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Monitoring Temperature Variation of Reactance Capacitance of Water Using a Cylindrical Cell Probe

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Abstract: In this study by using a capacitive cell probe the temperature variation of the electrical properties of the water liquids is investigated. Variation of the reactance capacitance parameter of liquids with temperature in the range of 17-60°C is measured for the plain water and water mixtures. The temperature variations of the capacitance for the cool distilled and tap water samples are studied for the range of 17-29°C obtained. Present results indicate an averaged variation of 4.69 μF/°C for the distilled water and 3.24 μF/°C for tap water in warm up process to a near room temperature. The cooling behaviors for the warm mineral, tap and salt water liquids are also investigated in this study. Average variations of 0.54 μF/°C for the mineral water, 0.76 μF/°C for the tap water and 1.44 μF/°C for the dilute salt water are obtained for the high temperature range. In comparing the results for different liquids, dilute salt water shows a factor of 2.6 increase in measured capacitance in comparison with the mineral water when temperature drops from 60.0 to 35.0°C. Hence the reported cell probe provides a relatively accurate method to determine the temperature dependence of reactive capacitance for the pure liquids and also liquids with a trace impurity.

Key words: Temperature, electrical, capacitance, water

INTRODUCTION

Capacitive sensors can be used in different applications for measuring a variety of parameters (Golnabi, 1997; McIntosh *et al*., 2006; Kasten *et al*., 2000; Moe *et al*., 2000; Ahn *et al*., 2005). Due to their inherent simplicity and low cost they also have found many industrial applications (Guo *et al*., 2000; Shuangfeng *et al*., 2008). Much emphasis has been placed on the works to construct a sensor with output capacitance, which varies linearly with the measured variable. On the other hand, efforts have been made on the development of the capacitance readout circuits to improve the measurement sensitivity and accuracy. A differential charge-transfer readout circuit for multiple capacitive sensors was reported recently by Rodjegard *et al*. (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 amplifier 1/f-noise and offset voltage. A new capacitive-to-phase conversion technique for measuring very small capacitance changes has been reported by Ashrafi and Golnabi (1999). This method provided a powerful means for recording very small capacitance changes.

The conductivity effects on capacitance measurements of two-component fluids using the charge transfer method for capacitance measurements has been reported by Huang *et al*. (1988). In another report capacitance sensors have been used for the measurement of the phase volume fraction in two-phase pipelines (Strizzolo and Converti, 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 and Haridy, 2003). Applications of the capacitance type sensors for measurement of water content of different materials have been reported. For example design of a planar capacitive sensor for water monitoring in a production line was reported by Tsamis and Avaritsiotis (2005).

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Monitoring water components plays important role in different applications. For example in wastewater contamination, monitoring the water components, in particular hazardous ones, plays a crucial role. Initial experiments indicated that the measured capacitance values are very sensitive to the liquid temperature and this led us to study of the temperature dependence. The idea here is to use the cell probe filled with liquid in order to monitor the capacitance variation of a liquid. Since the electrical temperature variation 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.

MATERIALS AND METHODS

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

$$C = \frac{2\pi \varepsilon L}{\operatorname{Ln}\frac{b}{a}} \tag{1}$$

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 and a more accurate formula should be used for the case of small L. Several problems such as edge effect, can also 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.

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 systems 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.

The capacitance measurements for the cylindrical probe 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

$$C_x = f_1(\varepsilon) \tag{2}$$

$$R_x = f_2(\sigma) \tag{3}$$

The capacitive part of C is obtained only by the insulation of the electrodes and reducing the conductivity effect. It must be pointed out that both the permittivity ε and conductivity, σ also vary with temperature. This leads to the fact that both the C_x and R_x can be a function of the filling medium temperature. In general it is hard to perform measurements to evaluate the temperature variation of both parameters in a single experiment. As a result, there are some ambiguities in the temperature variation, which led us to follow up on this topic as discussed here.

As described, in general there are invasive and non-invasive electrode arrangements for capacitive sensors. 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 turn 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_xC_x. As mentioned when R_x is not negligible in analysis then it must be considered as reactance term in capacitance measurements and its temperature variation must be included as well.

MATERIALS AND METHODS

The reported experiment was conducted in Institute of Water and Energy as part of Research Program of the Sharif University of Technology for the period of 2006-2008. Design and performance of a cylindrical capacitive sensor to monitor the electrical properties of liquids was introduced in a recent report (Golnabi and Azimi, 2008a). In the following study simultaneous measurements of the resistance and capacitance by using a cylindrical sensor system was reported by Golnabi and Azimi (2008b). 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. It includes the cylindrical capacitive sensor, a reference capacitor and two digital multimeter (DMM) modules (SANWA, PC 5000), that can be interfaced to 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 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 MÙ 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 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±1.0°C in temperature recording.

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.

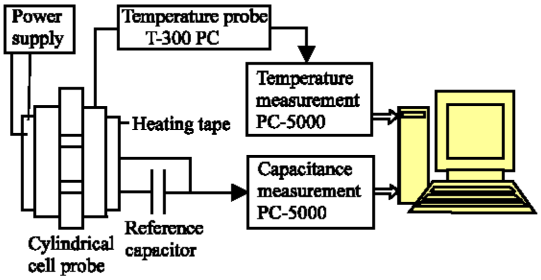

Fig. 1: Block diagram of the experimental arrangement for capacitance measurements

In this experiment a cylindrical geometry is chosen for the probe 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 an effective length of about 4 cm. The radial gap between the two tube electrodes for filling medium 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. The middle active part of the probe has a length of about 4 cm and outer guard electrodes have a length of about 3 cm.

The distilled water used in this experiment was produced by an apparatus operating based on the boiling technique. For the water salt preparation regular grade salt (NaCl) was used for the preparation of a sample with the concentration of about 124-492 mg L^{-1}. For the salt water original solutions with higher concentration was prepared first and then diluted according to the experiment requirement. These solutions were made carefully to ensure that the concentration of the salt was constant throughout a series of measurements.

RESULTS AND DISCUSSION

Initial experiments indicated that the measured capacitance values are very sensitive to the liquid temperature and this led us to study of the temperature dependence. The temperature dependence was measured in two ways in which either the temperature was increased from cool phase to the ambient temperature and also cooling process for hot water samples. As can be shown

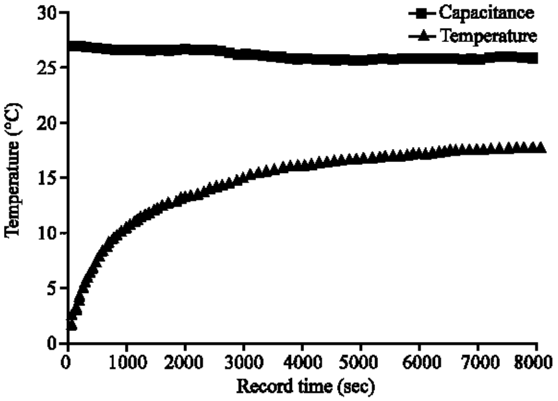

Fig. 2: Capacitance measurement at a constant ambient temperature for distilled water

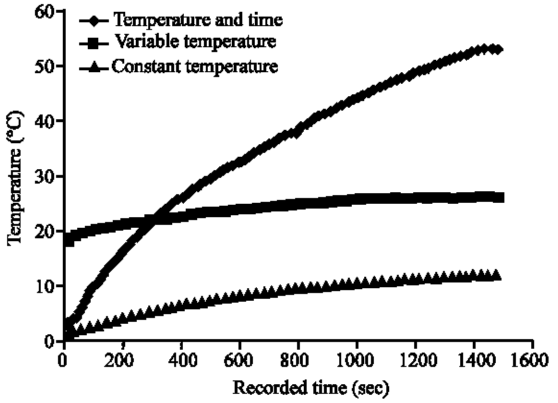

Fig. 3: Capacitance measurement for variable temperature and time for distilled water

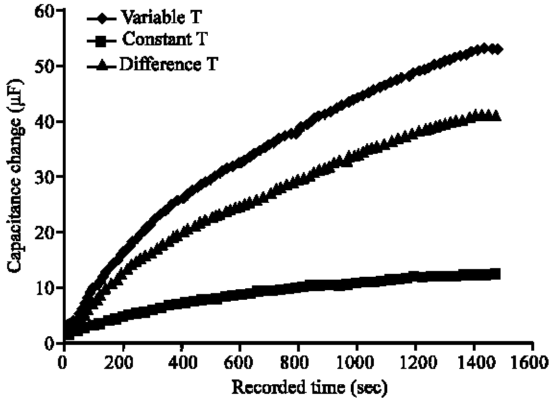

Fig. 4: Capacitance changes and the difference capacitance for the distilled water

in Fig. 2, ambient temperature variation is also indicated for a range of 25.8-25.0°C. This graph shows the dynamical behavior of the water liquid as a function of time in scale of 8000 sec. Figure 2 indicates that even at a relatively constant temperature the measured value starts from 0.5 µF and reaches to about 17.5 µF at the given time scale. Such dynamic behavior is explained elsewhere as related to the characteristic of a non-invasive cell probe.

The capacitance scale is in µF and temperature in °C, which are shown with the same vertical scale in Fig. 3. Such variation with time is recorded for a temperature range of 19-25°C and a time scale of 1500 sec. As can be shown in Fig. 3, the measured capacitance value is a function of both time and temperature. To see the time variation in the Fig. 3 the capacitance values are shown for an almost fixed value of temperature. Considering the temperature and time both as dominant variables the measured capacitance is changing from 0 to a value of about 54 µF. To see the effect of time variation, the lower curve shows the measured capacitance value which starts from zero and shows a gradual increase to about 12 µF in the given time scale of 1500 sec.

Variation with both the time and temperature are shown, which starts from 0.5 µF and increases to about 52 µF. Figure 4 the time dependency is following the same pattern as shown as the lower curve in the time rage of 0-1500 sec. The middle curve in Fig.4, shows the difference value of the total dependence and that of time, which shows a similar behavior for the given time scale. For all cases as can be seen from the start the increase rate is higher and gradually the rate is slower and finally it reaches to a kind of steady state.

For the temperature range of 17.4°C to 25.6°C where the capacitance value is increasing from 0.15 µF to about 38.61 µF. The average capacitance variation sensitivity for the distilled water for this temperature range is about 4.69 µF/°C. It is also noted that such an increase is in a non-linear fashion as can be shown in Fig. 5. As indicated in the inset of Fig.4, such value is corresponding to the difference values for measured capacitance when the time variation value is subtracted from the total overall variation for the case of cool distilled water. Our conclusion is that the net variation is mostly because of the temperature effect in the electrical property of the distilled water.

In a similar study the temperature dependence of the measured capacitance values for the warm up process of the cool tap water is investigated. Figure 6 shows the result for the temperature range of 22.8°C to 28.9°C where the capacitance value is increasing from 32.8 µF to about 52.6 µF. The average capacitance variation sensitivity for the tap water for this temperature range is about 3.24 µF/°C. Comparing the results of Fig. 5 for the distilled water with that of Fig. 6 for tap water, it is noted that for the low temperature range the sensitivity in temperature change is higher for the distilled water.

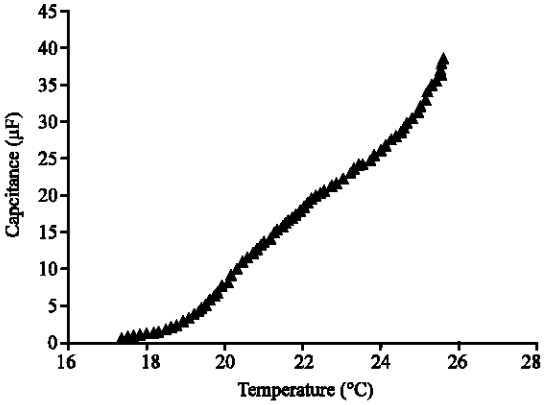

Fig. 5: Temperature dependence of the measured capacitance values for distilled water

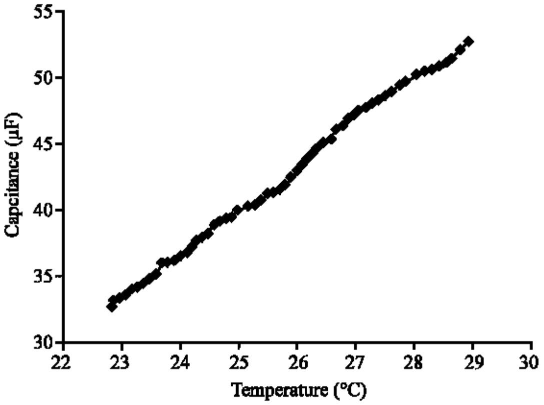

Fig. 6: Temperature dependence of the measured capacitance values for tap water

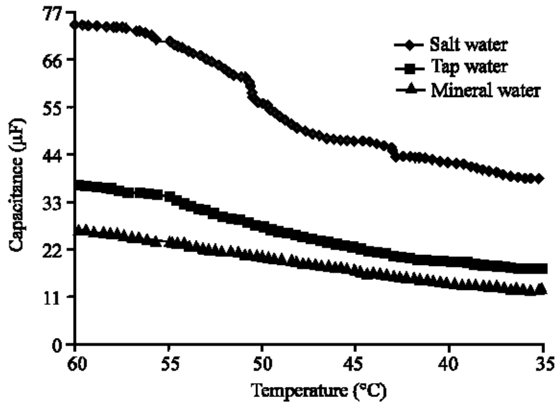

Fig. 7: Temperature variation for different water liquids in cooling process

In Fig. 7 the temperature variation of capacitance for different water liquids in cooling process is shown. Such variations for the mineral, tap and salt water samples are shown for a temperature range of 60°C to 35°C. As can be shown in Fig. 7, for all the tested samples the measured capacitances are decreased in cooling process, where such drop is more pronounced for the salt water. For the mineral water the measured capacitance at 60°C is about 26.7 µF while it drops to about 13.2 µF at 35°C. Similarly for the tap water the measured capacitance at 60°C is about 36.8 µF while it drops to about 17.8 µF at 35°C. For the salt water as can be shown in Fig. 7, the measured capacitance at 60°C is about 74.1 µF while it drops to about 38 µF at 35°C. As indicated in Fig. 7, for the salt water more fluctuation is noted, which is due to the dissolved salt in the water solution that affects the conductivity of the solution and as a result the measured reactance capacitance values.

As indicated in literature the conductivity of a solution typically increases with temperature. In moderately and highly conductive solutions, this increase can be considered nearly linear in temperature and can be compensated by the K factor (percentage change of conductivity per degree). However, in high purity water and solutions with a conductivity of 1 µS cm^{-1} or less, the conductivity increase with temperature is highly non-linear. Temperature compensation for the solutions must not only take into account the increase in conductivity of water, but also the increase in conductivity of the solute or the dissolved electrolyte. The increase in the conductivity due to solute depends upon what type of electrolyte is present; i.e., acid, base, salts. The typical K value for acid ranges from 1.0-1.6% /°C, base 1.8-2.2%/°C, salts 2.2-3.0%/°C and for fresh water is in the range of 2.0%/°C.

In present experiments the measured capacitance for all water liquids shows an increase by increasing temperature and vice versa. One might question that the effect of the temperature dependence could be related to the dielectric term or the conductance term in the given measurements. It must be pointed out that both parameters can vary with temperature. For the water the dielectric constant as stated in the handbook by Weast (1981) varies with any change in the medium temperature. As indicated 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 present measurements (Fig. 7), the measured capacitance values decreases by decreasing temperature, therefore such a variation is not related to temperature dependence of the dielectric constant of the tested water samples. As a result, the variation of the capacitance with the temperature in this case is mainly due to the conducting part as indicated in Eq. 3. With this reasoning it is concluded that the most contribution is related to the variation of the medium conductance/resistance with temperature.

Now it is useful to compare the results of this study with the earlier ones. In an experiment the fundamental conductivity and resistivity measurements of water have been given. In order to compare our results with the other experiments consider the given K factor for common materials (Light *et al*., 2005). As indicated among the listed solutions sugar syrup shows the highest temperature dependence (5.64%/°C) while the 5% Sulfuric acid shows the lower percentage dependence of about 0.97%/°C. Ultra-pure water also shows a strong temperature dependence of 4.55%/°C. For salt water such dependence is weaker (2.125% /°C) in comparison with the ultra-pure water (4.55%/°C). For tap water used in present experiment the dependence is about 3.24%/°C at 30°C, which is in a good agreement with Light *et al*. (2005) that should be between the salt water (2.125%/°C)and the ultra-pure water (4.55%/°C).

Sensitivity of water conductivity to changes in temperature for pure and salt water samples is reported by Light *et al*. (2005). This sensitivity for pure water at 30°C is about 5%/°C while it is reduced to 4.2%/°C at 45°C. Thus there is a decrease of 0.8% in conductivity for the temperature range of 30-45°C. This sensitivity for salt water at 30°C is about 3.4%/°C while it is reduced to 2.2%/°C at 45°C. In general there is a reasonable agreement between present experimental data and Light *et al*. (2005), for this range of temperature measurements. At temperature range of 20-30°C the sensitivity for the capacitance change for the tap water is about 3.24 μF/°C while for the range of 60-35°C this sensitivity is reduced to about 0.76 μF/°C. This reduction in capacitance sensitivity is in agreement with the reduction in the K factor related to the conductivity change as stated in given reference. The conductivity compensation factor at the 30°C is about 3.2%/°C for tap water, which is reduced to about 2.3%/°C at 45°C.

As indicated by Light *et al.* (2005), the temperature dependence of the conductibility of the impurity has a major effect on temperature compensated, conductivity measurements. For example in their experiment they used NaCl impurities in their reports. 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. Present results show that the capacitance sensitivity is dominated by the type and amount of impurity traces in water. For this reason the sensitivity for the salt water is much higher than that of mineral water and higher than tap water, which contains some impurity.

Present results show that the measured experimental capacitance values are strongly related to the resistivity part 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 (Golnabi and Azimi, 2008a). In that report the capacitance value starts from 24.2 μF and reaches to about 61.1 μF at 72.0°C. As can be shown in Fig. 7 of that reference, 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 that particular tap water sample was obtained. Comparing the results with the value of 0.76 μF/°C for this experiment a good agreement is noted even though these experiments are performed with waters from different sources. As indicated in literature the range of conductivity for the tap water varies a lot and the results reported in this investigation is very reasonable for such a tap water sample.

CONCLUSION

The goal here was to implement a capacitance cell probe for liquid temperature monitoring. The invasive sensor such as the one reported here provided a useful means to study the temperature effect of the reactance capacitance and its role in the capacitance measurements. The temperature dependence of the capacitance values for the warm up process of the cool distilled and tap water are investigated. The average capacitance variation sensitivity for the distilled water is 4.69 μF/°C and for the tap water for this temperature range is about 3.24 μF/°C. At high temperature (60.0 to 35°C), our results indicated an averaged variation of 0.32 μF/°C for the distilled water, 0.54 μF/°C for the mineral, 0.76 μF/°C for the tap and 1.44 μF/°C for the dilute salt water. Obtained results verified that the reported sensor could be effectively implemented for the temperature study of low conducting liquids such as water and water mixtures, which have wide spread applications. Such temperature dependence data can provide useful information for the estimation of liquid behavior and useful liquid lifetime with temperature change in different field applications. On the other hand, this method provides a sensitive way to measure the temperature changes of liquid conductance/resistance by using the reactive capacitance variations.

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