Abstract: In this paper design and operation of a capacitive cell sensor for liquid mixture monitoring is reported. The capacitive effect of small drop of different liquids in tap water was studied using this capacitive sensor. A small percentage of a contaminating agents such as oil in tap water is determined with a good sensitivity. Important factors concerning operation of the sensor such as the precision, reproducibility, and stability are reported. Output variation of the measured values with the temperature (27-73.5 °C) are also investigated for tap water and different water mixtures. An averaged variation of 0.8348 µF/°C in output measurement for tap water is obtained. Our results indicate an averaged variation of 0.4324 µF/°C for the fresh oil and a variation of 0.5121 µF/°C for the used water oil mixture. An averaged variation of 0.4840 µF/°C for methanol, 0.5048 µF/°C for the ethanol, and 0.8250 µF/°C for water antifreeze mixtures are obtained. For water + salt mixture our data shows that the sensitivity change exhibits a factor of 12.69 increase in sensitivity when temperature increases from 24.7 °C to 40.0 °C. Hence to determine a trace impurity, this methodology provides more accurate results at low temperatures (room temperature) and requires less temperature compensation for calibration.

Key words: Water, Water Mixture, Monitoring, Sensor, Capacitance, Resistance

INTRODUCTION

For several years capacitive sensors have been used in different applications for measuring a variety of parameters (Fasching et al., 1994; Golnabi, 1997; Guo et al., 2000; Kasten et al., 2000; McIntosh, R. B. and P. E. Mauger, 2006; Moe et al., 2000; Morgan, V. T. and D. E. Brown, 1969). Due to their inherent simplicity and low cost they have found many industrial applications. Much emphasis has been placed on the works to construct a sensor with output capacitance, which varies linearly with the measurand. On the other hand, efforts have been made on the development of the capacitance readout circuits. A differential charge-transfer readout circuit for multiple capacitive sensors was reported recently (Heidari, M. and P. Azimi, 2011; Rodjegard, H. and A. Loof, 2005). 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, A. and H. Golnabi, 1999). This method provided a powerful means for recording very small capacitance changes.

For the case of liquid mixture sensors, for example, the sensor output respond as a function of the volume content of one of the component materials within the sensing cell is desired. The conductivity effects on capacitance measurements of two-component fluids using the charge transfer method for capacitance measurements has been reported (Golnabi, H. and P. Azimi, 2008). The measuring method was the charge and discharge technique and the measured capacitance was described as a sum of the fluid capacitance and its conductance. They explained a way to determine the conductance term in order to determine the fluid capacitance using the Charge/Discharge method. Their model considers the invasive and non-invasive sensors for measuring capacitance for the conducting and non-conducting fluids.

In another report capacitance sensors have been used for the measurement of the phase volume fraction in two-phase pipelines (Strizzolo, C. N. and J. Cinverti, 1993). The effect of phase distribution or flow pattern was considered for determination of the 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 and they have shown such effect by an example. In that article they described the resulting capacitance when the electrodes are half filled vertically or horizontally similar to the series or the parallel capacitive forms.

In a report estimating water content in soil from electrical conductivity measurements with short time domain reflectometry (TDR) was given (Persson, M. and S. Haridy, 2003). In that experiment they have used TDR technique for measuring soil water content and bulk electrical conductivity. In most TDR application probes consisting of two or tree metals 0.02 -0.5 m in length are used. This instrument sends a broad band electromagnetic signal along a probe buried in the soil. The signal is reflected at the end of the probe and its travel time is measured from the resulting waveform. The travel time then can be related to the soil dielectric constant. For the dielectric constant, κ, calibration they have performed the experiment in the air and in the
water as references. For the electrical conductivity, \( \sigma \), calibration; they have used salt solution (KBr) over a range of 0.0017 to 10.6 dSm\(^{-1}\).

In literature applications of the capacitance type sensors for measurement of water content of different materials have been reported. For example in (Tsamis, E. D and J. N. Avaritsiotis, 2005), design of planar capacitive sensor for water monitoring in a production line was reported. Such methods are suitable to be used in real time lay out in which measurements are conducted in several places along the production line in order to monitor the product's moisture.

In another experiment the fundamental conductivity and resistivity measurements of water have been reported (Light et al., 2005). They have used the electrochemical method for such measurements. The conductivity and its reciprocal, resistivity are related to the basic chemical properties of water such as the density, specific conductance of H\(^+\) and OH\(^-\)(S-cm\(^{-2}\)/mol); and \( C_{H^+} \) and \( C_{OH^-} \), which show the concentration (mol/kg water) of these ions, respectively. In their design they have used an array of conductivity sensors and platinum resistance temperature devices that are positioned in the deionizing loop. Each conductivity cell consists of Thoroton 230-11 conductivity sensor and Thornton 770 MAX, was calibrated to 18.18 M\( \Omega \)-cm at 25 \( ^\circ \)C and the resistivity was measured to an accuracy of \( \pm 0.1\% \).

Monitoring water component plays important role in different applications. For example in wastewater contamination, monitoring the water components, in particular hazardous ones, plays a crucial role. The idea here is to use the conductance effect and as a result the capacitance variation of a mixture in order to monitor the added agent to water sample. Since the conductivity of the material differs, thus one can monitor the existence of the foreign agent in the pure water sample. This can be a sensitive method for monitoring water contents, in particular those which are hazardous for the drinking purpose and all other applications that the quality of the water is really important.

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 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 (SANWA ELECTRIC INSTRUMENT CO. LTD. Internet Gateway at http://www.sanwa-meter.co.jp/).

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 a resolution of about 0.01 nF. The nominal input impedance of the DMM is about 10 M\( \Omega \) and 30 pF. The specified accuracy of the DMM for 50.00-500.0 nF capacitance range is about \( \pm (0.8 \% \text{ rdg} + 3 \text{ dgt}) \) and \( \pm (2 \% \text{ rdg} + 3 \text{ dgt}) \) for the 50.00 \( \mu \)F range. The temperature probe consists of a platonic thin thermo resistor (1000 \( \Omega \) at 0 \( ^\circ \)C) with a temperature measurement range of -50 to 300 \( ^\circ \)C. The response time of this probe is about 7 seconds and offers an accuracy of about \( \pm 1.9 \ ^\circ \\text{C} \) in temperature recording.

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 17 mm and has a thickness wall diameter of about 3 mm. the overall height of the probe is about 18 cm while the active probe has a length of about 4 cm. The radial gap between the two tube electrodes is about 3 mm, and the overall diameter of the probe is about 5 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.

Using Gauss's law the capacity of a long cylindrical capacitor can be obtained from
\[
C = \frac{2\pi \varepsilon a L}{\ln \frac{b}{a}},
\]

where \(\varepsilon\) 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 \(L \gg a, b\) (in general, \(A \gg d\), \(A\) electrode area and \(d\) gap distance). 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, H., 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 can be considered.

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. 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; 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.

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 \(R_{on}\) and then discharging this capacitor into a charge detector via a second switch.

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. Since the reported reading module can not measure precisely the capacitance values smaller than 10 pF, 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. 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, \(\varepsilon\), of the liquid and its resistance factor that depends only on the conductivity, \(\sigma\), of the liquid. Thus one can write

\[
C_x = f_1 (\varepsilon),
\]

\[
R_x = f_2 (\sigma).
\]

The capacitive element \(C\) is obtained only by the insulation of the electrodes and reducing the conductivity effect. 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, 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 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 \(R_x C_x\).

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 usually measurements is 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 is used (Hach Company, Cat NO. 51800-18, sension5 Conductivity Meter Manual.), 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...
measured capacitance value of 47.8 μF. Thus the present probe provides a sensitive cell for the investigation of the conductance effect in such measurements. Among the tested water liquids the salt water shows the highest measured capacitance value recorded by the module is not only the liquid capacitance but also the capacitance compensated for the conductance effect. This leads to the fact that the measured value is not the capacitance value of the distilled water and must be pointed that the theoretical value is for the long cell and the mentioned difference seems reasonable. In order to test the precision of the capacitance measuring module, in the first experiment the capacitance of a known reference capacitor is measured (494.2 nF). By subtracting the value of the reference capacitance, thus the air gap capacitance for the designed probe is about 497-503 nF. The air gap capacitance of the probe when it is parallel with the reference capacitor is around 497-503 nF. By subtracting the value of the reference capacitance, thus the air gap capacitance for the designed probe is about 7-8 pF. However, as described this value is different from the calculated value of 4.35 pF from Eq. (1). It must be pointed that the theoretical value is for the long cell and the mentioned difference seems reasonable. In the next test the capacitance value for the distilled water is measured. In the first case using the reference capacitance in parallel with the probe the measured value is about 0.5 μF, which results a measured value of about 8 nF for the distilled water. 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 are performed and results are shown in Fig.3. As can be seen in Fig.3, the distilled water shows the lowest measured value and the water salt solution shows the highest (47.8 μF) value among the tested liquids. Next to the distilled water a solution of distilled water and the tap water shows the small measured capacitance value. For the 0.83% (v/v) addition of the tap water capacitance is about 11.56 μF, which results a measured value of about 16.12 μF, which increases to about 16.12 μF for the 1.66 % (v/v) mixture.

For the case of distilled water the capacitance value starts from the 0.5 μF and reaches to about 1.34 μF in a few seconds time interval. As described conductivity of the liquid material has important role in the capacitance measurements and as a result in sensor operation. From Fig.3 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 the conductance effect in such measurements. Among the tested water liquids the salt water shows the highest measured capacitance value of 47.8 μF while the distilled water shows the lowest measured value of 1.34 μF.
Considering a notable difference (46.46 μF for salt water) in capacitance values for the different water liquids is indicative of the high sensitivity of the reported sensor.

Second point is that the measured values are relatively constant for the 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. The designed sensor, therefore, 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 the distilled water the conductance effect is minimum while for the salt water has the considerable value. For the air gap such term vanishes and the measured capacitance is only due to the first \( f_1 \) term 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 the conductivity effect.

In the next study to see the capacitance variation of the different water mixtures containing foreign agents a series of measurements are performed. In Fig. 4 a comparison of the measured capacitance values for water and water-mixtures is presented. All measurements for mixtures are for the base solution of tap water at a temperature of 23 °C. The measured value for the tap water is 20.5 μF while all the mixtures except the water +antifreeze as can be seen in Fig. 4 show lower values. Among all the mixtures water +methanol shows the lower value of 13.8 μF while for the water +petroleum it is about 19.8 μF. The measured value for the water + antifreeze sample is about 29.4 μF. One interesting point is in this study is a comparison of the water containing the fresh oil and water mixture with the same type of consumed oil after the usage. The results displayed in Fig. 4 indicate that the cell sensor can be used to recognize different mixtures by comparing the results with that of a known standard water sample.

A comparison of the results for different water liquids and mixtures at given temperature is listed in Table 1. The electrical conductivity (EC), total dissolved solid (TDS), capacitance(C), volume fraction percentage(v/v) 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. 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 Table 1, it is noted that the salt water possesses the highest EC value of 21700 μS/cm while the distilled water shows the least EC value of 5.4 μS/cm at the same temperature. In Table 2 conductivity range for different aqueous solutions is shown (Hach Company, Cat. NO. 51800-18, sension5 Conductivity Meter Manual.). As can be seen in Table 2 among all the water samples the high pressure boiler water shows the least conductivity (0.1-0. 2 μS/cm) while the industrial process water has the highest electrical conductivity in the range of 8-130 mS/cm.

In Figure 5 the repeatability of the results for the 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 150 measurements were made consequently for a series of readings. Such measurements are performed for all the samples and for the case of tap water-gap is shown in Fig. 5. The reproducibility of the measured values for such consequent measurements is estimated to be about 1% of the full scale value.

Stability of a sensor is another important parameter, which is described in this section. 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 liquid-gap (tap water) is measured for a period of 600 s in 10 s increment. The result of such study is shown in Fig. 6. As can be seen measured values show a good stability for this period of time, which is about 1.5 % of the full scale. Since the response time of the sensor is in the order of a few seconds, therefore, the output fluctuation is negligible for such a short period of time. To look at the source of instability, it is noted that the major source of such fluctuations could be as a result of the ambient condition variation and the fluctuation of stray capacitances.

After several experiments we noticed the measured values are very sensitive to the liquid temperature. This led us to study the temperature dependence of measured values, which is presented in this part. The temperature dependence was measured in two ways in which the temperature was increased and also while cooling off to a lower temperature. In rising the sample temperature, it starts from the ambient temperature and was increased to about 75 °C. The cooling from 75 °C to the ambient room temperature is also monitored in such experiments. Since tap water is the base solution for all the mixtures, thus the temperature variation for this sample is investigated here. Fig. 7 shows capacitance variation of tap water as a function of temperature for a range of 27.8 – 72°C. The measured experimental values are related to the resistivity that is reciprocal of the conductivity. For the case of the tap water temperature variation is shown from 27.8 °C to 72.0 °C. The capacitance value starts from 24.2 F and reaches to about 61.1 F at 72.0°C. As can be seen in Fig. 7, for a range of 44.2°C a notable change of 36.9 μF is observed in the tap water measurement. An averaged temperature variation of 0.8348 μF/°C for this tap water sample is obtained. At 27.8 °C the sensitivity found to be 1.02 %, while at 30.1 °C it was 1.68 % and at 72 °C it was 4.58 %.
In Fig. 8 capacitance (resistivity) variation of the tap water+oil mixture as a function of temperature is shown. In Fig. 8a the temperature dependence is shown for the fresh oil mixture and for a better comparison for the used oil mixture is shown in Fig. 8b. For the case of the fresh oil temperature variation is shown from 29.1 °C to 73.5 °C. The capacitance value starts from 26.7 µF and reaches to about 45.9 µF. As can be seen in Fig. 8a, for a range of 44.4 °C a notable change of 19.2 µF is observed in the tap water+oil measurement. For the case of the used oil temperature variation is shown in Fig. 8b and changes from 30 °C to 71.4 °C. The capacitance starts from 26.3 µF and reaches to about 47.5 µF. As can be seen in Fig. 8b, for a range of 41.5 °C a notable change of 21.2 µF is observed in the tap water+used oil measurement. A comparison of the two results indicated a variation of 0.4324 µF/°C for the fresh oil and a variation of 0.5121 µF/°C for the used oil mixture.

Another point as can be seen in Fig. 8a and 8b, is that the pattern of the increase in the capacitance value or the resistivity term behaves differently for the two cases. This leads to the fact that such difference is related to the conductance term of the capacitance measurements, which behaves differently for two samples. As stated the resistivity is a function of the temperature and also the viscosity of the sample. Our results show such different behavior is most likely related to the viscosity change of the used oil in comparison with that of the fresh oil. For the fresh oil mixture the resistance variation with temperature is more linear than that of the curve for the used oil mixture.

Figure 9 shows the resistance change of water+ethanol mixture as a function of temperature. For this case temperature variation is shown from 40.0 °C to 71.5 °C. The capacitance value starts from 18.6 µF and reaches to about 34.5 µF. As can be seen in Fig. 9, for a range of 31.5 °C a notable change of 15.9 µF is observed in the tap water+ethanol measurement. In another experiment resistance variation of water+methanol mixture for the cases of increasing temperature was investigated. For this case temperature variation is from 29.1 °C to 72.9 °C. The capacitance starts from 16.7 µF and reaches to about 37.9 µF. For a range of 43.8 °C a notable change of 21.2 µF is observed in the tap water+ethanol measurement. A comparison of the two results for the ethanol and methanol indicated a variation of 0.5048 µF/°C for the ethanol and a variation of 0.4840 µF/°C for the methanol mixture. The resistance variation of water+petroleum mixture as a function of decreasing temperature is also studied for the cases of decreasing temperature. For this case temperature variation is from 56.0 °C to 29.6 °C. The capacitance starts from 51.0 µF and decreases to about 27.6 µF. For a range of 26.4 °C a notable change of 23.4 µF is observed in the tap water+petroleum measurement. Our results for the petroleum indicated an averaged variation of 0.8864 µF/°C.

Figure 10 represents the resistivity variation of tap water+salt mixture as a function of temperature. For this case temperature variation as shown in Fig. 10 is from 24.7 °C to 47.2 °C. The capacitance starts from 53.4 µF and reaches to about 486.5 µF. As can be seen in Fig. 10, for a range of 22.5 °C a strong change of 433.1 µF is observed in the tap water+salt measurement. A comparison of the results for the previous samples and the salt indicated for example a variation of 0.5048 µF/°C for the ethanol and an average strong variation of 19.2489 µF/°C for the salt mixture. As can be seen in Fig. 10, two points can be made about this study. First as mentioned the resistivity of the salt solution is much more sensitive to the temperature in comparison with the other tested samples. Second point is that as can be noted in Fig. 10, the temperature variation from 24.7 °C to about 42 °C is rather slower, but from 42 °C to 47.2 °C range a sharp increase is noted in the measured values. At higher temperature the resistance value changes so quickly that saturates the DMM module and the resulted values are out of the measuring range. The sensitivity for the first part of the curve is about 3.9769 µF/°C while it reaches to about 70.0577 µF/°C for the second part of the curve as shown in Fig. 10.

In order to compare our results with the other experiments consider the percentage change of conductivity per degree for common materials given in (Hach Company, Cat NO. 51800-18, sension5 Conductivity Meter Manual.). As indicated in (Hach Company, Cat NO. 51800-18, sension5 Conductivity Meter Manual.) among the listed solutions sugar syrup shows the highest temperature dependence (5.64% per degree) while the 5% Sulfuric acid shows the lower percentage dependence of about 0.97% per degree. Ultrapure water also shows a strong temperature dependence of 4.55% per degree. For salt water such dependence is weaker (2.125% per degree) in comparison with the ultra pure water (4.55%). For tap water used in our experiment the dependence is about 3.2 % per degree at 30 °C, which is in a good agreement with the one given in (Hach Company, Cat NO. 51800-18, sension5 Conductivity Meter Manual.) that should be between the salt water (2.125% per degree) and the ultrapure water (4.55%).

One might argue that the effect of the temperature dependence is related to the dielectric term in such measurements. For the water the dielectric constant also varies with any change in the medium temperature (Weast, R. C., 1981 ). As indicated in Ref. (Weast, R. C., 1981 ), the dielectric constant of water decreases by increasing temperature and vice versa. For example, at 0 °C this constant for pure water is 87.74 while decreases to 69.91 at 50 °C and at 100 °C this constant is about 55.72 for the tested samples. This constant for the temperature of 25 °C is found to be about 78.3.

Since in our measurements (see Fig. 7), the measured values increases by increasing temperature, therefore such a variation is not related to temperature dependence of the dielectric constant of the water. As a result the variation of the capacitance with the temperature in this case is mainly due to the conducting part. With this
reasoning it was concluded that the most contribution is related to the variation of the medium resistance with the temperature. To verify our results a comparison is made with the related data for water given in a recent article about the fundamental conductivity and resistivity of water (Light et al., 2005). The accurate values were given for conductivity of water for the 0-100 °C range. For instance, the reported conductivity (κ), and its reciprocal resistivity (ρ) at 25 °C for pure water is reported to be about 0.005501 ± 0.0001 μS/cm, and 18.18 ± 0.03 MΩ·cm, respectively. However, looking at Table 1, our water samples show higher conductivity, which indicates the higher impurity of the water samples.

Sensitivity of water conductivity to changes in temperature is given in Fig. 2 (pure) and Fig. 3 (salt water) (Light et al., 2005). As can seen in Fig. 2 and Fig. 3 of that report, the conductivity change per degree Celsius is plotted as a function of the water temperature. This sensitivity for pure water at 30 °C is about 5% per degree while it is reduced to 4.2% per degree at 45 °C. Thus there is a decrease of 0.8% in conductivity for the temperature range of 30-45 °C that corresponds to the range of our data in this experiment. This sensitivity for salt water at 30 °C is about 3.4% per degree while it is reduced to 2.2% per degree at 45 °C.

In general there is a reasonable agreement between our experimental data and the one reported in (Light et al., 2005) for this range of temperature measurements. However, the conductivity of the tap water as shown in Table 1 is closer to the data given for the salt water in (Light et al., 2005). Thus our results should be compared to Fig. 3 for the very low impurity (ppb) salt water. At temperature 45 °C the change of conductivity for the tap water (our result) is 2.38% while in (Light et al., 2005) is 2.3% and at 30 °C our result is 2.43% in comparison with 3.2% given in (Light et al., 2005). Considering a little difference in the impurity of the tap water and their salt water, there is a good agreement between our results and results reported in (Light et al., 2005).

As indicated in (Light et al., 2005) the temperature dependence of the conductivity of the impurity has a major effect on temperature compensated, conductivity measurements. For example in their experiment they used NaCl impurities measured in the μg/L domain (ppb of NaCl). Their data shows that the sensitivity change exhibits a factor of 12 decrease in sensitivity when temperature increases from 0 to 100°C. Most important, at 25 °C the sensitivity is 4% per ppb, while at 85 °C it is 1% per ppb. Hence to determine a trace impurity, a conductivity methodology must be four times as accurate to be as useful at 85 °C as it is at 25°C, and in turn cell constant calibration, instrument and sensor accuracy, and calculation procedures must be four times as accurate.

Such temperature dependence data can provide useful information for the usage of the liquids acting as the dielectric medium for the capacitance measurements. On the other hand, this method provides a sensitive way to measure the temperature changes of liquid resistance by using the capacitance variation.

### Table 1: Comparison of the capacitance values for different water and water mixtures.

<table>
<thead>
<tr>
<th>Sample</th>
<th>EC (μS/cm)</th>
<th>TDS (mg/L)</th>
<th>C (μF)</th>
<th>V F (%)</th>
<th>T (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distilled Water</td>
<td>5.4</td>
<td>2.1</td>
<td>1.3</td>
<td>100.0</td>
<td>25.2</td>
</tr>
<tr>
<td>Mineral Water</td>
<td>440.0</td>
<td>212.0</td>
<td>34.1</td>
<td>100.0</td>
<td>25.1</td>
</tr>
<tr>
<td>Boiled Water</td>
<td>485.0</td>
<td>235.0</td>
<td>35.0</td>
<td>100.0</td>
<td>23.9</td>
</tr>
<tr>
<td>Tap Water</td>
<td>560.0</td>
<td>272.2</td>
<td>39.1</td>
<td>100.0</td>
<td>24.9</td>
</tr>
<tr>
<td>Salt Water</td>
<td>21700.0</td>
<td>125.0</td>
<td>53.4</td>
<td>100.0</td>
<td>24.6</td>
</tr>
<tr>
<td>TW+Methanol1</td>
<td>244.0</td>
<td>116.8</td>
<td>16.3</td>
<td>6.25</td>
<td>22.8</td>
</tr>
<tr>
<td>TW+Methanol2</td>
<td>169.2</td>
<td>80.8</td>
<td>15.6</td>
<td>18.75</td>
<td>24.7</td>
</tr>
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<td>TW+Methanol3</td>
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<td>407.0</td>
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<td>17.0</td>
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<td>TW+Antifreeze3</td>
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<td>585.0</td>
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<td>TW+Used Oil1*</td>
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</tr>
<tr>
<td>TW+Used Oil2*</td>
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<td>260.0</td>
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<td>25.6</td>
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<td>TW+Used Oil3*</td>
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<td>TW+Fresh Oil1*</td>
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<td>TW+Fresh Oil2*</td>
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<td>19.5</td>
<td>31.25</td>
<td>24.7</td>
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<tr>
<td>TW+Fresh Oil3*</td>
<td>-</td>
<td>-</td>
<td>18.8</td>
<td>43.75</td>
<td>24.8</td>
</tr>
</tbody>
</table>

*Measurements not very accurate.
Table 2: Conductivity range for different aqueous solutions.

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Conductivity Range</th>
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</thead>
<tbody>
<tr>
<td>High Pressure Boiler Water</td>
<td>0.1&lt;μS/cm to 0.2 μS/cm</td>
</tr>
<tr>
<td>Demineralized Water</td>
<td>1 μS/cm to 80 μS/cm</td>
</tr>
<tr>
<td>Drinking Water</td>
<td>100 μS/cm to 1 mS/cm</td>
</tr>
<tr>
<td>Wastewater</td>
<td>85 μS/cm to 9 mS/cm</td>
</tr>
<tr>
<td>Surface Water</td>
<td>100 μS/cm to 10 mS/cm</td>
</tr>
<tr>
<td>Industrial Process Water</td>
<td>8 mS/cm to 130 mS/cm</td>
</tr>
<tr>
<td>Concentrated Acids and Dyes</td>
<td>85 mS/cm to &gt;1000 mS/cm</td>
</tr>
</tbody>
</table>

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

Fig. 2: Diagram of the designed cylindrical capacitive cell probe.
Fig. 3: Capacitance values for different water liquids. DW(distilled water), DW+TW (distilled water+ tap water), BW(boiled water), MW (mineral water ), TW( tap water), and SW(salt water).

Fig. 4: Comparison of the capacitance values for tap water and tap water-mixtures. W(water), W+M (water +methanol), W+E(water +ethanol), W+O(water +petroleum), W+O(water +oil), W+UO(water +used oil), and W+A(water +antifreeze).

Fig. 5: Reproducibility of the result for the sensor.
Fig. 6: Time stability of the reported sensor system.

Fig. 7: Resistance variation of tap water as a function of temperature.

Fig. 8: Resistance variation of water+oil mixture as a function of temperature. (a) Fresh oil and (b) used oil.
Conclusion:

The goal here was to introduce a capacitance sensor for liquid mixture monitoring and to study the role of a foreign agent in the capacitance measurements. The invasive sensor such as the one reported here provided a useful means to study the conductance effect of the reactance capacitance and its role in capacitance measurements. 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 the checking the quality of the water mixtures, which is required for different applications. The next objective was to recognize different water mixture liquids as a result of such capacitance measurements.

Our results showed that the reported sensor could be effectively implemented for the study of low conducting liquids such as water + oil, water+ methanol and other water mixtures, which have wide applications as lubricator, and cooling agents with a notable conductance contribution. Our results indicated an averaged variation of 0.4324 µF/°C for the fresh oil and a variation of 0.5121 µF/°C for the used water oil mixture for a temperature range of 29 to 73.5 °C. Most important for water+oil mixture the temperature behavior of the fresh oil mixture is different from that of the used oil. An averaged variation of 0.4840 µF/°C for methanol, of 0.5048 µF/°C for the ethanol, and 0.8250 µF/°C for water antifreeze mixtures for a temperature range of 29 °C to 73.5 °C are obtained. For water + salt mixture our temperature data showed that the measured value changes from 53.4 µF at 24.7 °C to 486.5.1 µF at 47.2 °C with an average variation of 19.2489 µF/°C, which was much different from other tested mixtures. At 24.7 °C the sensitivity found to be 0.75 %, while at 30 °C it was 2.84% and at 40 °C it was 12.69 %. Hence to determine a trace impurity, this methodology provides less temperature compensation at low temperatures rather than high temperatures. As described, the measured quantity is less sensitive at low temperatures, but for high temperature data monitoring a more accurate temperature compensation and calibration are required.
By using a reference liquid with a known capacitive characteristic, the capacitance and related parameters such as conductance for other unknown liquids can be obtained. Arrangement described also was used for liquid mixture temperature checking in order to see effect of impurities in the water solution conductance at different temperatures. For the on-line measurements of such a sensor it is possible to pump the liquid inside the two open ends of the probe cell and monitor the capacitance of the flowing fluids.

ACKNOWLEDGEMENTS

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