Characterization of Particles in the Ambience of the High-Tech Industrial Park of Central Taiwan

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ABSTRACT

Medical scholars have confirmed that prolonged exposure to high concentrations of suspended particles may result in respiratory and heart diseases. To identify the characteristics of particles around high-tech industrial parks, engaged in the manufacturing of semiconductors, electronics and electrical peripherals, this study performed a two-year monitoring program to measure the heavy metal composition in airborne particles in order to find the potential sources of pollution as well as the causal relationships between meteorological conditions and pollutant concentrations. Due to the complexity arising from the highly inter-related meteorological and topographical factors in local and regional wind fields, a comprehensive data-mining algorithm based on clustering analysis is proposed to explore the useful information obtained from the chaotic monitoring data sets, as well as to profile the pollution sources. Hierarchical cluster analysis confirms that the concentration of arsenic in fine particles significantly increased at the end of 2010, and increased in conditions of high relative humidity (50%–80%). During the periods with high wind speed, the amount of arsenic in fine particles increases and comes from the northeast. In contrast, dispersion controls the regional air quality at low wind speeds, and during such times the arsenic comes from the northwest.

Keywords: High-tech industrial park; PM$_{10}$ and PM$_{2.5}$; Meteorological factor; Data mining.

INTRODUCTION

Medical reports have confirmed that high concentrations of suspended particulate matter (PM) would be hazardous to health. When exposed in an environment with a high concentration of PM, the probability of respiratory and heart diseases can be increased (Sanchez et al., 2009). It is believed that motor vehicles, public transportation vehicles, and factory chimneys are the major sources of PM, and most fine PMs originate from human activities (Yang et al., 2002; Tsai et al., 2012). PMs is the complex mixture of metals, organic matters, nitrates and sulfates and rest others. The aerodynamic diameter of PMs does not only guide their physical and chemical characteristics, but also results in different transport behavior and the influence on health risk (William, 1999).

The majority of suspended particles of aerodynamic diameter greater than 10 μm are deposited in the nose and mouth. The remaining such particles pass into the respiratory tract before being captured or removed via panting and sneezing, so only the nose and mouth area are subjected to hazards. Coarse suspended particles with aerodynamic diameter of 2.5 to 10 μm, PM$_{2.5-10}$, deposited in the upper respiratory tract in the area of the trachea and bronchi are removed by mucociliary peristaltic motion back to the throat, where they can be swallowed or coughed. Fine suspended particles (fine particle fraction, PM$_{2.5}$), with an aerodynamic diameter of less than 2.5 μm, are deposited via respiration in the alveolar region. Many studies have pointed out that suspended particles are one of the influencing factors for respiratory and cardiovascular diseases. In particular, the increase in the concentration of fine particles will slow the blood oxygen and carbon dioxide exchange rate, causing shortness of breath, older age, and cardiovascular disease. In the elderly their heart rate variability (heart rate variability, HRV) slows down, resulting in increased risk of death (Vallejo et al., 2006).

The speciation and aerodynamic diameter of PMs have been used to quantify the health risk, together with the apportionment of the pollution sources for the purpose of air quality control (Sharma and Maloo, 2005; Kumar et al., 2007; Wu et al., 2007; Kim et al., 2008; Yu, 2010; Aldabe et al., 2011). The literature has also revealed that the compositions of PMs can be useful evidence to identify the sources, (Allen et al., 2001; Espinosa et al., 2001; Marcuzzan et al., 2001; Chao and Wong, 2002; Miranda et al., 2002;
To ensure the island’s continual economic growth, many industrial parks have been built, operated or planned in Taiwan. Due to the limited land area in Taiwan, most industrial complexes are inevitably situated adjacent to urban development areas where people reside and work. The public has been concerned with the health risk due to the emission of PM from these industrial complexes. The Taichung site of the Central Taiwan Science Park (CTSP) is one of the most important bases worldwide for the high-tech industries of semiconductors, electronics and electrical peripherals with a total investment of USD 25 billions. CTSP brings not only considerable economic profits but also massive emissions of various pollutants for the ambiance (Suzuki et al., 2007). Chein et al. (2004) found that arsenic compounds can be measured in the ambient environment of high technology industry complexes, where semiconductor and optoelectronics manufacturing processes exist, because Arsenine (AsH₃) is the major material in manufacturing processes (Chein et al., 2006). Facing the health concern of the public, understanding the features of pollutants around the site is critical to addressing the public concerns and searching for the responsible parties in environmental forensics (Gargava and Aggarwal, 1996; Neves, 1996). However, complex environmental conditions usually make it difficult for decision makers to excavate the useful information from the chaotic monitoring data sets without the help of comprehensive data analysis approaches. Actually, if the strongest pollution sources can be labeled by mathematic tools, the advanced quality control strategies such as monitoring, network planning, emission inventory, exacting quality standards, and equipment improvement can be carried out to decrease the health risk in the study area.

Principal component analysis is one of the common multivariate statistical techniques that are used to achieve great efficiency of data compression from the original data as well as to indicate natural associations between samples and/or variables (Wenning and Erickson, 1994; Astel et al., 2007) by gaining some information useful in the interpretation of environmental systems. PCA consists of diagonalization of the covariance or correlation matrix transforming the original measurements into linear combinations of these measurements, and then the explained variance of each principal component can be maximized. It has been widely used to reveal the relationships among variables as well as to classify them into different latent variables, so that some special features inherent in the measured system can be characterized (Fang et al., 2003; Lautre and Fernández, 2004; Maccioitta et al., 2006; Chen et al., 2007; Lucas et al., 2008; Ren et al., 2012). Though Fang et al. (2003) has proposed a monitoring program cooperated with PCA approach in the same study area to reveal the basic characteristics of PMs, their study didn’t reveal either the casual relationships between observations and meteorological conditions or potential pollution sources in their study. Recently, many comprehensive approaches consisting of PCA and other data analysis technologies such as geographic information system (GIS) and cluster analysis are also proposed (Han et al., 2006; Kao et al., 2006; Zhou et al., 2007; Lima et al., 2010). For these reasons, this study proposes a series of data analysis procedures to outline the difference of typical materials between fine and large size PMs after a three-year monitoring program in the period of 2008 to 2011. This paper attempts to develop a systematic framework to find the basic characteristic of pollutants as well as to explore the potential pollution sources for a given monitoring site around a high technology industrial park like CTSP.

METHODS

Study Area and Sampling Site

The Taichung site of the Central Taiwan Science Park (CTSP) launched its first test run in middle 2005, but was not fully operational until early 2007. Fig. 1(a) shows a site map of the Taichung site with a total area of 413 hectares. The east and south of the site are immediately connected to the Greater Taichung Metropolitan area with a population of 1.5 million. About 5 km to the south is the Taichung Industrial Park, a conventional machinery industrial complex being heavily operated for about 30 years. About 3 km to the southwest is the Taichung Refuse Incinerator with a daily throughput of 900 wet tons. About 2 km to the east is a national highway system. The coast line of the Taiwan Strait and Taichung coal-burning power plant are about 15 km to the east of the study site. The topography of the site is characterized by a low altitude terrain of 50–300 m above the sea level, declining from northwest to southeast as shown in Fig. 1(b). As shown in Fig. 1(b), Tunghai University (THU) is selected as the sampling site due to the fact that THU is surrounded by trees and capable of avoiding interference from traffic.

Sampling and Chemical Analysis

Size-fractionated airborne particulate samples (< 2.5 μm and 2.5–10 μm) were collected on a cellulose filter paper (Whatman 47mm diameter, 20 μm pore) using a high volume sampler equipped with a cascade impactor for a period of 24 hours and the flow rate set on 1.7 m³/min, which is calibrated with a calibrator (NIEA-PA102). 22 observations were measured during 2008 to 2011 when factories in CTSP were fully operating, so that these observations can be used to explain the emission characteristics of CTSP. The collected samples were prepared by the microwave digestion method for subsequent spectrometric analysis (Wang et al., 1996), in which cellulose filter papers are loaded in the closed digestion vessels with 0.5 mL HNO₃ and digested in a microwave oven with the digestion program setting of 200W and temperature setting between 80°C to 90°C. After microwave digestion, graphite furnace atomic absorption spectrometry (GFAAS) was utilized to quantify the heavy metal concentrations (As, Cd, Cr, Cu, Mn, Ni, Pb) (NIEA-PA301). Moreover, a quality control program (NIEA-PA104) was also implemented to ensure the data quality.

Principal Component Analysis and Hierarchical Cluster Analysis (HCA)

More and more spatial-temporal data for pollutants are...
Fig. 1. (a) Stationary industrial area and sampling site. (b) The map of high-tech industrial area and sampling site in 3D.
becoming available due to increasing monitoring programs. If some useful information inherent in these data can be explored by data mining technologies, it will be helpful for decision makers to outline the environmental situation and to plan advantageous strategies for groundwater conservation. In this respect, the PCA approach is utilized in the present study to simplify high dimensional variables while retaining most of the primary information as well as to integrate some individual variables to comprehensive factors which stand for a kind of conceptual environmental characteristic.

The basis of PCA has been well-explained (Jolliffe, 2002). Briefly, PCA is used for characterizing patterns within large sets of data by re-expressing to a rotated coordinate system in which as much variance as possible is explained by the first few dimensions, in which the eigenvectors of the variance covariance matrix are calculated, so that the principal component score, i.e., the weight of the eigenvector can be obtained. The scores of the original variables, also called principal component loadings (PC loadings), can be used to indicate the relationship between the variable and the principal component. In other words, the variable and the principal component will be more strongly related if the PC loading is larger. By doing this, the raw data matrix can be reduced to two or three principal component loadings that account for the majority of the variance. Thus, these factors can be used to account for approximately required information as the original observations do. Thus, this paper uses the software package SPSS for Windows to determine the structure in the relationships between air quality parameters and identify the most important factors contributing to this structure based on the eigen analysis of the correlation matrix. Following the PCA process for grouping the characteristic parameters of objects, HCA is utilized to explore the spatial relationships among the objects by examining their distances, and then a graphic display of how these objects are clustered can be obtained (Davis, 1986).

RESULTS AND DISCUSSION

Chemical Characteristics of Observations
Chemical data of 22 analyzed samples during the sampling period between 2008 and 2011 are summarized in Tables 1 and 2. Average concentrations of PM$_{2.5}$ and PM$_{2.5-10}$ were 75.31 $\mu$g/m$^3$ and 25.79 $\mu$g/m$^3$, respectively. The average ratio of PM$_{2.5}$/PM$_{10}$ was about 0.74, higher than the measurement in study area by Fang et al. in 2003 as well as other inventories in the literature (shown in Table 3). It reveals that the concentration of fine particulates has been increasing since the CTSP began full operation. As presented in Table 1 and Table 2, Cu and Pb are the main heavy metals in either fine or coarse particulars at the sampling site. The rest of the elements ranked in order were Mn, Ni and Cd. In the PM$_{2.5}$ fraction, As is a noteworthy element because of its high concentration. Referring to the concentration standard of As for environmental ambiance in European, there is about 20% probability that As may violate such a regulation during the sampling period.

Pollutant Characteristics Analysis
Source groupings were determined using principal component analysis (PCA) with Varimax rotation and retention of principal components by SPSS 19.0. As shown in Table 4, a three-factor model was determined by PCA, in which their percentage of variance and cumulative percentage of variance explained 88.40% and 85.11% of the total variance.
Table 3. The average ratio of PM$_{2.5}$/PM$_{10}$ in different areas.

<table>
<thead>
<tr>
<th>Country</th>
<th>Site</th>
<th>PM$<em>{2.5}$/PM$</em>{10}$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taiwan</td>
<td>Taichung</td>
<td>0.74 ± 0.98</td>
<td>This study</td>
</tr>
<tr>
<td></td>
<td>Taichung</td>
<td>0.62</td>
<td>Fang et al. (2008)</td>
</tr>
<tr>
<td>Hong Kong</td>
<td>Hok Tusi</td>
<td>0.50</td>
<td>Lai et al. (2007)</td>
</tr>
<tr>
<td></td>
<td>Hung Hom</td>
<td>0.68</td>
<td>Cheng et al. (2006)</td>
</tr>
<tr>
<td>China</td>
<td>Shenzhen</td>
<td>0.73</td>
<td>Lai et al. (2007)</td>
</tr>
<tr>
<td></td>
<td>Zhuhai</td>
<td>0.71</td>
<td></td>
</tr>
<tr>
<td>Korea</td>
<td>Ulsan</td>
<td>0.55</td>
<td>Hieu and Lee (2010)</td>
</tr>
<tr>
<td></td>
<td>Busan</td>
<td>0.56</td>
<td>Kim et al. (2006)</td>
</tr>
<tr>
<td></td>
<td>Seoul</td>
<td>0.73</td>
<td></td>
</tr>
<tr>
<td>UK</td>
<td>Birmingham</td>
<td>0.66</td>
<td>Yin and Harrison (2008)</td>
</tr>
<tr>
<td></td>
<td>Barcelona</td>
<td>0.64</td>
<td>Pérez et al. (2008)</td>
</tr>
</tbody>
</table>

Table 4. Results of the PCA on the dataset of heavy metal concentration in PM$_{10-2.5}$ and PM$_{2.5}$ with outliers removed.

<table>
<thead>
<tr>
<th>PM$_{2.5-10}$</th>
<th>Factor 1</th>
<th>Factor 2</th>
<th>Factor 3</th>
<th>PM$_{2.5}$</th>
<th>Factor 1</th>
<th>Factor 2</th>
<th>Factor 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>As</td>
<td>0.955</td>
<td>-0.050</td>
<td>0.034</td>
<td>0.878</td>
<td>0.181</td>
<td>0.092</td>
<td></td>
</tr>
<tr>
<td>Mn</td>
<td>0.889</td>
<td>0.128</td>
<td>0.147</td>
<td>0.062</td>
<td>0.804</td>
<td>0.434</td>
<td></td>
</tr>
<tr>
<td>Cd</td>
<td>0.868</td>
<td>0.136</td>
<td>-0.123</td>
<td>0.935</td>
<td>0.080</td>
<td>0.152</td>
<td></td>
</tr>
<tr>
<td>Cu</td>
<td>0.220</td>
<td>0.905</td>
<td>0.251</td>
<td>0.298</td>
<td>0.511</td>
<td>0.680</td>
<td></td>
</tr>
<tr>
<td>Cr</td>
<td>-0.052</td>
<td>0.922</td>
<td>-0.274</td>
<td>0.032</td>
<td>0.037</td>
<td>0.949</td>
<td></td>
</tr>
<tr>
<td>Ni</td>
<td>-0.273</td>
<td>-0.193</td>
<td>0.891</td>
<td>-0.146</td>
<td>-0.924</td>
<td>0.045</td>
<td></td>
</tr>
<tr>
<td>Pb</td>
<td>0.428</td>
<td>0.201</td>
<td>0.818</td>
<td>0.898</td>
<td>0.068</td>
<td>0.014</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Origin</th>
<th>Industry</th>
<th>Soil/Resuspended</th>
<th>Traffic</th>
<th>Industry</th>
<th>Soil/Resuspended</th>
<th>Traffic</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of Variance</td>
<td>42.692</td>
<td>24.502</td>
<td>21.202</td>
<td>47.115</td>
<td>24.200</td>
<td>13.807</td>
</tr>
<tr>
<td>Cumulative (%)</td>
<td>42.692</td>
<td>67.194</td>
<td>88.396</td>
<td>47.115</td>
<td>71.315</td>
<td>85.112</td>
</tr>
</tbody>
</table>

variance in the data set for coarse and fine particles, respectively. Looking into the dominant factors (PC2) that are revealed in Table 4, Cu and Cr are classified into the same factor either in causal or fine particles. If this factor could be identified as the ‘soil dust and/or resuspended’ source (Fang et al., 2003), it implies that Cu and Cr can be used to measure the contributions from soil dust sources for different particle sizes.

In the coarse part (PM$_{2.5-10}$), the third factor (PC3) consisted of Ni and Pb with 21.20% accounted variance, which may be considered as the pollution source related to exhaust emissions from both gasoline and diesel fuelled vehicles (Pant and Harrison, 2012). It is interesting to note that the patterns of characteristic pollutants with regarding to industrial and traffic sources in different particle size are not similar, where Pb, Cr and As dominate the industrial sources at this sampling site in this study.

In order to understand the causal relationships between pollution patterns and meteorological conditions, samples were further classified into two groups by HCA according to their dominant typical materials (Factor 1 in Table 4). The results are shown in Fig. 2, in which C2 and F2 stand for high concentrations of PM$_{2.5-10}$ and PM$_{2.5}$ referred to in Fig. 2, respectively. Interestingly, Fig. 2(a) coarse particles were more serious in 2008, but in Fig. 2(b), the fine particles are active in 2010 serious pollution trends when the CTSP was in full operation. The evidence seems to expose the fact that the CTSP has changed the pollutant patterns in the study area.

To further explore the influence of geochemical conditions upon the formation of particles, a radar chart is plotted as Fig. 3 in company with a normalization procedure. Fig. 3(a) shows the results that the cluster with high pollutant concentrations has similar meteorological conditions to the other cluster. The meteorological conditions such as relative humidity, temperature, and wind speed are not key factors resulting in the difference of pollution patterns for coarse particles. In addition, the pollutants may come from the north of the site, according to the results of the wind rose shown in Fig. 3(a). However, looking at Fig. 3(b), a surprising phenomenon can be found. There is a slight difference of relative humidity and average wind speed between the clustered groups. It is noteworthy that the characteristics of Ni in PM$_{2.5}$ are different from other pollutants such as As, Cr, Cu, and Pb. It is believable that Ni can be derived from the traffic sources with larger particle size (Zechmeister et al., 2005; Duan et al., 2012; Guéguen et al., 2012). The lower concentration of Ni in PM$_{2.5}$ may indicate that Ni is not the major pollutant in the study area.

Profiling the Pollution Sources

To outline the relationships between pollutants, wind speed, relative humidity, and wind direction, this study selects As as a case study to plot a 3D map (shown in Fig. 4). The results indicate that there are three high concentration peaks of As in fine particles, in which the red part means...
Fig. 2. The results of classification by HCA based on the first component presented in Table 4.
the concentration of As is over the Europe regulation. As may come from the north-east direction if high wind speed (4 m/sec–5 m/sec) occurs. In low wind speed conditions (< 2.5 m/sec), dispersion dominates the regional air quality, and then major pollution sources may be located north-west of the sampling site, especially in high relative humidity. The high relative humidity also reflects that rough terrain (shown in Fig. 1(b)) obstructs the diffusion of pollutants and results in the accumulation of pollutants. Because there are no heavy emission factories located north-west of the sampling site, the high concentration of As can be considered as an external pollutant.

**CONCLUSIONS**

To explore the pollutants pattern of airborne particles near a high-technology industrial park like the CTSP, this paper presents an integrated analysis procedure based on PCA and HCA methods. By clustering meteorological parameters and segmenting the monitoring data, inherent data complexity and dissimilarity are mitigated. The proposed algorithm is not only valuable in dealing with the problem of characterizing the air pollution but also in determining the regional pollution sources for a complicated environmental system like this study area.
The high-tech industrial area in central Taiwan was established in small hills so in this region the climatic factors are not so smooth as in the plains. Therefore the fine suspended particulate emissions may accumulate around the park due to topography and climate factors. This study concludes that fine particles were observed to be increasing at the end of 2009 in the study area. Several high concentration peaks of As occurred when prevailing wind velocity was higher than 4 m/sec and/or lower than 2.5 m/sec. Pollution sources located north-east of the sampling site dominate the concentration of As in fine particles when wind velocity is higher than 4 m/sec. The results of this study will serve as a basis for the air quality planning and management for the Taichung site.

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