Effect of mixed magnetic field on physical properties of atmospheric suspended fine particles

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ABSTRACT

In recent years, the fine particles suspended in the atmosphere, especially the particle size less than 10 μm, have caused very adverse effects on the climate environment and human health. However, the current research on the causes of air pollution mainly focuses on human activities and weather conditions. Considering the weak magnetism and chargeability of atmospheric fine particles, this study proposed a new view that space electromagnetic radiation may affect the physical properties of fine particles. We first analyzed the dynamic characteristics of magnetic micro-particle in the electromagnetic environment, and built a simulation model in the COMSOL simulation software. Finally, based on the theoretical analysis and simulation results, we built an experimental verification system to evaluate the effects of electromagnetic radiation on the physical properties of micro-particle, and carried out a 30-day control experiment. The experimental results showed that the physical properties such as particle size distribution, mass concentration, and morphology of suspended fine particles in the atmosphere under electromagnetic radiation are significantly different from those under non-electromagnetic radiation environment. It can be inferred that the aggregation, fusion, and deposition of suspended particles in the atmosphere are closely related to the complex electromagnetic environment in space.

1. Introduction

Micro-particles suspended in the atmospheric environment, especially fine particles with small particle size, large quantity, wide surface area, and complex chemical composition, in addition to affecting the atmospheric environment, are much more harmful to human health than coarse particles of the same mass, so it has been paid more and more attention by researchers at home and abroad (Singh et al., 2006; Jung et al., 2019; Stieb et al., 2002; Donaldson et al., 2005). Data showed that air pollution in China causes 1 million premature deaths each year and ranks first among many environmental concerns in terms of health. Among various sources that are attributable to air pollution, direct energy consumption in residential and transportation sectors contributes significantly to the emissions of air pollutants, such as carbon monoxide (CO), nitrogen oxide (NOx), sulfur dioxide (SO2), black carbon (BC), organic carbon (OC), and other organics (Sardar et al., 2006; Lelieveld and Evans, 2015; Yang et al., 2016; Huang et al., 2014a, 2014b). In addition, Chan and Yao (2008) found that heavy metals such as Al, Si, Ca, Mg and Fe, which have an important influence on human health, account for about 11%–16% of PM2.5. Iron oxide is one of the core components of coal-fired fly ash particles (Guo et al., 2005; Sun, 2001), therefore, micro-particle is easily magnetized in the magnetic field environment (Zhao et al., 2006). The electric charge distribution of micro-particles was measured with the help of electric low-voltage impactor (ELPI) technology, and it was found that the electric charge had a great influence on the behaviour of micro-particles, thereby affecting the number, size, and surface area of particles (Lamminen, 2011). In recent years, the research on atmospheric suspended particulates mainly focused on its sources, causes, components, and distribution laws, and the external factors affecting its physical-chemical and dynamic characteristics were more inclined to climate changes and human activities (Cai et al., 2017; Petajä et al., 2016; Song et al., 2015; Liu et al., 2018). The work (Sun et al., 2016) investigated the sources and formation mechanism of severe haze events in northern China and found that the formation of severe haze was closely related to the stagnation meteorological conditions characterized by inversion, and low wind speed, and high relative humidity. By analyzing pollution emission data from population migration in recent 30 years, it is found that population migration caused by urbanization reduces PM2.5 concentration in China (Shen et al., 2017). The investigation found that almost all studies ignored the effect and impact...
of electromagnetic environment in space on atmospheric suspended particles.

As we all know, the rapid development of information and communication technology worldwide has significantly improved the level of microwave electromagnetic field in the working and living environment. The electrostatic and electromagnetic interaction caused by lightning, solar storm, wireless system, single-particle effect and electrostatic discharge have made the natural environment in which human beings live become a complex electromagnetic environment (Constable, 2016; Biak and Pa, 2018). Several studies have found that electromagnetic fields may have positive or negative effects on biological systems exposed to them for a long time. The researchers experimentally demonstrated that the conversion of glycerol and acetate was 1.2–1.5 times lower than that under non-radiation conditions, although high frequency and high intensity magnetic fields had little effect on ethanol production and growth rate (Bertrand et al., 2018). The study in Wang et al. (2014a, 2014b) found that the static magnetic field had an important effect on the orientation of cell membrane phospholipids and affected their biomechanical properties. The electromagnetic field has a certain coalescence effect on the fly ash from coal burning with weak magnetic dust, and the coalescence effect on the particles of PM2.5 is more obvious (Li et al., 2007). By summarizing and analyzing the experimental results of previous studies, the work in Soghomonyan et al. (2016) proposed that millimeter wave or extremely high frequency and low intensity electromagnetic field will inhibit the growth of different bacteria, change their properties and activities, and affect the sensitivity of antibiotics. However, the influence of space magnetic field on the charged aerosol particles with weak magnetism have not attracted enough attention.

This study is intended to explore the effect of spatial mixed magnetic field on the physical properties of atmospheric suspended microparticles. Based on this research purpose, we first analyzed the dynamic characteristics of fine particles in the electromagnetic field and then established the system simulation model. Finally, according to the theoretical analysis results and simulation results, we designed a set of experimental verification system to evaluate the physical characteristics of microparticles affected by multi-band electromagnetic wave radiation. By conducting the control experiments in three groups of different environments (natural environment, electromagnetic shielding environment, and electromagnetic irradiation), the changes of physical characteristic parameters such as particle number, particle size, surface area, particle morphology, and total particle mass concentration under electromagnetic radiation were investigated.

2. Materials and methods

2.1. Experimental platform and procedures

Figure 1 is the schematic diagram of the experimental system to evaluate the physical characteristics of haze micro-particles under electromagnetic irradiation, which is mainly composed of particle generation system, electromagnetic environment simulation system, particle characteristics test system, and PC computer. The fine particles used in the experiment were prepared by the TDA-6D aerosol generator of ATI company in the United States. According to the haze composition of the current research (Fang et al., 2005; Huang et al., 2014a, 2014b; Li et al., 2016), 100 ml aerosol crude oil, 500 ml water, 40 g silica, 30 g calcium sulfate, 20 g iron oxide, 5 g carbon powder were fully stirred in the beaker at 20°C for simulating artificial haze particles (Wang et al., 2014a, 2014b; Zhou et al., 2017). The standard gain horn antenna of the HD-SGAH series was selected for the electromagnetic simulation system, which is designed according to the best pyramid horn design, and the frequency coverage is from 0.32 GHz to 300 GHz. Each antenna covers the corresponding full waveguide bandwidth, and the whole experimental system realizes the frequency band simulation from 1 GHz to 10 GHz. The particle characteristic test system used an air quality detector, temperature, and humidity measuring instrument and other equipment to measure the quantity and mass concentration of particles and the change of ambient temperature and humidity.

Figure 1. Schematic diagram of the experimental system.
To explore the variation of physical properties of fine particles under electromagnetic environment, the study conducted a comparative study in natural environment (Figure 2a), electromagnetic shielding environment (Figure 2b), and electromagnetic irradiation environment with different intensities (Figure 2c). Experimental steps consist of four steps: 1) Sample preparation. Carbon powder, silica powder, calcium sulfate powder, and ferric oxide powder were mixed with aerosol oil mist reagent PAO-4 produced by ATI Company in the United States in proportion in acidic solution, and then fine particles were uniformly dispersed through the aerosol generator TAD-6D. 2) Experimental environment initialization. Clean the acrylic box (30 cm × 30 cm × 30 cm) required for the experiment, close all equipment in the electromagnetic shielding room, and record the particle concentration, ambient temperature and humidity, space magnetic field intensity, and other parameters in the box under initial conditions. 3) Conduct research on particle characteristics in groups. The experimental chambers under the three environments were filled with equal concentrations of fine particles. At the same time, the electromagnetic signal emission source was opened, and the frequency and power density were set. A group of samples was extracted every 3 days for observation. The observation lasted for one month. 4) Filter sampling observation analysis. Before sampling, the slides (76 mm × 26 mm × 1 mm) were soaked in 1%–2% hydrochloric acid to remove the surface impurities and washed with distilled water and dried. The slides were placed in the bottom of the experimental, and the slides were numbered from 1 to 10 in turn. After extracting the target sample, the slides were removed and placed on the microscope observation platform for observation and analysis.

### 2.2. Microscopic visualization technology

In this paper, the microscopic visualization system constructed by the effective combination of high-speed camera technology and microscopic camera technology is utilized to realize the intuitive research on the microscopic characteristics of fine particles. The entire system consists of the light source, microscopic objective, eyepiece, high-speed camera and computer. When the light source illuminates the experimental observation sample, the fine particles in the field of view are amplified by the objective lens and the continuous zoom lens, and recorded and stored by the high-speed camera at a certain shooting speed. After analysis and processing by professional image processing software, the data of particle size, particle number, and particle roundness can be obtained, and the intact motion process of fine particles in the field of view can be observed. Particle measurement by microscopic image method is to measure the information of particles without converting into other relevant variables, which eliminates the possible errors in the conversion process and makes the measurement results accurately reflect the information of particles (Meng et al., 2004; Tomohiko and Eaton, 2010).

Generally, the higher the magnification of the microscope objective, the narrower the field of view. Although the shape of static fine particles can be clearly observed, the motion tracking of fine particles will be more limited by the shallow depth of field. Therefore, in this experiment, the 20X objective lens was first used for the initial optical amplification of the extracted fine particle samples, which could ensure a sufficient working distance and observe the movement of fine particles in a large range. Secondly, the microscope objective was connected to the eyepiece through the specialized optical transfer interface, and the 100X eyepiece was used for the secondary optical amplification of fine particles in the specimen. Finally, the fine particles after two optical amplifications were photographed and recorded by the qualified high-speed industrial camera BD-FL20. Based on the experimental requirements and the performance of the high-speed camera, the frame frequency of the high-speed camera is set to 15 fps, that is, 15 pictures per second, and the image resolution is $5472 \times 3648$ pixels. Using the microscopic visualization system described above, the microscopic visualization research can be started after focusing the microscopic objective and the observation object.

### 2.3. Morphological parameters detection

Particle morphology includes the definition, distribution, measurement, and shape characterization of particle size. The retention time and transmission distance of atmospheric particles in the air are closely related to the particle size of particles. Therefore, the monitoring of particle size is of critical significance to the environment, climate, and human health (Wu et al., 2008). At present, the measurement methods of particle size mainly include screening method, sedimentation method, microscope method, and inductive stress method (Liu et al., 2009; Shao et al., 2018), but these detection methods have limitations, such as long measurement time, many measurement steps and measurement accuracy are greatly affected by subjective factors. Therefore, this paper adopted the method of combining image processing technology and microscopic observation to calculate the particle size.

Firstly, after denoising, image enhancement and binary filtering of the source image observed by the microscope, the particles in the visual field are marked. Then the edge is tracked from the first contour point, and the edge contour is extracted to calculate the perimeter of the particles. In the algorithm of statistical perimeter, when the contour point is at the inflection point, if the total number of contour points is added to 1, there will be a large error, so the total number of contour points is added to $\sqrt{2}$ to correct. Finally, the area of each particle is calculated by the scanning labeling method, and the equivalent diameter $d$ of particles can be obtained by formula (1).

$$d = 4A/p$$

(1)

![Figure 2. Three groups of controlled experimental environment.](image-url)
Considering that particles with the same particle size have different shapes, in order to quantitatively analyze and describe the particle characteristics, the shape factor \( F \) is introduced and determined by the expression
\[
F = \frac{p^2}{4\pi A}
\]
where \( A \) is the particle area and \( p \) is the particle perimeter.

### 2.4. Motion of particles under electromagnetic irradiation

Due to the existence of various kinetic behavior such as deposition, condensation (Dolatabadi et al., 2022; Kafaei et al., 2022), vaporization, and nucleation of particles, these behavior lead to constant changes in particle number concentration, volume concentration, and particle size. When particles are in different flow field environments, they will be coupled with turbulent flow and their own dynamic behavior. Therefore, to accurately predict the evolution law of the physical properties of particles, it is necessary to establish the corresponding dynamic coupling equation for numerical research.

Suspending particles in the atmosphere are mainly affected by the following three types of forces: fluid force, inter-particle force, and external force (Ku et al., 2019). Particle size is the most prominent factor affecting various forces, and these forces vary with particle size. Among them, the fluid force mainly includes buoyancy, drag force, and Brownian force. For gas-solid two-phase flow, the effect of buoyancy is usually ignored because the order of magnitude of the ratio of buoyancy to gravity is 10^{-3}. Since the main object of this study is fine particles in the atmosphere, it is found that the velocity of such particles in air is low, and the drag force of fluid on particles can be simplified as Stokes resistance according to the Navier-Stokes equation. Brownian force is the wave force caused by the thermal motion of gas molecules around the particle. The smaller the particle size is, the stronger the Brownian diffusion motion is. The formation and fragmentation of particles are the result of the combined action of inter-particle force and gas-solid-liquid interaction force. The inter-particle force includes van der Waals force, capillary force, viscosity force, electrostatic force, and contact force. Within the particle size range of 10^{-6} – 10^{-4} m, van der Waals force plays a major role, and other forces can be neglected (Xin and Liu, 2006). When charged particles are in a constant electromagnetic field, in addition to gravity, the magnetic field force will also change the trajectory of particles. According to Newton’s second law, the three-dimensional motion equation of particles in electromagnetic field can be expressed as
\[
\begin{align*}
\frac{dp_x}{dt} &= F_{ax} + F_{Dx} + F_{Vx} + F_{Qx} \\
\frac{dp_y}{dt} &= F_{ay} + F_{Dy} + F_{Vy} + F_{Qy} \\
\frac{dp_z}{dt} &= F_{az} + F_{Dz} + F_{Vz} + F_{Qz} + F_g
\end{align*}
\]
where \( m_p \) is the particle mass. \( F_B, F_D, F_V, F_G \) are Brown force (6), Stokes resistance (7), van der Waals force (10), gravity (11), and magnetic force (12), respectively; \( x, y, z \) respectively represent the three dimensions in Cartesian rectangular coordinate system.

#### 2.4.1. Brown force
In the Newton framework of mechanics, the Brownian motion of particles can be regarded as the result of a random force, which acts continuously on a single particle. The random force causing particle motion is equal to Stokes Einstein dispersion (Michaelides, 2015).
\[
F_B = \xi \sqrt{\frac{6\pi \eta_d k_B T}{\Delta t}}
\]
where \( \xi \) is a Gaussian distributed random variable (standard normal distribution), \( \mu \) is the fluid viscosity, \( d_p \) is the particle radius, \( k_B \) is the Boltzmann constant, \( T \) is the absolute thermodynamic temperature, and \( \Delta t \) is the calculation time step.

#### 2.4.2. Stokes resistance
Particles in the Stokes region are subjected to gas drag can be written as,
\[
F_D = \frac{3\pi \eta_d d_p}{C_1} \frac{dp}{dt}
\]
where \( u \) is the relative velocity between particles and airflow. For particles with particle size less than 1 \( \mu \)m especially when the particle size is close to the average free mean path \( \lambda \), the surface velocity of Stokes resistance is 0, and the Cunningham correction coefficient \( C_c \) needs to be introduced.
\[
C_c = 1 + \frac{2.52 \lambda}{d_p}
\]
Under general standard atmospheric conditions, the molecular free path \( \lambda \) takes an average value of 0.066 \( \mu \)m.

#### 2.4.3. Van der Waals force
Van der Waals force is a cohesive force between particles. When the particle size is micron, Van der Waals force has an important influence on the change of particle motion state, which cannot be overlooked. For two spherical particles with different particle sizes, Van der Waals force can be simply expressed as follows,
\[
F_V = -\frac{A}{12\pi h^3} \frac{d_1 d_2}{d_1 + d_2}
\]
where the value of the Hamaker constant \( A \) is about 10 to 19 to 10 to 20 J, \( h \) is the surface distance between two particles, and \( d_1 \) and \( d_2 \) are the particle sizes of two spherical particles, respectively. However, Hesselink and Overbeek believed that van der Waals force was transmitted through electromagnetic waves between atoms, and it took a period of time for electromagnetic waves to transmit from one atom to its adjacent atoms, which led to the hysteresis of van der Waals force (Qiao et al., 2013). Especially when the sphere diameter is larger than 10 \( \mu \)m, the hysteresis effect is obvious, so many scholars propose to modify the Van der Waals force. The modified van der Waals force expression between particles is shown below,
\[
F_V = \begin{cases} 
\frac{A}{12\pi h^3} \frac{d_1 d_2}{d_1 + d_2} \left( \frac{1 + 22.24 \frac{h}{\lambda V}}{h + 11.12 h^2} \right) & h \leq 7.96\text{nm} \\
\frac{A}{12\pi h^3} \frac{d_1 d_2}{d_1 + d_2} \frac{\lambda V}{100 h^3} \left( 1.56 \frac{11 \lambda V}{100 h^3} + \frac{2.718 \lambda V^2}{100 h^3} \right) & h > 7.96\text{nm} 
\end{cases}
\]
The London length of \( \lambda \) atom is usually taken as 100 nm. It can be seen from the above equation that the main factors affecting the Van der Waals force are the Hamaker constant on the particle surface, the particle size and the distance between particles.

#### 2.4.4. Gravity
The gravity acting on particles is shown as follows,
\[
F_g = \rho_p \frac{\pi d_p^3}{6} g
\]
where \( \rho_p \) is the density of particles, \( g \) is the acceleration of gravity.
2.4.5. Magnetic field force

\[ F_Q = \chi_m \mu_0 \left( \mathbf{H} \cdot \nabla \mathbf{H} \right) \]  

where \( \chi_m \) is the magnetic susceptibility of particles, \( \mu_0 = 4\pi \times 10^{-7} \text{ H/m} \) is the vacuum permeability, \( V_m \) is the volume of particles, \( H \) is the magnetic field intensity of the external magnetic field, and the unit is \( \text{A/m} \).

According to the above stress analysis, it can be seen that under the same continuous medium and working condition, the particle air resistance and Stokes resistance, Brown force and gravity force are related to the particle size, density and flow rate. When the particle size and density are constant, the force of particles can be simplified. When the particle size \( d < 0.1 \mu\text{m} \), the diffusion of particles should be considered. When the particle size is \( d \geq 1.0 \mu\text{m} \), the particle gravity effect is mainly considered.

3. Results and discussion

3.1. Mixed frequency electromagnetic environment simulation

The vast majority of haze particles in atmospheric suspended particles are weakly magnetic, and the iron oxides carried by a few particles are ferromagnetic. The magnetic susceptibility of haze pollutants is positively correlated with the content of heavy metals (Shao et al., 2017; Wang et al., 2017). It is found that the original particles are approximately electrically neutral in the air, and the particles generated by the secondary reaction will bring different electric quantities due to different particle sizes, materials, and generation methods. Especially, collision and high temperature will make the electric quantity of particles increase sharply. After the particles are charged, the particle electric field will be formed around them, which will further affect the agglomeration, deposition and spatial electric field effect of particles.

In this study, the mixing electromagnetic environment is constructed through the simulation software COMSOL, the electric field intensity is set to be \( E = 100 \text{ V/m} \), and the electromagnetic waves with frequency \( f = 10 \text{ kHz}, 100 \text{ MHz}, 1 \text{ GHz} \) are applied respectively. The temperature in the simulation space is set to 293.15 K. The speed of the particle swarm creep flow with time is obtained by simulation operation, as shown in Figure 3. It can be seen from Figure 3a, b, c that within a certain time range \((0.5 \text{ s} \leq t \leq 5 \text{ s})\), the effect of electromagnetic field on particle agglomeration is obvious, which promotes particle agglomeration. With the increase of simulation time, as shown in Figure 3d and e, the influence of electromagnetic field on particle agglomeration reaches saturation, and particle swarm movement remains stationary. Figure 3(f) intuitively reflects the change trend of particle swarm motion speed. After 10 s, the motion of particle swarm tends to be stable as a whole and is no longer affected by electromagnetic wave radiation.

3.2. Particle size distribution

3.2.1. Effect of action time on particle size distribution

Table 1 shows the experimental data of the total number, particle size, surface area, and roundness of particles under natural environment, electromagnetic shielding environment and electromagnetic irradiation environment. The experiment went on for 30 days. Three groups of experiments were carried out at the same time. Two groups of slides at different sampling positions in the experimental box were taken out every three days and observed under a microscope. In order to clearly compare the characteristics of particles under different observation times, the particles with obvious and representative observation under microscope were selected as the research object. In view of the huge amount of data, Table 1 only shows the experimental data (maximum/minimum)
The observation data on January 15, 2021 showed that the number of particles in this group was very small. On the contrary, the particle size and particle area increased synchronously, and the corresponding particle roundness decreased, indicating that particle fusion was noticeable in this group. Tiny particles collided and fused into irregular large particles. Since the overall experimental conditions have not changed, the changes in the group of data may be interfered by other external factors, which have yet to be verified. Through the distribution map of particle roundness, it can be observed that the particles in three environments have good roundness, and the distribution range is between 0.600 and 0.675. The roundness of particles characterizes the particle morphology. Under the initial conditions, the particle morphology is a spherical object with the particle size of about 0.65 μm and the roundness tends to 1. After settlement, collision, and fusion, the morphology changes.

In order to verify the correlation between the number of particles and the roundness, the normality test of the experimental data was carried out first, and it was verified that the data met the normal distribution. It can be seen from Figure 5 that the particle roundness was negatively correlated with the total number of particles, and the correlation coefficient \( r = -0.67 \), that is, the two variables were moderately correlated. Experiments showed that with the increase of the observation date, the more particles were deposited on the sample, and the probability of deformation of particle fusion increases, and the roundness decreases.

### 3.2.2. Effect of electromagnetic intensity on particle size distribution

It can be seen from Figure 3 that the characteristic parameters of particles under electromagnetic irradiation were significantly different from those under natural environment and electromagnetic shielding. It is reasonably suspected that the weak magnetic particles were affected by the magnetic field force, which changes the settlement and fusion process of particles affected by the motion trajectory, and further affects the change of physical characteristics parameters of particles. In this experiment, considering the horn antenna is a kind of microwave antenna which is widely used in military and civil. It has the advantages of simple structure, wide frequency band, larger power capacity, and ease to use. When the horn size is reasonable, it can obtain excellent radiation characteristics, sharp main lobe, small side lobe, and high gain. Therefore, in this study, five groups of horn antennas are selected as the source.
of electromagnetic radiation. The radiation frequency covers a wide range of 1 GHz–10 GHz.

The energy formula \( E = hv \) \((h = 6.626 \times 10^{-34} \text{ J} \cdot \text{s})\) shows that the energy of an electromagnetic wave is proportional to the frequency, that is, the higher the frequency, the greater the energy, but the penetration is reduced. Therefore, during the experiment, the experimental box was close to the antenna mouth. Figure 6 shows the variation trend of particle number (Figure 6a), particle size (Figure 6b), particle area (Figure 6c), and particle circularity (Figure 6d) under different frequency electromagnetic wave irradiation. It can be seen from the figures that the
physical properties of particles are different under the irradiation of electromagnetic waves with different frequencies. The variation trend of particle size is consistent with that of the particle area, and the roundness of particle changes inversely. In addition, the physical properties of particles do not show a linear growth or decrease trend with the increase of the power density of the signal source, so it is impossible to determine the significant impact of the frequency and power changes of the radiation electromagnetic wave on the particles, which needs to be further analyzed.

To study the influence of frequency and power on the physical characteristics of particles, we used the repeatable two-way ANOVA method, which can be used to analyze whether the different levels of the two factors have a significant impact on the results and whether there are interaction effects between the two factors. Firstly, the combination of different levels of two factors is designed and tested. It is required that the content of samples obtained under each combination is the same, and the samples are independent of each other, and the population corresponding to the samples follows the normal distribution. In this experiment, the electromagnetic wave frequency of factor 1 has five levels, corresponding to $f = 1.3, 4.2, 5.5, 9$ GHz, and the electromagnetic power of factor 2 also has five levels, corresponding to $P = -30, -25, -20, -20, -10$ dBm, respectively. After the normality test of 25 groups of samples in this study, they all obeyed the normal distribution. The data analysis software Origin was used to analyze the influence of the two factors on the particle total number, particle size, particle area, and roundness at the level of $\alpha = 0.05$. The results are presented in Table 2.

In Table 2, samples, columns, and interactions in the different sources correspond to the power factor effect, frequency factor effect, and power-frequency interaction effect. In each column, SS, df and MS respectively represent the sum of squares of corresponding deviations, corresponding degrees of freedom and corresponding mean squares. F-crit is the critical value of F. According to F and P values, when $F > F_{\text{crit}}$ or $P < \alpha$, it can be said that the effect is significant at the significant level $\alpha$, otherwise not significant. It can be seen from the table that the effects of two groups of factors on particle characteristics parameters are always obvious, so the physical properties of particles under electromagnetic irradiation will change due to electromagnetic irradiation.

### 3.3. Variation of particle mass concentration

The mass concentration of atmospheric particulate matter is an essential property of particulate matter. The latest ‘ambient air quality standard’ (GB3095-2012) incorporates PM2.5 mass concentration into the air quality evaluation system for the first time, which is part of the
indicators reflecting air quality. Therefore, we also monitored and compared the mass concentration of particulate matter in diverse environments. At present, the monitoring methods of atmospheric particle mass concentration mainly include filter membrane weighing method, β-ray absorption method, micro-oscillating balance method, and laser scattering measurement method. In this experiment, an efficient and intelligent laser scattering measurement method was adopted, and the laser was invoked as the light source. Outside the direction of the incident light, the particle weight and the aggregation state structure were obtained by detecting the intensity, frequency shift and angle dependence of the scattered light.

Figure 7 shows the variation trend of particle mass concentration with time without external magnetic field. As we can see from the picture, when there is no external magnetic field, the mass concentration of particulate matter decreased rapidly in the opening 30 min, showing a logarithmic function trend. After 30 min, the decline rate became gentle, and the movement of particles tends to be stable after a period of time. At this time, the observed mass concentration gradually remained unchanged.

Without an external magnetic field, the aerosol particles with initial concentrations of 180 μg/m³, 320 μg/m³ and 480 μg/m³ were respectively introduced into three groups of experimental boxes to study the change of mass concentration of aerosol particles. As shown in Figure 8, the overall motion trend of particles in the three groups was basically the same, showing a linear decline. The effect of initial particle mass concentration on the overall mass concentration was weak.

To determine the effect of electromagnetic irradiation on particle mass concentration, two groups of control experiments were performed. The aerosol particles with the same initial concentration were injected into the experimental box under electromagnetic irradiation and natural environment, respectively. The variation tendency of particle mass concentration in a fixed time was observed. The experimental results are shown in Figure 9. The mass concentration of particles in both environments showed a linear downward trend, and the decline rate of mass concentration of particles without electromagnetic effect was higher than that with electromagnetic irradiation. The concentration difference between the two gradually narrowed with time which indicated that the particle motion tends to be stable and the mass concentration changes slowly.

The experimental box was placed in 1.1 GHz, –10 dbm and 2.2 GHz, –20 dbm electromagnetic environment for continuous irradiation. After a period of time, the mass concentration change trend was observed as shown in Figure 10.

From the above diagram, it can be seen that the decline trend of particle mass concentration in the two groups showed a quadratic

### Table 2. Two-way ANOVA of electromagnetic wave frequency and power.

| Type          | Difference source | SS       | df | MS       | F        | P-value    | F crit  |
|---------------|-------------------|----------|----|----------|----------|------------|---------|
| Particle number | Sample            | 42016.98 | 4  | 10504.24 | 8.609782 | 1.75E-06   | 2.411768 |
|                | Column            | 72052.86 | 4  | 18013.21 | 14.76449 | 9.99E-11   | 2.411768 |
|                | Interactive      | 45526.9  | 16 | 2845.431 | 2.33252  | 0.003308   | 1.688627 |
| Particle size  | Sample            | 26.84066 | 4  | 6.71064  | 15.26455 | 4.65E-11   | 2.411768 |
|                | Column            | 32.13851 | 4  | 8.034626 | 18.27749 | 5.12E-13   | 2.411768 |
|                | Interactive      | 91.1375  | 16 | 5.696094 | 12.9577  | 4.46E-24   | 1.688627 |
| Particle area  | Sample            | 903.9172 | 4  | 225.9793 | 12.80515 | 2.08E-09   | 2.411768 |
|                | Column            | 1032.887 | 4  | 258.2217 | 14.63217 | 1.22E-10   | 2.411768 |
|                | Interactive      | 2683.888 | 16 | 167.743  | 9.505179 | 6.5E-18    | 1.688627 |
| Particle circularity | Sample | 0.132772 | 4  | 0.033193 | 21.92904 | 2.68E-15   | 2.411768 |
|                | Column            | 0.079816 | 4  | 0.019954 | 13.18265 | 1.15E-09   | 2.411768 |
|                | Interactive      | 0.323597 | 16 | 0.020225 | 13.36153 | 9.37E-25   | 1.688627 |

**Figure 7.** Variation of particle mass concentration over time.
function change, and the functions were: \( y = 0.0032t^2 + 1.5138t + 294.61 \) and \( y = 0.0042t^2 - 1.8894t + 409.12 \), respectively. Thus, the velocity functions of the two groups were: \( y = 0.0064t + 1.5138 \) and \( y = 0.0084t + 1.8894 \). According to the calculation equations, we knew that when \( t = 187.7 \) min, the mass concentration decline rates of the two groups of particles are equal. When \( t < 187.7 \) min, the mass concentration decline rate of particles under the electromagnetic environment of \( f = 2.2 \) GHz was greater than that of the control group, and the mass concentration decline rate of the two groups decreased with time. From the fact that the difference between the two curves decreases with time, it can be seen that the particle mass concentration under the action of low-frequency electromagnetic field decreases more slowly than that under the high-frequency magnetic field.

### 3.4. Morphological changes of particles

According to the previous experimental results, the particle number, particle size, surface area and particle morphology of particles will change under electromagnetic irradiation. In order to intuitively show the changes of particle morphology, we choose to place the sampling glass under the same electromagnetic environment to observe the changes of particle morphology for 1 h, 1 day, and 10 days respectively. The experimental results are shown in the succeeding figures.

Figure 11(a) is the particle morphology observed after 1 h, it can be clearly seen that the particles maintain a good roundness, concentrated in the range of 0.75–0.85. After standing for one day (Figure 11b), the number of particles deposited on the sample slide increased. At the same time, the particle morphology gradually evolved from the initial circle to a strip.
shape. From the circularity distribution histogram, it can also be seen that the circularity in this stage was mainly distributed in the range of 0.55–0.8. With the passage of time, momentous changes in particle morphology were observed after 10 days (Figure 11c), most of which showed irregular shapes, and the number of particles decreased. At this time, the roundness of particles was evenly distributed in the range of 0.45–0.8.

4. Conclusions

In this study, an experimental method was constructed to evaluate the effect of mixing magnetic field on the physical characteristics of atmospheric suspended particles. The experimental results show that the important parameters characterizing the physical properties of particles such as the total number of particles, particle size, particle surface area, and particle morphology will change under the long-term effect of electromagnetic radiation. In conclusion, according to the results obtained, the sedimentation and fusion of particles are independent of the initial concentration and related to the magnetic field intensity. Although electromagnetic fields with different frequencies and intensities have an impact on the physical characteristics of particles, the specific impact mode needs long-term experimental observation and verification.

Figure 10. Variation of particle mass concentration with the same initial concentration at different frequencies.

Figure 11. Variation of particle roundness with time under electromagnetic irradiation.
Declarations

Author contribution statement

Binbin Han: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.
Zhengfeng Ming: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data.
Yuhu Zhao: Performed the experiments; Analyzed and interpreted the data.
Tao Wen, Melin Xie: Contributed reagents, materials, analysis tools or data.

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Data availability statement

The authors do not have permission to share data.

Declaration of interest’s statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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