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Tracking the Presence of Lead Contaminant in Water using Geophysical Model

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Abstract: Dielectric mixing model has been successfully employed to characterize the presence of lead in water-logged porous media, contaminated by lead at different temperatures and concentrations. This work has demonstrated the influence of temperature and concentration of lead on the bulk relative permittivity (ε_b) of lead-water system in porous media. Generally, the bulk relative permittivity of the lead-water-soil system, ε_b, decreases with rising temperature and the least value of ε_b was obtained in this work at 30°C while the highest ε_b was obtained at 20°C. It is visible from the combined plot that the bulk permittivity, ε_b, of lead-water system decreases as the lead concentration increases. The ε_b is highest at lead volume fraction of 0.05. This is closely followed by that at 0.01 and so on, while the least ε_b occurs at lead volume fraction of 0.1. The reason for this is owing to the fact that as the fraction of lead increases, that of water decreases. This work is important in the monitoring of water quality and contamination by lead in the subsurface.

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Keywords: Permittivity; Lead; Silicate; Porous media; Water quality

I. Introduction

Flow of multiple phases in the subsurface can occur as a form of contamination of the useful resources like water by contaminants like petroleum oil and gas. It can also occur as a form of contamination by leachate from waste or refuse field as well as carbon-dioxide subsurface migration from storage reservoir into the potable water aquifer. Cases of two-phase flow abound and has been a subject of research for many years [1]-[5]. For example, subsurface contamination by accidentally-spilled non-aqueous phase liquids, i.e., NAPLs (e.g., oils, perchloroethylene (PCE), etc.), by various chemical process industries (CPIs) has generated many toxic contaminants which may remain in the subsurface for several years and continue to pose environmental threats globally [6,7].

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Among the contaminants of concern in water in the current time are the heavy metals. They are currently being found in several industrial and household wastes. Leachates from community land refuse are particularly rich in these heavy metals. [8] investigated the presence of heavy metals in the Densu river, Ghana. The metal contaminants were suspected to have come from popular landfill along the bank of the river.

The work on the effect of heavy metals on groundwater in Alimosho area (Lagos State) which was suspected to be contaminated by landfill leachate around the area was explored [9].The two authors concluded that leachates of heavy metals from the landfill have impacted on the groundwater. Thus, landfill can be seen as veritable source for heavy metals.

Presence of contaminants in water can be detected by a number of methods. These methods include laboratory analysis using UV spectrophotometer, Atomic Absorption Spectrometry, GC/MS technique and also by using electrical parameters (electrical conductivity (σ) and relative permittivity (ε)) relating to the property of the contaminants. [8] used Atomic Absorption Spectrometry methods to measure the presence of heavy metals like lead, cadmium, arsenic and mercury. This is a costly and high-risk method owing to the possibility of radiation exposure by users. However, it is relatively easier to use electrical parameter techniques owing to its low cost and accessibility. It is also dependable owing to its uniqueness, in large number of cases. Recent studies by [2] have utilized dielectric permittivity to monitor movement of fluids in the subsurface. As a result of its uniqueness, for large number of researchers, application of electrical parameters (electrical conductivity (σ) and relative permittivity (ε)) will remain vital in the monitoring of contaminants.

Relative or dielectric permittivity is a technique that utilises the dielectric characteristics of materials under test. It is a measure of the electrical polarization of the material, which takes place when an electric field is applied across it [10]. In principle, the bulk dielectric property of the fluid-fluid-soil composite is utilized for monitoring for multiphase system like contaminant-water system.

The works on the demonstration of the geo-electrical behaviors of the fluid-fluid-solid system with supercritical CO_2 and water/brine in the porous media have been studied [2]. The bulk electrical conductivity (σ_b) and relative permittivity (ε_b) were measured with the aid of the time domain reflectometry method (TDR). Also, [4] demonstrated the field measurements of electrical conductivity (σ) to monitor the subsurface CO_2 movement by installing several copper electrodes at different depths (e.g., 18.5 m below the ground level) to monitor CO_2 injection site by tracking the movement of injected CO2 in the space surrounding the injection site.

This work considers the use of dielectric permittivity in the detection of the presence of lead contaminant in the potable water by the use of mathematical models that were expounded in the works of [11-12]. The work of recent study [13] serves as precursor to this work by laying the foundation for successful utilization of dielectric mixing model for monitoring two-phase flow in the porous media.

II. Methods

The methods used in this work involve the application of mathematical models that were expounded in the works of [11-13]. The approach requires the determination of bulk relative permittivity (ε_b) of lead-water-soil system at different lead concentrations and temperatures.

A. Bulk Relative Permittivity of Lead-Water-Soil System

The development of an important equation for the bulk relative permittivity of multiphase system was explored [12]. The equation is used in this work in the format presented for three-phase system [11]:

$$\varepsilon_b = (\theta\varepsilon_w^\alpha + (1-\phi)\varepsilon_s^\alpha + (\phi-\theta)\varepsilon_l^\alpha)^{1/\alpha} \qquad (1)$$

where, ε_b is the composite or bulk relative permittivity for the system. ε_w, ε_s and ε_l represent the relative permittivities for water (phase 1), sand/soil (phase 2) and lead (phase 3), respectively. ϕ is the soil's porosity, 1-ϕ, θ, and $\phi - \theta$ are the volume fractions for soil, water and lead, respectively. In the model, the constant parameter 'α' was described as crucial to the description of the composite dielectric number for different soils. The value of α as 0.5 was found to be appropriate in various studies [11], [14], [15].

B. Water relative Permittivity (ε_w)

Temperature and pressure are factors that affect relative permittivity of water, ε_w. Using equation (2), various studies such as [11-12] relate the temperature to ε_w:

$$\varepsilon_w = 78.54[1 - 4.579x10^{-3}(T-25) + 1.19x10^{-5}(T-25)^2 - 2.8x10^{-8}(T-25)^3] \quad (2)$$

However, a model for ε_w that is dependent on temperature and pressure was presented [16]. The work of [13] showed that both equation that was explained by [11], [16] give very similar ε_w, since the water is less affected by pressure.

C. Relative permittivity of lead (ε_s)

Lead is a very abundant mineral in nature. It can contaminate water via pipes or connectors of lead solder used to connect pipes and brass fixtures. Also, it can come from lead-lined tanks [17]. The problem is compounded when there is a level of acidity in the water which can readily aid the dissolution of lead into it. The acidic water will greatly increase the amount of lead that will leach from lead plumbing. Lead can exist as nitrate, chlorate, chloride and oxide compounds. In the environment, lead is known to be toxic to plants, animals, and microorganisms. Most of the lead in the environment is in the inorganic form and exists in several oxidized states [18]. As a result, this work utilized lead oxide as a form of lead that is found in water. The relative permittivity of the lead oxide used in this work is 25.9 [19].

D. Programming

The equations (1-2) shown above were automatically solved using MATLAB coding technique in order to obtain value of the bulk permittivity (ε_b) of the lead oxide-water system.

III. Results and Discussion

Figure 1 shows the behaviour of lead contaminant in water under the influence of temperature. The bulk permittivity, ε_b, changes with temperature. As the temperature increases, the ε_b continues to fall. This begins from 20°C and continues till 30°C. The highest and the lowest ε_b are 20.39 and 19.67, corresponding to 20 °C and 30°C, respectively. Thus, the ε_b of lead-water system and temperature have inverse relationship. This is the same as the findings of different studies e.g. [2], [20]. They similarly found inverse relationship between the ε_b of lead-water system and temperature. In this work, this change in ε_b is about 3.5% decrease for 50% rise in temperature. Figure 1 represents the lead volume fraction of 0.005.

Figure 2 shows the bulk permittivity, ε_b of lead-water system changing with temperature at lead fraction of 0.01. In the figure, similar to Figure 1, the ε_b continues to fall as the temperature increases. As before, there is also about 3.5% decrease in ε_b for 50% change in temperature. This again affirms the negative relationship between ε_b and temperature.

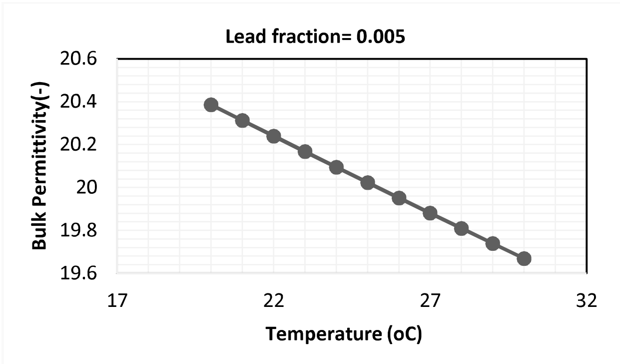

Figure 1: Change in bulk permittivity of lead-water system with temperature at lead fraction of 0.005

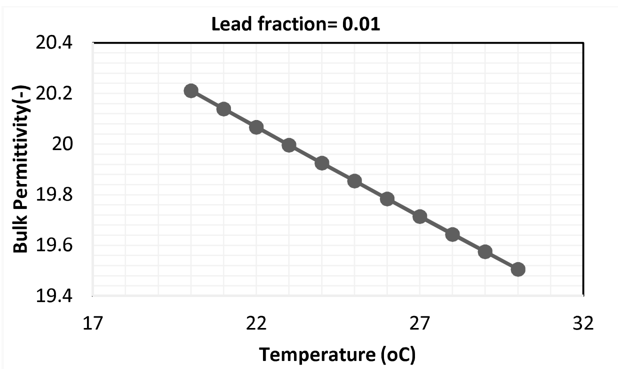

Figure 2: Change in bulk permittivity of lead-water system with temperature at lead fraction of 0.01

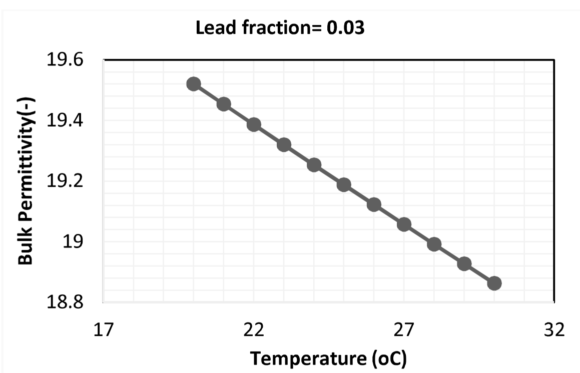

Figure 3: Change in bulk permittivity of lead-water system with temperature at lead fraction of 0.03

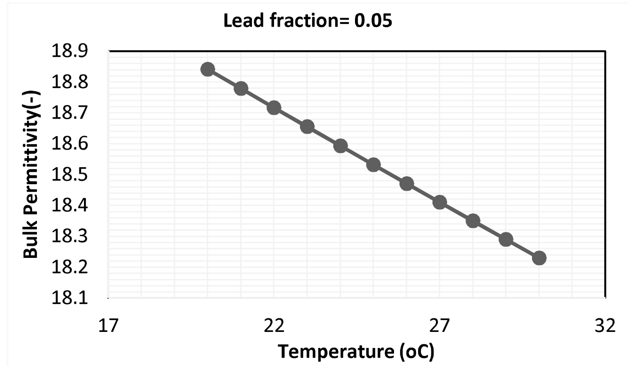

Figure 4: Change in bulk permittivity of lead-water system with temperature at lead fraction of 0.05

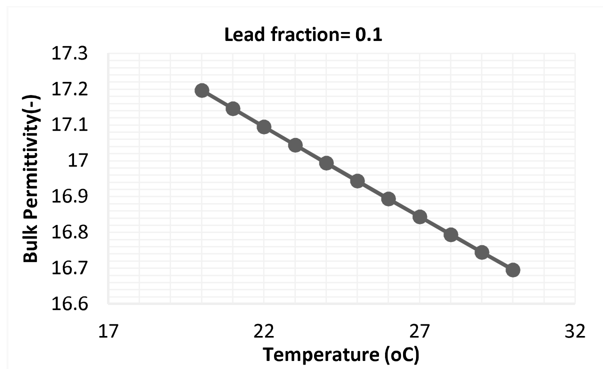

Figure 5: Change in bulk permittivity of lead-water system with temperature at lead fraction of 0.1

Figures 3, 4 and 5 show the bulk permittivities, $\varepsilon_{b,}$ of lead-water system changing with temperature at lead fractions of 0.03, 0.05 and 0.1, respectively. The figures revealed similar facts as earlier discussed. Generally, the $\varepsilon_{b,}$ of lead-water system decreases with rising temperature.

In order to understand the influence of lead concentration on the ε_b of lead-water system, Figure 6 shows combined plots of all concentrations of lead that were used in this work. It can be seen that the bulk permittivity, ε_b of lead-water system decreases as the lead concentration increases. The Figure shows that ε_b is highest at lead fraction of 0.05. This is closely followed by that at 0.01 and so on, while the least ε_b occurs at lead fraction of 0.1. The behaviour is owing to the fact that as the fraction of lead increases, that of water decreases. Meanwhile, water has the highest relative permittivity in the bulk. So, as the fraction of lead increases, the bulk permittivity of the system reduces owing to the reduced concentration on water.

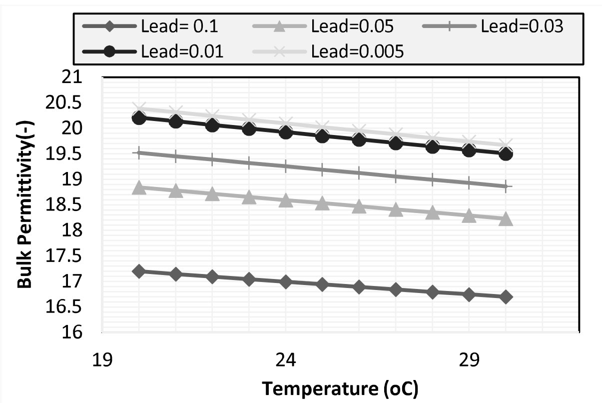

Figure 6: Combined plots of bulk permittivity of lead-water system with temperature at various lead fractions

IV. Conclusion

This work has investigated the alternative measurement method for heavy metals presence in potable water by using dielectric characteristics of water-logged porous media, contaminated by lead at different temperatures and concentrations. This work has demonstrated the influence of temperature and concentration of lead on the bulk relative permittivity (ε_b) of lead-water system in porous media.

Generally, the bulk relative permittivity of the lead-water-soil system, $\varepsilon_{b,}$ decreases with rising temperature and the least value of ε_b was obtained in this work at 30°C while the highest ε_b was obtained at 20°C. In order to understand the influence of lead concentration on the ε_b of lead-water system, combined plots of all concentrations of lead-water-soil system was made. It is visible from the combined plot that the bulk permittivity, $\varepsilon_{b,}$ of lead-water system decreases as the lead concentration increases. The ε_b is highest at lead volume fraction of 0.05. This is closely followed by that at 0.01 and so on; while the least ε_b occurs at lead volume fraction of 0.1. The reason for this is owing to the fact that as the fraction of lead increases, that of water decreases. Meanwhile, the water has the highest relative permittivity in the bulk. So, as the fraction of lead increases, the bulk permittivity of the system reduces owing to the reduced concentration on water. This work is important in the monitoring of water quality and contamination by lead in the subsurface.

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