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Analyzes the effect of temperature on characteristics of crude oil permittivity sensor based on Interdigital Capacitors (IDCs)

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Abstract. This study aims to analyze the effect of temperature on characteristics of crude oil permittivity sensor based on interdigital capacitors (IDCs), including linearity, repeatability and hysteresis. IDCs have been fabricated using the DC Magnetron Sputtering method in three designs with different electrode materials and the same electrode configuration. The electrode materials used silver (Ag), copper (Cu) and molybdenum (Mo) deposited on a FR-4 PCB substrate with a thickness of 1μm. The electrode configuration each design is 15 mm electrode length, 0.5 mm electrode width, 0.5 mm electrode distance and 40 electrodes number. The crude oil was tested at a temperature range of 30 - 70^{o}C. The measurement system uses a PM6303A automatic RCL Meter at a frequency of 1 kHz. The sensor linearity test results showed an increase in the sensitivity value of the IDCs Ag, Mo and Cu sensors when the temperature was more than 50^{o}C. The repeatability sensor test results showed that IDCs made from Ag had the highest measurement precision with a value of %repeatability is 2.5%. The hysteresis test results showed that the design IDCs made from Ag have high stability at high and low temperatures.

1. Introduction

Several studies on permittivity sensors have been carried out. Such as, permittivity sensor with automatic temperature compensation for measuring the alcohol content of alcohol-mixed fuel for use in automotive engines. Microwave SIW sensor based on PBG structure for measuring the permittivity of oil and other industrial liquid applications [1]. FDR (frequency domain reflectometry) sensors formed from two stainless steel parallel wave guides for the measurement of the complex dielectric permittivity of porous materials [2].

In this study will develop permittivity sensors for crude oil using interdigital capacitors (IDCs). IDCs sensor is shaped periodic electrode and printed on board. IDCs has been researched and developed because of low price and easily combined with sensing components [3], [4]. IDCs has been used since 1970 in many applications, such as measures the relative permittivity and the concentration of sugar in a sugar solution [5] and examines the dielectric properties of the fluid by using IDCs to measure the changes of capacitance [4], [6], [7]. Study on the effect of temperature on dielectric constant of material crude oil using IDCs has never been conducted by other researchers. This study is important because the temperature effect affects the dielectric constant of crude oil so that it will affect the heating process of crude oil [7], [8].

Crude oil is a liquid in underground geologic formation and remains liquid when brought to the surface after separation process at normal conditions. The important step in the processing of crude oil is the heating of crude oil [9], [10]. This process aims to eliminate vapor and reduce viscosity of crude oil. There are several physical properties that affect the heating process of crude oil, such as permittivity, conductivity, viscosity and electric field intensity [11].

Interdigital capacitors sensor is a good candidate for determination of crude oil permittivity as they provide an easy fabrication, low-cost, fast, non-destructive and straight forward adaptability to measurement systems. Analyzes the effect of temperature on the characteristics of crude oil permittivity sensor is needed to determine the accuracy of the sensor, by measuring linearity, repeatability and hysteresis [1]. This study is focused on measuring the sensor of crude oil permittivity in the frequency of 1 kHz.

2. Methodology

2.1. Fabrication of crude oil permittivity sensor

The crude oil permittivity sensor based on interdigital capacitors (IDCs) was fabricated by using DC magnetron sputtering in Thin Film Research Laboratory (TFR-L), Sakon Nakhon Rajabhat University (SNRU), Thailand. There are 3 designs of IDCs, different in electrode thin film material and same in electrode configurations. Each IDCs design consists of 40 electrodes, 15 mm electrode length, 0.5 mm electrode width and 0.5 mm electrode distance. Electrode materials used are silver (Ag), copper (Cu) and molybdenum (Mo). Each target is a cylindrical slab with a diameter of 60 mm and a thickness of 3 mm. The substrate is made of FR-4 PCB material with a thickness of 2 mm, which length and width are adjusted to the IDCs mask design [12].

Substrate of FR-4 PCB was cleaned by acetone, methanol and distilled water in ultrasonic cleaner, 20 minutes respectively, then was dried by air compressor. Finally, the mask was attached on the substrate and loaded on substrate holder in vacuum chamber, 6 cm above the target. The electrode thin film was deposited by using DC magnetron sputtering in high purity argon (99.99%) at vacuum state. The operating pressure was continuously monitored and controlled with the pressure gauge and the pressure control gate valve of the sputtering system. The base pressure and operating pressure used for the deposition of Ag thin film are 0.03 Pa and 1.2 Pa, Cu thin film are 0.8 Pa and 3 Pa and Mo thin film are 0.04 Pa and 3 Pa.

2.2. Measurement the characteristics of crude oil permittivity sensor

Measurement the characteristics of crude oil permittivity sensor to temperature changes include linearity, repeatability and hysteresis. Analyzes of the crude oil permittivity sensor characteristics is performed by graph analyzes and calculation analyzes. Calculation analyzes the value of hysteresis, accuracy, and repeatability use the following equation [10].

$$\text{True}_{out}=\text{Desired}_{out}\times\text{Actual}_{out} \quad (1)$$

$$\%\text{FSO}=\frac{\text{True}_{output}\text{-Actual}_{output}}{Y_{FSO}} \quad (2)$$

$$\%\text{Hysteresis}=\%\text{FSO}_{increase}-\%\text{FSO}_{decrease} \quad (3)$$

$$\%\text{Repeatability}=\frac{\text{Stand.deviasi}_{max}-\text{Stand.deviasi}_{min}}{\text{Fullscale}}\times 100\% \quad (4)$$

Where, FSO = output measurement range, YFSO = maximum output, $FSO_{increase}$ = FSO at temperatures increase and $FSO_{decrease}$ = FSO at temperature decrease.

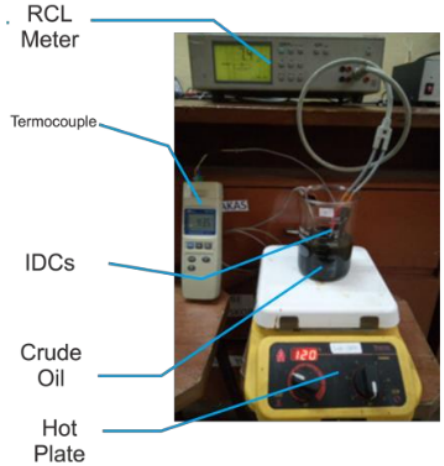

Figure 1. Measurement the permittivity of crude oil

The linearity of IDCs is tested by measuring the increasing temperature on a hot plate. The measurement range for the linearity test is 30 - 70°C with an increase in each measurement of 5°C. Thermocouple type K is used as a calibrator with a measurement range of 400°C.Data obtained from IDCs are capacitance data measured using an RCL meter. The crude oil capacitance data is measured by using IDCs sensor which is connected to the RCL meter then the crude oil permittivity value is calculated.

The repeatability of IDCs was tested by repeating the measurement of the effect of temperature increase on changes in the permittivity of crude oil in three times. The measurement range for repeatability tests is at temperatures 30 - 55°C.

The hysteresis testing of IDCs is carried out by measuring changes in the dielectric constant during heating and cooling. A hysteresis test is needed to determine the IDCs precision on the temperature response when the temperature is increased and decreased. The temperature measurement range for hysteresis tests from 30 - 55°C. Data acquisition of permittivity changes is every 5°C increase.

The crude oil permittivity is obtained from the change in the value of the crude oil capacitance detected by IDCs. The capacitance of crude oil was measured by-1 kHz frequency of PM 6303A RCL meter at temperature changes as shown in Fig. 1. IDCs was connected to RCL meter and inserted into beaker glass contained crude oil. Thermocouple K was inserted into crude oil to know its temperature and to heat the crude oil using by hot plate.

By using symmetry and ignoring capacitance at the tip of IDCs, the total capacitance of IDCS is calculated by the equation:

$$C_{TOTAL} = C_{uc}(N-1)L \tag{5}$$

C_{TOTAL} is the measured crude oil capacitance (F), C_{uc} is the unit cell capacitance (F), N is number of electrodes and L is the length of electrode (m). By using equation (5), the capacitance value of the unit cell (C_{uc}) can be obtained. Then, the relative permittivity can be known by the equation:

$$C_{uc} = \varepsilon_0 \frac{(\varepsilon_r + \varepsilon_s)}{2} \frac{K\left(\sqrt{1-k^2}\right)}{K(k)} + \varepsilon_0 \varepsilon_r \frac{t}{g} \tag{6}$$

So, the relative permittivity of crude oil is:

$$\varepsilon_r = \frac{2\frac{C_{uc}}{\varepsilon_0} - \varepsilon_s \frac{K\left(\sqrt{1-(k)^2}\right)}{K(k)}}{\frac{K\left(\sqrt{1-(k)^2}\right)}{K(k)} + 2\frac{t}{g}} \tag{7}$$

Where, ε_r is relative permittivity of crude oil, ε_s is relative permittivity of substrate, g is distance between electrodes (m), λ is length of unit cell (m), k is a simplification of $\frac{g}{2\lambda}$, t is electrode thickness (m) and K is complete elliptic integral of the first kind, where k is the modulus and $\sqrt{1-k^2}$ is a complementary modulus.

3. Result and Discussion

3.1. The linearity of crude oil permittivity sensor

The results of linearity measurements using the IDCs Ag thin film are shown in Figure 2, while for the IDCs Mo thin film and Cu thin film are shown in Figures 3 and 4.

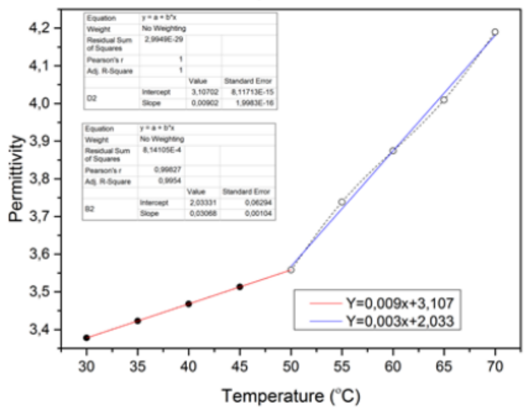

Figure 2. Linearity measurement result of crude oil permittivity to temperature by using IDCs Ag thin film.

The graph in Figure 2 shows that the permittivity increases when the temperature of crude oil increases. The straight line equation is obtained in the temperature range of 30 - 50°C, which is ε_r = 0.009T + 3.107. By differentiating the straight line equation, the IDCs sensitivity is $0.009 \pm 1.99 \times 10^{-16}$.

At temperatures above 50°C the permittivity of crude oil rises faster than in the temperature range of 30 - 50°C. The straight line equation is obtained in the temperature range of 50 - 70°C, which is ε_r = 0.003T + 2.033. By differentiating the straight line equation, the IDCs sensitivity is 0.003 ± 0.001. Further delving into the linear fittings revealed that sensor sensitivity at temperatures more than 50 degrees better when compared to temperatures less than 50 degrees (0.03 °C^{-1} and 0.009 °C^{-1}).

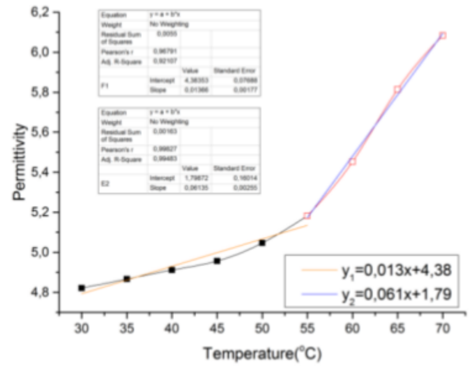

Figure 3. Linearity measurement result of crude oil permittivity to temperature by using IDCs Mo thin film.

The graph in Figure 3 shows shows that the permittivity increases when the temperature of crude oil increases. The straight line equation is obtained in the temperature range of 30 - 50°C, which is ε_r = 0.013T + 4.38. By differentiating the straight line equation, the IDCs sensitivity is 0.013 ± 0.001.

At temperatures above 55°C the permittivity of crude oil rises faster than in the temperature range of 30 - 50°C. The straight line equation is obtained in the temperature range 55 - 70°C, which is ε_r = 0.061T + 1.79. By differentiating the straight line, the IDCs sensitivity obtained is 0.061 ± 0.002.

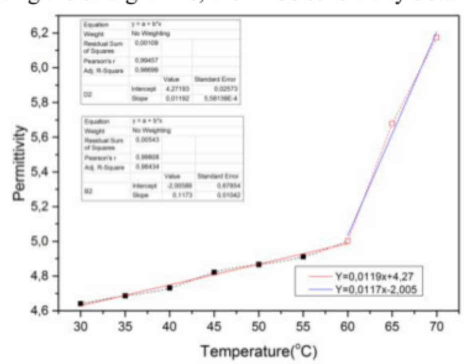

Figure 4. Linearity measurement result of crude oil permittivity to temperature by using IDCs Cu thin film.

The linearity measurement of IDCs Cu thin film is divided into 2 straight line, where IDCs Cu thin films have different sensitivity at temperatures 30 - 60°C and 60 - 70°C. This shows the different characteristics on the IDCs Cu thin film linearity measurement curve obtained. The straight line equation is obtained in the temperature range of 30 - 60°C, which is ε_r = 0.0119T + 4.27. The sensitivity of Cu thin film IDCs was obtained at 0.0119 ± 5.58×10^{-4}. Whereas at the temperature of crude oil greater than 60 ° C the straight line equation ε_r = 0.117T-2.005 was obtained. By using the straight line equation, the sensitivity of IDCs Cu thin film is 0.117 ± 0.01.

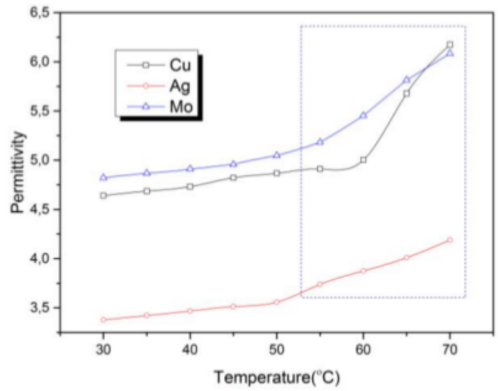

Figure 5. Comparison of linearity measurement result of IDCs Cu, Ag and Mo thin films.

Figure 5 shows that the comparison of IDCs permittivity measurement results with variations of electrode material to temperature changes. In the measurement range of 30 - 70°C IDCs Ag thin films have the lowest permittivity values compared to IDCs Cu and Mo thin films. The measurement results obtained that the IDCs Cu and Mo thin films have almost the same permittivity value. However, based on Figure 5, all three IDCs show the same path, where there is an increase in the sensor sensitivity value when the temperature is more than 50°C. The results obtained that at these temperature conditions, the greatest sensitivity obtained by IDCs Cu thin film is equal to 0.117. Hence, increasing the permittivity increases the sensitivity as more electric flux enters the chamber and the object under investigation.

3.2. The repeatability of crude oil permittivity sensor

The results of measuring the repeatability using IDCs Ag thin film can be seen in Figure 6. The graph in Figure 6 shows that IDCs Ag thin film is stable even though repeated measurements are made under different environmental conditions. The calculation of %repeatability of IDCs Ag thin film uses equation 4. The maximum standard deviation is 0.13, while the average standard deviation is 0.05. The maximum measurement range is 4.18975 then the repeatability of IDCs Ag thin film is

$$\%\text{Repeatability (IDCs Ag thin film)} = \frac{0.130232544 - 0.026046509}{4.18975} \times 100\% = 2.5\%$$

The results of the calculation of standard deviations and repeatability tests show that the precision of the data obtained is 0.025. It is means that if the IDCs measurement results show a value of 4.18975, then if the measurement is repeated, the readings will range from 4.16475 - 4.21475. From the data obtained and analysis of calculations that IDCs Ag thin film shows good stability and repeatability to the influence of temperature.

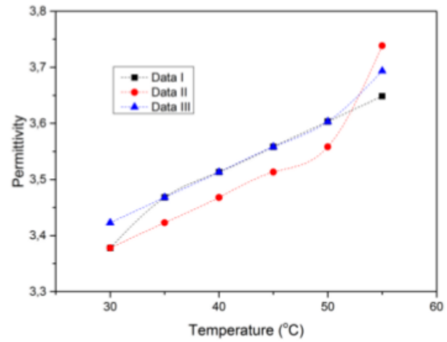

Figure 6. IDCs Ag thin film repeatability test results.

The results of measuring the repeatability using IDCs Mo thin film can be seen in Figure 7. The Calculation of %repeatability of IDCs Mo thin film uses equation 4. The maximum standard deviation is 0.68, while the average standard deviation is 0.22. The maximum measurement range data is 6.44545 then the repeatability of IDCs Mo thin film is

$$\%\text{Repeatability(IDCs Mo thin film)} = \frac{0.675704874 - 0.026046509}{6.44545} \times 100\% = 10{,}08\%$$

The calculation results of the standard deviation and the repeatability test it can be shown that the precision of the data obtained is 0.1008. It is means that if the IDCs measurement results show a value of 6.44545, then if the measurement is repeated, the reading will range from 6.3446 - 6.54625.

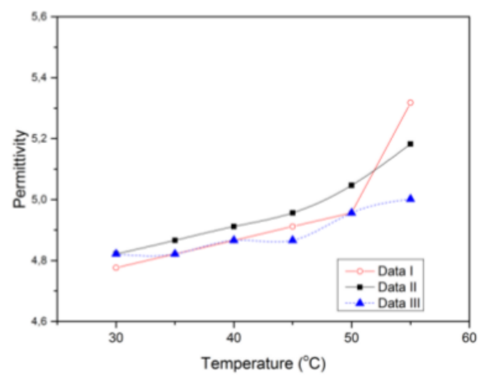

Figure 7. IDCs Mo thin film repeatability test results.

The repeatability test results of IDCs Cu thin film are shown in the graph in Figure 8. These results indicate that the data II and III have a curve which coincides with each other while in the data curve I do not coincide with the other curves. These results indicate that IDCs made from Cu have a low measurement precision. IDCs repeatability testing is equipped with standard deviation calculations. Calculation of standard deviation is intended to see the deviation of each data repeat.

The repetition of the measurement of the effect of temperature rise on the crude oil permittivity carried out 3 times, it was found that the largest standard deviation at 45°C. These results indicate that the precision of IDCs measurements is lowest at 45°C.

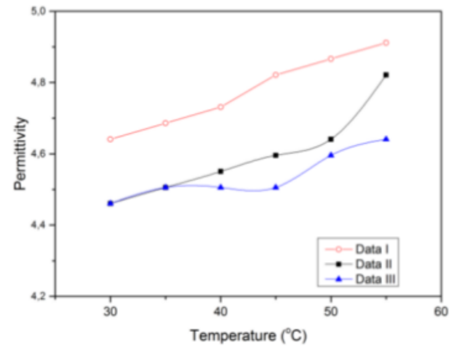

Figure 8. IDCs Cu thin film repeatability test results.

3.3. The hysteresis of crude oil permittivity sensor

The results of IDCs Ag thin film hysteresis testing are shown in the graph in Figure 9. Calculation of hysteresis value uses equation 3. An example of hysteresis value calculation is as follows:

- Based on observations, at a temperature of 40°C obtained ε_r heating = 3,513 and ε_r cooling = 3.467.
- True $_{output}$ at a temperature of 40°C is 3.4962, and YFSO = 3.648

From these data, the value of $\%FSO_{increase}$ and $\%FSO_{decrease}$ can be obtained.

$$\%\mathrm{FSO} = \frac{\mathrm{True_{output}} - \mathrm{Actual_{output}}}{\mathrm{Y_{FSO}}}$$

$\%FSO_{increase} = -0.4617$

$\%FSO_{decrease} = 0.7748$

Then the %hysteresis obtained at 40°C is -1.236 %FSO. The results of the %hysteresis calculation show that IDCs Ag thin film hysteresis occurs at 35°C, 45°C and 55°C and has the largest hysteresis error at 35°C and 40°C that is -1.2365. The %hysteresis value at 55°C is 1.2212E-13. The graph in Figure 9 shows the results of IDCs Ag thin film hysteresis testing. Whereas at the temperature of 45 - 55°C, the curves in the heating and cooling graph of crude oil coincide. These results indicate that IDCs Ag thin film has high stability at temperature range 30 - 55°C.

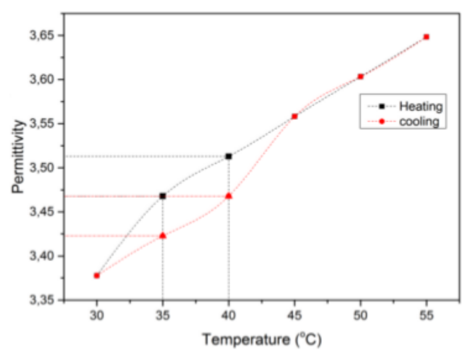

Figure 9. IDCs Ag thin film hysteresis test results

The results of the IDCs Mo thin film hysteresis test are shown in the graph in Figure 10. Hysteresis testing by increasing and decreasing the temperature of crude oil and then observing the crude oil permittivity value at each increase of 5°C. Using the same calculation method as IDCs Ag thin film, the %hysteresis IDCs Mo thin film calculation results are obtained. Figure 10 shows that there is a large hysteresis error at temperatures of 30 - 60°C, while at crude oil temperatures over 65°C, the curves are coincide. This result is confirmed by the results of the calculation of% hysteresis where the largest hysteresis error is at 30°C, 35°C, 40°C, 50°C that is 91.016. These results indicate that the IDCs Mo thin film has stability at crude oil temperatures over 65°C. Whereas, at temperatures lower than 65°C IDCs Mo thin film has low stability.

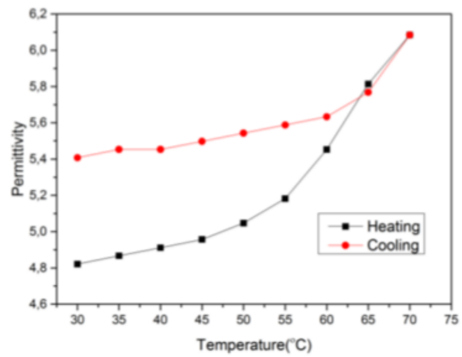

Figure 10. IDCs Mo thin film hysteresis test results.

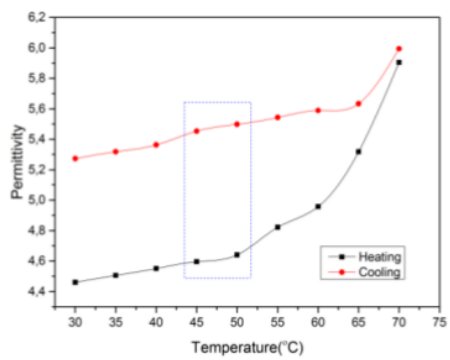

Figure 11. IDCs Cu thin film hysteresis test results.

Hysteresis testing is also performed on Cu thin film IDCs. Tests are carried out using the same procedure as IDCs with other types of materials, varying the temperature by raising and lowering the temperature of crude oil and then observing changes in the permittivity of crude oil. The observations are displayed in the graph in Figure 11. Figure 11 shows that the overall permittivity value when crude oil is heated has a lower value than when crude oil was cooled. Based on the curve shape on the graph, it shows that the trend is the same in both treatments. To get a more detailed analysis, a calculation is performed to obtain the hysteresis value at each observation temperature point. The largest hysteresis error is indicated by the largest% hysteresis is at temperature of 45°C and 50°C, with a% hysteresis value of 14.299% FSO. This result also shows that the higher the temperature, the more narrow the curve, where at temperatures greater than 65°C% the hysteresis obtained decreases. Based on observations, the greater the temperature of IDCs Cu thin film has an increasingly stable stability, but at lower temperatures the resulting hysteresis is higher.

By observing the hysteresis test which is one of the sensor characteristics testing methods, where observations are made with variations of IDCs material, namely Ag, Mo and Cu with the same IDCs configuration design. The results displayed in graphical form and calculations show that IDCs Ag has better stability compared to IDCs Mo and Cu. It is clearly seen that in the heating and cooling treatment of crude oil, IDCs Ag produces curves that coincide with each other while in the variation of Mo and Cu materials the resulting curves do not coincide or produce hysteresis errors. However, the Mo and Cu hysteresis curves show the same measurement trend, which has improved stability at temperatures greater than 65°C. This shows that the characteristics of Mo and Cu IDCs are more stable at temperatures over 65°C.

4. Conclusion

This study has analyzed the effect of temperature on characteristics of crude oil permittivity sensor based on interdigital capacitors (IDCs), including linearity, repeatability and hysteresis. There are three designs of IDCs difference on electrode material, namely Ag, Mo and Cu with the same electrode configurations. The linearity measurement of IDCs showed that in the measurement range of 30 - 70°C IDCs Ag thin films have the lowest permittivity values compared to IDCs Cu and Mo thin films. The repeatability analyze shows that IDCs Cu thin film has the lowest measurement precision than IDCs Ag and Mo thin films. It is clearly seen that in the heating and cooling treatment of crude oil, IDCs Ag thin film produces curves that coincide with each other while in the variation of Mo and Cu thin films the resulting curves do not coincide or produce hysteresis errors. Based on the analyze, it can be concluded that IDCs Ag thin film has better stability and accuracy compared to IDCs Mo and Cu thin films. The best design of IDCs is used to measure the permittivity of crude oil in heating process of crude oil by microwave. For future research directions it is necessary to analyze other need to do an analysis of the effect of thin film thickness on the performance of the sensor. Experimental results need to be compared with computer simulations to show optimization of sensor performance.

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