Fugitive emission rates assessment of PM$_{2.5}$ and PM$_{10}$ from open storage piles in China

Yiqi Cao, Tao Liu*, Jiao He

Department of Environmental Science and Engineering, University of Tongji, Shanghai 200092, China

Corresponding author. Tel.: +86 6598 1926; fax: +86 6598 1926.
E-mail address: liutao45@163.com.

Abstract. An assessment of the fugitive emission rates of PM$_{2.5}$ and PM$_{10}$ from an open static coal and mine storage piles. The experiment was conducted at a large union steel enterprises in the East China region to effectively control the fugitive particulate emissions pollution on daily work and extreme weather conditions. Wind tunnel experiments conducted on the surface of static storage piles, and it generated specific fugitive emission rates (SERs) at ground level of between ca.10$^{-1}$ and ca.10$^2$ (mg/m$^2$·s) for PM$_{2.5}$ and between ca.10$^1$ and ca.10$^3$ (mg/m$^2$·s) for PM$_{10}$ under the $u^*$ (wind velocity) between ca.3.0 (m/s) and 10.0 (m/s). Research results show that SERs of different materials differ a lot. Material particulate that has lower surface moisture content generate higher SER and coal material generate higher SER than mine material. For material storage piles with good water infiltrating properties, aspersion is a very effective measure for control fugitive particulate emission.

1. Introduction

Fugitive emissions are emitted gaseous or aerosol materials that can not pass through vents, stacks, or other openings. This definition includes gases, liquid droplets, and solid particulate matter (PM). Various indirect techniques have been used to estimate fugitive particulate emissions and relate them to some human activity and physical process using empirical methods or mathematical modelling.

Over the past 42 years, researchers have studied different fugitive dust source such as unpaved roads (Cowherd et al. 1974), bare soils (Harris and Davidson 2009), or open storage piles (Diego et al., 2009; Lazaridis et al 2012) like waste compost piles(Taha et al.2005), mineral piles (Torano et al., 2009,2007) and coal piles(Mueller et al., 2015,2013). Cowherd et al. (1974) employed a mass balance approach to derive fugitive dust emission rates from unpaved roads and other surfaces. The U.S. Environmental Protection Agency (EPA) has adopted emission factors (EFs) based on this method and has derived a formula that estimates the amount of fugitive emissions. Based on EPA AP-42 Emissions Handbook (EPA 1995, with subsequent updates), wind erosion potential $P_w$ from a dry aggregate storage pile is given by

$$ P_w = 58(u^* - u_t)^2 + 25(u^* - u_t^*) $$

(eq.1)

With $P_w$=0 for $u^* \leq u_t$, $u_t^*$ (a predictor of particle entrainment from the surface)is the threshold wind friction velocity and $u^*$ is the friction velocity. However, the fugitive dust emission is a complex dynamic process of interaction, and it should be mainly the interplay between particles at the surface and the flow shear. The relative microscopic mechanism of the problem was largely unknown or just
assumptions and guesses. Fugitive dust from storage piles contributes significantly to the local ambient concentration of total suspended particulate level (Badr and Harion, 2005) thus estimating the fugitive dust emission of open storage piles accurately needs further study.

There are several factors which influence the process of fugitive dust emission from piles such as stored material’s bulk density, surface crust, moisture content, and pile geometry. But the most prominent are the turbulent wind flow kinetic energy and the availability of erodible particles (Badr and Harion, 2005; Lazaridis and Drossinos, 1998; US EPA, 2006; Xuan, 2004). The wind tunnel simulate technique was used to find the threshold wind friction velocity and static dust emission for different coal-dust particle diameters and moisture contents (Chen and Cong, 2010). The common method of the wind tunnel simulate technique is placing a scaled model on the aggregate pile to experiment the dust emission. This method can easily figure out some single factors of dust emission, but it is difficult to simulate the realistic condition. A portable wind tunnel approach was confirmed feasible for estimating fugitive bio aerosol releases from static compost windrows (Taha et al., 2005). This approach can be used in the work site applied the scene environment as a condition of the experiment to test the actual emission rate on the surface of static windrows.

The study objects of the fugitive dust emission were related to our daily life. Here we describe a study of fugitive particulate emissions from open storage piles that contain several kinds of mineral powders and coal fines which are stored in a large union iron and steel enterprises. Large amounts of PM are emitted into the atmosphere at populated and industrialised urban areas, especially in China, where the number of coal mines and steel plants is high.

This paper describes a study based on eight kinds of typical coal mine materials’ physical properties analysis. To estimate fugitive dust pollution from a large union enterprises open storage piles, using a portable wind tunnel approach to quantify the dust emission rate of PM$_{10}$ and PM$_{2.5}$ on the surface of corresponding spot static piles and analyse the factors of dust emission rate for different kinds of materials.

2. Materials and methods

2.1. Wind tunnel measurements system

The experimental and methodological rationale is summarised in Fig 1. The fugitive dust emission rate in the open storage piles is related to the surface blowing $u^*$. A portable wind tunnel system (Fig. 1) with air volume regulator was used for mensurating the fugitive PM$_{10}$ and PM$_{2.5}$ emission rate of different storage materials. The blowing $u^*$ can be regulated from 0 to 10 m/s (considering the local meteorological conditions and equipment capacity) by frequency modulation fan and was monitored by a differential pressure flow meter. The fugitive dust emitted from the surface area was sampled within the horizontal air stream of the wind tunnel at a known velocity (ca.3.0 m/s) across the surface. In the tunnel, in coming air was filtered by HEAP filter to eliminate the ambient particulate matter. The wind tunnel was conducted by stainless steel and includes air inlet pipe, converging-diverging pipe, the main section of the wind tunnel, reducing pipe, elbow and air outlet pipe. Three guide plates were placed in the converging-diverging pipe to make the airflow distributed evenly. The base of the wind tunnel was embedded ca. 20 mm inside the surface of the pile to ensure no loss of air volume around the sides and was equipped with ca. 50 mm wide valgus wing around the under opening edge to keep the wind tunnel opening at the same level with the storage pile. The wind tunnel three-dimensional size is in Fig. 2.
1. Frequency modulation fan 2. HEAP filter 3. Differential pressure flow meter 4. Wind tunnel

Fig.1 Schematic diagram of a portable wind tunnel sampler system

2.2. Wind tunnel measurements system
Eight kinds of typical material particles which include five kinds of mineral fines (Ha-Yang mixed fines, PB fines, Chile fine meal, Dolomite fines, Tubarao fines) and three kinds of coal fines (Shen Fu gas coal, Yong Xia coal injection, Lu Jing coking coal) were selected to experiment. Sampling eight typical material particles from the subsurface of storage piles in the range 20 m² to experiment typical material properties including particle size distribution, true density, and aerodynamic diameter distribution and infiltrating experiment. We sampled about 1kg for each material. Before experiment typical diameter properties, all the samples were stoving in the oven at 180 °C for 2 hours. The lost weight was the material’s water content.

After desiccation pretreatment, eight kinds of samples were sieved by 30 mesh (200μm) and 300 mesh Taylor sieves (50μm) after removing spot adjunct (size >10mm) and analyse particle size sieving distribution. Using resuspension subsystem to resuspend the screened materials by 300 mesh and test their aerodynamic diameter distribution by APS 3310 (measuring range is from aerodynamic diameter 0.4 to 30 micrometres).

Removing large particles (size >12.5mm) from samples to measure true density by Pycnometer Test Method. All kinds of samples were sieved by 80 mesh Tylor sieve to test 8 kinds of samples’ invasive at 5 minutes and 20 minutes by reference to “dust property testing method (GBT16913-2008)”

2.3. Wind tunnel measurements system
The specific fugitive PM emission rate (SER) is the quantity of fugitive PM emitted per unit time from a unit surface. The equation is adopted from that used to determine the specific fugitive emission rate (Jiang and Kaye, 2001) from surfaces:

\[
SER = \frac{Q \times PC}{A}
\]

where “SER” is the specific fugitive PM emission rate (mg·s⁻¹·m⁻²); “Q” is the flow rate through the wind tunnel (m³·s⁻¹); “PC” is the PM concentration (mg·m⁻³); “A” is the area covered by the wind tunnel (m²).

PC data was monitored at the air outlet pipe by the Aerosol Tester (DUSTTRAK 8530-TSI company). All the PM concentration data were the average value of a minute. Eight kinds of material storage piles were selected to estimate the fugitive PM₂.₅ and PM₁₀ emission rate. During the experimental period, meteorological conditions were relatively stable, and we can think eight kinds of material piles were in the same condition (mainly refers to the environmental meteorological conditions). The environment temperature is about 6 °C. The air relative humidity is about 57%, The dominant wind direction is the west and the average wind speed is about 1.5m/s.
3. Materials and methods

3.1. The fugitive PM$_{2.5}$ and PM$_{10}$ emission rate

The fugitive PM$_{2.5}$ and PM$_{10}$ emission rate in a series of wind velocities of 8 kinds of material particles are presented in Fig.3. The meteorological conditions and environment temperature were mentioned at section 2.3. No matter PM$_{2.5}$ or PM$_{10}$, eight kinds of materials show significant differences in SER. Lu Jing coking coal and Shen Fu gas coal SERs are about one to two orders of magnitude larger than the others under the same surface $u^*$. To show all kinds of materials SER trend in the Fig.1, there are two y-axes (left and right) linked to the same x-axes. The SER of Lu Jing coking coal was shown in the right y-axes.

When the $u^*$ was 3.6m·s$^{-1}$, the PM$_{2.5}$ SER of Lu Jing coking coal was 12.3 mg·m$^{-2}$·s$^{-1}$, and the PM$_{10}$ SER of Lu Jing coking coal was 71.8 mg·m$^{-2}$·s$^{-1}$ which were higher than all the other materials under the total $u^*$ range. Except for Lu Jing coking coal, the PM$_{2.5}$ and PM$_{10}$ SER curves of Shen Fu gas coal were almost above the rest of curves. Also, the PM$_{10}$ SER of PB fines is relatively outstanding.

![Fig.2](a) PM$_{2.5}$ SER trend of eight kinds of material ![Fig.3](b) PM$_{10}$ SER trend of eight kinds of material

3.2. The fugitive dust emission rate impact factors

Our experiments research the fugitive dust emission rate impact factors and compare the fugitive dust emission of eight typical material particle. The impact factors can be divided into intrinsic and extrinsic factors. Intrinsic factors mean the material particle properties like true density, particle size distribution and surface moisture. Extrinsic factors mean some environmental or human actions like rainfall and purling water or coagulator that impact the fugitive dust emission.

When the $u^*$ was 3.6m·s$^{-1}$, the PM$_{2.5}$ SER of Lu Jing coking coal was 12.3 mg·m$^{-2}$·s$^{-1}$, and the PM$_{10}$ SER of Lu Jing coking coal was 71.8 mg·m$^{-2}$·s$^{-1}$ which were higher than all the other materials under the total $u^*$ range. Except for Lu Jing coking coal, the PM$_{2.5}$ and PM$_{10}$ SER curves of Shen Fu gas coal were almost above the rest of curves. Also, the PM$_{10}$ SER of PB fines is relatively outstanding.

3.3. Wind tunnel measurements system

3.3.1. Eight kinds of material particle size analysis. The material particle size sieving distribution data is presented in Fig.4 (a). For Ha-Yang mixed fines and Yong Xia coal injection, their coarse particles mass fractions are up to 90% which indicate that these two kinds of materials are mainly composed of coarse particles. For Tubarao fines, Lu Jing coking coal, PB fines and Dolomite fines, their coarse particles mass fractions are ca. 70% and fine particles mass fractions are less than 10%. Shen Fu gas
coal’s fine particles mass fraction is up to 30% that is the highest proportion in eight kinds of materials. As we can see in the particle size sieving distribution data, most of them have great wind erosion potential especially for Shen Fu gas coal which has the highest fine particle mass fraction and relatively small true density. After sieving experiment, we selected the particle size which is less than 300 mesh (particle size<50μm) and measured Aerodynamic diameter distribution Through the suspension system. Aerodynamic diameter distribution data is presented in Fig.4 (b). For all of them, the proportion of \( PM_{10} \) and \( PM_{10} \) (\( PM_{10}/PM_{30} \)) is ranging from 80% to 90% and the proportion of \( PM_{2.5} \) and \( PM_{30} \) (\( PM_{2.5}/PM_{30} \)) are ranging from 10% to 20%. This result indicates that all of them have the potential to generate fugitive dust pollution for long-term suspension.

3.3.2. Eight typical material particle property analysis. Eight kinds of typical material particles true density data is presented in Table.1 which shows significant variation between mineral and coal fines. For three kinds of coal fines, the average true density is \( 1.42 \times 10^{-3} \) (g·cm\(^{-3}\)), and for five kinds of mineral fines, the average true density is \( 4.17 \times 10^{-3} \) (g·cm\(^{-3}\)) almost three times than the former. Considering the material’s cohesion that we can not verify the relevance between true density and SER, we just speculate that coal fines may cause higher fugitive dust emission under wind blowing or human activities.

| Table.1 Typical material particle property |
|------------------------------------------|
| True density \( \left( 10^{-3} \text{g·cm}^{-3} \right) \) | Surface moisture content (%) | Water infiltrating length (cm) 5mins | Water infiltrating length (cm) 20mins |
| Yong Xia coal injection | 1.38 | 2.85 | 2.47 | 3.23 |
| Shen Fu gas coal | 1.49 | 12.93 | 0 | 0.76 |
| Lu Jing coking coal | 1.39 | 4.37 | 0 | 0 |
| Dolomite fines | 2.43 | 1.82 | 5.13 | 16.34 |
| Chile fine meal | 5.17 | 10.38 | 0.57 | 1.90 |
| Tubarao fines | 4.88 | 4.60 | 3.99 | 7.41 |
| PB fines | 4.39 | 1.42 | 25.65 | 102.6 |
Differences in materials have different water infiltrating properties, and under the working conditions, they also have different surface moisture. Surface moisture is an influencing factor of fugitive particle emission, and if the material has good performance on the infiltrating property, fugitive particle emission can be controlled well through aspersion or after raining.

Eight kinds of materials' water infiltrating properties are on behalf of water infiltrating length (Table 1). PB fines show a great advantage in water infiltrating property than other materials and mineral fines' water infiltrating properties are usually great 24.65 cm. But for Shen Fu gas coal and Lu Jing coking coal, they show little infiltrating property after 20 minutes experiment and Lu Jing coking coal is the worst one that its 24 hours infiltrating length is just 2.35 cm. These experiment results indicate that raining or aspersion may not have obvious effects for controlling Shen Fu gas coal and Lu Jing coking coal storage piles fugitive particle emissions. After the study of material particle property, we can summarise the Shen Fu gas coal and Lu Jing coking coal relatively have small true density and worse water infiltrating property than other materials and these properties may cause great fugitive PM pollutions. The further analysis focus on the SERs of 8 materials and the emission factors about SERs.

As stated above, Lu Jing coking coal belongs to the materials which have small true density and bad water infiltrating capacity. The higher PM$_{2.5}$ and PM$_{10}$ SERs of these two materials add weight to the above conclusion that the material with lower true density and worse water infiltrating capacity may cause greater fugitive PM pollution. As we know, the fugitive dust emission was related to the $u^*$ and surface moisture. The Fig.6 shows that the PM$_{2.5}$ and PM$_{10}$ SERs were positively correlated with $u^*$. 

4. Conclusions

There are certain differences between 8 kinds of typical material particles at the large union enterprises open storage piles in surface moisture content, water infiltrating property, true density, the particle size distribution and aerodynamic diameter distribution. We conclude that:

These data and the material particle properties they help to illustrate are important for environmental assessment and the enterprise environmental management on daily work and extreme weather conditions;

Comparing the eight kinds of material particle properties, the material which has lower surface moisture content and true density may generate higher fugitive dust emissions. The Lu Jing coking coal which has the lower surface moisture content, true density and higher content of fine dust particles should be seriously considered as the key fugitive dust pollution object. Its PM$_{10}$ SER and PM$_{2.5}$ SER are up to 71.8 mg·m$^{-2}$·s$^{-1}$ and 12.3 mg·m$^{-2}$·s$^{-1}$ ($u^* = 3.6$ m/s) much higher than the others (PM$_{10}$ SERs $\leq$ 10.0 mg·m$^{-2}$·s$^{-1}$, PM$_{2.5}$ SERs $\leq$ 1.0 mg·m$^{-2}$·s$^{-1}$, average $u^* = 3.3$ m/s).

Future work will focus on improving the measurement and technology to estimate fugitive dust emission more accurate and efficient, analysis of worksite fugitive dust emission and assess the fugitive PM$_{2.5}$ and PM$_{10}$ pollution to the ambient area environment.

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