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Laboratory study of the impact of evaporative coolers on indoor PM concentrations

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Abstract

Evaporative cooling is used extensively in low humidity areas of the Southwest United States desert region and throughout other dry climate areas worldwide for residential thermal comfort. A literature review suggested the possibility of evaporative cooling increasing personal exposures to particulate matter along with increased incidences of respiratory illnesses.

Indoor and outdoor particulate matter concentrations have been measured to determine the effects of evaporative cooling on ambient air in an evaporative cooler test chamber. The test chamber experiment was conducted to better evaluate the impact of evaporative cooling without interference by household activities such as cooking, cleaning, smoking, etc. Measurement of particulate matter was performed with tapered element oscillating microbalance (TEOM) instruments to provide a larger number of data points for comparison. Based on the experiments performed on two popular models of evaporative coolers, it was found that the evaporative cooler reduces indoor PM_{10} by approximately 50%, and has a varying reduction effect of between 10 and 40% on $PM_{2.5}$. These findings are consistent with the predicted outcomes suggested by particulate matter deposition models.

Keywords: Air pollution; Evaporative cooler; Particulate matter; Indoor–outdoor ratio

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1. Introduction

1.1. Evaporative cooling impact on PM and health

Evaporative cooling provides an economical means of personal thermal comfort in arid climates. It is used in about 90% of the residences in the West Texas region and approximately 4.5 million residences throughout the United States (Foster, 1999). Worldwide, evaporative cooling is used extensively in regions of dry climate such as northern India, South Africa, and Australia (Watt and Brown, 1997). With the mounting scientific evidence (U.S. EPA, 1997) on the health effects associated with exposure to airborne particulate matter (PM), and the increased air exchange between the indoor and outdoor environments caused by the evaporative cooler, the impact of evaporative cooling on indoor environment becomes an important issue for the residents of the southwest U.S. and inhabitants of dry arid regions in the world.

1.2. Indoor/outdoor ratios for PM with evaporative cooling

At present time, there appears to be relatively little information available regarding the indoor exposure to atmospheric pollutants for persons using evaporative cooling in their residences. Quackenboss et al. (1989)

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found a median PM indoor/outdoor (I/O) ratio of 0.63 for homes without reported smoking, and 1.1 for those with smoking during an epidemiological study in the Tucson, Arizona area. They reported that both $PM_{2.5}$ and PM_{10} concentrations in the homes equipped with evaporative coolers were consistently lower than those homes not equipped with evaporative coolers by 40–70%. Quackenboss' observations suggest that the usage of evaporative coolers in many homes during several months of the year may act as a significant removal mechanism in homes.

Thompson et al. (1973) investigated two schools and one private home with evaporative coolers for I/O ratios. In all three locations with evaporative cooling, the indoor PM concentration was higher than the outdoor. Higher indoor PM concentrations did not occur in any of the eleven other locations with refrigerated air conditioning. Impeller humidifiers (similar in concept to the evaporative cooler) create elevated levels of PM in residences (Highsmith and Rodes, 1988). Residential indoor PM concentrations appeared to vary proportionately with regard to the type of humidifier and the mineral content of the water. A correlation coefficient of 0.97 was found between fine particulate concentrations and total dissolved solids in the water used in the humidifiers. While steam humidifiers resulted in no discernible change in typical indoor $PM_{2.5}$ levels (measured to be about 16 $\mu g\, m^{-3}$), the use of ultrasonic humidifiers resulted in measured household $PM_{2.5}$ levels of up to 593 $\mu g\, m^{-3}$ and $PM_{2.5-10}$ levels between 25 and 65 $\mu g\, m^{-3}$. Even more alarming were the PM concentrations resulting from the use of ultrasonic humidifiers in closed rooms where $PM_{2.5}$ levels exceeded 6000 $\mu g\, m^{-3}$ and $PM_{2.5-10}$ levels were above 770 $\mu g\, m^{-3}$.

Contradictory findings have been reported about the contribution of evaporative cooling to indoor PM levels. Quackenboss et al. (1989) suggested that evaporative cooling reduces indoor PM and the California study (Thompson et al., 1973) indicated higher indoor PM where evaporative cooling is used. Highsmith and Rodes (1988) showed that humidifiers ("cousins" of the evaporative cooler) increase PM levels in the home.

1.3. Health effects in homes with evaporative cooling

Among the health effects, dust-borne organisms affecting the lives of thousands of residents of Arizona, California and other southwestern states, the so called "valley fever" or "desert fever" caused by the fungus *Coccidioides immitis*, are of particular concern to the residents of dry arid regions (Leathers, 1981). Aldous et al. (1996) examined the relationship between several home environmental factors and lower respiratory tract illness (LRI) in infants at homes equipped with evaporative coolers. A statistically significant relationship between wheezing LRI in infants living with other children in a house and the use of evaporative cooling was found (24% versus 15% for non-evaporative air cooled homes). This study also found an increased occurrence of non-wheezing LRI for infants as neighborhood dustiness increased. Unfortunately, no measurements of PM levels were made and the assessment of "dustiness" was based on subjective records provided by the adult test subjects participating in the study. The study suggested that outdoor PM is related to chronic cough, bronchitis, and "chest illness", but not to asthma or wheezing and that evaporative cooling may introduce pollutants other than ambient PM (pollen, fungi, or other particulates) contributing to increased LRI rates.

1.4. Research objective

Our research objective is to determine the effect of evaporative cooling on indoor PM concentrations in a community where evaporative cooling is the prevalent method of summertime residential cooling. To implement the objective, evaporative cooling effects on indoor PM concentrations were first evaluated under several laboratory controlled conditions. The laboratory studies are intended to isolate the effects of evaporative cooling without interference by human or other activities within a house. PM removal mechanisms were examined and their respective removal efficiencies were quantified for PM sizes ranging from 0.1 to 20 μm based on physical characteristics of evaporative coolers. Comparisons between predicted and measured PM levels are presented.

2. Experimental setup

2.1. Evaporative coolers

A residential evaporative cooler consists of a blower fan and moisture-laden pads. A pump delivers water to pads, generally a cellulose product, and the dry outside air is drawn through the pads and delivered into the home. The temperature drop of the air is a function of the difference between wet- and dry-bulb temperatures and the efficiency of the evaporative cooler system. The system efficiency is dependent on the ambient temperature, relative humidity, cooler blower air speed, turbulence in and thickness of the moisture pad, area of the wetted pad, and water quality.

The most popular evaporative coolers employ two categories of cooler pads: aspen excelsior and rigid cellulose media. The aspenpad cooler draws outside air into all four sides through metal panels that support the aspenpads. The aspen wood is used due to its properties of being odorless, chemically inert, and easily absorbent and wettable (Watt and Brown, 1997). The wood is shaved into excelsior strands generally between 0.25 and 2.5 mm wide and thick with lengths of at least 25 mm. These strands are formed into rectangular pads approximately one inch thick and inserted into the vertical holders to prevent sagging. Figs. 1 and 2 show a typical aspenpad in its holder with a close-up view of the aspenpad media.

Rigid media pads are made of special wettable cellulose in corrugated sheets bonded together at opposing angles to form a 15-cm thick filter. The angles of the corrugated cellulose are intended to maximize air contact and evaporation (Watt and Brown, 1997). The rigid media pad has a longer useful life than aspenpads, but is higher in initial cost. Figs. 3 and 4 show a commercially available rigid media pad with a close-up of the cellulose material.

The evaporative coolers used in our laboratory experiment are the MasterCool Model M63C (rigid media pad) and the Champion Model 4800DD (aspenpad). These coolers were purchased from a large home furnishing supplier and are representative of evaporative cooler models installed homes in the Southwest United States. Most large residential evaporative cooler units can be run at either low or high fan speeds. The MasterCool MC63C has rated discharge speeds of 5500 cfm (high speed) and 3575 cfm (low speed). The Champion 4800DD has rated discharge speeds of 4800 cfm (high speed) and 3120 cfm (low speed). The water pump used to soak the media pads can be turned on or off during ventilation. In the water pump "off" position, the evaporative coolers essentially become ventilators. Physical dimensions and flow characteristics in the pad media are listed in Table 1.

2.2. The environmental chamber

A chamber was built to install and run the evaporative coolers under relatively controlled conditions. The chamber has a cross-section of 4-feet × 4-feet and a length of 20 feet to assure uniform mixing from the inlet end to the discharge end. The evaporative cooler was installed on the top of the inlet end of the chamber to

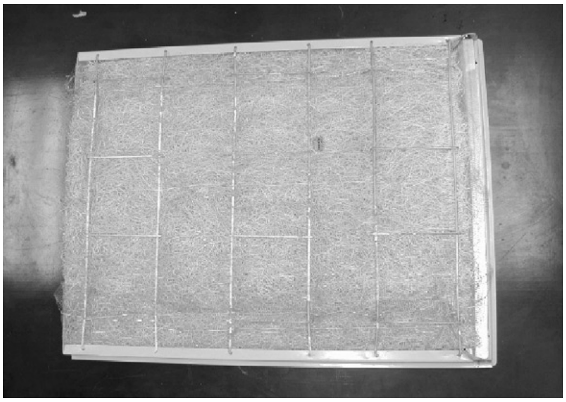


Fig. 1. Aspenpad in holder.

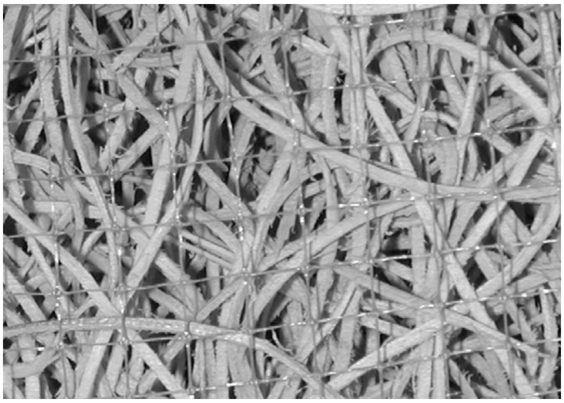


Fig. 2. Close-up of aspenpad media.

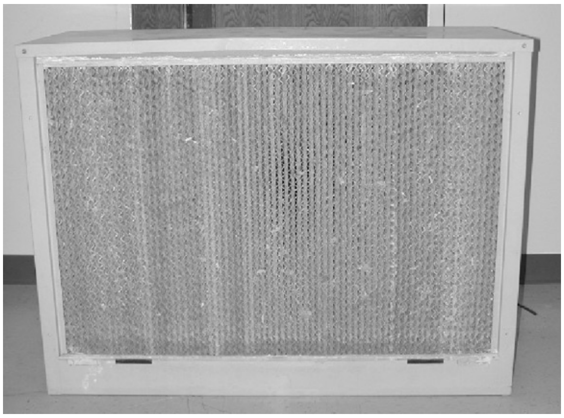


Fig. 3. Rigid media pad in holder.

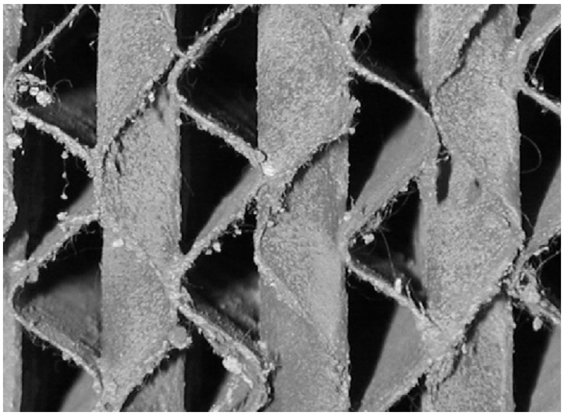


Fig. 4. Close-up of rigid media pad.

Table 1
Flow characteristics in the media pads

Flow characteristics in the pad media		Rigid media	Aspenpad
Characteristic thickness of the pad (D)		0.00025 m	0.0007 m
Characteristic width of pad spaces (D)		0.011 m	0.001 m
Air flow velocity—High (U)		3.87 m s^{-1}	1.10 m s^{-1}
Air flow velocity—Low (U)		2.52 m s^{-1}	0.74 m s^{-1}
Reynold Number around the pad fiber	High speed	64	51
	Low speed	41	34
Reynold Number inside the pad media	High speed	2829	730
	Low speed	1841	492
Kinetic viscosity (v)		15.05×10^{-6} m s^{-1}	

simulate the downdraft of cooling air in a typical house. Cabinets were installed under the discharge end of the chamber to house both controller units and one TEOM (indoor) sensor within the chamber. A damper was installed on the discharge end of the chamber to reduce sunlight and heat in the chamber, prevent the backwash of ambient air during periods of high winds, and exclude the entry of particles during periods of non-use. The chamber was situated outdoors in a secured area to prevent interferences during experimentation.

2.2.1. The TEOM

PM levels were measured using the TEOM (Tapered Element Oscillating Microbalance) instruments manufactured by Rupprecht and Patashnick Co., Inc. (1996). TEOM instruments were selected for this experiment due to their ability to provide continuous pseudo-instantaneous short-term average PM mass concentrations down to 10-minute increments. The TEOM instrument has been commercially available since 1988 and was designated as an EPA PM_{10} Federal equivalent method in 1990 (Meyer et al., 2000). The TEOM instrument calculates PM concentrations using the physical laws of spring-mass behavior. The instrument automatically provides adjustment for atmospheric variables such as temperature, pressure and humidity (Rupprecht and Patashnick, 1996).

Two TEOM units were used to record indoor and outdoor $PM_{2.5}$ and PM_{10} mass concentrations in this study. Prior to experimentation, a number of side-by-side runs were performed in adjacent locations under the same environmental conditions for quality assurance. For experimentation, the outdoor TEOM sensor unit was placed with a white climatic protection enclosure on a platform such that the inlet head was about six feet from the vertical center of the evaporative cooler inlet. The "indoor" TEOM sensor unit was installed in the test chamber, approximately three feet from the discharge end with the collection head slightly less than three feet above the chamber floor.

The TEOMs were set to record 10-min increments of mass concentration. Both units had their internal clocks synchronized to assure simultaneous time-period readings. Data were periodically downloaded via an RS232 port into a notebook computer and then transferred to Excel spreadsheets for analysis.

2.2.2. Experiment procedures

The evaporative coolers were operated under a variety of conditions including fan speed (low or high), water (on or off), water type (distilled or tap) and use of water supply bleed-off (on or off). Distilled water was used to minimize the possible effect of dissolved solids that are found in the tap water. The bleed-off valve for the water pump allows a partial draining of the cooler pan water and increases the influx of fresh water supply to dilute the concentration of dissolved solids in the water pan. It is designed to reduce the subsequent deposition of mineral salts that impede airflow through the media pad and damage the internal structure of the cooler through corrosion.

A total of 28 cooler operating conditions (16 for PM_{10} and 12 for $PM_{2.5}$) were examined in the environmental chamber. Concurrent indoor and outdoor 10-minute concentrations were recorded for various lengths of sampling duration. Sampling durations were set to 24-h for all operating conditions; however, distilled water duration was reduced to a minimum of two-hours due to the difficulty of physically supplying water to the reservoir mounted above the environmental chamber. Measurements were continued, typically by days, into weekends or holidays for convenience and additional data. The final size of sample runs varies due to the various sampling durations and the elimination of invalid data. Invalid data were caused by incomplete sampling time, power failure, occasional instrument malfunction due to excessive sunlight, change of operating conditions, or signal interference by the research personnel during the experiments.

2.2.3. QA/QC

During the course of this study, instrument data, instrument and chamber physical conditions and environmental factors were carefully monitored and PM data was downloaded as often as possible. TEOM maintenance, service, and filter changes were performed according to the manufacturer's recommendations. Periodic flow rate checks were performed on the TEOM instruments using the mini-Buck Calibrator, Model M-30, calibrated 8/3/00. Side-by-side outdoor TEOM $PM_{2.5}$ and PM_{10} monitoring was performed before and during the experiments to assure data repeatability. Repeatability between the two TEOMs appears to be excellent for PM_{10}, with more than 99% ($R^2 = 0.997$) of the data explained by a linear relationship within 5% accuracy. The accuracy for the $PM_{2.5}$ measurement remains within 5% error, but the repeatability decreases somehow to explain only 76% of the data. Inherent "noise" and operation of the TEOM (Williams et al., 2000), wind gusts, short-term averaging time, as well as inhomogeneous concentration distribution between the two TEOMs, spaced approximately six feet from each other, could have contributed to the deviation.

3. Results and discussions

Graphs were generated for each operating condition with linear regression analysis listing slope and the coefficient of determination, R^2. Tables 2 and 3 summarize all results of the indoor/outdoor (I/O) ratios and the associated regression analyses for $PM_{2.5}$ and PM_{10}, respectively. In the tables, "Dry" represents the runs with no water, "Speed" refers to the two blower fan's ventilation rates: "Low" and "High", "Bleed" refers to blower fan operation with local tap water in system using bleed-off to remove water and help decrease solids accumulation, "Di" for de-ionized water and "Tap" for tap water used for evaporative cooling, and "n" indicates the number of 10-min samples used in the analysis.

Table 2
$PM_{2.5}$ results for rigid media pad and aspenpad coolers

$PM_{2.5}$ indoor/outdoor (I/O) ratio, R^2, and sample size n

Operating condition	Rigid media pad			Aspen pad		
	I/O ratio	R^2	n	I/O ratio	R^2	n
Dry, low speed	0.93	0.81	30	1.04	0.81	289
Dry, high speed	1.14	0.94	107	1.02	0.83	185
Di-water, low speed	1.09	0.52	33	1.12	0.48	23
Di-water, high speed	1.01	0.97	31	0.89	0.04	24
Tap-water, low speed	1.04	0.71	122	0.76	0.85	359
Tap-water, high speed	0.89	0.98	133	0.80	0.93	253
Tap, bleed on, low	0.99	0.54	137	0.63	0.84	327
Tap, bleed on, high	0.92	0.88	175	0.50	0.52	236

Table 3
PM_{10} results for rigid media pad and aspenpad coolers

PM_{10} indoor/outdoor (I/O) ratio, R^2, and sample size n

Operating condition	Rigid media pad			Aspen pad		
	I/O ratio	R^2	n	I/O ratio	R^2	n
Dry, low speed	0.72	0.92	145	0.73	0.97	408
Dry, high speed	0.70	0.98	241	0.72	0.83	143
Di-water, low speed	[a]			0.99	0.30	13
Di-water, high speed	[a]			0.79	0.33	41
Tap-water, low speed	0.53	0.94	422	0.62	0.99	270
Tap-water, high speed	0.51	0.51	828	0.59	0.92	429
Tap, bleed on, low	[a]			0.61	0.99	273
Tap, bleed on, high	[a]			0.50	0.99	238

[a] Runs not performed.

3.1. Baseline PM indoor/outdoor ratio without evaporative cooling

Baseline measurements were performed to evaluate the I/O PM ratios when the evaporative cooler was basically used as a house fan. With no other indoor sources, the increase or decrease of PM indoors is essentially the result of the presence of the dry pad in the ventilation duct.

The $PM_{2.5}$ I/O ratio, as shown in Table 2, remains stable at 1.0 for aspen pad and fluctuates around 1.0 for the rigid media pad indicating that outdoor fine particulate can infiltrate into the indoor environment with little difficulty through the dry pads. As indicated in Table 1, the potentially transitional flow inside the rigid media pad under the high fan speed operating condition (with a Reynolds number around 3000) may re-suspend the fine particulate previously deposited on the pad and transport it into the indoor environment resulting in a $PM_{2.5}$ I/O ratio exceeding 1.0 at high fan speed. The 1.1 I/O ratio may also reflect resuspension of PM previously deposited during prior experimental runs in the environmental chamber. During the dry experimental runs, $PM_{2.5}$ was recorded in concentrations ranging from 0.0 to 88 $\mu g\ m^{-3}$ outdoors and 67 $\mu g\ m^{-3}$ indoors. Regardless the type of the media pad and potential difference in the flow pattern inside the media pads, in general, ambient fine particulate is transported into the indoor environment through the dry media pads with no reduction.

Significant reduction in indoor PM_{10} was observed in all test runs without the application of water. The PM_{10} I/O ratio stays at 0.7 with excellent explanation of the data variation. The difference in the media pads employed appears to have indistinguishable effect on the infiltration of coarse particulate into the indoor environment. An approximate 30% reduction of ambient PM_{10} was achieved when the airflow was re-directed into the indoor environment through dry media pads, regardless of possible resuspension occurrence. During the dry experimental runs, PM_{10} was recorded in concentrations ranging from 0.0 to almost 800 $\mu g\ m^{-3}$ outdoors and 600 $\mu g\ m^{-3}$ indoors. Mechanisms of PM reduction caused by the presence of media pad will be further assessed in Section 3.3.

3.2. PM indoor/outdoor ratio with evaporative cooling

Two types of water (de-ionized and tap water) were used in the current study. The de-ionized water was used to assess the impacts of total dissolved solids (TDS) in water on the indoor PM concentration.

3.2.1. I/O ratio with di-ionized water for evaporative cooling

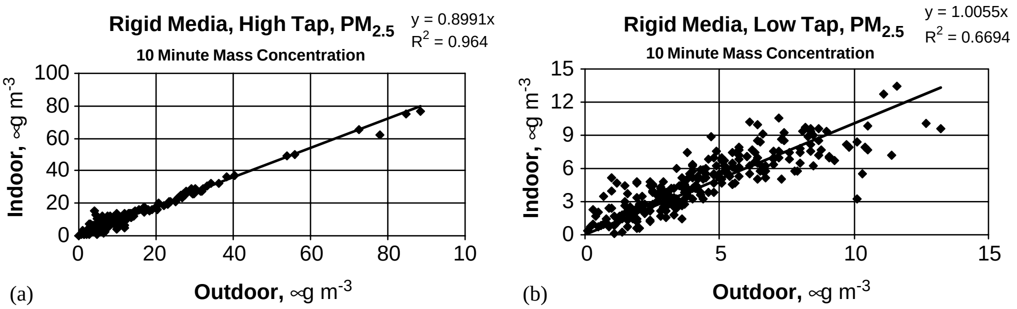
TDS in the water used for evaporative cooling may increase the level of ambient PM concentrations when water droplets evaporate in the air and TDS becomes airborne. Since no formation of water mists/droplets were observed inside the media pads, TDS is not expected to be a contributor to the increase of indoor PM as observed with the use of ultrasonic humidifiers (Highsmith and Rodes, 1988). Tables 2 and 3 show a relatively low correlation (with $R^2 < 0.5$) was found for all but one test run using de-ionized water. Feeding of de-ionized water into the media pads during the experiment was found to be unsteady, insufficient to wet the whole pads at all time, and disturbing to the environmental chamber system when accessing the de-ionized water tank. In addition, one notices that although our environmental chamber afforded us to evaluate the impacts of evaporative coolers on indoor PM levels, the PM drawn into the environmental chamber was actual PM in the ambient air. Thus, a clean day with steady low PM concentrations will result in low PM readings with high degrees of fluctuation due to the accuracy and resolution of the TEOM instrument. Consequently, some of our test runs results (e.g. results for de-ionized water, high fan speed $PM_{2.5}$ run and de-ionized water, low fan speed PM_{10} run) collected during low PM days suffered a high degree of indetermination in their respective regression analysis. As a result, these results were excluded from further evaluation.

3.2.2. I/O ratio with tap water for evaporative cooling

Tap water was used with "bleed" control on and off in this phase of study. Because "bleeding" of the evaporative pan water changes only the TDS levels in the water and because TDS does not contribute to the formation of airborne PM, those test runs associated with evaporative pan water bleeding were combined with those no-bleeding runs. Combination of test runs increases the size of the samples and helps to stabilize the results of the regression analysis.

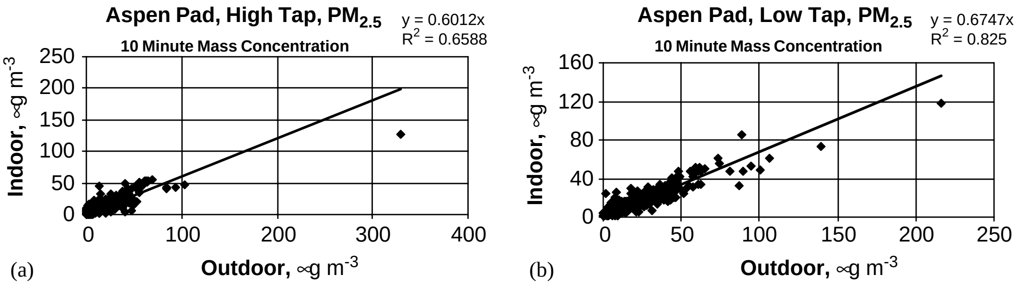
Fig. 5 shows the $PM_{2.5}$ I/O ratios for the rigid media pad at two fan operating conditions. It is shown in Fig. 5a that approximately 10% of the outdoor $PM_{2.5}$ is removed upon the entrance of the indoor environment through the rigid media pad at high fan speed, and 0% at low fan speed (Fig. 5b). The removal mechanism becomes more effective for the aspen pad where 40% of $PM_{2.5}$ was removed when the cooler was operated at high fan speed (Fig. 6a), and approximately 30% at low fan speed (Fig. 6b). Both rigid media and aspen pads provide approximately the same level of removal efficiency in reducing the ambient PM_{10} level by approximately 50%, as shown in Figs. 7 and 8, respectively.

With the presence of water, the moisture laden rigid media pad increased the efficiency of $PM_{2.5}$ removal from 0% to less than 10%, but more effectively from 30 to 50% for PM_{10}. The improvement of PM removal for the moisture-laden aspen was from 0% to



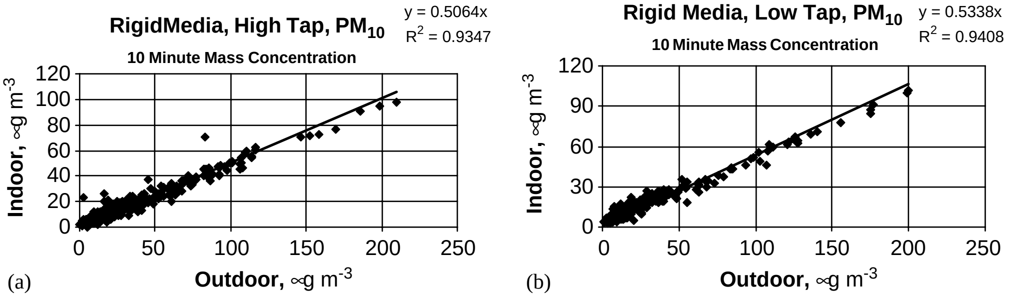
(a) (b)

Fig. 5. Indoor/outdoor $PM_{2.5}$ air concentration with wetted rigid media pad under (a) high fan speed with tap water (high tap) and (b) low fan speed conditions with tap water (low tap).



(a) (b)

Fig. 6. Indoor/outdoor $PM_{2.5}$ air concentrations with wetted aspenpad under (a) high fan speed with tap water (high tap) and (b) low fan speed conditions with tap water (low tap).



(a) (b)

Fig. 7. Indoor/outdoor PM_{10} air concentrations with wetted rigid media pad under (a) high fan speed with tap water (high tap) and (b) low fan speed conditions with tap water (low tap).

approximately 30% for $PM_{2.5}$ and from 30% to 50% for PM_{10}. The reduction may be attributable to the increased thickness and surface areas of a water-laden pad, reduced air space in the pad, or elimination of particle re-suspension from the pad surfaces. Discussions of PM reduction caused by soaked media pad are deferred to Section 3.4.

3.3. Removal mechanisms associated with evaporative coolers

Airborne PM could be removed from the air stream via particle deposition on the media pad by impaction, diffusion, interception, or settling. Mathematical models exist to quantify the effects of these PM removal mechanisms (Hinds, 1999). Impaction is the removal of PM by a “head-on” collision with the pad media. Diffusion is the deposition of PM onto the pad material as the particles move in a laminar or turbulent motion within the air spaces inside the pad; however, due to the insignificant effect of diffusion on particles greater than 0.1 μm, this mechanism will not be included as a viable particle removal mechanism in this section. Interception occurs as PM passes by the pad media and “sideswipes” or contacts the filter material for removal. Finally, gravitational settling is the collection of PM on the pad

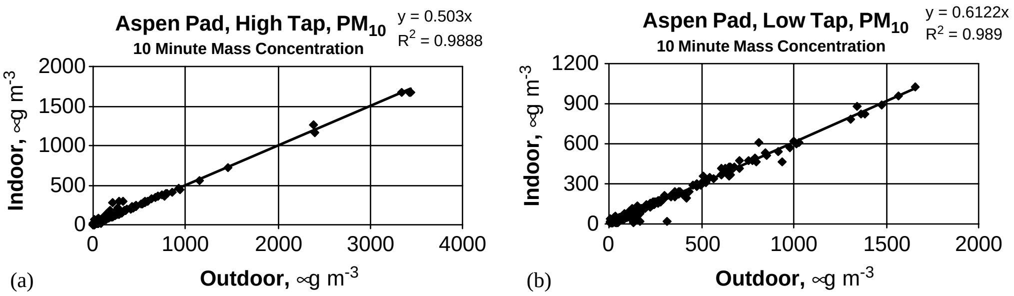


Fig. 8. Indoor/outdoor $PM_{2.5}$ air concentrations with wetted rigid media pad under (a) high fan speed with tap water (high tap) and (b) low fan speed conditions with tap water (low tap).

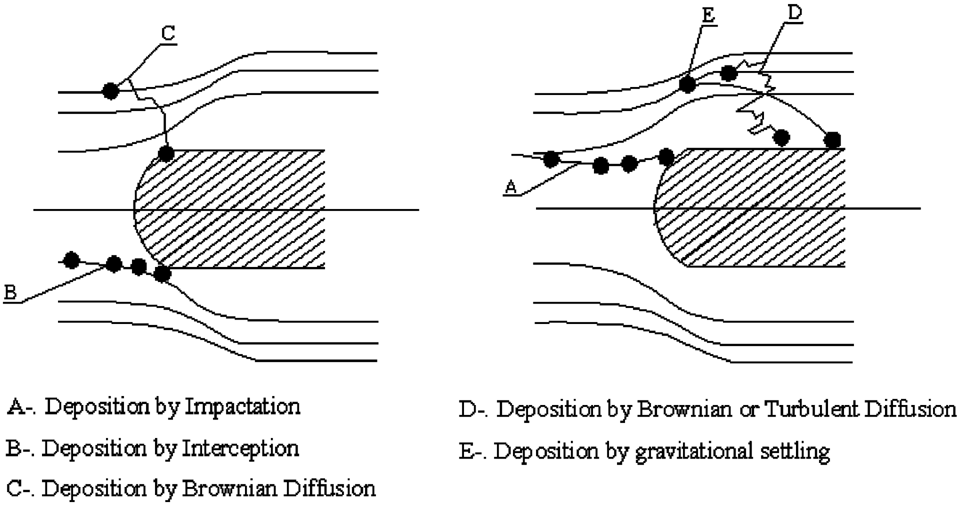


Fig. 9. Conceptual diagram of particle deposition mechanisms.

or chamber caused by gravity or van de Waals force, which is a function of surface contact geometry, air velocity, particle diameter and particle density (Sehmel, 1984). Fig. 9 shows a conceptual schematic of particle deposition inside the cooler pad media.

Atmospheric particles are brought towards the cooler media pad in a flow field similar to the flows around cylinders or ribbons. Particles could be impacted onto or intercepted by the pad going through the media pad. Mathematical descriptions of the particle movements near the irregular meshes or interwoven fibers of the cooler pad would be extremely complicated, if not impossible. We assume that the size of the mesh of fiber is uniform and that particles are moving through a series of ribbons in the media pad. Based on the dimensions of the media pad and the pump performance (ventilator fan performance), impaction and interception of particles by the media pad would occur in a laminar or near laminar field where the Reynolds number characterizing the flow around the mesh/fiber is less than 65 and 3000 for the flow inside the spaces in the media pad, as shown in Table 1, respectively.

In a laminar flow field, particle removal due to inertia impaction on a moisture-laden pad is a function of the airflow speed, the particle aerodynamic diameter, and the size of the impact area (de Nevers, 1999; Hinds, 1999). We defined a separation number, N_s, to indicate the probability that particles will impact an obstacle, as described by Hinds (1999) and Langmuir and Blodgett (1946) in the study of flow around a cylinder.

$$N_s = \frac{\rho D^2 V}{18 \mu D_b}, \tag{1}$$

where N_s is the separation number, ρ the density of material, 2000 kg m^{-3}, D the diameter of the particle, (m), V the velocity of the gas stream, m s^{-1}, μ the viscosity of air, 1.8×10^{-5} kg m^{-1} s^{-1}, and D_b the thickness or diameter of the "barrier" to airborne particles, (m).

For a rigid media evaporative cooler, where 10-µm particles move at 3.87 m s^{-1} during high-speed fan operation through the filter and the "ribbon" face thickness of the rigid media cooler pad "barrier" is 0.00022 m, we calculate an N_s of 10.9. Using a reference table of target efficiency (de Nevers, 1995) constructed for various separation numbers and barrier shapes, we find the target efficiency to be 0.97 for a "ribbon" shape barrier, a good representation of the rigid media pad. If the cross-sectional area of the rigid media pad accounts for about 4.3% of the area where the particle laden air enters, we could expect a reduction of about 4.2% (4.3% times 0.97 efficiency) for the effects of impaction. Similarly, a particle size of 2.5 μm under the same conditions results in a calculated N_s of 0.68 that has a target efficiency of only 0.70, resulting in a removal efficiency of about 3.0%. The effects of inertial impaction are greater as particle size and air velocity increase.

Interception removal efficiency also can be calculated in a laminar flow field using the following equation:

$$\eta_s = \frac{3D^2 V^{1/2}}{v^{1/2} D_b^{3/2}}, \tag{2}$$

where η_s is the collection efficiency, v the kinematic viscosity of air, $1.49 \times 10^{-5}\ \mathrm{m^2\,s^{-1}}$, and other parameters are the same as defined in Eq. (1).

Using a 10-μm particle as an example in the aspen pad evaporative cooler, we find a reduction of 0.04 under high fan speed operation. It was found that only particles 5 μm and greater are theoretically reduced by more than 1% due to interception under high fan speed conditions in the aspen pad cooler. For the rigid media pad cooler, interception would affect particles of 2.5 μm and above, with a calculated removal efficiency of 3.8% for 10-μm particles.

Finally, deposition onto the surfaces within the filter or inside the chamber due to gravity can be estimated as

$$N_{\mathrm{mixed}} = 1 - \exp\left(\frac{-LgD^2\rho}{18HV\mu}\right), \tag{3}$$

where N_{mixed} is the percentage of particles deposited onto the surfaces, L the length of filter or chamber, (m), g the gravity, 9.81 m s^{-1} and H the height of filter or chamber, (m).

The first deposition calculation describes PM removal within the actual filter and is reduced by the PM amount previously removed by the impaction and interception mechanisms. The deposition removal efficiency for the chamber (which simulates ducts and the home) is also reduced to compensate for particulates removed by the cooler filter prior to entry into the chamber. Deposition

Table 4
Predicted percent removal of PM for various removal mechanisms and PM sizes—rigid media pad, low and high fan speeds

Rigid media pad removal mechanism	Particle size (μm)							
	Low fan speed				High fan speed			
	2.5	5	10	15	2.5	5	10	15
Impaction	2.8%	3.8%	4.1%	4.2%	3.0%	3.9%	4.2%	4.3%
Interception	0.2%	0.9%	3.8%	8.5%	0.3%	1.2%	4.7%	10.5%
Gravity deposition—filter	0.6%	2.2%	8.1%	16.3%	0.4%	1.4%	5.3%	10.7%
Gravity deposition—chamber	0.1%	0.5%	1.9%	3.5%	0.1%	0.3%	1.3%	2.4%
Total removal	3.7%	7.4%	17.9%	32.5%	3.8%	6.8%	15.4%	27.9%

Table 5
Predicted percent removal of PM for various removal mechanisms and PM sizes—aspen pad, low and high fan speeds

Aspen pad removal mechanism	Particle size (μm)							
	Low fan speed				High fan speed			
	2.5	5	10	15	2.5	5	10	15
Impaction	0.0%	4.2%	15.5%	18.1%	0.0%	8.4%	17.2%	18.9%
Interception	0.0%	0.1%	0.4%	0.8%	0.0%	0.1%	0.4%	1.0%
Gravity deposition—filter	1.3%	4.8%	15.8%	30.3%	0.9%	3.1%	10.7%	21.6%
Gravity deposition—chamber	0.2%	0.6%	1.8%	2.9%	0.1%	0.4%	1.3%	2.3%
Total removal	1.5%	9.8%	33.5%	52.1%	1.0%	12.1%	29.7%	43.8%

removal increases with larger particle sizes and slower air velocity.

3.4. Predictions of PM removal efficiency

The prior equations were applied to the low and high-speed scenarios in the experimental set-up for the rigid media pads, resulting in Table 4, and the aspen pads, resulting in Table 5. These tables summarize calculated PM reductions, expressed as a percentage, for the removal mechanisms in four different PM sizes. All reductions presented in Tables 4 and 5 are calculated based on parameters obtained from manufacturer's data or actual measurements of the pads. The face of the rigid pad was treated as a "ribbon", with a measured width of 0.22 mm. The aspen pad fibers were treated as having an average thickness of 0.7 mm. Other pad characteristics were obtained by direct measurements, as shown in Table 1.

3.5. Comparison with theoretical predictions

Fig. 10 shows a comparison between the measured and predicted PM I/O ratios for dry operating conditions.

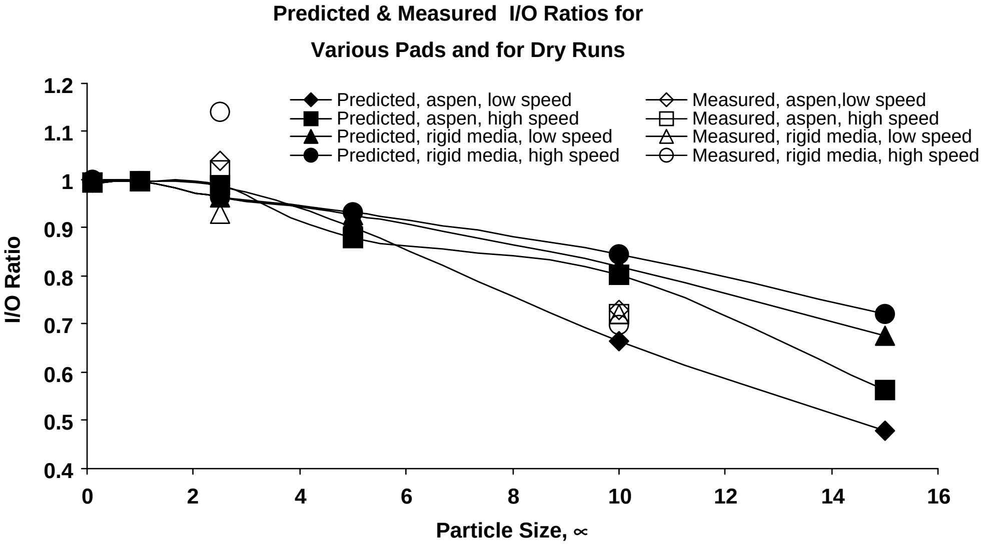


Fig. 10. Comparison of predicted and measured I/O ratios for dry (vent only) runs.

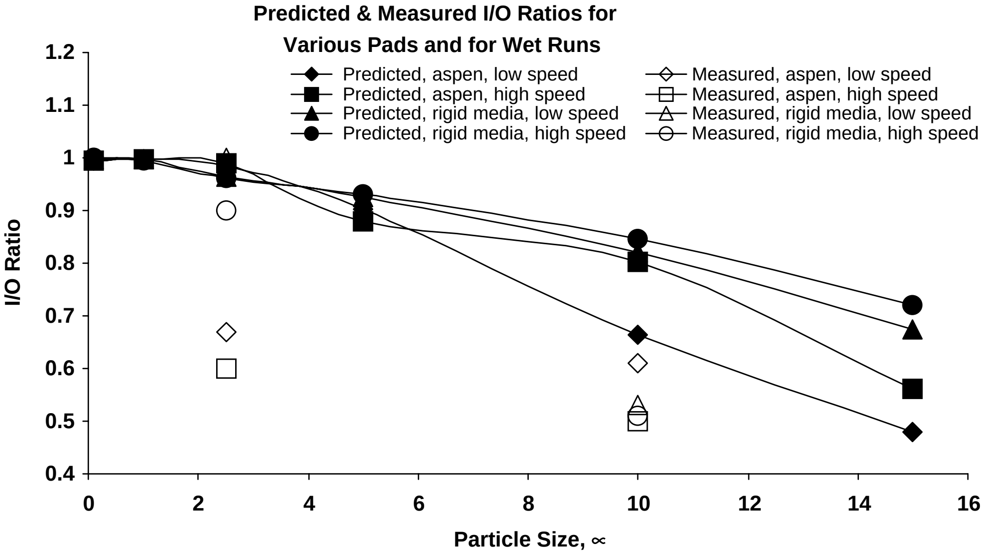


Fig. 11. Comparison of predicted and measured I/O ratios for wet runs.

Table 6
Comparison of measured (dry and wet) and predicted I/O ratios for $PM_{2.5}$

$PM_{2.5}$ indoor/outdoor ratios						
Operating condition	Rigid media pad			Aspen pad		
	Measured		Predicted	Measured		Predicted
	Dry	Wet		Dry	Wet	
Dry, low speed	0.93	1.04	0.97	1.04	0.76	1.00
Dry, high speed	1.14	0.89	0.96	1.02	0.80	1.00

Table 7
Comparison of measured (dry and wet) and predicted I/O ratios for PM_{10}

PM_{10} indoor/outdoor ratios						
Operating condition	Rigid media pad			Aspen pad		
	Measured		Predicted	Measured		Predicted
	Dry	Wet		Dry	Wet	
Dry, low speed	0.72	0.53	0.82	0.73	0.62	0.69
Dry, high speed	0.70	0.51	0.85	0.72	0.59	0.67

One notices that the predicted I/O ratios shown in the figure are developed based on a constant particle size while the measured ratios are not comprised solely of particulate of the same size. As limited by the sampling instrumentation, "$PM_{2.5}$" actually represents a statistical distribution of particles where 50% of the size distribution is comprised of particles of 2.5 μm or less in diameter (Chow, 1995; Perkins, 1974). In addition, the predicted I/O ratios do not take into consideration of re-suspension that is likely to occur inside the pad media.

The "dry" predicted and measured I/O ratios appear to agree with each other reasonable well except the value obtained under the dry, high fan speed, rigid media pad operating condition. The above 1.0 I/O ratio for the rigid media pad cooler is most likely due to re-suspension of material within the cooler and chamber.

With the coolers operating in the wet mode, no re-suspension of particles within the cooler pads could be assumed due to removal or binding by the water. Fig. 11 shows that the measured I/O ratios with tap water circulation are much lower than those found during the dry operations as well as predicted by the model. The use of water greatly reduces the I/O ratios under all conditions. The measured I/O ratios for PM_{10} with tap water circulation are lower than those found during the dry operations for both the aspen pad and rigid media coolers. The aspen pad cooler appears to result in lower I/O ratios than the rigid media pad cooler. Wetted pads have greater particle adhesion abilities and eliminate particle re-suspension from the pad surfaces. Slight swelling of the pads would occur when the pads are soaked with water. The swelled pads and potential formation of water film on the pad surfaces would increase the effective pad surfaces and frontal areas, increasing impaction and interception removal efficiencies. The swelling of pad would also reduce the cross-sectional area for air passage, enhancing the removal mechanisms associated with particle diffusion and deposition inside the pads. Future research on the PM removal mechanisms associated with evaporative coolers would greatly advance the knowledge on the effects of evaporative coolers on PM air quality. Summaries of predicted and measured findings are contained in Tables 6 and 7.

4. Conclusions

Evaporative coolers appeared to have a greater overall reduction effect on PM_{10} than $PM_{2.5}$ based on comparisons of I/O ratios for the various operating modes. The most notable difference between PM size removal efficiency is during dry (vent only) operating conditions, with PM_{10} removal 30% greater than $PM_{2.5}$. The greatest I/O ratio reductions occurred during wet (tap water) operating conditions, especially for PM_{10}. The evaporative cooler provides multiple filtration mechanisms for particle removal.

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