Extinction performance of microwave by core-shell spherical particle

Youpeng Wu¹,³, Jinxing Cheng¹,², Wenping Zhou¹, Fengtao Zhao¹, Weiwei Wen¹, Junhui Liu¹ and Yuxin Hu¹

¹Kadinuo Science and Technology (Beijing) Co., Ltd., Beijing 100013, China
²Institute of Nuclear and New Energy Technology, Tsinghua University, Beijing 100084, China

E-mail: pengpengstudent@163.com

Abstract. A new method was presented for calculating extinction cross-section of electromagnetic wave by the core-shell spherical granule. An equivalent method was used to calculate the equivalent permittivity of the core-shell spherical granule. A concentric core-shell spherical granule can be replaced by a solid granule possessing the same radius with the original coating shell, and the equivalent permittivity is equal to that of the product of equivalent coefficient and the kernel permittivity. Based on the electromagnetic wave theory and the equivalent method, the scattering and absorption characteristics of the electromagnetic wave by a core-shell spherical particle were analyzed under the condition that wavelength was far greater than the particle diameter. The influence of geometrical and dielectric parameters on the scattering and absorption of microwave was discussed numerically in detail.

1. Introduction

Particle with core-shell structure, a kind of functional composite material, possesses the properties of both the shell layer and the core material, meanwhile it also has different physical and chemical characteristics from the shell layer and the core material. Therefore, studies on the core-shell granules have attracted extensive concern due to their preparation and their electrical, magnetic, optical as well as catalytic properties [1-5]. Composites with core-shell granules owning electromagnetic absorbing function have been widely applied not only in the military stealth technology, but also in the civil domain for reducing disturbance of electromagnetic wave to microelectronic communication systems, eliminating the radiation of electromagnetic wave to human body as well as controlling environmental pollution of electromagnetic wave [6-10]. The outer shell can change and endue the nucleus granule with special optical, electrical and magnetic properties. Thus a solid granule can be upgraded to a core-shell one, and then its electromagnetic loss and frequency dispersion characteristics can be adjusted by the way of altering the shell layer, which is an effective method to develop composites with excellent absorbing capacity, thin thickness and little weight.

This paper presents an equivalent method to investigate the effective permittivity of core-shell particle. A complex model of permittivity of two-phase composites is established and utilized to
simplify the composite system with core-shell granules into the one with solid granules. The concentric core-shell spherical particle randomly mixed with matrix is replaced by solid particle mixed with the same matrix. The permittivity of the equivalent solid particle, which possesses the same radius with the original coating shell, is equal to that of the product with equivalent coefficient and permittivity of the original nucleus. Then the electromagnetic scattering and absorption characteristics of spherical core-shell particle are analyzed. In the condition that the particle diameter is much smaller than the wavelength of incident electromagnetic wave, the formulas are deduced for calculating extinction coefficient of core-shell particle. The influence of the structure and dielectric parameters on the scattering and absorption performance is investigated numerically. The results are beneficial to the theoretical direction on the design of absorbing coating materials with core-shell granules.

2. Extinction model of core-shell particle

2.1. Effective theory of composite with core-shell spherical particle

An equivalent method, integrating the shell layer and the core particle as a “complex particle”, is adopted to investigate the effective permittivity of the core-shell particle. Here a model with three-phase components is established. Usually, the filler granules can be considered as spherical ones. For simplicity, the permittivity of the core is assumed to be unchangeable. It is supposed that \( a \) and \( b \) are the radii of core particle with permittivity \( \varepsilon_1 \) and shell with permittivity \( \varepsilon_2 \) of the complex particle, respectively. The permittivity of matrix is \( \varepsilon_m \), and the thickness of the shell layer is \( t = b - a \). Under quasi-static approximation, when an electromagnetic field \( \mathbf{E}_0 \) is perpendicularly incident to the complex particle, the electric potential in each component of the composite is given by the Laplace equation. The overall electrical dipole moment of the spherical core-shell particle \( \mathbf{p} \) is calculated through the electric potential generated by the electrical dipole moment in the space [11].

\[
\mathbf{p} = \frac{\gamma \varepsilon_1 - \varepsilon_m}{\gamma \varepsilon_1 + 2 \varepsilon_m} \frac{4 \pi \varepsilon_m b^3 \mathbf{E}_0}{(1)}
\]

Where \( \gamma = [\beta(1 + 2\beta) + 2\alpha \beta(1 - \beta)] / [(1 + 2\beta) - \alpha(1 - \beta)] \) and \( \alpha = R_1^3 / R_2^3 \) are called equivalent coefficient and structure parameter, respectively, and \( \beta \) represents the ratio \( \varepsilon_1 / \varepsilon_2 \).

Solid spherical granules with permittivity \( \varepsilon_1 \) and radius \( b \) embedding in the same homogeneous matrix can be made up of another composite. Illuminated perpendicularly by electromagnetic field \( E_i \), the overall electrical dipole moment of solid particle is calculated with the following formula.

\[
\mathbf{p} = \frac{\varepsilon_1 - \varepsilon_m}{\varepsilon_1 + 2 \varepsilon_m} \frac{4 \pi \varepsilon_m b^3 \mathbf{E}_0}{(2)}
\]

Comparing equations (1) with (2), it is shown that the difference in the two equations is just to replace \( \gamma \varepsilon_1 \) in equation (1) with \( \varepsilon_1 \) in equation (2). Therefore spherical particle with interface equates another spherical one without shell layer, and this leads to a result that the composite system can be replaced by solid sphere with equivalent permittivity \( \varepsilon_1 \) and equivalent radius \( b \) mixed with the same matrix. Consequently, the particle is simplified from binary components to the single component.

2.2. Scattering and absorption of electromagnetic wave by core-shell particle

When the wavelength of the incident electromagnetic wave is much larger than the scale of a scatterer, the scattering effect of the scatterer on electromagnetic field can be accurately processed by the Mie scattering theory. By this means, the scattering cross-section \( C_{\text{sca}} \), the absorption cross-section \( C_{\text{abs}} \) and the extinction cross-section \( C_{\text{ext}} \) can be expressed as follows [10, 12].

\[
C_{\text{sca}} = \frac{8}{3} \pi k a^4 |\varepsilon_r - 1|^2 / |\varepsilon_r + 2|^2
\] (3)
Where \( a \) is the radius of spherical particle with relative permittivity \( \varepsilon_r = \varepsilon_r' - i\varepsilon_r'' \), \( k = 2\pi/\lambda \) serves as the propagation constant, and \( \lambda \) is the wavelength of incident wave in the background. It is shown in equation (4) that extinction properties of single particle are determined by the granule diameter \( a \), permittivity \( \varepsilon_r \), as well as wavelength \( \lambda \) of incident wave.

Now the scattering and absorption characteristics of dielectric core-shell particle to electromagnetic wave are investigated. The parameters of the core-shell particle are the same as the front signs \( a, b, \varepsilon_1 \) and \( \varepsilon_2 \). According to the above equivalent method, core-shell particle can be considered as symmetrical solid particle with permittivity \( \gamma \varepsilon_1 \) and radius \( b \). To make the results more reasonable, extinction properties are replaced by extinction parameters per unit volume. Thereby, the three cross-sections per unit volume are expressed as follows.

\[
C'_{\text{sca}} = 2k^2b^2|\gamma\varepsilon_1 - 1|^2/|\gamma\varepsilon_1 + 2|^2
\]

(6)

\[
C'_{\text{abs}} = 9k \text{Im}[\gamma\varepsilon_1]/|\gamma\varepsilon_1 + 2|^2
\]

(7)

\[
C'_{\text{ext}} = C'_{\text{sca}} + C'_{\text{abs}}
\]

(8)

Where \( \text{Im}[\gamma\varepsilon_1] \) denotes taking the imaginary part of \( \gamma\varepsilon_1 \). The above formulas are also suitable to multilayer core-shell particle. Based on the deduction mentioned above, several investigations are carried out to explore the impact of particle parameters on the scattering and absorption properties.

3. Results and discussion

Usually the main operating frequency range of radar is between 2 GHz and 18 GHz, so the incident electromagnetic wave with wavelength \( \lambda = 3 \times 10^{-2} \) m is selected as representative. It is supposed that \( a = 50 \) nm and \( \varepsilon_1 = 20 - 5i \) are the radius and permittivity of core particle, respectively, \( b \) and \( \varepsilon_2 \) are the radius and permittivity of shell layer, respectively, and then \( \beta = \varepsilon_2/\varepsilon_1 \). The thickness of shell is \( d = b-a \), and the structure parameter \( \alpha = a^3/b^3 \). Based on equations (6)-(8), the effects of shell parameters on scattering and absorption properties are analyzed.

Firstly, the influence of core-shell structure parameter on scattering and absorption capacity is explored. It is given that the ratio \( \beta \) is 0.1 and 2.0, respectively. Figure 1 presents the relationship between the extinction cross-section and the shell thickness. Figures 1(a) and 1(b) respectively display the variational tendency of absorption cross-section and the scattering cross-section along with the shell thickness.

![Figure 1. Extinction cross-section versus ratio d/a.](image-url)
As shown in these two figures, the absorption cross-section is much greater than the scattering one, where their difference achieves more than 10 orders of magnitude. Therefore the impact of scattering on extinction can be ignored usually. The numerical results indicate that scattering cross-section enhances along with the increase of shell thickness when other parameters are identical. Absorption cross-section is fairly sensitive to the shell permittivity, which makes the variational tendency of absorption cross-section versus different shell thickness evident. Along with the increasing shell thickness, absorption cross-section rises when the value of $\beta$ is relatively great and decreases when the value of $\beta$ is relatively small. Absorption cross-section changes rapidly when the value $d/a$ is lower than 0.5 (especially for higher $\beta$), and then mildly goes to a fixed value.

Secondly, the influence of core-shell dielectric parameter on scattering and absorption capacity is explored. It is given that the ratio $d/a$ is 0.02, 0.1 and 0.2, respectively. Figure 2 presents the relationship between the extinction cross-section and the shell permittivity. Figures 2(a) and 2(b) respectively display the variational trends of the absorption cross-section and the scattering one along with the shell permittivity. The numerical results indicate that scattering cross-section is enhanced straight along with the increase of shell permittivity while other parameters are identical, whereas absorption cross-section shows a reverse tendency. When $\beta<1$, a variety of shell permittivities put significant impact on absorption cross-section. It seems easier to obtain higher absorption cross-section by decreasing shell permittivity and increasing shell thickness simultaneously.

Finally, the difference of extinction characteristics between solid particle and hollow particle is discussed. It is given that shell radius is $b=50$ nm, and shell permittivity $\varepsilon_2=20-5i$. The frequency range of incident wave is between 2 GHz and 18 GHz. Figure 3 displays the relationship between the extinction cross-section and the frequency. As shown in figures 3(a) and 3(b), the extinction cross-sections of both solid particle and hollow particle increase along with the enhancing the frequency. Being identical in other conditions, the scattering cross-section of solid particle is superior to that of hollow particle, and increasing shell thickness is in favour of raising the scattering capacity to the electromagnetic wave. Yet, absorption capacity exhibits an opposite feature. This phenomenon occurs due to the following reasons. As shown in equation (4), extinction properties of single particle are determined by its permittivity $\varepsilon_r$ while the granule radius and wavelength are fixed. Given that $\varepsilon_r = \varepsilon'_r - i\varepsilon''_r$, absorption cross-section per unit volume can be expressed as follows.

$$C_{abs} = \frac{9k\varepsilon''_r}{\left|\varepsilon_r + 2\right|^2} = \frac{9k\varepsilon''_r}{\left[\varepsilon'_r + 2\right]^2 + \varepsilon''_r^2}$$

The extreme values of equation (9) happen at $\varepsilon''_r = \varepsilon'_r + 2$. As shown in this equation, absorption cross-section decreases along with the enhancing $\varepsilon'_r$, and $\varepsilon''_r$ deviates further from the optimal value with a smaller absorption cross-section. As given $\varepsilon_2=20-5i$, when the permittivity of the hollow
particles is closer to the optimal values, higher absorption cross-section can be achieved. Therefore, the absorption capacity of the core-shell particle can be improved by adjusting the structural parameters and dielectric parameters, which would also help reduce the weight of the compound particle.

![Figure 3. Extinction cross-section versus frequency.](image)

4. Conclusion

In summary, this work puts emphasis on the effect of core-shell particle parameters on the scattering and absorption properties. An equivalent method, replacing the concentric core-shell spherical particle with equivalent solid particle, is used to reduce the complexity of composite system. The equivalent solid particle possesses the same radius with the original shell layer, and its equivalent permittivity is equal to that of the product with equivalent coefficient and nucleus permittivity. Then formulas for scattering, absorption and extinction cross-sections of core-shell particle are deduced. In the condition that the particle diameter is far less than the wavelength of the incident wave, the impact of the geometry and dielectric parameters on the scattering and absorption properties is investigated. Numerical analysis shows that scattering cross-section increases along with the increasing thickness and permittivity of shell layer. Increasing the shell permittivity and thickness cannot certainly enhance the value of absorption cross-section, indicating that there exist a group of optimum values. The absorption capacity of the core-shell particle can be improved by adjusting the structural parameters and dielectric parameters simultaneously. The results provide theoretical foundation and guidance for the design of core-shell structure composites to optimize some desired electromagnetic properties.

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