FRACTAL APPROACH TO CONCENTRATION DISTRIBUTION OF ATMOSPHERIC FINE PARTICLE SIZES

by

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With the increase of particulate pollution in the atmosphere, it becomes extremely significant to understand the overall distribution characteristics of particulates and their adsorption of toxic gases for the source analysis and precise controlling of atmospheric particulate matters. The fractal theory was adopted to analyze particle sizes distribution characteristics in Xi'an city, China. Results showed the fractal dimension of particulate matters distribution ranged from 4.32-4.83, with an average fractal dimension of 4.54. A higher fractal dimension predicts a higher concentration of fine particles.Additionally the effects of outdoor temperature, humidity, and wind speed on the fractal dimension were also studied experimentally.

Key words: *atmospheric particles, concentration, distribution, fractal theory, fractal dimension*

Introduction

Problems of air pollution are more imminent than before [1]. Many countries have adopted relevant measures to control the environmental pollution [2], and much research shows that particles of different particle sizes in the atmosphere have different degrees of harm to the human body [3]. Some of them will enter the human lungs or some will come into the human blood. People who live in an deteriorated environment for a long-term might suffer death [4]. With the outbreak of 2019-nCoV [5], people were paying more and more attention a series of health problems caused by environmental pollution.

Many researchers focused on the distribution characteristics of atmospheric particulate matters [6, 7], distribution of heating period [8], correlations between particulate matters and other gaseous pollutants [9, 10]. Much achievement had been achieved already. There were still many deficiencies in the study of the distribution of particulate matters in the atmosphere. On the one hand, particulate matters in the atmosphere were not uniform, and its dynamic characteristics and motion characteristics were obviously different from those for spherical particles [11]. Some research achievements were obtained through the assumption of the spherical particles. On the other hand, the distribution of existing atmospheric particulate matter was a big difference due to regional differences, the type of urban economic structure and the adjustment of heating energy consumption methods [12]. Therefore, the distribution of atmospheric particulate matters at some a place became a hot topic, for examples, in Guangzhou [13], Beijing [14], and Shanghai [15]. No such research was carried out for a northern city of Xi'an in China.

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Fractal theory is one of the effective ways to solve complex problems, which has been widely applied to various disciplines now [16, 17]. Much achievement had been made in environmental science, especially for atmospheric particulate matters. As a result, fractal dimension of particle sizes distribution of atmospheric environment of Xi'an will be carefully calculated in this paper based on the fractal theory. It will provide characteristic parameters for controlling the particles of atmosphere.

Mathematical model and methods

Mandlbrot's fractal theory is adopted in this paper to establish a mathematical model for the distribution particles of the atmosphere. The number of particles can be expressed [18]:

$$n(>x)=Cx^{-D} \tag{1}$$

where n ($> x$) is the number of particles with a particle size larger than x in the system, D – the distribution fractal dimension, and C – a constant.

Fractal dimension D can be obtained according to the slope of ln(n) [18]:

$$D=-k \tag{2}$$

where k is the slope of the straight line of ln(x).

In our examperiment, the GRIMM1.109 portable aerosol particle size spectrometer was used to measure the concentration of particles in the atmosphere. Measuring range was 0.1~100.000 μg/m^3. Counting range was 2000000 P/L, and 31 particle size channels were divided between 0.25-32 μm. Repeatability was 5%. The TESTO480 climate measuring instrument was used to measure the temperature and humidity. Measuring range was –100 °C~+400 °C. Measurement accuracy was ±(0.3 °C~0.1% measured value). Humidity measuring range was 0~100% RH. Measurement accuracy was ±(1.4% RH~0.7% measured value). Location of samples was in a college in Beilin District of Xi'an. Testing time was from January 17 to 22, 2019. Each group was tested for 10 minutes, and the average of 10 minutes was used for analysis.

Results and discussion

Distribution of atmospheric particulates during the testing period was showed in fig 1.

Figure 1. showed distribution of atmospheric particles from January 17-22, 2019, and particles with size from 0-0.5 μm accounted for 97.9%, 98.0%, 97.8%, 98.0%, 97.5%, and 97.1%, respectively, and particles with size from 0.54-1.0 μm accounted for 1.92%, 1.84%, 1.88%, 1.63%, 2.10%, and 2.53%, respectively, particles with size from 1.0-2.5 μm accounted for 0.19%, 0.17%, 0.22%, 0.25%, 0.29%, and 0.27%, respectively. Particles above 2.5 μm accounted for 0.04%, 0.04%, 0.07%, 0.13%, 0.11%, and 0.08%, respectively.

Particle sizes of 0-2.5 μm accounted for most of the atmosphere during the testing, accounting for 99.9%. Particle sizes of 0-1.0 μm accounted for more than 99.7%. Particles in Xi'an were mainly fine particles. This conclusion was consistent with the literature [19], which are easy to enter the human respiratory tract and lungs, and seriously harmful to human health [20].

Fractal dimension of atmospheric particle sizes

Relationship between the fractal dimension and particle sizes of atmospheric particulate matters in Xi'an was calculated by eq. (1). Results were showed in fig. 2.

Figure 3 showed that a higher contents of small particles resulted in a higher fractal dimension. The fractal dimension could well reflect the uniformity of the composition of atmo-

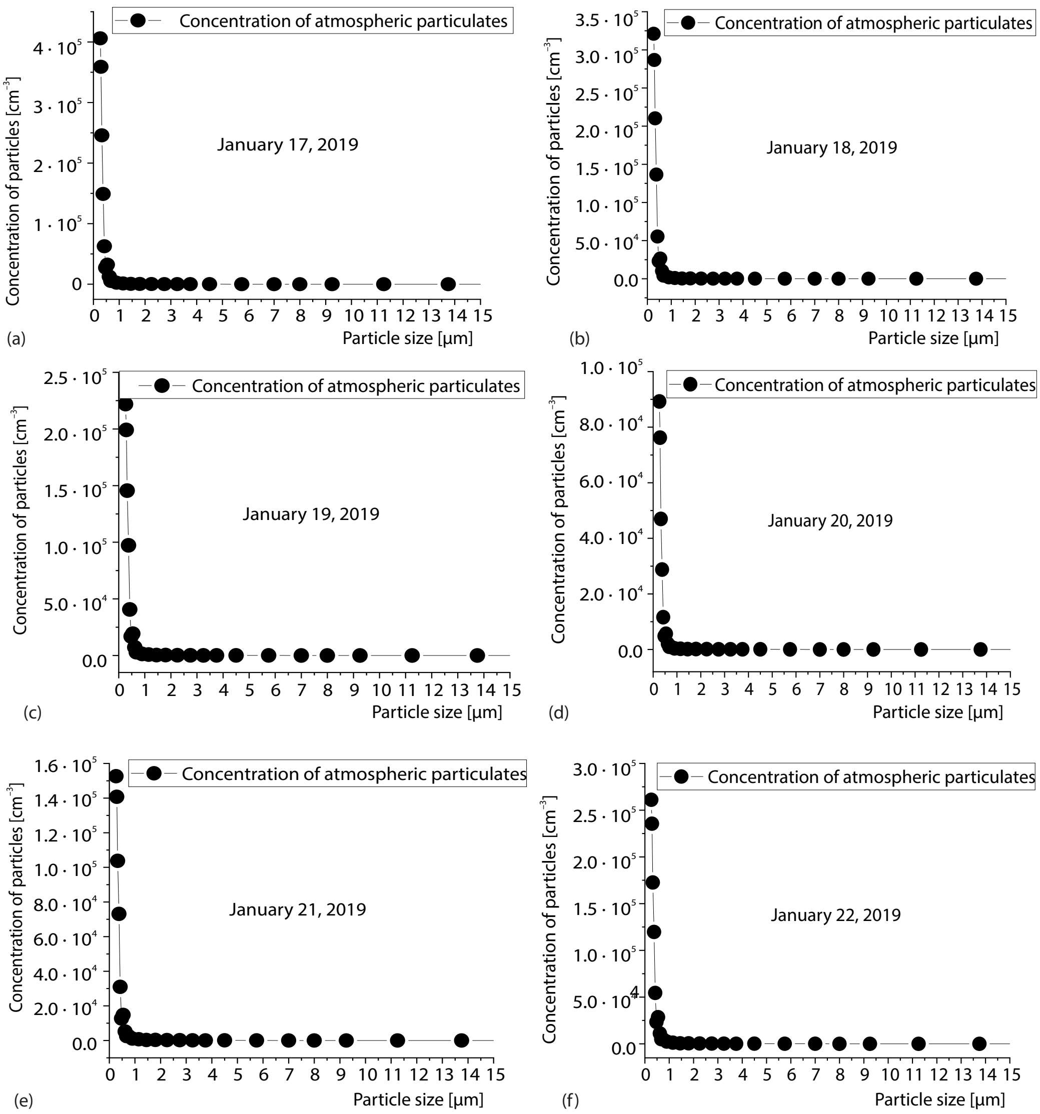

Figure 1. Distributing of atmospheric particles

spheric particles. Results of fractal dimension of particle sizes distribution of atmospheric fine particles of the test period are shown in tab. 1.

Table 1 showed distribution of fine particles had a fractal dimension from 4.32-4.83, with an average quantile of 4.54. The largest distribution fractal dimension, *D*, of particulate matters was on January 18, 2019. At this time, the value of *D* was 4.83. There were 99.8% of the particulate matter in the atmosphere which was distributed among the equivalent particle size <1.0 μm. The smallest fractal dimension, *D*, of particulate matters was on January 20, 2019. At this time, the value of *D* was 4.32. There were 99.6% of the particulate matter in the atmosphere which was distributed among the equivalent particle size <1.0 μm.

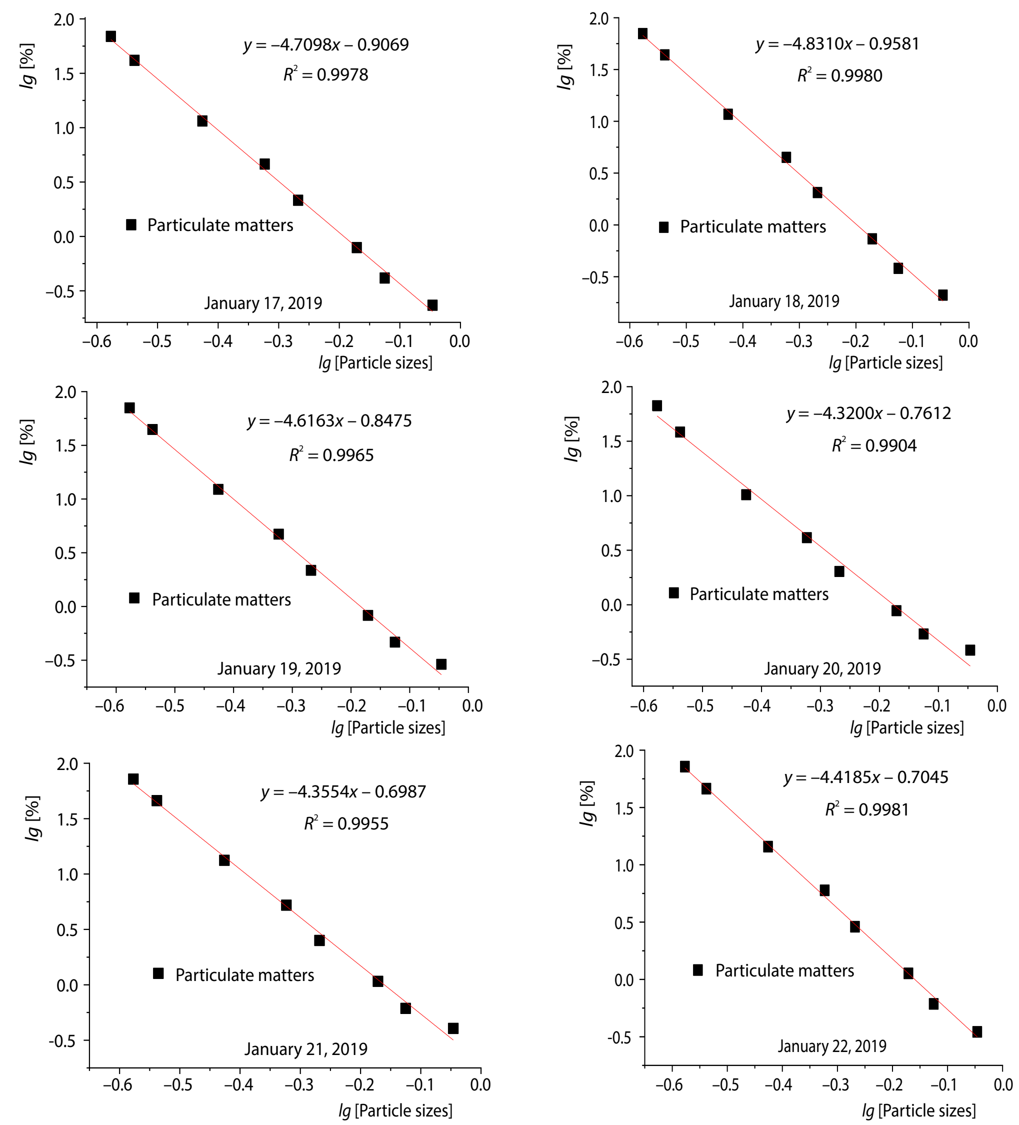

Figure 2. Calculation of the fractal dimensions of inhalable particles

Table 1. Fractal dimension of particle sizes in Xi'an at different test time of 2019

Number	Time	Wind	Temperature	Humidity	Particulates	
					D	R^2
1	January 17, 2019	4-6	–5~–2°C	61~69%	4.71	0.998
2	January 18, 2019	4-5	0~2°C	51~56%	4.83	0.998
3	January 19, 2019	5	0~3°C	49~62%	4.62	0.997
4	January 20, 2019	6	5~6°C	19~22%	4.32	0.990
5	January 21, 2019	4-6	1~3°C	36~49%	4.36	0.996
6	January 22, 2019	2-3	0~10°C	25~48%	4.42	0.998
Average					4.54	0.996

Most current researches gave the values of D were between 1 and 3 [21]. However, the value range of D of atmospheric particulate matters in Xi'an was relatively large. On the one hand, it illustrated that atmospheric particulate matters in Xi'an were relatively irregular and rough. This result was consistent with the results given in [18]. On the other hand, it showed that the particulate matters in Xi'an were mainly composed of fine particles. In addition, outdoor weather conditions, temperature, humidity, wind and other factors would cause changes in the quantile of the particle size distribution of particulate matters [18]. Therefore, distribution fractal dimension of particle sizes could be used to represent well the distribution of atmospheric particulate matters.

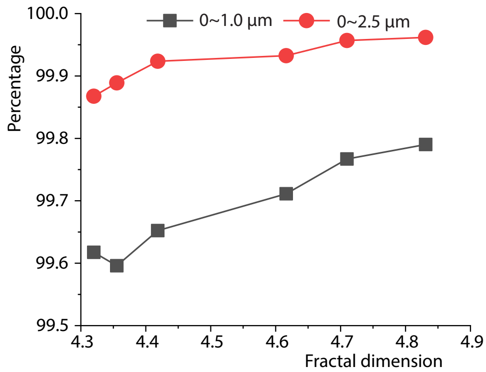

Figure 3. Particle size dependent fractal dimension

The relationship between fractal dimension and particulate matters

Particulate matter could be a porous medium by default, which had a large specific surface area [11]. It would adsorb some harmful substances. The more complex morphology of particulate matters was, the larger the specific surface areas were and the stronger the ability to adsorb pollutants was. Pfeifer gave the relationship between the single-layer saturated adsorbed molecule number N_m and the adsorbed molecule cross-sectional areas S [22]:

$$N_m = cS^{(-D/2)} \tag{3}$$

where c is the scale factor and D – the fractal dimension of the adsorbent.

If the molecular weight of the adsorbate is M and the density is ρ, the adsorption capacity is Q [22]:

$$Q = N_m \frac{M}{\rho} = c\frac{M}{\rho} S^{(-D/2)} \tag{4}$$

Therefore, adsorption of toxic gas from atmospheric particulate matters was related not only to the relevant properties of gas molecules, but also to the fractal dimension of the surface of the particulate matter. The roughness of the surface of the particulate matters direct-

Table 2. Quantile of distribution of different particulate matters and the corresponding cumulative percentage of specific surface area [%]

Number	D	R (<x)								
		0.265	0.375	0.475	0.54	0.675	0.75	0.9	2.25	9.25
1	4.71	0.310	0.885	0.954	0.979	0.992	0.996	0.998	1	1
2	4.83	0.297	0.883	0.955	0.980	0.993	0.996	0.998	1	1
3	4.62	0.293	0.877	0.953	0.978	0.992	0.995	0.997	0.999	1
4	4.32	0.332	0.898	0.959	0.980	0.991	0.995	0.996	0.999	1
5	4.36	0.281	0.867	0.948	0.975	0.989	0.994	0.996	0.999	1
6	4.42	0.283	0.856	0.940	0.971	0.989	0.994	0.997	0.999	1
Average	4.54	0.300	0.878	0.951	0.977	0.991	0.995	0.997	0.999	1

ly affects the adsorption of harmful substances by the particles, which affect the health of the human body. Table 2 shows the quantile of the particle sizes distribution of different inhalable particles and the corresponding cumulative percentage of specific surface area.

Table 2 showed with the increase of the distribution fractal dimension *D*-value, the specific surface area and other parameters of particulate matters would increase rapidly. The ability of atmospheric particulate matters to adsorb toxic and harmful pollutants would also increase deeply. Therefore, relevant parameters of the particulate matter were obtained by using fractal method, which would provide a new technical mean for the comprehensive management of particulate matters.

Conclusion

Fractal dimension of particle sizes distribution and the distribution relationship between fractal dimension and particle concentration in the atmospheric environment of Xi'an were all calculated in this paper based on the fractal theory. The following results are initially obtained.

- Atmospheric particles of Xi'an were mainly composed of fine particles, more than 99.7% particles were between 0 and 1.0 μm.
- Fractal dimensions of particulate matters distribution ranged were from 4.32-4.83, with an average fractal dimension of 4.54.
- Fractal dimension of particle sizes had a strong negative correlation with particle size. The higher the proportion of fine particles was, the larger the fractal dimensions were and the more complex the composition of atmospheric particulate matters were.
- Distribution of overall particle sizes and their adsorption of toxic gas was all by well using particle sizes fractal dimension.

In addition, factors such as outdoor temperature, humidity and wind speed will cause changes in the fractal dimensions of particle size distribution. It will provide characteristic parameters for understanding the source, concentration distribution, and effective control of atmospheric particles.

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