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Research into Haze Removal Method Based on Diffusion and Relative Motion

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ABSTRACT

A method for purifying polluted air in large open space was proposed and verified based on concentration gradient diffusion theory and relative motion principle of purifying device to polluted air. As to the sources of particle emitting, the purifying device works as a sink no matter it is moving or not. Both indoor and outdoor experiments have been made. In the indoor experiment, severe haze environment was simulated by fuming. The purifying device was made of metal wire and carbon cloth. The fixed device took 2.7, 6.2 and 13 minutes to reduce the particle concentration in the 7 m farthest corner of the laboratory to 50%, 20% and 0 respectively. By moving the device at 1 m s^{-1}, the concentration could be reduced to 50% in merely 15 seconds. In outdoor experiment, 23.5% decrease of haze concentration was measured.

Keywords: Concentration gradient; Diffusion; Relative motion; Haze removal.

INTRODUCTION

The formation mechanism, component distribution, and migration characteristics of haze, and their influence on the environment and human health have attracted increasing research attention, especially in China (Poynting, 1889; Owens, 1927; Xiao *et al*., 2011; Lin *et al*., 2012; Wu, 2012; Park *et al*., 2013; Zhang *et al*., 2013; Chen *et al*., 2014; Huang *et al*., 2014; Zhou *et al*., 2014). In recent years, China has made significant effort in the fight to control haze by reducing polluting emissions. Some haze removal methods have been proposed, such as buried ground coil, spraying liquid carbon dioxide in air, fog artillery, urban ventilation channels and so on (Xin, 2013; Editor, 2014; Wang, 2014). Although haze removal is important and has attracted global research attention, fewer research achievements have been made in fact. Those methods abovementioned have yet to be mature due to their less ideal effects or prohibitive cost. Up to now, there is no paper which is focus on haze removal published in the world.

Haze control by the inhibition of the emission of fine particle (particulate matter/$PM_{2.5}$) is urgent. But unlike developed countries, it is not the best-suited and well-timed solution in some developing countries, such as China. Because of vast, huge population, variety of resources and complex national conditions, haze removal technologies are necessary. In addition, even though the haze can be controlled by only reducing emission from all of the various pollutant sources, people maybe still have to live in polluted air for 10, 20, or even 30 more years. Furthermore, due to the particle collection become increasingly less efficacious in a high collection efficiency condition, to capture a small amount of $PM_{2.5}$ needs a huge amount of cost. Taking a typical power plant in China as an example (Xin, 2013), the cost of decreasing standard emissions from about 50 mg m^{-3} to 20 mg m^{-3} is nearly equal to that of from 50 g m^{-3} to 50 mg m^{-3}, while the benefits decrease 400 times. However, better overall air quality can be achieved at the same cost for air-borne haze removal. Here, the removal refers to those hard purified particles generated by vehicle exhaust, dusts resulting from transportation and construction activities, smog and dust produced by industrial discharge, etc. So, some methods of removing $PM_{2.5}$ from air require to be proposed.

Although haze removal and industrial dust collection both are to separate solid particles from air, they are different. The particle concentration in industries reaches to about 50 g m^{-3}, while a concentration of 500 µg m^{-3} is considered to be heavy haze (Wang, 2014). The difference is about 100, 000 times. Even though one billion particles with a size of 1 µm are more visible than that of a particle with the size of 1 mm, their volumes and masses are same. Hence, unlike industrial collection device, haze removal device (purifying device) only takes up little surface area. For the sake of being simple, the purifying device can be designed as a no shell electrostatic precipitator. Metal mesh or carbon fibre sheet with coarse aperture can therefore be applied as absorption surface to reduce wind resistance and cost. In addition, the electrostatic precipitator merely required a half-electric field rather than three or four electric fields, but the windward area affected increases significantly.

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This study proposed two haze removal methods (as following) and verified their principles in an airproof laboratory and an outdoor experimental site in Cangzhou, Hebei Province, China.

A. Haze Removal Based on Diffusion

Similar to Brownian diffusion of molecules, fine particles also show intensive concentration gradient diffusion (Lin *et al*., 2007; Lin *et al*., 2009). Because of the concentration gradient, after the haze particles which is near purifying device are removed, the particles at a distance are likely to move to the device and then removed. Therefore, purifying devices, sometime as a long folding screen, can be set in suitable locations such as the roof-space in buildings, combined with advertising light boxes, on exterior walls, along the boundary of parks, etc. If the number of purifying devices are enough, they are expected to decrease the $PM_{2.5}$ significantly. In the case of an available wind and temperature gradient, air flow tends to strengthen the purifying effects. Based on prevailing wind directions, the wind transports polluted air into purifying devices.

B. Haze removal Based on Relative Motion

Usually, a purifying process for polluted air requires collection, pressure, and transportation. However, this traditional method is ineffective when controlling polluting air in large, open spaces. For this condition, the moving direction can be changed from device to polluted air. A light haze removal device can be made by getting rid of the shell of electrostatic precipitator, keeping half of electric field, enlarging windward area, using carbon fibre frame and using coarse carbon fibre sheet as collection plate. Then, the huge haze removal net moved forward by a remote-controlled airship, or by airborne balloons accompanied by dragged vehicle on the ground. In this case, although the haze net fails to achieve complete spatial coverage, the diffusion effects can decrease the heavy haze concentration to a certain extent.

METHODS

Laboratory Research

The laboratory had an area of 7 m × 7 m and was about 3 m in height. The experimental process is shown in Fig. 1. The experimental model - purifying device was 1.5 m in height, 1 m in depth and 3 m in width, had six channels, which were 500 mm wide. Each channel was equipped with two discharge electrode wires which were made of metal helical wire and therefore there were 12 wires in total. Seven carbon fibre sheets measuring 1 m × 1.5 m were used as collection surface. The volume of the purifying device was about 3.1% of the room total volume.

The smog was produced by burning the smog block used in fire control exercises. The blocks were made of sawdust, sulphur, combustion improver, adhesive, etc.

The power was provided by a 100 kV/10 mA high-voltage silicon rectifier controllers by employing a Q4-V electrostatic voltmeter for conducting voltage test, and a 4 1/2 multi-meter for current test.

To obtain information about the particles, both a PDSA-2 system and 3 AQM-8000 systems were used as the particle concentration measurement instruments. The former was a Phase-Doppler Sizing Anemometry which was applied to measure the photoelectric current signals representing particle concentration. The latter was an on-line system for monitoring air quality ($PM_{2.5}$ concentration) by testing the difference of laser scattering amount in the instrument chamber. Both instruments showed consistent trends in variation, but the latter had a more obvious delay. In this research, the photoelectric current information was used to investigate particle concentration changes over time, while the $PM_{2.5}$ concentration information was used to analyse the concentration change both temporally and spatially.

Outdoor Research

Experiments were carried out in Cangzhou, Hebei Province, China. The site was an L-shaped yard, surrounded by the workshops of factories. The relationship between the experimental model (purifying device), measurement instruments, and surrounding edifices is shown in Fig. 2.

The purifying device consisted of RS tubular barbed wire and two types of wire meshes. The RS barbed wire were hung on the upper mesh, which was insulated from, and fixed to, the walls on both sides using plastic plates; while the wire meshes were fixed to the ground directly. For the meshes, the diameter and the interval of the wires were 1 mm and 5 mm, and the other is 1.8 mm and 25 mm respectively. In this experiment, 48 m RS barbed wire and a total wire mesh area of 38 m^2 were used.

A high voltage power unit was applied to provide the power for purifying device.

The AQM-8000 on-line system was also used to monitor the air quality. As shown in Fig. 2, the measurement instruments ($PM_{2.5}$ monitor) were set on both sides of the purifying device at a spacing of 3 m.

RESULTS AND ANALYSIS

Particle Concentration Change with Time in Still Air

The purifying device was placed in the middle of the room, and the PDSA-2 system was set on one side of the

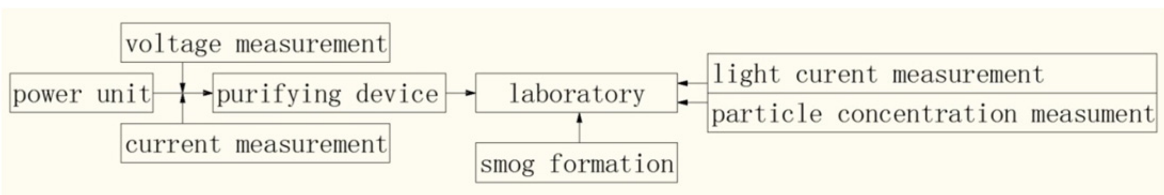


Fig. 1. Experiment procedure.

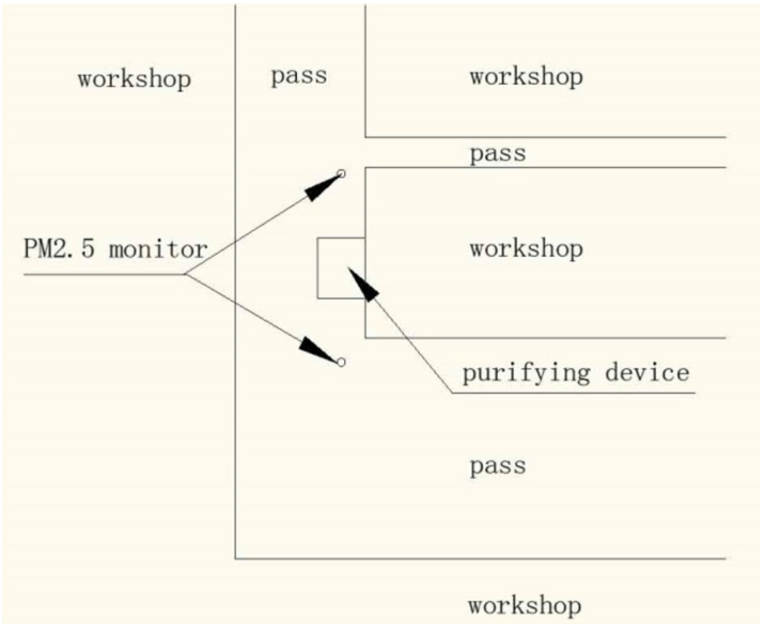


Fig. 2. Outdoor Experimental position.

room, 3 m from the purifying device. Before burning smog block, all of the windows and doors were closed and sealed to ensure no particle leaking out and no wind in the room. After the smog was dispersed uniformly, the prevailing conditions were allowed to reach static equilibrium for at least 30 minutes, to guarantee there is no change. Then start-up of the purifying devices was conducted with their applied voltage of 50 kV and current of 8 mA. The time was set to zero. The comparison images before and after start-up 3, 6, and 10 minutes are shown in Fig. 3 respectively. The variation of photoelectric current is shown as Table 1, where 0 is the start-up time; while –1 denotes the condition before the production of smog.

The decreasing particle concentration with time can be seen from Fig. 3 and Table 1. Based on Table 1, it can be calculated that it took about 2.7 minutes for the concentration to decrease to 50%, 6.2 minutes to 20%, and 13 minutes to reach the state before production of smog. The purifying ability decreased with time: the lower the original concentration, the longer the time taken by a given purifier set-up.

The decrease of particle concentration far from the purifying device in a sealed room indicated that fine particles showed strong diffusion capabilities. The fine particles' concentration in air was likely to be uniform. The particle which is remote from a purifying device could be removed from the polluted air. The experiments were repeatedly conducted in morning, afternoon, and evening, and basically consistent relationships were obtained wherein the flows caused by room temperature gradient could be excluded. Furthermore, though the ionic wind in static fields disturbed the surroundings, its contribution to the air in the room was negligible due to its low velocity and amplitude. Moreover, because there is no any swing at other instruments' cover fibre in the room before and after the start-up of the purifying device, it was inferred that there was no apparent air flow in the room. Hence, the particle motion merely involved the diffusion velocity instead of the entrainment of the surrounding air. In fact, the operation of the purifying device informed us that its purifying effects would be better if there is a turbulent transfer of particle in an environment with a certain wind speed.

Particle Concentration Change with Time for the Relative Motion of Purifying Device to Air

By using the aforementioned experimental methods, the purifying devices were powered on and moved at a speed of 1 m s^{-1} for 15 s to cover the room area. The particle concentration reduced to 50% approximately.

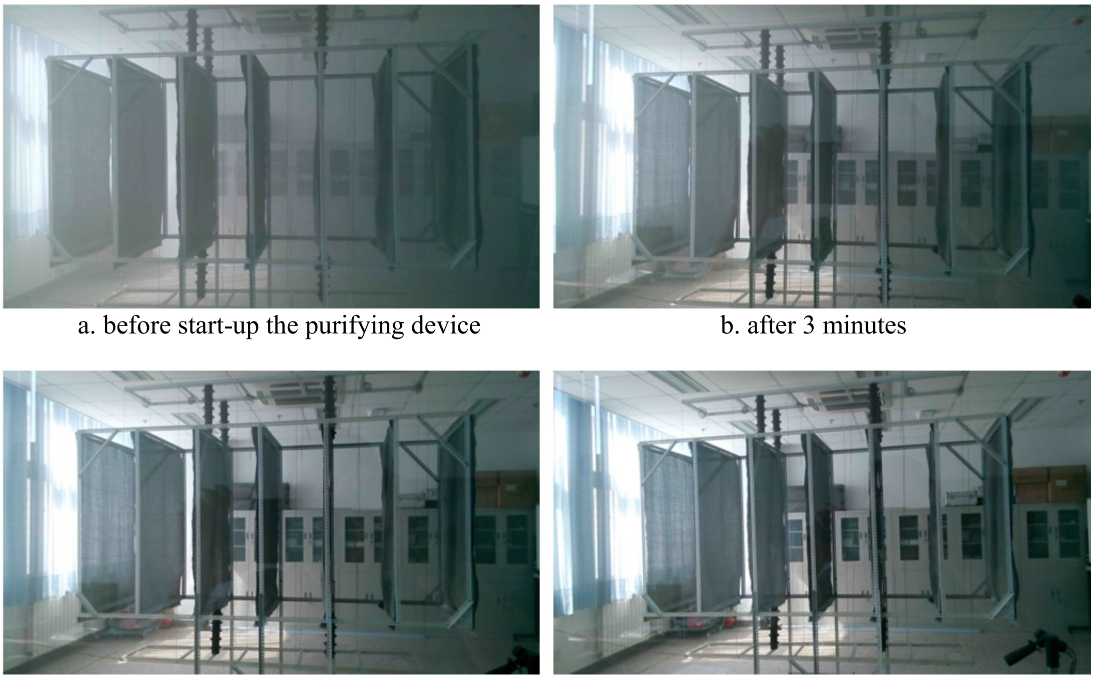
It was observed that the purification caused by direct contact was far higher than that resulting from the scattering of particles. The particles within the purifying device can be removed rapidly at any time. To achieve the same purifying effect, the method took less time than that using a fixed purifying device.

By using the method, the horizontal sweeping motion of the purifying device resulted in violent disturbance of the surrounding air. It contributed to a more rapid re-distribution of particle concentration in the space, and was conducive to shortening the purifying time.

The Measurement of Concentration Gradient

The purifying device was placed at the furthest corner of the room. Three instruments for testing $PM_{2.5}$ concentration were placed 1 m, 3 m, and 5 m away from the device, respectively. The variations in measured values from each instrument are shown in Fig. 4. In the figure, 2 minute is the time when the purifying device was turned on.

Data indicated that the concentration did not decrease with distance obviously. The concentration values from three instruments in different places were generally similar at any given time. This proved that particle had strong diffusion capabilities. But without doubt, an apparent concentration



a. before start-up the purifying device

b. after 3 minutes

c. after 6 minutes

d. after 10 minutes

Fig. 3. The contrast of visual sense.

Table 1. The change of photoelectric current with time.

Item	Numerical value														
Time/min	–1	0	1	2	3	4	5	6	7	8	9	10	11	12	13
Photoelectric current/μA	6	110	90	70	50	40	33	29	20	17	15	12	9	8	6

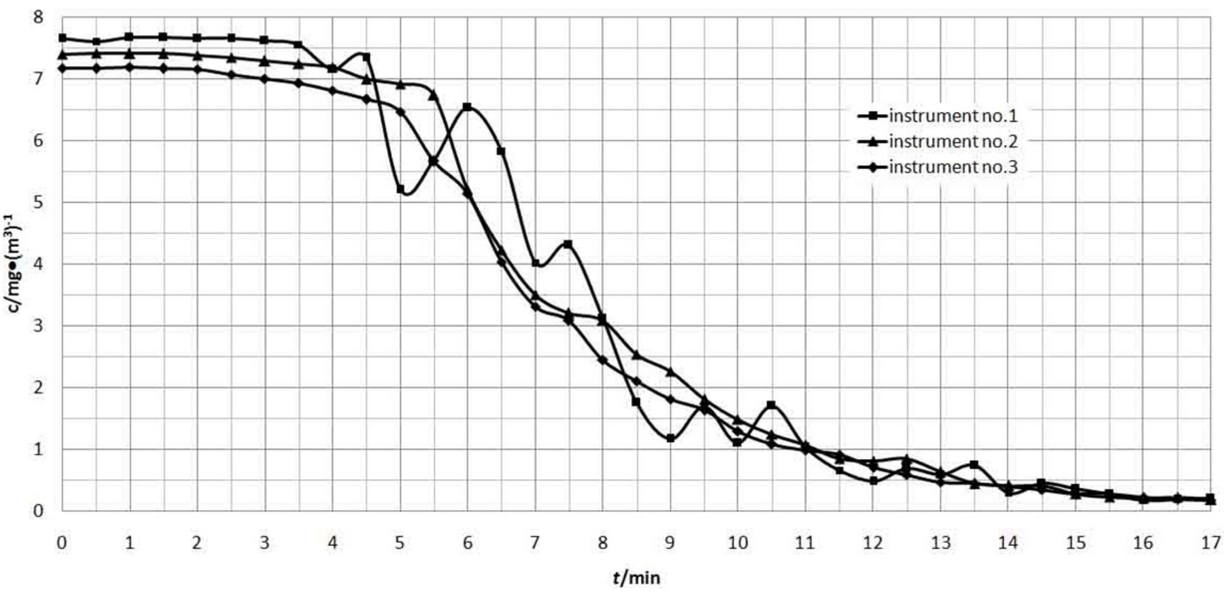


Fig. 4. The value of concentration of $PM_{2.5}$ with time at different positions.

gradient value will be measured if the distances between pairs of instruments is longer enough. Instrument no.1, which was nearest the purifying device, exhibited fluctuations possibly due to the influences of the ionic wind and vibrations in the electrical field. Although the ionic wind is within the electrical field, its inertia could affect the outside. During the experiment, due to the random vibrations caused by loose discharge electrode wires and the dust collection carbon fibre sheet, as well as flotation of particle strings in the presence of polarised charges, flash-over occurred randomly (both temporally and spatially). This process possibly showed apparent influences on the nearest instrument.

The Influence of Power Supply Parameters on Purifying Efficiency

To verify the relationship between purifying device's ability and the voltage applied in the electrical fields, the particle concentration variations with time by adjusting the voltages were measured. In Fig. 5, the mean values measured by three instruments at 50 kV and 45 kV are compared. The results showed that, similar to electrostatic precipitator, the efficiency of the purifying device increased with increasing voltage.

The time 0 minute indicated the initial state of the room before producing smog; 1 minute referred to the time at which the purifying device was powered on. As the applied voltage decreased, a longer time was taken to achieve the same purification. So, a higher voltage in the electrical field had to be applied to obtain better particle removal effects within a given distance.

Temporal $PM_{2.5}$ Changes Based on Outdoor Experiments

Due to the limits of experimental model (purifying device) and field conditions, the test data from different locations, distances, directions, and wind speeds were not systematically logged. In addition, the site had intermittent and non-directed (gusting/swirling) winds at speeds from 0 to 2.3 m s^{-1}.

A voltage of 63.71 kV was applied in the electrical field when the purifying device was turned on. The changes were almost the same at different times, as were the data from each side. Fig. 6 shows data obtained using one of the $PM_{2.5}$ monitors from 8:34:24 to 10:37:58 am on October 23, 2014.

The purifying device was powered-on at 8:40:25 am. The power supply was cut at 9:00:01 after about 20 minutes. After 10 minutes, the purifying device was turned on again at 9:10:04 with the same power supply for a further 20 minutes, and then the power supply was cut at 9:30:09. Some 10 minutes later, the device was re-started at 9:40:12 with the same power supply for 20 minutes, then it was cut at 10:00:18; after 12 minutes, the device was turned on again at 10:12:21; finally, the supply was cut at 10:32:27 am after 20 minutes.

As seen in Fig. 6, the $PM_{2.5}$ concentrations at the measuring points decreased after the start-up of the purifying device, and increased again after turning off the device. The $PM_{2.5}$ data fluctuated slightly because of the cyclical operation of the sky when power supply was off. This phenomenon was in agreement with air haze concentration data across a region for a short period. After the start-up of the device, $PM_{2.5}$ data showed significant variation. This was possibly because the polluted air was highly purified as the wind blew from the opposite direction in the case of non-directed (gusting/swirling) wind on site. $PM_{2.5}$ values were therefore small; when the wind direction was reversed, the $PM_{2.5}$ values were likely to increase because the purifying efficiency decreased merely by removing fine particles through the diffusion of upwind concentration gradients. Since the maximum fluctuating value, at device start-up, was still smaller than the minimum value when it was turned off, the device was confirmed to have been capable of purifying air to each side at certain wind speeds and at certain distances. This proved that fine particles presented strong diffusion capabilities along their concentration gradients.

Fig. 6 also shows the mean $PM_{2.5}$ concentration in both cases (powered-on and powered-off). The mean concentration was the average of downwind, upwind, and no wind data. The average concentration for decreasing amplitude of $PM_{2.5}$ in four periods (powered-on and powered-off) was 23.5%. However, the decreasing amplitude in downwind areas was expected to increase more during actual haze removal operations owing to the purifying device being placed upwind.

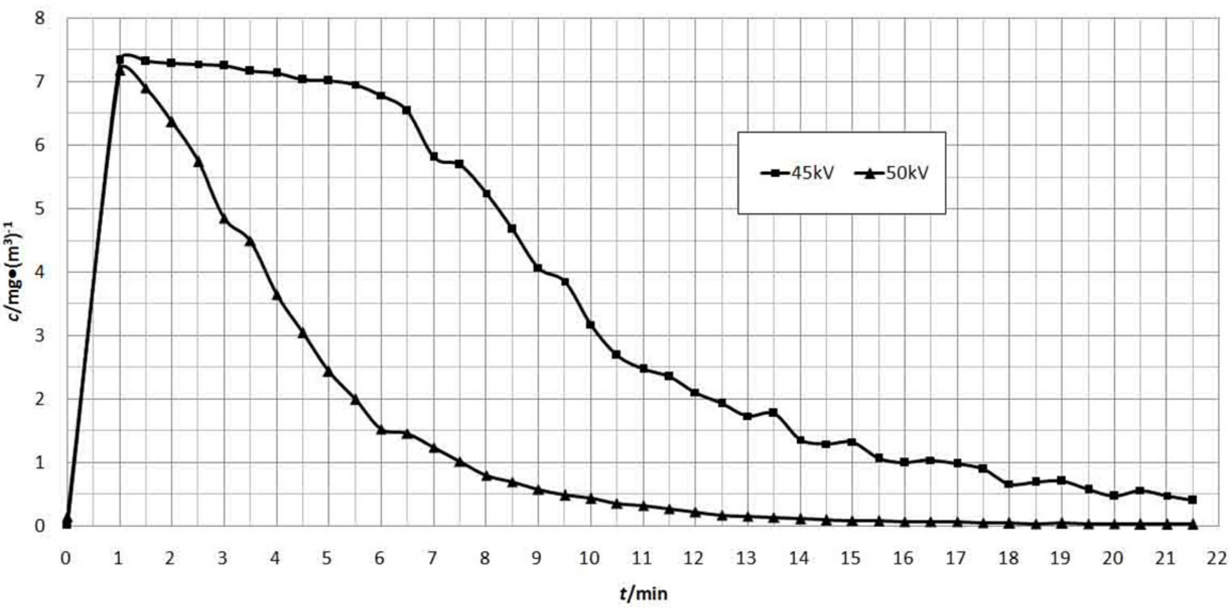


Fig. 5. The value of concentration of $PM_{2.5}$ with time at different voltages.

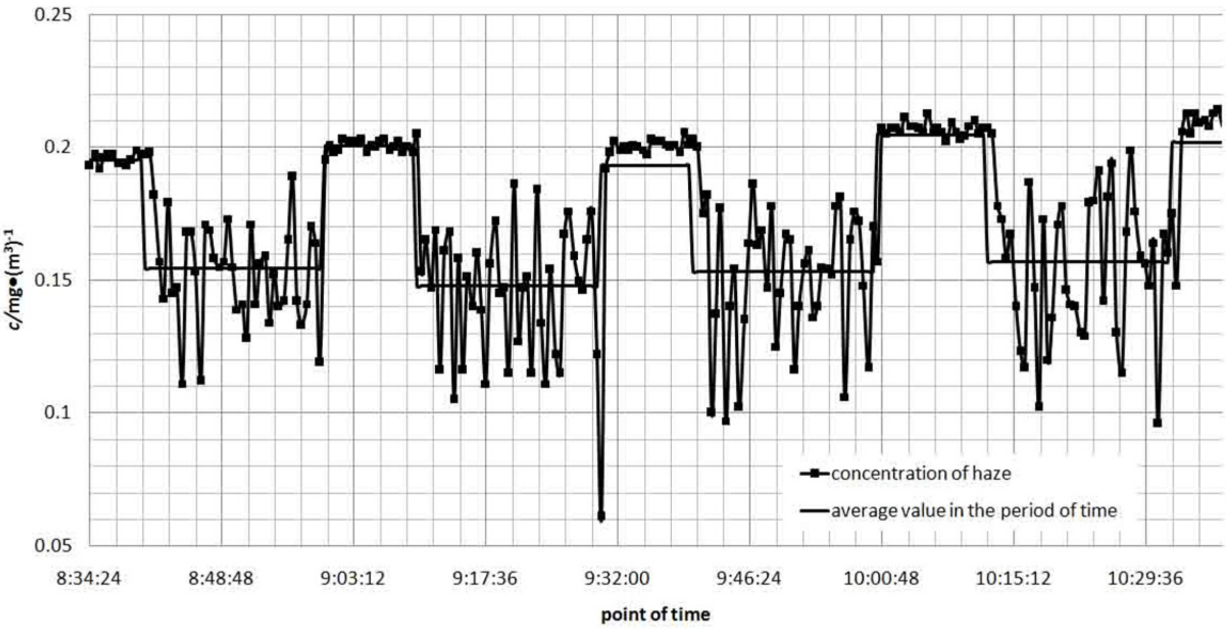


Fig. 6. The value of concentration of outdoor $PM_{2.5}$.

DISCUSSION

The aforementioned experimental results showed that the concentration gradients of fine particles presented intense diffusion effects. The haze concentration in adjacent areas could be reduced as long as there were sufficient haze removal devices. In the meantime, the natural breeze, the activities of human beings, and the motion of passing vehicles also increase the turbulent transfer and the purifying capabilities of fine particles. Surely, the purified area was soon full of haze which came from a distance; however, the overall haze concentration was reduced. By setting the haze removal devices appropriately, a heavy haze concentration could be decreased to medium, and even light levels through direct purification or diffusion balance.

It proved that the method of sweeping the polluted air using a purifying device (haze removal net) was effective but complex. Aviation passenger transports maybe also suffer from many difficulties; however, the occasional safety problems were ignored when people compared the advantages with its disadvantages. Additionally, the power-off protection for the haze removal devices can be performed in an emergency. Although the haze net was large, it posed little threat to life even if it fell off as a result of its low mass and exposed location.

To remove the haze in a city, apart from the purification effects of sufficient haze removal devices, haze removal nets, and haze removal vehicles, are also required in cases of high haze concentration. If several purifying devices were arranged into a specific shape, a bath-tub curve of concentration distribution will be formed.

CONCLUSION

(1) Diffusion effects enable the purifying device to remove those fine particles which were far from the device in polluted air. The concentration of fine particles decreased, and purifying efficiency decreased with increasing time. In wind caused by presence of pressure or temperature gradients, turbulent transfer was likely to aid the diffusion mechanism and enhance particle purifying efficiency.
(2) The relative motion of the purifying device through polluted air, efficiently and rapidly purified it. The motion's velocity had to be adapted to suit the volume of the device. Higher velocity needs a more depth of the device.
(3) The purifying efficiency was influenced by the applied voltage across the electrical fields. The higher the voltage, the shorter the time taken to achieve the same purifying effect.

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