | CO |
|---------------|---------|---------|----|
|               | GC (%)  | MD (g)  | GC (%)  | MD (g)  |
| Saturated     |         |         |         |         |
| C12: Lauric   | 0.3     | 0.3     | 48.6    | 20.0    |
| C14: Myristic | 1.1     | 0.9     | 39.3    | 9.5     |
| C16: Palmitic | 37.7    | 43.0    | 4.2     | 3.2     |
| C18: Stearic  | 48.6    | 20.0    | 3.2     | 3.2     |
| Mono-unsaturated |     |         |         |         |
| C18: Oleic    | 3.9     | 43.0    | 4.2     | 3.2     |
| Poly-unsaturated |     |         |         |         |
| C18: Linoleic | 48.6    | 20.0    | 3.2     | 3.2     |
| Vitamin E     | -       | 75 m    | -       | -       |
| Vitamin A     | -       | -       | -       | -       |

* GC = Gas Chromatography, MD = Manufacturer’s Datasheet

Table 2. Basic physiochemical and electrical properties of RBDPO and CO.

| Properties                      | RBDPOA | RBDPOB | CO   |
|---------------------------------|--------|--------|------|
| Viscosity @ 40 °C, cSt         | 40.56  | 40.67  | 26.96|
| Density @ 20 °C, g cm⁻³         | 0.914  | 0.915  | 0.924|
| Acidity, mg KOH g⁻¹             | 0.001  | 0.002  | 0.009|
| Dissipation factor @ 90 °C      | 0.046  | 0.037  | 0.996|
| Relative permittivity @ 90 °C   | 2.86   | 2.82   | 3.03 |

Table 3. Basic physiochemical and electrical properties of Al₂O₃ nanoparticle [33].

| Properties          | Al₂O₃  |
|---------------------|--------|
| Size (nm)           | 40     |
| Appearance colour   | White  |
| Shape               | Spherical |
| Density (g cm⁻³)    | 3.96   |
| Relative permittivity | 9.9     |
| Electrical conductivity (S m⁻¹) | 1 x 10⁻¹² |
| Thermal conductivity (W m⁻¹ K) | 30      |
| Relaxation time (s) | 42.2   |

Table 4. Basic physiochemical properties of CTAB, SDS and OA surfactants [29].

| Properties          | CTAB  | SDS  | OA   |
|---------------------|-------|------|------|
| Description         | Cationic | Anionic | Non-ionic |
| Form                | Solid  | Solid | Liquid  |
| Colour              | White  | White | Colourless |
| Melting point (°C)  | 248–251| 204  | 13–14 |
| Flash point (°C)    | 244   | 170  | >113 |
| Flammability        | Not flammable | Flammable | Not flammable |

2.3. Nanofluids characterization

The characterization of the samples was carried by Fourier transform infrared (FTIR) spectra and size distribution using Thermo Scientific Nicolet 6700 FT-IR spectrometer. The transmission mode for FTIR measurement was carried out in the range between 400 and 4000 cm⁻¹. The samples were scanned in an inert atmosphere whereby attenuated total reflection (ATR) was chosen as the sampling approach. The resolution and number of scan were set to 4 and 32 respectively. The transmittance spectra were then normalized. The size distribution of Al₂O₃ in RBDPO and CO was measured by Malvern Zetasizer Nano S laser particle size analyzer based on dynamic light scattering instrument.

2.4. Lightning breakdown voltage

The lightning breakdown voltage measurement was carried out according to IEC 60 897 [35]. The test configurations for lightning breakdown voltage under non-uniform field can be seen in figure 3. Non-uniform field configuration is normally carried out by point-sphere configurations to represent an event where a discharge is initiated by an apparent defect or imperfection in transformers [36, 37]. The oils were filled into a 300 ml transparent Perspex cylindrical test cell with a copper needle and sphere electrodes configuration as shown in figure 4. The diameters of the needle tip and sphere electrodes were 12.7 mm and 50 μm respectively. The gap distance between needle and sphere was set to 25 mm. A 3-stage T ERCO impulse generator was configured in order to generate standard lightning impulse voltage of 1.2/50 μs with a maximum voltage of 420 kV. All tests were performed under both positive and negative polarities.

In this study, rising-voltage method was used of which the initial voltage was set at 50 kV for positive polarity and 100 kV for negative polarity. The step voltage was set to 10 kV. For
each set of testing, the applied voltage was increased gradually from a pre-determined initial voltage until breakdown. Next, the applied voltage was reduced to 0 kV whereby the time interval between each breakdown was set between 10 and 15 min. The process was repeated at an increasing rate of one shot per step. In total, 10 lightning breakdown voltages measurement for each of the oils were recorded and the average value was taken for the analysis.

3. Results

3.1. Nanofluids characterization

3.1.1. FTIR spectroscopy. FTIR spectroscopy can be used to determine the chemical properties of compound and identify the surface bonding condition and absorbance between Al₂O₃ and surfactants [38, 39]. The FTIR spectra of RBDPO and CO at 0.05% of Al₂O₃ with and without surfactants can be seen in figure 5. For all samples, the analysis indicated absorption peaks at 415 cm⁻¹, 460 cm⁻¹, 583 cm⁻¹ and 721 cm⁻¹ which corresponds to Al–O–Al vibration related to metal oxide bands. A strong band is found at 721 cm⁻¹ which corresponds to the symmetrical stretching vibration of Al–O–Al [40]. The absorption peaks at 1460 cm⁻¹ and 1710 cm⁻¹ suggest the presence of O–H bending vibrations. The absorption peaks at 2850 cm⁻¹ and 3005 cm⁻¹ indicate the presence of asymmetric –CH₂ and symmetric –CH₃ bonds. Since there is no observable shift in RBDPO and CO symmetrical stretching vibration after addition of CTAB, SDS or OA, it can be concluded that the surfactant molecule does not affect the chemical structural characteristics of Al₂O₃ nanofluids. There are apparent variable intensities of peaks are found in the FTIR spectra of RBDPOA and RBPDOB. With CTAB, an intense peak at 721 cm⁻¹ (red line) is observed for RBDPOA based Al₂O₃ nanofluid as shown in figure 5(a). The peak intensity which usually scales to the dipole moment and bond density is the indication of relative abundance or concentration [41]. Hence, it can be concluded that apparent symmetric stretching bonds of Al₂O₃ with CTAB exist in RBDPOA based on the finding in figure 5(a). It is not the case for RBDPOB whereby apparent reductions of peaks at 721 cm⁻¹ (red, blue and green lines) are found as surfactants are added which indicate low concentration of symmetric stretching bonds of Al₂O₃ as shown in figure 5(b). For CO, the shapes of the FTIR spectra for all samples are quite similar with no apparent broadening of the peaks as shown in figure 5(c). A slight symmetric stretching bond of Al₂O₃ with CTAB is observed
Figure 6. Particle size distribution of (a) RBDPOA, (b) RBDPOB and (c) CO based Al$_2$O$_3$ nanofluids.

Figure 7. Lightning breakdown voltages of RBDPO and CO based Al$_2$O$_3$ nanofluids without surfactants under (a) positive (b) negative polarities.

peak attributed to the stretching vibration of C = O and O–H groups (from carboxylic acid) should be visible at absorption peak of 1714 cm$^{-1}$ and within 2500 cm$^{-1}$ to 3300 cm$^{-1}$ regions, respectively, for OA. However, the peaks of all surfactants could not be identified due to its overlapping with the C = O and O–H stretching vibration of carboxylic acid group in RBDPO and CO.

3.1.2. Particle size distribution. The particle size distributions of Al$_2$O$_3$ in RBDPO and CO with and without surfactants are shown in figure 6. For RBDPOA, only CTAB exhibits smaller particle size distribution as compared to other surfactants. On the other hand, SDS and OA tend to promote higher agglomeration of Al$_2$O$_3$ in RBDPOA in comparison with CTAB at different size distributions (peak at 471.5 d nm and 456.6 d nm) as shown in figure 6(a). The presence of CTAB leads to a narrow size distribution of RBDPOA based...
Al₂O₃ nanofluid, which indicates small number of Al₂O₃ agglomeration. It is in line with the FTIR analysis that indicates high intensity/concentration of Al₂O₃ in RBDPOA with CTAB. It appears that both hydrophobic hydrocarbon tail and charged head of CTAB surfactant play a major role in the absorption of CTAB on Al₂O₃ surfaces. The hydrocarbon tail of C16 for CTAB is longer than the C12 for SDS. Due to this factor, it is anticipated that the covalent bonding between CTAB and Al₂O₃ will be promoted and at the same time lead to the reduction of the agglomeration [42]. No apparent pattern of the particle size distribution of RBDPO based Al₂O₃ nanofluid with and without surfactants as shown in figure 6(b). With OA, RBDPOB has the smallest particle size distribution of Al₂O₃. The particle size distributions of Al₂O₃ in RBDPOB for CTAB and SDS are almost similar. It is observed that the presence of CTAB or SDS in RBDPOB has no apparent effect on the agglomeration of Al₂O₃ in comparison as compared to without surfactants. Apparent deviations on the particle size distributions of Al₂O₃ in CO are observed as the surfactants are introduced shown in figure 6(c). Both CTAB and OA exhibit 2 ranges of particle size distribution of Al₂O₃ in CO. The first ranges are close to CO without surfactants whereby for CTAB, it is between 146 d nm and 170.1 d nm while for OA, it is between 146 d nm and 138.5 d nm. The second ranges for CTAB and OA are at higher particle size distributions, which signify agglomeration of Al₂O₃ in CO. A narrow particle size distribution of Al₂O₃ in CO could only be observed with SDS, which indicates small number of Al₂O₃ agglomeration in comparison with other surfactants. It is possibly due the hydrogen bonding between SDS (through one or two of the three sulfate oxygens) and Al₂O₃, which causes the reduction of agglomeration in CO [42].

3.2. Lightning breakdown voltage

3.2.1. RBDPO and CO based Al₂O₃ nanofluids without surfactant. Without surfactants, the introduction of Al₂O₃ increases the positive lightning breakdown voltages of the RBDPO and CO as shown in figure 7(a). The highest percentage of increment for positive lightning breakdown voltage of RBDPOA is 15% at 0.05% of Al₂O₃. At 0.035% of Al₂O₃, the positive lightning breakdown voltages of RBDPOB and CO increase by 23% and 13% respectively.

Similar as positive polarity, the highest increments of negative lightning breakdown voltages for RBDPOA due to the Al₂O₃ for RBDPOA is lower than RBDPOB and CO as shown in figure 7(b). The highest percentage increment of negative lightning breakdown voltage for RBDPOB is 9% at 0.035% of Al₂O₃. RBDPOB and CO experience the highest improvements of negative lightning breakdown voltages at 0.001% of Al₂O₃ with 24% and 14% increments respectively.

Without surfactants, RBDPOA and RBDPOB have higher times to breakdown than CO under positive polarity at most of the volume concentrations of Al₂O₃ as shown in figure 8. The pattern is slightly different for negative polarity as shown in figure 8. CO has higher time to breakdown as compared to RBDPOA and RBDPOB at most of the volume concentrations of Al₂O₃.

Figure 8. Time to breakdown of RBDPO and CO based Al₂O₃ nanofluids without surfactants.

The streamer velocity was calculated based on the gap distance between needle-sphere electrode, \(d\) and the average time to breakdown, \(t\) based on equation (1) [13]. Without surfactants, the average positive streamer velocities for both RBDPO are in the range between 1.37 km s\(^{-1}\) and 1.57 km s\(^{-1}\) while for CO, it is in the range between 1.53 km s\(^{-1}\) and 1.62 km s\(^{-1}\) at all volume concentrations of Al₂O₃ as shown in figure 9. The streamer velocities for both RBDPO vary between 0.95 km s\(^{-1}\) and 1.07 km s\(^{-1}\) while for CO, the range is between 0.87 km s\(^{-1}\) and 0.94 km s\(^{-1}\).

\[ v = \frac{d}{t}. \]  

(1)

3.2.2. RBDPO and CO based Al₂O₃ nanofluids with CTAB. With CTAB, the increment patterns of the positive lightning breakdown voltages for RBDPO and CO at all volume
concentrations of Al₂O₃ are almost similar as without surfactants as shown in figure 10(a). The presence of CTAB in RBDPOA and CO leads to higher improvements of positive lightning breakdown voltages than without surfactants and the highest percentages of increments are 21% and 19% at 0.001% and 0.035% of Al₂O₃. However, the introduction of CTAB in RBDPOB causes lower improvement of positive lightning breakdown voltages than without surfactants and the highest percentage of increment is 16% at 0.025% of Al₂O₃. Under negative polarity, the pattern of the lightning breakdown voltages improvements of RBDPO and CO are the same as under positive polarity once the CTAB is introduced. RBDPOA and CO still experience higher improvements of negative lightning breakdown voltages than without surfactants whereby the highest percentages of increments are 17% and 20% at 0.001% and 0.025% of Al₂O₃ as shown in figure 10(b). Similarly, RBDPOB still has lower improvement of negative breakdown voltage than without surfactants and the highest percentage of increment is 15% at 0.025% of Al₂O₃.

With CTAB, the patterns of times to breakdown for RBDPOA and CO under positive polarity is the same as without surfactants. The time to breakdown for RBDPOA under positive polarity maintain the highest followed by RBDPOB and CO at most of the volume concentrations of Al₂O₃ as shown in figure 11. The pattern of times to breakdown for RBDPO and CO under negative polarity is slightly different than without surfactants. The time to breakdown for CO still maintain the highest followed by the RBDPOA and RBDPOB at most of the volume concentrations of Al₂O₃.

There is an effect of CTAB on the average streamer velocities of RBDPO and CO as the volume concentration of Al₂O₃ is increased as seen in figure 12. As compared to without surfactants, the introduction of CTAB causes the decrement of the average positive average streamer velocities for RBDPO to a range between 1.32 km s⁻¹ and 1.49 km s⁻¹ while for CO, it is between 1.5 km s⁻¹ and 1.55 km s⁻¹ at all volume concentrations of Al₂O₃. Meanwhile, the CTAB leads to the increment of average negative streamer velocities for RBDPO.
to a range between 0.96 km s\(^{-1}\) and 1.23 km s\(^{-1}\) while for CO, it is between 0.84 km s\(^{-1}\) and 0.89 km s\(^{-1}\).}

### 3.2.3. RBDPO and CO based Al\(_2\)O\(_3\) nanofluids with SDS

The introduction of SDS has no significant impact on the further improvement of positive lightning breakdown voltages for both RBDPO based on Al\(_2\)O\(_3\) nanofluids as compared to without surfactants. With SDS, the improvements of positive lightning breakdown voltages for RBDPOA and RBDPOB are lower than without surfactants and the highest percentage of increments are 10% and 11% at 0.025% and 0.05% of Al\(_2\)O\(_3\) as shown in figure 13(a). In contrast, the improvement of the positive lightning breakdown voltage for CO is higher than without surfactants whereby the highest percentage of increment is 18% at 0.025% of Al\(_2\)O\(_3\).

SDS does not further improve the negative lightning breakdown voltage of RBDPO and CO as shown in figure 13(b). As compared to without surfactants, the improvement of the negative lightning breakdown voltage is quite low with the highest percentages of increments for RBDPOA, RBDPOB and CO are 7%, 16% and 12% at 0.05%, 0.05% and 0.001% of Al\(_2\)O\(_3\), respectively.

With SDS, the times to breakdown for RBDPOA and RBDPOB are quite close to CO at most of the volume concentration as shown in figure 14. As compared to without surfactants, the SDS leads to slight changes on the patterns of times to breakdown for RBDPO and CO under negative polarity. The time to breakdown for for CO remains the highest at most of volume concentrations of Al\(_2\)O\(_3\). Meanwhile the times to breakdown for RBDPOA and RBDPOB remain close to each other at most of the volume concentrations of Al\(_2\)O\(_3\).

As compared to without surfactants, SDS leads to the decrements of the average positive streamer velocities of RBDPO and CO as shown in figure 15. The range for RBDPO is between 1.41 km s\(^{-1}\) and 1.52 km s\(^{-1}\) while for CO, it is between 1.5 km s\(^{-1}\) and 1.56 km s\(^{-1}\). Similar pattern is observed for the average negative streamer velocity of CO whereby the range is between 0.83 km s\(^{-1}\) and 0.9 km s\(^{-1}\). However, the range of negative average streamer velocity
for RBDPO increases slightly higher than without surfactants whereby the range is between 0.97 km s$^{-1}$ and 1.13 km s$^{-1}$.

3.2.4. RBDPO and CO based Al$_2$O$_3$ nanofluids with OA.

Similar as SDS, OA has no significant effect on the further improvement of positive lightning breakdown voltages of RBDPO. As compared to without surfactants, the improvements of positive lightning breakdown voltages for RBDPOA and RBDPOB are quite low and the highest percentage of increments are 14% and 14% at 0.001% and 0.025% of Al$_2$O$_3$, as shown in figure 16(a). However, OA leads to further improvement of positive lightning breakdown voltage for CO as compared to without surfactants and the highest percentage of increment is is 18% at 0.05% of Al$_2$O$_3$.

OA has no apparent effect on the further increment of negative lightning breakdown voltages of RBDPO and CO as shown in figure 16(b). The improvements of lightning breakdown voltage of RBDPOA, RBDPOB and CO are lower than without surfactants and the highest percentages of increments are 9%, 13% and 10% at 0.025%, 0.001% and 0.001% of Al$_2$O$_3$.

With OA, the times to breakdown for RBDPOA and RBDPOB maintain quite close to CO under positive polarity at most of the volume concentrations of Al$_2$O$_3$ as shown in figure 17. Under negative polarity, the patterns of times to breakdown for RBDPO and CO are similar to without surfactants as OA is introduced at most of volume concentrations of Al$_2$O$_3$.

OA leads to the increment of the average positive streamer velocities of RBDPO and CO as compared to without surfactants as shown in figure 18. The range for RBDPO is between 1.45 km s$^{-1}$ and 1.53 km s$^{-1}$ while for CO, it is between 1.52 km s$^{-1}$ and 1.63 km s$^{-1}$. Similar pattern is observed for the average negative streamer velocity of RBDPO and CO. The range for RBDPO is between 0.94 km s$^{-1}$ and 1.23 km s$^{-1}$ while for CO, it is between 0.84 km s$^{-1}$ and 0.9 km s$^{-1}$. 

Figure 16. Lightning breakdown voltages of RBDPO and CO based Al$_2$O$_3$ nanofluids with OA under (a) positive (b) negative polarities.

Figure 17. Time to breakdown of RBDPO and CO based Al$_2$O$_3$ nanofluids with OA.

Figure 18. Streamer velocity of RBDPO and CO based Al$_2$O$_3$ nanofluids with OA under.
4. Discussion

Based on the study, it is shown that Al\textsubscript{2}O\textsubscript{3} could improve the performance of lightning breakdown voltages of RBDPO and CO under both positive and negative polarities as shown in tables 5 and 6. Without surfactant and under positive polarity, the highest increments of lightning breakdown voltages for RBDPOA, RBDPOB and CO are 15%, 23% and 13%. Under negative polarity, in total, 9%, 24% and 14% highest increments of lightning breakdown voltages are recorded for RBDPOA, RBDPOB and CO under negative polarity. The presence of nanoparticles leads to the changes on the space charge distribution in the oils which affect the mobility of electrons [13]. With the application of positive lightning impulse voltage, ionization occurs in the oils of which electrons are generated [13]. These high mobility electrons are captured by nanoparticles whereby slow negative ions and negatively charge nanoparticles are left in the region [13, 43]. As a result, superposition spatial electric fields are present which reduce the distortion of the external applied electric field [13, 43]. The discharge is therefore suppressed whereby higher applied positive lightning impulse voltage is required to cause breakdowns in nanofluids [13, 43]. According to [33, 44], the Al\textsubscript{2}O\textsubscript{3} has a large relaxation time which hinder its ability to capture electrons at the time scale of streamer propagation. However according to [13], once the samples are exposed to external electric field, the free charges will not have enough time to accumulate at the surface of the Al\textsubscript{2}O\textsubscript{3}. By contrast, the charges produced by the polarization will change the surface potential distribution of the Al\textsubscript{2}O\textsubscript{3}. Thus, the polarization of Al\textsubscript{2}O\textsubscript{3} is created by the polarization charges instead of free charges [13]. These polarized Al\textsubscript{2}O\textsubscript{3} will also produce potential wells that are required for trapping electrons. As the negative lightning impulse voltage is applied, accumulation of positive ions and negatively charged nanoparticles occurs at the needle tip which weakens the nearby electric field [13, 21, 45, 46]. Due to this phenomenon, higher voltage is required to strengthen the electric field and promote streamer propagations in order to cause the breakdowns [13, 45]. However, the increments of lightning breakdown voltages for RBDPOA, RBDPOB and CO from positive to negative polarities are not apparent with the introduction of nanoparticles as shown in tables 5 and 6. It is possibly due to viscosity effect which affects the mobility of the electrons in vegetable oils [16, 47]. Previous study in [4] has shown that the viscosity could influence the dielectric breakdown voltage, heat transfer and thermal conductivity of dielectric insulating fluids [4]. According to [4, 48], the viscosity of the base fluids could affect the Brownian motion of nanoparticles and in turn influences the breakdown voltage and thermal conductivity of nanofluids [4, 48]. It is suspected that the mobility of negatively charged nanoparticles in vegetable oils are restricted whereby it could not accumulate close to needle tip to cause the distortion of the electric field same as previous studies on MO under negative lightning impulse voltage [21, 46].

The effect of different types of surfactants on the lightning breakdown voltages is still unclear based on the current findings. Generally, the presence of surfactants can reduce the surface tension of the base oils and increases the immersion of nanoparticles by uniformly distribute nanoparticles in oils which in turn caused majority of the fast electrons to be converted into slow negatively charged particles [4, 11]. The presence of CTAB does provide the highest improvement of lightning breakdown voltage for RBDPOA based Al\textsubscript{2}O\textsubscript{3} nanofluid with 21% and 17% increments for positive and negative polarities for as shown in tables 5 and 6. The introduction of the surfactants does not help with further enhancement of the lightning breakdown voltage of RBDPOB based Al\textsubscript{2}O\textsubscript{3} nanofluid as compared to without surfactants for both polarities. For CO based Al\textsubscript{2}O\textsubscript{3} nanofluid, the presence of any of the surfactants does provide higher improvement of lightning breakdown voltages of RBDPO and CO Al\textsubscript{2}O\textsubscript{3} based nanofluids under positive polarity.

### Table 5. Percentages of increment or decrement for lightning breakdown voltages of RBDPO and CO Al\textsubscript{2}O\textsubscript{3} based nanofluids under positive polarity.

| Samples | Volume of concentration (%) | Without surfactant | With surfactants |
|---------|----------------------------|-------------------|-----------------|
|          |                            | CTAB             | SDS             | OA               |
| RBDPOA  | 0.001                      | +12.6            | +21.1           | +6.7            | +13.5           |
|         | 0.025                      | +12.7            | +15.4           | +9.8            | +7.3            |
|         | 0.035                      | +12.9            | +14.6           | +6.9            | +11             |
|         | 0.05                       | +15.4            | +11.9           | +8.3            | +10.6           |
|         | 0.001                      | +20.8            | +15.5           | +3.7            | +10.8           |
| RBDPOB  | 0.025                      | +10.2            | +16             | +4.5            | +14.3           |
|         | 0.035                      | +23.2            | +12.5           | +7.2            | +10.4           |
|         | 0.05                       | +9.5             | +14.2           | +10.7           | +9.6            |
| CO      | 0.025                      | +9.7             | +10.7           | +16.8           | +14.9           |
|         | 0.035                      | +10.3            | +16.9           | +17.5           | +9.4            |
|         | 0.05                       | +12.5            | +19             | +15             | +10.6           |
|         |                            | +8               | +15.8           | +13.4           | +18.1           |

*The percentage was calculated based on breakdown voltage values of base oil: ‘+’ increment and ‘-’ decrement.

### Table 6. Percentages of increment or decrement for lightning breakdown voltages of RBDPO and CO Al\textsubscript{2}O\textsubscript{3} based nanofluids under negative polarity.

| Samples | Volume of concentration (%) | Without surfactant | With surfactants |
|---------|----------------------------|-------------------|-----------------|
|          |                            | CTAB             | SDS             | OA               |
| RBDPOA  | 0.001                      | +8.3             | +17             | +2.7            | +5.7            |
|         | 0.025                      | +4.2             | +12             | +4.3            | +9.2            |
|         | 0.035                      | +9.1             | +10.5           | +5.7            | +5.7            |
|         | 0.05                       | +8.2             | +12.2           | +7.2            | +8.7            |
| RBDPOB  | 0.025                      | +15.2            | +14.7           | +9.5            | +11.2           |
|         | 0.035                      | +23              | +7.7            | +6              | +7.4            |
|         | 0.05                       | +14.1            | +9.5            | +15.8           | +9.8            |
|         | 0.001                      | +13.6            | +13.4           | +12.2           | +9.6            |
| CO      | 0.025                      | +8.3             | +19.6           | +2.9            | +8.8            |
|         | 0.035                      | +9.8             | +11.8           | +10.1           | +9              |
|         | 0.05                       | +3.5             | +12.5           | +10.9           | +6.2            |

*The percentage was calculated based on breakdown voltage values of base oil: ‘+’ increment and ‘-’ decrement.
voltage than without surfactants. CTAB provides the highest improvement of the lightning breakdown voltage of CO based Al₂O₃ nanofluid with 19% and 20% enhancements for both positive and negative polarities.

For freshly prepared nanofluids, both electrostatic and hydrophobic interactions between the surfactants molecule and nanoparticles surface contribute to the stability of the samples. A stable nanofluid is obtained once the electrical double layer repulsive force surpasses the Van der Waals attractive force which prevent the clustering of the nanoparticles [4, 49]. For example, the negatively charged head of SDS could change the surface charges of Al₂O₃ and form repulsion forces among the nanoparticles. As a result, the agglomeration of nanoparticles could be reduced by the act of the repulsion forces and lead to the improvements of the lightning breakdown voltages [50]. As compared to the electrostatic interaction of the head group charges in SDS, the hydrophobic interaction of the CTAB tail is more prominent in its adsorption on the Al₂O₃ surface. The CTAB absorbed on the surface of Al₂O₃ stabilizes the overall charge neutrality, thus forming an electrical double layer to create the mutual repulsion and provides dispersion stability [51]. Subsequently, the aggregation of Al₂O₃ particles are formed. This phenomenon mainly contributes to the apparent symmetric stretching bonds of Al₂O₃ with CTAB in RBDPOA based on the FTIR and particle size distribution analyses in figures 5(a) and 6(a). On the other hand, the weak electrostatic attraction between the OA and Al₂O₃ is the one of the reason for the low adsorption as compared to CTAB [52]. OA contains no ionic charges in its head whereby the layer formed by the OA surface prevents the Al₂O₃ head groups to satisfy its hydrogen bonds capabilities. The loss of hydrogen bonds weakens the attractive attraction of the OA and Al₂O₃ surfaces [53]. However, with a passage of time or under external electrical stress, the depletion of the electrostatic attraction could causes the decrement in the electrical double layer, which leads to the reduction of the surface charge [54]. This could lead to the decrement of the physical stability of the nanofluids after some time. For CO based Al₂O₃ nanofluid, it appears that CTAB is more effective in producing a stable nanofluid compared to SDS and OA. The predominance of hydrophobic interactions over electrostatic interactions is found to occur based on the findings of the lightning breakdown voltages. Even though, the particle size distribution analysis of Al₂O₃ in CO as shown in figure 6(c) indicates that SDS could reduce the agglomeration, it is believed that the dominancy of the hydrophobic tail of CTAB contributes to the overall suspension stability. The longer hydrophobic tail of CTAB (C16) possess a larger hydrodynamic radius than SDS (C12), which could increase the suspension of Al₂O₃ particles in CO [55]. In addition, it is also shown that there is a slight symmetric stretching bond of Al₂O₃ with CTAB in CO based on FTIR analysis as seen in figure 5(c).

Previous study have shown that the the introduction of either nanoparticles and surfactants lead to inconsistent findings on the times to breakdown and average streamer velocities of nanofluids [5, 13, 18, 21, 56]. One study has shown the increment of either positive or negative lightning breakdown voltages of MO in the presence of Fe₃O₄ and SiO₂ results in increment of times to breakdown and decrement of average streamer velocities [5, 13, 21]. The introduction of OA in MO based Fe₃O₄ nanofluid also shows the similar findings [18]. Other study has shown that the introduction of positive impulse breakdown voltage of MO based Fe₃O₄ under uniform field results in decrement of times to breakdown [56]. Similar pattern is observed for RBDPO and CO whereby the introduction of Al₂O₃ leads to the increment of times to breakdown under both polarities as shown in tables 7 and 8.

The introduction of CTAB lead to the further increment of the times to breakdown for RBDPOA at most of the volume concentration of Al₂O₃. On the other hand, both CTAB and

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**Table 7.** Percentages of increment or decrement for time to breakdown of RBDPO and CO Al₂O₃ based nanofluids under positive polarity.

| Samples | Volume of concentration (%) | Without surfactant | With surfactants |
|---------|-----------------------------|-------------------|-----------------|
|         |                             | CTAB             | SDS             | OA               |
| RBDPOA  | 0.001                       | +15.1 +12.0 +5.7 | +4.4            |
|         | 0.025                       | +12.0 +19.5 +5.0 | +5              |
|         | 0.035                       | +13.8 +6.9 +5.7 | +7.5            |
|         | 0.05                        | +12.6 +13.8 +11.3 | +2.5         |
|         | 0.001                       | +12.0 +10.1 +4.4 | +2.5            |
| RBDPOB  | 0.025                       | +7.6 +7.6 +3.1 | +6.3            |
|         | 0.035                       | 0 +13.2 +3.1 | +8.8            |
|         | 0.05                        | +12.6 +5.7 +11.3 | +8.2          |
|         | 0.001                       | 0 +4.6 +3.9 | +6.5            |
| CO      | 0.025                       | +4.6 +8.4 +8.4 | +1.9            |
|         | 0.035                       | +4.6 +8.4 +8.4 | −0.6            |
|         | 0.05                        | +5.8 +5.2 +3.9 | +1.3            |

*the percentage was calculated based on time to breakdown values of based oil ‘+’: increment and ‘−’: decrement

**Table 8.** Percentages of increment or decrement for time to breakdown of RBDPO and CO Al₂O₃ based nanofluids under negative polarity.

| Samples | Volume of concentration (%) | Without surfactant | With surfactants |
|---------|-----------------------------|-------------------|-----------------|
|         |                             | CTAB             | SDS             | OA               |
| RBDPOA  | 0.001                       | +2.6 +13.7 +8.4 | −10.1           |
|         | 0.025                       | +8.3 +15 +2.2 | −4              |
|         | 0.035                       | +2.6 +11.9 +0 | +4.4            |
|         | 0.05                        | +7.1 +5.7 +13.7 | +10.6          |
|         | 0.001                       | −6.4 −18.1 −10.8 | −8.8          |
| RBDPOB  | 0.025                       | +1.2 −12.9 −6 | −1.6            |
|         | 0.035                       | +6 +0.8 −7.2 | −1.2            |
|         | 0.05                        | −3.2 −0.4 +1.2 | +7.2            |
|         | 0.001                       | +13.2 +23.8 +21.3 | +26          |
| CO      | 0.025                       | +21.7 +20 +18.7 | +20.4           |
|         | 0.035                       | +21.7 +27.2 +25.1 | +21.7         |
|         | 0.05                        | +16.6 +24.7 +28.5 | +17.9          |

*the percentage was calculated based on time to breakdown values of based oil ‘+’: increment and ‘−’: decrement
SDS cause further increment of times to breakdown for CO at most of the volume concentration of Al2O3. For RBDPOB, the increment of times to breakdown is not consistent with the introduction of Al2O3 under both polarities. It is found that the time to breakdown of RBDPOB could remain unchanged as 0.035% of Al2O3 is introduced under positive polarity as shown in table 7. Under negative polarity, the time to breakdown of RBDPOB could further decrease as 0.001% of Al2O3 is added as seen in table 8. The introduction of surfactants in RBDPOB based Al2O3 nanofluid does not further affect the increment of the times to breakdown for RBDPOB under positive polarity as shown in table 7. Meanwhile, under negative polarity, the times to breakdown RBDPOB further decrease at most of the volume concentration of Al2O3 as shown in table 8. Under both polarities, the average streamer velocities of RBDPOA and CO shows the same consistent pattern whereby its decrease as the Al2O3 is introduced. CTAB leads to further decrement of average streamer velocities for RBDPOA at most of the volume concentration of Al2O3 as shown in tables 9 and 10. The introduction of CTAB and SDS further decrease the average streamer velocities of CO at most of the volume concentration of Al2O3 under positive polarity as shown in table 9. Under negative polarity, all surfactants contribute to further decrement of the average streamer velocities of CO at most of the volume concentration of Al2O3 as seen in table 10. Under both polarities, the decrement of average streamer velocities of RBDPOB is inconsistent as the Al2O3 is introduced. Under positive polarity, the average streamer velocity of RBDPOB remain unchanged as 0.001% of Al2O3 is added as shown in table 9. The average streamer velocity of RBDPOB could increase as 0.001% and 0.05% of Al2O3 are added under negative polarity as seen in table 10. Under positive polarity, the average streamer velocities of RBDPOB based Al2O3 nanofluid does not further decrease with the introduction of surfactants as shown in table 9. Meanwhile, the average streamer velocities of RBDPOB further increase at most of the volume concentration of Al2O3 as shown in table 10. The average negative streamer velocity of CO is lower than that of RBDPO based Al2O3 nanofluids either with or without CTAB, SDS and OA. Under positive lightning breakdown voltage, the highest streamer velocities for base RBDPO and CO are around 1.57 km s\(^{-1}\) and 1.62 km s\(^{-1}\). As the Al2O3 is introduced, the highest positive average streamer velocities for RBDPOB, RBDPOB and CO decrease to 1.4 km s\(^{-1}\), 1.57 km s\(^{-1}\) and 1.62 km s\(^{-1}\). As compared to without surfactants, the introduction of CTAB further decreases the highest positive average streamer velocities of RBDPOB and CO based Al2O3 nanofluids to 1.49 km s\(^{-1}\) and 1.55 km s\(^{-1}\) while for RBDPOB based Al2O3 nanofluid, it increases to 1.47 km s\(^{-1}\). Similarly, in the presence of SDS, the highest positive average streamer velocities of RBDPOB and CO based Al2O3 nanofluids decreases to 1.52 km s\(^{-1}\) and 1.56 km s\(^{-1}\) while for RBDPOB based Al2O3 nanofluid, it increases to 1.5 km s\(^{-1}\). OA could lead the increment of the highest positive average streamer velocities for RBDPOB based Al2O3 nanofluid to 1.53 km s\(^{-1}\) while for RBDPOB and CO based Al2O3 nanofluids, its value remain at 1.53 km s\(^{-1}\) and 1.63 km s\(^{-1}\). On the other hand, the highest negative average streamer velocities for base RBDPOA, RBDPOB and CO are 1.1 km s\(^{-1}\), 1 km s\(^{-1}\) and 1.06 km s\(^{-1}\). The introduction of either Al2O3 or surfactants has inconsistent effect on the highest negative average streamer velocities of RBDPO. Once the Al2O3 is added, the highest negative average streamer velocity for RBDPOA and RBDPOB based Al2O3 nanofluid slightly decrease to 1.07 km s\(^{-1}\). As compared to without surfactants, the highest negative average streamer velocities for RBDPOB based Al2O3 nanofluid increase to 1.23 km s\(^{-1}\), 1.13 km s\(^{-1}\) and 1.1 km s\(^{-1}\) as the CTAB, SDS and OA are introduced. On the other hand, only CTAB lead to the decrement of the highest negative average streamer velocity of RBDPOA with a value of 1.04 km s\(^{-1}\). The highest negative average streamer velocities of RBDPOA increase to 1.1 km s\(^{-1}\) and 1.23 km s\(^{-1}\) in the presence of SDS and OA. Meanwhile, the highest negative average streamer velocity for CO decrease to 0.94 km s\(^{-1}\) as the Al2O3 is introduced. With the introduction of CTAB, SDS and OA, the highest negative average streamer velocities further decrease to 0.89 km s\(^{-1}\), 0.9 km s\(^{-1}\) and 0.9 km s\(^{-1}\). Regardless with and without surfactants, it is found that for both RBDPO and CO based Al2O3 nanofluids are classified as second mode streamer whereby the range of average positive and negative streamer velocities are between 1 km s\(^{-1}\) and 1.6 km s\(^{-1}\) [40, 41].

The differences on the patterns of lightning breakdown voltage increments between RBDPOA and RBDPOB based Al2O3 nanofluids are believed to be contributed by the presence of vitamin E since the fatty acids compositions of these oils are quite similar. As shown in table 1, RBDPOB has higher vitamin E than RBDPOA. In general, it is the repulsive forces between the head groups of surfactants that cause the aggregation which lead to the suspension of nanoparticles in the nanofluids [57]. However, according to [58], the addition of vitamin E could facilitate the aggregation process of the surfactants itself. This is likely due to the hydrophobic interaction.

| Samples | Volume of concentration (%) | Percentage increment or decrement (%) |
|---------|-----------------------------|----------------------------------------|
|         | Without surfactant | CTAB | SDS | OA |
| RBDPOA  | 0.001 | −13.1 | −10.7 | −5.4 | −4.2 |
|         | 0.025 | −10.7 | −16.3 | −4.8 | −4.8 |
|         | 0.035 | −12.2 | −6.5 | −5.4 | −7.0 |
|         | 0.05  | −11.2 | −12.2 | −10.2 | −2.5 |
|         | 0.001 | −10.7 | −9.1 | −4.2 | −2.5 |
| RBDPOB  | 0.025 | −7.0  | −7.0  | −3.0  | −5.9 |
|         | 0.035 | 0     | −11.7 | −3.0  | −8.1 |
|         | 0.05  | −11.2 | −5.4  | −10.2 | −7.6 |
|         | 0.001 | 0     | −4.3  | −3.8  | −6.1 |
| CO      | 0.025 | −4.3  | −7.8  | −7.8  | −1.9 |
|         | 0.035 | −4.3  | −7.8  | −7.8  | +0.7 |
|         | 0.05  | −5.5  | −4.9  | −3.8  | −1.3 |

*The percentage was calculated based on streamer velocity values of based oil without surfactants.

\[\text{Increment} = \frac{V_{\text{With surfactant}} - V_{\text{Without surfactant}}}{V_{\text{Without surfactant}}} \times 100\%\]

\[\text{Decrement} = \frac{V_{\text{With surfactant}} - V_{\text{Without surfactant}}}{V_{\text{With surfactant}}} \times 100\%\]
of α-tocopherol molecules in vitamin E with the alkyl chain of the surfactants. In other words, the presence of vitamin E causes the electrical double layer between surfactants and nanoparticles to decrease and further to the decrement of the electrostatic interaction between the materials [57]. Thus, instead of getting adsorb to the Al$_2$O$_3$ surface, the surfactants form an aggregation with the vitamin E molecules. Previous study in [58] showed that the particle size distribution could increase due to the aggregation of vitamin E with the CTAB molecules. Thus, it can be concluded that in the presence of both vitamin E and surfactants i.e. CTAB, the Al$_2$O$_3$ particles tend to agglomerate by itself which could be the possible reason for the inconsistent patterns of the lightning breakdown voltage increments of RBDPOB based Al$_2$O$_3$ nanofluid in comparison with RBDPOA based Al$_2$O$_3$ nanofluid. Nevertheless, further systematic study can be carried out in the future to validate the effect vitamin E on the other types of nanofluids. On the other hand, there is no apparent effect of vitamin A on the lightning breakdown and streamer properties of RBDPOA.

### 5. Conclusions

This study examines the effect of surfactants on the lightning breakdown voltage of RBDPO and CO based Al$_2$O$_3$ nanofluids. FTIR analysis reveals clear symmetric stretching bond of Al$_2$O$_3$ with CTAB for RBDPOA. This phenomenon is not apparent in RBDPOB. Meanwhile, weak chemical interaction or surface bonding of Al$_2$O$_3$ with surfactants i.e. SDS and OA is found for CO. The particle size distribution analysis of RBDPOA shows consistent finding as FTIR whereby the introduction of CTAB promotes lower agglomeration of Al$_2$O$_3$ in comparison with other surfactants. However, the pattern is slightly different for RBDPOB of which the introduction of OA leads to the lower agglomeration Al$_2$O$_3$ in comparison with other surfactants. On the other hand, SDS promotes lower agglomeration of Al$_2$O$_3$ in comparison with other surfactants. Generally, the positive and negative lightning breakdown voltages of RBDPOA, RBDPOB and CO could improve with Al$_2$O$_3$. The percentage of improvement of lightning breakdown voltages of RBDPOA, RBDPOB and CO are almost the same for both positive and negative polaritiss. The introduction of CTAB could further improve the positive and negative lightning breakdown voltages of RBDPOA and CO at most of the volume concentration of Al$_2$O$_3$. In addition, SDS and OA could also promote further improvement of the lightning breakdown voltage of CO at certain volume concentration of Al$_2$O$_3$. However, the presence of surfactants do not promote further improvement of lightning breakdown voltage for RBDPOB. CTAB is identified as the suitable surfactants that could provide improvement on the lightning breakdown voltages of RBDPOA and CO based Al$_2$O$_3$ nanofluids. Al$_2$O$_3$ leads to the increment of times to breakdown and decrement of average streamer velocities of RBDPOA and CO under both polarities. The introduction of CTAB further increase the times to breakdown and decrease the average streamer velocities for RBDPOA at most of the volume concentration of Al$_2$O$_3$. Under positive polarity, both CTAB and SDS cause further increment of times to breakdown and decrement of average streamer velocities for CO at most of the volume concentration of Al$_2$O$_3$. All surfactants increases the times to breakdown and it cause further decrement of the negative average streamer velocities of CO at most of the volume concentration of Al$_2$O$_3$. The streamer velocities and times to breakdown patterns of RBDPOB are inconsistent either in the presence of Al$_2$O$_3$ or surfactants. Regardless with and without surfactants, it is found that RBDPO and CO based Al$_2$O$_3$ nanofluids still exhibit second mode streamer whereby positive streamer velocities are higher than negative streamer velocities.

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