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Evaluation of Indoor PM Distribution by CONTAM Airflow Model and Real Time Measuring: Model Description and Validation

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Abstract
Particulate Matter (PM_{10}, $PM_{2.5}$, and PM_1) entry into hospital buildings is important for human exposure and is associated with health effects. The present study investigated the entry of particles into Imam Khomeini general hospital building under different ventilation systems and scenarios using a multi-zone airflow and contaminant transport model. Concentrations of PM_{10}, $PM_{2.5}$, PM_1, and meteorological variables (atmospheric pressure, air temperature, and relative humidity) were measured and recorded in 6 medical treatment floors and outdoor atmosphere of hospital, from June 2014 to June 2015, 7 days at each season as simulation input variables. Simulated ventilation rates were assessed using the model and then validated using both measured data and simulations. In this study, CONTAM was used as a multi-zone indoor air quality and ventilation analysis software to determine airflows and contaminant concentrations. The simulation results for $PM_{2.5}$ concentration as an important contaminant in hospital floors from basement to the top and based on airflow design were 21.3, 16.5, 22, 25.4, 27.6, and 24.2 μg/m³ respectively which showed 8.1% average deviation with actual measurements in selected locations. The assessment of air ventilation effect on $PM_{2.5}$ concentration proved more accumulation in winter. The study results showed that accurate particle deposition and penetration are effective in predicting the time-varying particle concentrations in all floors of hospital building. The comparison between measurements and CONTAM prediction suggests that a multi-zone particle transport model can provide insight into particle entry into the hospital building under various weather and building operating scenarios.

Keywords: Particulate matters, Validation, Indoor air quality, CONTAM, Multi-zone modeling

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1. Introduction

Among the many airborne contaminants, PM_{10}, $PM_{2.5}$, and PM_1 are of great importance owing to their association with adverse health effects such as cardiac and respiratory mortalities (1). In the absence of indoor sources, particulate matter (PM) concentrations in hospital buildings are determined by the entry of outdoor air particles (2). Outdoor PM_{10}, $PM_{2.5}$, and PM_1 originating from vehicle engines and fossil fuels can penetrate through the building envelope (3). In urban environments, in particular, entry of outdoor PM into buildings has a significant impact on PM_{10}, $PM_{2.5}$, and PM_1 levels in occupied spaces (4). Understanding the dynamics of urban particles entry into a building is important for evaluating exposure to PM and the associated health effects. Previous studies have examined transport of outdoor PM to the indoor environments using laboratory-based or field measurements (5). For example, Rim et al based on measurements in testing a hospital building found that PM infiltration is a function of particle size and air change rate (6). Other studies have monitored indoor and outdoor PM concentrations and found that the indoor/ outdoor ratio varies with particle size, building characteristics, weather conditions, season, and heating, ventilation, and air conditioning (HVAC) systems operation including fan and filter usages. Previous studies are valuable in identifying these important factors which determine PM entry through the building envelope; however, they are mostly limited to a specific set of conditions, since they are experimental studies on specific buildings in a given geographic location over a certain time period (7). Outdoor conditions vary daily and seasonally, on one hand. On the other hand, building characteristics and operation conditions vary for different buildings, and it is a difficult task to collect indoor and outdoor PM_{10}, $PM_{2.5}$, and PM_1 data in each of different buildings over long time periods. Moreover, indoor PM sources such as electric and gas stoves or chemical reactions are not readily controlled during experiments, thereby complicating estimates of indoor concentrations of outdoor-originated PM (8). Given these complications, multi-zone airflow and contaminant transport modeling offers the ability to investigate transport of outdoor PM into a building under a wide range of building operating and weather conditions. A few studies have used multi-zone modeling approach to investigate the particle dynamics within buildings (9,10). For example, Dols and Walton investigated indoor/outdoor dynamics of fine particles for a two-story office building using the CONTAM multi-zone model, and showed the capability of the model to predict airflow and transport of fine particles by proper model inputs (9). Sohn et al simulated transport of environmental tobacco smoke particles (0.07 mme1.2 mm) into a three-room multi-zone chamber using the COMIS (conjunction of multi-zone infiltration specialists) which is a multi-zone airflow model, along with an indoor aerosol dynamics model (MIAQ4). They showed good agreement on particle size distributions (0.07 mme1.2 mm) between measurements and simulations (11). Liu et al performed CONTAM simulation of particle re-suspension due to human activities in a three-zone office building. Their study results demonstrated that the CONTAM model could simulate indoor particle deposition, re-suspension, and dispersion (12). Emmerich and Nabinger evaluated the ability of the CONTAM multi-zone model to predict concentrations of airborne particles (0.3 mme5.0 mm) in a residential building with the operation of 2 different air cleaners, considering particle deposition, penetration, and filtration efficiencies. They reported that simulated 24-hour average particle concentrations were within30% of measurements for all particle sizes (13). Previous multi-zone modeling studies have shown simulation capabilities for predicting transport behavior of airborne particles within buildings (14). Nonetheless, the multi-zone modeling studies (10-15) have focused on the impact of indoor sources and not on particle penetration through the building envelope. Furthermore, previous multi-zone modeling studies have rarely examined transport of PM or nano-scale particles (16). The objective of this study was to compare multi-zone modeling of indoor/outdoor PM dynamics with actual measurement data. Validation is critical to ensure that such modeling is able to provide reasonable predictions under a range of conditions, thereby supporting further model application to broader contexts. As a consequence, we used CONTAM, a validated multi-zone indoor air quality (IAQ) model, to develop and demonstrate a framework which could predict PM concentrations and simulate transient airflow and entry of ambient PM into a building under different building operation and weather conditions (17). In this regard, PM_{10}, $PM_{2.5}$, and PM_1 samples were collected from the indoor environments of the hospital and the adjacent outdoor environments during the 4 seasons and 2 scenarios (windows closed/HVAC Off and windows open/HVAC on), which were defined for the model. The present study intended to highlight the important model input parameters and the accuracy that could be achieved in predicting the entry of outdoor PM into a hospital building.

2. Materials and Methods

This study was conducted in an old urban hospital located in central area of Tehran, Iran, during the 4 seasons from June 2014 to June 2015. Among numerous buildings, a 50-year-old building in the hospital was selected for the study. All 6 floors of the building were occupied by patients, visitors, and staff all day. This hospital is located in a densely populated urban commercial area and is adjacent to a heavy-traffic road (see Fig. 1).

Owing to the hot summer days during which sampling was done, this hospital was cooled by either evaporative coolers or air conditioning systems, and in cold seasons was heated by heating radiators. PM analyzer (Dust Trak 8520) and ambient air condition analyzer (Lutron MHB 38SD) were used in the medical center for sampling, monitoring, and recording data. The sampling was done from 3 types of locations including nurses stations, inpatient wards, and outdoor environment of 6 floors of the monitored hospital and all 4 seasons of summer, fall,

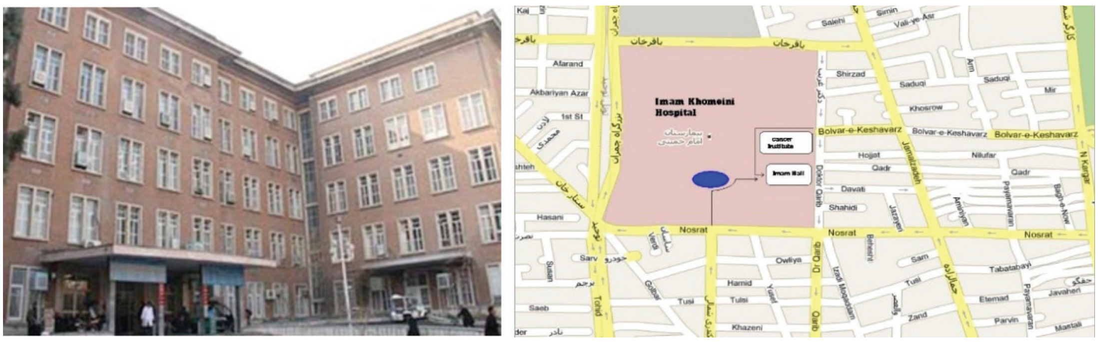

Fig. 1. Imam Khomeini Hospital and Its Location.

winter, and spring were covered. Totally, 1512 PM samples (PM_{10}, $PM_{2.5}$, and PM_1) were analyzed in this study. Sampling was performed from Saturday to Friday, during three 8-hour shifts in all the seasons. The 24-hour PM_{10}, $PM_{2.5}$, and PM_1 samples were simultaneously collected per day from different sites for 7 consecutive days. During the sampling, the inlets of the indoor samplers were located at about 1.1 m above the ground level of the sampling sites to simulate the breathing zone of the patients. For outdoor sampling, the samplers were located far from barriers such as buildings, trees, and stacks and in the direction of the dominant winds; therefore, sampling was done at the front side of the building (18). Indoor and outdoor measurements were taken alternately after each 15 minutes due to the lack of multiple samplers. Kulmala et al reported that a variation between 4% and 12% was observed in the mass concentration of PM between alternately and continuously sampled particles in indoor and outdoor measurements for one successive week (19). Therefore, the individual 1512 (1008 indoor and 504 outdoor) PM samples for measurements were obtained from the hospital throughout all seasons in order to cover both meteorological conditions and pollutant concentrations. The ambient temperature, air pressure, and relative humidity in each location were measured simultaneous with PM measurement. A particle counter was factory-calibrated, prior to the sampling campaign and the calibration was repeated every season. All data were normalized before application of multivariate linear regression procedure. Data analysis was carried out using the SPSS statistical software (Statistical Package for Social Sciences, version 20.0). Bivariate correlation analysis was used to assess pairwise association among various variables. Further, Pearson's coefficient (r) was used for measuring linear association, the strength, and direction of the relationship between 2 variables. Stepwise multiple regressions were also carried out for PM_{10}, $PM_{2.5}$, PM_1 and the results were checked for multi-linearity by examining the variance inflation factors of the predictor variables. Multivariate analysis of variance (MANOVA) was used for 4 variables (season, week days, floor no., and location). Moreover, Pillai's trace, Wilks' lambda, Hotelling-Lawley trace, and Roy's largest root methods were used for providing tests of between-subjects effects table for PM_{10}, $PM_{2.5}$, PM_1 arrays. Yet, the stepwise linear regression was used to evaluate the relationship of air condition parameters including temperature, pressure, and relative humidity with PM concentrations. The hospital building described was modeled using the CONTAM multi-zone air movement and contaminant transport program (20). CONTAM is an established simulation tool for predicting airflows and contaminant concentrations in multi-zone airflow systems of a building. When using CONTAM, a building is represented as a series of interconnected zones (e.g. rooms), with the airflow paths (e.g. leakage sites and open doors) between the zones, and the outdoors are defined as mathematical relationships between the airflow through the path and the pressure difference across it (21). Outdoor weather conditions and system airflow rates are used to describe mass balances of air into and out of each zone, which are solved simultaneously to determine the inter-zone pressure relationships and resulting airflow rates between each zone, including the outdoors (22). These airflow rates can be calculated over time as weather conditions and system airflow rates change. Once the airflows are established, the model can then calculate contaminant concentrations over time in each building zone based on contaminant source characteristics and contaminant removal information, such as that associated with deposition and other loss mechanisms (23). In the present study, the CONTAM model simulated time-varying indoor/outdoor particle transport for size-resolved PM, and the model results were compared to the 1512 measurements performed in the Imam Khomeini hospital building. Fig. 2 is an image of the building in the CONTAM graphical interface, which depicts different zones, airflow paths (doors, wall joints, windows, etc.), and ducts on the main floor of the building. The attic and crawl spaces were also included in the model but not shown in this figure. The leakage areas of the individual airflow paths were determined previously (24).

With regard to particle penetration into a building, most of the multi-zone modeling studies (25) have explored the impact of indoor sources on indoor particle concentrations and therefore not considered particle penetration through the building envelope. The predictions of time-series data for 24-hour particle concentrations were compared to the measured values using ASTM D5157 Standard Guide for Statistical Evaluation of Indoor Air Quality Models (26).

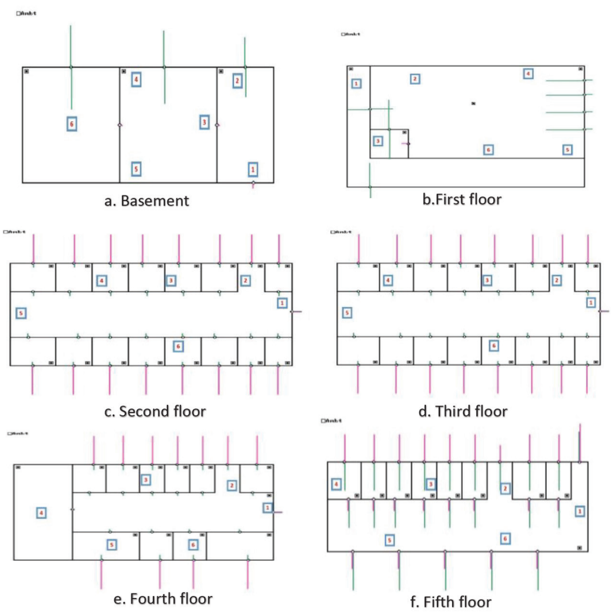

Fig. 2. Graphic Interfaces of CONTAM for the 6 Floors of the Hospital.

ASTM D5157 provides 3 statistical tools for evaluating the accuracy of IAQ predictions and 3 additional statistical tools for assessing bias. The first 3 parameters are correlation coefficient (r), regression slope (M), and regression intercept (b). These parameters are related to the goodness of fit of a linear plot of the measurement and simulation results. A line with a slope of 1.0, intercept of 0.0, and a correlation coefficient of 1.0 would indicate perfect agreement between measurements and model predictions (27).

3. Results and Discussion

The results of this study were prepared in 3 major parts as follows: the first part presents the results with air condition parameters and total PM_{10}, $PM_{2.5}$, and PM_1 concentrations as well as a summary of statistical analyses and the effect of meteorological parameters on PM concentrations revealed by linear regression method. The second part provides details of measured PM concentrations in different locations of each of the 6 floors. The third part consists of comparison, relationship, and parametric analysis of measured and predicted PM concentrations, considering windows positions and placement of HVAC systems.

3.1. Part 1

Results of minimum, maximum, mean of PM_{10}, $PM_{2.5}$, PM_1 measurements, and indoor/outdoor ratio for 6 floors, and the effect of meteorological parameters on PM concentrations by linear regression method are shown in Tables 1 and 2. The statistics for PM concentrations at indoor/outdoor locations in hospital (μg /m³) are summarized in Fig. 3. The PM_{10}, $PM_{2.5}$, PM_1 average concentrations were 27.75, 20.05, 15.50 and varied between

Table 1. Indoor/Outdoor Concentrations of PM_{10}, $PM_{2.5}$, PM_1 in the Hospital (μg /m³)

Site	Statistics	Indoor			Outdoor			I/O		
		PM_{10}	$PM_{2.5}$	PM_1	PM_{10}	$PM_{2.5}$	PM_1	PM_{10}	$PM_{2.5}$	PM_1
NB	Min	15	11	9	20	16	11	0.75	0.6875	0.818182
	Max	35	22	19	49	33	28	0.714286	0.666667	0.678571
	Mean	24.67	16.85	13.32	32.46	24.6	17.96	0.760012	0.684959	0.741648
TB	Min	17	11	9	20	16	11	0.85	0.6875	0.818182
	Max	39	27	24	49	33	28	0.795918	0.818182	0.857143
	Mean	27.28	20.03	16.5	32.46	24.6	17.96	0.840419	0.814228	0.918708
N1	Min	11	6	6	13	12	11	0.846154	0.5	0.545455
	Max	27	23	17	44	37	33	0.613636	0.621622	0.515152
	Mean	19.53	13.6	10.62	31.64	24.64	20.17	0.617257	0.551948	0.526525
T1	Min	7	7	6	13	12	11	0.538462	0.583333	0.545455
	Max	24	18	14	44	37	33	0.545455	0.486486	0.424242
	Mean	14.92	12.21	9.42	31.64	24.64	20.17	0.471555	0.495536	0.46703
N2	Min	15	12	10	28	15	12	0.535714	0.8	0.833333
	Max	44	25	22	45	37	28	0.977778	0.675676	0.785714
	Mean	28.39	20.28	16.89	33.75	25.85	21.07	0.841185	0.784526	0.801614
T2	Min	14	11	11	28	15	12	0.5	0.733333	0.916667
	Max	45	30	21	45	37	28	1	0.810811	0.75
	Mean	29.28	19.78	15.92	33.75	25.85	21.07	0.867556	0.765184	0.755577
N3	Min	14	11	5	21	17	11	0.666667	0.647059	0.454545
	Max	41	27	21	44	31	27	0.931818	0.870968	0.777778
	Mean	27.1	18.5	14.78	31.78	23.67	18.78	0.852738	0.78158	0.787007
T3	Min	14	10	10	21	17	11	0.666667	0.588235	0.909091
	Max	43	29	22	44	31	27	0.977273	0.935484	0.814815
	Mean	27.71	19.82	15.39	31.78	23.67	18.78	0.871932	0.837347	0.819489
N4	Min	14	12	10	24	19	10	0.583333	0.631579	1
	Max	41	29	19	42	29	25	0.97619	1	0.76
	Mean	28.35	20.1	14.21	32.08	24.39	17.28	0.883728	0.824108	0.822338
T4	Min	19	12	13.92	24	19	10	0.791667	0.631579	1.392
	Max	40	31	20	42	29	25	0.952381	1.068966	0.8
	Mean	29.14	20.32	10	32.08	24.39	17.28	0.908354	0.833128	0.578704
N5	Min	15	12	8	17	13	9	0.882353	0.923077	0.888889
	Max	43	27	21	44	29	28	0.977273	0.931034	0.75
	Mean	28.35	17.64	13.5	28.67	20.57	15.85	0.988839	0.85756	0.851735
T5	Min	20	16	9	17	13	9	1.176471	1.230769	1
	Max	49	33	19	44	29	28	1.113636	1.137931	0.678571
	Mean	32.46	24.6	17.96	28.67	20.57	15.85	1.132194	1.195916	1.133123

N: Number of floors, TB: Treatment Basement; T: Treatment rooms; B: Basement; N1 to N5: Floor 1 to floor 5.

Table 2. The Effect of Meteorological Parameters on PM Concentrations Declared by Stepwise Linear Regression Method

Model		Unstandardized Coefficients		Standardized Coefficients	*t*	*P* Value
		B	Standard Error	Beta		
Dependent Variable: PM_1						
1	(Constant)	20.621	0.556		37.093	0.000
	T	-0.232	0.024	-0.411	-9.759	0.000
2	(Constant)	-103.134	23.442		-4.399	0.000
	T	-0.203	.024	-0.358	-8.507	0.000
	P	0.140	.026	0.222	5.281	0.000
Dependent Variable: $PM_{2.5}$						
1	(Constant)	26.866	0.658		40.851	0.000
	T	-0.318	0.028	-0.463	-11.304	0.000
2	(Constant)	-132.498	27.579		-4.804	0.000
	T	-0.280	0.028	-0.407	-9.996	0.000
	P	0.180	0.031	0.235	5.780	0.000
Dependent Variable: PM_{10}						
1	(Constant)	-335.820	38.783		-8.659	0.000
	P	0.412	0.044	0.397	9.368	0.000
2	(Constant)	-266.634	38.186		-6.982	0.000
	P	0.341	0.043	0.328	7.902	0.000
	T	-0.274	0.039	-0.293	-7.061	0.000

7-49 μg/m³, 6-37 μg/m³, and 5-33 μg/m³, respectively. In general, the average indoor levels of PM_{10} did not exceed 150 μg/m³, the outdoor PM_{10} standard recommended by USEPA, and the $PM_{2.5}$ level was significantly lower than the standard of 65 μg/m³ (27). High correlations were found between $PM_{2.5}$, PM_{10}, and PM_1 showing that they came from similar PM emission sources (Fig. 4). Table 1 shows that the average indoor concentrations of elements were lower than those measured outdoors by a factor of approximately 0.67 for $PM_{2.5}$, 0.76 for PM_{10}, and 0.8 for PM_1, indicating that outdoor-to-indoor transportation affected indoor element levels. Therefore, we believed that indoor elements originated mainly from outdoor emission.

For evaluating the effect of air condition parameters (temperature, pressure, and relative humidity) on PM concentrations, the stepwise linear regression was applied. It was found that increasing the pressure and decreasing the temperature resulted in the increase of PM concentration. It was observed that PM_1 and $PM_{2.5}$ were

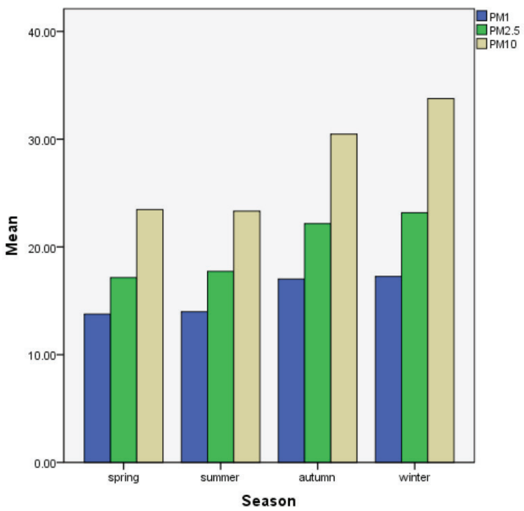

Fig. 3. Mean PM Concentrations (μg/m3) for 4 Seasons.

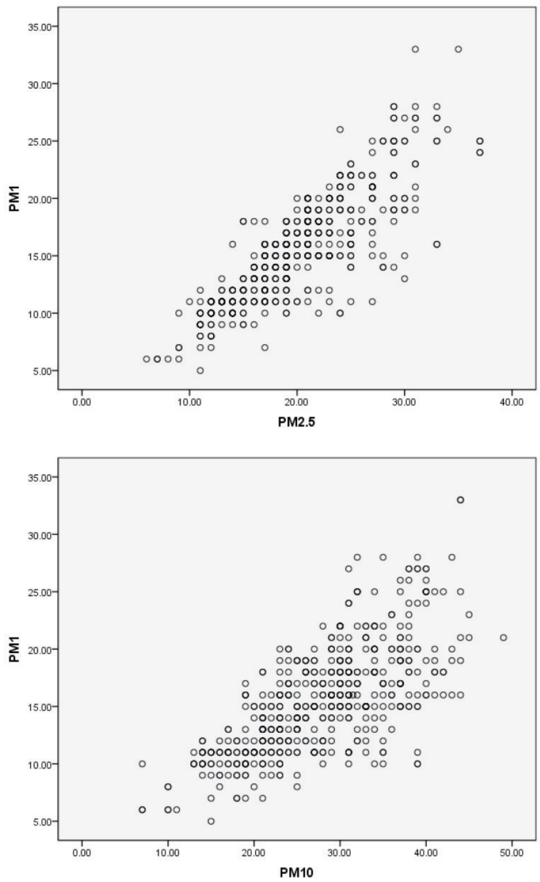

Fig. 4. Linear Correlation of PM_1, $PM_{2.5}$, and PM_{10}.

sensitive to temperature changes, while PM_{10} was sensitive to pressure (Table 2). The mean PM concentrations for 4 seasons are shown in Fig. 3.

3.2. Part 2

Details of $PM_{2.5}$ concentrations (as a major parameter) in different locations of each of the 6 floors of the hospital building are shown in Fig. 5. Generally, variation of $PM_{2.5}$ concentration in each floor depended on sink and source types, windows positions and sizes, type and performance of air conditioning systems, number of patients and visitors, and the type of equipment located in each floor.

3.3. Part 3

Fig. 6 and Fig. 7 provide 24-hou concentration profiles for $PM_{2.5}$ based on measurements and CONTAM simulation in 6 floors for 2 scenarios (windows closed/HVAC Off and windows open/HVAC on). The CONTAM model prediction results showed that the indoor $PM_{2.5}$ concentration in close windows/HVAC off scenario was more than that in open windows/HVAC on condition in all floors. The figures indicate that model performance was relatively good (8.1% mean difference) for the selected PM. It means that the model predicted temporal changes in particle concentration with reasonable accuracy and therefore they can be expanded to other models.

The assessment of air ventilation effect on $PM_{2.5}$ concentration proved more accumulation in winter season (windows closed/HVAC off). The study results showed that accurate particle deposition and penetration was effective in predicting the time-varying particle concentrations in all floors of hospital building.

4. Conclusion

Given the challenges in measuring airborne particle transport into hospital buildings under varied building operation and weather conditions, the present study investigated the ability of a multi-zone model to predict the entry of size-resolved outdoor particles into Imam Khomeini hospital building and the effects of meteorological parameters (temperature, pressure, and relative humidity) on PM concentrations. CONTAM simulations and experimental studies were performed for this building under 2 different ventilation scenarios (windows closed/HVAC Off and windows open/HVAC on). The results showed that the model needs to consider both size-resolved deposition and penetration to predict accurately the time-varying particle concentrations in hospital buildings. Particle deposition and penetration have significant effects in the model prediction for closed window condition, while deposition is more important than penetration for open window condition. For open window scenario, the filtering effect of the building envelope decreases as relatively more of outdoor particles enter the building through the open windows and also indoor/outdoor concentrations ratio varies with particle

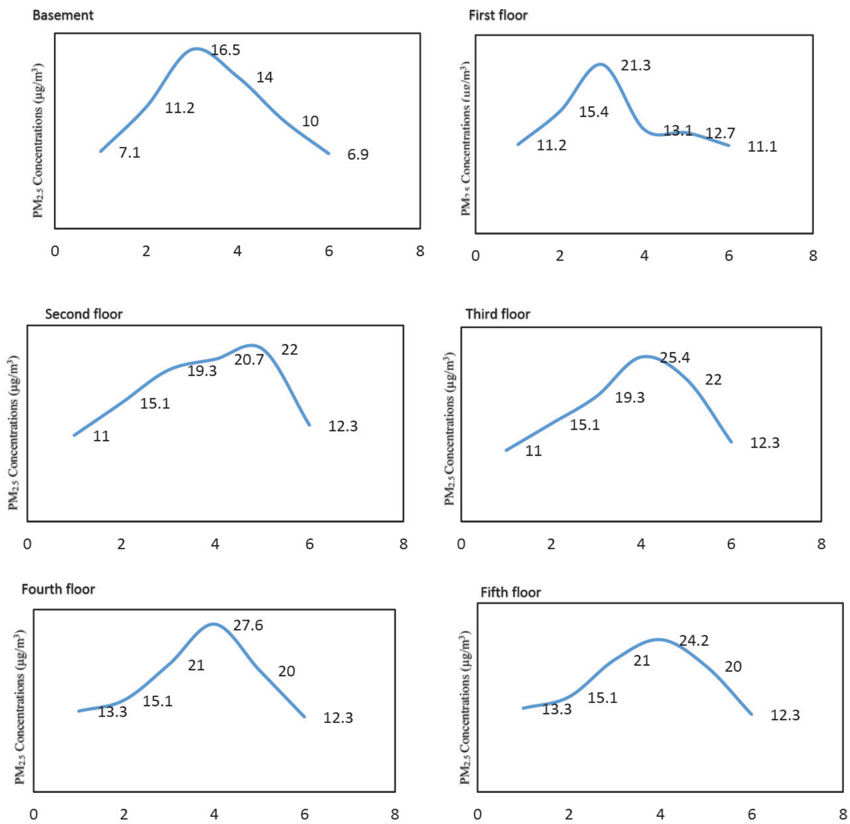

Fig. 5. $PM_{2.5}$ concentrations in Different Locations of Each of the 6 Floors.

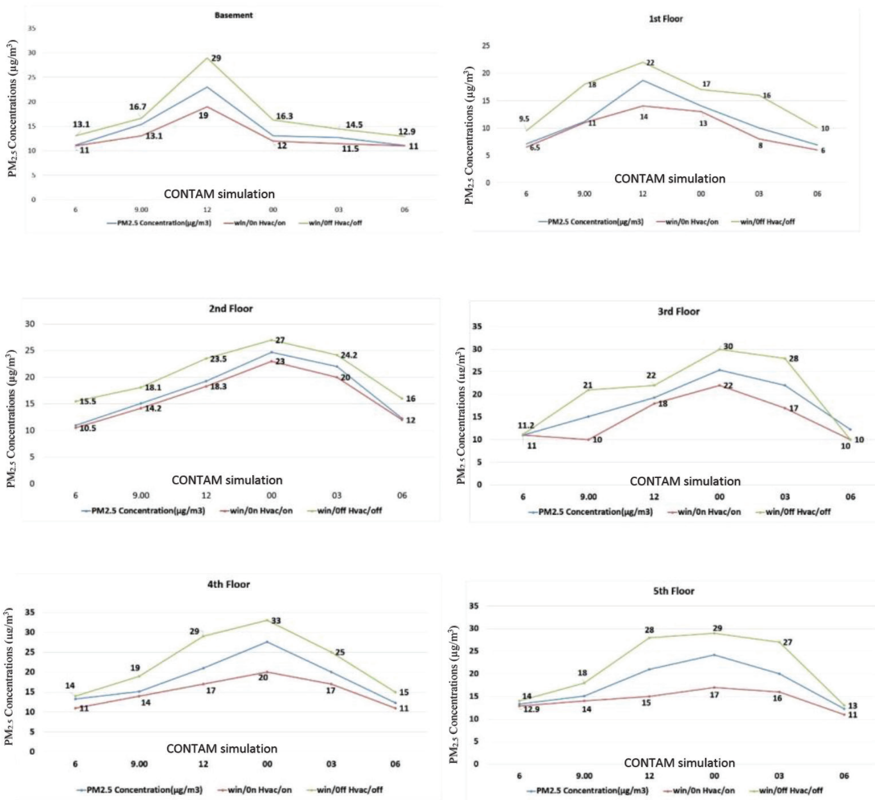

Fig. 6. Comparison of Measured and Simulated PM Concentrations in 6 Floors for 2 Scenarios (Windows Closed/HVAC Off, Windows Open/HVAC on).

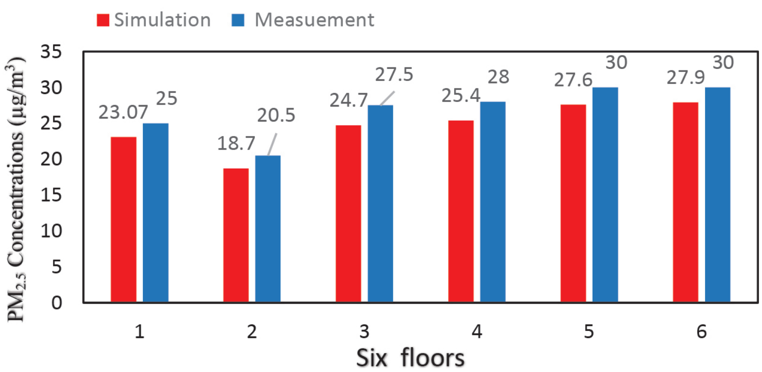

Fig. 7. Deviation Between Simulation and Measurement Data for 6 Floors.

size and building operating conditions. The model validation and statistical analyses results indicated that CONTAM model could provide a great insight into the general trend of PM entry into buildings under various building operating scenarios, and results of stepwise linear regression represented that increasing the pressure and decreasing the temperature caused the increase of PM concentrations. However, the temperature was more effective on PM_1 and $PM_{2.5}$ concentration levels and pressure was only effective on PM_{10} concentration level. Furthermore, it was found that cold seasons had meaningful correlation especially with outdoor location in that PM concentrations were higher in cold seasons compared to the other seasons. The main reasons were air stability and unpleasant atmospheric conditions. In addition, high correlations were found between PM_1, $PM_{2.5}$, and PM_{10}, showing that they came from similar PM emission sources. The indoor particle levels were correlated with the corresponding outdoor levels (R^2 of 0.7 for PM_1, 0.81 for $PM_{2.5}$, and 0.78 for PM_{10}), demonstrating that outdoor infiltration could lead to direct transport into indoors. In addition to outdoor infiltration, human activities and ventilation types could influence indoor PM levels.

In conclusion, here are provided some recommendations for hospital staff to consider:

- Periodical monitoring of air quality based on concentrations of PM_{10}, $PM_{2.5}$, PM_1 and meteorological parameters (atmospheric pressure, air temperature, and relative humidity),
- Monitoring and constant supervision of HVAC systems performance,
- Filters on time replacements,
- Managing hospital visitors and preventing unnecessary visits,
- Installation of new and improved air conditioning systems.

Conflict of Interest Disclosures

The authors declare that they have no conflict of interests.

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