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Characteristics and the Potential Influence of Fugitive PM₁₀ Emissions from Enclosed Storage Yards in Iron and Steel Plant

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Abstract: Fugitive particle emission of enclosed storage yards in iron and steel plant is a complicated and multivariable problem, which will have negative impacts on the environment and economy. Researchers have discussed methodologies of emission estimation in open storage yards, but rarely focused on enclosed ones. However, enclosed storage yards are commonly adopted in most industries in China. This paper links onsite observation and computational fluid dynamics (CFD) to estimate the impact of fugitive PM₁₀ emissions from enclosed storage yards on the open air. By collecting and analyzing PM₁₀ samples at three sites inside the yard and one site outside, The result shows that PM₁₀ concentration is in the range of 7.3 ± 1.5 – 13.4 ± 4.2 mg/m³, which is extremely high in an enclosed storage yard, and significantly influences workers' health inside and outside atmospheric aerosols. The CFD model simulation is conducted by considering particle deposition, particle emission sources of shovel loader and road dust emission, as well as different wind direction and wind speed. The result shows that PM₁₀ discharge rate from the enclosed area to open-air is significantly influenced by wind velocity and direction, e.g., the result of northwest wind with wind speed in 12.7 m/s is eight times higher than wind speed in 2.5 m/s with the same wind direction, and are 47 and 62 times higher than the east and west wind direction with the same wind speed in 12.7 m/s, respectively. In this case, the PM₁₀ discharge rate is about 131.7 ton/year, which contains about 38–55 ton/year iron-relating particles. This will directly contribute PM₁₀ to open-air and may produce secondary aerosols, due to heterogeneous catalytic reaction. This work identifies the important contribution of fugitive emissions and provides an approach for fugitive emission estimation of industries to the surrounding air. The results provide a reference for material yard zoning and fugitive emission control from minimizing influence from the meteorological condition and reducing source discharge inside.

Keywords: PM₁₀ emission; iron and steel plant; storage yard; CFD simulation; wind speed and direction

1. Introduction

China has increased emission of aerosols along with rapid economic development over the past three decades [1]. For example, more than 33% of aerosols were associated to industrial emission sources over the East China Sea, which have series of impacts on human health and atmospheric environment [2].

Centralized and fugitive emissions are two main atmospheric pollution sources over the industrial area. Atmospheric fugitive emission plays an important role in industrial air pollution, especially in iron and steel plants [3,4]. As reported, fugitive emissions contribute more than 60.5% of total

primary $PM_{2.5}$ from the iron and steel industry in 2012 in China, based on an estimation [5]. Moreover, fugitive emissions have been identified directly to be a major contributor to PM_{10} [6–8]. For example, Fe-rich particles present size distribution peaking at about 6 μm from ironmaking, steelmaking and coking process [9]. Fugitive emissions are generally caused by equipment leaks [10], raw materials handling, wind erosion effect around storage yards, etc. [11–14]. Many processes in iron and steel plants can produce fugitive particulate matter (PM), such as coking, pelletizing, sintering, blast furnace ironmaking, steel making, steel rolling, finishing process and slag treatment etc. [4,11,15].

The material storage yard is one of the main area sources of primary fugitive PM emission in iron and steel plant, e.g., every production process in the storage yard of steel plants will generate emission, like material piling and feeding, transport process, traffic around, etc. [16]. In recent work, it was found that lots of dust emissions will be generated in an open storage yard under certain wind condition with CFD model [17]. However, almost all the storage yards have been enclosed among iron and steel plants in BTH area for the local environmental requirement. The enclosed yard will help reduce wind erosion emissions from outside material piles. Hence, the fugitive emission from enclosed storage yards was neglected by people. While piling and feeding process can generate lots of PM, and will discharge to the ambient atmosphere from entrances and vents normally open. Moreover, the impact of fugitive emission from enclosed storage yards on the open-air have rarely been reported.

Therefore, we conducted onsite observation and CFD simulation on the characteristic of fugitive PM in an enclosed storage yard, in order to investigate the influence of fugitive PM from enclosed storage yards to open air. This work provides a chance to show the situation of undervalued emission in material enclosed storage yards. It also reveals the emission source control is a key issue for reducing PM_{10} fugitive emissions in the industrial area, and will support the enclosed storage yard builders to consider more meteorological conditions to minimize the PM_{10} emission rate.

This study provides a decent way of considering major pollution sources in an enclosed storage yard. Moreover, it helps find a reasonable path for estimating fugitive discharge rate in the enclosed storage yards of steel plants. The emission rate of the dust source is calculated at the scale of annual average, so it might be advisable to assess the average situation of fugitive emission of the entire storage yard. Whereas, the method in this work is not appropriate to assess the transient situation.

2. Materials and Methods

2.1. Sample Collection and Analysis

The PM samples were collected at one enclosed storage yard of iron and steel plant (36.73° N, 113.93° E) in Hebei province in China (Figure 1). Sampling site-1 was set near the sinters loading area, site-2 was in the middle of the yard, site-3 was within 30 m of Gate 1 inside the yard, and site-4 was set in the outside of the yard and adjacent to the entrance Gate-1 (Figure 2). PM_{10} samples were collected using a medium volume sampler (100 L·min⁻¹, Laoying 2030 AIR PARTICLE SAMPLER). Particles were collected on Whatman® 41 cellulose filters with a duration of 1 hrs for each sample. 44 PM_{10} samples were collected, including blanks in total during 07:00–18:00, on 29 April 2019.

1/8 of the sample (PM_{10}) and blank filters were cut and digested with 10 mL nitric acid in a microwave digestion system. Then each sample was diluted by Milli-Q water (18.25 M Ω ·cm⁻¹) with a constant volume of 25 mL. Element contents were determined using an Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES, PE Optima 8000), and detailed procedures for analysis of elements were given in previous studies [10,18]. Main component of air dust are Al, Ca, Si, Mg, Fe, Mn, K, Ti, Na, and Zn [18]. In this paper, air dust came from plant and steel plant-and as a result, Fe and Ca content were very high. Therefore, all these elements were analyzed, and some elements with minor content, such as Cu, Ni, Co, Cd, were ignored.

Figure 1. (a) Map of storage yard of iron and steel plant with accurate coordinate; (b) practical scenery of storage yard inside.

Figure 2. (a) Target enclosed yard for this work; (b) sampling site for onsite observation and horizontal plane at 3m above the ground in research area.

2.2. CFD Simulation

2.2.1. Modeling Method

COMSOL Multiphysics is a general-purpose simulation software based on finite element method and partial differential equations. It is commonly used in modeling processes in all fields of engineering, manufacturing and scientific research. COMSOL Multiphysics is used in this research to perform 2D numerical simulation on wind field and PM_{10} concentration distribution in the enclosed stockpile yard under various wind conditions. The horizontal plane at 3 m above the ground is selected as the research plane. Figure 2 was introduced to COMSOL as the layout of the research area.

There are five gates in this enclosed stockpile yard—each 15 m in width. A section of road, which is 20 m in length and 5 m in width, is set inside each gate to generate road dust caused by traffic. The yard is supported by eight square pillars with a side length of 7 m. The side wall of the yard is 0.1 m in thickness. The raw materials are separated and stored in three piles. Pile 1 stores sinters, pile 2 and

pile 3 stores iron ore powder. There is 1 shovel loader loading point in pile 1 and pile 2. There are 2 shovel loader loading points in pile 3.

2.2.2. Governing Equations

The simulation process was completed by the mixture model in the CFD module. The standard k- ε model was accepted as the turbulence model after considering the model application, accuracy and computation load. The set of control functions used in the model are [19]:

The continuity Equation:

$$\nabla u = 0 \quad (1)$$

The turbulent motion Equation:

$$\frac{\partial(u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\mu}{\rho} \frac{\partial^2 u_i}{\partial x_i \partial x_j} - \frac{\partial(\overline{u_i' u_j'})}{\partial x_j} + f_i \quad (2)$$

The transport Equation for k :

$$\rho(u \cdot \nabla)k = \nabla \cdot \left(\left(\mu + \frac{\mu_T}{\sigma_k} \right) \nabla k \right) + P_k - \rho \varepsilon \quad (3)$$

The transport Equation for ε :

$$\rho(u \cdot \nabla)\varepsilon = \nabla \cdot \left(\left(\mu + \frac{\mu_T}{\sigma_\varepsilon} \right) \nabla \varepsilon \right) + C_{\varepsilon 1} \frac{\varepsilon}{k} P_k - C_{\varepsilon 2} \rho \frac{\varepsilon^2}{k} \quad (4)$$

The turbulent viscosity was modeled as

$$\mu_T = \rho C_\mu \frac{k^2}{\varepsilon} \quad (5)$$

The production term was modeled as

$$P_k = \mu_T \left(\nabla u : \left(\nabla u + (\nabla u)^T \right) \right) \quad (6)$$

Notation used refers to:

ρ	Density
u	Velocity
P	Pressure
T	Temperature
μ_T	Dynamic viscosity
k	Turbulent kinetic energy
ε	Turbulent dissipation rate

The model constants in Equations (4) and (5) are

$$C_{\varepsilon 1} = 1.44, C_{\varepsilon 2} = 1.92, C_\mu = 0.09, \sigma_k = 1, \sigma_\varepsilon = 1.3$$

2.2.3. Boundary Conditions

The inlet boundary condition is the velocity field of a certain external wind field. According to local meteorological radar observation result, the atmospheric boundary layer is approximately

100 m. The wind speed at the research plane is calculated by logarithmic wind profile under neutral stratification condition as Equation (7) [20], using local wind speed data measured at 10 m above ground.

$$\bar{U} = \frac{U_*}{\kappa} \ln \frac{z}{z_0} \quad (7)$$

Notation used refers to:

- $\bar{U}$ Average wind speed at the research plane
- U_* Friction velocity
- κ Von Karman constant
- z Height of the research plane
- z_0 Roughness length

The boundary condition of turbulent kinectct energy k and the energy dissipation rate ε is set based on previous research data [21]. The outlet boundary condition is fixed to be 101,325 Pa. No-slip boundary condition is applied to all the gas-solid interface.

The momentum flux to the walls obeys the wall-function method [19].

$$\frac{U_P}{(\tau/\rho)_W} C_\mu^{1/4} k_P^{1/2} = \frac{1}{\kappa} \ln \left(E y_P \frac{C_\mu^{1/4} k_P^{1/2}}{\nu} \right) \quad (8)$$

Notation used refers to:

- U_P Time-average velocity of the fluid at a point P adjacent to the wall
- τ_W Shear stress on the wall in the direction of the velocity U_P
- ν Kinematic viscosity
- y_P Distance of the point P from the wall
- E A function of the wall roughness

2.2.4. Solution Procedure, Computational Grid, Convergence and Time Requirements

The typical CPU time for a full simulation process varies from 369 s to 448 s, depends on the boundary conditions. The computer used to solve the model was equipped with an Intel Core i7-7700HQ processor @2.80 GHz with four cores and 16 Gb of RAM, over Windows 10 64 bits. A general convergence plot of the segregated solver is given as Figure 3. A mesh with normal element size in COMSOL consisting of triangles and quads was created for the simulation (Figure 3), which contains 71133 elements. The grid convergence index was calculated to be 0.15%.

Figure 3. (a) Convergence plot for a typical simulation process; (b) computational grid.

2.2.5. Fugitive Dust Sources

Shovel Loader

The fugitive dust emission rate from the shovel loader loading process was estimated according to Technical Guidelines for Compiling Emission Inventories of Particulate Matter from Fugitive Dust Sources (Technical Guidelines) [22]. The parameters in the function were obtained from the average hourly value in the enclosed yard, measured on 29 July 2019. The workload on that day is representative of the workload on a routine workday.

The emission factor was calculated as:

$$E_h = k * 0.0016 * \frac{\left(\frac{u}{2.2}\right)^{1.3}}{\left(\frac{M}{2}\right)^{1.4}} * (1 - \eta) \quad (9)$$

- E_h Emission factor of the loading process (kg/t)
- k Granularity factor, 0.35 for PM₁₀
- u Average wind speed (m/s), obtained from CFD simulation result
- M Moisture content, 0.1% for sinters and 8% for powdered iron
- η Removal efficiency of related dust control method (0 in this case)

The time interval between two loading actions was 60 s. The amount of raw material fed at one loading action was estimated to be 6 metric ton. The emission rate Q_h (kg/s) was eventually calculated as:

$$Q_h = \frac{E_h * 6}{60} = k * 0.00016 * \frac{\left(\frac{u}{2.2}\right)^{1.3}}{\left(\frac{M}{2}\right)^{1.4}} * (1 - \eta) \quad (10)$$

Road Dust Emission

Road dust from inside the enclosed yard was neglected, since sprinklers will humidify the road regularly. Whereas, the sprinklers do not cover the road near the gate. The traffic through the gate trampled the larger particle into smaller particle. The fugitive dust emission rate of the road by the gate was estimated according to Technical Guidelines [23].

The road emission rate was calculated as:

$$Q_R = E_R * L_R * N_R * 10^{-3} \quad (11)$$

- Q_R Road dust emission rate (kg/s)
- E_R Average emission factor of road dust (g/km)
- L_R Road length (km)
- N_R Number of passed vehicle per second

For paved road, the average emission factor of road dust was calculated as:

$$E_R = k * (sL)^{0.91} * (W)^{1.02} * (1 - \eta) \quad (12)$$

- E_R Emission factor of the road dust (g/km)
- k Granularity factor, 0.62 for PM₁₀
- sL Dust load of the road, 10 g/m² (as onsite measurement)
- W Average vehicle weight, 60 metric ton.
- η Removal efficiency of related dust control method (0 in this case)

2.2.6. Particle Deposition

When the wind speed is low, the particle residence time gets longer. The contribution of particle deposition to concentration decrease cannot be neglected. In this research, the average PM₁₀ deposition velocity was obtained from Lin Guo's research [18], which is 0.57 cm/s (An average value for $D_p < 10 \mu\text{m}$).

3. Results and Discussion

3.1. PM Characteristics of Enclosed Yard

The mass concentration of each sampling site of PM₁₀ and total elements were shown below (Figure 4a). The result of fugitive PM₁₀ at site-1, site-2, site-3 and site-4 were $13.4 \pm 4.2 \text{ mg/m}^3$, $9.6 \pm 1.6 \text{ mg/m}^3$, $7.3 \pm 1.5 \text{ mg/m}^3$ and $2.1 \pm 1.5 \text{ mg/m}^3$, respectively. Sinter continued to be fed at sinter loading area during the sampling period. Site-1 was close to this handling area so that site-1 could be most influenced by the material operation-hence, PM₁₀ concentration at this site was the highest. The PM₁₀ concentration decreased gradually from site-2 to site-4. Site-4 was impacted by both the discharge from enclosed yard and ambient air dilution, corresponding with the lowest PM₁₀ concentration. However, the average level of PM₁₀ of inside enclosed storage yards is so high that it will have significant influence workers' health in this area. People working in an environment with high dust concentration tend to get a serious pulmonary disease, like pneumoconiosis [23]. The high diagnosis rate of multiple sclerosis was found in a Turkish city adjoining an iron and steel plant, which supports a link between PM₁₀ and the changes of tissues [24].

Figure 4. (a) Concentration of PM₁₀ at each site; (b) element contents at each site.

According to the result of component analysis, Fe, Ca, Si, Al, and Mg were the major elements in PM₁₀ in the storage yard (Figure 4). Fe was the most abundant element in PM₁₀ content, and Ca came next. This result was close to the chemical property of fugitive particles from sintering process [25]. In this work, Fe content fell in the range of 286–419 mg/g in PM₁₀, and Ca fell in the range of 47–66 mg/g. This is because that the material fed in the yard was sinter, which was the main source of the fugitive PM emission. Other material feeding and piling area had little PM emission load, because iron ore powder has higher water content (about 8–10%). Therefore, in fugitive PM₁₀ emission in this yard, accumulated Fe was originated from sinter, and relative high Ca content was due to calcined lime required in sintering process [26,27]. Other elements like Si, Al, Mg, etc., were from crustal substances and additives like dolomite (a kind of fusing agent) in the sinter burdening process.

From Figure 4, the element content difference of site-1 to site-3 was relatively consistent. This was because all these three sites were affected by emission sources and airflow transportation. The element concentration reduced gradually along with the distance to the emission source. Lowest element concentrations were found in site-4, due to the impact of the outside environment. Fe contributed to almost $\frac{1}{2}$ of PM₁₀ concentration in site-1, site-2 and site-3, with 49%, 55%, and 57% Fe-relating fractions,

respectively. Fe content of 108.7 mg/g was found in PM₁₀ (with about 22% contribution) at site-4, due to complicated airflow and multiple impact factors from the outside environment.

3.2. Test of Simulation Results

The onsite measure data is compared with the simulation results to test the modeling process. Table 1, which provides the input wind field condition for the model, contains the average wind speed and wind direction data of each sampling period. The data is obtained from meteorological data of local monitoring site and a meteorological data sharing website [28].

Table 1. Average wind speed and wind direction data of each sampling period.

Sampling Period	Wind Direction (°)		Wind Speed (m/s)	
8:00–8:50	S	180	light air	0.5
9:00–9:50	S	180	light breeze	2.5
10:00–10:50	NE	45	fresh breeze	9.4
11:00–11:50	S	180	light air	0.5
13:00–13:50	N	0	light air	0.5
14:00–14:50	NE	45	fresh breeze	9.4
15:00–15:50	NE	45	fresh breeze	9.4
16:00–16:50	S	180	light breeze	2.5
17:00–17:50	N	0	light breeze	2.5

The temperature and relative humidity (RH) along with direction and velocity is shown as Figure 5A. After considering factors like temperature and RH by model analyzing. It was found that the relative difference of PM concentration caused by 20 °C ΔT is less than 10^{-6} . A similar result is found in RH. Therefore, the effects of temperature and RH on the simulation result are negligible. The correlation between measured and simulated data was shown below (Figure 5B). The relationship was good between observation in this case, and the model result. The correlation coefficient is about 0.7243 and passed the significant test (Sig. < 0.001).

The PM₁₀ concentration of the modeling result is the average value of the surrounding 25m². Figure 5C shows a comparison between measured value and modeling result. The trend of the two types of data is identical, especially at site-1 and site-2. It means that the mainly fugitive PM₁₀ sources were material loading process and road dust emissions in material enclosed storage yards, and wind erosion had very little impact on the emission. This result reveals the emission source control, such as material loading process and road dust emissions control, is a key issue for reducing PM₁₀ fugitive emissions in the industrial area. At site-3 and site-4, the trend of modeled PM₁₀ concentration is similar than measured one. While the concentration from the simulation is generally higher than measured one, this might be caused by the exclusion of vertical wind speed during 2D simulation. Vertical motion of the particles is not well assessed except for normal deposition.

3.3. Wind Field of Enclosed Stockpile Yards

From the simulation result of the wind field in an enclosed stockpile yard (Figure 6), the yard wall exhibits great obstruction to the outside wind. Multiple simulations, under the same wind direction, have proved that wind speed has little effect on relative wind field distribution inside the enclosed yard. The yard is a distorted rectangle shape. The gates are distributed on two opposite walls. There are no gates on the west wall and the east wall. When the wind direction was perpendicular to the gate, it would generate strong airflow in the enclosed yard. When the wind direction was parallel to the gate, the airflow in the enclosed yard was weak.

Figure 5. (A) Time series of temperature, relative humidity (RH), direction and velocity. (B) The correlation between measured and simulated data. (C) Comparison of measured and modeling PM_{10} concentration at each site.

Figure 6. Wind field inside the enclosed yard under external wind from (a) north; (b) north-east; (c) east; (d) south-east; (e) south; (f) south-west; (g) west; (h) north-west.

The Coanda Effect was observed from the wind field simulation. The airstream tended to flow along the side wall when its flow direction was approximately parallel to the wall.

Under the northwest wind direction, the stockpiles and the loading area were directly exposed to the airstream through the gates, creating favorable conditions to generate dust. In order to reduce the airflow at the stockpile and loading area, local prevailing wind direction should be taken into consideration during the construction and zoning of an enclosed yard.

3.4. PM_{10} Distribution Simulation

The background PM_{10} concentration used in particle concentration simulation was 0.143 mg/m^3 , according to the local annually average PM_{10} concentration of 2018. The PM_{10} concentration distribution varies with wind speed and wind direction (Figure 7). Moreover, the PM_{10} concentrations over each gate were calculated under different external wind conditions according to fugitive PM_{10} emission source intensity in result of Section 3.2 (Table 2). When the inside wind field was significantly affected by outside wind, e.g., north and south wind, fugitive PM_{10} would spread outside the yard soon after it was emitted, causing pollution to the external environment. When the inside wind field was slightly affected by outside wind, fugitive PM_{10} would be detained in the enclosed yard. The internal PM_{10} concentration would increase. However, if the fugitive emission could not be effectively controlled, the whole yard would turn into a secondary fugitive emission source when the wind direction changes.

Figure 7. The PM_{10} concentration distribution at a wind speed of 6.7 m/s under different wind direction: (a) north; (b) north-east; (c) east; (d) south-east; (e) south; (f) south-west; (g) west; (h) north-west. (Different wind speed will lead to different PM_{10} concentration distribution in the enclosed yard, here only shows the result with a wind speed of 6.7 m/s.).

Table 2. PM₁₀ concentrations under different external wind condition at each gate.

Wind Direction	Wind Speed (m/s)	PM ₁₀ Concentration (mg/m ³)				
		Gate1	Gate2	Gate3	Gate4	Gate5
N	0.5	8.7	13.2	21.1	0.143	0.143
	2.5	12.9	14.3	10.4	0.143	0.145
	4.4	14.2	15.4	10.7	0.145	0.145
	6.7	16.7	17.9	12.7	0.144	0.143
	9.4	19.0	20.2	13.3	0.144	0.143
	12.7	20.9	22.1	15.0	0.144	0.145
NE	0.5	8.0	16.0	16.5	0.6	0.4
	2.5	8.5	13.2	10.9	0.4	0.6
	4.4	9.1	10.3	4.8	0.2	0.9
	6.7	10.0	11.1	5.3	0.2	1.1
	9.4	10.6	11.6	4.8	0.2	1.2
	12.7	8.8	9.5	3.8	0.2	1.0
E	0.5	10.2	21.4	68.1	97.5	14.0
	2.5	2.8	5.4	17.2	28.4	4.6
	4.4	2.0	3.6	10.9	18.4	3.4
	6.7	1.7	2.8	8.0	13.5	2.9
	9.4	1.5	2.3	6.4	10.6	2.5
	12.7	1.2	1.8	5.0	8.3	2.1
SE	0.5	14.9	22.6	8.2	21.8	6.8
	2.5	11.8	16.9	1.8	10.1	5.4
	4.4	19.0	27.0	1.1	13.4	8.9
	6.7	24.0	30.4	1.1	14.7	8.8
	9.4	20.8	29.6	0.6	14.3	10.6
	12.7	21.8	31.1	0.5	14.8	10.9
S	0.5	0.177	0.147	0.148	18.1	31.2
	2.5	0.143	0.143	0.143	5.0	9.7
	4.4	0.145	0.143	0.145	5.4	15.1
	6.7	0.144	0.145	0.145	4.7	15.8
	9.4	0.144	0.144	0.143	3.2	13.6
	12.7	0.143	0.144	0.143	2.5	13.0
SW	0.5	0.4	0.2	43.8	18.3	11.6
	2.5	0.7	0.1	9.2	10.0	10.7
	4.4	1.3	0.1	5.6	16.0	20.8
	6.7	1.5	0.1	3.9	18.0	24.7
	9.4	1.4	0.1	2.9	17.3	23.7
	12.7	1.5	0.1	2.3	17.3	23.6
W	0.5	66.2	46.0	38.5	95.2	14.7
	2.5	20.1	16.2	8.9	31.1	5.0
	4.4	13.5	10.6	5.3	20.9	3.6
	6.7	10.5	7.9	3.7	15.6	2.9
	9.4	8.7	6.4	2.9	12.6	2.5
	12.7	7.6	5.4	2.4	10.6	2.2
NW	0.5	14.3	14.9	22.2	5.4	1.1
	2.5	36.6	34.2	13.4	1.8	1.6
	4.4	46.3	42.7	13.6	1.4	2.0
	6.7	48.2	46.2	7.8	0.6	1.9
	9.4	58.5	54.4	13.5	1.0	2.4
	12.7	64.2	59.7	14.5	1.0	2.6

PM₁₀ discharge rate from the enclosed yard was simulated based on local historical meteorological data, using below method:

$$Q_P = \sum_{n=1}^{N_d} \int_{D_n} H_n c u \sin \theta \quad (13)$$

Q_P PM₁₀ discharge rate of enclosed yard (mg/s)

N_d Number of gates

D_n The nth gate

H_n Height of the nth gate, 6 m in this case

c PM₁₀ concentration at the nth gate (mg/m³)

u Air velocity at the nth gate (m/s)

θ Included angle between airflow direction and extension line of the gate

Under the same external wind direction, there was a positive correlation between external wind speed and PM₁₀ discharge rate (Figure 8). Meridional wind-generated far more PM₁₀ discharge than zonal wind under the same external wind speed. The yard discharged most PM₁₀ under northwest wind (NW). From Figure 6h, when the external wind blows from the northwest, the inflow through gate 5 blew directly towards the sinter loading area. The local air velocity at the loading area was significantly greater than average level, leading to the peak value of 39.1 g/s in PM₁₀ discharge rate at wind speed 12.7 m/s. This level was eight times higher than wind speed in 2.5 m/s with the same NW wind direction. In contrast, the entire enclosed yard was under the static condition when the wind blows zonally. Air velocity at loading area was at the same order of magnitude as deposition velocity at this time, so the PM₁₀ discharge rate became small, e.g., under east and west wind direction, PM₁₀ discharge rate were 47 and 62 times lower than NW wind with the same wind speed in 12.7 m/s, respectively. Therefore, PM₁₀ discharge rate from the enclosed area to open-air is significantly influenced by wind velocity and direction.

Figure 8. PM₁₀ discharge rate under different external wind condition.

We estimated this enclosed storage yard discharged about 131.7 ton/year PM₁₀ to the outside atmospheric environment (Table 3) using local meteorological data of 2018 as calculation conditions. This amount of PM₁₀ could contain 38~55 ton Fe-related particles. Moreover, Fe-contained particles will promote secondary aerosols generation and lead to worse air quality. For example, the heterogeneous

reaction can occur on HCOOH gas and produce HCOO^- on the surface of $\alpha\text{-Fe}_2\text{O}_3$, and part of HCOO^- could be decomposed into CO_2 when SO_2 gas exists [29]. In addition, the heterogeneous reaction can also occur with the presence of both SO_2 gas and ambient $\alpha\text{-Fe}_2\text{O}_3$ aerosols, producing SO_4^{2-} [30], which is one of the major anthropogenic pollutants over East China. By this principle, at least 3700 ton/year SO_4^{2-} and 0.83 ton/year Fe (II) ion will be produced in this research case [31]. This could be one of the reasons that soluble-Fe was found higher in anthropogenic aerosols [31,32].

Table 3. Estimated PM_{10} discharge level of the enclosed storage yard under different wind speed and wind direction in 2018.

Wind Direction	Daily PM_{10} Net Emission Rate (t/d) and (Cumulative Days)				
	0.5 m/s	2.5 m/s	6.7 m/s	9.4 m/s	12.7 m/s
N	0.06 (61)	0.22 (65)	0.76 (44)	1.17 (7)	1.63 (3)
NE				0.48 (1)	
E		0.05 (1)			
S	0.14 (53)	0.21 (73)	0.77 (44)	0.87 (7)	
SW	0.05 (1)				
W	0.02 (1)		0.04 (1)		
NW		0.41 (1)	1.36 (1)	2.36 (1)	
Yearly Total PM_{10} discharge amount				131.7 (t/year)	

Therefore, the fugitive emissions from enclosed storage yards is not only discharging PM directly to atmospheric environment, but also contributing indirectly to expediting secondary aerosol production. As a result, a series of reactions may have an impact on regional biogeochemistry cycles by providing kinds of nutrients and toxic substances [32].

4. Conclusions

This work investigated the fugitive PM_{10} emission level via onsite observation in a certain enclosed storage yard of an iron and steel industry. It is found that the fugitive PM_{10} emission was significant from enclosed storage yards in the iron and steel industry. Iron-relating particles were the major components in PM_{10} from enclosed storage yard emissions, which might lead to more reactions and effects in the atmosphere. Material loading process and road dust emission were two mainly emission sources for fugitive PM_{10} in the enclosed storage yard. PM_{10} concentration distribution and discharge rate were significantly affected by wind direction and wind speed. Therefore, we suggest taking more effort to enhance controlling measures for fugitive emissions of industries. Furthermore, this work provides an approach for assessing the fugitive discharge load.

This work is limited by the factory's operational conditions so that we could only set four sites for PM_{10} samples collecting, and the observation period is one day. These factors could lead to an error in the PM_{10} annual level evaluation. Moreover, this work was using two-dimension (2D) flow field analysis, which ignored the influence of airflow in three-dimension (3D) space. We will improve our research to consider 3D analysis and complete more influence factors to estimate fugitive emission accurately in future works.

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