Dielectric Studies of Wet Soil at X-band Microwave Frequency

Kamlesh Kumari
Department of Physics, R. R College Alwar (Raj) India

Abstract

The real and imaginary parts of dielectric permittivity (ε' and ε'') for artificially moistened soil at different levels of soil moisture content SMC (0.0% to 21.0%) of Alwar region determined at single microwave frequency 9.78 GHz and at 35.0 ^{0}C using wave-guide cell method. Further, ε' and ε'' of same soil are also determined by Dobson empirical model. The ε' and ε'' of moist soil shows the respective correlation with soil moisture content (SMC).

Key words — Dielectric constant, soil moisture content.

1. Introduction

The study of SMC has enormous importance in various environmental studies like meteorology, hydrology, agriculture and climate change. The role of soil moisture in the top one to two meters of the Earth's surface is widely recognized as a key parameter plays an extremely important role in various environmental processes. Jackson and Schmugge[1] explained that, SMC is one of the few directly observable hydrological variables, plays an important part in the water and energy budgets necessary for climate studies. Dielectric properties of soil at microwave frequencies depend upon a large number of parameters like SMC, textural composition, structure, temperature, bulk density, pore size, intrinsic materials, chemical composition, frequency, salinity, organic matter, humus, presence of fertilizers and manure, contamination and pollution. Ulaby *et al*[2] studied that at 1.0 GHz and at room temperature ε' and ε'' of water are approximately 80.0 and 4.0 while the value of ε' for dry soil varies from 2.0 to 5.0 and ε'' is typically less than 0.05. The large contrast between the dielectric constant of water and dry soil results in a range from 4.0 to 40.0 for dielectric constant of moist soil. This wide range can be directly related to the presence of volumetric soil water content, and is further influenced by soil texture, frequency, temperature and salinity. The direct relation between soil bulk dielectric constant and volumetric soil water content is not straightforward and many empirical and theoretical dielectric models are suggested by various researchers[3-8].

2. Experimental Procedure and Theory

Soil sample from superficial horizons (0-15 cm) of Alwar region has been selected for the experimentation. Texture of soil (Sand=59.6%, Silt=29.5% Clay=10.9%) is determined using sieving and sedimentation methods. For sample preparation oven dried for soil is divided in the seven groups and desired amount of conductivity water was mixed to obtain volumetric soil moisture content having the values 3.0% 6.0% 9.0% 12.0% 15.0%, 18.0% and 21.0%. These soil samples are kept in air tight plastic container for twenty four hours for proper mixing (homogeneous distribution of SMC within the entire volume of soil) and to avoid any evaporation from soil. Due to saturated and unsaturated flow of SMC and its vapor in mixture, homogeneous distribution of SMC within the entire volume is obtained.

Experimental Determination of Dielectric Permittivity of Moist Soil

The values of ε' and ε'' are determined at microwave frequency 9.78 GHz and at 35.0^{0}C using wave guide cell method developed by Yadav and Gandhi[9]. The experimental set up, theory and procedure for the present work is the same as used earlier by other researchers[10]. The ε' and ε'' of the soil are measured using shift in minima of the standing wave pattern inside the slotted section of an X-band rectangular wave guide excited in TE_{10} mode.

Determination of Dielectric Permittivity of Moist Soil by Dobson Model

The ε' and ε'' of moist soil samples (3.0% 6.0% 9.0% 12.0% 15.0%, 18.0% and 21.0 %.) are determined at 35.0 ^{0}C by Dobson Model[16].

Dobson *et al* [11] describe the ε' and ε'' of soil over the frequency range 1.0 to 18.0 GHz as a function of soil moisture, temperature, texture and frequency by following equations (5) and (6).

$$\varepsilon' = \left[1 + \frac{\rho_b}{\rho_s}\left(\varepsilon_s^{\alpha} - 1\right) + \theta^{\beta'}.\varepsilon'^{\alpha}_{w} - \theta\right]^{1/\alpha} \quad (5)$$

$$\varepsilon'' = [\theta^{\beta''}.\varepsilon''^{\alpha}_{w} - \theta]^{1/\alpha} \quad (6)$$

where ρ_b and ρ_s are the soil bulk density (1.51 g/m^3) and particle density (2.66 g/m^3), θ is the volumetric soil water content, ε_s is the dielectric constants of the soil solids depends on the particle density . ε'_w and

$\varepsilon_w^{''}$ are the real and imaginary parts of complex permittivity of water, α is an empirical shape factor equal to 0.65. The empirical constants β' and β'' are related to the texture of soil by equations (7) and (8).

$$\beta' = 1.2748 - 0.519S - 0.152C \qquad (7)$$

$$\beta'' = 1.33797 - 0.603S - 0.166C \qquad (8)$$

Where, S and C are the sand and clay fractions of soil.

The empirically derived expression for effective conductivity σ_{eff} in this model is also dependent on texture.

$$\sigma_{eff} = -1.645 + 1.939\rho_b - 2.013S + 1.594C \qquad (9)$$

The real part of complex permittivity of water ($\varepsilon_w^{'}$) is given by well-known Debye[12] relaxation equation (10).

$$\varepsilon_w^{'} = \varepsilon_{w\infty} + \frac{(\varepsilon_{w0-}\varepsilon_{w\infty})}{1 + (2\pi f \tau_w)^2} \qquad (10)$$

Dobson *et al* [8] used a slightly different version of Debye relaxation equation for the calculation of imaginary part of complex permittivity of water ($\varepsilon_w^{''}$) to account the effective ionic conductivity σ_{eff} of the soil is given by equations (11).

$$\varepsilon_w^{''} = \frac{2\pi f \tau_w (\varepsilon_{w0-}\varepsilon_{w\infty})}{1 + (2\pi f \tau_w)^2} + \frac{\sigma_{eff}(\rho_s - \rho_b)}{2\pi\varepsilon_0 f \rho_s \theta} \qquad (11)$$

Where, ε_{w0} is the static dielectric constant of pure water, $\varepsilon_{w\infty}$ is the high frequency limit of the dielectric constant of pure water, f is the observation frequency in Hertz and τ_w is the relaxation time of water.

Further, the static dielectric constant (ε_{w0}) and the relaxation time of pure water (τ_w) are strong function[13-14] of temperature (T ^{0}C) as given by following equations (12) and (13).

$$\varepsilon_{w0}(T) = (87.134 - 1.949\times10^{-1}\times \mathrm{T} - 1.276\times10^{-2}\times \mathrm{T}^2 + 2.491\times10^{-4}\times \mathrm{T}^3) \qquad (12)$$

$$2\pi\tau_W(T) = (1.1109\times10^{-10} - 3.824\times10^{-12}\times \mathrm{T} + 6.938\times10^{-14}\times \mathrm{T}^2 - 5.096\times10^{-16}\times \mathrm{T}^3) \qquad (13)$$

3. Results and Discussions

Variations of ε' and ε'' of soil with at different levels of SMC (0.0% to 21.0%) determined, experimentally and Dobson model are shown in figure-1. An examination of figure-1, leads to the following inferences:

(i) Figure 1 reveals that ε' increases with increasing percentage concentration of SMC. Initially ε' increases slowly when water is added to dry soil but at a certain moistness around SMC=10% addition of more water in soil causes the increases of ε' rapidly. Molecules of water possess permanent electric dipole moment and high dielectric constant of water depends on the molecule's ability to align its dipole moment along an applied field. Hindrance to the molecule's alignment (adsorption, freezing, tight binding to a soil particle) reduces the dielectric constant of water. Since the initial water quantity added to dry soil is tightly bound to the surface of the particles, it will cause only a small increase of the soil dielectric constant. This water is referred to as bound water. As more water is added, the soil dielectric constant will rapidly increase because the additional molecules are far from the soil particle surface and free to align. Water in this phase is referred to as free water. Dielectric constant of free water is higher than that of bound water.

(ii) It is evident from figure 1 that ε'' increases with increasing percentage concentration of SMC. Since, the dielectric loss factor of water is high in comparison of dry soil, so that, ε'' of soil water mixture increases with SMC. Further, chemical reaction of water with minerals, humus, salts and clay portion of the soil produces cat ions and anions in the soil solution. The presence of large number of ions changes the dielectric properties of the soil. In wet soil, availability of large number of cat ions and anions increases the conduction and polarization losses. Due to increases in the SMC, conduction loss, polarization loss, rotational inertia are increases. Hence, there is increasing lag between the forcing field and orientation of dipole. Resulting more power absorption in the soil and causing enhancement in the dielectric losses. Addition of more water with soil, more and more polar molecules are available to interact with microwaves, dielectric constant of moist soil is proportional to the number of water dipoles per unit volume, so that real and imaginary part of dielectric constant of soil increases as the SMC of soil increases.

(iii) An inspection of figure-1 reveals that the experimentally determined values of ε' at different volumetric moisture content (0.0% to 21.0%) are a slight lower than that of Dobson model values and show that experimental results are in close agreement with Dobson models values which is somewhat based on theoretical principles and include many parameters of soil (texture, structure, particle density, bulk density, SMC).

(iv) Experimentally determined values for ε'' are approximately same as Dobson model values. Minor difference between experimental and model results due to semi empirical nature of Dobson models.

4. Conclusion

Dielectric studies of moist soils reveal that real and imaginary part of complex permittivity increases with increasing percentage concentration of SMC. Further, non linear behaviour of SMC with ε' is due to the presence of bi-phase of SMC in the soil (bound and free water). In dry soil, the water is tightly bound and contributes little to the dielectric constant of the soil water mixture. As more water is added to the soil the molecules will be farther from the surface of soil particle and will be able to rotate more freely. The subsequent influence of the enhanced free water portion increases the dielectric constant of soil non-linearly. The present investigations indicate that the Dobson model is suitable regarding dielectric characterizations of soil . But slight difference leads to a possibility of modification of model according to soil of Alwar region.

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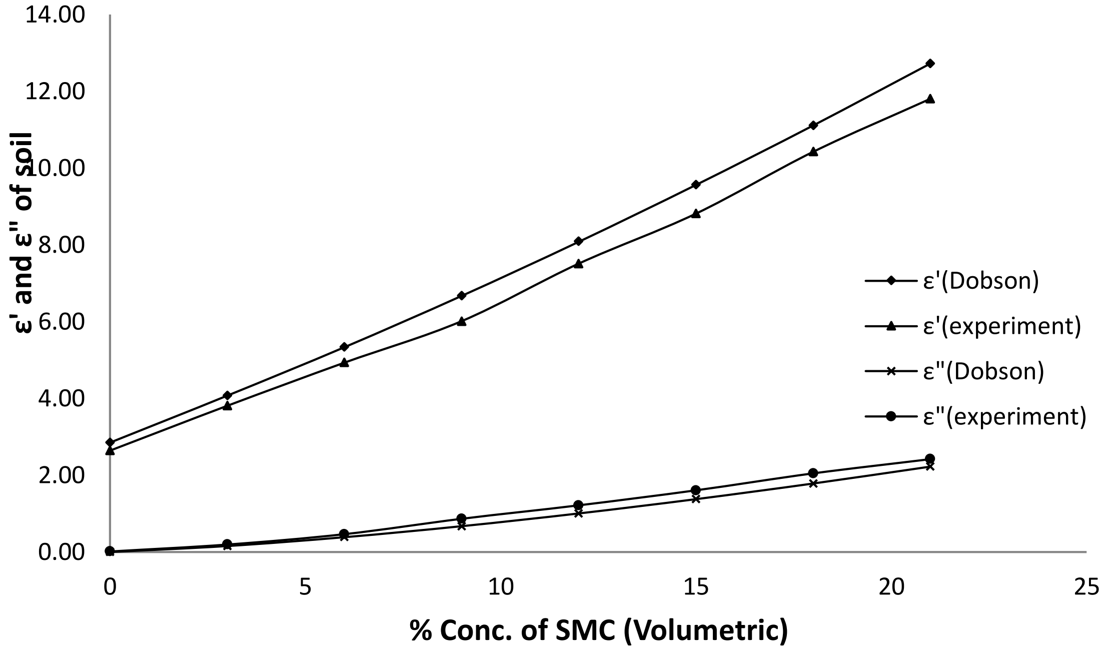

Figure: 1 Variation of real and imaginary parts of dielectric constant w.r t. **% Conc**. of SMC (Volumetric) by Dobson model and Experiment