Cross sensitivity of Ionic concentration on Admittance type measurement

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Abstract— An attempt has been made to study theoretically electrical admittance type level measurement and its cross sensitivity with ionic concentration of liquid. The analysis has been made for single and double electrodes and found there is significant cross sensitivity which varies with the ionic concentration of the liquid. This study will help further to design and develop continuous level measurement transmitter in Boiler drum.

Keywords- Admittance type level transmitter, conductivity, permittivity, Cross sensitivity, Boiler drum

I. INTRODUCTION

The electrical parameter "Admittance" of electrode electrolyte interface is reciprocal of Impedance often used in different application of engineering but not much effective till date due to its cross sensitivity with other sensible parameters. In process industry the Boiler drum water level is one of the most important parameter for measurement and control in power plants [1]. The primary function of a utility boiler is to convert water into steam, which is used to turn a steam turbine, thus generating electricity. Water level control is critical for the safe operation in the boiler. An objective for safe and efficient boiler operation is to maintain a constant level of water in the boiler drum. If the level is too low, boiler tubes will be damaged by overheating. If the level is too high, steam separators will not function properly, temperature control will be difficult, and the super heater tubes and turbines could be damaged by moisture water treatment chemical carryover. Unfortunately boiler drum level control is complicated by changes in electrical load requirements or variation in the fuel and air supply. It is very important to measure the level of the boiler drum in a continuous manner. In the recent days, different methods for measuring the level of water in the boiler drum like discrete conductivity probe level transmitters, magnetic level gauges, are used in the industries [2].

Earlier workers tried to develop Admittance type continuous level measurement [3] system in metallic or non-metallic storage vessel, which is one of the low cost sensing methods for continuous monitoring the level. This measurement is suitable for particular type of liquid with specific temperature zone. Earlier study indicates that there is good temperature sensitivity during level measurement with admittance technique [4].

But electrical property of the measuring liquid greatly depends on its ionic mobility as well as permittivity. The challenge lies to remove those cross sensitivities and extract the relevant features for measurement and control. The present work attempts to study the physical nature of Admittance in level measurement with variation of the significant change of water quality i.e. the liquid having varying ionic concentration. The purpose of the studies are:-a) to identify the nature of cross sensitivity for single and double electrode in liquid, such that the result can be utilized to remove the error by developing suitable technique and design the continuous boiler drum level monitoring system using admittance method, b) To use the multifunction [5] properties of the sensor for measurement purpose.

II. STUDY OF AN ADMITTANCE TYPE SINGLE ELECTRODE TRANSDUCER FOR CONTINUOUS MONITORING OF LIQUID LEVEL

Let us assume that a cylindrical metallic electrode A of radius r is immersed to a depth h in a liquid of permittivity ε and conductivity σ in a cylindrical metallic storage vessel of diameter D as shown in Fig.1.

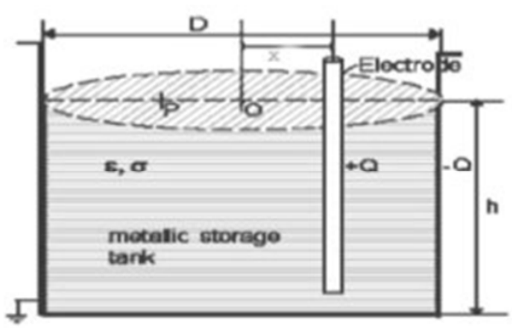

Fig.1: Single electrode in a conducting vessel [4]

The impedance between the electrode and the vessel is given by:

$$Y_{parallel} = \frac{1}{\mathrm{R_{parallel}}} + j\omega C_{parallel} \qquad (1)$$

Where, $Y_{parallel}$ is the admittance between the electrode and the vessel. $C_{parallel}$ is the equivalent of fringe capacitance and double layer capacitance between the electrodes and the vessel. $R_{parallel}$ is the equivalent resistance of fringe, electrode double layer resistance between the electrode and the vessel.
The equivalent admittance between the electrode and the vessel is given by

$$Y_{parallel} = \frac{2\pi\sigma h}{\ln(\frac{d}{r})} + j\omega \frac{2\pi\varepsilon h}{\ln(\frac{d}{r})} = \frac{2\pi h}{\ln\left(\frac{d}{r}\right)}(\sigma + j\omega\varepsilon) \qquad (2)$$

Where, $Y_{parallel}$ is the admittance between the electrodes and the vessel
h is the height of the liquid level
d is the separation between the electrodes
r is the radius of the electrode
σ is the conductivity of the liquid
ϵ is the permittivity of the liquid

The magnitude of the admittance parallel is given by

$$|Y_{parallel}| = \frac{2\pi h\sqrt{\sigma^2 + \omega^2\varepsilon^2}}{\ln\left(\frac{d}{r}\right)} \qquad (3)$$

The above equation is rewritten as

$$|Y_{parallel}| = K\left(\sqrt{\sigma^2} + \omega^2\varepsilon^2\right) \qquad (4)$$

Where, $K = \frac{2\pi h}{\ln(\frac{d}{r})}$

The characteristic curve is plotted between the admittance ($Y_{parallel}$) and the height of the liquid level (h) using MATLAB.

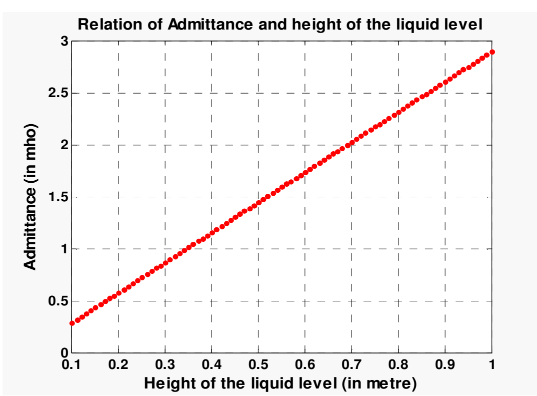

Fig.2: Plot between Admittance and height of the liquid level for single electrode of admittance type level measurement with change at fixed ionic concentration and temperature.

Admittance depends on conductivity and permittivity of the liquid. It is noted that if there is no change in temperature and ionic concentration then admittance within the two electrodes is proportional to level of the tank. Here the variation of ionic concentration on the conductivity and permittivity of the liquid is considered at a constant temperature.

i. Variation of conductivity with ionic concentration

Relation between conductivity of the liquid and the variation of ionic concentration in the solution is given by [4]

$$C = A_0 + A_1(\sigma_{ref}) + A_2(\sigma_{ref})^2 \qquad (5)$$

Where C = Ionic concentration
σ_{ref} = conductivity corrected to T_{ref} temperature
A_0, A1 and A_2 are specific constants depend on the type of solvents present in the solution.

The curve between the conductivity and ionic concentration of NaCl solution is plotted using MATLAB.

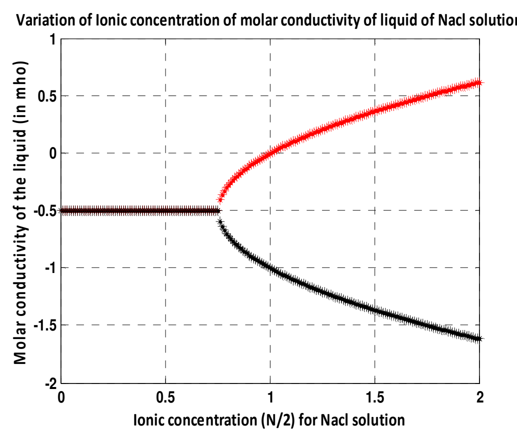

Fig.3: Plot between molar conductivity of the liquid and variation of ionic concentration of the liquid of NaCl solution.

There are two roots of the quadratic equation. The variation of the roots is shown in equation (5).

Considering the physical measurement, the negative roots are not accepted because they give imaginary solution.

ii. Variation of permittivity with ionic concentration

Relation [6] between permittivity of the liquid and the variation of ionic concentration in the solution is given by

$$\varepsilon = \frac{\varepsilon_0}{1+\sum_{ions} A_i x_i ln(1+B_i\sqrt{I_i})} \qquad (6)$$

Where,

Ɛ is the dielectric constant of the liquid due to presence of all dissolved solute in solvents.
$Ɛ_0$ is the dielectric constant results from the presence of all neutral species including solvents and ions pairs.
I_i is the ionic strength on the mole fraction basis.
A_i and B_i are temperature dependent Parameters
x_i is the mole fraction of the component i.

The temperature dependent parameters A_i and B_i are related by given equation-5,

$$A_i = a_{i1} + a_{i2}T$$
$$B_i = b_{i1} + b_{i2}T$$

Where T is temperature in Kelvin and a_{i1}, a_{i2}, b_{i1} and b_{i2} are the parameters determined from experimental dielectric constant data for electrolytic solutions. By analyzing experimental data that constant values of the parameters can be used for any of the ionic species in all of the aqueous solutions [7, 8,9].

The curve between the permittivity and ionic concentration of NaCl solution is plotted using MATLAB.

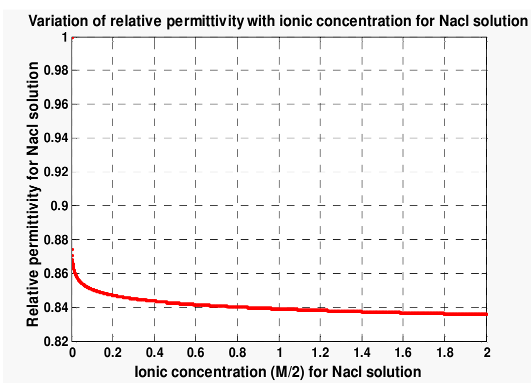

Fig.4: Plot between molar permittivity of the liquid and variation of ionic concentration of the liquid of NaCl solution [10].

Now the variations of σ_c and $Ɛ_c$ solution are substituted in the equation [4]. The $Y_{parallel}$ is represented as

$$|Y_{parallel}| = K[(\sigma_c^2) + (Ɛ_c^2)] \qquad (7)$$

Where, σ_c is the molar conductivity of solution considering the effect of change in ionic concentration. $Ɛ_c$ is the permittivity of the solution considering the effect of change in ionic concentration.

The curve Yparallel and height of the liquid level is plotted considering the effect of variation in ionic concentration is computed using MATLAB and shown in figure-5.

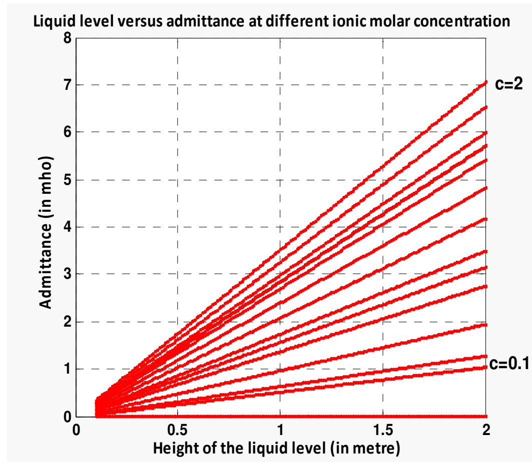

Fig.5: Plot between Admittance of single electrode type and height of the liquid level with different values of molar concentration c=0.1 to 2.

The above figure-5 shows the variation of the admittance due to the variation of the ionic concentration of NaCl in the solution. For fixed values of liquid level, % error in admittance can be computed by taking the difference of the admittance ideal (without the variation of ionic concentration) and actual admittance (with the effect of variation of ionic concentration). The difference value is the divided by the ideal admittance value to calculate the error. The error curve due to effect of ionic concentration can be calculated from these set of curves and is shown in figure-6.

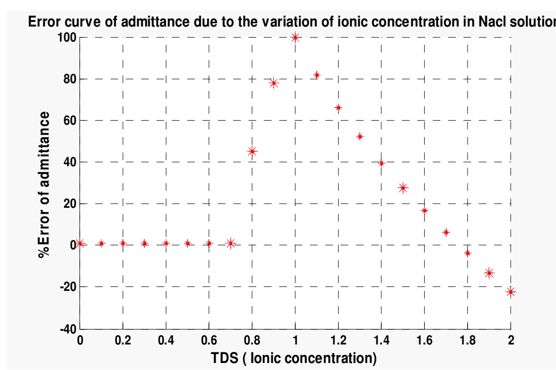

Fig.6: Error curve of admittance of the liquid at different range of total dissolved solids in the solution of NaCl.

The error in the measurement of admittance with variation of ionic concentration shows that there is no error in admittance up to the ionic concentration range from 0M to 0.7M. Further variance of total dissolved solid of NaCl gives a nonlinear characteristic of admittance of the solution. Total dissolved solids of NaCl are 58.44gm/L and the total dissolved solid for drinking water is 100-500mg/L. Since the solution in the boiler drum is de-ionized water, admittance value comes under the no error portion of the error curve. But if we use other type of water with TDS value more than 0.7M, variation of ionic concentration shows a significant effect on the admittance of the solution .

II. STUDY OF AN ADMITTANCE TYPE DOUBLE ELECTRODE TRANSDUCER FOR CONTINUOUS MONITORING OF LIQUID LEVEL

The same study has been carried out with double electrode in an insulating vessel with admittance type level measurement. Let us consider two metallic electrodes "A" & "B" separated by distance D, immersed to a depth 'h' in a liquid of permittivity and conductivity σ as shown in Fig.8. Let a static electric charge +Q be given to the electrode A with the other electrode B connected to ground.

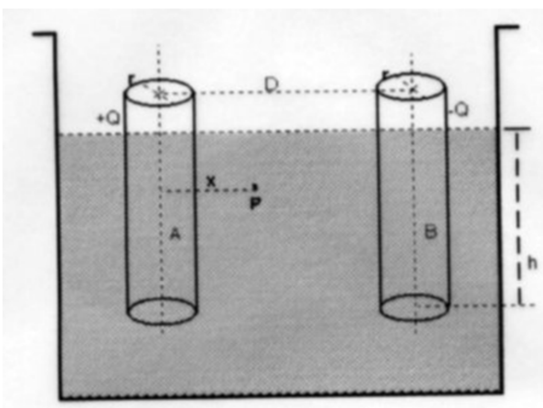

Fig.7: Double electrode in a conducting vessel [1]

The impedance between the electrode and the vessel is given by

$$Y_{parallel} = \frac{1}{R_{parallel}} + j\omega C_{parallel} \qquad (8)$$

Where, $Y_{parallel}$ is the admittance between the electrodes and the vessel. $C_{parallel}$ is the equivalent of fringe capacitance and double layer capacitance between the electrodes and the vessel. $R_{parallel}$ is the equivalent resistance of fringe, electrode double layer resistance between the electrode and the vessel.

$$Y_{parallel} = \frac{2\pi\sigma h}{\ln\left(\frac{D-r}{r}\right)} + j\omega\frac{\omega\pi\varepsilon h}{\ln\left(\frac{D-r}{r}\right)} \qquad (9)$$

The equivalent admittance between electrodes and the vessel is

$$Y_{parallel} = \frac{\pi h}{\ln\left(\frac{D-r}{r}\right)}(2\sigma + j\omega\varepsilon) \qquad (10)$$

The characteristic curve is plotted between the admittance ($Y_{parallel}$) and the height of the liquid level (h) using MATLAB. This figure-9 shows a linear relationship of admittance of double electrode type admittance level transmitter with the variation in height of the liquid level without considering the effect of change in ionic concentration of the solution. As the conductivity and permittivity depends on the variation of ionic concentration of the solution.

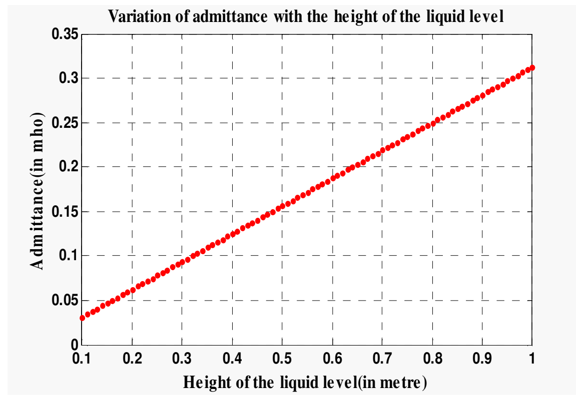

Fig.8: Plot between Admittance and height of the liquid level for double electrode of admittance type level measurement without the effect of ionic concentration of the solution.

As the conductivity and permittivity depends on the variation of ionic concentration of the solution. Substituting the variation of conductivity with change in ionic concentration (equation 5) and variation of permittivity with change in ionic concentration (equation 6) in equation 10, the following equation is derived,

$$\left|Y_{parallel}\right| = K[(4\sigma_c^2) + (\mathcal{E}_c^2)] \qquad (11)$$

Where, $K = \frac{\pi h}{\ln\left(\frac{D-r}{r}\right)}$

And σ_c is the molar conductivity of solution considering the effect of change in ionic concentration. $\mathcal{E}_c$ is the permittivity of the solution considering the effect of change in ionic concentration.

The graph between $Y_{parallel}$ and height of the liquid level for double electrode type admittance transmitter considering the effect of variation of ionic concentration is plotted using MATLAB. Again admittance shows a linear behavior with the variation of height of the liquid level after considering the effect of ionic concentration on molar conductivity and permittivity of the solution.

Ionic concentration at c= 0-0.7M, admittance values are positive and beyond c= 0.8-2M, admittance values shows negative value. In the equation-11 for the physical measurement, the negative roots are not considered because they give imaginary solution.

The percentage error between Ideal admittance (without the effect of ionic concentration) and actual admittance (with the effect of ionic concentration) is calculated by taking the difference of both admittance value divided by ideal admittance. Figure 11 shows the error curve of admittance value at different ranges of ionic concentration (TDS) of NaCl solution.

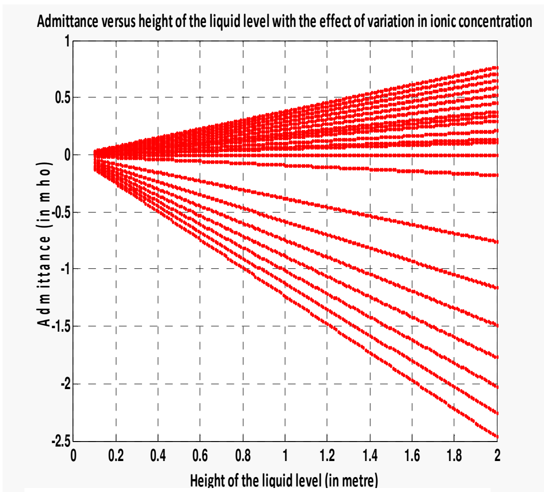

Fig.9: Plot between Admittance of double electrode type and height of the liquid level at different levels of ionic concentration of the solution.

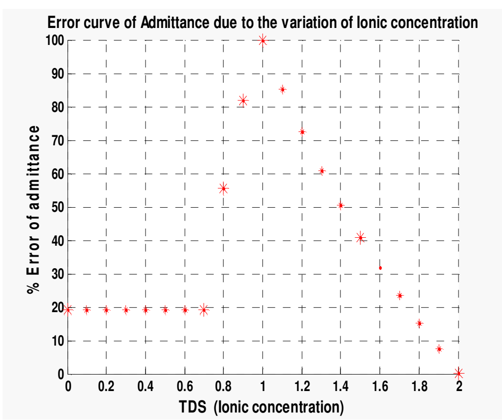

Fig.10: Error curve of admittance (double electrode) of the liquid at different range of total dissolved solids in the solution of NaCl.

Double electrode type admittance transmitter shows same error characteristics up to the TDS range of 0-0.7M of NaCl solution. Since the solution in the boiler drum is de-ionized water, admittance value comes under the 20% error portion of the error curve. But if we use other type of water with TDS value more than 0.7M, variation of ionic concentration shows a significant effect on the admittance of the solution.

1. Removal of cross sensitivity due to temperature and ionic concentration
2. Simultaneous Measurement of temperature and ionic concentration, level measurement from admittance.

IV. CONCLUSIONS

This study reveals that there is significant cross sensitivity after certain ionic concentration similar cross sensitivity like temperature. For Boiler drum level measurement and control correction of temperature cross sensitivity is required but for other application using normal drinking or non-drinkable water correction of ionic concentration and temperature are required. This study is computational based and to be validated by experiment and suitable method of correction of cross sensitivity will be required. Use of soft computing may help to isolate cross sensitivity components then the same sensing system will able to give level, ionic concentration and temperature values simultaneously.

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