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Design and Performance of a Cylindrical Capacitive Sensor to Monitor the Electrical Properties

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Abstract: In this study, design and operation of a cylindrical capacitive sensor based on the dielectric and reactance capacitance changes of the gap medium is reported. The proposed system was used to determine the electrical properties of different water liquids as a result of the capacitance variations. For capacitance measurement, the cylindrical gap can be filled up by water liquids under study, the electrical characteristics of different water liquids, mixture of ethanol and water, mixture of methanol and water, mixture of petroleum and water and other liquid mixtures were studied. In this research a big difference about 16200 nF was noticed in the measured capacitance of the corresponding liquids. It must be pointed out that the measuring capacitance of the sensor is different from that of the liquid capacitance, but the liquid electrical characteristics can be compared relatively with each other. The experimental results are promising for water liquids and verify the successful operation of such device as a liquid sensor and is a useful method for checking the electrical quality of the water mixture that is required for different applications.

Key words: Sensor, capacitive sensor, electrical properties, water liquids, capacitance measurement

INTRODUCTION

Concentration measurement of two-component fluids using capacitance sensing techniques is sometimes affected by conductivity variations of the components. Typical examples of this problem occur in measurement of water content of oil-water mixtures in the oil industry and of glass bead concentration in water slurries in the machining industry (Strizzolo and Cinverti, 1993). The conductivity problem has been of most concern in the area of dielectric measurement. There has been a great deal of interest in the development of precise capacitive sensors in recent years. Different reports on the design, characterization, operation and possible applications of such devices have been given by Golnabi (1997), Ahn *et al*. (2005) and Zadeh and Sawan (2005). 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 the problems in this field a variety of the capacitive sensor systems have been developed and reported. In this respect, for example, the effects of a guard ring electrode on the operation of a capacitive transducer have been investigated (Golnabi, 2000). Development of a three-dimensional capacitance imaging system for measuring the density of fluidized beds was reported (Fasching *et al*., 1994). In another report design and operation of a capacitive sensor for water content monitoring in a production line was presented (Tsamis and Avaritsiotis, 2005).

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 the operational amplifier1/f-noise and offset voltage. A new capacitive-to-phase conversion technique for measuring very small capacitance changes has been reported (Ashrafi and Golnabi, 1999). This method provided a powerful mean for recording very small capacitance changes. Much progress has been made over the last years in developing the capacitor transducers and complementing measuring circuits. For the precision in instrumentation and measurements, the small capacitances to be measured are in the range of 0.01-10 pF with a required resolution of better than

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0.01-10 fF. This requirement along with other considerations such as environmental effects, structural stability and standardization challenges the development of a much more sensitive and reliable capacitance sensor systems (Woodard and Taylor, 2007).

MATERIALS AND METHODS

Experiment: Capacitance measurement system in general includes a sensing probe and a measuring module. Present 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 cylindrical capacitive sensor, two digital multimeter (DMM) modules (SANWA, PC 5000), a reference capacitor and a PC. As shown in Fig. 1, one of the digital multimeters is used for the capacitance measurement and a similar one together with a temperature probe (T-300PC) is used for the temperature measurements. The DMM has features such as the real time graphic display with scale grid, real-time display of MAX and MIN values with time stamp and current measuring window (SANWA ELECTRIC INSTRUMENT CO.).

It provides more functions with optional accessories such as temperature probe that is used in this experiment. The software (PC Link plus) allows one to log measuring data into PC through RS232 port with digital multimeter 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 the best nominal accuracy of ± (0.8% rdg +3) and a resolution of about 0.01 nF. The temperature probe consists of a platonic thin thermoresistor (1000 Ω at 0°C) with a temperature measurement range of -50 to 300°C. The response time of this probe is about 7 sec and offers an accuracy of about ±0.1°C in temperature recording.

May I attract your attention to these experiments that are performed in institute of water and energy laboratory in Sharif University of technology in November 2007.

The proposed capacitive probe shown in Fig. 2 consists of a three-part coaxial capacitive sensor in which the middle one is acting as the main sensing probe and the other two capacitors considered as the guard rings in order to reduce the stray capacitance effect and source of errors in measurements (it must be mentioned that such design is more useful for the case of small capacitance change measurements). As shown in Fig. 2, in this experiment a cylindrical geometry is chosen and aluminum materials are used as the capacitor tube electrodes. The diameter of the inner electrode is about 12 mm and the inner diameter of the outer electrode is about 23 mm and has a thickness wall diameter of about 3.5 mm. The overall height of the probe is about 12 cm while the active probe has a length of about 4 cm. The radial gap between the two tube electrodes is about 5.5 mm and the overall diameter of the probe is about 3 cm. The length of the employed wire connection to the inner active electrode is about 5 cm. As shown in Fig. 2, the middle active part of the probe has a length of 4 cm and outer guard electrodes have a length of about 3 cm.

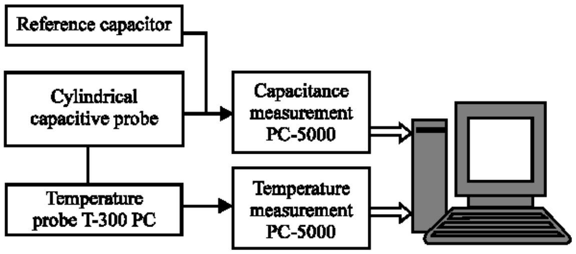

Fig. 1: Block diagram of the experimental arrangement for capacitance measurements

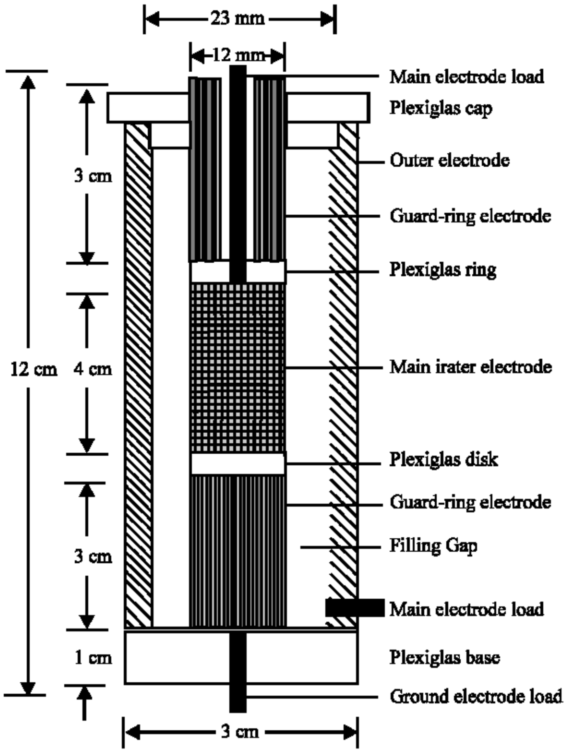

Fig. 2: Diagram of the designed cylindrical capacitive sensor

Using Gauss's law the capacity of a long cylindrical capacitor can be obtained from

$$C = \frac{2\pi\varepsilon L}{\mathrm{Ln}\frac{b}{a}} \quad (1)$$

where, ε is the permittivity of the gap dielectric medium. Here a is the inner electrode radius, b outer electrode radius and L is the capacitor length. However Eq. 1 is only valid when L>> a, b. Several problems such as edge effect, can cause deviation in the actual capacity from the given formula in Eq. 1. For this reason, various attempts have been made to reduce errors due to limited size effects. One simple remedy has been the use of a Kelvin guard-ring (Golnabi, 2000) in which the main inner electrode is shielded by a grounded guard-ring electrode.

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 the given permittivity and conductivity, the equivalent circuits for the case of non-invasive and invasive sensors have been investigated by Stott *et al.* (1985).

It must be mentioned that the given capacitance value is the measured value by the charge transfer reading circuit and fluid capacitance must be deduced from the measured values. Also noted that the capacitance sensing is affected by the conductivity variations of the components (Light *et al.*, 2005). 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. As a result an investigation into the effects of component conductivity should be done for precise measurements.

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 (Fig. 3a). In this analysis R_x representing 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. 3b 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 is depending on both C_x and R_x of the fluid under measurement.

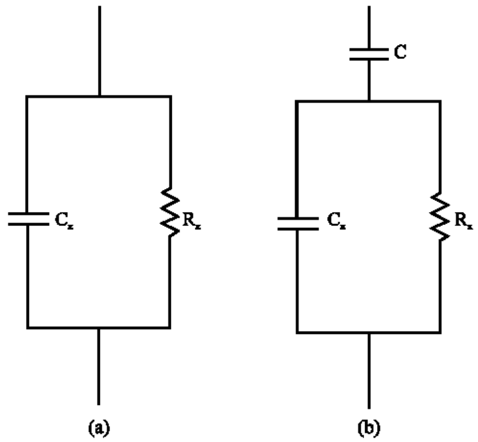

Fig. 3: Equivalent circuits for the invasive (a) and non-invasive (b) electrode arrangements

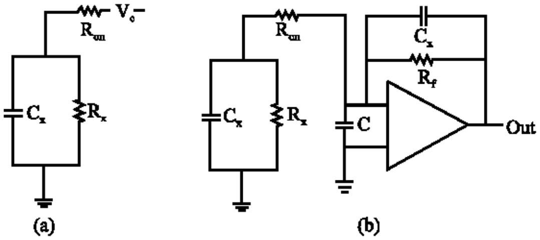

Fig. 4: Schematics of the capacitance charge (a) and discharge (b) processes

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 C_x to a voltage V_c via a CMOS switch with resistance R_{on} (Fig. 4a) and then discharging this capacitor into a charge detector via a second switch (Fig. 4b). The charge transferred from C_x to the detector in a single C/DC cycle is:

$$Q = V_c.\ C_x. \quad (2)$$

Such operation is repeated at a frequency f under the control of a clock. The discharging current pulse is averaged in the detector to produce an average current I_m that is

$$I_m = V_c.\ C_x.\ f. \quad (3)$$

And this signal is further converted by the detector to give a dc output voltage V' such as

$$V' = R_f.\ V_c.\ C_x.\ f, \quad (4)$$

where, R_f is the detector feedback resistance as shown in Fig. 4b.

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 10 nF to 50 mF. Since the reported reading module can not measure precisely the capacitance values smaller than 10 nF, thus for such cases a reference capacitor (470 nF), as shown in Fig. 1, is used in parallel with the sensor capacitance to assure the proper readings for the small capacitances. In this arrangement smaller capacitance values can be measured more precisely and with a high resolution of about 0.01 nF. However, for high capacitance values such a reference capacitor is not required.

The capacitance measurements for the cylindrical probe shown in Fig. 2 depend on the permittivity, ε (F/m), of the mixture of liquids and its resistance factor that depends only on the conductivity, σ (S/m), of the liquid. The capacitive value is obtained only by the insulation of the electrodes and reducing the conductivity effect. Complex permittivity of a medium can be written as:

$$\varepsilon - j\frac{\sigma}{\omega} \tag{5}$$

where, $\omega = 2\pi f$ and f is the frequency of the readout measurements. For Charge/Discharge method the measurement frequency is in kHz-MHZ range. Thus a comparison of $\sigma/\omega\varepsilon$ to unity could be carried out to determine whether a particular medium is predominantly a dielectric, quasi-conductor or a conductor.

As described, in general there are invasive and non-invasive electrode arrangements. For the case of non-invasive sensors, in measuring capacitance of a liquid mixture, 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 can not be neglected and the effect of conductivity of the liquid mixture 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 with the time constant given by $T_x = R_x C_x$.

RESULTS AND DISCUSSION

Since the minimum reliable limit of DMM is about 0.01 nF, therefore the results for air reading were not so reliable and as mentioned a parallel reference capacitor is used as indicated in Fig. 1. However, when the gap is filled with a liquid mixture, since the dielectric constant of the fluid is larger than that of the air, then the measured capacitance value is increased and the reference capacitance is not necessary. As described, our measuring apparatus is operating under the charge/discharge technique.

In order to test the precision of the capacitance measuring module, in the first experiment the capacitance of a known reference capacitor is measured. For a capacitor with the nominal value of 470 nF the average measured capacitance for this reference is about 494.2 nF. The extra value of the capacitance is most likely due to the lead probe capacitance, which is added to the capacitance of the reference capacitor. As mentioned the best accuracy of the DMM for capacitance measurement is about ± (0.8% rdg+3dgt) which are ±0.7 nF for 50 nF, ±7.0 nF for 500 nF and ±0.7 μF for 50 μF range.

As described the averaged measured capacitance for the reference capacitor is found to be 492.5 nF and after this investigation the air gap capacitance of the sensor was investigated. The averaged air gap capacitance of the probe when it is parallel with the reference capacitor is around 497.5 nF. By subtracting the value of the reference capacitance, thus the air gap capacitance for the designed probe is about 5 pF. However, as described this value is different from the calculated value of 3.6 pF from Eq. 1. It must be pointed that Eq. 1 is obtained with the assumption that the length of the probe is much higher than its gap, which is not satisfied for our probe; therefore the observed difference looks reasonable.

Stability of a sensor is another important parameter, which is 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 mixture-gap cases are measured for a period of 100 sec in 1 sec 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 conditions a number of about 100 measurements were made consequently. The error of the measured values for the consequent measurements is estimated to be about 2% of the full scale.

To understand the importance of permittivity variation as a result of different liquids, in Fig. 5 we consider the measured values for a period of 50 sec in 1 sec increments. As indicated in Fig. 5 the average

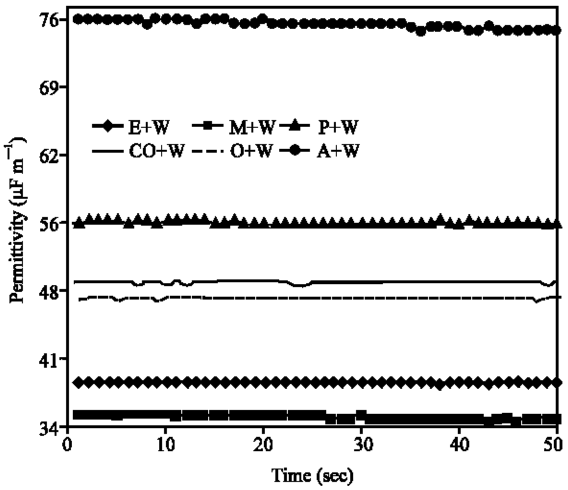

Fig. 5: Comparison of the permittivity values for different water liquids as a function of time

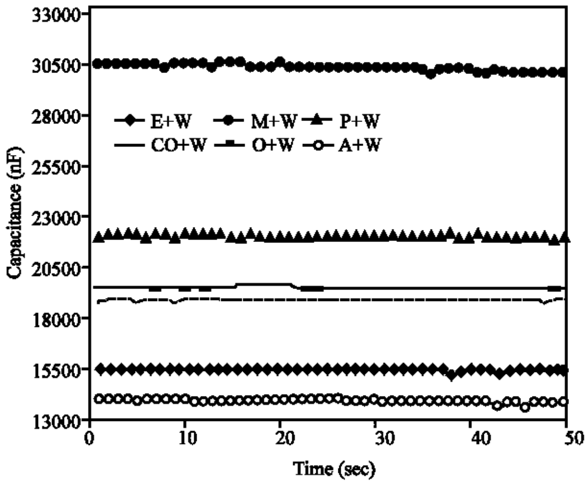

Fig. 6: Comparison of the capacitance values for different water liquids as a function of time

permittivity values given for different liquids are 75.76, 54.94, 48.67, 46.91, 38.38, 35.12 μF m^{-1}, for the mixture of antifreeze and water (A+W), mixture of petroleum and water (P+W), mixture of consumed oil and water (CO+W), mixture of oil and water (O+W), mixture of ethanol and water (E+W), mixture of methanol and water (M+W). Generally the permittivity is more dependent on temperature and purity of materials. As described the highest measured permittivity value is 75.76 μF m^{-1} for the mixture of antifreeze and water while the lowest measured permittivity is 35.12 for mixture of methanol and water, considering a significant difference (40.64 μF m^{-1}) in permittivity value for different liquids is indicative of the highest sensitivity of the reported sensor, then finally from Fig. 5 we find out stability and sensitivity are two major properties for the application of this sensor.

To understand the importance of capacitance variation as a result of different liquid mixtures, in Fig. 6 we consider the measured values for a period of 50 sec in 1 sec increments. As indicated in Fig. 6 the average capacitance values given for different liquid mixtures are 15300, 14000, 21900, 19400, 18700, 30200 nF, for mixture of ethanol and water, mixture of methanol and water, mixture of petroleum and water, mixture of consumed oil and water, mixture of oil and water, mixture of antifreeze and water, the capacitance is more dependent on conductance and purity of materials. As described before, these values are just the measured capacitance values, which are much higher than the capacitance value of the liquid mixtures. 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.

We considered the highest measured capacitance value is 30200 nF for mixture of antifreeze and water, while the lowest measured capacitance is 14000 nF for mixture of methanol and water, considering a significant difference (16200 nF) in capacitance value for different liquid mixtures is indicative of the highest sensitivity of the reported sensor, then finally from Fig. 6 we find out stability and sensitivity are two major properties for the application of this sensor.

From Fig. 6 two major points can be concluded. First, the measured capacitance signal value recorded by the module is not only the liquid mixture capacitance but also the output due to the liquid conductance. Such measured value is due to both of the dielectric reactance capacitance, conductance term and the stray terms. Thus the present device provides a sensitive probe for the investigation of the conductance effect in such measurements.

Second point is that the measured values are relatively constant for the mixture of water and, ethanol, methanol, petroleum, consumed oil, oil, antifreeze measurements, but as indicated in Fig. 6, larger capacitance are observed in the mixture of water and antifreeze measurements. This leads to the fact that such capacitance is certainly due to the conductivity effect, which are more pronounced for the mixture of water and antifreeze due to higher conductivity. As can be seen in Fig. 6, such effect is smaller for the mixture of water and methanol. The designed sensor, therefore, can be used to investigate dynamic behavior of the liquid in such measurements.

Figure 7 shows the comparison of capacitance measurement for different liquid mixtures with the different

Table 1: Comparison of the electrical properties for different water liquids

Sample	Electrical conductivity ($\mu S\ cm^{-1}$)	Total dissolved solid density ($mg\ L^{-1}$)	Measured capacitance (nF)	Volume percentage additive	Temperature (°C)
Tap water	560.00	272.00	22000.00	0	23.60
Mixture of methanol and water	244.00	116.80	16300.00	43.75	22.80
Mixture of ethanol and water	432.00	193.00	19000.00	43.75	24.00
Mixture of antifreeze and water	1493.00	741.00	26000.00	43.75	22.90
Mixture of petroleum and water	500.00	242.00	20200.00	43.75	23.20
Mixture of oil and water	507.00	245.00	20800.00	43.75	23.00
Mixture of consumed oil and water	514.00	249.00	20900.00	43.75	22.90
Mixture of ethanol and water	244.00	116.80	16300.00	43.75	22.80

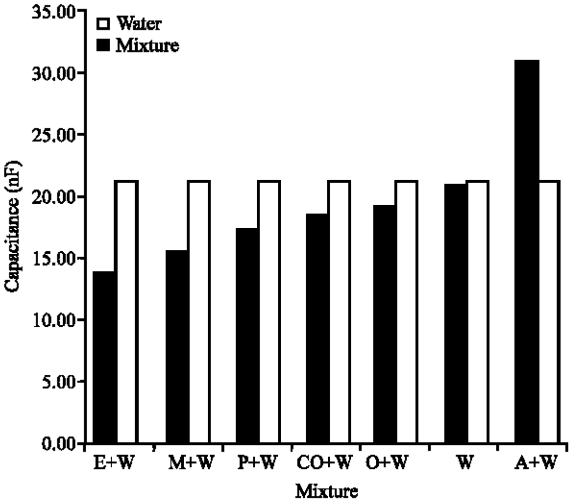

Fig. 7: Comparison of capacitance measurement for different liquid mixtures. Measurements are for water (W), mixture of ethanol and water (E+W), mixture of methanol and water (M+W), mixture of petroleum and water (P+W), mixture of consumed oil and water (CO+W), mixture of oil and water (O+W), mixture of antifreeze and water (A+W)

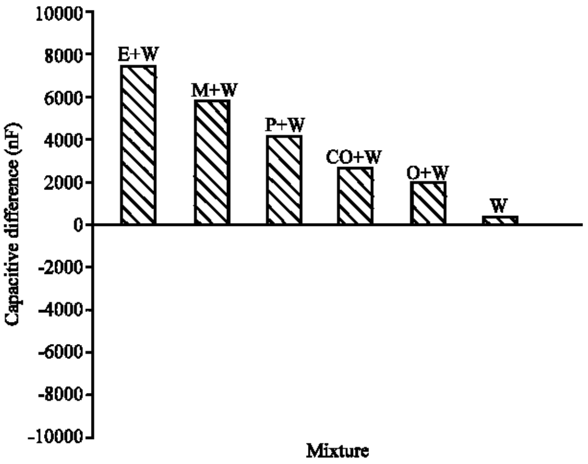

Fig. 8: Capacitance difference for different liquid mixture. Measurements are for water (W), mixture of ethanol and water (E+W), mixture of methanol and water (M+W), mixture of petroleum and water (P+W), mixture of consumed oil and water (CO+W), mixture of oil and water (O+W), mixture of antifreeze and water (A+W)

electrical conductivity from 244.00 $\mu S\ cm^{-1}$ for mixture of methanol and water to 1493.00 $\mu S\ cm^{-1}$ for mixture of antifreeze and water. These mixtures have different total dissolved solid density (TDS) that it is important factor in capacitance measurements. The reported capacitances are for mixture of ethanol and water (E+W), mixture of methanol and water (M+W), mixture of petroleum and water (P+W), mixture of consumed oil and water (CO+W), mixture of oil and water (O+W), mixture of antifreeze and water (A+W). As can be seen in Fig. 6 the mixture of antifreeze and water capacitance in general is higher than the other mixtures because of its electrical conductivity and TDS is more than the other liquids (Table 1).

In this sensor operation the capacitance difference between the tap water and water mixture is more important and hence in Fig. 8 such a capacitance difference is indicated for the same liquid mixtures. The capacitance difference for the water is about 500 nF while it reaches to about 7500 nF for the mixture of ethanol and water, which shows the reasonable sensitivity of the reported design for the liquid mixture sensing.

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.

In this sensor such a parameter indicates the ability of the cylindrical capacitive sensor to reproduce output reading when the same measurement is applied to it consequently, under the same condition. To provide such a similar ambient conditions measurements were made consequently for a series of 40 readings. The output capacitances for such repeated measurements are shown in Fig. 9, which varies from 494.1 to 494.3 nF at most. The average signal value calculated to be 494.20 with the standard deviation of 0.1414 in measurements. For a better comparison average value of capacitance measurement (Dry signal) is also indicated as a dashed line in Fig. 9.

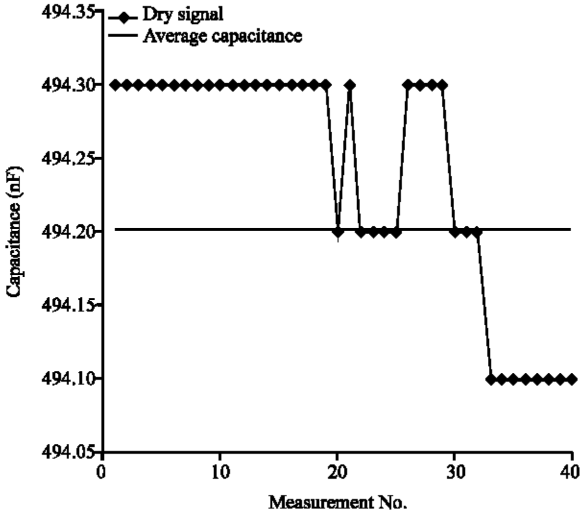

Fig. 9: Reproducibility of the results for the designed sensor

To analyze electrical condition of the tested water liquids, another device was used to measure the electrical conductivity (EC) and total dissolved solid (TDS) density of the water samples used in this experiment. As can be seen the EC factor is increased as well as the TDS in the given order for the tested water liquids. Considering the capacitance value with the EC values confirms our argument about the effect of the electrical conductance on the capacitance measurements. It is noted that there is a relation between the increase of the electrical conductivity of the liquids and the increase of the measured capacitance. Looking at the given values for the electrical conductivity in Table 1, it is noted that the Mixture of antifreeze and water possess the highest EC value of 1493.00 μS cm^{-1} while the Mixture of methanol and water shows the least EC value of 244.00 μS cm^{-1} at the same room temperature.

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. Considering the results both of the capacitive probe and the capacitance readout circuits have important role in the accuracy of the 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 cylindrical probe to measure capacitance. This was a useful method for checking the electrical quality of the water mixture, which is required for different applications, the results reported here were for these such as industrial oils and liquids, which have wide applications as lubricator, electric insulator and cooling agents with a notable conductance contribution. Arrangement described above is used for liquid mixture checking and also to see the effect of impurities in the water solution.

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