Micro-Morphological Characteristics and Size Distribution of PM$_{2.5}$ in the Kuitun-Dushanze Region of Xinjiang, China

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ABSTRACT

The micro-morphological characteristics of PM$_{2.5}$, collected in the Kuitun-Dushanze petrochemical area of the Xinjiang Uygur Autonomous Region, China, were studied using a high-resolution field emission scanning electron microscope with energy dispersive X-ray spectroscopy (FESEM-EDX). The individual particle types of PM$_{2.5}$ were identified, including mineral particles (regular minerals and irregular minerals), spherical particles (coal-fired fly ash and some secondary particles), soot aggregates, and other particles (some particles remained unclassified). Factories, power plants, vehicle emissions, and road dust were major sources of PM$_{2.5}$ in the Kuitun-Dushanze petrochemical area. Vehicle exhaust and waste gas from a power plant were defined as primary sources of mineral particles. Wind speed in September which was higher than July during the sampling time leads to the lower concentration of regular mineral particles since high wind speeds would reduce the chance of secondary particle generation. As a high wind speed would also easily diffuse the fine particles, the coarse-grained mineral particles had the highest percentages in September; the chain-like soot aggregates and the compact soot aggregates were the majority of all kinds of particles. The sizes of various particles in July and September primarily ranged from 0.1 to 0.5 µm.

Keywords: Kuitun-Dushanze region; SEM-EDX; PM$_{2.5}$; Micro-morphology.

INTRODUCTION

PM$_{2.5}$ refers to airborne particulates with aerodynamic diameters no larger than 2.5 µm; it is also called Respirable Particulate Matter since it can enter the alveoli (Shao et al., 2000). Epidemiological and toxicological studies have highlighted a link between increases in PM concentration and increases in childhood and adult morbidity and mortality due to cardiopulmonary disease (Schwartz and Neas, 2000; Maynard, 2001; Pope et al., 2002). It is noticed that various diseases could increase four percent with every 10 µg m$^{-3}$ increase in particulate matter concentration, and cardiorespiratory disease and lung cancer mortalities could increase six and eight percent, respectively (Pope et al., 2002). There is convincing evidence that particle size distribution determines the position of deposition in the human lung and has a major influence upon toxicity (Anderson et al., 2001). Airborne particulates can also directly influence the climates by scattering and absorbing solar radiation and indirectly impact the global climate by changing a cloud’s optical properties (Kanakidou et al., 2005; Poschl, 2005). Particulate matter is also the main factors that determine the effects of PM on atmospheric visibility (Watson et al., 2002). To date, the pollution of inhalable particulates, especially fine particulate matter (PM$_{2.5}$), has become a highlighted atmospheric environmental issue.

In addition to natural processes, such as wind-induced resuspension of crustal material and volcanic activity, suspended particles are due to coal and oil combustion, motor vehicle exhaust fumes, the construction industry, metal working industries, and other anthropogenic sources (Li et al., 2015). Urban and industrial areas are the sites mainly affected by such emissions, which pose a serious health risk to human health, since pollution derived trace elements may be absorbed by the human respiratory tract and deposited deeper in the pulmonary region (Bosco et al., 2005). The Bosco et al. (2005) conducted an investigation on the Gela area (Sicily, Italy) where one of the largest petroleum refineries in Europe is based and they have noticed that high levels of trace metals in the airborne particles may come from three main sources: soil, vehicle traffic, and industrial emissions. Therefore, the petrochemical plant appears to be associated with raised levels of heavy metals.

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such as As, Mo, Ni, Se, V, and Zn (Bosco et al., 2005).

The Kuitun-Dushanzi region is an important petrochemical base of China which is located in the western part of the Xinjiang Uygur Autonomous Region, China. In this area, the petroleum industry is a major contributing source of air pollution. The mass concentrations of PM$_{2.5}$ in the Kuitun-Dushanzi region can be as high as 210 µg m$^{-3}$, but the sources and properties of the PM$_{2.5}$ in this area remain unclear.

In recent years, more and more investigations have been carried out on the physicochemical properties of the particles which are believed to be closely related to the health effect and climatic effects of the particles (Shao et al., 2012; Li et al., 2015). The individual particle analysis has become an important method in characterization of physicochemical properties of atmospheric particles (Schwartz, 1996; Anderson et al., 1988; Buseck et al., 1999, 2000; Conner, 2001; Abel et al., 2003; Masatoshi et al., 2004). Individual particle analysis has a lot of advantages compared to the bulk analysis and it can provide a great deal of information on physics and chemistry of the airborne particles that the bulk analysis can't. In addition, the information of individual particle analysis can be used as "fingerprint" of the natural sources and/or anthropogenic sources (Ma et al., 2001; Li et al., 2015).

In this paper, the micro-morphological characteristics and size distribution of PM$_{2.5}$ in the Kuitun-Dushanzi petrochemical area were studied. The results could be conducive to the investigation of the sources and origins of PM$_{2.5}$ in this region, providing a scientific basis for urban atmospheric pollution regulations.

SAMPLING AND LABORATORY EXPERIMENT

Sampling

A total of four sampling sites were chosen for sample collection in the Kuitun-Dushanzi petrochemical area, with all of them located in the residential area and industrial parks. The sampling sites in residential area were denoted by 1# and 2#; 1# represents the Kuitun environmental monitoring station and 2# represents the Dushanzi environmental monitoring station. The sampling sites in industrial parks were denoted by 3# and 4#, and were located at the south and north gates of the ethylene plant respectively. The distributions of the sampling sites were shown in Fig. 1.

Ambient air particulate matter was continuously collected using a three-staged impactor sampler (TH-β10, Wuhan Tianhong Instrument Factory). The impactor head of the first stage was for total suspended particulates (TSP), the second was for PM$_{10}$ and the third one for PM$_{2.5}$. In this paper, we use the PM$_{2.5}$ samples from the third stage for the FESEM-EDX analysis. A polycarbonate filter membrane was used for sample collection, and the flow rate was set at 5 L min$^{-1}$. The polycarbonate filter (85 mm in diameter, 0.6 µm in pore size) are well suitable for microscopic analysis because it has a smooth surface which makes individual particles much more easily to be differentiated. The samples were collected in five days (7–21, 7–22, 9–25, 9–26, 9–27) in 2012. The sampling process lasted approximately 2 to 2.5 hours every day. A total of 12 samples were collected and the sample information is shown in Table 1.

Sample Analysis

The 12 samples were characterized using a field emission scanning electron microscope (FESEM, LEO-1430VP, Germany), a digital microscopic imaging granulometer, and an energy dispersive X-ray spectrometry (EDX, Oxford-200). The following preparation procedures were used for the FESEM and EDX observation. First, approximately one
Mineral Particles are one of the main types of the airborne particulates in the study area. Mineral particles have irregular (Fig. 2) and regular shapes. The EDX spectra of these irregular mineral particles show that they contain major elements of Si, Fe, Al, Mg, and sometimes Zn, and these compositions indicate that they are mostly aluminosilicates with a crustal source (Shi et al., 2003). The regular-shaped mineral particles are commonly bar-shaped, and composed of elongated crystals, and the EDX spectra indicated a major elemental composition of S and Ca, suggesting that these crystals are mostly sulphates (gypsum or anhydrite). The elongated particles and the bar-shaped particles are possibly formed by secondary atmospheric reactions (Shi et al., 2003). The study area is adjacent to the Gobi or desert area where mineral particles can be easily suspended and brought in by wind. Although the irregular minerals are typical for crustal sources, the regular sulfates are also common in the arid desert regions and can be suspended into air. Surface soil in some Chinese desert areas contains substantial sulfate (Abuduwaili et al., 2008; Zhu and Yang, 2010). An investigation on the mineralogy of surface particles in the Taklimakan region by Wu et al. (2012) confirmed that sulfate could be substantially derived from surface soil at the desert area. Therefore, both regular and irregular mineral particles can be regarded to be primarily sourced from re-suspension of surface dust.

### Soot Aggregates

Soot particles commonly showed two physical forms: individual chains (Fig. 3(e)) and densely compacted aggregates (Fig. 4). The EDX spectra revealed that the soot particles were mainly composed of C, internally mixed with minor Si, S, and K fractions. Soot aggregate is a beaded aggregate formed by tiny spheres produced during fuel combustion at temperatures higher than 600°C. Coal combustion and vehicle exhaust pollution are the main sources of soot aggregates (Hu et al., 2009). Soot aggregates generated by coal combustion are similar to those produced by vehicle exhaust and are chain-like (Shi et al., 2003), as shown in Figs. 4(a)–4(d). The soot aggregates obtained in this study were analogous to the soot aggregates collected by coal combustion sources (Yang et al., 2007). Particles from vehicle exhaust is mostly comprised of compact soot aggregates (Figs. 4(e)–4(f)); most of the micro-morphological images of Kuitun-Dushanzi region were chain-like and compact. The vehicles in Kuitun-Dushanzi region are dominated by gasoline engine cars. Mean diameters for the number-size distributions of particles emitted by gasoline engines ranged from 40 nm to 80 nm (Ristovski et al., 1998). The larger particles composed of small spherical particles as shown in Figs. 4(e) and 4(f). These small particles formed by the homogeneous nucleation may grow by condensation.

### RESULTS AND DISCUSSION

#### Major Individual Particle Types of PM$_{2.5}$

**Mineral Particles**

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### Table 1. Sample information.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Sampling Date</th>
<th>Sampling Time</th>
<th>Concentration (µg m$^{-3}$)</th>
<th>Location</th>
<th>Total particle number under SEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2012.7.21</td>
<td>00:41–01:41</td>
<td>110</td>
<td>1* (Living area)</td>
<td>657</td>
</tr>
<tr>
<td>2</td>
<td>2012.7.21</td>
<td>17:45–19:15</td>
<td>80</td>
<td>1*</td>
<td>691</td>
</tr>
<tr>
<td>3</td>
<td>2012.7.21</td>
<td>20:08–21:38</td>
<td>150</td>
<td>1*</td>
<td>813</td>
</tr>
<tr>
<td>4</td>
<td>2012.7.21</td>
<td>22:41–00:11</td>
<td>100</td>
<td>2* (Living area)</td>
<td>480</td>
</tr>
<tr>
<td>5</td>
<td>2012.7.22</td>
<td>18:01–19:31</td>
<td>190</td>
<td>2*</td>
<td>899</td>
</tr>
<tr>
<td>6</td>
<td>2012.9.25</td>
<td>22:30–00:30</td>
<td>130</td>
<td>1*</td>
<td>1156</td>
</tr>
<tr>
<td>7</td>
<td>2012.9.26</td>
<td>15:56–17:56</td>
<td>180</td>
<td>3* (Industrial zone)</td>
<td>1061</td>
</tr>
<tr>
<td>8</td>
<td>2012.9.26</td>
<td>21:10–23:10</td>
<td>210</td>
<td>3*</td>
<td>1011</td>
</tr>
<tr>
<td>9</td>
<td>2012.9.26</td>
<td>23:41–01:41</td>
<td>80</td>
<td>2*</td>
<td>553</td>
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<tr>
<td>10</td>
<td>2012.9.27</td>
<td>10:17–12:47</td>
<td>80</td>
<td>2*</td>
<td>960</td>
</tr>
<tr>
<td>11</td>
<td>2012.9.27</td>
<td>17:04–19:04</td>
<td>160</td>
<td>4* (Industrial zone)</td>
<td>738</td>
</tr>
<tr>
<td>12</td>
<td>2012.9.27</td>
<td>21:31–23:31</td>
<td>120</td>
<td>4*</td>
<td>1212</td>
</tr>
</tbody>
</table>
and coagulation and shift towards larger diameters with increasing distance from the roads. This suggests that the particles with this size ranges measured possibly correlated with traffic emissions (Wu et al., 2008). Thus, the emissions of industrial production, coal combustion and vehicle exhaust were the main sources of PM$_{2.5}$ over Kuitun-Dushanzi during sampling. Similar to the Gela petroleum refineries (Sicily, Italy) (Bosco et al., 2005), the Kuitun-Dushanzi petrochemical industry area also had three main particle sources; soil, vehicle traffic, and industrial emissions.

**Spherical Particles**

The spherical and ellipsoidal particles observed under FESEM were primarily formed by coal-fired fly ash and secondary particles. The fly ash particles are, in most cases, nearly spherical (Xie et al., 2005). When fly ash particles were deformed, resulting in ellipsoidal shapes, peach shapes or surface defects. Spherical coal-fired fly ash is the main emission of coal combustion and plants. As the EDX analysis demonstrated, the spherical particles, primarily a product of high temperature combustion, were mainly composed of Si and Al, associated certain amount of Ti, Fe, K, and Ca. Normally, spherical particles are derived from fluid melts due to high-temperature combustion (Xie et al., 2005). Two types of spherical particles were differentiated from the Kuitun-Dushanzi region. Type 1 was coal-fired fly ash...
Fig. 4. FESEM images of soot aggregates: (a) individual chain-like soot aggregates; (b) soot aggregates composed of chain-like aggregates; (c) soot aggregates composed of chain-like aggregates; (d) soot aggregates covered with irregular minerals; (e) compact soot aggregates; (f) wet compact soot aggregates.

Fig. 5. FESEM images of spherical particles: (a) coal-fired fly ash covered with fine particles; (b) coal-fired fly ash covered with fine particles and attached to soot aggregates; (c) secondary spherical particles; (d) secondary spherical particles; (e) secondary spherical particles; (f) coal-fired fly ash with smooth surfaces.

particles (Figs. 5(a), 5(b) and 5(f)), mixed with other absorbed particles or covered by soot aggregates. Type 2 was smaller ellipsoidal particles which were secondary particles formed by atmospheric chemical reactions (Figs. 5(c)–(e)). Coal-fired fly ash with ultra-fine particles and secondary spherical particles were common in the Dushanzi-Kuitun region.

Other Unknown Ultra-Fine Particles
In the Kuitun-Dushanzi region, some particulate matters with special morphologies were found, such as fiber and unknown particles (Figs. 6(a)–(b)). The size of some particulates was so small that the micro-morphological characteristics were difficult to identify even under high-resolution FESEM. These particulates were therefore categorized as other particles which may come from combustion (e.g., vehicle exhaust, natural gas, coal or chemical oil combustion) or secondary particles (such as acidic condensate, sulfate, and nitrate) produced by various atmospheric chemical reactions (Shi et al., 2003; Shao et al., 2012).
Fig. 6. FESEM images of other particles: (a) fiber; (b) other particles.

Table 2. Number percentages and volume percentages of the different types of individual particles in PM$_{2.5}$ in the Kuitun-DuShanzi region.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Mineral particles</th>
<th>Soot aggregates</th>
<th>Spherical particles</th>
<th>Other particles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number percentage</td>
<td>Volume percentage</td>
<td>Number percentage</td>
<td>Volume percentage</td>
</tr>
<tr>
<td>1</td>
<td>51.27</td>
<td>97.73</td>
<td>3.31</td>
<td>1.84</td>
</tr>
<tr>
<td>2</td>
<td>33.79</td>
<td>56.04</td>
<td>15.59</td>
<td>42.27</td>
</tr>
<tr>
<td>3</td>
<td>47.52</td>
<td>90.67</td>
<td>9.75</td>
<td>2.86</td>
</tr>
<tr>
<td>4</td>
<td>53.49</td>
<td>78.16</td>
<td>18.25</td>
<td>21.71</td>
</tr>
<tr>
<td>5</td>
<td>56.64</td>
<td>79.82</td>
<td>12.83</td>
<td>16.23</td>
</tr>
<tr>
<td>6</td>
<td>67.84</td>
<td>79.37</td>
<td>2.31</td>
<td>14.1</td>
</tr>
<tr>
<td>7</td>
<td>61.17</td>
<td>70.51</td>
<td>3.11</td>
<td>17.06</td>
</tr>
<tr>
<td>8</td>
<td>67.98</td>
<td>75.46</td>
<td>2.93</td>
<td>17.56</td>
</tr>
<tr>
<td>9</td>
<td>61.03</td>
<td>69.69</td>
<td>11.6</td>
<td>26.2</td>
</tr>
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<td>10</td>
<td>63.07</td>
<td>86.14</td>
<td>8.86</td>
<td>13.54</td>
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<tr>
<td>11</td>
<td>49.52</td>
<td>87.88</td>
<td>12.58</td>
<td>11.27</td>
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<tr>
<td>12</td>
<td>56.83</td>
<td>89.2</td>
<td>10.32</td>
<td>9.98</td>
</tr>
<tr>
<td>Summer</td>
<td>48.54</td>
<td>80.48</td>
<td>11.95</td>
<td>16.98</td>
</tr>
<tr>
<td>Autumn</td>
<td>63.98</td>
<td>78.40</td>
<td>7.59</td>
<td>17.95</td>
</tr>
<tr>
<td>Residential area</td>
<td>63.98</td>
<td>78.40</td>
<td>7.59</td>
<td>17.95</td>
</tr>
<tr>
<td>Industrial area</td>
<td>58.88</td>
<td>80.76</td>
<td>7.24</td>
<td>13.97</td>
</tr>
</tbody>
</table>

Relative Percentages of the Different Individual Particles and Source Analysis of PM$_{2.5}$ at the Different Sampling Sites in Different Periods

For total sample, more than 10231 particles on twelve images were measured. FESEM image analyses of PM$_{2.5}$ in the Kuitun-DuShanzi region were shown as Table 2. It was dominated by spherical particles (3.30% by number and 3.13% by area), mineral particles (55.85% by number and 80.06% by area), soot aggregates (9.29% by number and 16.22% by area) and other particles (32.20% by number and 0.81% by area) respectively. The presence of mineral particles and other particles in most collections was over 50% and 30%, indicating that mineral particles and other particles (ultrafine particles) had a regional distribution in Kuitun-Dushanzi region air. Mineral particles are mainly from sand carried by wind, re-suspended matters from road dust, construction, coal combustion, and secondary atmospheric reactions. Other particles might be formed in more complex ways, such as secondary particles that formed from gas phase pollutants and long range transportation particles.

Mineral particles and spherical particles accounted for 63.98% and 6.40% in autumn which was higher than summer. Soot aggregates and other particles accounted for 7.59% and 23.92% in autumn which was lower than summer. Since the high temperatures in July exacerbated the production of major atmospheric pollutants (sulfate and nitrate) through secondary chemical reactions, compact and wet compact soot aggregates formed the majority of soot aggregates obtained in July.

Mineral particles and spherical particles accounted for 63.98% and 6.40% by number respectively for the residential area, which was higher than industrial area (32.16%). Indicating that road dust, construction dust and the secondary particle during particle transportation had contribution on mineral particles of residential area. Additionally, emissions of industrial pollutants were the dominant sources of other particles in the sampling area. The primary explanation for this difference is the distance between the residential area and the industrial parks, which allows enough time required for secondary reaction in the atmosphere. Additionally, some obstacles, such as the high-rise buildings in the residential area, imposed adverse effects on the diffusion of particulate matter, thereby increasing the quantity of single particulate matters. In contrast, the industrial parks were located in
open areas, with high wind speeds; the fine particles in this area were easily dispersed. However, the mass concentrations of PM$_{2.5}$ in industrial parks were higher than those in the residential area, with a maximum mean value up to 210 µg m$^{-3}$. This distance provided enough time for atmospheric secondary reactions, and the obstacles throughout the residential area (such as high-rise buildings) impacted the particle diffusion. In contrast, the industrial zone was located in an open area with high wind speeds, where fine particles easily dissipated to downwind areas. The mass concentration (with a highest mean value of 21 µg m$^{-3}$) of PM$_{2.5}$ in the industrial zone was higher than in the residential area; thus, the industrial zone was more polluted than the residential area.

**Size Distribution Characteristics of PM$_{2.5}$ in Different Sampling Time**

**Size Distribution Characteristics in Residential Area in July**

The number-size distribution of particle in July shows in Fig. 7. The mineral particles comprised the highest percentage of the total various particles (48.56%), followed by other particles (37.21%), soot aggregates (11.95%) and spherical particles (2.69%). Regarding the number-size distribution, the peak of the mineral particles was mainly distributed within 0.2 µm to 0.3 µm and 0.3 µm to 0.4 µm, and the number percentages were 10.5% and 11.54%, respectively, the mineral particles, with size distributions of 0.1 µm to 0.5 µm, accounted for 31.55% of the total particles. The peak of the other particles ranged from 0.1 µm to 0.2 µm, with a number percentage of 25.86%, the peak of the soot aggregates ranged from 0.3 µm to 0.4 µm to 0.5 µm, with number percentages of 2.44% and 2.55%, respectively, the spherical particles were mainly distributed within the range of 0.2 µm to 0.3 µm, with a number percentage of 0.62%, particles with a size less than 0.5 µm accounted for 76.88% of the total particles.

As shown in the volume-size distribution in Fig. 8, the volume percentages of the mineral particles, soot aggregates, spherical particles, and other particles were 80.52%, 16.99%, 2.07%, and 0.48%, respectively. The volume of the mineral particles with sizes more than 1 µm accounted for 68% of the total particle volume. The primary peak was within the range of 1 µm to 2.5 µm with a volume percentage of 36.35%, and the secondary peak emerged in the sizes greater than 2.5 µm, with a volume percentage of 31.89%. The peak of the soot aggregates emerged in the range of 1 µm to 2.5 µm, with a volume percentage of 6.17%, the sizes and volume percentages of the other particles and spherical particles were significantly small.

**Size Distribution Characteristics in Residential Area in September**

The number-size distribution of PM$_{2.5}$ in September at the residential area is shown in Fig. 9. The percentages of the various particles of the residential areas in September was in the descending order that the mineral particles (62.13%), other particles (23.13%), soot aggregates (8.33%) and spherical particles (6.43%). The peak of the mineral particles ranged from 0.2 µm to 0.3 µm and 0.3 µm to 0.4 µm with number percentages of 19.98% and 15.77%, respectively, the peak of the other particles ranged from 0.1 µm to 0.2 µm with a percentage of 19.56%, the peak of the soot aggregates ranged from 0.3 µm to 0.4 µm to 0.5 µm, with number percentages of 2.44% and 2.55%, respectively, the spherical particles were mainly distributed within the range of 0.2 µm to 0.3 µm, with a number percentage of 0.62%, particles with a size less than 0.5 µm accounted for 76.88% of the total particles.

Fig. 7. Number-size distribution of the different types of individual particles in PM$_{2.5}$ collected in the Kuitun-DuShanzi region in July.
Fig. 8. Volume-size distribution of the different types of individual particles in PM$_{2.5}$ collected in the Kuitun-DuShanzi region in July.

Fig. 9. Number-size distribution of the different types of individual particles in PM$_{2.5}$ collected in the residential areas of the Kuitun-DuShanzi region in September.

the soot aggregates ranged from 0.4 µm to 0.5 µm and 0.5 µm to 0.6 µm with number percentages of 1.92% and 1.36%, respectively, the peak of the spherical particles ranged from 0.2 µm to 0.3 µm with a percentage of 2.42%, and the particles with sizes smaller than 0.5 µm occupied 82.86% of the total particles.

Fig. 10 shows the volume-size distribution of PM$_{2.5}$ in September at the residential area. The volume percentages of the various particles in September, in descending order, were the mineral particles (76.45%), soot aggregates (19.07%), spherical particles (4.15%) and other particles (0.32%). As shown in the volume-size distribution, the mineral particles, with a volume percentage of 43.17%, occupied the greatest volume in the range of 1 µm to 2.5 µm, the soot aggregates, with a volume percentage of 10.47%, made the greatest contribution in the range of 1 µm to 2.5 µm, the spherical particles and other particles contributed to a small percentage of the volume.
In general, the sizes of the particles in July and September mostly ranged from 0.1 µm to 0.5 µm, with the mineral particles contributing most. The different particle types had different sizes.

As Table 2 shows, the number percentage of the mineral particles was greater in September than in July as the samples in the industrial zone were included. The number percentage of the soot aggregates in September was larger than that in September, indicating that the atmosphere in July tended to be impacted by vehicle exhaust. More regular mineral particles emerged in July due to the increased likelihood of chemical reaction as a result of high temperatures. As shown in the analysis on the PM$_{2.5}$ volume-size distribution in July and September, the other particles only occupied a small fraction, while the volumes of the mineral particles, soot aggregates, and spherical particles essentially more than 1 µm. The mineral particles in July were more than 1 µm, with a volume percentage of 68.24%, the volume percentage in September was 60.91%.

### Size Distribution Characteristics in Industrial Area in September

Fig. 11 shows the number-size distribution of PM$_{2.5}$ in September at the industrial area. As shown in the figures, the mineral particles contributed the most with a percentage of 58.7%, and accounted for 18.33% in the range of 0.2 µm to 0.3 µm, and 15.69% in the range of 0.3 µm to 0.4 µm. The other particles contributed 32.16% and mostly occurred from 0.1 µm to 0.2 µm with a percentage of 28.15%, the proportion of the soot aggregates and spherical particles were 7.23% and 1.72%, respectively, particles less than 0.5 µm accounted for 81.74% of the total particles.

The volume-size distribution of PM$_{2.5}$ in September at the industrial area is shown in Fig. 12. The volume percentages of the particles, in descending order, were the mineral particles (80.76%), soot aggregates (13.97%), spherical particles (3.71%), and other particles (1.55%). The primary peak of the mineral particles was more than 2.5 µm, with a percentage of 39.49%, and the secondary peak ranged from 1 µm to 2.5 µm, with a percentage of 25.5%. The soot aggregates were mainly distributed from 1 µm to 2.5 µm and accounted for 9.65% of the total volume; the peak of the spherical particles ranged from 1 µm to 2.5 µm and occupied 2.62% of the total volume; and the other particles only contributed a small fraction.

Regarding the number-size distribution of the residential areas and industrial area in September, the particles were mainly distributed in the range of 0.1 µm to 0.5 µm. The mineral particles (50.57%), soot aggregates (3.96%), spherical particles (5.20%), and other particles (23.13%), within the
range of 0.1 \( \mu m \) to 0.5 \( \mu m \), occupied the major fraction of the number-size distribution in the residential areas; the mineral particles (45.89%), soot aggregates (2.93%), spherical particles (0.81%), and other particles (32.11%), within the range of 0.1 \( \mu m \) to 0.5 \( \mu m \), were also the major contributors in the industrial zones. However, the percentages of the different particles types with various sizes were different.

Table 3 shows that, in the industrial zones, there were a large number of unknown particles with a small size, and the sizes of the spherical particles were larger than that in the residential areas due to the impact of the nearby power plant and gas station. As shown in the analysis of the PM2.5 volume-size distribution of the residential areas and the industrial zones, the volumes of the mineral particles, soot
aggregates, and spherical particles with sizes more than 0.5 µm accounted for the majority of the volume in the residential areas and industrial zones, with percentages of 67.37%, 17.95%, and 3.29%, respectively, in the residential areas, and 75.05%, 13.65%, and 3.53%, respectively, in the industrial zones. The mineral particle sizes in the industrial zones were larger than in the residential areas.

In this study, the results indicated that the individual particle types of the Kuitun-Dushanzi Petrochemical Base included mineral particles, soot aggregates, spherical particles, and other particles (mostly secondary ultrafine particles). The most significant characteristics of the PM$_{2.5}$ micro-morphology during the low-heat period of the Kuitun-Dushanzi region were that the particle types are more diverse and other particles take a majority. This was most likely due to the fine particles produced by the atmospheric chemical reactions which were related to the particle and gas emissions from industry in the Kuitun-Dushanzi region.

CONCLUSIONS

1. Analysis on the morphological characteristics of PM$_{2.5}$ in July and September showed that the individual particles primarily included mineral particles (regular and irregular), spherical particles, soot aggregates, and other particles (some particles remained unclassified), mineral particles occupied the majority of individual particles. In July, mineral particles occupied 48.56% of the individual particles, followed by other particles (37.21%), soot aggregates (11.95%) and spherical particles (2.69%). In September, mineral particles comprised 60.27% of the individual particles.

2. The highest concentration of mineral particles were found in July and September, and mostly ranged from 0.2 to 0.3 µm in size. Although the soot aggregates and spherical particles were not large in number, they both had larger proportions between 0.4 and 0.5 µm in size.

3. In July, mineral particles comprised 80.52% of the total volume of individual particles of PM$_{2.5}$, followed by soot aggregates (16.98%), other particles (2.07%) and spherical particles (0.47%). In September, mineral particles comprised 78.91% of the total volume of individual particles of PM$_{2.5}$, followed by soot aggregates (16.15%), spherical particles (3.89%) and other particles (1.02%). According to the results of the analysis, the volume of mineral particles was the largest in July and September, and mainly ranged from 1 to 2.5 µm in size.

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REFERENCES


