Conductivity Effect on the Capacitance Measurement of a Parallel-plate Capacitive Sensor System

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In this article, the design and operation of a parallel-plate capacitive sensor based on the dielectric capacitance and conductance change of the gap medium is reported. The designed system was used to determine the characteristics of different water liquids as a result of the capacitance variations. The air gap capacitance is measured and then by filling the gap with a liquid the capacitance is monitored for different liquids. The proposed sensor is used for the distilled, tap, boiled, and salt water measurements and the capacitance results are compared. A difference of about 45.5μF in the capacitance values for salt and distilled water shows a high sensitivity, which can be used to recognize different water liquids. The experimental results are promising for water liquids and verify the successful operation of such a device as a liquid sensor, a useful method for checking the electrical quality of the water that is required for different applications.

1. Introduction

There has been a great deal of interest in the development of precise capacitive sensor in recent years. Different reports on the design, characterization, operation and possible applications of such devices have been given by Golnabi and Azimi [1, 2] and others [3-7]. A CMOS-compatible capacitive high temperature pressure sensor was reported in [8]. Measurements in the range of 50-340°C for temperature and pressure in the range of 0-125 bar were performed by such a sensor. Also for pressure measurement in harsh environment, a capacitive differential sensor has been reported that was operated for the pressure range of 0-1 bar [9]. In another study, a monolithically integrated surface micro-machined touch mode capacitive pressure sensor was reported in [10]. Their fabrication was reported to be a fully CMOS-compatible touch mode capacitive pressure sensor. The frequency and voltage output of such sensors were about 5-25 Hz/psi, and 10-50 mV/psi in the linear pressure range of 8-60 psi.

Capacitive sensors have been used in many industrial applications to control processes and in machine diagnostic tasks. However, several problems including stray capacitance, baseline drift, stability and sensitivity have motivated the development of new transducers and measuring systems. To alleviate some of these problems in this field, a variety of capacitive sensor systems have been developed and reported. For example, the effect of a guard ring electrode on the operation of a capacitive transducer have been investigated in [11]. The development of a three-dimensional capacitance imaging system for measuring the density of fluidized beds was reported in [12]. In another report, the design and operation of a capacitive sensor for water content monitoring in a production line was presented [13]. The design and performance of a simple capacitive sensor for mass measurement is given in [3]. The scale industry has been developing rapidly in recent years and there are demands for weighting devices with good qualities at low prices.

In another report, capacitance sensors have been used for the measurement of the phase volume fraction in two-phase pipelines [14]. The effect of phase distribution or flow pattern was considered for the determination of volume fraction in two phase pipe-line by using the capacitance measurements. They have shown that the capacitance measured depends not only on the volume fraction but also on the phase distribution. Such an effect was shown by an example in that article and described the resulting capacitance when the electrodes are half filled vertically or horizontally, similar to the series or the parallel capacitive forms.

On the other hand, many researchers have focused on the development of the readout circuits. The goal of such research has been to introduce a readout circuit that can be used for low-noise operation with the cancellation of operational amplifier1/f-noise and offset voltage [15]. A new capacitive–to-phase conversion technique for measuring very small capacitance changes has been reported in [16]. This method provided a powerful mean for recording a very small change in

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capacitance. Much progress has been made during the last few years in developing the capacitor transducers and complementing measuring circuits. To have the required precision in instrumentation and measurements, the small capacitance to be measured is in the range of 0.01-10 pF with a required resolution of better than 0.01-10 fF. This requirement along with other considerations, such as environmental effects, structural stability and standardization, challenges the development of a highly sensitive and reliable capacitance sensor systems [17].

2. Experiment

The experimental setup, measurement method, materials and sample preparations are described in this section.

2.1 Setup

Capacitance measurement system in general includes a sensing probe and a measuring module. Our experimental setup is a simple one, which uses the capacitive sensing probe and the measuring module as shown in Fig. 1. The experimental arrangement includes the parallel-plate capacitive sensor, two digital multi-meter (DMM) modules (SANWA, PC 5000), and a PC. As shown in Fig. 1, one of the digital multi-meters is used for capacitance measurement and a similar one, together with a temperature probe (T-300PC), is used for the temperature measurements [18]. The software (PC Link plus) allows one to log measuring data into the PC through RS232 port with digital multi-meter PC series. The operation of this software is possible by using any operational system such as the windows 98, NT4.0/2000/ME/XP versions. It provides function for capacitance measurements using the charge/discharge method and capacitance in the range of 0.01 nF to 9.99 mF can be measured with a resolution of about 0.01 nF. The nominal input impedance of the DMM is about 10 MΩ and 30 pF. The specified accuracy of the DMM for 50.00-500.0 nF capacitance range is about ± (0.8 % rdg+3dgt) and ± (2 % rdg+3dgt) for the 50.00 μF range. The temperature probe consists of a platonic thin thermo-resistor (1000 Ω at 0 ˚C) with a temperature measurement range of -50 to 300 ˚C. The response time of this probe is about 7 seconds and offers an accuracy of about ±1.9 ˚C in temperature recording.

The proposed capacitive probe, shown in Fig. 1, consists of two parallel plates that are separated by 2mm and the total length of electroplates is 18.5 cm, whereas the width of electroplates is 17.5 cm. When the space between the capacitor plates is completely filled with the water liquid, the capacitance is

$$C = \varepsilon \frac{A}{d} \qquad (1)$$

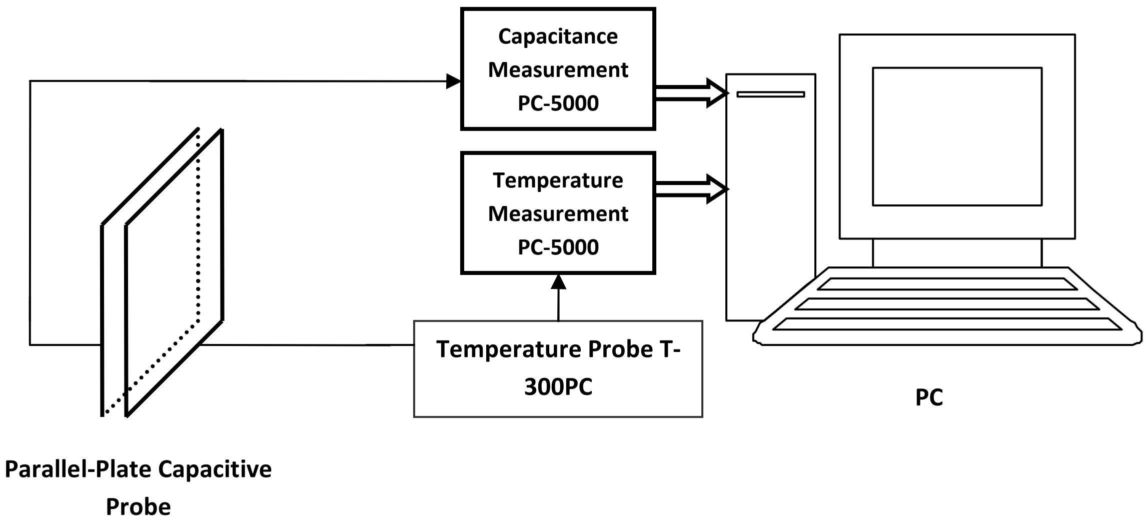

Fig.1. Block diagram of experimental arrangement for the capacitive sensor.

Where, ε, is the permittivity of the dielectric medium between two plates. A is electrode area and d is the gap distance between electrodes. However, Eq. (1) is only valid when A>>d. Several problems, such as edge effect, can cause deviation in the actual capacity from the one obtained in Eq. (1). For this reason, various attempts have been made to design different transducers in order to reduce these effects.

2.2 Measurement method

Depending on the capacitance electrode configuration of the sensor, the equivalent circuit can be considered for the case of invasive (direct contact between the metal electrode and liquid) and non-invasive (no contact between the metal electrode and liquid) sensors. In a simple form, if we consider a uniform liquid with a given permittivity and conductivity, then the equivalent circuits for the case of non-invasive and invasive sensors can be considered [19].

It must be mentioned that a given capacitance value is the measured value by the charge transfer reading circuit, and the fluid capacitance must be deduced from these measured values. Also note that the capacitance sensing is affected by the conductivity variations of the components [20]. This conductivity problem has been the main concern in the field of dielectric measurements and several attempts have been made to compensate for such variation and for a simple case the effect of conductivity is presented by a resistive element in parallel with the sensor capacitance. However, for sensors using non-invasive electrodes and those measuring two-component fluids, the sensor system must be represented by more complex equivalent circuit models. As a result, an investigation into the effects of component conductivity should be done for precise measurements.

Equivalent circuits for the invasive and non-invasive cases are shown in Fig. 2(a) and Fig. 2(b), respectively. In the invasive situation when there is a contact between the metal and liquid, it is equivalent to a circuit consisting of a capacitor C_x in parallel with a resistor R_x. In this analysis, R_x represents the resistance of the fluid due to its conductivity effect and C_x shows its capacitance as a result of its permittivity. For the non-invasive case, as shown in Fig. 2 (b), an extra capacitor C is considered in series with R_x and C_x, which are acting in parallel. As can be seen, measured capacitance element depends on both C_x and R_x of the fluid under measurement.

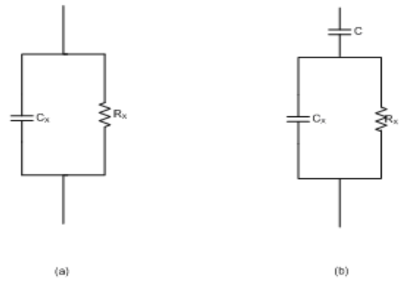

Fig.2. Equivalent circuits for the invasive (a) and non-invasive (b) electrode arrangements.

In general, a variety of techniques have been employed for measuring the absolute and relative capacitance changes. Oscillation, Resonance, charge/discharge, AC Bridge, and capacitive-to-phase conversion are the most common methods for such capacitance measurements. Since the measurement module uses the charge/discharge (C/DC) circuit, therefore, this method is described here. The charge/discharge operation is based on the charging of an unknown capacitance under study C_x to a voltage V_c via a CMOS switch with resistance R_{on} (Fig. 3a) and then discharging this capacitor into a charge detector via a second switch (Fig. 3b).

A DMM with the given specification based on the charge /discharge operation is used here for the capacitance measurements. This capacitance measuring module is capable of measuring precisely the capacitance values in the range of 0.01 nF to 50 mF.

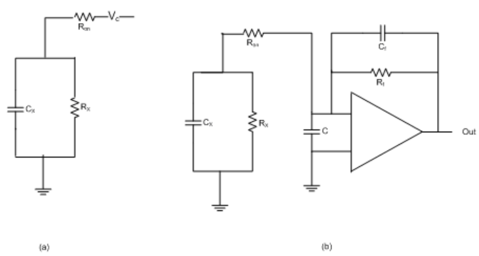

Fig.3. Schematics of the capacitance charge (a) and discharge (b) processes.

The capacitance measurements for the parallel-plate capacitive probe shown in Fig. 1 depend on the permittivity, ε, of the liquid and its resistance factor that depends only on the conductivity, σ, of the liquid. Thus one can write:

$$C_x = f_1 (\varepsilon), \quad (2)$$

$$R_x = f_2 (\sigma) \quad (3)$$

The capacitive element C is obtained only by the insulation of the electrodes and reducing the conductivity effect. As described, there are in general invasive and non-invasive electrode arrangements. For the case of non-invasive sensors, in measuring capacitance of a liquid, the effect of resistive component is usually very small because of the dielectric insulator. For the invasive sensors, the effect of R_x on the measurement of C_x cannot be neglected and the effect of conductivity of the liquid must be considered in analysis. However, the effect of R_x can be negligible if the on resistance of the charge switch R_{on} is small compared with R_x, and if the discharge time, which is determined by the switching-on time of the resistance of the discharging switch, is short compared to the time constant given by R_xC_x.

To analyze electrical conduction of the tested water liquids, additional measurements were made on the electrical conductivity (EC) and total dissolved solid (TDS) density of the samples used in this experiment. In conductivity meters, measurement is usually made by placing a cell (probe) in an electrolytic solution. The cell consists of two electrodes of specific size, separated at a specific distance that defines the cell K factor. The conductivity of a liquid is determined from the ratio of current to the voltage between the two electrodes.

For measurements, a conductivity meter (Hach Company, Sension 5) is used [21], which is useful for a variety of applications such as water quality, measuring salinity (a measure of dissolved salts in a given mass of solution), acids, bases, and other qualities of aqueous samples. The meter features a digital LCD display that simultaneously displays temperature and other measurement results. The specifications of this meter are as follows: Conductivity range of 0-199.9 mS/cm and resolution ranges from 0.01 μS/cm to 0.1 mS/cm, respectively, for the selected measurement ranges. The ranges for TDS are: 0-50 g/L with a resolution of 0.1 mg/L to 0.1 g/L for different ranges. Measurement range for salinity is 0- 42 ppt with a resolution of ± 0.1 ppt and an accuracy of ± 0.1 ppt. The measuring temperature range is from -10 ˚C to 105 ˚C. The accuracy for conductivity is ± 0.5%, for TDS it is ± 0.5% of full scale, and for temperature it is ± 0.3 ˚C for 0-70 ˚C and ± 1.0 ˚C for 70-105 ˚C. Calibration of this device is based on a standard NaCl solution having a conductivity of 1000 μS/cm at 25 ˚C.

2.3 Samples and procedures

Fortunately, this experiment does not require many reagents and complicated chemical procedures for the sample preparation. In this experiment, one type of samples was used (including the single aqueous solutions). The single phase solution includes the samples from the distilled water, tap water, boiled water, and mineral drinking water. The distilled water used in this experiment was made by an apparatus operating based on the boiling technique. All other agents and liquids were at regular grade purchased from the related suppliers. For the water salt preparation regular grade salt (NaCl) was used for the preparation of a sample with the concentration of about mg/L.

3. Results

The minimum reliable limit of DMM is about 0.01 nF, therefore the direct results for air reading were not so reliable. However, when the gap is filled with a liquid, since the dielectric constant of the fluid is larger than that of the air, then the measured capacitance value is increased and the capacitance value is acceptable for these water liquids. As described, our measuring apparatus is operating under the charge/discharge technique. In order to test the precision of the capacitance measuring module the capacitance of air is measured (0.12 nF) in the first experiment.

The air gap capacitance of the probe is around 0.09-0.12 nF. The air gap capacitance for the designed probe is about 0.11 nF. However, as described earlier this value is different from the calculated value from Eq. (1). It must be pointed out that the theoretical value is for the cell that has air gap between two plates very small (maximum 2mm) and the mentioned difference seems reasonable. In the next test, the capacitance value for the distilled water is measured. In the first case, the measured value is about 6.5 μF. The theoretical capacitance due to a dielectric constant of about 80 for the distilled water leads to a dielectric capacitance value of 0.348 nF, which is much less than the measured value. This leads to the fact that the measured value is not the capacitance value of the distilled water and must be compensated for the conductance effect.

In the next study, to see the capacitance variation of the different water liquids, a series of measurements were performed (results shown in Fig. 4). As can be seen in Fig. 4, the distilled water shows the lowest measured value and the water salt solution shows the highest (61.8 μF) value among the tested liquids.

For the case of distilled water, the capacitance value starts from the 6.5 μF and reaches to about 15.3 μF in a few seconds time interval. As described, the conductivity of liquid material plays an important role in the capacitance measurements and as a result, in sensor operation. From Fig. 4, two major points can be concluded. First, the measured capacitance value recorded by the module is not only the liquid capacitance, but also the capacitance due to the liquid conductance. Thus, the present probe provides a sensitive cell for the investigation of conductance effect in such measurements. Among the tested water liquids, the salt water shows the highest measured capacitance value of 61.8 μF, whereas the distilled water shows the lowest measured value of 15.3 μF. A notable difference (45.5 μF) for salt water in capacitance values for different water liquids is indicative of the high sensitivity of the reported sensor.

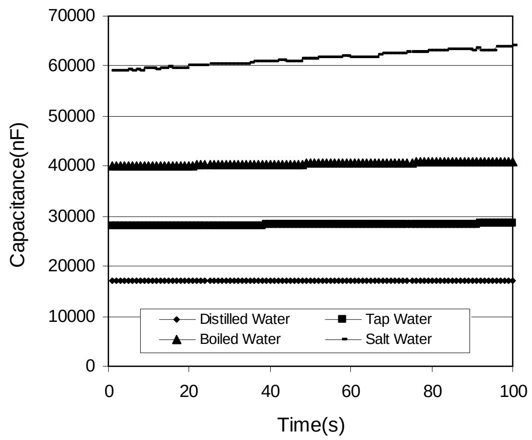

Fig.4. Capacitance values for different water liquids.

The second point is that the measured values are relatively constant for distilled, boiled, and tap water measurements, but larger fluctuations are observed in the salt water measurements. This leads to the fact that such fluctuations are certainly due to the conductivity effect. Therefore, the designed sensor can be used to investigate dynamic behavior of the liquid in such measurements. It can be concluded that the measured capacitance values are due to the dielectric term and a second term related to the conductivity of the liquid. For distilled water, the conductance effect is minimum but considerable for the salt water. For the air gap, such term vanishes and the measured capacitance is only due to first term f_1 as shown in Eq. 2. Thus the fluid capacitance can be obtained from the difference of the measured capacitance values and the f_2 term, Eq. (3), due to conductivity effect.

A comparison of results for different water liquids at given temperature is listed in Table 1. The electrical conductivity (EC), total dissolved solid (TDS), capacitance (C), and temperature (T) are listed in Table 1. As can be seen in Table 1 for the water samples, the EC factor is increased as well as the TDS in the given order for the tested water liquids. The capacitance value with the EC values confirms our argument about the effect of electrical conductance on capacitance measurements. It is noted that there is a relation between an increase in the electrical conductivity of the liquids and corresponding increase of the measured capacitance. Looking at Table 1, it is noted that the salt water has the highest EC value, 22100μS/cm, but the distilled water has the least EC value, 9.2 μS/cm, at the same temperature.

In Fig. 5, the repeatability of the results for reported capacitive cell sensor is shown. Such parameter indicates the ability of the sensor to reproduce output reading when operating under the same ambient condition. To provide such a condition, a number of measurements (100) were made sequentially for a series of readings. Such measurements, performed for all samples and for the case of air-gap, are shown in Fig. 5. The reproducibility of the measured values for such measurements is estimated to be about 1% of the full scale value.

The stability of a sensor is another important parameter described in this study. In general, such factor shows the ability of the sensor to maintain its performance characteristics for a certain period of time. In this experiment, the capacitance values for the air-gap and liquid-gap cases are measured for a period of 100sec in 1sec increment. Both measured values (dry and wet cases) show a good stability for this period of time, which is about 1% of the full scale. The repeatability of the reported sensor is also investigated. Such parameter indicates the ability of the sensor to reproduce output reading when operating under the same condition. To provide such a similar ambient condition, about 100 measurements were made in sequence.

Table 1: Comparison of the capacitance values for different water liquids.

Sample	Electrical Conductivity (μS/m)	Total Dissolved Solid Density (mg/L)	Measured Capacitance (μF)	Temperature (°C)
Distilled Water	9.2	11.3	19.6	25.4
Boiled Water	590	293.2	39.5	25.6
Mineral Water	443	220.5	36.1	25.6
Tap Water	375	190.1	29.2	25.1
Salt Water	22100	13100	61.4	25.4

*For the stabilized condition

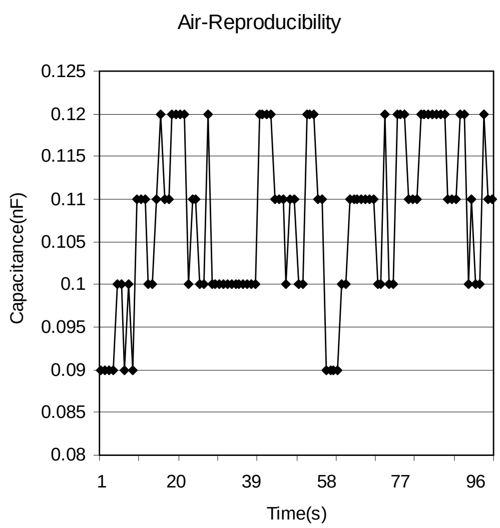

Fig.5. Reproducibility of the result for the sensor.

The error of the measured values in these measurements is estimated to be about 2% of the full scale.

To understand the importance of permittivity variation as a result of different liquids, we consider the measured values for a period of 100s in 1s increments (Fig. 6). As indicated in Fig. 6, the average permittivity values given for different liquids are 1246.455, 868.625, 721.654, 421.325 $\frac{nF}{m}$, for salt, boiled, tap, and distilled water, respectively. In general, the permittivity is more dependent on temperature and purity of materials. As described earlier, the highest measured permittivity value is 1246.455 $\frac{nF}{m}$ for salt water, while the lowest measured permittivity is 421.325 for distilled water. A significant difference (825.13 $\frac{nF}{m}$) in permittivity value for different liquids is indicative of the highest sensitivity of the reported sensor. From Fig. 6, we then find out that stability and sensitivity are two major properties for the application of this sensor.

To see the capacitance variation as a result of different water liquids, a series of measurements are performed and the measured values are shown in Fig. 4. As can be seen in Fig. 4, results of recorded capacitance values for distilled, boiled, tap, and salt waters as a function of measuring time are presented. The average capacitance values are 19278.54 nF, 29345.26, 41235.47, 61516.12 nF for distilled, tap, boiled, and salt waters, respectively. As described before, these values are just the measured capacitance values, which are much higher than the capacitance value of the liquids. The capacitance value of distilled water is around 3 pF as reported in Ref. [20]. It is noted that the measured values are mainly related to the conductance term and can be used effectively to monitor the conductance and its dynamic developments in liquid filling.

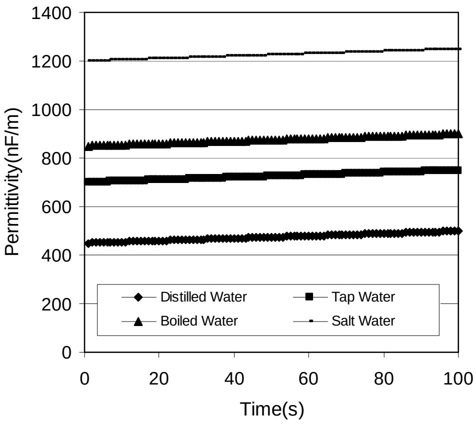

Fig.6. Comparison of the permittivity values for different water liquids as a function of time.

For the case of distilled water, the capacitance value starts from the 6.5 μF and reaches to about 19.59 μF in a 450sec time interval (as can be seen in Fig. 7.). As indicated, the value given for the distilled water in Fig. 4 is for the case of stabilized final condition. However, for other water liquids, the stable condition is reached quickly in about a few seconds and then the measured values are plotted. As described, the conductivity of liquid material has important role in the capacitance measurements and as a result in sensor operation.

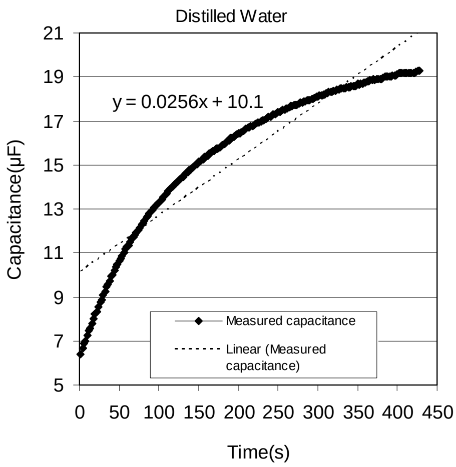

Fig.7. Capacitance measurement as a function of time for distilled water.

From Fig. 4, two major points can be concluded. First, the measured capacitance signal value recorded by the module is not only the liquid capacitance, but also the output due to the liquid conductance. Such measured value is due to dielectric reactance capacitance, conductance, and the stray terms. Thus the present device provides a sensitive probe for the investigation of conductance effect in such measurements. Among the tested water liquids the salt water shows the highest measured capacitance value of 61.51 μF, while the distilled water shows the lowest measured value of 19.52 μF. A notable difference (41.99 μF for salt water) in capacitance values for the different water liquids is an indication of high sensitivity of reported sensor. To verify this point in another experiment, the capacitance and the resistance of the sensor cell filled with different liquids are measured at the recorded temperature and the results of these measurements are listed in Table 1. As can be seen, the reciprocal of the resistance shown as conductance is also obtained and shown in Table 1. It is noted that there is a direct relation between the increase of the conductance and that of the measured capacitance output.

The second point is that the measured values are relatively constant for distilled, boiled, and tap water, but as indicated in Fig. 8, larger fluctuations are observed in the salt water measurements. This leads to the fact that such fluctuations are certainly due to the conductivity effect, which are more pronounced for the salt water due to higher conductivity. As can be seen in Fig. 4, such effect is smaller for pure distilled water, but the presence of conductive impurity plays an important role in the case of salt water. The designed sensor, therefore, can be used to investigate dynamic behavior of the liquid in such measurements.

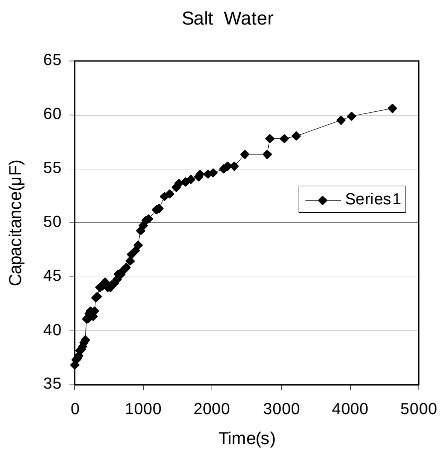

Fig.8. Variation of the capacitance as a function of time for salt water.

The variation of capacitance as a function of time for distilled water is presented in Fig. 7. The capacitance value starts from 6.5 µF at about 5sec and reaches to about 19.27 µF at 450sec. Using the add trend line option of the program, a fitted curve (dashed-line) is also presented in Fig. 7. As can be seen in Fig. 7, the measured value shows a rapid growth and reaches a stable condition in about 7.5 minutes. Comparing the experimental results with the fitted polynomial curve, it is noted that there is a good agreement between the measured values and the fitted one for the rising part and there is only a little deviation for the later times. This time variation situation tested several times and it was reproducible for the distilled water. Such dynamic behavior can be explained as follows. The physical model of the situation, when there is no contact between the electrode metal and liquid, is equivalent to a circuit consisting of a capacitor of reactance X_1 in series with a resistor R_x (liquid resistance). When there is a contact between the electrode metal and liquid, the equivalent circuit is different from the first case and can be considered to be a capacitor of reactance X_2 in parallel with a resistor R_b, both in series with a resistance of R_2 in which R_b is the resistance of the liquid bridge and R_2 is the resistance of the main bulk of the liquid. At the start, the liquid filling the bridge resistance is not fully formed and the measured value is low. As time goes on, the bridge resistance is build up and the reading value is rapidly increased. After some time, the contact resistance is fully formed and the output reading of the sensor is almost constant. The reported sensor also provides a mean to investigate the dynamic behavior of such liquid bride resistance formation. Comparing our results for the cases of distilled, tap, and salt water, it was noticed that such a bridge contact is formed very quickly for the samples with high conductivity effect, which verifies the described bridge contact physical model.

Precision is defined as a measure of the reproducibility of the measurements that is considered as a figure of merit for such a sensing device. Fig. 9 shows the repeatability of the reported sensor. In this sensor, such a parameter indicates the ability of the capacitive sensor to reproduce output reading when the same measurement is performed in sequence and under the same condition. To provide such similar ambient conditions, measurements were made consequently for a series of 50 readings. The output capacitances for such repeated measurements are shown in Fig. 9, which varies from 0.09 nF to 0.12 nF at most. The average signal value calculated to be 0.1054 with the standard deviation of 0.009521 in measurements. For a better comparison average value of capacitance measurement (dry signal) is also indicated as a dashed line in Fig. 9.

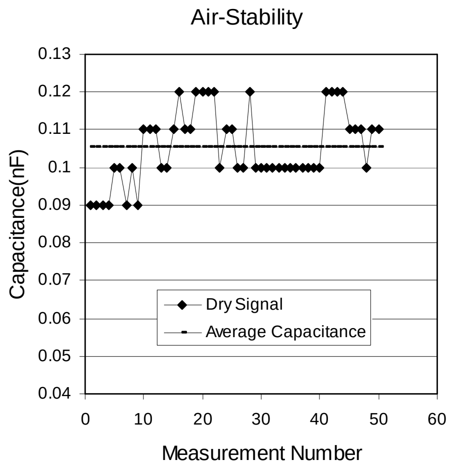

Fig.9. Reproducibility of the results for the designed sensor.

5. Conclusion

As described, the invasive sensor such as the one reported here, provided a useful mean to study the conductance effect of the reactance capacitance and its role in capacitance measurements. On the other hand, the non-invasive design is more suitable for studies concerning the permittivity effect of the liquids. In either case, one needs to minimize the impact of the other factor in order to obtain more reliable readings. The results, both of the capacitive probe and the capacitance readout circuits, have important role in the accuracy of absolute measured values for different type of conducting and non-conducting liquids.

For the case of a gap material with low conductivity, the charge/discharge method was used with the proposed parallel-plate probe to measure capacitance. This was a useful method for checking the quality of the water, which is required for different applications. Although the results reported here were for the water liquids, the reported sensor could be effectively implemented for the study of other conducting liquids such as industrial oils, and liquids, which have wide applications as lubricator, electric insulator, and cooling agents with a notable conductance contribution. Arrangement described also can be used for liquid mixture checking and also to see the effect of impurities in the water solution.

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