Influence of Operating Parameters on the Collection Efficiency and Size Distribution of Street Dust during Street Scrubbing

Chung-Shin Yuan[1]*, Su-Wen Cheng[1], Chung-Hsuang Hung[2], and Tai-Yi Yu[3]

[1]*Institute of Environmental Engineering, National Sun Yat-sen University, Kaohsiung, Taiwan, ROC*

[2]*Department of Safety, Health and Environmental Engineering, National Kaohsiung First University of Science and Technology, Kaohsiung, Taiwan, ROC*

[3]*Department of Environmental Engineering, Lan-Yang Institute of Technology, E-Land, Taiwan, ROC*

This study investigated the influence of operating parameters on the efficiency of collection of street dust using a street scrubber. Street scrubbing tests were performed in a full-scale, street scrubbing testing field, and on roads. The full-scale testing field was 40 m long and 1.95 m wide, specifically designed and constructed for this study. It was operated semi-automatically. The operating parameters investigated included nozzle type, street dust load, scrubbing speed, water injection loading, water injection pressure, distance above the ground, and water injection angle. Two types of nozzle, flat fan and hollow cone, were selected in the field tests. Four levels of street dust loading (level A: 0.39±0.28 g/m^2, level B: 2.98±1.34 g/m^2, level C: 8.02±2.08 g/m^2, level D: 17.15±4.77 g/m^2) were used. The experimental results showed that, during scrubbing, the efficiency of collection of street dust decreased as street dust loading, scrubbing speed and distance above the ground increased, but increased with water injection loading and pressure. The determined optimal operating parameters were a scrubbing speed of less than 15 km/hr, a water injection loading of 0.8 L/m^2, a water injection pressure of 2.0 kg/m^2, distance above the ground of 30 cm and a water injection angle of 45^o. Additionally, the efficiency of collection of fine particles was higher than that of coarse particles. A multiple regression model was developed to predict the collection efficiency of street dust, based on experimental results obtained from street scrubbing field tests. The results suggested that street scrubbing should be able to reduce the fugitive emissions of street dust from paved roads.

Keywords: street scrubbing, street dust loading, particle size distribution, collection efficiency, operating parameters

1. Introduction

Emitted from stationary, mobile, and fugitive sources, particulate matter (PM_{10}) is one of two major air pollutants responsible for the poor ambient air quality in most metropolitan areas in Taiwan (Yuan et al., 1999). Particulate emission from paved and unpaved roads is a major fugitive source in urban areas. Watson et al. (1989) and

*Corresponding author:
Tel: +886-7-5254409
Fax: +886-7-5254449
E-mail address: ycsngi@mail.nsysu.edu.tw

Chow et al. (1992) stated that, in metropolitan areas, street dust re-entrainment and tail pipe exhaust contributed approximately 30-50% and 4-40%, respectively, of ambient particulate matter smaller than 10 μm (PM_{10}). Additionally, receptor-modeling studies have shown that fugitive dust generated from vehicles that travel on roadways can be a major source of PM_{10} in the South Coast Air Basin of California (Gaffney, 1995).

Claiborn et al. (1995) reported that the emission factors PM_{10} from vehicle kilometer traveled on the road (VKT) were 6.7±3.7 g/VKT and 1.0 ±0.5 g/VKT, for VKT ≤10,000 and >10,000, respectively. The emission factor for fugitive particulate matter from a paved road is highly correlated with the silt content (dp < 75 μm) of the street dust and the mean mass of the vehicles that travel on the roads (Watson et al., 1999; Hesketh et al., 1982). Kuhns (2001) concluded that the emission factor and average size of particulate matter varied with the speed of the vehicles. Jeng et al. (1998) also reported that the concentration of ambient particulate matter varied with the silt content of street dust, scrubbing frequency, traffic flow and wind speed. However, some researchers have claimed that only a slight correlation exists between the emission of fugitive dust and the silt content of street dust (Kantamaneni et al., 1996; Zimmer et al., 1992). Silt content generally accounts for about 4-22% of street dust and its collection efficiency ranged from 20.4% to 70.4% at an average of 41.9% (Jeng et al., 1998).

Removing debris from roadways has been suggested as a method for controlling the fugitive emission of PM_{10} (USEPA, 1984), although this has not been practically implemented in the U.S.A. (Chow et al., 1990; Fitz, 1998). Fitz and Bumiller (2000) reported that street scrubbing and sweeping are the Best Available Control Measures (BACM) for reducing ambient particulate matter in areas that do not comply with the National Ambient Air Quality Standards (NAAQS) for PM_{10}. Street scrubbing and sweeping are generally performed to remove street dust, particularly silt, to reduce the re-entrainment of street dust into the ambient atmosphere that would otherwise be caused by traveling vehicles and wind.

Street scrubbing is more efficient than street sweeping for removing street dust and reducing the amount of ambient particulate matter. Previous research has demonstrated that street scrubbing can reduce the ambient concentration of total suspended particles (TSP) and PM_{10} by approximately 3.2-12.6% and 8.6-30.0%, respectively (Chang et al., 2000; Tainan EPB, 1997). However, the influence of operating parameters on the efficiency of collection of street dust during street scrubbing and sweeping remains unknown.

Under the auspices of the Air Pollution Abatement Fund, the Taiwan Environmental Protection Administration (TEPA) and local governments have undertaken a consecutive street scrubbing and sweeping project for the past several years. Local governments routinely clean roads using street sweepers and scrubbers, primarily for aesthetic and safety reasons, rather than merely to meet regulations. The efficiency of this project in reducing ambient particulate matter is controversial, being questioned by researchers and the general public since experimental data to support its effectiveness has been lacking.

Therefore, the objectives of this study were to evaluate the collection efficiency of street dust and to investigate the influence of operating parameters on the collection efficiency and particle size distribution of street dust during street scrubbing.

2. Methods

2.1 Street Dust Loading

Street dust was sampled in situ using a vacuum cleaner (SANYO, Model SC-6L) in streets, from clean to dirty, characterized by cleanliness levels A to D. Each sampling run exceeded 17 minutes to ensure at least 98% efficient collection of street dust. The mean area loading of street dust was determined by sampling street in three separate zones with areas of 12.5 m^2 (2.5 m (W) x 5.0 m (L)). In this study, the street dust sampling protocol was used on 37 streets in metropolitan Kaohsiung. Street dust, collected by filter bags with 2.0 μm micropores, was temporarily stored in a tagged Tedlar bag, and then transported to the central laboratory at National Sun Yat-sen University for size distribution analysis by weighing. Before weighing, the street dust was dried at 103-105^{o}C for at least two hours in an oven to prevent the adsorption of moisture, which could affect the measured weights of the dust samples.

2.2 Size Distribution of Street Dust

Street dust sampled on the floor was screened using a laboratory test sieve (Octagon, Model 200) to determine its size distribution. The test sieve consisted of eight plates (8” (ID) x 2” (H)) with pore size ranges of <45, 45-75, 75-106, 106-150, 150-212, 212-300, 300-425, 425-850, >850 μm, respectively (U.S. Standard Wire Mesh Series, ASTM E11:87). The test sieve was operated for more than 17 minutes per run to achieve an error of less than 3% between the results of two consecutive weighings. The efficiency of collection for each range of sizes was then determined by comparing the mass of the street dust deposited on each plate before and after street scrubbing.

2.3 Street-Scrubbing Simulation Tests

A full-scale, street-scrubbing testing field was specifically designed for this study. The testing field was 40 m long and 1.95 m wide, with a gradient of about 2%. Designed to move on rails, a street-scrubbing simulation apparatus was operated by changing scrubbing speed, water injection loading, water injection pressure, distance above the ground and angle of water injection. The field tests were performed to investigate the influence of operating parameters on the collection efficiency of street dust during street scrubbing.

The surface of the testing field was swept using a vacuum cleaner before the tests were conducted. Scrubbing was usually performed for more than 17 minutes to ensure that the street had been completely cleaned. Street dust collected from 37 streets in metropolitan Kaohsiung was prepared as testing material, being dried at 103-105^{o}C in an oven for two hours. The dust was mixed to simulate area loadings and size distributions of streets with various levels of cleanliness; the mixed dust was then spread and deposited uniformly on the surface of the testing field for the street scrubbing test. Street dust sampled in three separate zones with areas of 6.0 m^2 (1.5 m (W) x 4.0 m (L)) in the testing field before and after street scrubbing were used to determine the efficiency of collection, as follows.

$$\eta = \frac{W_i - W_f}{W_i} \times 100\%$$

where η represents the collection efficiency of the street dust (%); W_i is the street dust loading before scrubbing (kg/m^2); W_f is the street dust loading after scrubbing (kg/m^2).

2.4 Operating Parameters of Street Scrubbing

The influence of major operating parameters on the collection efficiency of street dust was investigated to obtain the optimal operating conditions of street scrubbing. The operating parameters investigated herein included scrubbing speed, water injection loading, water injection pressure, distance above the ground and water injection angle. Table 1 describes and presents the ranges of operating parameters.

Table 1. Operating parameters tested in the street scrubbing simulation field.

Operating Parameters	Range or Descriptions
Type of nozzle	Flat fan, hollow cone
Area dust loading (g/m^2)	0.39, 2.98, 8.02, 17.15
Scrubbing speed (km/hr)	10, 15, 20
Water injection loading (L/m^2)	0.4, 0.8, 1.2
Water injection pressure (kg/m^2)	1.70, 1.85, 2.00
Distance above the ground (cm)	20, 30, 40
Water injection angle (^{o})	10, 40, 70

Water injection angle is defined as the angle between water spraying trajectory and horizontal line.

Two most commonly used nozzles - flat fan and hollow cone - on the street scrubbers, were selected for the simulation field tests. The street scrubbers traveled on the streets at 10, 15 and 20 km/hr. The amounts of water on the streets were 0.4, 0.8, and 1.2 L/m^2. The static pressures at which water was delivered onto the surface of the streets were 1.70, 1.85, and 2.00 kg/cm^2. Water was atomized using nozzles at approximately 20, 30 and 40 cm above the ground, and at angles of 10^o, 40^o, and 70^o. The water injection angle was defined as the angle between the direction in which the water is sprayed and the horizontal.

3. Results and Discussion

3.1 Area Loading and Characteristics of Street Dust

In this study, a wide range of area loadings of street dust was observed in metropolitan Kaohsiung. The area loading of street dust measured on 37 major streets ranged from 0.08 to 24.66 g/m^2,

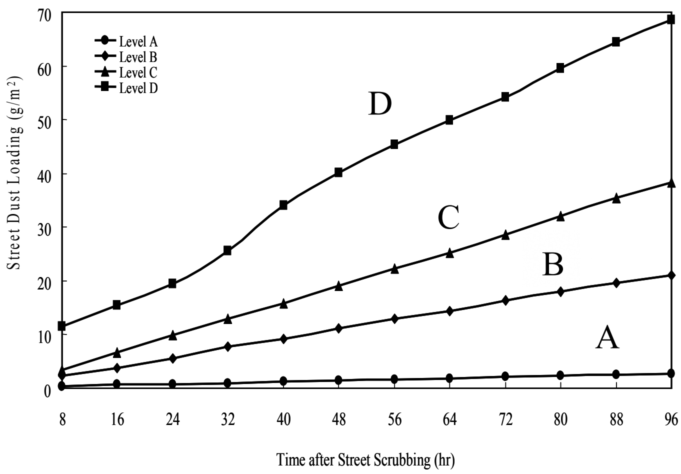

Figure 1. Variation of street dust loading with time after street scrubbing.

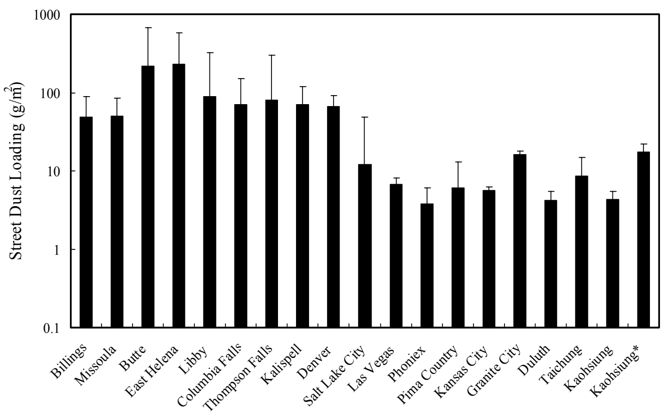

Figure 2. Comparison of street dust loading in metropolitan Kaohsiung with that in other major cities.

according to which, the cleanliness of the streets was classified into four levels (Levels A (clean) – to D (dirty)), Table 2 summarizes the range, average and standard deviation of street dust loading for the various cleanliness levels. The ranges of street dust loading for street cleanliness levels A-D were <1, 1-5, 5-11, and 11-25 g/m^2, respectively. The average and standard deviation of the street dust loadings measured in metropolitan Kaohsiung for cleanliness levels A-D were 0.39±0.28, 2.98±1.34, 8.02±2.08 and 17.15±4.77 g/m^2, respectively.

Street dust was continuously sampled for 96 hours to determine the amounts of dust deposited on the surface of the streets. The street dust was

Table 2. Classifying street cleanliness levels and area loading of street dust.

Cleanliness Level	Sample Number	Street Dust Loading			Street Dust Accumulates (g/m^2-day)	Scrubbing Frequency
		Range(g/m^2)	Average(g/m^2)	S.D. (g/m^2)		
A	14	<1	0.39	0.28	0.6	once/week
B	9	1-5	2.98	1.34	5.7	once/3-days
C	8	5-11	8.02	2.08	9.6	Once/2-days
D	6	11-25	17.2	4.77	15.6	once/day

S.D. is the standard deviation of field measured street dust loading.

Scrubbing frequency is determined by maintaining street dust loading less than 20 g/m^2.

Table 3. Size distribution and area loading of street dust for various street cleanliness levels.

Particle Size Range (μm)	Street Cleanliness Levels			
	A (%)	B (%)	C (%)	D (%)
<45	2.48	4.91	5.75	5.96
45-75	7.02	7.23	9.74	9.96
75-106	2.07	2.04	3.62	3.82
106-150	3.72	5.40	6.13	6.39
150-212	6.20	7.34	8.36	8.35
212-300	9.92	8.72	9.95	9.83
300-425	13.2	13.5	12.0	11.8
425-800	21.5	19.9	20.4	20.0
>850	33.9	31.0	24.0	23.8
Street Dust Loading	0.39	2.98	8.02	17.2

The unit of street dust loading is g/m^2.

collected from floors with the four different cleanliness levels every eight hours after the street had been scrubbed. Figure 1 shows the variation of street dust loading with time after the street was scrubbed. The daily increments of street dust loading for cleanliness levels A-D were 0.6, 5.7, 9.6 and 15.6 g/m^2-day, respectively, as shown in Table 2. The results show that the daily increments of the amount of deposited dusts on the roads varied with the cleanliness level of the street. The dirtiest street (Level D) accumulated street dust approximately 26 times faster than the cleanest street (Level A). The frequency of street scrubbing for cleanliness levels A, B, C and D were at least once per week, once per three days, once per two days and daily, respectively, to maintain street dust loading of less than 20 g/m^2 (Table 2).

Figure 2 compares the street dust loading in metropolitan Kaohsiung obtained herein with that in 17 major cities in the world. The results show that, overall, the mean area loading of street dust in metropolitan Kaohsiung was lower than that in most major cities in the world, and was comparable to that in Las Vegas, Phoenix, Kansas City and Duluth in U.S.A. However, the average dust loading of 14 streets with cleanliness levels C and D was comparable to the street dust loading in other major cities in the world.

Table 3 presents the size distribution of street dust sampled from streets at various cleanliness levels. In thiis study, the size of street dust was bimodally distributed. The results indicate that

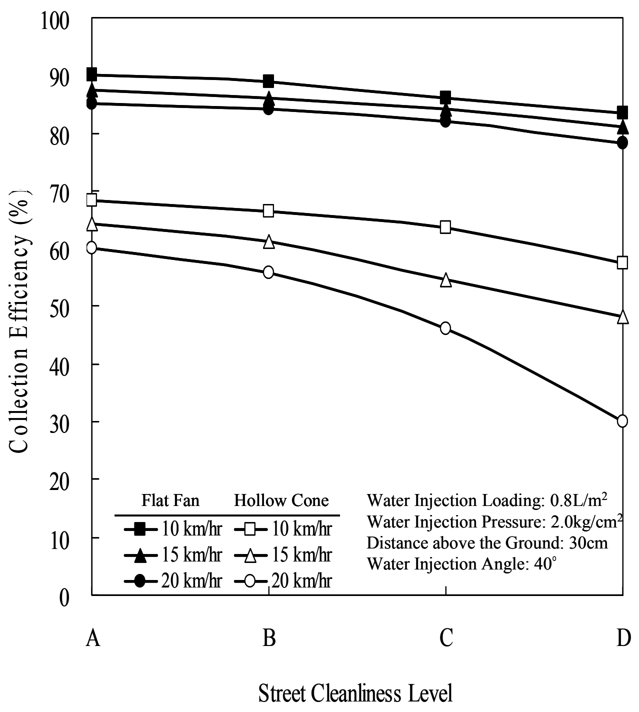

Figure 3. Comparison of collection efficiency of street dusts between flat fan and hollow cone nozzles.

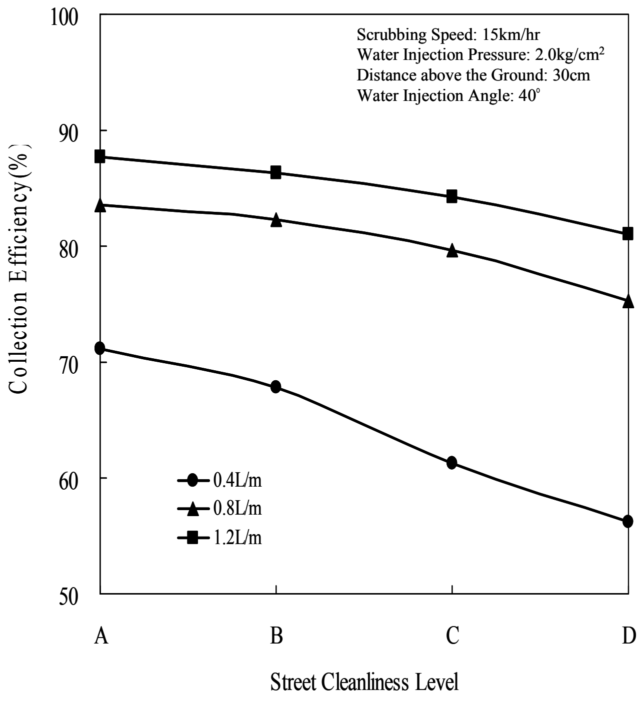

Figure 4. Variation of collection efficiency of street dust with water injection loading.

street dust were primarily coarse. Street dust with a particle size of under 45 μm (silt) accounted for 2.48-5.96% by mass of all street dusts, while that with particle sizes above 300 μm accounted for approximately 55.5-67.7% by mass of all street dust. The breaking of coarse dust into fine dusts on roads by vehicles is an important contributing factor to the emission of fugitive dust to the atmosphere.

3.2 Influence of Operating Parameters on Collection Efficiency of Street Dust

One of the objectives of this study was to examine the influence of operating parameters on the collection efficiency of street dust during street scrubbing. The operating parameters included scrubbing speed, water injection loading, water injection pressure, distance above the ground and water injection angle. As well as operating parameters, the variation of the collection efficiency of street dust with nozzle type and the cleanliness level street was also discussed.

The results of the field tests showed that, as shown in Fig. 3, the flat fan nozzle (nozzle A) exhibited a greater scrubbing efficiency than the hollow cone nozzle (nozzle B). Nozzle A yielded a collection efficiency of over 79.5%, while nozzle B yielded a collection of over 30.3%. Moreover, nozzle B demonstrated a wider variation of collection efficiencies than nozzle A, especially for street cleanliness levels C and D. Regardless of the type of nozzle, the cleaner streets were flushed more efficiently than the dirtier streets. Consequently, the flat fan nozzle (nozzle A) was highly recommended for scrubbing streets and was used as the testing nozzle in this particular study.

Although most street scrubbers in Taiwan operate at speeds of less than 15-20 km/hr to guarantee reasonable collection efficiency, no optimal scrubbing speed has been proposed or experimentally determined. Therefore, scrubbing speeds of 10, 15, and 20 km/hr were investigated. Figure 4 plots the variation of collection efficiency of street dust with the traveling speed of the street

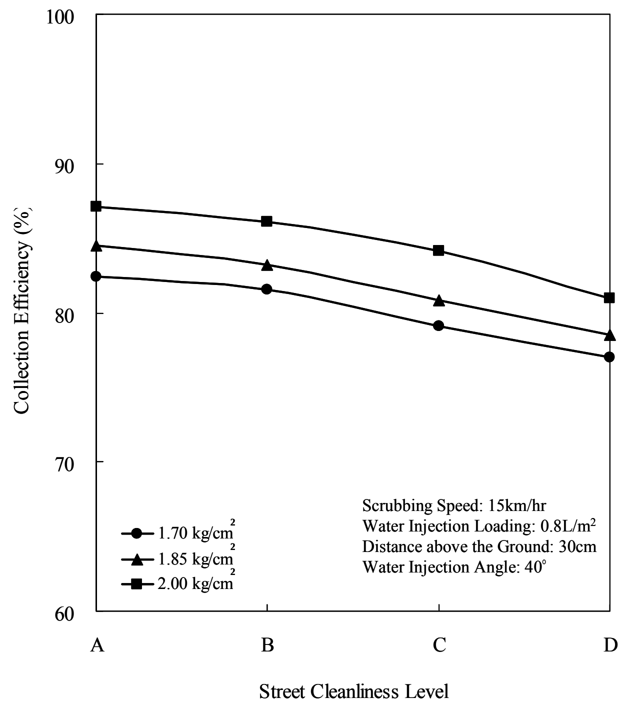

Figure 5. Variation of collection efficiency of street dust with water injection pressure.

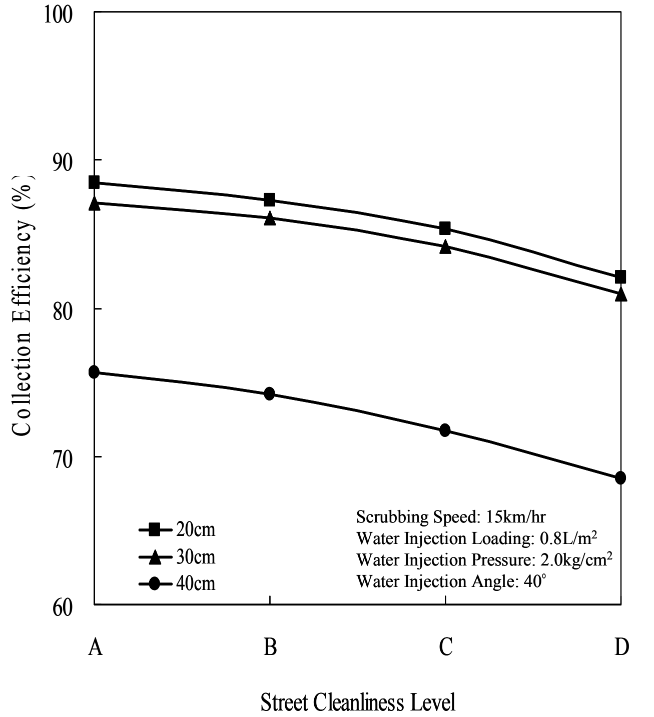

Figure 6. Variation of collection efficiency of street dust with distance of nozzle above the ground.

scrubber. The results indicate that lowering the traveling speed of the street scrubber increases the collection efficiency. Reducing the scrubbing speed from 20 km/hr to 15 km/hr and 10 km/hr reduces the collection efficiency by approximately 3% and 5%, respectively. The collection efficiency decreased as the street cleanliness fell from that of level A to that of level D. The collection efficiency was always least on the dirtiest streets (Level D). A minimum collection efficiency of 80% for the dirtiest streets required that the optimal travelling speed of the street scrubbers was lower than 15 km/hr.

This study also revealed that the collection efficiency varied with water injection loading, defined as the amount of water spread per area of street. The investigated water injection loadings were 0.4, 0.8, and 1.2 L/m^2. Figure 4 plots the variation of collection efficiency with water injection loading. The results show that increasing the amount of water injected onto the streets increased the collection efficiency of street dust. Spreading 0.8 and 1.2 L/m^2 of water onto the surface of the street maintained a collection efficiency of above 80%. However, spreading less than 0.8 L/m^2 of water significantly lower collection efficiency of street dust. Water spread on the street surface transported the road dust to the edge of the sidewalk and drained it to the sewer. Spreading insufficient water on the streets did not cause the water to flow with a sufficient velocity to carry street dust to the sewer very effectively. The results suggest that water injection loading is a very important parameter for increasing the collection efficiency of street dust.

Water injection pressures of 1.70, 1.85, and 2.00 kg/cm^2 were also tested. As plotted in Fig. 5, injecting water at a higher pressure enhanced the collection efficiency of street dust. For example, for a street with cleanliness level D, increasing the water injection pressure from 1.70 kg/cm^2 to 1.85 and to 2.00 kg/cm^2 enhanced the collection efficiency of the street dusts from 77.0% to 78.5 and 82.0%, respectively. Operating street scrubbers with a water pressure of 1.70 and 1.85 kg/cm^2 achieved a minimum collection efficiency of 79.1% for street cleanliness levels A-C. However, increasing the water injection pressure to 2.00

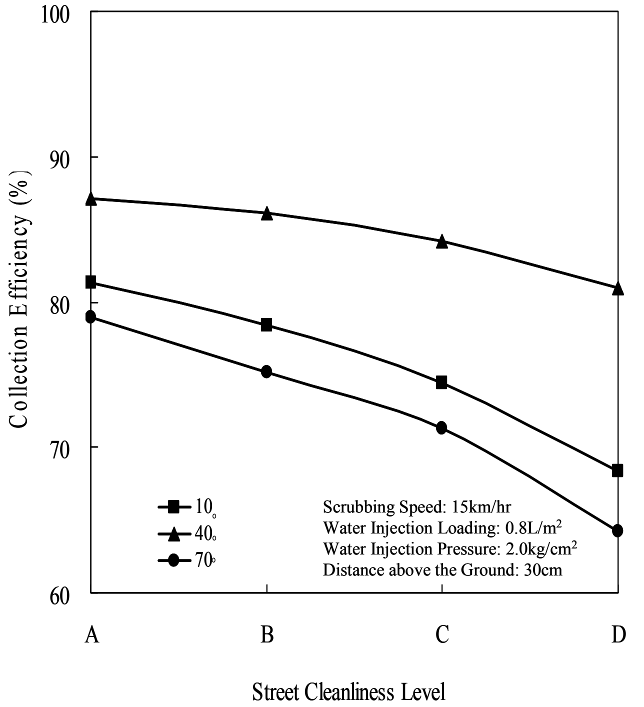

Figure 7. Variation of collection efficiency of street dust with water injection angle.

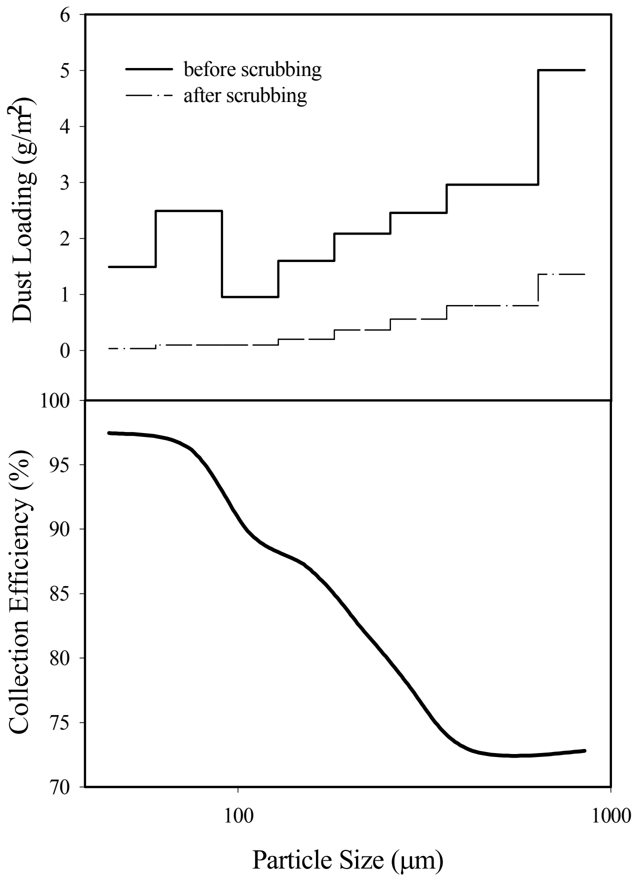

Figure 8. Size-resolved collection efficiency of street dust obtained from simulation tests.

kg/m^2 increased the collection efficiency above 82.0% for all cleanliness levels of streets.

The distance between the nozzle and the ground is also crucially determines the collection efficiency of street dust. In this study, distances above the ground of 20, 30, and 40 cm were investigated. As shown in Fig. 6, the collection efficiency of street dust decreased as the distance above the ground increased from 20 to 40 cm. The results indicate no significant differences between distances of 20 and 30 cm. However, the collection efficiency of street dust decreased by approximately 11-12% as the distance increased from 30 to 40 cm. Therefore, the maximum efficiency of collection can be achieved by atomizing water at 20 cm above the ground. However, operating the water injection nozzle at distances too close to the ground can damage the nozzle as the street scrubbers pass over obstacles. Hence, the nozzles are preferably operated at 30 cm above the ground.

Angles of water injection from 10^o to 70^o were examined to maximize collection efficiency. The water injection angle is defined as the angle between direction in which the water is sprayed and the horizontal. Figure 7 shows the influence of water injection angle on the collection efficiency. The results show that injecting water at an angle of 40^o yields the highest collection efficiency.

Overall, the collection efficiency during scrubbing could be enhanced by reducing scrubbing speed or increasing water injection loading and pressure. Experimental results indicate that flat fan nozzles should be used at 30 cm above the ground with an angle of 40^o.

3.3 Collection Efficiency and Particle Size

Researchers have reported that finer dust is more easily emitted to the atmosphere by wind and/or disturbances due to traveling vehicles (Fitz, 1998; Chow et al., 1992). Thus, understanding the collection efficiency of street dust as a function

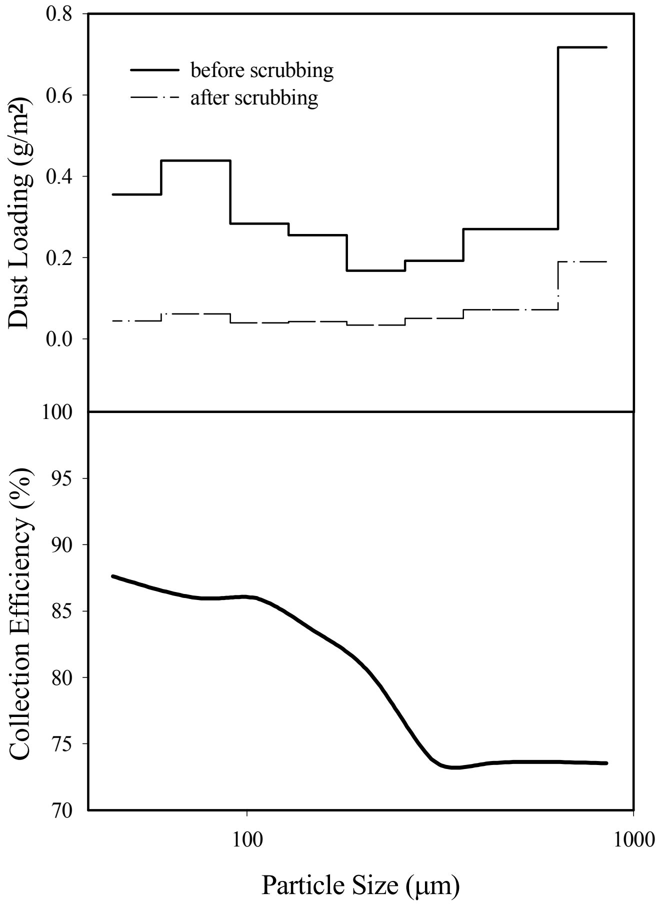

Figure 9. Size-resolved collection efficiency of street dusts obtained from the in-situ tests.

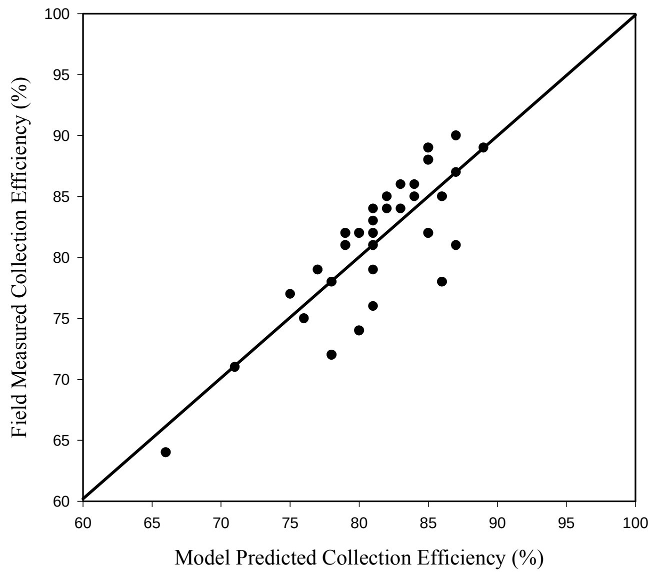

Figure 10. Comparison of model-predicted and field-measured collection efficiencies.

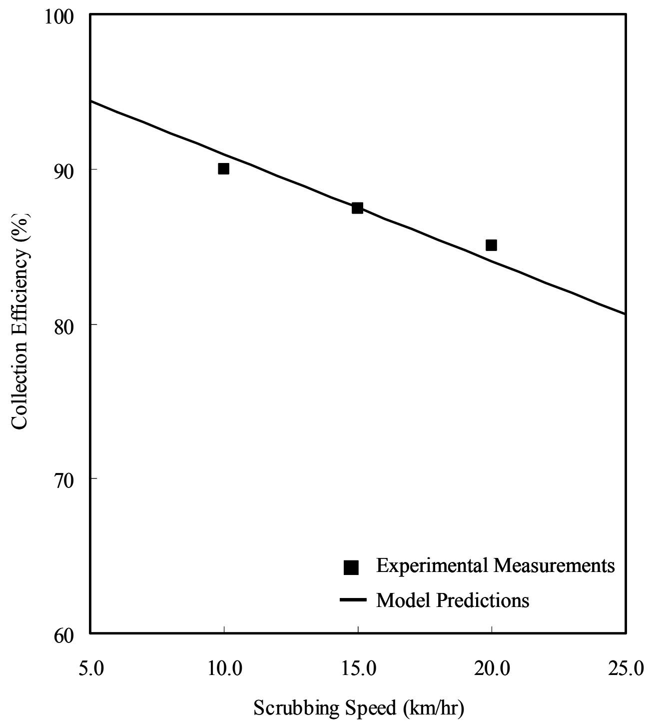

Figure 11. Comparison of model-predicted with field-measured collection efficiencies as functions of scrubbing speed.

particle size during street scrubbing is difficult. An investigation was conducted to ascertain the amount of dust removed from the street as a function of particle size. The study was performed both in the scrubbing simulation test field (simulation tests) and on the roads (in-situ tests) of metropolitan Kaohsiung. Figures 8 and 9 plot the size distributions of street dust before and after street scrubbing, and their collection efficiency against particle size.

The results indicate that the overall collection efficiency in the simulation testing field was 86.06%. However, a lower overall collection efficiency of 80.81% was observed in the *in-situ* tests on the roads. Further investigation of different particle sizes indicated that finer particles were removed more efficiently than coarser particles. The highest collection efficiency of street dusts was always of particles with diameters of less than 45 μm (PM_{45}), both in the simulation testing field and on the road. Thus, the collection efficiency of particles with diameters of less than 10 and 2.5 μm (PM_{10} and $PM_{2.5}$) can be reasonably assumed to be even higher than, or as high as, that of PM_{45}. The results suggest that street scrubbing should be able to reduce the fugitive emissions of street dust from paved roads to the atmosphere, and is expected to

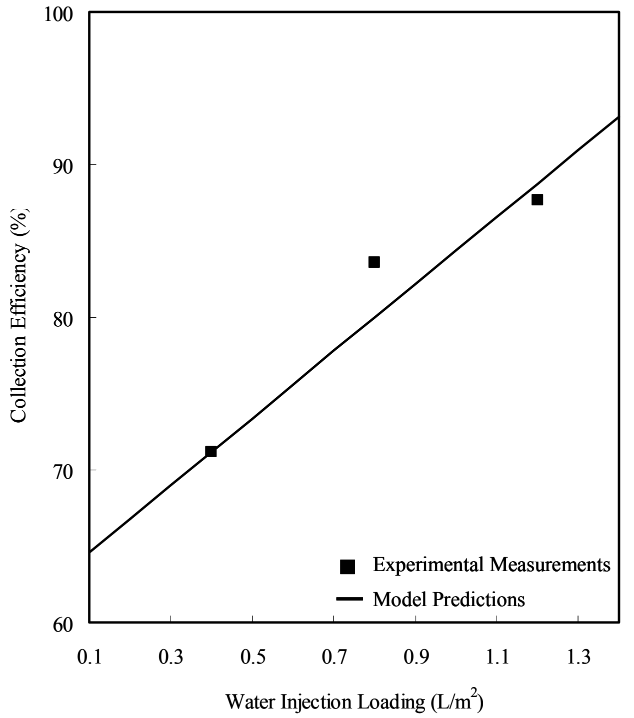

Figure 12. Comparison of model-predicted with field-measured collection efficiencies as functions of water injection loading.

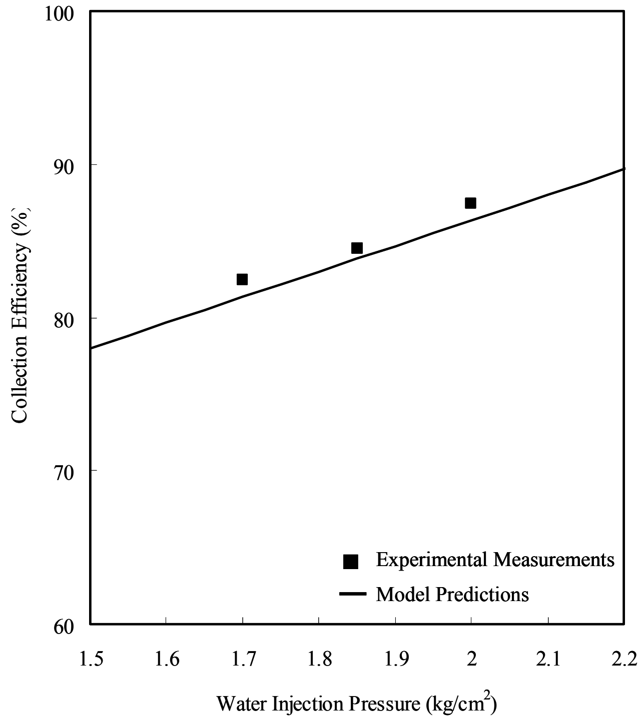

Figure 13. Comparison of model-predicted with field-measured collection efficiencies as functions of water injection pressure.

be involved importantly in improving the ambient air quality.

3.4 Modeling Street Scrubbing

Dimensional analysis was applied to cluster the operating parameters that significantly impact the collection efficiency of street dust during street scrubbing. First, a dimensionless analysis of operating parameters was performed using Buckingham's π Theorem. Three dimensionless parameters were extracted from the experimental results of six operating parameters (W, V, q, P, H, and θ); they were Pq/V^2W, H/q, and sin2θ. A multiple regression model was successfully developed, based on the aforementioned three dimensionless parameters, to simulate the collection efficiency of street dust.

$$\eta = 1.5222\left(\frac{Pq}{V^2W}\right)^{0.0233}\left(\frac{H}{q}\right)^{0.1434}\left(Sin2\theta\right)^{0.1086}$$

where η is the collection efficiency of street dust (%); V is the scrubbing speed (km/hr); q is the water injection loading (m^3/m^2); P is the water injection pressure (N/m^2); W is the street dust loading (kg/m^2); H is the distance above the ground (m), and θ is the water injection angle.

As shown in Fig. 10, model predictions agree quite well with experimental measurements. A strong correlation between model predictions and experimental measurements with a correlation coefficient (r) of 0.83 was observed. Figures 11-15 compare the experimental measurements with the predictions of the model for various operating parameters. Water injection loading is the most important parameter in determining the collection efficiency of street dust. Moreover, mathematical modeling suggested that the optimal water injection angle should be around 45^o instead of 40^o, as measured experimentally.

4. Conclusions

This study examined the influence of operating

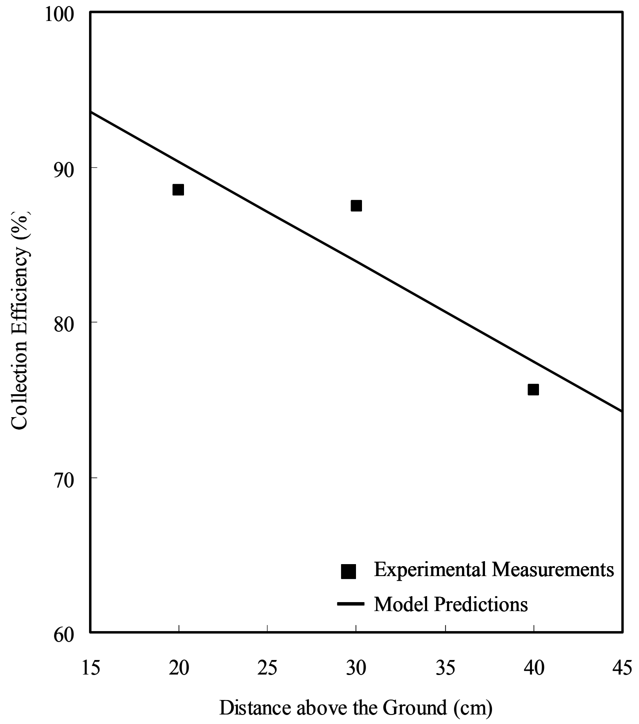

Figure 14. Comparison of model-predicted with field-measured collection efficiencies as functions of water injection height above the ground.

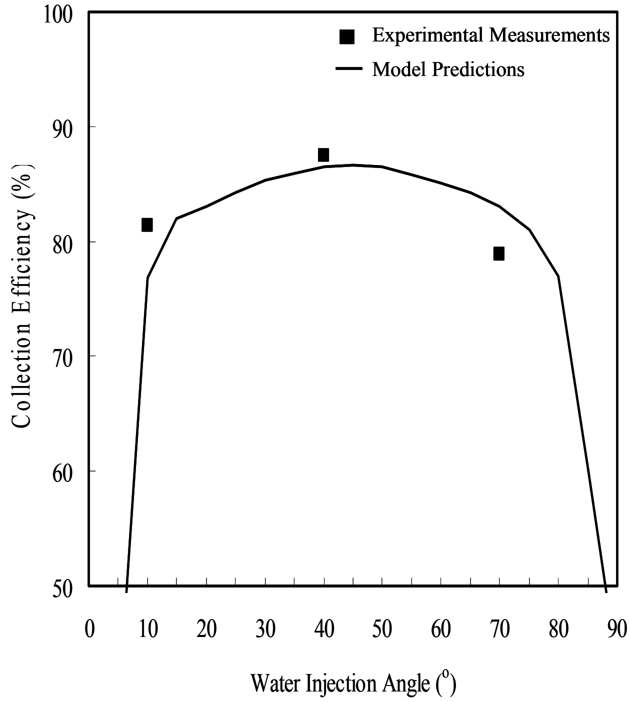

Figure 15. Comparison of model-predicted with field-measured collection efficiencies as functions of water injection angle.

parameters on the collection efficiency of street dust during scrubbing. Results obtained from the field tests implied that the collection efficiency can be raised either by increasing water injection loading and pressure or by reducing scrubbing speed. Flat fan nozzles 30 cm above the ground at an injection angle of 45^{o} are preferred. The most suitable nozzle is also important for improving the efficiency of collection. The flat fan nozzle generally achieves a higher collection efficiency than a hollow cone nozzle. Further investigation of the collection efficiency of particles with various sizes revealed that finer particles were usually more efficiently removed than coarser particles, suggesting that street scrubbing is one of the most efficient ways of reducing fugitive emission of street dust from paved roads. Based on dimensionless analysis, a multiple regression model was successfully developed to simulate the collection efficiency of street dust during street scrubbing.

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