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A Method of Measurement of Permittivity and Opacity of Fluid

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Abstract
Fluids play important role in wide variety of industrial, medical and consumer equipments. Many of the process system utilizes fluid supply, may be a small bottle of reagent in medical diagnosis, or a large tank of acid in chemical process, or a hydraulic system in machineries of various sectors. Fluid characteristics and quality are critical in automotive process and protecting equipments. Liquid properties like buoyancy, pressure at depth, electrical permittivity, conductivity, absorption of radiation, surface reflection of sound at light etc. are some of the parameters to be monitored in different types of design and applications. There exist various methods to measure these parameters where the sensors have to make contact with the liquids that have disadvantages in many applications. In this paper focus has been given to measure the permittivity as well as opacity of liquids in easy, non-contact type and conventional way.
Keywords: Permittivity, Electrical Conductivity, Dielectric Polarization, Electrostatic Field, Microcontroller, Light Dependent Resistor, Signal Conditioner.

1. INTRODUCTION

Fluid properties like weight, buoyancy, electrical conductivity, heat conductivity, permittivity, assimilation of radiation, surface reflection towards sound and light etc. are the distinctive parameters which are required to be taken care of while designing the transducers in any industry. The contact type sensors are of less complexities and easier to fabricate, but have hindrance of change of trademark properties of fluids because of physical and reactive responses between fluid and sensing materials influencing the accuracy and life time. This may also affect the process parameters. The non-contact type sensors do not have such disadvantages and hence it is non-destructive type; however these require different arrangements and preparatory measures.

Dielectric constant or permittivity of any substance plays important role in physical as well as other inherent properties of the substance. It can influence the capacitance, opacity, reflectivity, and refractivity, absorption of radiation, electrical conductivity, and heat conductivity. If the fluid is contaminated with impurities of both soluble and insoluble types, its permittivity is affected. Therefore it is important to measure and monitor this parameter of fluid in the use. Temperature variation also affects properties of fluid as well as the permittivity.

There are several methods to measure the dielectric constant or permittivity. An overview of various measurement techniques has been presented by M.S. Venkatesh et al [1]. Use of microwave frequencies for measurement of permittivity is very popular [2, 3, and 4]. Technical information for measurement of opacity are provided books and technical information center [5, 6 and 8]. In this paper a non-contact and non destructive yet economic method of capacitance measuring procedure of fluids is discussed to determine permittivity change as well as opacity change in fluids with soluble as well as insoluble substances.

2. THEORY

A dielectric material is a poor conductor of electricity, but an efficient supporter of electrostatic fields. It can be polarized by an applied electric field. When a dielectric is subjected to an electric field as shown at figure 1, electric charges do not flow through the material like a conductor, but only slightly shift from their average equilibrium positions causing dielectric polarization. Because of this dielectric polarization, positive charges are displaced toward the field and negative charges shift in the opposite direction. Thus creates an internal electric field that reduces the overall field within the dielectric itself. If a dielectric is composed of weakly bonded molecules, those molecules not only become polarized, but also reorient so that their symmetry axes align to the field.

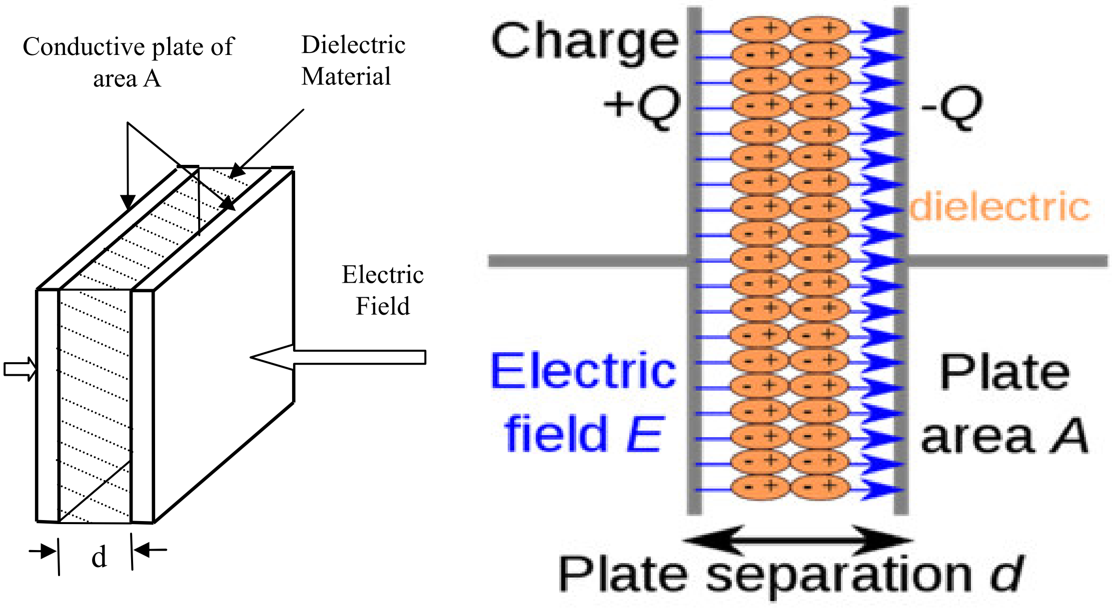


Figure 1: Orientation of dipoles under the influence of electrical field

If the flow of current between opposite electric charge poles is kept to a minimum while the electrostatic lines of flux are not impeded or interrupted, an electrostatic field can store energy. This property is useful in capacitors and able to support an electrostatic field while dissipating minimal energy in the form of heat. The lower the dielectric loss (the proportion of energy lost as heat), the more effective is a dielectric material. The permittivity or dielectric constant describes the interaction of the electrostatic lines of flux under an electric field and is related by the following relation.

$$\varepsilon = \varepsilon_r \varepsilon_0$$

Where ε, ε_0 are the absolute permittivity of substance and permittivity of vacuum respectively and ε_r is the relative permittivity or dielectric constant of the material. Hence the dielectric constant ($\varepsilon_r = \varepsilon/\varepsilon_0$) is the ratio of absolute permittivity to the permittivity of vacuum which implies how easy a material can be polarised by the imposition of an electric field. Permittivity is related to capacitance as per following equation.

$$C = \frac{\varepsilon_r \varepsilon_0 A}{d} \qquad \text{...........(1)}$$

Where C is the capacitance developed between two electrodes each of area A separated by distance of d, ε_0 and ε_r respectively are the permittivity of vacuum and relative permittivity of the material. Therefore measurement of dielectric constant is possible from measurement of capacitance.

Opacity is the measure of impenetrability to electromagnetic or other kinds of radiation, especially visible light. An opaque object is neither transparent (allowing all light to pass through) nor translucent (allowing some light to pass through). When light strikes an interface between two substances, in general some may be reflected, some absorbed, some scattered, and the rest transmitted. An opaque substance transmits no light, and therefore reflects, scatters, or absorbs all of it. Opacity depends on the frequency of the light and can be quantified by the mathematical descriptions as below. [1, 2].

$$I(x) = I_0 e^{-k_v \rho x} \qquad \text{............(2)}$$

Where x is the distance the light has travelled through the medium, I_x is the intensity of light remaining at distance x and I_0 is the initial intensity of light, at $x = 0$, ρ is the mass density of the medium and k_v is the constant termed as opacity which is also the termed as the mass attenuation coefficient or mass absorption coefficient at a particular frequency v of electromagnetic radiation. The opacity has a numerical value for a given medium at a given frequency that may range between zero and infinity with units of length^2/mass.

3. MEASUREMENT SCHEME

In this paper a low cost method is presented that can measure both permittivity as well as the opacity of liquid.

Microcontroller has been employed for controlling and calculation purpose. The schematic diagram is shown at figure 2. For capacitance measurement parallel plate method is used which involves two electrodes. A thin sheet of test material or a specially built container filled with test liquid, for which capacitance to be measured is placed between the electrodes. Capacitance of test material can be measured from the change in capacitance values of with and without the test material. This arrangement has been schematically shown at figure 3(a). Permittivity is calculated by setting up proper algorithm in the microcontroller.

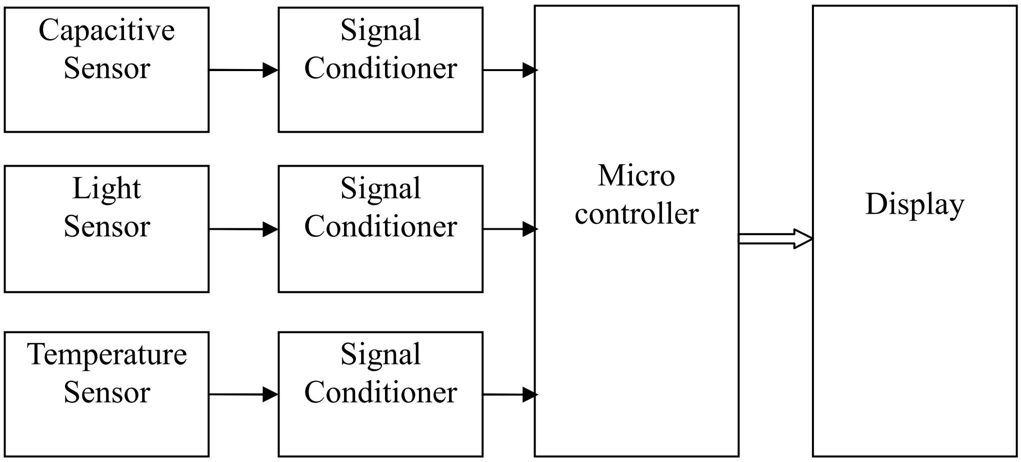


Figure 2: Schematic diagram

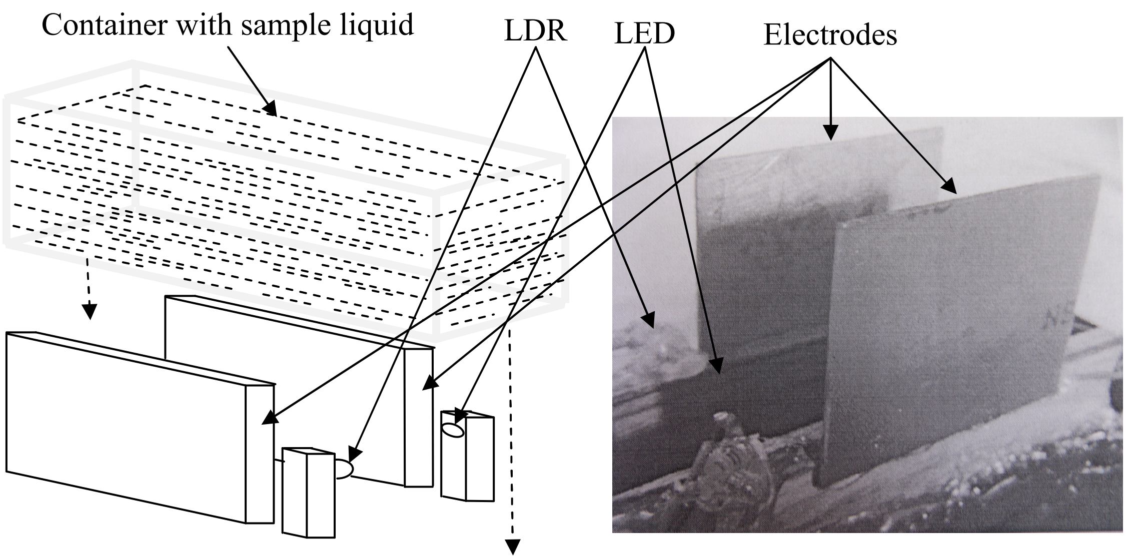


Figure 3(a): Sensors arrangements schematic view

Figure 3(b): Sensors arrangements in laboratory

Opacity measurement is accomplished by placing the sample material in between a LED and LDR (light dependent resistor) as shown at figure 3(b). LED and LDR are aligned in line such that light from LED falls on LDR. Whenever sample material is placed in between, LDR receives less light depending on the opacity of the material that leads to change in resistance of it. Opacity depends on the concentration of suspended insoluble particles or soluble impurities in liquid. Additionally temperature sensor LM35, which shows linear variation in room temperature range, has been used to sense and monitor the temperature. Sensors arrangement in laboratory for experimental purpose is shown at figure 3(b).

4. MEASUREMENT ALGORITHM

Algorithms for calculation of permittivity and opacity are as below.

(i) Permittivity measurement: capacitance in free air is noted first. From equation (1), assuming permittivity of free air ε_r is 1, capacitance of free air C_a is

$$C_a = \frac{\varepsilon_0 A}{d}$$

.............(3)

Capacitance C_s measured when container of sample material is placed is

$$C_s = \frac{\varepsilon_{rs}\varepsilon_0 A}{d}$$

.............(4)

Therefore, from equation (3) and (4), the permittivity of sample liquid is

$$\varepsilon_{rs} = C_a / C_s$$

.............(5)

(ii) *Opacity measurement*: From equation (2), assuming opacity at free air k_v is zero, intensity at LDR at free air is $I_a = I_0$. ....(6)

Intensity at LDR with sample fluid, where d is the distance between LED and LDR,

$$I_s = I_0 e^{-k_v \rho d}$$

.............(7)

Hence, from equations (6) and (7),

$$e^{-k_v \rho d} = I_s / I_a$$ or, $$e^{k_v \rho d} = I_a / I_s$$ or, $$k_v \rho d = \ln \frac{I_a}{I_s}$$

$$k_v = \frac{1}{\rho d} \ln \frac{I_a}{I_s}$$

So, ...(8)

From equations (5) and (8), the permittivity and opacity values can be calculated by the setting up the algorithm in microcontroller. LDR resistances are related to intensities, variation of which can be noted by the signal conditioner circuits and microcontroller.

5. RESULTS AND ANALYSIS

The test container is filled with distilled water and capacitance was measured at different temperatures. Permittivity and Opacity are calculated though microcontroller and results are tabulated at Table 1 as well as the Capacitance and Permittivity values are presented in graphical form at figure 4(a) and 4(b). It indicates that the capacitance as well as the permittivity increase with the increase of temperature. Opacity also changes with the temperature, but with minor variation.

Temperature	Capacitance	Permittivity	Opacity
27	534	7.91	961
28	547	8.10	962
29	574	8.55	963
30	587	8.69	964
31	595	8.81	965
32	596	8.83	965

Table 1: Distilled Water

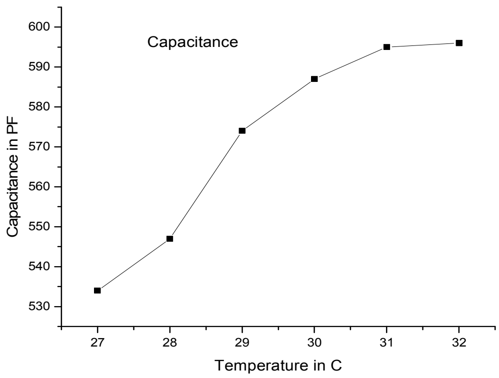


Figure 4(a): Capacitance at Distilled water

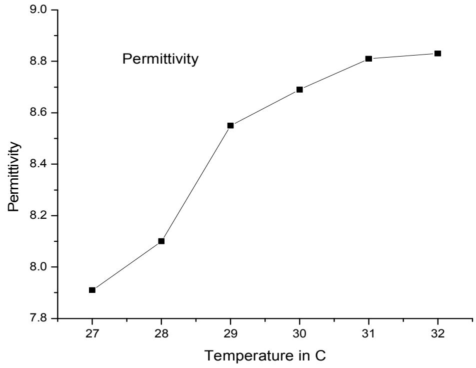


Figure 4(b): Permittivity at Distilled water

Temperature	Capacitance	Permittivity	Opacity
27	416	6.16	930
30	418	6.20	930
34	424	6.30	931
35	427	6.36	931
37	432	6.40	932
40	440	6.50	932
42	444	6.60	933

Table 2: Mustard Oil

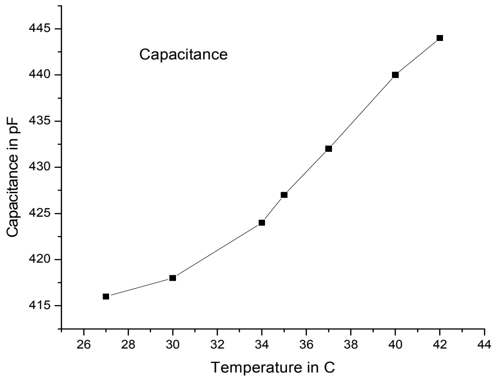


Figure 5(a): Capacitance at Mustard Oil

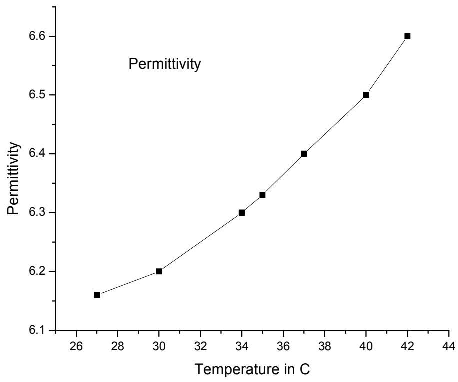


Figure 5(b): Permittivity at Mustard Oil

Temperature	Capacitance	Permittivity	Opacity
20	390	5.7	964
25	398	5.9	964
27	402	6.0	960
31	410	6.1	956
35	418	6.2	956

Table 3: Diesel

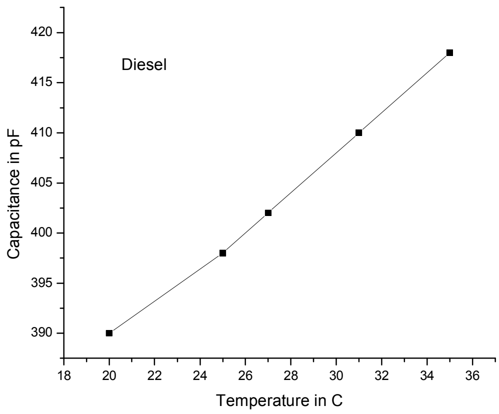


Figure 6(a): Capacitance at Diesel

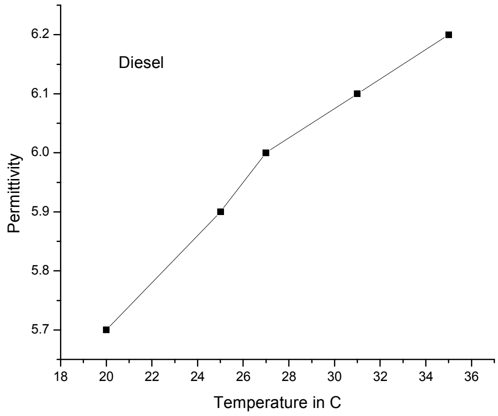


Figure 6(b): Permittivity at Diesel

Temperature	Capacitance	Permittivity	Opacity
25	472	7.00	964
30	481	7.13	964
32	513	7.60	961
35	516	7.64	960
37	520	7.70	960

Table 4: Glycerine

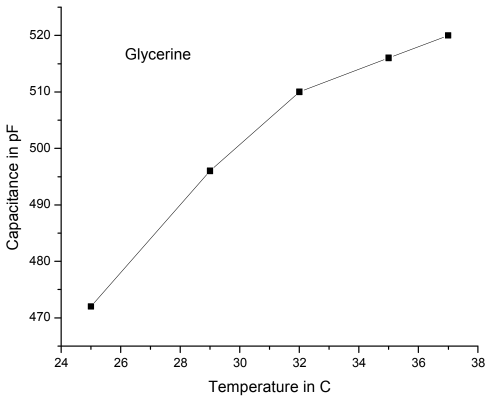


Figure 7(a): Capacitance at Glycerine

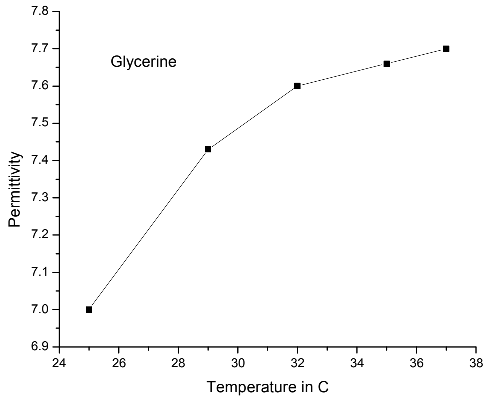


Figure 7(b): Permittivity at Glycerine

Similarly, measurements and observations are carried out on Mustard Oil, Diesel and Glycerine. The experimental values are tabulated at Table 2, 3 and 4 respectively. The graphical representation is shown at Figure 5, 6 and 7 respectively.

From the experimental results on distilled water, mustard oil, diesel and glycerine, it is observed that capacitance as well as permittivity increases with increase of temperature. However there is very little variation of opacity. Experiment is extended for distilled water contaminated with dissolved and nondissolved materials. Sugar is selected as dissolved material which is dissolved into 100 ml of water at different weights. Measurements are taken at room temperature. The results are tabulated at table 5 and presented in graphical form at figures 8(a) and 8(b). It may be noted capacitance as well as permittivity substantially increase when water density increases by dissolved sugar, however rate of increment of these parameters reduces when water becomes saturated with sugar.

As nondissolving material, sand is mixed in water at different weights and stirred vigorously. The sand particles have tendency to settle down with time. Therefore measurements are taken at different time after mixing the sand. Here substantial variation in opacity was observed. The experimental data is tabulated at table 6 and graphical form is represented at figure 9. It may be noticed that opacity increases with the lapse of time as sand becomes settled down, however it decreases when sand content is increased.

Weight of Sugar	Capacitance	Permittivity	Opacity
0	503	7.48	959
4	506	7.49	959
8	523	7.74	960
12	541	8.00	960
16	558	8.26	961
20	564	8.35	962
28	567	8.39	963
36	569	8.42	963

Table 5: Sugar in water

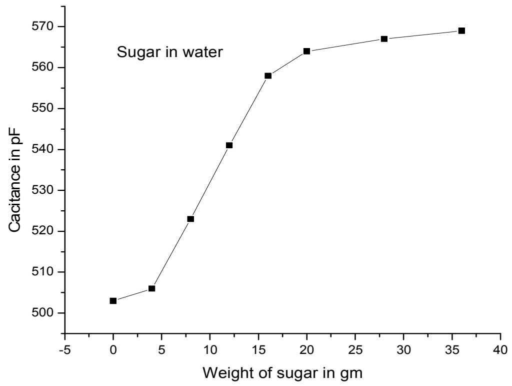


Figure 8(a): Capacitance at water dissolved with sugar

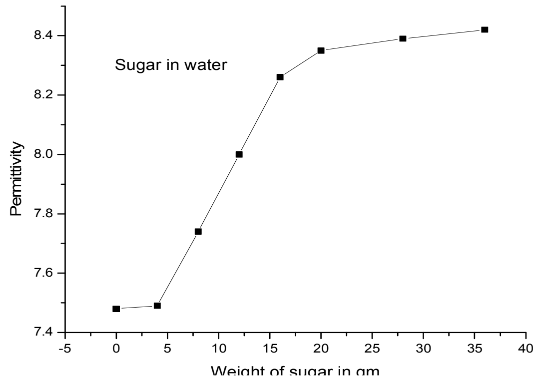
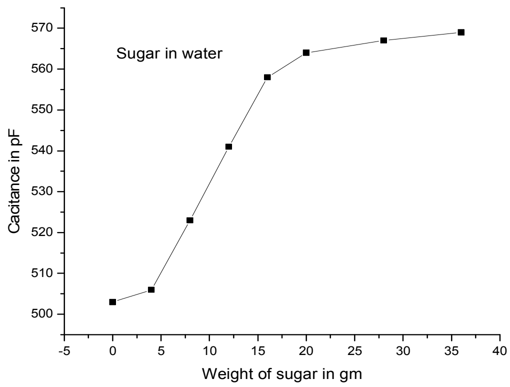


Figure 8(b): Permittivity at water dissolved with sugar



Weight of Sand in gm	Opacity		
	After 5 sec	After 15 sec	After 25 sec
4	943	946	947
8	941	942	944
12	936	940	940
16	924	931	935
20	920	928	932
24	917	926	928

Table 6: Opacity when water is mixed with sand at 34 ℃

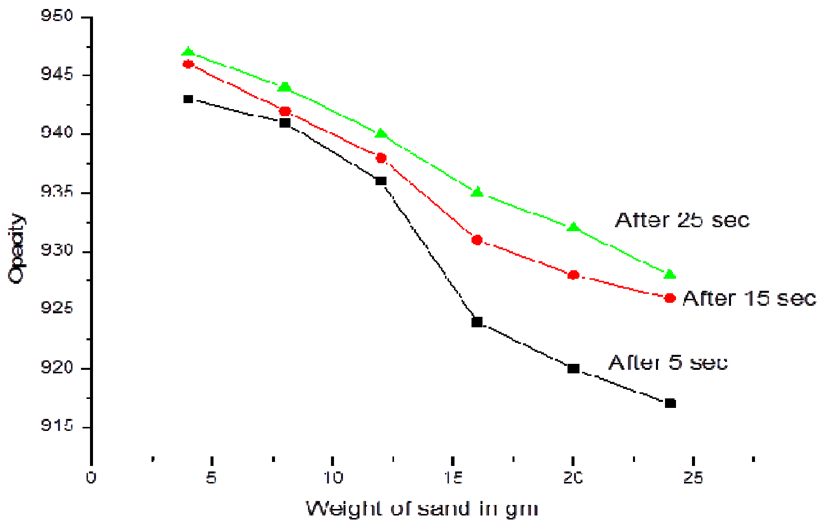


Figure 9: Variation of opacity when water is nixed with sand

6. DISCUSSIONS

A simple procedure of measurement of capacitance, permittivity and opacity is presented here which is also economic. It is a safe and non-destructive method of measurement that can be applied for any type of liquid. The basic properties of liquid are unaltered by this non-contact type of measurement. The experimental results show good consistency. As it is observed that capacitance and opacity vary with the impurity in liquid at dissolved state or undissolved manner, the degree of impurity in liquid can be detected. Therefore the method has the potential to be employed in quality assurance in many fields. However accuracy depends on the material and dimension of test container. For better accuracy, error correction algorithm may be incorporated in the microcontroller itself.

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Nilotpal Manna obtained B.E. degree in Electronics and Telecommunication Engineering in 1979 from Bengal Engineering College, Sibpore, Kolkata, now renamed as Bengal Engineering and Science University and received M Tech degree in 1981from Indian Institute of Technology Madras (Chennai). He has wide industrial experience of twenty-two years from semi-government sectors like Instrumentation Ltd, Kota and several private industries like Toshniwal Instruments Manufacturing Pvt Ltd and others. He served mostly in the Research and Development wings and was associated in development of various electronic and communication instruments meant for military application as well as development of analytical instruments. At present he is Head of the Department of Electronics and Instrumentation Engineering of JIS College of Engineering, Kalyani, West Bengal, India. He has several research publications in national and international journals and conferences, and authored four technical books.

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