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DESIGN OF INTER-DIGITAL CAPACITOR SENSOR FOR THE MEASUREMENT OF PERMITTIVITY OF CRUDE OIL

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DESIGN OF INTER-DIGITAL CAPACITOR SENSOR FOR THE MEASUREMENT OF PERMITTIVITY OF CRUDE OIL

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ABSTRACT

The purpose of the research is to design and make an interdigital capacitor sensor (IDC) in order to pursue the measurements of permittivity of crude oil.

The scope of our research is to design and make an interdigital capacitor sensor, to perform the calibration of the sensor, to make the measurements of permittivity of the available crude oil samples, and to compare the obtained data with the ones available in the literature.

The sensor is fabricated in the ITS Instrumentation laboratory with the use of Printed Circuit Board (PCB) technology. It measures the capacity of fluid being under the investigation.

The capacitance measurements were performed using the PM 6303 A RCL meter at the frequency of 1 kHz. The IDC is directly connected to the instrument via test cable with Kelvin clips. The measurement were performed for one fixed frequency of 1 kHz at room temperature of 25 ℃ and humidity of the air of 84%.

The measurements of permittivity were performed for three samples of crude oil. As a result we obtained a reliable value of permittivity only for the sample one of crude oil. The result is as it follows: $20 \cdot 10^{-12}\ \frac{\mathrm{F}}{\mathrm{m}}$ with the total relative error of 8 percent. The table values of permittivity of crude oils are between $19{,}7 \cdot 10^{-12}\ \frac{\mathrm{F}}{\mathrm{m}}$ and $21{,}5 \cdot 10^{-12}\ \frac{\mathrm{F}}{\mathrm{m}}$ for the measurement performed at 1 kHz frequency [12] (depends on the sample). The permittivity obtained in this experiment fits in this brackets.

Since the sensor is capable of differentiate of various samples of crude oil and its cost of production is relatively low it could be put into a good use in the research of heating crude oil by microwave energy.

Keywords: crude oil, fabrication of interdigital capacitor sensor, error analysis, permittivity, IDC

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CHAPTER 1

INTRODUCTION

1.1. BACKGROUND

Crude oil is a naturally occurring petroleum in its unprocessed form. It contains thousands of different chemical compounds, but the vast majority of them are hydrocarbons. Its chemical structure can change as a response to heating treatment. Since the cost of the heating process is relatively low, the heating of crude oil is most influential technique in the production of crude oil.

The formation of emulsions during the extraction of crude oil is a serious problem and it is crucial to separate crude oil from the water before further processing. Since the research team from Malaysia [1] proved that microwave heating can significantly enhance the demulsification rate of crude oil the members of Crude Oil Research Team at Technological Institute Sepuluh Nopember Surabaya have been working on heating crude oil by microwave energy. The results of their work were presented in a publication [2].

My work is a continuation of their research. Since the dielectric parameters of crude oil depends on the composition of crude oil it is possible to compare different samples obtained from different sources of crude oil using the permittivity parameter. The interdigital capacitor sensor which I am working on would allow to establish the purity of crude oil by determining its permittivity.

The sensor is an inter-digital capacitor sensor designed on a printed circuit board (PCB) and it measures the capacity of fluid being under the investigation.

1.2. PURPOSE OF THE RESEARCH

The purpose of the research is to design and make an interdigital capacitor sensor in order to pursue the measurements of permittivity of crude oil. By the comparison of the obtained data during the experiment with the ones available in the literature we will be able to determine if the sensor made in our laboratory is a possible way of comparing different types of crude oil samples.

1.3. SCOPE OF THE RESEARCH

The scope of our research is as it follows:

- To design and make an interdigital capacitor sensor.
- To perform the calibration of the sensor.
- To make the measurements of permittivity of the available crude oil samples
- To compare the data obtained during the permittivity measurements with the ones available in the literature in order to determine if the sensor designed and made in our laboratory is a possible tool for determining the purity of crude oil samples.

CHAPTER 2

THEORY

2.1. CRUDE OIL

As it was said before crude oil is a naturally occurring petroleum in its unprocessed form. Petroleum hydrocarbons can be divided into three groups: alkanes, cycloalkanes and aromatic compounds. The nonhydrocarbon part are: sulfur and nitrogen compounds, porphyrins, oxygen compounds, asphaltenes, and trace metals [3].

Crude oil extraction consists of three phases:

- Primary recovery, when the natural mechanisms are used to force oil to surface,
- Seconday recovery, when the fluids are injected into reservoir in order to increase its drive,
- Enhanced recovery, among which the most common are thermally enhanced recovery methods like steam injection and fire flooding (where some of the oil is burned to heat the surrounding oil). In both cases the idea is to heat the oil in order to reduce its viscosity and thus make it easier to extract.

The emulsions which are created during the recovery process of crude oil need to be demusificated before further processing. Microwave heating of crude oil in drilling wells seems to be a possible way of doing so. The novel microwave heating technique has been presented by research group from Technological Institute Sepuluh Nopember Surabaya.

2.2. CAPACITIVE SENSORS

Capacitive sensors are widely used in our everyday life. For example relative humidity (RH) sensors are the capacitive sensors which use thin polymer layer in between two electrodes in order to measure relative humidity of the air. In this kind of sensors the polymer layer absorbs water from the air causing the change of the capacitance of the sensor.

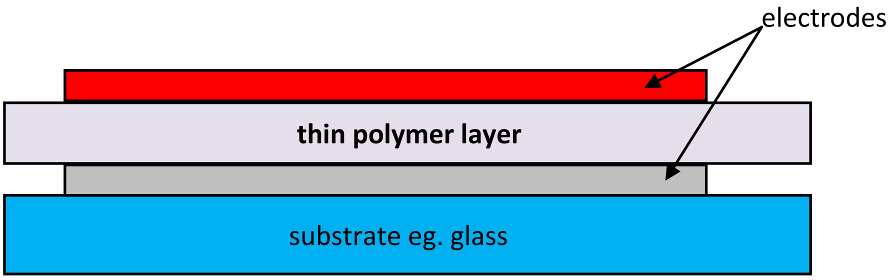

Figure 1.
Capacitive sensor of relative humidity

the electrodes (A):

$$C = \frac{\varepsilon\varepsilon_0 A}{L}, \qquad (1)$$

where:

ε_0 – dielectric constant in the free space (in $\left[\frac{F}{m}\right]$),

ε – relative permittivity of the polymer (dimensionless),

A – overlapping areas of upper and lower electrode (in $[m^2]$),

L – thickness of the polymer film (in [m]).

The thickness of the film of thin polymer layer is usually 1-10 μm.

As we can see, since the thickness of the film is constant, as well as overlapping areas of the electrodes, only the relative permittivity changes when the water is absorbed into polymer layer. The temperature range for this kind of sensors is from $-40°C$ up to $150°C$ [4]. Despite the relative high cost of these sensors they are widely used due to their quick response time.

Other applications for interdigital capacitor sensors are in telecommunications, biotechnology, chemical sensing, dielectric imaging, acoustic sensors and micro-electromechanical systems (MEMS) applications [5-7].

2.3. WORKING PRINCIPLE OF INTER-DIGITAL CAPACITOR SENSOR

Inter-digital capacitor sensor that we make is a comb like periodic pattern of electrodes deposited on a PCB (see Figure 2).

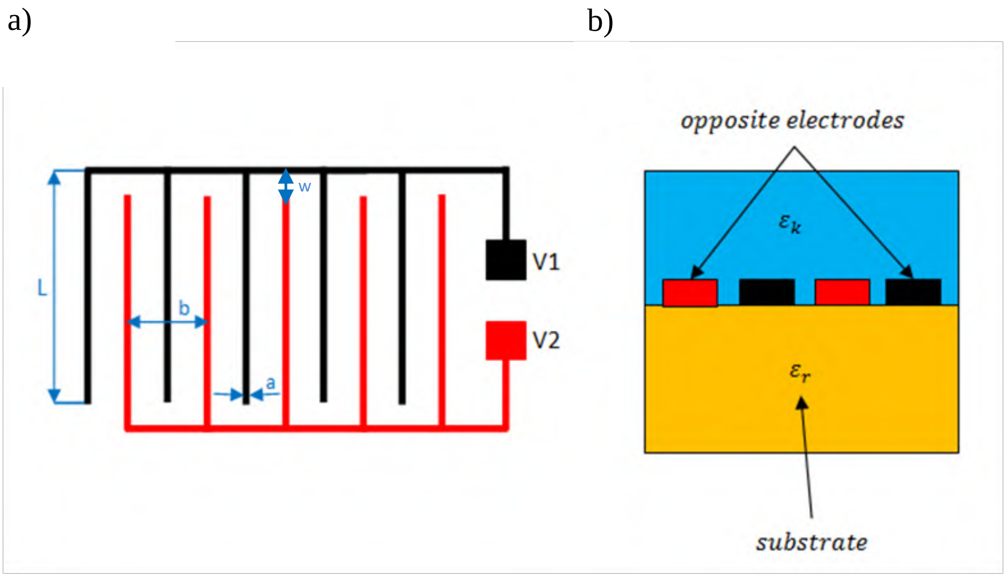

Figure 2.

a) Interdigital capacitor (IDC). a - elecrode’s width, b - distance between fingers, L – length of the electrode.
b) Cross-section of a IDC

As shown on Figure 2 the sensor consists of two electrodes in the xy plane, each electrode consists of N fingers.

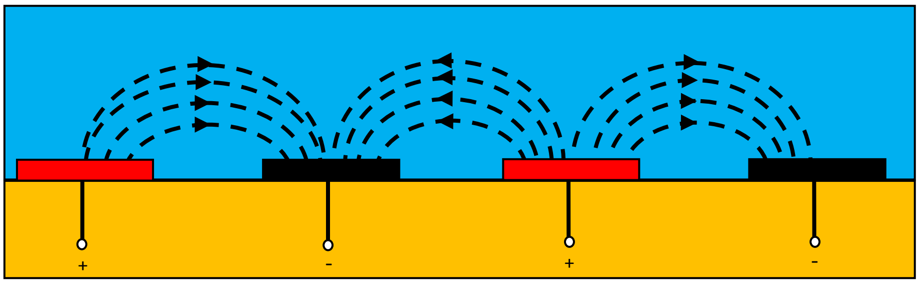

Figure 3.
Electric field lines of coplanar interdigital sensor.

The electric field lines generated by the sensor penetrate into the material under test and changes the impedance of the sensor. The sensor behaves as a capacitor in which the capacitive reactance becomes a function of system properties. Therefore by measuring the capacitive reactance of the sensor the system properties can be evaluated.

By applying an AC voltage source on the interdigitated electrodes V1 and V2 the generated electric field travels from one electrode, penetrating the dielectric film, as well as the substrate underneath the electrodes, to the other electrode. An electric field is formed from positive terminal to negative terminal as we can see on the Figure 3.

There are novel planar interdigital sensors with more than one negative electrodes in between positive ones, whose sensitivity of the measurement is better (and with better response to material under test) [8]. Due to limitations resulting from the equipment we used in our work in my thesis I will focus on conventional planar interdigital sensors whose have only one negative electrode in between positive electrodes (as it is shown on the Figure 2a)).

2.4. CALCULATION OF CAPACITANCE

The capacitance measured between the electrodes depends on the dielectric constants of the substrate and the dielectric film. Fringing capacitance between the interdigitated electrodes depends on electrodes width, where transverse capacitance depends on the electrode’s thickness, and the distance between the adjacent electrodes. The parameter w is small compared to the length of the electrode L and thus the impact of it on the capacitance can be ignored. When the dielectric film is an isotropic material, the unit cell capacitance per length is given by the formula [10]:

$$\mathrm{C_{uc}} = \varepsilon_0(\varepsilon_\mathrm{r} + \varepsilon_\mathrm{k})\frac{\mathrm{k}\left(\sqrt{1-\left(\frac{\mathrm{a}}{\mathrm{b}}\right)^2}\right)}{\mathrm{k}\left(\frac{\mathrm{a}}{\mathrm{b}}\right)} + 2\varepsilon_0\varepsilon_\mathrm{k}\frac{\mathrm{t}}{\mathrm{a}} \qquad (2)$$

where:

ε_0 - vacuum permittivity,

ε_r- dielectric constant of the substrate (glass fiber reinforced (fiberglass) epoxy resin), $\varepsilon_r = 3{,}6$ [9],

ε_k - dielectric constant of the dielectric film (liquid),

k - complete elliptic integral of the first kind,

t - elecrode's thickness,

a - elecrode's width,

b - distance between fingers.

By making full use of the symmetry and neglecting the capacitances of the edges, the total capacitance of the IDC is calculated by:

$$C_{TOTAL} = C_{uc}(N - 1)L \qquad (3)$$

where:

N - number of unit cells the capacitor,

L - length of the electrode fingers [10].

2.5. PERMITTIVITY

Dielectrics are the materials that can absorb microwave radiation and thus can be heated rapidly by microwaves. To describe the properties of dielectric materials we use complex relative permittivity. The real part of complex dielectric permittivity is called dielectric constant and it tells us how much energy from external electrical field is deposited in the bulk of the material. The imaginary part tells us how much energy from external electrical field was dissipated in the material. Loss tangent $\tan\delta$ is a ratio of the imaginary part and the real part of complex permittivity and it is related to the ability of a material to absorb energy while placed in a microwave cavity.

There are many methods to measure complex permittivity, some of them are listed below:

- Transmission/reflection line method

  In this method a material under the test is placed inside of a transmission line (e.g. rectangular waveguide) and the permittivity is computed from the measurement of the reflected and transmitted signal (S_{11} and S_{21} respectively).

- Open ended coaxial probe method

  In this method the probe is an open ended transmission line which is either dipped into the material under the investigation (if it is a liquid), or touching the flat surface of it (if it is a solid). The permittivity is computed from the measurement of reflected signal S_{11}.
- Free space method

  It is a non-contacting method that uses antennas (which work also as receivers) to focus microwave energy on a sample. The permittivity is computed from the measurement of the reflection and transmission coefficients.
- Resonant method

  In this method a sample placed inside of a cavity changes its resonant frequency and quality factor Q which allows to calculate the complex permittivity of a material being under the test.

In our experiment we use the data obtained from the capacitance measurements (C_{TOTAL}) and the modifications of the equations (2) and (3) to calculate the relative permittivity of the fluid being under the test:

$$C_{uc} = \frac{C_{TOTAL}}{(N-1)L} \tag{4}$$

$$\varepsilon_k = \frac{\frac{C_{uc}}{\varepsilon_0} - \varepsilon_r \frac{k\left(\sqrt{1-\left(\frac{a}{b}\right)^2}\right)}{k\left(\frac{a}{b}\right)}}{\frac{k\left(\sqrt{1-\left(\frac{a}{b}\right)^2}\right)}{k\left(\frac{a}{b}\right)} + 2\frac{t}{a}} . \tag{5}$$

The elliptic integral of the first kind was computed with the online calculator [11].

The unit of a relative permittivity $[\varepsilon_k]$ obtained using the (5) formula is as it follows:

$$[\varepsilon_k] = \frac{\frac{\mathrm{F}/\mathrm{m}}{\mathrm{F}/\mathrm{m}} - 1 \cdot \frac{1}{1}}{\frac{1}{1} + 2\frac{\mathrm{m}}{\mathrm{m}}} = []$$

which means that relative permittivity is dimensionless (has no unit).

In order to obtain the actual permittivity (which is a function of frequency) we have to multiply obtained relative permittivity by the vacuum permittivity ε_0:

$$\varepsilon = \varepsilon_k \cdot \varepsilon_0 \qquad (6)$$

and thus the unit of a permittivity ε is equal to the unit of vacuum permittivity, which means $\frac{\mathrm{F}}{\mathrm{m}}$.

The total error of the relative permittivity is computed using the finite difference method:

$$\Delta\varepsilon_k = \sqrt{\left(\frac{\partial\varepsilon_k(C_{uc},t,a,b)}{\partial C_{uc}}\Delta C_{uc}\right)^2 + \left(\frac{\partial\varepsilon_k(C_{uc},t,a,b)}{t}\Delta t\right)^2 + \left(\frac{\partial\varepsilon_k(C_{uc},t,a,b)}{a}\Delta a\right)^2} \qquad (7)$$

where:

- ΔC_{uc} - is the total error of the unit cell capacitance per length obtained from the formula:

$$\Delta C_{uc} = \sqrt{\left(\frac{\partial C_{uc}(C_{TOTAL},L)}{\partial C_{TOTAL}}\Delta C_{TOTAL}\right)^2 + \left(\frac{\partial C_{uc}(C_{TOTAL},L)}{\partial C_L}\Delta L\right)^2} = \sqrt{\left(\frac{\Delta C_{TOTAL}}{4L}\right)^2 + \left(-\frac{C_{TOTAL}}{4L^2}\Delta L\right)^2} \qquad (8)$$

  where ΔC_{TOTAL} is a place of least significant number from the capacitance measurement on a RCL meter (the resolution of RCL meter).

- Δt is the error of a thickness of a electrode $\Delta t = \pm 0{,}05$ mm
- Δa is the error of the width of a electrode $\Delta a = \pm 0{,}5$ mm
- ΔL is the error of the length of the electrodes fingers $\Delta L = \pm 0{,}5$ mm

Which leads us to the formula for the total error of the relative permittivity used in this publication:

$$\Delta\varepsilon_k = \sqrt{\left(\frac{\frac{1}{\varepsilon_0}}{\frac{k\left(\sqrt{1-\left(\frac{a}{b}\right)^2}\right)}{k\left(\frac{a}{b}\right)}+2\frac{t}{a}}\Delta C_{uc}\right)^2 + \left(-\frac{2}{a}\frac{\frac{C_{uc}}{\varepsilon_0}-\varepsilon_r\frac{k\left(\sqrt{1-\left(\frac{a}{b}\right)^2}\right)}{k\left(\frac{a}{b}\right)}}{\left(\frac{k\left(\sqrt{1-\left(\frac{a}{b}\right)^2}\right)}{k\left(\frac{a}{b}\right)}+2\frac{t}{a}\right)^2}\Delta \mathrm{t}\right)^2 + \left(\frac{2t}{a^2}\frac{\frac{C_{uc}}{\varepsilon_0}-\varepsilon_r\frac{k\left(\sqrt{1-\left(\frac{a}{b}\right)^2}\right)}{k\left(\frac{a}{b}\right)}}{\left(\frac{k\left(\sqrt{1-\left(\frac{a}{b}\right)^2}\right)}{k\left(\frac{a}{b}\right)}+2\frac{t}{a}\right)^2}\Delta a\right)^2} \quad (9)$$

In order to obtain the error of permittivity we need to multiply the obtained error of relative permittivity (equation 9) by the value of vacuum permittivity, according to the equation 6.

Summarizing, the error of the permittivity parameter depends on:

- Accuracy of the measurement of
    - thickness of a electrode t,
    - the width of a electrode a
    - length of the electrodes fingers L
- The resolution of RCL meter during the measurement of the capacitance C_{TOTAL}.

CHAPTER 3

RESEARCH METHODOLOGY

3.1. FLOWCHART OF THE RESEARCH

The flowchart of our research is as it follows:

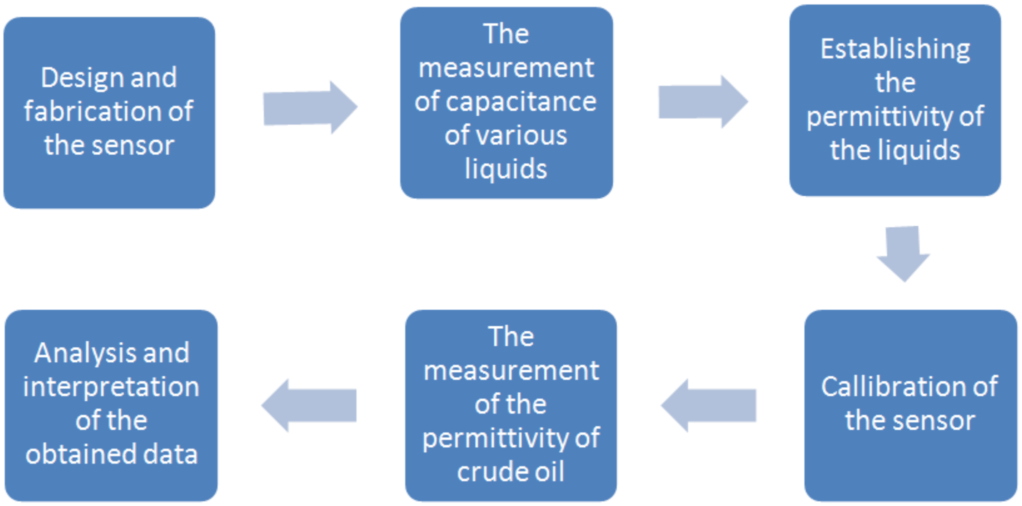

Figure 4.

The flowchart of the research

3.2. INSTRUMENTATION AND MATERIALS

To perform measurements on the IDC sensor designed and fabricated by us we used PM 6303 RCL meter Phillip type A for detecting changes in capacitance. Test materials used in the measurements are 300 ml of tap water, cooking oil, acetone, salt water, sugar water and crude oil. The measurement were performed for one fixed frequency of 1 kHz at room temperature of 25 ℃ and humidity of the air of 84%.

3.3. DESIGN AND FABRICATION PROCESS OF THE SENSOR

It takes up to five hours to fabricate the sensor. In order to do that we used single sided PCB (Printed Circuit Board with one copper layer) technology. PCB plate is an insulating substrate covered with conducting copper layer. In order to fabricate IDC sensor we transferred our comb like design into the PCB plate and did chemical etching. Chemical etching process removed the unwanted copper, leaving only the desired copper trace. As a result of this step we obtained PCB plate with the pattern of comb like electrodes with the design which allows us to plug in a voltage source and probes to measure the capacitance of the sensor.

The sensors design and parameters are presented in the chapter 3.3.2.

3.3.1. THE OPTIMUM EQUATION FOR IDC

We derive the optimum equation for the IDC from the conditions given below:

$$\begin{cases} \frac{\delta \mathrm{C_{uc}}}{\delta a} = 0 \\ \frac{\delta \mathrm{C_{uc}}}{\delta b} = 0 \end{cases} \rightarrow a, b \tag{10}$$

$$\frac{\delta \mathrm{C_{uc}}}{\delta a} = \varepsilon_0(\varepsilon_\mathrm{r} + \varepsilon_\mathrm{k}) \frac{k'\left(\sqrt{1-\left(\frac{\mathrm{a}}{\mathrm{b}}\right)^2}\right) k\left(\frac{\mathrm{a}}{\mathrm{b}}\right) - k\left(\sqrt{1-\left(\frac{\mathrm{a}}{\mathrm{b}}\right)^2}\right) k'\left(\frac{\mathrm{a}}{\mathrm{b}}\right)}{\left(k\left(\frac{\mathrm{a}}{\mathrm{b}}\right)\right)^2} - 2\varepsilon_0\varepsilon_\mathrm{k}\frac{\mathrm{t}}{\mathrm{a}^2} = 0 \tag{11}$$

$$\frac{\delta \mathrm{C_{uc}}}{\delta b} = \varepsilon_0(\varepsilon_\mathrm{r} + \varepsilon_\mathrm{k}) \frac{k'\left(\sqrt{1-\left(\frac{\mathrm{a}}{\mathrm{b}}\right)^2}\right) k\left(\frac{\mathrm{a}}{\mathrm{b}}\right) - k\left(\sqrt{1-\left(\frac{\mathrm{a}}{\mathrm{b}}\right)^2}\right) k'\left(\frac{\mathrm{a}}{\mathrm{b}}\right)}{\left(k\left(\frac{\mathrm{a}}{\mathrm{b}}\right)\right)^2} = 0 \tag{12}$$

where:

$$k'\left(\sqrt{1-\left(\frac{\mathrm{a}}{\mathrm{b}}\right)^2}\right) = \frac{1}{\sqrt{1-\left(\sqrt{1-\left(\frac{\mathrm{a}}{\mathrm{b}}\right)^2}\right)^2 sin^2\frac{\pi}{2}}} - \frac{1}{\sqrt{1-\left(\sqrt{1-\left(\frac{\mathrm{a}}{\mathrm{b}}\right)^2}\right)^2 sin^2 0}} = \frac{b}{a} - 1 \tag{13}$$

$$k'\left(\frac{\mathrm{a}}{\mathrm{b}}\right) = \frac{1}{\sqrt{1-\left(\frac{\mathrm{a}}{\mathrm{b}}\right)^2 sin^2\frac{\pi}{2}}} - \frac{1}{\sqrt{1-\left(\frac{\mathrm{a}}{\mathrm{b}}\right)^2 sin^2 0}} = \frac{1}{\sqrt{1-\left(\frac{\mathrm{a}}{\mathrm{b}}\right)^2}} - 1 \tag{14}$$

So:

$$\frac{\delta \mathrm{C_{uc}}}{\delta a} = \varepsilon_0(\varepsilon_\mathrm{r} + \varepsilon_\mathrm{k}) \frac{\left(\frac{b}{a}-1\right) k\left(\frac{\mathrm{a}}{\mathrm{b}}\right) - k\left(\sqrt{1-\left(\frac{\mathrm{a}}{\mathrm{b}}\right)^2}\right)\left(\frac{1}{\sqrt{1-\left(\frac{\mathrm{a}}{\mathrm{b}}\right)^2}}-1\right)}{\left(k\left(\frac{\mathrm{a}}{\mathrm{b}}\right)\right)^2} - 2\varepsilon_0\varepsilon_\mathrm{k}\frac{\mathrm{t}}{\mathrm{a}^2} = 0 \tag{15}$$

And:

$$\frac{\delta \mathrm{C_{uc}}}{\delta b} = \varepsilon_0(\varepsilon_\mathrm{r} + \varepsilon_\mathrm{k}) \frac{\left(\frac{b}{a}-1\right) k\left(\frac{\mathrm{a}}{\mathrm{b}}\right) - k\left(\sqrt{1-\left(\frac{\mathrm{a}}{\mathrm{b}}\right)^2}\right)\left(\frac{1}{\sqrt{1-\left(\frac{\mathrm{a}}{\mathrm{b}}\right)^2}}-1\right)}{\left(k\left(\frac{\mathrm{a}}{\mathrm{b}}\right)\right)^2} = 0 \tag{16}$$

3.3.2. IDCs PARAMETERS

Our IDCs specifications are as follows:

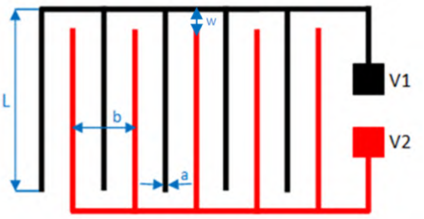

Figure 5.

Interdigital capacitor (IDC)

- The width of the electrode
  $a = (2 \pm 0,5)$ mm
- The distance between the electrodes
  $b = (2,0 \pm 0,2)$cm
- Electrode length $L = (5,0 \pm 0,2)$ cm
- 5 electrodes on each side
- electrodes thickness (the thickness of the copper layer on the PCB) $t = (0,20 \pm 0,05)$ mm
- $w = (0,4 \pm 0,1)$ cm
- $\epsilon_0 = 8,8542 \cdot 10^{-12}$ F/m

Presented parameters of the sensor were chosen due to the conditions of the optimum equation for IDC (see the chapter 3.3.1.) and due to the accuracy of the method of making a sensor (the PCB technique used in this research allowed us to carry a pattern not smaller in width than 2 mm).

3.4. MEASUREMENTS

The sensor is tested by giving a direct contact between the electrodes against the test material (Figure 6). Our goal at this step is to detect capacitance of each substance being under the investigation and to measure the changes of the capacitance when given a particular treatment (e.g. increase the amount of sugar in the water). The capacitance measurements are performed using the RCL meter, at the frequency of 1 kHz.

After each measurement the active area of the sensor was cleaned with the use of detergent and wiped off with the cotton soaked with acetone.

Figure 6.

The measurement of capacitance

The PM 6303 A RCL meter is used for measurements of resistances, capacitances and inductances. It allows to make high precision measurements of passive components. The IDC is directly connected to the instrument via test cable with Kelvin clips.

CHAPTER 4

RESULTS AND ANALYSIS

Before the measurement of permittivity of crude oil the calibration of the sensor has to be made.

Calibration of IDC sensor was performed in the following steps:

1. The measurement of capacitance for various liquids were made.
2. The capacitances were changed into relative permittivity values, accordingly to the procedure described in the chapter 2.5.
3. The comparison of obtained permittivity values with the table ones available on the website [9] was made.

Since the permittivity is a linear function of unit cell capacitance per length C_{uc} (see the equation 5) in order to perform the calibration procedure we need at least two points to compare the actual values of permittivity with the ones obtained in the measurement. The substances used to calibrate my sensor are vegetable oil and acetone.

After the calibration procedure the capacitance measurements of crude oil were performed.

The results of the measurements of permittivity of various liquids (with the exception of crude oil) are presented as a table (Table 1) and an histogram (Figure 7). The plot of permittivity as a function of solution in the water is presented as well (Figure 8).

The total error of permittivity was calculated using the exact differential method, as it was said in the chapter 2.5.

Table 1. Results of measurements of permittivity for various liquids with the exception of crude oil

Substance	**Permittivity** $\varepsilon\left[\frac{F}{m}\right]$	$\Delta\varepsilon\left[\frac{F}{m}\right]$	**Relative error** [%]
tap water	$54 \cdot 10^{-8}$	$4 \cdot 10^{-8}$	7
5 gr salt	$64 \cdot 10^{-7}$	$5 \cdot 10^{-7}$	7
15 gr salt	$49 \cdot 10^{-6}$	$4 \cdot 10^{-6}$	7
25 gr salt	$46 \cdot 10^{-6}$	$3 \cdot 10^{-6}$	7
35 gr salt	$54 \cdot 10^{-6}$	$4 \cdot 10^{-6}$	7
45 gr salt	$63 \cdot 10^{-6}$	$5 \cdot 10^{-6}$	7
55 gr salt	$71 \cdot 10^{-6}$	$5 \cdot 10^{-6}$	7
5 gr sugar	$47 \cdot 10^{-8}$	$4 \cdot 10^{-8}$	7
15 gr sugar	$43 \cdot 10^{-8}$	$3 \cdot 10^{-8}$	7
25 gr sugar	$39 \cdot 10^{-8}$	$3 \cdot 10^{-8}$	7
35 gr sugar	$30 \cdot 10^{-8}$	$2 \cdot 10^{-8}$	7
45 gr sugar	$31 \cdot 10^{-8}$	$2 \cdot 10^{-8}$	7
55 gr sugar	$30 \cdot 10^{-8}$	$2 \cdot 10^{-8}$	7
acetone	$16 \cdot 10^{-11}$	$1{,}2 \cdot 10^{-11}$	7
vegetable oil	$81 \cdot 10^{-13}$	$9 \cdot 10^{-13}$	11

The data obtained in an experiment and presented in a Table 1 suggest that it is possible to distinguish various liquids by the measurement of permittivity with the sensor designed and fabricated in our laboratory.

According to the dielectric constant table [9] the actual relative permittivity of the acetone is $15{,}7 \cdot 10^{-11}\,\frac{F}{m}$. The result obtained by us is $16 \cdot 10^{-11}\,\frac{F}{m}$ with the total error of 7 % which is a good approximation of the actual value.

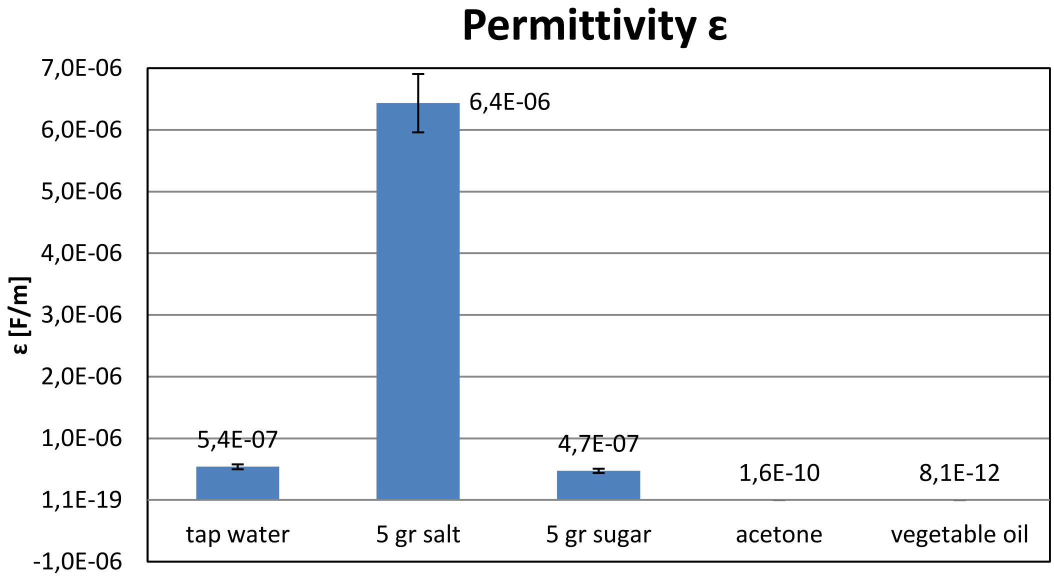

Figure 7.

The results of the measurement of the relative permittivity of different liquids with the exception of crude oil

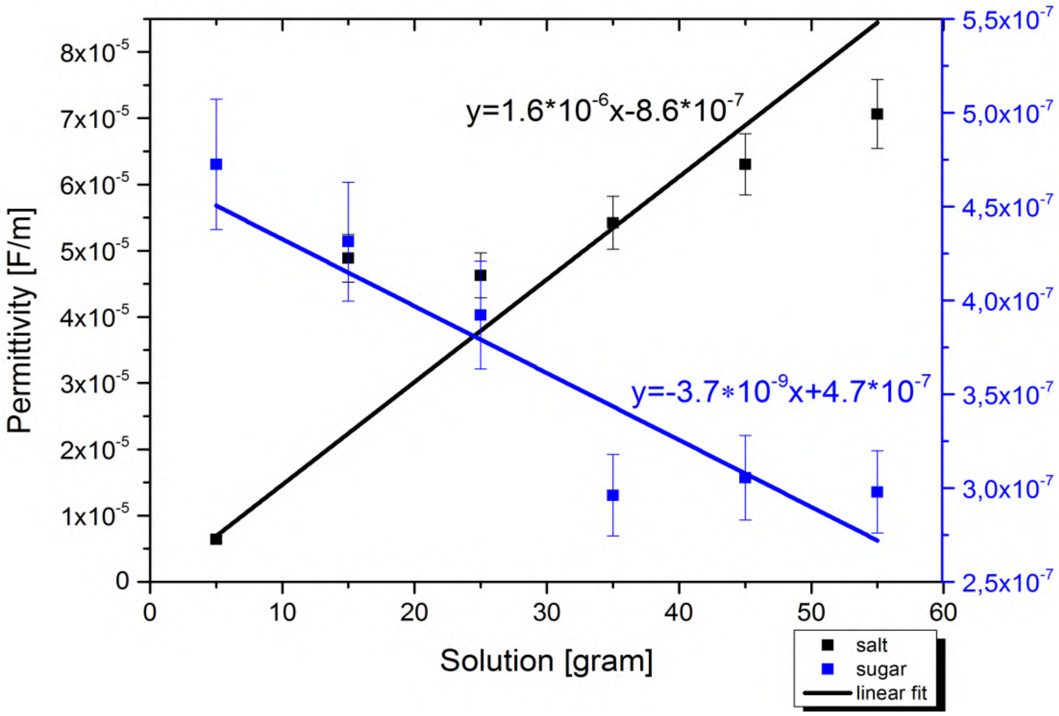

Figure 8.

The change of trend for the relative permittivity with different amount of solution dissolved in the water

The obtained data suggest the change in the relative permittivity of the fluids according to different amount of salt and sugar added to the water. The trend is raising for the salt (the more salt added to the water the bigger the relative permittivity is) and decreasing for the sugar (the more sugar added to the water the smaller the permittivity). Both trends are presented on the Figure 8.

The change of the concentration of material (like salt and sugar) in the water causes the change in permittivity of measured materials. The polar nature of the water molecules tends to align with local ion field so it raises the permittivity of electrolyte materials when the salt is added, and decreases it when a non-aqueous electrolyte is added like sugar [13].

After the calibration procedure the measurements of permittivity of crude oils were made. The results are presented in a Table 2.

Table 2. Results of measurements of permittivity for various crude oil samples

Stripes covered	**Substance**	**Permittivity** $\boldsymbol{\varepsilon}\left[\frac{\mathbf{F}}{\mathbf{m}}\right]$	$\boldsymbol{\Delta\varepsilon}\left[\frac{\mathbf{F}}{\mathbf{m}}\right]$	**Relative error** [%]
10	crude oil sample 1 (black in colour, high density, high viscosity)	$20 \cdot 10^{-12}$	$2 \cdot 10^{-12}$	8
2	crude oil sample 2 (black in colour, medium density, low viscosity)	$54 \cdot 10^{-6}$	$4 \cdot 10^{-6}$	7
2	crude oil sample 3 (light in colour, low density, low viscosity)	$41 \cdot 10^{-11}$	$3 \cdot 10^{-11}$	7
2	crude oil sample 1 (black in colour, high density, high viscosity)	$98 \cdot 10^{-6}$	$7 \cdot 10^{-6}$	7

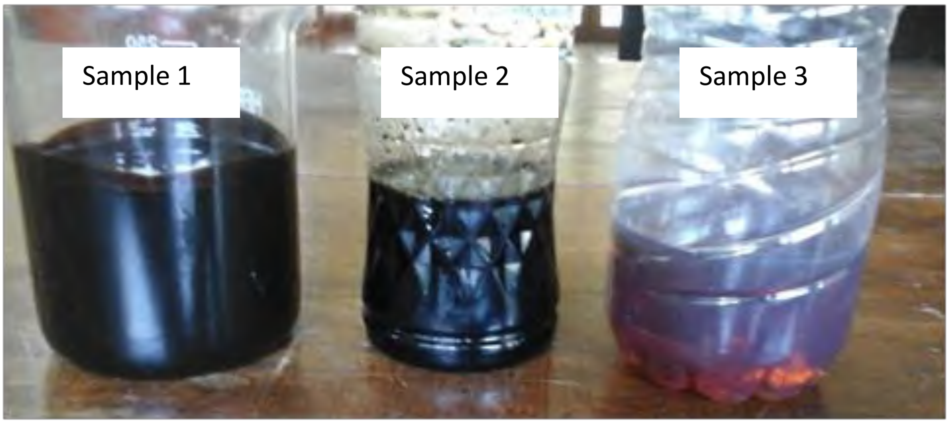

Figure 9.
Crude oil samples used during the experiment

Unfortunately we did not have enough crude oil to cover all the stripes of the capacitor sensor in order to perform proper measurements for the samples two and three (due to limited access to samples of crude oil). Thus we were able to perform proper measurement (with all the stripes of the capacitor covered with liquid) only for sample one. The result of that measurement is presented in the first row in a Table 2.

Since we were not able to cover all the stripes of the capacitor sensor for the samples two and three the following solution was implemented: we measured the capacitance values of all crude oil samples for the same amount of the liquid in a glass (namely: two stripes of the capacitor sensor were covered with crude oil). It is not a proper way of performing the measurement with the use of a sensor designed and fabricated by us (thus we were not able to obtain reliable results of permittivity for these samples) but it would allow us to compare the properties of these samples. It is also worth to mention that during that measurement the system could not obtain equilibrium (the values of capacitance were changing during the measurement), especially for the samples containing high density, black in colour crude oil (namely sample one and two), with the emphasis on the sample one.

As it was expected we did not obtain the same result of permittivity value for the sample one for the measurement performed for all stripes covered and the one with only two stripes covered. The result differs by three orders of magnitude.

As it was said before the measurement for only two stripes covered is not reliable and it is performed only to compare the samples of crude oil. The result of this comparison is as follows: the crude oils with the highest densities (black in colour, namely: samples one and two) have the smallest permittivity values.

CHAPTER 5

CONCLUSION

Interdigital capacitor sensor (IDC) used in this research is designed to be able to measure the capacitance of the fluid being under the investigation which allows us to obtain the permittivity value of these liquids with the use of the equation 5 mentioned in the chapter 2.5. The obtained data suggest that it is possible to distinguish different liquids with the use of the interdigital capacitor sensor fabricated in our laboratory.

The measurement of permittivity were made for various liquids (tap water, acetone, vegetable oil, sugared water, salted water and crude oil). The result of the measurement for the different amount of salt and sugar dissolved in the water suggest the changes of permittivity of these fluids accordingly to the amount of the substance added to the water. The trend is raising for the salt (the more salt added to the water the bigger the permittivity is) and decreasing for the sugar (the more sugar added to the water the smaller the permittivity). Both trends are presented on the Figure 8.

The expalantion of this phenomena is as it follows: the polar nature of the water molecules tends to align with local ion field so the permittivity of electrolyte materials raises when the salt is added, and decreases it when a non-aqueous electrolyte is added like sugar.

Since the permittivity is a linear function of the unit cell capacitance per length $\mathrm{C_{uc}}$ (see the equation 5, chapter 2.5) the two-point calibration of the sensor was performed with the use of the dielectric constant table [9] before the measurement of permittivity of crude oil. The substances used in order to do that are acetone and vegetable oil.

The measurements of permittivity were performed for three samples of crude oil. Unfortunately we did not have enough of crude oil to cover all the stripes of the sensor for the samples two and three. As a result we obtained a reliable value of permittivity only for the sample one of crude oil. The result is as it follows: $20 \cdot 10^{-12}\ \frac{\mathrm{F}}{\mathrm{m}}$ with the total relative error of 8 percent. The table values of permittivity of crude oils are between $19{,}7 \cdot 10^{-12}\ \frac{\mathrm{F}}{\mathrm{m}}$ and $21{,}5 \cdot 10^{-12}\ \frac{\mathrm{F}}{\mathrm{m}}$ for the measurement performed at 1 kHz frequency [12] (depends on the sample). The permittivity obtained in this experiment fits in this brackets.

In order to compare the samples the following solution was implemented: we measured the permittivity of all the samples for only two stripes of the sensor covered in the liquid being under the investigation (the sensor was not fully dipped in the substance). The results of permittivity obtained during that measurement are not reliable since we obtained different value of permittivity for the sample one compared to the measurement performed with all the stripes covered (they differ by the three orders of magnitude). But as it was said before – this measurement is performed to compare the samples of crude oil. The results of this comparison are as follows: the crude oils with highest densities (samples one and two) have the smallest permittivity values. The difference between the permittivity values of the low density oil (namely sample 3) and the highest density oil (sample one) differs by five orders of magnitude.

Since the sensor is capable of differentiate of various samples of crude oil and its cost of production is relatively low it could be put into a good use in the research of heating crude oil by microwave energy.

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BIOGRAPHY

I was born and raised in Poland. I have finished high school focusing on languages in a city called Sokołów Podlaski, which is located 100 km from Warsaw.

In 2013 I have finished the first cycle of my studies at the Faculty of Physics at the Warsaw University of Technology, where I obtained my degree of Bachelor of Science in Engineering. I studied Applied Physics majoring in Medical Physics.

Furthermore, I took an internship in the Heavy Ion Laboratory University of Warsaw, where I participated in a project that studies ‘Single diamonds and diamond polycrystal layers obtained by the MWCVD process’ (I have performed the electronics for diamond detectors). Therefore, I had developed a strong interest in doing research work.

At the same time I was an active member of Scientific Circle of Physicists in our university. I participated in various projects focusing on propagating science among children. I became a teacher in Uniwersytet Dzieci (Children University) where I taught Physics. Working with children has brought a lot of joy into my life.

In 2013 I was a member of a research group in the Institute of Electron Technology, where I worked on superconducting nano – wire single photon detectors. I participated in all the steps of detector fabrication – from design up to test measurement of fully developed structures. I was responsible for optical and electric measurements of obtained structures as well as interpreting the data collected from XPS measurements. The results of my work were presented at the 38th International Conference of IMAPS-CPMT Poland in Czarna.

During my studies I finished an internship in a publishing house New Era as a substantive editor of Physics textbooks for high school. After the internship, I started to work there on a permanent basis. I have been working there for one year and a half, participating in many projects, such as:

- Physics textbook for high school Zrozumieć fizykę 2,

- A set of exercises in Physics for high school Zbiór zadań 1. Fizyka,
- Internet website terazmatura.pl.

Working in a publishing house was a great opportunity for me to acquire new skills, for example, paying attention to minor and major details, and working under pressure.

My main goal is to start a career in the area of science where I can combine my knowledge in Physics and medicine.