Measurements and modelling of particulate matter building ingress during a severe dust storm event

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Abstract: Dust storms are a common phenomenon that occurs in many dry and arid areas, demonstrates very high levels of particulate matter (PM), can spread significantly further than its origin, affects both outdoor and indoor air quality, and can cause serious health problems although it is a low frequency event. Focus of this study is the prediction of PM (PM_{2.5} and PM₁₀) infiltration at typical commercial and office building environments during severe dust storms. Therefore, a two-month field campaign was conducted to capture such an event in Doha, Qatar,

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and a modelling methodology is proposed based on the one-way coupling of a multi-zone and a computational fluid dynamics software. The predicted levels are in fair agreement with the measurements for both the dust storm and typical days, attributed to the accurate estimation of the external wind pressure and representation of the building envelope. The agreement further improves when ventilation filters' efficiency is estimated rather than extracted from specification sheets. Finally, predictions are found to conform with physical reality and to offer useful insights into PM building infiltration during dust storm events when cross examined with measurements.

Highlights

- High temporal resolution of outdoor/indoor PM measurements during a severe dust storm
- Dust storm $PM_{2.5}/PM_{10}$ ratios are typical to literature but not constant indoors
- Coupling of indoor air quality modelling with accurate building pressure estimations
- Predictions with standard input parameters show fair agreement with measurements
- Employment of corrected HVAC filter performance improved predictions

Keywords: dust storm; indoor air quality; building ingress; field measurement; QUIC; CONTAM

1. INTRODUCTION

Dust storm events are characterised by enormous amounts of airborne dust and reduce of visibility, in several cases from a distance less to 1 km [1]. The most common causes for dust storm events are the lift of sand and dust from the land surface to atmosphere through turbulent strong winds and deflation process [2, 3], as well as convective “Haboobs”[4-6]. These events are responsible for large scale transport of particulate matter, pathogens and other pollutants,

affecting the downwind ecosystem, population [7], and human health [8]. Effects that are probably beyond to what is already known for the association of PM₁₀ and PM_{2.5} levels with respiratory problems [9, 10] cardiovascular diseases [11, 12] and dermatological disorders [13, 14].

The occurrence of dust storm events and their magnitude vary during the year and differ for each region [15, 16]. According to Song, *et al.* [17] the storm events for the northeast Asia are classified as floating dust, blowing dust, dust storm and severe dust storm, based on the values of total suspended particles (TSP), particulate matter (PM) and wind velocity. For example, during a severe dust storm, the observed values of TSP are equal or larger than 6000 $\mu\text{g m}^{-3}$ and the PM₁₀ (PM with aerodynamic diameter less than 10 μm) concentrations can reach a value of 5000 $\mu\text{g m}^{-3}$ or higher, while the wind velocity exceeds values of 10 m s^{-1} . In another occasion, Chen, *et al.* [18] reported PM₁₀ concentrations to be approximately twice the levels of normal days during an Asian Dust Storm. Krasnov, *et al.* [19] also observed very high levels of PM on dust days in Northern Africa, up to 2643 $\mu\text{g m}^{-3}$, while significantly less, around 42 $\mu\text{g m}^{-3}$, on normal days. The above values of PM₁₀ levels imply several days per year of exceedance for any known air quality standard (e.g. European Directive 2008/50/EC at 50 $\mu\text{g m}^{-3}$, no more than 35 days/year) [1, 19, 20]. Note that most countries in MEA follow the U.S. National Air Quality Standards, which for PM₁₀ are 150 $\mu\text{g m}^{-3}$ (annual average) and 50 $\mu\text{g m}^{-3}$ (24hr average) [21].

Undoubtedly, dust storms not only affect the health of those outdoors but also the people living in nearby buildings and indoor environments. Outdoor particulate matter can penetrate indoor through the ventilation system, window gaps and cracks. This process of air infiltration between the building and outdoor environment is defined as ingress [22]. Kuo and Shen [23] investigated the insights into outdoor/indoor PM_{2.5} and PM₁₀ levels in relation to dust storm events. They found a three-fold increase in PM_{2.5} and PM₁₀ levels of pollutants for both indoor

and outdoor environment during the dust storm. They also highlighted the influence of the ventilation system on the indoor air quality during dust events. Kanatani, *et al.* [24] reported a 20-fold and 50-fold increase in indoor and outdoor PM values during an Asian dust storm event in Kyoto, Japan. According to this study, the indoor PM levels of an apartment room reached 70% of the outdoor air PM levels when a window remained open for just 10 minutes. In another study of Krasnov, *et al.* [25], on the impact of atmospheric dust events, an infiltration factor of 0.82 for fine particles was reported despite houses being protected by closed windows with indoor PM₁₀ concentrations reaching 1000 µg m⁻³, while the infiltration factor for normal days was found to be 0.26. Wong and Huang [26] stressed on the infiltration differences between naturally ventilated rooms and to those with air-conditioners, with the former showing higher values.

From the above it is obvious that the quantification of the PM infiltration plays a significant role in investigating the risk assessment of population exposure [27, 28], especially in areas where PM concentrations can frequently reach very high levels due to dust storm events. In one of the few related studies Longueville, *et al.* [14] exhibited strong correlations between dust events and human health for West Africa. Nevertheless, building ingress is highly complex and depends on multiple factors, in addition to the PM atmospheric dispersion, such as building wind pressures, the ventilation systems, and the leakage characteristics of the building envelope [29]. Other driving factors which affect the infiltration rates are the building architecture and the effect of the surrounding buildings [30]. Both Kuo and Shen [23] and Chen and Zhao [31] reviewed the correlations between the outdoor and indoor PM concentrations and discussed the available modelling techniques, however, with emphasis on simple infiltration ratios for buildings and advanced modelling techniques for single openings. Apparently, there is a lack of validated and

comprehensive simulation methodologies for PM building infiltration; an issue also supported by the recent review of Amoatey, *et al.* [32].

Therefore, aim of this work is to propose and validate a computational methodology for the simulation of indoor and outdoor (I/O) PM building infiltration under normal day conditions and during severe dust storm events. To achieve this, a widely used multi-zone model, CONTAM by NIST [33], was coupled with a CFD model, Quick Urban Dispersion Model (QUIC) by Los Alamos National Laboratory [34], to compute the indoor PM levels in a complex building while considering the external wind pressures and velocities. In the past, the combination of such models has been proposed to study building ingress of gaseous pollutants [35], air flow between isothermal rooms [36], and air quality in full buildings Wang and Chen [37], among others. The literature on the building ingress of gaseous components is richer and with validated simulation tools that can address the complex phenomena for the whole building at once e.g. [38, 39]. However, to the best knowledge of authors, this is one of the very few studies to investigate the PM infiltration during a dust storm event by collecting high temporal resolution measurements of the I/O levels and by coupling multi-zone and CFD models with validation of the obtained results.

2. MATERIALS AND METHODS

This chapter provides details on the two main approaches employed in this work. At first, section 2.1 describes the field campaign with the objective to collect high temporal resolution of indoor and outdoor PM measurements capturing both normal and dust storm conditions. This data will be used to evaluate the performance of the proposed integrated modelling approach on three different scenarios. Therefore, the details of the modelling tools and scenarios are provided in sections 2.2 and 2.3 respectively. Specifically on the modelling approach, building infiltration

is mainly affected by two factors the wind pressure exerted on the building envelope, driven by the meteorological conditions, and the building design itself i.e. the ventilation systems (HVAC) and openings. Thus, herein an advanced numerical tool is employed for estimation of the wind pressure and detailed technical data are extracted for the building design. Past studies ([22, 40]) showed that HVAC and the filtration systems in place are critical, especially in extreme events, and thus the three selected scenarios (section 2.3) address them.

2.1. Field campaign and measurements

A monitoring campaign of PM measurements was performed at an office building, Al Rumaila West, Doha City, Qatar. Simultaneous indoor and outdoor PM_{2.5} and PM₁₀ measurements took place from 1 March to 30 June 2015. Details of this campaign can be found in a PM characterization study [41]. At the same period, Qatar Meteorological Department issued eleven warnings for strong winds accompanied with major, medium, or slight dust events (2, 13, 24-April; 2, 5, 23-May; 2, 4, 8, 13 and 21 June). Since focus of this study is the PM infiltration during severe dust events the period between 31-Mar to 16-April has been selected as study period which includes both a major dust event and normal dust levels. The city of Doha is the capital of Qatar situated on the Doha bay with a population of more than 1.7 million people (2010 census; estimated to 2.5 million today). The building is located next to a very busy road, 500 m from the beachfront at 18 m above the mean sea level. It has a rectangular shape (130 m length and 30 m width) and seven floors, all used as office space; it is aligned along the NNW to SSE axis. The nearby area is characterised by intense construction activities and low-rise buildings, which is representative of the whole metropolitan area. The building is mechanically ventilated (8-10 air changes per hour-ACH; provided by the building's HVAC study) using 75-90% fresh air, and with minimum diurnal/weekly variations. Indoor conditions were very well regulated at

temperature 22.5 ± 1 °C and relative humidity $51 \pm 9\%$. It is also quite busy over the weekdays (Sunday to Thursday) and 07:00 to 14:00h (local time), while it is closed to the public and employees during the weekend (Friday to Saturday). For the campaign, we established one outdoor and one indoor sampling site. The outdoor site is located on the NNW fence line, ten meters from the narrow building facade. The indoor site is on the 3rd floor reception area, in the middle of the building length. The whole floor is carpeted and it includes two rows of office and meeting rooms, along the length of the building and one at each side, while in the middle there are open areas with office cubicles (Figure 1). The selected floor was considered representative of the building's indoor conditions. The reception area is also quite busy over the day; it connects the office areas with the utility rooms (restroom, prayer room, elevators, and stairs), but it is not directly exposed to either of these areas and thus was selected as the indoor sampling location.

Figure 1: Building layout for the 3rd floor reception area (green area), where the indoor sampling took place (marked with a red star), and the neighbouring rooms and offices (white areas).

During the study period, mean temperature ranged from 27 °C to 40 °C; there was no precipitation and the average wind speed was 5.1 m s⁻¹ with maximum being ~15 m s⁻¹. Hourly meteorological data was collected for Hamad International Airport from the National Centres for Environmental Information, National Oceanic and Atmospheric Administration, U.S. (Figure 2) and wind was blowing mainly from NNW.

Figure 2: Temperature and relative humidity (%) (own measurements) along with wind direction and velocity (from Hamad International Airport) for the study period (31-March to 16-April).

PM number concentrations, with one-minute resolution, were collected using two Environ Check EDM 365, which is an air quality monitoring station manufactured by Grimm Aerosol Technik GmbH & Co. KG, Germany [42]. The measurement method is based on laser light scattering. The monitoring station was used to measure both, particle number and mass concentrations, over a size range of 0.25 up to 32 µm in 31 size channels using a sampling rate of 1.2 L min⁻¹. It produces particle mass concentrations (µg m⁻³) using a proprietary algorithm

calibrated to the National Institute of Standards and Technology (NIST, USA) Arizona test dust. According to vendor's certificate, measurements are equivalent to the European Standard EN 12341:2014 (superseding EN 14907:2005). Prior to the field campaign, a side-by-side inter-comparison was conducted between the two monitoring stations for a week, which resulted in standardized differences of less than 7% (i.e. the maximum of the distribution of the differences was in all cases within the uncertainty limits of the calibration standards $\pm 3\%$). In addition, the correlation of the PM_{10} measurements performed by the two stations was checked through an inter-comparison, for the same study period, against a reference gravimetric method according to (European standard EN 12341:2104) using a low-volume sampler (LVS16 by GRIMM Aerosol Technik GmbH & Co.). The results show reasonable good agreement between the two methods (Pearson correlation $r = 0.95$ with $p\text{-value} < 0.001$). More details about the employed gravimetric method and protocols are provided by Saraga, *et al.* [43].

2.2. Simulation tools

Wind pressure is of high importance for the accurate calculation of the air infiltration rates. It depends on the wind direction and speed, the urban airshed, the building heights and the local terrain effects. Such input data can be loaded from CONTAM libraries, which contain correlations of wind pressure profiles for low rise buildings [44]. However, these data express average wind pressure coefficients for a simplified cubical building and do not consider the exact building geometry.

To surpass this problem, the QUIC-CFD model is employed to compute the wind pressure coefficients for the airflow paths, the point representing an opening on the building envelope, required by CONTAM. The exact coordinates of these points are provided by CONTAM through

the generation of the Path Location Data (PLD) file. QUIC calculates at each location point the hourly pressure coefficient and generates a Wind Pressure and Contaminant (WPC) file.

The above combination is superior for more realistic and accurate predictions of airflow and pollutant transport in large buildings [38]. The overall outline of the numerical methodology is presented in **Figure 3**.

Figure 3: Outline of the developed numerical methodology.

2.2.1. Building infiltration

Over the last few decades, many models have been developed to study building infiltration and indoor air quality (IAQ) for different types of buildings, such as COMIS and CONTAM [45]. The latter is one of the most widely used models [33], it is a multi-zone IAQ model appropriate for the determination of (a) airflows and pressures, (b) contaminant concentrations, and (c) personal exposure under different specified conditions.

Many researchers and engineers have used it for investigating indoor concentrations, relative humidity and PM_{2.5} level concentrations [46, 47] in buildings, infiltration of ultra-fine

particles [48] and recently PM level concentrations inside school bus [49]. Estimation impact of the envelope air-tightening characteristics regarding the infiltration rates is one of the main features of the model. The CONTAM airflow analysis is based on the initial algorithms developed by Walton [50] for AIRNET computer program [51].

According to CONTAM, the transient partial differential equations for airflow analysis can be written as follows [52]:

$$\frac{\partial m_i}{\partial t} = \rho_i \frac{\partial V_i}{\partial t} + V_i \frac{\partial \rho_i}{\partial t} = \sum_j F_{ji} + F_i \quad (1)$$

where m_i is the mass of air for i zone, t is the time, ρ_i is the density for i zone, V_i is the volume for i zone, F_{ij} is the air flow rate from j to i zone and F_i non-flow processes for i zone (add or remove significant quantities of air from i zone). The F_{ij} and m_i are given by the following equations:

$$F_{ij} = f(P_j - P_i) \quad (2)$$

$$m_i = \rho_i V_i = \frac{P_i V_i}{RT_i} \quad (3)$$

where P_j is the pressure for j zone, P_i is the pressure for i zone, $f(P_j - P_i)$ is the function of the pressure drop along the flow path, T_i is the temperature for i zone and R is the ideal gas constant.

The flow of air through doors, windows gaps and cracks due to pressure difference is defined as infiltration. In CONTAM, this phenomenon is governed by Bernoulli's equation [52].

$$\Delta P = \left(P_1 + \frac{\rho V_1^2}{2} \right) - \left(P_2 + \frac{\rho V_2^2}{2} \right) + \rho g(z_1 - z_2) \quad (4)$$

where ΔP is the pressure drop between points 1 and 2, P_1 is the inlet static pressure, P_2 is the outlet static pressure, g is the gravitational acceleration, ρ is the air density, z_1 is the inlet elevation and z_2 is the outlet elevation. The detailed indoor building geometry and information about the HVAC system (inlets and hourly airflows schedule) and envelope openings (doors, windows etc) were extracted from the building's HVAC study and the as-built drawings (CAD - Computer Aided Design) (personal communication with the maintenance engineers).

The mass fractions of PM are solved after the flows have been computed, by simultaneous solution of the non-symmetric, linear algebraic equations. More specifically, for each contaminant species, CONTAM solves one transient conservation equation per control volume. Herein, PM is the employed contaminant considered as non-trace, meaning that it does not affect the density of air, and split into two ($PM_{10-2.5}$ and $PM_{2.5}$) or three ($PM_{10-2.5}$, $PM_{2.5-1}$, PM_1) size fractions depending on the scenario (see next section). Three additional processes are employed to accurately simulate the PM behaviour i.e. filtration, deposition, and resuspension. The first process is applied for all openings and HVAC filtration points (intake and discharge locations), and the other two for all vertical and horizontal building elements (walls and floors). Filter information has been extracted from the building HVAC study (personal communication) and the deposition/resuspension parameters have been selected from the available CONTAM libraries to match the building's materials. Each zone has been considered as an individual control volume.

Finally, outdoor concentration levels were provided by the field measurements, which are imported into the CONTAM via the ambient contaminant (CTM) file. Similarly, the required weather data for were prepared either as a simple tabular file or a CONTAM-compatible weather (WTH) using real hourly data from the local meteorological authority.

2.2.2. Wind flow and pressure

In this study, a CFD software known as QUIC was selected to calculate the external wind pressures during a dust storm event. During the past few years, the model has been validated and improved extensively by many scientists and engineers [53-55]. QUIC is comprised by three sub-models, namely the QUIC-URB (3-D wind model), the QUIC-PLUME (Lagrangian dispersion model) and the QUIC-CFD model [34].

QUIC-URB is characterised as a 3-D empirical-diagnostic wind model which predicts the wind profiles around complex buildings by using empirical parameterizations and mass consistent techniques [56, 57].

QUIC-CFD model consists of the continuity and Navier-Stokes equations for 3-D turbulent fluid flow. The 3-D Reynolds-Averaged Navier-Stokes (RANS) equations are solved explicitly in time until a steady state is reached using a projection method [58]. All the governing equations can be written in the following general form known as transport equation for property ϕ .

$$\frac{\partial}{\partial t}(\rho\phi) + \text{div}(\rho\mathbf{u}\phi) = \Gamma_{\phi} \text{grad } \phi + S_{\phi} \quad (5)$$

where ρ is the density of the fluid, ϕ is the dependent variable (i.e. u_x, u_y or u_z for momentum, the variable ϕ also stands for the turbulence kinetic energy, or a turbulence length scale 1 for mass continuity), Γ_{ϕ} is the “effective” exchange coefficient of variable ϕ , and S_{ϕ} is the source/sink term per unit volume, of variable ϕ . The turbulence modelling is achieved by a simplified zero-equation model based on the Prandtl’s mixing length model [59, 60]. The continuity and RANS equations, along with the appropriate boundary conditions have been solved by means of the Finite Volume Method [61] on a staggered grid. For the discretisation of partial differential equations, a second-order central difference scheme in space and a second-

order Adams-Bashforth scheme in time were selected, respectively, maintaining second-order accuracy in overall [39, 58].

For every hour in the study period a steady state simulation was conducted using mesoscale data for the initialization (generated with the MM5-Fifth-Generation Penn State/NCAR Mesoscale Model see [62] for details on the configuration and setup). The average roughness length for the bottom layer, representing the non-resolved ground and not the whole urban environment, was estimated to be equal to 0.2 m by imposing a logarithmic profile at the inlet boundary and matching the result with the mesoscale data. Also, a free slip boundary condition is applied at the rigid surfaces i.e. walls of the buildings. The top and side boundaries of the domain are handled by QUIC with no further requirements from the user. The 3-D computational domain for the simulations extends to 1000 m length (X), 1100 m width (Y) and 50 m height (Z). The first two dimensions are large enough to include the wider area and neighbouring buildings and they also follow related guidelines for CFD simulations in urban environments [63]. The third dimension has been set equal to the height of the first layer in MM5. A uniform Cartesian grid was also selected with 4 m resolution in X and Y directions and 1 m in Z. The external building geometry was extracted from the above same CAD files as for CONTAM while dimensions for all other buildings, within the domain, have been extracted from Google Earth images. Overall configuration, e.g. boundary conditions, followed the instructions of QUIC literature [58].

2.3. Investigated scenarios

The selection of modelling scenarios for investigating the building infiltration of $PM_{2.5}$ and PM_{10} involves the study of three different cases. The first one takes into account the filter specifications of the HVAC system of the commercial building on the simulation input parameters, as it is without fitting or calibration using only the available libraries of CONTAM

software. The use of filters is to achieve efficient removal of particles from the HVAC system. The filters specifications in the commercial building based on the American National Standard Institute (ANSI)/ American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) Standard 52.2 Minimum Efficiency Reporting Value (MERV) 14. According to MERV 14, the filter % efficiency (E) for PM at Range 1 ($0.3 - 1.0 \mu\text{m}$) is $75 \leq E_1 \leq 85$, at Range 2 ($1.0 - 3.0 \mu\text{m}$) is $E_2 \geq 90$ and at Range 3 ($3.0 - 10.0 \mu\text{m}$) is $E_3 \geq 95$. The filtering efficiency is a very important parameter for the building simulation in order to identify the size and distribution of the outdoor particles from the mechanical ventilation system to the building.

The second scenario uses own estimated filter efficiencies for the HVAC system based on the measured data only for the non-operational hours of the first day of the study period. Coincidentally, this was the day prior to the dust storm event. More specifically, CONTAM and QUIC, coupled as described earlier, were employed to calculate the hourly PM_{10} (transformed to $\text{PM}_{2.5-10}$) and $\text{PM}_{2.5}$ indoor concentration levels from March 31st 15:00 to April 1st 05:00 without considering any PM removal from the HVAC filters (e.g. filters' efficiency set to 0%). Using the linear least squares method the best fitting coefficients (slope) were obtained through the calculated and measured concentrations, assuming that these coefficients represent the filters' efficiencies for the $\text{PM}_{2.5-10}$ and $\text{PM}_{2.5}$ respectively. The obtained fitted filters' efficiencies were 98.2% and 98% for the $\text{PM}_{2.5-10}$ ($\pm 0.5\%$) and $\text{PM}_{2.5}$ ($\pm 1.0\%$), respectively. They are relatively higher than the nominal ones (according to MERV 14), which could be attributed to the larger loads of PM and the subsequent formation of a thicker and denser filter cake during operation.

Finally, the third scenario involves the calculation of PM levels based on the HVAC operation "off" i.e. the HVAC system does not operate. **Table 1** presents the considered scenarios.

All simulations with CONTAM had very short computational times, less than a few minutes. The QUIC simulations lasted around nine hours for the whole study period and were executed at the Texas A&M University at Qatar High Performance Computing Facility (Cray® XC40-AC) using eight CPU cores (Intel Xeon E5-2690 V3).

Table 1: The considered scenarios with the varying input parameters.

Name	Filter % efficiency for PM	HVAC
MERV14 – HVAC ON	[Based on ASHRAE Standard 52.2] $PM_{3-10} \geq 95$ $PM_{1-3} \geq 90$ $75 \leq PM_{0.3-1} \leq 85$	On
FIT-HVAC ON	[Based on own estimations/fitting] $PM_{2.5-10} = 98.2$ $PM_{2.5} = 98$	On
HVAC OFF	-	Off

3. RESULTS AND DISCUSSION

3.1. Field measurement analysis

Figure 4a exhibits the time series of the outdoor and indoor $PM_{2.5}$ and PM_{10} mass concentration levels between 30/03/2015 and 16/04/2015. In general, the outdoor PM_{10} varied from $55 \mu g m^{-3}$ to over $30,000 \mu g m^{-3}$, while outdoor $PM_{2.5}$ from $30 \mu g m^{-3}$ to $5,550 \mu g m^{-3}$. On the other hand, the indoor PM_{10} measurements were found to be in the range of $1-700 \mu g m^{-3}$, while indoor $PM_{2.5}$ between 0.4 and $180 \mu g m^{-3}$. Although, the outdoor $PM_{2.5}$ and PM_{10} levels varied significantly during the measurement period, the minimum values were always above the PM_{10} Qatar National Ambient Air Quality Standards ($150 \mu g m^{-3}$ daily average). Indoor $PM_{2.5}$ and PM_{10} concentration values are lower and affected only during severe outdoor conditions. It is also observed that the hourly variation of the indoor PM is driven by the pattern of the outdoor

with just a small delay, which is attributed to the slow infiltration of particles in the building envelope.

Figure 4. Outdoor and indoor PM concentrations for the a) whole study period (hourly averages) and b) dust storm event (1-min averages). The yellow and orange solid lines represent the proposed severe dust storm threshold levels according to the classification of Song, et al. [17] and Draxler, et al. [64]. The blue solid line at $150 \mu\text{g m}^{-3}$ presents the Qatar National Air Quality Standard (AQS) for PM_{10} (daily average). The light grey shaded area represents the time period of the selected severe dust storm event.

Figure 4b shows the minute values for outdoor and indoor $\text{PM}_{2.5}$ and PM_{10} levels from 21:00h April 1st until 10:00h. Note that after 14:00h, the building is closed for the public and most occupants have left until 16:00. This means that the building doors were practically closed but PM infiltrated almost immediately. The PM mass concentration levels remained at the highest values for almost 8 hours. Then, they decayed rapidly to normal for the region levels. The indoor

PM mass concentrations decrease twice as slower than the outdoor which is attributed to the characteristic behaviour of the isolated building envelope.

Figure 5: Before, during and after the dust storm event: (a) $I/O - PM_{2.5}$ and $I/O - PM_{10}$, and (b) indoor and outdoor ratio of $PM_{2.5} / PM_{10}$, respectively. The light grey shaded area represents the time period of the severe dust storm event.

To demonstrate better this effect, in **Figure 5a**, the temporal evolution of indoor to outdoor ratio is presented. The ratio is constant throughout the initiation and duration of the dust storm event (see grey shaded area). However, the ratios do not follow the decay of the event, as it takes around 4 hours to reach back to the normal levels (~ 0.03). Probably, this would have been even

longer if the building remained closed the next day (operation hours start around 08:00 am in the morning). It is also noticed that the I/O ratio for both the $PM_{2.5}$ and PM_{10} displays low values before the initiation of the dust storm event which is associated with the filtration and tightness of the building and thus significantly lower than past studies focusing on residential buildings [31]. Furthermore, the normal I/O ratios of PM_{10} are little higher than those of $PM_{2.5}$, as seen before and after the dust event, excluding few periods, as shown in **Figure 5a**.

Figure 5b exhibits the ratios of $PM_{2.5}/PM_{10}$ before, during, and after the severe dust storm period. It is seen that before and after the event there are not great differences between the outdoor and indoor ratios. On the onset of the severe dust storm event around 21:00 we notice a rapid decrease of both the outdoor and indoor ratios. The former is characteristic of large dust storms that are usually dominated by larger particles. The latter, indicates the start of infiltration process in the building. However, the indoor ratio is progressively increasing during the event until the opening of the building (08:00h) thereafter it follows the outdoor ratio. This behaviour can be explained by a) the higher deposition rates of the larger particles and their subsequent removal from the atmosphere, and b) the higher infiltration of smaller particles. The data collected in this study are not enough to identify the contribution of each mechanism, with some reservations, we propose (a) as a more prominent mechanism compared to (b), based on interpretation of the four ratios (**Figure 5**) and measured concentration levels (**Figure 4**).

3.2. Prediction of indoor PM mass concentrations

In this study, the indoor $PM_{2.5}$ and PM_{10} were calculated for three different scenarios (Section 2.3).

Figure 6 presents the collected measurements for $PM_{2.5}$ from 30/3/2015 to 16/04/2015, together with the predicted $PM_{2.5}$ values according to the considered scenarios; the light gray shaded area identifies the period of the severe dust storm event.

It is observed that the predicted and measured values of indoor $PM_{2.5}$ follow a relatively similar pattern, excluding the case for HVAC operation “off”. The predicted $PM_{2.5}$ values for scenario “MERV14-HVAC ON” tend to overestimate the measured values for $PM_{2.5}$, while the “FIT-HVAC ON” model seems to approach much better the measured $PM_{2.5}$ levels. Again, this is supported from **Figure 6a-b** which illustrates the highest peaks of the measured $PM_{2.5}$ levels along with the predicted values for the three developed models during the severe dust storm event, indicating the performance (overestimation or underestimation) of the models. It is clear that the performance of FIT-HVAC ON scenario (max predicted $\sim 200 \mu g.m^{-3}$ vs. max measured $180 \mu g.m^{-3}$) is much better than “MERV14-HVAC ON” scenario (max predicted $\sim 550 \mu g.m^{-3}$ vs. max measured $180 \mu g.m^{-3}$), especially during the period ($\sim 22:00-06:00h$) when the levels of $PM_{2.5}$ concentrations reach the highest values. It is also seen that the two models with HVAC operation “on” provide insights not only during the main dust storm event, but also for normal days and secondary storm events (e.g. on 13 April 2015, see **Figure 6a-b**).

In the case of HVAC operation “off”, the predicted $PM_{2.5}$ values initially increase but not to the level of the measured $PM_{2.5}$. In this scenario, PM infiltrate only via the building’s and windows’ cracks. Furthermore, after the end of the severe dust storm event the $PM_{2.5}$ levels remain stable because there is no ventilation to refresh the indoor air, as shown in **Figure 6b**.

In addition, neither model can capture the much lower concentrations during the closed-office hours, whatsoever just a few $\mu g.m^{-3}$ lower. Specifically, a $3.9 \mu g.m^{-3}$ and $2.8 \mu g.m^{-3}$ relative and absolute deviation was estimated for the “MERV14-HVAC ON” and $0.9 \mu g.m^{-3}$ and $0.6 \mu g.m^{-3}$, respectively, for the “FIT-HVAC ON”. These differences between the predicted and

measured $PM_{2.5}$ could be attributed to the models' assumptions and also to the measurements uncertainty of the experimental instruments.

Figure 6: Comparison of indoor measured and predicted $PM_{2.5}$ levels for a) all the collected data and b) the dust storm period. Also, the scatter plots of measured versus predicted mass concentration c) in full graph scale and d) zoom graph scale including the additional linear

fitting for FIT (red solid line) and MERV14 (blue solid line) scenarios. The black solid line indicates perfect agreement, while the black dashed lines represent the fraction of predictions within a factor of two of measurements (FAC2). The light grey shaded areas represent in (a) the period of the selected dust event and in (c) the zoom area.

Figure 7 depicts the collected measurements for the PM₁₀ concentration levels (30/3/2015 - 16/04/2015) along with the predictions obtained from the three selected numerical scenarios. The light gray shaded area presents from start to finish the severe dust storm event. It is seen that the predicted PM₁₀ values follow relatively similar motif to measured PM₁₀, except for the case at which the HVAC system operation is “off”. It is also observed that in a few cases the predicted PM₁₀ concentration levels are also approaching or matching the measured PM₁₀.

This can be seen clearly in **Figure 7b**, at which the PM₁₀ levels for the case of “FIT – HVAC ON” scenario almost match the measured PM₁₀ levels at 22:00 and 01:00, while for the high peak period of PM₁₀ (21:30 – 05:30) the specific model overestimates the measured PM₁₀. In the case of “MERV14 - HVAC ON”, the model overestimates the measured PM₁₀ during the high peak period but approaches well at the end of the severe dust storm event.

The comparison of measured and predicted mass concentration levels for PM_{2.5} is presented in **Figure 6c-d**. It is noticed that the measured and predicted PM_{2.5} levels are highly correlated with an adjusted R² equal to 0.82 for “Linear - MERV14” and 0.97 for “Linear – FIT” scenarios, respectively, as shown in **Figure 6d**. It is clear that the estimated PM_{2.5} concentrations are in good agreement with the measurements, while the performance of “PM_{2.5} – FIT” model is better than PM_{2.5} – MERV14 model. Subsequently, the most concentration values of PM_{2.5} mainly fall within FAC2 (Factor of two), which also constitutes a common metric for the performance of atmospheric dispersion models.

Figure 7: Comparison of indoor measured and predicted PM_{10} levels for a) all the collected data and b) the dust storm period. Also, the scatter plots of measured versus predicted mass concentration c) in full graph scale and d) zoom graph scale including the additional linear fitting for FIT (red solid line) and MERV14 (blue solid line) scenarios. The black solid line indicates perfect agreement, while the black dashed lines represent the fraction of predictions

within a factor of two of measurements (FAC2). The light grey shaded areas represent in (a) the period of the selected dust event and in (c) the zoom area.

Finally, the mass concentration levels for PM_{10} are shown in **Figure 7c-d**. A better performance is observed for “ PM_{10} – FIT” model with an adjusted R^2 equal to 0.92, while for $PM_{2.5}$ – MERV14 model a value of 0.83 is obtained. It is concluded that the predicted PM_{10} levels for both models are in fair agreement with the measured PM_{10} concentration, giving some confidence for the accuracy of the present numerical methodology.

3.3. Qualitative analysis of the meteorological conditions impact

Previous paragraphs presented and discussed the field measurement data and the modelling calculations focusing on the observed levels and ratios for the I/O levels and for $PM_{2.5}/PM_{10}$. The qualitative discussion of how the outdoor meteorological conditions affect the PM infiltration and ratios can also lead to interesting hypothesis. **Figure 8** presents the polar plots of the dependence of these two ratios ($PM_{2.5} / PM_{10}$ and I/O) on the wind direction and velocity. In **Figure 8a** is noted that the outdoor $PM_{2.5}/PM_{10}$ ratio tends to be larger at low wind speeds but not at calm conditions (typically less than 1 m.s^{-1}), and mainly from two specific wind segments West and East. These segments match somehow the direction of the coastline and of two trafficked streets but not exactly (building orientation NNW to SSE). The indoor $PM_{2.5}/PM_{10}$ ratio (**Figure 8b**) increases when both the outdoor ratio and wind velocity are high. The PM_{10} I/O ratio (**Figure 8c**) does not reveal any pattern. On the contrary, the $PM_{2.5}$ I/O (**Figure 8d**) shows a very distinct pattern for the strong North and South winds. Based solely on this figure, a frivolous conclusion could have been that there is a strong correlation of the $PM_{2.5}$ I/O ratio with the wind velocity. However, examining **Figure 8a** and **d** it is clear that the $PM_{2.5}$ I/O increase during these periods it

is driven by the outdoor $\text{PM}_{2.5}/\text{PM}_{10}$ decrease. Indeed, a correlation analysis including all the above ratios and the wind velocity revealed no identifiable correlation among them (figure or detailed results not shown here).

Figure 8: Polar plots displaying the dependence of $PM_{2.5} / PM_{10}$ and I/O ratios on the wind direction and velocity for the whole study period. The arc segment encloses the observed conditions during the severe dust event.

4. CONCLUSIONS

Dust storm events are common natural phenomena of dry and arid climates that severely affect human life and infrastructure. This study presented the measurements of an experimental campaign that captured one of the most severe such events in Middle East of the past decade and its impact to indoor air quality at a typical office-building. Infiltration of PM during the dust event was almost immediate for both PM_{10} and $PM_{2.5}$. After the event, cleaning of the indoor air was slow when HVAC was the only mechanism but it accelerated when the building doors opened. Ratios of indoor and outdoor, and $PM_{2.5}$ and PM_{10} levels showed interesting patterns. For example, outdoor $PM_{2.5} / PM_{10}$ was around 0.2 during the event but the indoor ratio started from this value and progressively increased owe to PM_{10} deposition. Overall, outdoor levels during normal and event days where mostly above WHO and Qatar National Air Quality standards, but not the indoor levels.

A combination of modelling tools was presented for predicting the airborne PM building infiltration during severe dust storm events and normal days. The numerical results present encouraging agreement with measurements when standard HVAC information is employed, using the CONTAM libraries. The agreement is improved when more representative information for the HVAC filters is available i.e. by obtaining specific PM removal filter efficiencies using measured data. Finally, it is important to note that future studies are required to capture more

similar events, study the infiltration at residential buildings, and assess the available mitigation strategies against dust events.

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CONFLICT OF INTEREST STATEMENT

The authors declare no competing interests.

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