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Effects of humidity and temperature on the optical properties of wet sand

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ABSTRACT

Prediction method for the effect of air humidity and temperature on the optical properties of wet aerosol particles is a key research point on the atmospheric science, earth science, and so on. This paper firstly discussed the effect of moisture, salinity, and temperature on the particle's dielectric constant, and then analyzed the effect of these parameters on the electromagnetic scattering properties of wet sand. The results showed that with the increasing of the temperature, the real part of the permittivity of sand decreased, but its imaginary part increased, and the variation on the real part was much smaller than the imaginary part. With the increasing of the humidity, the equivalent permittivity of wet sand increased, and the difference of permittivity between the sand covered by pure water and the saline sand became obvious. In addition, the extinction efficiency, the scattering efficiency, the back-scattering efficiency and the asymmetry factor of dry sand particle are smaller than those of the wet sand, and with the increasing of the wavelength of electromagnetic wave, the scattering efficiency, the back-scattering efficiency and the asymmetry factor of the dry and wet sand particle are all exponential increased, but the extinction efficiency showed a different changing rule.

1. Introduction

Scattering and absorption of electromagnetic wave by the small particle is a common research subject in some areas, for example, the atmospheric science, biology, medicine and chemistry [1,2]. With the increasing interest of the extraterrestrial exploration, and the close attention on the atmospheric environmental pollution, it is important to understand the impact mechanism of various particles in different environment on the propagation of electromagnetic wave, and to achieve an accurate prediction on these processes. Now there are some methods to solve these problems, which can simulate the optical properties of particles with various shapes, diverse structure, and even charged [2-20]. Some researchers also have discussed the effect of the moisture content [21,22], the wind-blown sand electric field [23], and the components on the particle's optical characters [24-26]. However, few attempts have been done on the influence of the absorption processes of multiply charged ions (particularly in the Mars, Moon, et al.), on the impact of the chemical reaction process on the surface of the hygroscopic particle (for example the aerosols in the city), and on the effect of temperature change [27].

Actually, the permittivity depended on the temperature and the component of particle. The effect of the first factor can be described by the thermal coefficient, the second one usually contains the chemical component and the moisture content. Usually, the permittivity increases with a rise in temperature [28], some changes in temperature must influence the particle's optical properties. Therefore, this paper considered the effect of temperature on the sand, and it also discussed the impact of moisture content.

2. Basic physical model

2.1. Permittivity of wet sand considering the temperature changes

The main component of sand is quartz. Rajeev et al. [29] found the quartz's thermal coefficient is $(19.4 \pm 2.2) \times 10^{-6}/°C$ while the temperature of particle is between 15 and 25 °C, and Zhang also found that when the temperature is smaller than 100 °C, the influence of temperature on the permittivity of quartz can be neglected [30]. Therefore, the effect of environmental factors on the sand's optical properties is mainly from the air humidity, which can increase the moisture content of sand. Now we will analyze it.

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In order to discuss the effect of air humidity on the particle's physical properties, we must theorize the relation between the air humidity and the sand's moisture content. Awakuni [31] measured the mass percent of absorption water by dry sand in moist air. We can obtain the relationship between air humidity H and the absorption water w through data fitting method with the soft of MATLAB7.0, it can be represented as follow:

$$w = 7.069\times10^{-7}H^3 - 8.112\times10^{-7}H^2 + 3.509\times10^{-3}H + 1.793\times10^{-4} \tag{1}$$

H is a dimensionless parameter. We assumed that the mass density of sand and water is ρ_s,ρ_w, respectively, then we can obtain the sand's humidity p, which is shown in Eq. (2),

$$p = \frac{\rho_s}{\rho_w+\rho_s w}\times w \tag{2}$$

Supposed that the particle surface is free from foreign matters, and the water on the particle is pure. The permittivity of water can be calculated through the Debye equation, which can be represented as following [32,33].

$$\varepsilon_w = \varepsilon_{w\infty} + \frac{\varepsilon_{w0}-\varepsilon_{w\infty}}{1+(2\pi f\tau_w)^2} - i\frac{2\pi f\tau_w(\varepsilon_{w0}-\varepsilon_{w\infty})}{1+(2\pi f\tau_w)^2} \tag{3}$$

Here $\varepsilon_{w\infty}=4.9$, ε_{w0} is the static dielectric constant. τ_w is the relaxation time, which depends on the temperature T(°C). These parameters can be obtained through Eqs. (4) and (5).

$$\varepsilon_{w0} = 88.045 - 0.4147T + 6.295\times10^{-4}T^2 + 1.075\times10^{-5}T^3 \tag{4}$$

$$\tau_w = \frac{1}{2\pi}\left(1.1109\times10^{-10} - 3.824\times10^{-12}T + 6.938\times10^{-14}T^2 - 5.096\times10^{-16}T^3\right) \tag{5}$$

which is appropriate for $T \in [0, 40\ °\mathrm{C}]$.

Actually, some salt ions distribute on the surface of particles on the earth [34], which means the water on particle's surface is saline water. The permittivity of saline water can be calculated through Eq. (6),

$$\varepsilon_w = \varepsilon_{w\infty} + \frac{\varepsilon_{w0}-\varepsilon_{w\infty}}{1+(2\pi f\tau_w)^2} - i\left[\frac{2\pi f\tau_w(\varepsilon_{w0}-\varepsilon_{w\infty})}{1+(2\pi f\tau_w)^2} + \frac{\sigma_f}{2\pi f\varepsilon_0}\right] \tag{6}$$

Here $\varepsilon_0=8.854\times10^{12}\ F/m$, σ_f is the ionic conductivity, $\sigma_f=0.16S_{sw}-0.0013S_{sw}{}^2$, S_{sw} is the salinity of saline water, N *is* the equivalent concentrations, which can be calculated through Eq. (7)

$$N = A\cdot S_{sw}\left(1.707\times10^{-2}+1.205\times10^{-5}S_{sw}+4.058\times10^{-9}S_{sw}^2\right) \tag{7}$$

Here A is a constant, for the *NaCl* solution, it is 1, but for the seawater, it is 0.9141. These equations also can be found in Ref. [33].

The permittivity of wet sand can be estimated through the effective-medium approximation (EMA). Mishchenko et al. [35-37] have approved that the EMA can indeed be realized for inclusion size parameters smaller than a threshold value, and the existence of the effective-medium regime is the important case of dust aerosols with hematite or air-bubble inclusion. Li et al. [13] also have verified the validity of EMA to calculate the electromagnetic scattering properties of small sand/dust particles at the microwave frequency range. Then we can obtain the permittivity of wet sand

$$\varepsilon_m^* = \varepsilon_s\left[1+\frac{3p(\varepsilon_w-\varepsilon_s)/(\varepsilon_w+2\varepsilon_s)}{1-p(\varepsilon_w-\varepsilon_s)/(\varepsilon_w+2\varepsilon_s)}\right] \tag{8}$$

Here ε_s is the permittivity of dry sand, p is the moisture content, ε_w is the dielectric constant of water. All the physical parameters are in the International System of Units.

2.2. Mie scattering of spherical particle

The Mie theory is the main method to calculate the electromagnetic scattering properties of sphere [9]. The scattering cross section, the extinction cross section, the back scattering cross section, and the asymmetry fact can be represented as follows [5],

$$Q_{sca} = \frac{2\pi}{k^2}\sum_{n=1}^{\infty}(2n+1)\left(|a_n|^2+|b_n|^2\right) \tag{9}$$

$$Q_{ext} = \frac{2\pi}{k^2}\sum_{n=1}^{\infty}(2n+1)Re(a_n+b_n) \tag{10}$$

$$Q_{back} = \frac{1}{x^2}\left|\sum_{n=1}^{\infty}(2n+1)(-1)^n(a_n-b_n)\right|^2 \tag{11}$$

$$g = \frac{4}{x^2}\left[\sum_{n=1}^{\infty}\frac{n(n+2)}{n+1}Re\left(a_na_{n+1}^*+b_nb_{n+1}^*\right) + \sum_{n=1}^{\infty}\frac{2n+1}{n(n+1)}Re(a_nb_n^*)\right] \tag{12}$$

Here

$$a_n = \frac{[D_n(mx)/m+n/x]\psi_n(x)-\psi_{n-1}(x)}{[D_n(mx)/m+n/x]\xi_n(x)-\xi_{n-1}(x)}$$

$$b_n = \frac{[mD_n(mx)+n/x]\psi_n(x)-\psi_{n-1}(x)}{[mD_n(mx)+n/x]\xi_n(x)-\xi_{n-1}(x)}$$

$$D_n(x) = \frac{d}{dx}\ln\psi_n(x)\ \psi_n(x)=xj_n(x),\ \xi_n(x)=xh_n(x),$$

$j_n(x)$,$h_n(x)$ is the first and the third kinds of the spherical Bessel function, respectively, and '*' represents complex conjugate.

3. Numerical simulation and discussion

3.1. Effect on the particle's permittivity

Firstly we discuss the effect of temperature on the wet sand's permittivity for a given moisture content, and make a comparison between two conditions that the sand covered by the pure water or the saline water. Here we assume the relative dielectric constant of the dry sand is $2.634+0.734i$, the moisture content is 0.1, and the salinity of the saline water is 20. If no other definition, these parameters remain unchanged. Calculation results are shown in Fig. 1. From the Fig. 1a and b we can know that, with the increasing of the temperature, the real component of the permittivity for the wet sand decreases continuously, but the imaginary part increases. Fig. 1c shows that with the temperature increasing, the real part of permittivity of wet sand decreases slightly, but the imaginary part of it obviously increases, which means that the rise of temperature should enhance the absorption of incident wave by wet sand. In addition, the permittivity of sand covered by saline water is smaller than the one of sand covered by pure water, which means the effect of salinity on the permittivity of sand is much smaller than the one from particle humidity.

Fig. 2 discusses the effect of humidity on the permittivity of sand, and we have set the temperature as 25 °C. From it, we can know that the permittivity increases with the increasing humidity, and the difference of dielectric constant between pure water sand and the salty sand becomes more obvious.