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A comparison of the performances of dry and wet vacuum cleaners for the control of indoor particulate matters

Bahtiyar OZTURK*

Ondokuz Mayis University, Engineering Faculty, Environmental Engin. Dept., 55139-Kurupelit Samsun- Turkey

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Abstract: Most of us use a vacuum cleaner (VC) in our home to remove dust deposits on the floor. But the fundamental question is: do the vacuum cleaners (VCs) really remove all dust constituents in our home? I investigated this question by using a room an ($12.6m^3$) and fully furnished living rooms of different houses. The work was carried out using two different types of vacuum cleaners: The first type absorbs dust/dirt in water located in a basin (called as wet vacuum cleaner, WVC) and the second one vacuums dusts using a filter-bag (called as dry vacuum cleaner, DVC). Most of the filters in the market were tested and their dust eliminating capability was compared with the results of wet dust absorbers as they are most efficient. WVC absorbed almost 100% of the dust while dust eliminating filters used in DVCs ranged between 91-98% depending on the type of filter used. The concentration of suspended particle in some living rooms has also risen by a factor of three when the floor of the room was cleaned using DVC.

***Keywords**: Particulate matter, PM10, dry vacuum cleaner, wet vacuum cleaner.*

Introduction

The importance of indoor air quality has increased significantly over the last 35 years. After the 1970’s, because of energy conservation measures, the design of buildings and mechanical systems have continuously been changed by engineers and architects. These new energy efficient designs minimized the infiltration of outdoor air contributing to in increase the concentration of indoor air contaminants which can cause poor air quality in buildings. Indoor concentrations of many pollutants are often higher than those typically encountered outside. Therefore, scientist gave more attention to indoor air pollution in the last decade due to the larger amount of time we spend indoors. It is estimated that urban people spend on average 87% of their time indoors and only a mere 6% outdoors (Jenkins et al., 1992).

One of the major indoor air pollutants is particulate matters. Many studies have found that the concentrations of suspended particulates (SPs: particles with aerodynamic diameters <10μm, similar to PM_{10} using the US environmental standards) were higher indoors than outdoors when there were sources of indoor particulates in domestic homes (Chao et al., 1998; Jones et al., 2000; Kamens et al., 1991; Spengler et al., 1981; Wallace, 1996). The main sources of indoor particulates are outdoor air, tobacco smoke, combustion systems, building materials,

Corresponding author: E-mail: bozturk@omu.edu.tr, Tel: +90-362-4576020/1317 Fax:+903624576094

upholsterys, furniture, clothing, cleaning materials and pets. The sources vary depending on the type of building studied. Smoking is the most important indoor air pollutant in homes and offices (Wanner, 1993). Some researchers (Neas *et al*., 1994; Phillips *et al*., 1998; Phillips et al., 1999) reported that indoor PM_{10} concentrations were higher in smoking homes than non-smoking homes. It has been found that concentrations of fine particle were as high as 300 $\mu g\ m^{-3}$ when a smoker kept smoking for up to 30 min until the cigarette had burn out, also the 24-h average concentrations of fine particles could be elevated by 20 $\mu g\ m^{-3}$ (Spengler et al., 1981).

Particles which are inhaled and have a small enough diameter to enter and remain in the lung, may pose a hazard to health and are important to study because of their impact on indoor air quality. The USEPA (Environmental Protection Agency of United States) defines "respirable particles" as particles having an aerodynamic diameter (D_p) less than 10 μm, while ACGIH (American Conference of Governmental Industrial Hygientists) defines "respirable particles" as particles having an aerodynamic diameter less than 2,5 μm. In this study, particles with D_p<2,5 μm are called fine or respirable particles, those with 2,5 μm <D_p<*10*μm are called coarse particles and particles with 0,1 μm <D_p<*10* μm are called as PM_{10}.

Particulate matter comprises a mix of organic and inorganic substances including aromatic hydrocarbon compounds (Garban *et al*., 2002; Mandalakis *et al*., 2002; Manoli *et al*., 2002), trace metals (Adgate *et al*., 1998; Chao & Wong, 2002; Hirosihi *et al*., 1994; Li, 1994; Mugica *et al*., 2002; Pakkanen *et al*., 2001; Saitoh *et al*., 2002) and nitrates and sulphates (Godish, 2001; Lin, 2002; Yao *et a*l., 2002). Researchers found that the average PM_{10} elemental species mass fraction (total mass of elements in one cubic meter of air/ total mass of PM_{10} in cubic meter of air) collected from 64 indoor environments was 24.3% (Adgate et al., 1998). A large variety of biological materials are also components of dust (Molhave *et al*., 2000; Montarano, 1997).

Each of the chemical or biological components of dust may be an important risk factor for human health associated with exposures. Irritant effects of inhaled particles may result in airway constriction. It has been reported (Koening *et al*., 1993) that infants exposed to woodsmoke were more likely to have asthma symptoms. Abbey et al. (1998) observed a reduction in lung function in non-smokers exposed to high concentrations of indoor particles over a period of 20 yrs. Sometimes an adsorbed constituent on airborne particulate becomes more important for human health than particulate matter itself. For instance, polycyclic aromatic hydrocarbons (PAHs) which are fat-soluble, containing two or more benzene rings (Godish, 2001) are known as carcinogenic. And Po-218 and Po-214, which are the progeny of radon and electrically charged, can be adsorbed onto particles and inhaled either directly or indirectly through their attachment to airborne particles (Cohen, 1998). Once inhaled, these particles tend to remain in the lungs, where they may eventually cause cancer. Some detailed informations have been cited in the literature about the relationship between respirable particles and their health effects (Heinsohn & Kabel, 1999; Jones, 1999).

Generally, vacuum cleaners are used to remove particles deposited on floors of residential homes and offices. We, as consumers, tend to believe that all particles vacuumed from floor are retained on the filter of our vacuum cleaner. But, there are two questions that we should ask: 1) Does the filter of a vacuum cleaner really retain all dust particles when we vacuum? and 2) Why do we observe an increase in the amount of dust that has settled on furniture after vacuuming the floors of our home or office? According to findings of researchers (Corsi & Chiang, 2000; Lee *et al*., 2002) house cleaning activities such as sweeping and vacuuming may cause the re-suspension of indoor particulates from domestic floors and furniture. This means that using a vacuum cleaner does not thoroughly clean. Is there another method to remove all dusts from our home? In this study, we investigated the answers to these questions.

Experimental

In this study, experiments were performed in an isolated experimental room and in fully furnished living rooms (N=13) of different houses. The stages of experimental work the paper explores: 1) determination of the particle retention efficiencies of filters of dry vacuum cleaners (DVCs) and comparison with wet vacuum cleaner's (WVC), and 2) determination of the effect of dry and wet vacuum cleaners on suspended particle (SP) concentrations in living rooms.

DVCs and WVCs vacuum the dust loaded air by a motor in the vacuum cleaner, then DVCs force that vacuumed air to pass through pores of a filter placed in it while WVCs blow it into water filled basin. Particles which have aerodynamic diameters larger than the pore diameter of the filter are retained and accumulate on the filter while particles absorbed by the water in a WVC during blowing dust-loaded air into water. Filtered air is vented directly out of the DVC as dust free air (it is assumed so), but the air leaves the WVC after passing through a mist eliminator.

Determination of Dust Retention Efficiencies

Dust retention efficiencies of filters of different DVCs and dust absorption efficiency of a WVC were determined in a small experimental room prepared for this purpose. The floor of the room measures 2.0x2.25 meters and the ceiling height is 2.8 m (volume=12.6 m^3). This is the gross volume of the room; because it includes the author standing in the room, a vacuum cleaner, four fans, a small table (90 cm height, 50x70cm^2 surface area) and a mobile infra-red dust monitor. The floor and the sides of the room were covered with a clean smooth ceramic, except door and ceiling. The door was well sealed with varnish and the ceiling of the room had just been painted with a white Acrylic paint. Axial fans were used in order to provide a homogenous air mixture in the room atmosphere. Two of four fans were located at ground level and the other two fans were placed 1.2m above the floor. The fans were placed 0.5m away from the room wall.

An average airspeed of 8 cm/s was applied in the experimental room. This air speed is kept slightly higher then those measured in typical indoor environments, because the air speed must not be too high to fix the particle on the wall and must not be too low to allow for particle deposition. Researchers (Matthews et al., 1989) reported that the median air-speed ranged between 1.5 to 5.8 cm/s in four residences. The airspeeds of fans were adjusted by changing the voltage applied to the fans. The room was illuminated with a fluorescent lamp in the ceiling. During the experimental, the outhor wore a polyethylene garment from head to foot and breathed fresh air from outside the experimental room via a hose. Fig.1 shows the location of equipment within the experimental room.

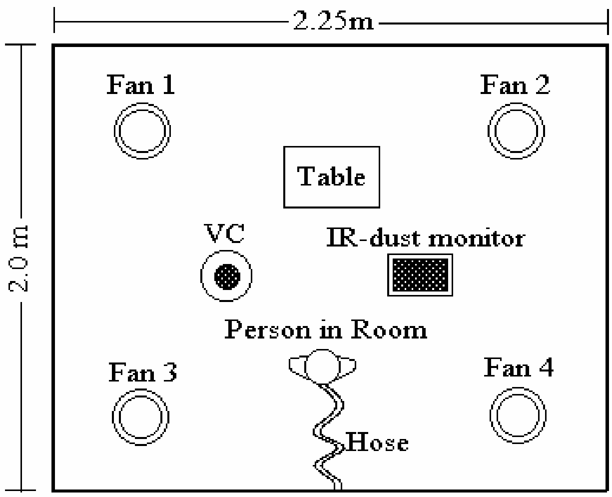

Figure 1. The Configuration of the experimental room

Suspended particle concentrations in the experimental room atmosphere, as well as living rooms atmospheres, were measured by a mobile infra-red (IR) dust monitor (Split 2 direct reading dust monitor, SKC, USA). The IR-dust monitor uses the principle of near-forward light scattering of infra-red radiation to immediately and continuously measure the concentration in mgm^{-3} of airborne dust particles (0.1 $\mu m < D_p < 10$ μm). As the airborne particles enter the infra-red beam, they scatter the light. The amount of light received by the photodetector is directly proportional to the aerosol concentration in the surrounded air. The IR-dust monitor had been calibrated by the manufacturer using Arizona road dust (particle size range from 0.1 to 10 μm). Sensing range of the IR-dust monitor is between 10-20,000 μgm^{-3}. During the experiment the particle concentration in the room atmosphere was measured at five points (four at the corners and one in the middle) of the room. All measurements were done 1.5m above the floor and 0.8m away the wall. The average measurement was given as the PM_{10} (particles with D_p <10 μm) or SP concentration in the room air.

There are many kinds of filter bags on the market for different vacuum cleaners. These filter bags are basically made of cellulose and have micropores. Some filters are mono-layer while others are double-layered. The inner layer of double layer filters is generally made of polypropylene and has larger pores than outer cellulosic layer. The images in Fig. 2 were obtained by microscopic examination of two filter samples, which have mono-layer and double-layers. Fig. 2a, 2b and 2c demonstrate inner, outer and both parts of a double layer filter, respectively; while Fig. 2d is just for the mono-layer filter. It is clearly seen on the images, that there are holes on the filter media at different shapes and sizes. All the filters used in this work have similar holes. The surface area of a hole on an image was determined by conveying the image from the microscope (Nikon, model: ECLIPSE E200, Japan) to the computer by a camera (Color video camera, model: TK-C601 EG, Japan). Micrografx Designer^{TM} (ver.3.1) was used to evaluate the areas of the holes. A hole was enlarged first in this program and then the area of the hole was divided to squares and rectangles of known. The area of a hole is equal to the total areas of squares and rectangles. In order to compute the original area of a hole one must not forget the enlargement coefficient of the microscope and the enlargement percentage in the program. The areas of holes of the filters used in this study ranged between 0.0-2.55 μm^2.

Twenty different filter bags were purchased on the market. Comparison of efficiencies of these filters was performed by cutting a 4.5 cm diameter circular sample from each filter. These filter samples were placed in a desiccator containing silica-gel and kept until use. Each filter sample was weighed by a high precision mass balance (Sartorius, model: BP1105, serial number: 50506574, readability is 0.1mg, Germany) just before and after use in order to measure the particle amounts retained by the filter. The mass of the dust retained by the filter was found by subtracting the initial mass of the blank filter by the final mass of the sampled filter.

Instead of house dust, a pumice powder (D_p<300 μm) was used for dust retention experiments as the pumice powder is more homogenized than the house dust. The house dust is a mixture of organic and inorganic materials and living biologicals, some house dusts are in the fibre form and also collecting of very small sized house dust particles by a filter is quite difficult. Therefore, a bulk dust sample was prepared using pumice, which is a volcanic rock from the Kayseri region in the Middle Anatolia of Turkey. Coarse pumice was crushed, sieved by a 60 mesh-cut sieve (in order to get a pumice dust or a pumice powder which has an aerodynamic diameter less than 300μm), dried at 105 C for 24h in an oven and kept in an air tight container. Some amount of pumice powder sample was analyzed with XRF. According to EDXRF analysis the composition of the pumice was 6.5% Al_2O_3, 57.0% SiO_2, 0.14%P_2O_5, 1.05%K_2O, 32.6%CaO, 0.05%TiO_2, 0.03%MnO and 1.3% total Fe_2O_3.

Before dust retention experiments, inner surfaces of the experimental room were cleaned with a dust-cloth, the room was aerated with fresh air, and then it was left to dry. A filter bag of the DVC was taken out and the inner surface was cleaned with a dust-cloth. After cleaning, the DVC was switched on and fresh air was vacuumed for 15 min in order to remove possible dust and moisture residuals. All these procedures were carried out before each experiment.

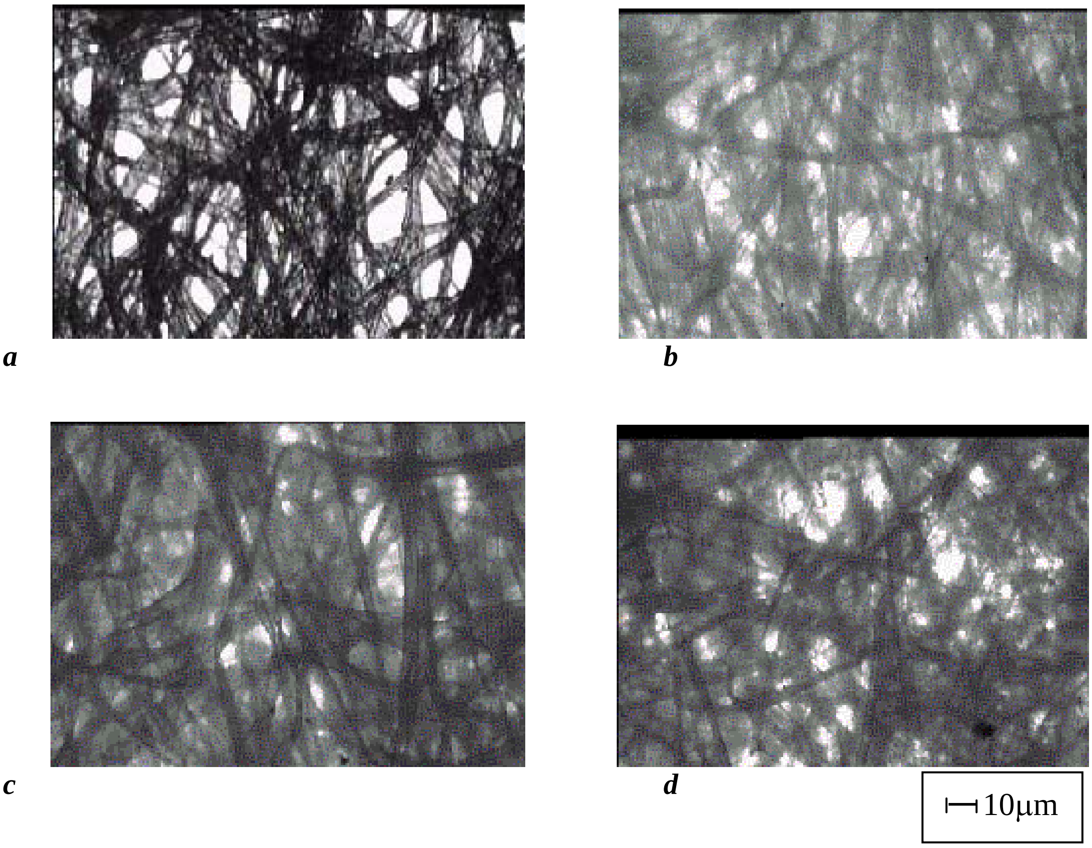

Figure 2. Photomicrographs of some filters used in DVCs, magnified 400x.
a) support layer of a double-layer filter.
b) filter layer of the double- layer filter.
c) the combination of the layers of the double-layer filter.
d) just a mono-layer filter.

In order to measure the dust retention efficiency of a filter, the filter sample was housed in a filter cell (Type: ME 4R, ABM, Germany). Then the cell was connected to a DVC which has a 1000 Watt power source similar to WVC's. The DVC was switched on and about 0.50g pumice powder was slowly and proportionally poured on the filter sample. Then the filter sample was taken out and put into another desiccator containing silica-gel, which was kept in it one hour untill weighing again. The dust retention efficiency of a filter was also cross-checked by measuring (before and after each experiment) the SP concentration in the room atmosphere by IR-dust monitor.

The dust absorption efficiency of the WVC was also investigated in this experimental room. After performing all necessary cleaning procedures for the room and WVC, about 0.50g pumice powder was spread on a clean glass surface and vacuumed by the WVC. The dust absorption efficiency of the WVC was calculated from the difference between the two measurements (before and after the absorption) of SP concentration in the room atmosphere.

The Effect of VCs on the SP Concentrations of Indoors

This study was performed in living rooms of five residential houses in order to determine the effect of vacuuming of deposited dust on the SP concentration. Five different DVCs (each one has a 1,000 Watt vacuuming power) and one WVC were used for this study. Before the experiment, DVC and WVC were cleaned as mentioned above, a new filter bag installed in the DVC and tap water filled the basin of WVC, furniture was allowed to remain, but persons residing in the home were removed, possible air passages to the room were closed, and four fans were placed at each corner. Two of four fans were located 50cm above the floor and the other two were placed 1.2m above the floor. After 3 min activating the fans, the initial SP concentration of the room was measured (one measurement at each corner and one on the middle for a total five measurements; measurement position is 1.0m away the wall and 1.5m above the floor) by the IR-dust monitor. Deposited dust on a carpet by normal activities of residences was vacuumed by the vacuum cleaners. Half the area of the carpet was vacuumed for 5min by a DVC while the fans were on, then SP concentration in the room atmosphere was measured by the IR-dust monitor for a second time. Fans were turned off and the outher observed the settlement rate of the SPs over time by IR-dust monitor untill the SP level decrease to initial level. The fans were activated again for 3 min and the initial SP concentration of the room was measured prior to a second vacuuming. Thereafter, the other half of the carpet was vacuumed by WVC for 5min while the fans were running, and then the SP concentration of the room was measured again.

The effect of the vacuuming (by DVC or by WVC) on the SP concentration of a room was determined by the difference between the SP concentrations measured before and after each vacuuming.

Determination of the SP Removabilities of VCs

This study was performed in living rooms of eight different residential houses. These rooms were fully furnished with carpeting, chairs, table, bookcase and curtains. The location of equipment and furnishings within the room were changed room to room. Four fans were placed at each corner of the room as mentioned in previous section. This part of the study was performed in three stages and all these stages were carried out in each living room.

Stage One: After all occupants of the house were taken out, possible air passages to the room were closed and fans were activated. Indoor SP concentration was elevated by shaking a used carpet. Then indoor SP concentration was measured by IR-dust monitor on five points of the room as mentioned in preceding section. Following turning off the fans, the decay rate in SP concentration within the room was determined by measuring the SP concentration over time with the IR-dust monitor. These measurements continued untill the SP level decrease to about 10% of the initial value.

Stage Two: A clean DVC (different DVC was used in each house) was placed in the middle of the room (80cm above the floor) and a clean dust bag placed in it. A 40cm hose was attached to the DVC and directed upward. A second time fans were activated and the SP level in the room atmosphere was elevated by shaking a used carpet out, and then the SP concentration was measured by IR-dust monitor as mentioned previously. Then the fans were turned off, the DVC was turned on and changing of the SP concentration in the room atmosphere was measured over time. These measurements were continued till the SP level decrease to about 10% of the initial value.

Stage Three: In this stage, a clean WVC was placed in the middle of the room instead of the DVC. Tap water filled its basin as directed in the user guide. A 40cm hose which was directed upward was attached to the WVC. The SP level in the room atmosphere was elevated as done previously and the initial concentration was measured by IR-dust monitor while fans were running. Then the fans were turned off and the motor of the WVC was powered. Decreasing SP concentrations in the room atmosphere was detected by IR-dust monitor till its level decrease to about 10% of the initial value.

Result and Discussion

Dust Retention Efficiency of Filters

Dust retention efficiencies of filters of different vacuum cleaners are given in Table 1. One can see, in the sixth column of the table, which dust retention efficiencies of the filters range between 91-99%. Column seven shows that these dust retentions are not very efficient, because SP concentrations in the experimental room increase to very high levels after vacuuming. There are some discrepancies between the calculated and experimental results of SP concentrations measured in the experimental room. For example, one can calculate the SP concentration in the room atmosphere after the first filter experiment as 2,515 $\mu g.m^{-3}$ [SP, $\mu g.m^{-3}$ = (initial amount of dust-retained amount of dust)/(the room volume) x10^6]. But, the SP concentration in the room atmosphere was measured as 2.450 $\mu g.m^{-3}$ by IR-dust monitor after the first filter experiment. This lower measurement is due to the settling out of dust on the surfaces of everything in the experimental room.

Table 1. Dust retention efficiencies of dry vacuum cleaner filters.

Filter No	Initial filter weigh (g)	Final filter weigh (g)	Initial amount of dust (g)	Retained amount of dust (g)	Dust retention efficiency (%)	Initial SP concentration in the room ($\mu g.m^{-3}$)	Final SP concentration in the room ($\mu g.m^{-3}$)	Increase in the SP concentration of the room (%)
1	0.1142	0.5833	0.5008	0.4691	93.67	<10	2,450	99.59
2	0.1240	0.6104	0.5011	0.4864	97.07	<10	1,100	99.10
3	0.1806	0.6555	0.5009	0.4749	94.80	12	1,910	99.37
4	0.1457	0.6215	0.5005	0.4758	95.06	<10	1,860	99.46
5	0.1423	0.6085	0.5013	0.4662	93.00	<10	2,670	99.62
6	0.1628	0.6406	0.5013	0.4778	95.31	<10	1,770	99.43
7	0.1414	0.5991	0.5010	0.4577	91.36	11	3,280	99.66
8	0.1472	0.6162	0.5008	0.4690	93.65	13	2,430	99.46
9	0.1216	0.6011	0.5009	0.4795	95.72	<10	1,270	99.20
10	0.1377	0.6096	0.5007	0.4719	94.25	<10	2,170	99.54
11	0.1592	0.6445	0.5003	0.4853	97.00	<10	1,100	99.10
12	0.1000	0.5859	0.5010	0.4859	96.98	<10	1,100	99.10
13	0.1120	0.5952	0.5008	0.4832	96.48	12	1,320	99.10
14	0.1116	0.5922	0.5005	0.4806	96.02	12	1,490	99.20
15	0.1337	0.6114	0.5009	0.4777	95.37	<10	1,750	99.43
16	0.1163	0.5645	0.5007	0.4582	91.57	<10	3,220	99.70
17	0.1084	0.5658	0.5006	0.4574	91.37	14	3,250	99.57
18	0.1378	0.6268	0.5007	0.4890	97.66	11	840	98.70
19	0.1091	0.5945	0.5009	0.4854	96.90	13	1,140	98.86
20	0.1333	0.6247	0.5008	0.4914	98.12	15	720	97.72
WVC	------	----	0.5011	------	100.0	<10	<10	0.00

These SPs, which pass through the filter media, because of the pore size limitations of filter bags are less than 2 μm. That size particles can penetrate the alveolar of the lung when inhalated. Such a release of fine particles out of a vacuum cleaner can occur every time if vacuum cleaners which use a filter media for dust retention are used to remove deposited dust on floors.

There were no SPs measured in the experimental room when the dust sample was vacuumed by the WVC. This means that the WVC absorbed all the dust it vacuumed into the water. One can say that the comparison of dust retention efficiency of a filter of a DVC with dust absorption efficiency of a WVC is not meaningful, because both are different processes. This is correct when we look at the occurrence from the view point of the dust removal process. But the important thing to remember is that the dust removal efficiency not the same as the dust removal process.

Removal of Dust from House Floor

In order to compare the dust removal efficiencies of vacuum cleaners one-half the carpet, on which dust was already deposited by normal house activities, was vacuumed by the DVC and the other half was vacuumed by the WVC. These operations were carried out in five different living rooms using five different DVCs and one WVC. All the VCs used had the same motor power.

Table 2 shows the dust removal efficiencies of dry and wet vacuum cleaners from a carpet. In order to see the dust removal efficiency of a vacuum cleaner one must compare the amount of SP concentrations measured in a living room atmosphere before and after each vacuuming. The vacuuming activity elevated the suspended particle concentrations 2-3 times when DVCs were used. It has been reported that the indoor concentrations of PM_{10} were usually elevated above 100 μg m^{-3} when vacuuming was carried out (Corsi and Chang, 2000). It has also been indicated that indoor activities, such as vacuuming, dusting, washing and carpet cleaning, contributed from 50% to 80% of the indoor concentrations of 2-10 μm particles (Abt et al., 2000). The aerodynamic diameters of particles mentioned in those citations range between 0.0-10 μm. The SP concentration measured by IR-dust monitor in this study is also PM_{10}, but the particles which have aerodynamic diameter less than 2 μm can just be released out of the DVCs because of the pore size limitations of their filters. This size of particles is more important due to their penetration capability into the lung. Despite the DVCs, concentrations of SPs in rooms were not increased when the other half of the carpet was vaccumed by the WVC (Table 2). This means that the WVC absorbed all the dust it vacuumed into water.

Table 2. Dust removal efficiencies of dry and wet vacuum cleaners from the room floors.

Room No	Gross volume of the room (m^3)	Carpet size (m^2)	Initial SP concentration in the room (μg m^{-3})		Final SP concentration in the room (μg.m^{-3})		Increase in SP concentration (%)	
			Before to DVC	Before to WVC	After DVC	After WVC	By DVC	By WVC
1	67.2	4.6	15	18	60	20	300.0	11.1
2	60.4	3.8	37	39	110	41	197.3	5.1
3	72.4	5.4	27	31	80	32	196.3	3.2
4	68.8	3.6	21	25	70	25	233.3	0.0
5	71.7	6.0	12	15	53	15	341.7	0.0

Removal of Suspended Particles

The results of removal efficiencies of airborne particles by self deposition and by vacuuming are given in this section. In every living room the following operations were carried out: 1) measuring normal SP concentration level by IR-dust monitor, 2) shaking a used carpet out and measuring the SP concentration level while fans were on and then determining the decaying rate of SPs by time while fans were off, 3) shaking another used carpet out and measuring the SP concentration level with fans are on and then determining the decaying rate of SPs by time while fans were off and a DVC was on, and 4) shaking a third used carpet out and measuring the SP concentration level while fans were on and then determining the decaying rate of SPs by time while fans were off and the WVC was on.

Table 3 summarizes the removals of airborne particles from the atmospheres of eight different living rooms. As can be seen from the Table 3, there are no differences between the removal rates of SPs from a living room atmosphere by self-deposition or by vacuuming with a

DVC. Even though, the effect of DVC on the stability of the room air, the time required for the removal of SPs of 90% when a DVC was on was higher than that of self deposition time.

A comparison of the removal rates of the SPs from the atmospheres of different living rooms by self deposition, by DVCs and by WVC are illustrated in Fig.3. Although the DVCs used have the same motor power, surface areas and characteristics of their filters were different. Therefore, experimental results obtained from every room were illustrated separately. It is clearly seen from the Fig.3 that removal SPs of 90% occurred in about seven minutes when the WVC was used. It is also possible to remove almost 100% of the SPs from a sealed room atmosphere by running a WVC for an additional time period. When a room air was vacuumed by a DVC, the SPs self deposition occurred and the SP removal curves reached a plateau (Fig. 3). In reality, the apparent plateau is not constant, but decays slowly as the concentration of small particles decreases. This means that some airborne particles (such as fine particles) can be suspended for long periods oftime in a room atmosphere after resuspension by the occupants' activities.

Table 3. Removal of SPs by self deposition, by DVCs and by WVC

Room No	Gross volume of the room (m^3)	Normal PM_{10} level of the room ($\mu g\ m^{-3}$)	Self deposition exps.		DVC exps.		WVC exps.	
			PM_{10} level after shaking a used carpet out ($\mu g\ m^{-3}$)	Time for self deposition of SPs of 90% (min)	PM_{10} level after shaking a used carpet out ($\mu g\ m^{-3}$)	Time for the removal of SPs of 90% (min)	PM_{10} level after shaking a used carpet out ($\mu g\ m^{-3}$)	Time for the removal of SPs of 90% (min)
6	53.8	18	1,140	22	1410	24	1,260	5.22
7	59.2	25	1,260	18	1400	22	1,320	6.10
8	55.2	35	1,720	23	1580	23	1,540	5.48
9	69.6	22	1,130	20	1250	20	1,280	7.35
10	63.9	19	980	17	1110	18	1,270	6.48
11	61.0	18	1,050	17	980	18	970	6.15
12	74.2	13	720	18	830	18	810	6.00
13	65.9	17	1,020	19	1050	19	1,150	6.15

Removal of SPs in a room atmosphere by self deposition depends on properties of the particles, such as size, shape, and density, as well as properties of the deposition environment such as surface area and orientation, surface roughness, air flow conditions, electrical charge, and surface-to-air temperature difference. Gravitational deposition of particles reduced substantially the concentration of indoor SPs, but the use of a WVC increased removals of SPs. In addition, some amount of deposited dust can always be re-suspended by normal housing activities; but absorption of airborne particles into water by a WVC can reduce a portion of the dust which has resuspension characteristics.

As it has seen in Table 2 and Table 3, the SP concentrations measured in thirteen living rooms before the vacuuming or shaking out the carpets changed between 12-37 $\mu g.m^{-3}$. The average values of SP concentrations measured in this work are given in Table 4 with the literature values. These PM_{10} values measured in Samsun which is located the Black Sea coast in northern Turkey and similar to the SP concentrations measured in Europe.

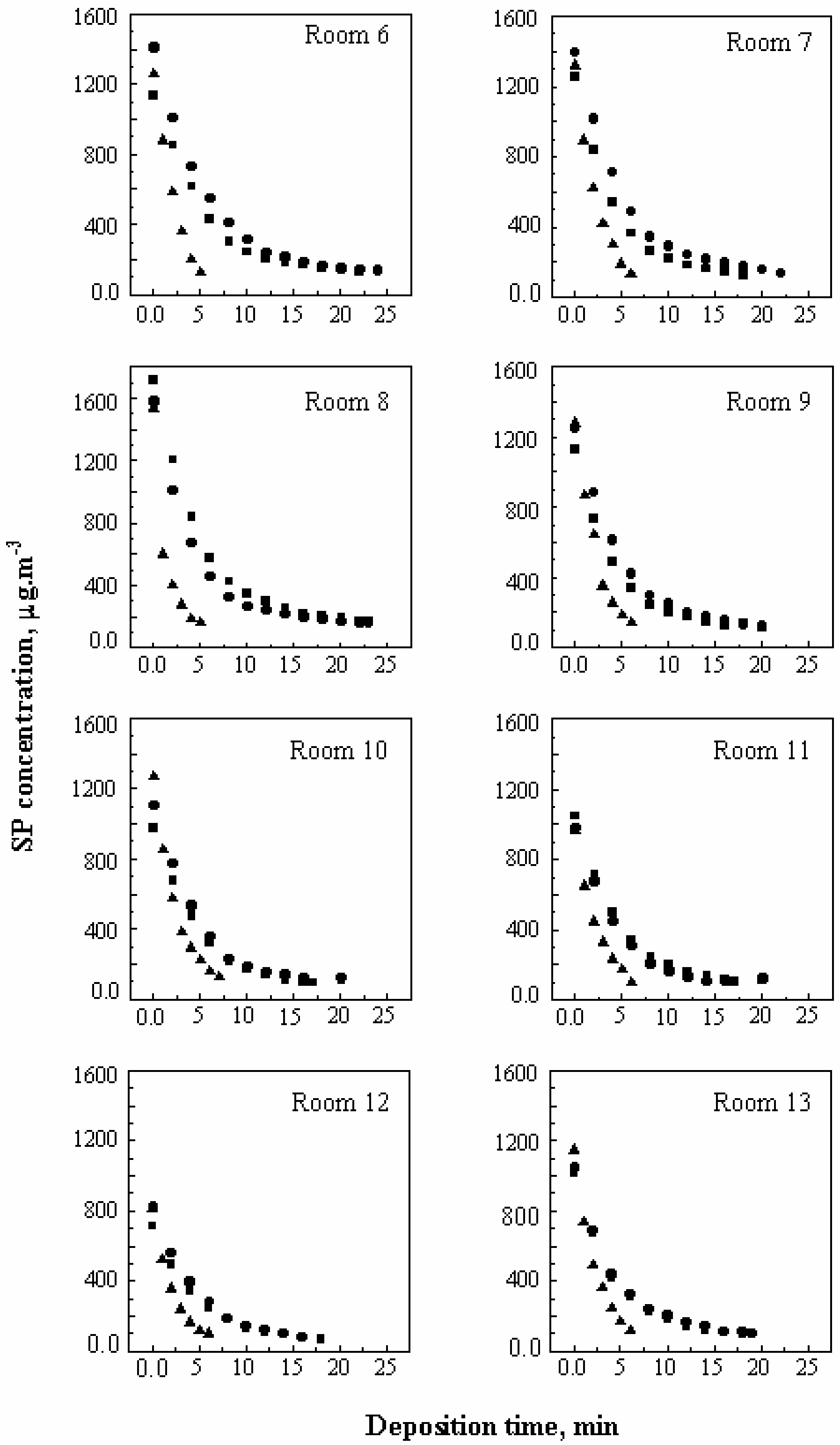

Figure 3. Removal of SPs by vacuum cleaners together with self deposition

▪ self deposition of SPs

● self deposition of SPs plus the effect of DVC

▲ self deposition of SPs plus the effect of WVC

Table 4. Comparison of the average PM_{10} value determined in this study with the literature values.

Place	Indoor		Outdoor		References
	$PM_{2.5}$ μg m^{-3}	PM_{10} μg m^{-3}	$PM_{2.5}$ μg m^{-3}	PM_{10} μg m^{-3}	
U.S.A	$17.3^{(f+g)}$ $48.5^{(e+g)}$				Neas *et al*., 1994
U.S.A	10.8	23.8			Haller *et al*., 1999
U.S.A	$15.45^{(a,b)}$	$5.63^{(a,b)}$	$15.02^{(a+b)}$	$8.61^{(a,b)}$	Geller 2002
U.K (Birmingham)	7.9	16.5	9.1	13.4	Jones *et al*., 2000
Portugal		40^{e} 38^{f}			Phillips *et al*., 1998
Switzerland		60^{e} 31^{f}			Phillips *et al*., 1999
Taiwan(Taipei)		82.8		107.5	Li, 1994
Japan(Tokyo)	69.9^{a} ;34.6^{c}				Hirosihi *et al*., 1994
Hong Kong		78.8^{g}		73.3^{g}	Tung *et al*., 1999
Hong Kong	22.2^{a}; 14.3^{d} 50.6^{e}; 42.7^{f}	104.6^{a}; 86.2^{d} 71.5^{e}; 60.0^{f}	56.4^{a}; 40.1^{d}	76.7^{a}; 57.5^{d}	Chao & Wong 2002
Hong Kong		155^{e}; 148^{f}			Lee *et al*., 2002
Turkey (Samsun)		$21.46^{(b+f)}$			This study

a: winter measurement, *b*: spring measurement, *c*: summer measurement,
d: autumn measurement, *e*: with smoker, *f*: without smoker,
g: annual mean concentration

Summary and Conclusion

In this study, dust retention efficiencies of typical vacuum cleaners bags were analyzed comparatively with dust absorption efficiency of a wet dust absorber. Results showed that a vacuum cleaner bag retained large particles and blew fine dust laden air into the indoor atmosphere. In comparison a typical vacuum cleaner bag, a wet dust absorber (wet vacuum cleaner), trapped all the dust it vacuumed. The wet vacuum cleaner also absorbed suspended particles.

In addition to inadequate dust retention efficiency of bags, large particles quickly clog the tiny holes in the bag; reducing air flow through the bag and the cleaning efficiency. Therefore, the bags of dry vacuum cleaners must be replaced frequently. However, wet vacuum cleaner has stable cleaning efficiency even for fine particles.

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