Dielectric Sensing (Capacitive) On Cooking Oil's TPC Level

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***Abstract*— Total Polar Compound (TPC) is a chemical parameter, which reflects the deterioration of the high temperature of cooking oil. The repeated use of cooking oil at high temperatures results in the generation of undesirable substances, which may cause health problems. This project designed a sensor based on capacitive (dielectric sensing) using interdigitated electrode (IDE) to detect the TPC level of cooking oil obtained from the experiment to measure the electrical properties and matched it to the TPC level of the oil samples. A total of 15 samples of 150 ml palm oil was heated up to 15 hours. The expected result determined the levels of TPC in cooking oils obtained from the experiments and showed its relationship to the capacitance of the samples. The dielectric properties of oil samples were investigated in the frequency range of 0.1-10 kHz. The stability and the sensitivity of the result were measured in terms of frequency with the linearly increased capacitance as the oil samples were heated. The results analysis of significant correlation between the electrical capacitance of the oil sample with TPC against heated time with R2 ranged from 0.805 to 0.852.**

***Index Terms*— Capacitive sensing; IDE; Oil; TPC.**

I. INTRODUCTION

Frying is one of the earliest and most popular ways of cooking. It is the process, in which food is submerged into the hot oil or fat at elevated temperatures (150–190℃). In most cases, frying oil degradation is evaluated based on visual inspection, for instance chefs make decision when to discard oil based on factors, such as excessive foaming, odor, smoking and color changes or by tasting the food products. However, these are not reliable methods due to their subjective nature and these parameters may manifest only when the oil has already become unsafe to be reused. These tests are extensively used; however, they are not decisive in themselves.

Color, for example, basically depends on the sort of food fried as well as the oil used, while taste and odor depend on the food type used for frying. The amount of smoke emitted from frying oil is related to the temperature as well as to the amount of low molecular weight breakdown in the oil. Presently, interdigitated electrodes (IDEs) are applied in many sensing devices including surface acoustic wave, chemical sensors, and MEMS biosensors. IDE could be used in solving complex calibration requirements and improving the accuracy of sensory sensitivity.

Further, the IDE shape has some advantages, such as no moving parts, ease of fabrication, flexible in design, and cost effective. In this study, a capacitive sensor was designed using IDE platform to assess frying oil degradation due to heating at different frequencies. The aims of this study were to develop and evaluate a new sensor for determining the degradation of frying oil by measuring the changes of its electrical properties.

Figure 1: Sample of sensor design

A. *Previous Studies*

A number of researchers [3]-[19] reported the growing needs of an analysis on repeated used of frying oil. The method in sensing the changes of the TPC level and the sensitivity are some of the criteria.

Takeoka et al. [1] showed that previous research tend to focus on the effect of heating on frying oils based on the characteristics and chemical composition. The repetitive usage of cooking generates several unwanted substances, which can cause health problems. Hydrolysis, polymerization and thermal oxidation are numerous chemical processes occurred during frying. These outcomes are due to the presence of water produced during the frying of the food, high temperature and oxygen that leads to the breakdown of the food, which badly affect the flavor and color of the fried food.

The observed effects range from weight loss, growth suppression, increased liver and kidney weight to cellular damage of the liver, thymus, epidydimides, and testes are happening when the highly oxidized and heated oils are fed to laboratory animals [2].

Mostly in homes, restaurants, cafeterias and food service, the time they consider to change the frying oil is when the oil emits too much smoke, turns into greased texture, becomes dark in color and has strong odor. Nevertheless, all of these changes are obvious when the oil is totally unusable.

There are some analysis [3]-[5] that state that there are a lot of instruments and kits that can be used to determine oil degradation, such as Vibro Viscometer, Testo 270 and Ebro FOM 310. However, it is constrained by the limitations of the current devices, such as the suitability for different type of oil and complex calibration. The sensing method is based on interdigitated electrode (IDE). The variables of the sensor include the electrodes number N, electrode width w, electrode spaces, and the electrode length L, with dimension of 41, 100 lm, 60 lm, and 8 mm, respectively. Every other electrode finger is electrically connected together through a common electrode arm.

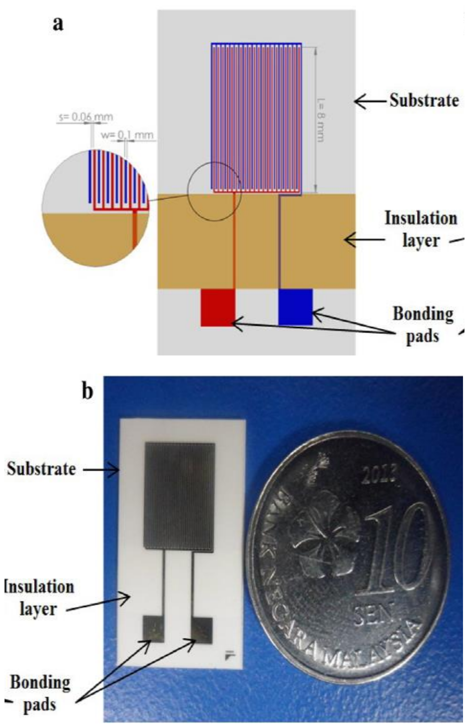

Figure 2: (a) Illustration of capacitance sensor probe, (b) Prototype of the device [3]

Perez et al.'s view that oil quality monitoring techniques are observed in real time to minimize the downtime, reduce maintenance costs and protect important industry assets. Lubricants impedance monitoring is an important tool to detect the state of the oil. The sensor is dedicated to monitor changes on the impedance of the sensing electrodes at high frequencies. The circuit provides an output voltage related to the dissipation factor. Therefore, it provides an indication of the oil condition as the dissipation factor tends to increase with the increasing presence of contaminants in lubrication oil. The proposed sensor shows three important characteristics: It is a very low cost design, it can be custom calibrated for a specific lubricant and it provides effective detection oil quality [6].

In contrast to other researches, Markus et al. [7] presents dielectric sensors for determining soil and snow moisture. Dielectric methods are good for a precise measurement. For soil sensor (Electromagnetic Moisture), all of the developments are based on the determination of the dielectric properties of the material, which are largely affected by the moisture due to the high dielectric permittivity of water. The measurements were evaluated and the results were presented such as the soil moisture (SM) profiling method via access tubes with LUMBRICUS, which uses Frequency Domain (FD) Technique that uses capacitance to measure the dielectric permittivity of a surrounding medium and operates at a single measurement frequency.

Referring to all the previous work studied in Table 1 [3]-[9], this research focuses on increasing the sensitivity of the IDE sensor by using TAGUCHI method. Then, the most sensitive design is fabricated, tested and compared using TESTO to get the relation between impedance and TPC's level.

II. Materials And Methods

A. Taguchi Method

Taguchi method or robust design is a statistical method designed to enhance the fundamental function and performance of productivity. Noise factor has been taken into consideration in this design to maximize the improvement.

In this experiment, there are a few factors affect or influence the dielectric sensing sensitivity. The control factors that affect in this design are listed below:

- Electrode width
- Electrode length
- Spacing between electrode
- Frequency supplied

Based on theTaguchi method analyzed, the parameters of the interdigitated electrode are given below:

- Electrode width – 0.5mm
- Electrode length – 13mm
- Spacing between electrode – 0.5mm
- No. of teeth electrode – 30
- Frequency supplied – 0.1- 10 kHz

B. Capacitive sensor design

The capacitive sensor was designed based on the interdigitated electrodes (IDE) as shown in Figure 1. The sensor design was first drawn by using COMSOL software, before the photomask of the probe was formed on PCB. The variables of the sensor are the number of the electrodes N, width of the electrode w, electrode space s, and the length of the electrode L, with the dimension of 41, 0.5 mm, 0.26 m, and 14 mm, respectively. Every other electrode finger is connected electrically together through a common electrode arm. These dimensions have been experimented based on the maximum fabrication capability. It is carried out through the requirements to detect the changes in the quality of the frying oil. The equation of the electrical capacitance is given by:

$$C = \frac{\varepsilon_o \varepsilon_r A}{s.N - 1} \quad (1)$$

Table 1
Comparative review of previous studies

Ref	Method	Parameters	Advantage	Disadvantage
[3]	Impedance Sensing Probe Design	• Impedance • cooking oil • interdigitated sensor • total polar compound	• Alternative method for measuring oil quality	• At high frequency all the impedance measurement values are overlapped
[6]	Real time oil quality monitoring	• oil quality • impedance spectroscopy • viscosity • dielectric • permittivity • lubrication oil • on-line monitoring	• provides an indication of the oil condition • low cost design, it can be custom calibrated for a specific lubricant	
[7]	Dielectric Methods	• Electromagnetic • Dielectrics • Time Domain Reflectometry • Frequency Domain • soil moisture • Snow moisture.	• Use capacitance to measure the dielectric permittivity of a surrounding medium and operate at a single measurement frequency.	• for large scales • bulky
[8]	Capacitive Sensing Technique	• Crude palm oil • Capacitive sensing • Diesel contamination.	• low cost capacitive sensing • real-time monitoring • portability • fast response • high accuracy	• unstable reading
[4]	Capacitive Sensing Probe Design	• Capacitance sensor • Frying oil quality	• Good potential for simple and inexpensive way of determining frying oil quality	• Using LCR meter.

Where ε_0 is the permittivity of free space, which is equal to 8.854 pF/m, er is the relative dielectric constant of oil, which is equal to 2–4, s is the electrode space and measured by (mm), and N is the number of electrodes. The designed from COMSOL is then converted to CorelDraw to ease the fabrication process. The design from CorelDraw is as shown below:

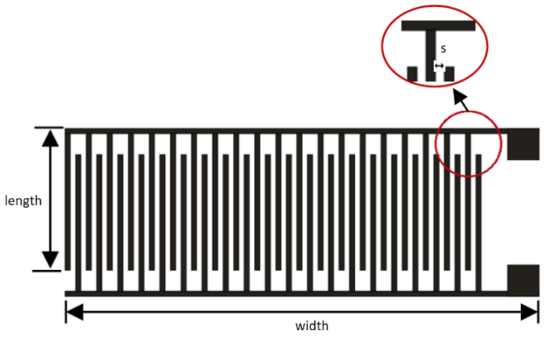

Figure 3: Design of interdigitated electrode

The materials used to construct the sensor were a standard copper of fabrication lab. The mechanism of this sensor is that once the oil oxidative and thermally breaks down during the frying, there will be a rise in the number of polar molecules, which directly increases the dielectric constant.

While an electric field is enforced across the faces of IDEs, the dipole and molecular charges in the testing of the frying oil are forced out from their equilibrium locations, and those dipole charges lay up through the electrodes of the detector. Consequently, as long as the frying oil yields polar molecules through different chemical reactions during frying, the more charges will lay up in the electrodes.

C. Sample preparation

Fresh oil was bought from a local market in Ayer Keroh, Melaka, Malaysia. Then the oil was divided into five samples, where each sample contained 150 ml. All samples were heated in a laboratory oven at the temperature of 150℃. The heated time of the samples was from 1 h up to 15 h, where one sample was taken out from the oven at every hour. After heating, all samples were kept at 40 ℃ to 45℃ for further analysis.

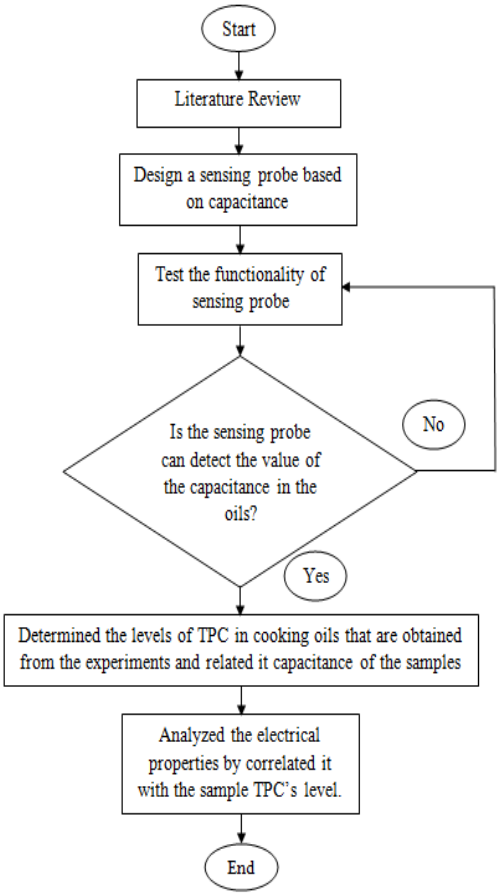

Figure 4: The flow chart of the designing sensor

D. *Electrical capacitance and TPC measurement*

The distinction among each heated oil sample was analyzed by measuring its electrical capacitance and TPC. The electrical capacitance was measured using the custom built IDE sensor immersed into the oil sample. The sensor was connected to a LCR meter with Kelvin clip leads depicted in Figure 4. The LCR meter has a frequency range from 100 Hz and to 100 kHz. Before doing the measurements using the LCR meter, calibration was performed following the standard procedure of the instrument operation manual.

Then, the calibration for the capacitance sensor was also conducted using distilled water. The equation used to calibrate sensor is as follows:

$$Z = \frac{s \cdot N - 1}{2\pi f \varepsilon_o \varepsilon_r A} \quad (2)$$

Where ε_r is the relative dielectric constant of distilled water in room temperature between 70-80℃, s is the electrode space and measured by (mm), N is the number of electrodes, A is the area of the sensor and *f* is the frequency used.

Then, the TPC of each heated sample was measured using a frying oil tester (Testo 270, InstruMartlnc, Germany). Before TPC measurement, the oil tester was calibrated using the reference oil supplied with the device, which has a TPC value of 6.5 ± 0.5%. The reference oil was heated to approximately 50°C for 10 min. Then, the oil tester was immersed in the reference oil and adjusted to get the reference value. After each testing, the IDE sensor and the oil tester probe was cleaned using soft tissues. All measurement were repeated three times.

Figure 5: Lab oven used to heat oil

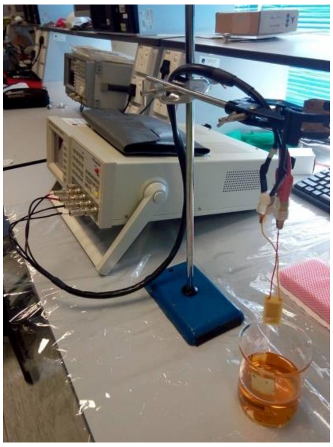

Figure 6: LCR meter connected to capacitance sensor

Figure 7: Oil samples for the experiment

Figure 5, 6 and 7 show the equipment and tools used to get the TPC's level of the oil heated up to 15 hours for each of the selected frequency. Oil that has been heated needs to be used to test at different frequency. New batch of oil samples were used to get an accurate and reliable results.

III. Result And Discussion

A. Relationship Between Capacitance Measurements And TPC Measurements

Figure 8, 9, and 10 and 11 show the results of the capacitance measurements to evaluate the deterioration of they frying oil quality. Three oil samples underwent the same method of experiment to determine its capacitance. For each frequency, new unheated oil samples were used to get accurate results.

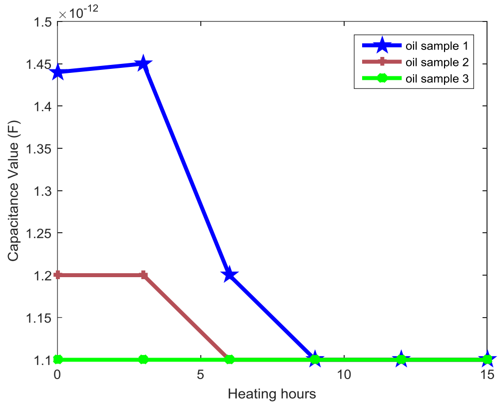

Figure 8: Graph of capacitance value of oil sample at frequency 100 Hz

Figure 8 shows a significance capacitance difference between the three samples, but the capacitance value for oil samples #3 is constant, even if it is heated up to 15 hours.

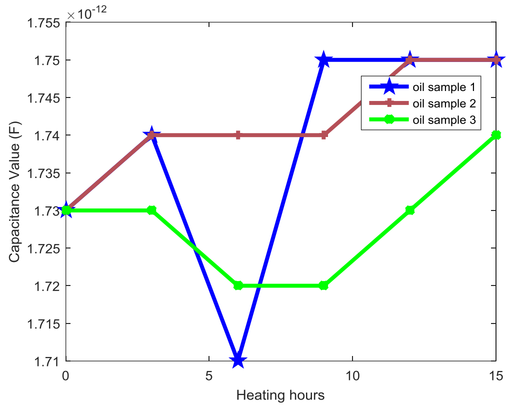

Figure 9: Graph of capacitance value of oil sample at frequency 1 kHz

In Figure 9, oil sample #2 results a stable capacitance value compared to other samples.

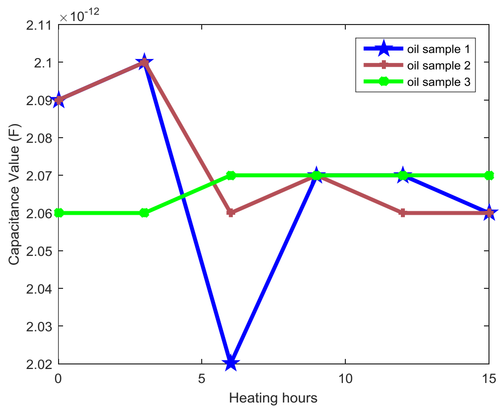

Figure 10: Graph of capacitance value of oil sample at frequency 10 kHz

While in Figure 10, oil sample #3 caused an opposite result than the other samples. As the frequency increases with heated oil, the capacitance results in an unstable reading.

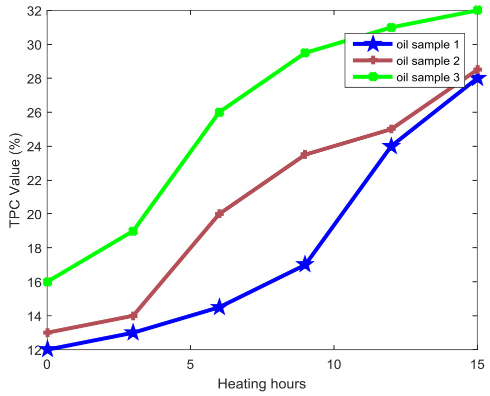

Figure 11: Graph of TPC value of oil samples at frequency 10 kHz

In terms of TPC level, oil samples #3 in Figure 11 shows the most affected samples as the hour spent for heating the oil increases. This shows that sample #3 is the least healthy oil to be used as cooking oil. The result also shows that the trend of measured capacitance by the IDE sensor followed the same trend of TPC measured using Testo 270, but it is not slightly the same. The value of capacitance should increase directly with the time of heating hours, like the TPC value. However, the fluctuation in the capacitance results might be caused by the changes in temperature of the oven during the conducted experiments, besides the ranges of the capacitance value, which were too small and might be too sensitive.

B. Statistical Analysis Result

Regression analysis was performed to evaluate the relationships between degradation indices of TPC with the capacitance of the heated oil samples. The adjusted R square value indicated the percentage of Y that is determined by X. The adjusted R square is 0.815 or equals to 81.5%. The adjusted R square for IDE sensor design indicates the result of TPC value and the capacitance of the reheating hour of oil samples is linearly related to more than 80%.

IV. Conclusion

The present study was designed to develop a custom built sensor to evaluate frying oil degradation. Electrical capacitive based on spectroscopy technique was adapted as an alternative method for measuring the oil degradation. The variations of capacitance measurements had significant correlation with the changes of TPC during the heating process in frying oil. The capacitance measured by sensor has shown significant correlation with TPC measured by commercially tester (Testo 270), where the coefficient correlation R2 is from 0.80 to 0.85. The capacitive sensing technique has good potential in developing a simple and inexpensive way of monitoring frying oil degradation. The drawback of this type of technique is the interferences by moisture since only a few of pF were observed as sensor response. Therefore, a more extensive research on this area is recommended.

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