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Impact of ventilation method on residential indoor PM dispersion during dust storm events in Saudi Arabia

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\textbf{ABSTRACT}
Dust storms are a major environmental hazard in arid regions such as the Middle East and other parts of Asia including China and Mongolia. The prevalence of dust storms has been widely linked with high atmospheric Particulate Matter (PM) concentrations. The atmospheric PM concentration is considered as being positively correlated with the PM concentration of the indoor environment. High indoor concentrations of PM compromise the Indoor Air Quality (IAQ) leading to adverse impacts on building occupants’ health with increased occurrences of asthma attacks, spread of disease-causing fungus, skin allergies and other ailments. There is, therefore, an increased risk of compromised IAQ in places that experience dust storms. This risk may be exacerbated by the incorporation of mechanical ventilation systems in attempts to condition the indoor ambient air. Instead of minimizing the problem of PM contamination, these systems may potentially nurture it. Using Computational Fluid Dynamics analyzes in ANSYS Fluent, this study seeks to investigate the impact of ventilation method on outdoor-originating indoor PM dispersion within the occupied indoor environment during dust storm events in Saudi Arabia. Four ventilation methods are studied and the one that yields the least amount of particle trajectories terminating within the breathing zone is recommended for use.

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\textbf{KEYWORDS}
Dust storm; particulate matter; computational fluid dynamics; indoor air quality; Saudi Arabia

\section*{Background and introduction}
Dust storm events are a common meteorological phenomenon in arid regions (Goudie, 2014; Indoitu, Orlovsky, & Orlovsky, 2012; Middleton, 2017; Shao & Dong, 2006). They are characterized by turbulent wind systems which carry substantial amounts of sand and dust particles.

The prevalence of dust storms has been widely linked with high atmospheric PM concentrations. A study by Leys, Heidenreich, Strong, McTainsh, and Quigley (2011) reported excessively high PM concentrations at several locations in Australia during a dust storm event dubbed Red Dawn. In another study, Draxler, Gillette, Kirkpatrick, and Heller (2001) undertook periodic measurements of PM concentration at several locations in the Middle East and they found that higher concentrations were attributable to dust storm events in the region. Prasad and Singh (2007), investigating the seasonal variability of Aerosol Parameters during dust storm events in India, found that the Aerosol Optical Depth (AOD) increased with the prevalence of dust storms indicating an increase in the atmospheric
PM concentration. Another study by Alam, Trautmann, Blaschke, and Subhan (2014) in the Middle East and South West Asia showed a similar trend.

The atmospheric PM concentration is considered as being positively correlated with the PM concentration of the indoor environment. Several studies have shown that high outdoor PM concentrations are generally responsible for high indoor PM concentrations (Braniš, Řezáčová, & Guignon, 2002; Jamriska, Thomas, Morawska, & Clark, 1999; Jones, Thornton, Mark, & Harrison, 2000; Latif et al., 2014; Morawska, Jayaratne, Mengersen, Jamriska, & Thomas, 2002; Tippayawong, Khuntong, Nitawitchit, Khunatorn, & Tantakitti, 2009). The high indoor concentrations of PM compromise the Indoor Air Quality leading to adverse impact on occupants’ health (Gaffin et al., 2017).

There is an increased risk of compromised IAQ in places that experience dust storms. This risk may be exacerbated through the incorporation of mechanical ventilation systems in attempts to condition the indoor ambient air. Instead of minimizing the problem of contamination, these systems may potentially nurture it.

This study seeks to investigate the impact of ventilation method on outdoor-originating indoor PM dispersion within the occupied indoor environment during dust storm events in Saudi Arabia. Four ventilation methods are studied and a recommendation of the one that yields the least amount of particle trajectories terminating within the breathing zone is recommended for use.

**Literature review**

Dust storms are a major environmental hazard in arid regions such as the Middle East and other parts of Asia including China and Mongolia. These events have been variably defined by different authors. Nonetheless, there seems to be a general consensus that they are severe weather events characterized by substantial concentrations of dust and sand carried by strong winds (Bobrowsky, 2013; Wang, Wang, Zhou, & Shang, 2005). The atmospheric dust and sand can be transported over great distances from their points of origin (Goudie & Middleton, 2006). During dust storm events, the atmospheric Particulate Matter concentration can rise sharply to hazardous levels. A study by Alghamdi et al. (2015) compared the atmospheric PM concentration during a dust storm and non-dust storm events in western Saudi Arabia. Their findings showed that the PM concentration rises sharply during dust storms. In a similar study conducted in Iran, Shahsavani et al. (2012) reported a similar positive correlation between dust storm occurrence and atmospheric Particulate Matter concentration. The same trend was also reported in several other studies (Alam et al., 2014; Draxler et al., 2001; Leys et al., 2011).

The rise in atmospheric PM concentration is a major health hazard to human beings. A study by Johnston, Hanigan, Henderson, Morgan, and Bowman (2011) reported a 15% increase in non-accidental mortality in the immediate aftermath of dust storm events in Australia. In a similar study, Lee et al. (2014) reported a higher increase of up to 18% for South Korea, Taiwan and Japan. A lower figure was reported for the USA at 7.4% (Crooks et al., 2016). The PM carried by the dust storms has been linked to increased occurrences of asthma attacks (Gyan et al., 2005; Kanatani et al., 2010; Wang, Chen, & Lin, 2014), the spread of disease causing fungus (Leathers, 1981) and symptoms of dry eyes, dry itchy throat and skin allergies amongst others (Zhao & Wang, 2010). The increase in the mortality rates can be attributed to either direct exposure to the PM in the outdoor environment or indirect exposure through the occupation of indoor environments whose air quality has been compromised by way of infiltration of the outdoor originating PM. The latter is a major problem for Indoor Air Quality (IAQ) research. Several studies have been undertaken to investigate outdoor originating indoor particulate matter infiltration, dispersion, removal and deposition.

In one study, Zhang and Chen (2006), used a CFD tool with a Lagrangian Particle Tracking method to study the dispersion and concentration of particles in ventilated rooms. Three ventilation systems namely ceiling, side wall and underfloor air distribution were evaluated on the basis of their particle removal performance. With the particle source at floor level for all the
three systems, it was found that the underfloor air distribution system yielded the best performance.

Similar studies were conducted by Gao and Niu (2007), Zhong, Yang, and Kang (2010), Jurelionis et al. (2015) and Ansaripour, Abdolzadeh, and Sargazizadeh (2016). Gao and Niu (2007) investigated particle dispersion and deposition rates under 3 ventilation systems namely, displacement, mixing and Under Floor Air Distribution (UFAD) Systems. Zhong et al. (2010) investigated the effect of pollutant source location and ventilation strategy on the dispersion of the particles within a ventilated room. The ventilation systems studied were the mixing and underfloor air distribution. Using both experimental and numerical approaches, Jurelionis et al. (2015) studied the impact of displacement and mixing ventilation methods on the aerosol particle dispersion and removal. The study showed that mixing ventilation method yielded better pollutant removal efficiency. Ansaripour et al. (2016) sought to investigate the effects of displacement and mixing ventilation systems on the transportation and distribution pattern of particles emitted from a laser jet printer located within a ventilated room. A seated manikin, under heated and unheated conditions, was included in the study, and the particle concentration within its breathing zone investigated under the different ventilation configurations. It was found that under heating, the particle concentration in the manikin’s breathing zone was higher. It was also found that the mixing ventilation resulted into a lower particle concentration than the displacement ventilation systems.

In other studies, using CFD simulations, Zhou, Deng, Wu, and Cao (2017) sought to investigate the effect of ventilation and heating systems on indoor particulate matter concentration in buildings located in the northern part of China. It was found that higher ventilation velocity rates and temperatures yielded faster particle concentration decay rates. A very similar study was undertaken by Jurelionis, Stasiuliene, Prasauskas, and Martuzevicius (2018) who sought to investigate the impact of floor heating systems on the dispersion of particulate matter from flooring materials such as carpets. It was reported that floor heating minimized pollutant dispersion. Zhuang, Yang, Long, and Hu (2017) investigated two air conditioning systems namely central and split type, with regard to the efficiency with which they removed indoor air particulate matter and the resulting deposition of the particles. It was found that the central air conditioning system removed particles more efficiently while depositing them on the floor surface. The split type system on the other hand, was found to deposit the particles on the walls.

Hänninen et al. (2004) note that outdoor PM2.5 can have very high infiltration factors into the indoor environment, at times reaching as high as 1.0. In a study conducted to investigate the infiltration of ambient PM2.5 in residences of four European cities, the infiltration factors were found to range from 0.59 in Helsinki to 0.70 in Athens, with Basle and Prague in between. Yang, Kang, Gao, and Zhong (2015) sought to investigate the effect of wall transparency ratio on the infiltration of traffic generated PM into the indoor environment.

In another study, Kearney et al. (2014) investigated infiltration of PM into residential houses in Canada. They studied seasonal variations in infiltration factors in summer and winter and their results showed a range between 0.10 and 0.99. The summer registered higher infiltration factors due to the longer hours that windows remained opened as opposed to the winter season.

Wan et al. (2015) sought to investigate the effect of window airtightness on indoor concentration of PM2.5 in two office buildings in Beijing, China. It was found that particle concentrations were higher with lower window airtightness. This study also showed that however high the airtightness, atmospheric PM2.5 can still infiltrate into the indoor environment.

In spite of the considerable amount of research work that has been undertaken in this area, there appears to have remained a lack of interest on the interaction between outdoor originating PM2.5 and indoor ventilation systems, and particularly within the context of dust storm events in the Middle East and similarly characterized geographical locations. The present study seeks to contribute towards efforts in filling this existing literature gap.
Methodology

This study was primarily dependent on Computational Fluid Dynamics simulations in ANSYS Fluent. A computational model was developed to replicate a room in a Saudi Arabian residential housing unit. Simulations were then executed to study the impact of four different ventilation methods on the dispersion trajectories of Particulate Matter infiltrating into the indoor environment from the outside during a dust storm event.

Simulation environment

This study is based on a housing project being undertaken by the King Abdulaziz City for Science and Technology (KACST) in Saudi Arabia and the Virginia Tech Centre for High Performance Environments (CHPE) in the USA. This is a Saudi Arabian government funded project aimed at developing prefabricated housing units that combine automation, structural integrity and energy efficiency while cutting on the construction time and site labor intensity (KACST). A floor plan of one of the prototypical housing units in this project is shown in Figure 1:

For the purposes of this study, the investigation zeroed in on the dining room that appears encircled in red in Figure 1 above. The dining room was selected due to its large wall transparency ratio at 6.5 m² and thus the significant potential for outdoor originating particulate matter infiltration into the indoor environment.

The study identified four possible methods that may be used in delivering ventilation air in the prototypical housing units. These included the ducted method, Under-Floor Air Distribution (UFAD) system, wall mounted mini split system and ceiling mounted mini split system. According to Alrashed and Asif (2014) and Shash and Al-Mulla (2002) these methods constitute some of the most widely used and recently emerging in Saudi Arabia.

Basing on the aforementioned ventilation methods, four scenarios were defined for this study as described in Table 1 and Figure 2:

Inlet boundary conditions

The boundary conditions in ANSYS Fluent were set such that the ventilation methods achieved 14 Air Changes per Hour (ACH) as required by ASHRAE (ANSI/ASHRAE, 2007). The PM infiltration flow rate was set at 0.001 ms⁻¹ while the ventilation air supply rate was set at 1.5 ms⁻¹. For ease of management of the simulation environment, all PM infiltration had been resolved to occur from the center of the window opening over a total surface area of 0.3 m², being 5% of the total window opening area. This infiltration area was characterized as a surface injection point, injecting particles having an

Figure 1. Floor plan of prototypical housing unit and the dining room (CHPE, 2018; KACST).
average diameter of about 1e–06 m at a velocity of 1e–03 ms−1 and a total flow rate of 1e–20 Kgs−1. Dust particles range in size from about 1 μm to 100 μm (Mahowald et al., 2014). This study was particularly interested in particles having a diameter of about 2.5 μm which constitute the major problem for indoor air quality (Hänninen et al., 2004; Kearney et al., 2014; Rivas et al., 2015; Wan et al., 2015).

Outlet boundary conditions
There are two exhaust outlets of the outflow type, one on each of the side walls adjoining the window opening, where the dining room connects with the negative pressure zones created by the exhaust fans in the kitchen and bathrooms. The dining room measures 4.5 × 3.9 m.

Turbulent air flow model
This study employed the Reynolds Averaged Navier Stokes (RANS) equations and the Standard $k-\varepsilon$ model to solve the incompressible turbulent air flow in a ventilated room.

The RANS equations are the conservation equations governing the continuity, momentum and energy of the air flow in the room. They are given as below:

Continuity Equation:

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0$$

<table>
<thead>
<tr>
<th>Scenario number</th>
<th>Ventilation method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>Ducted System</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>Under Floor Air Distribution</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>Ceiling Mounted Mini Split</td>
</tr>
<tr>
<td>Scenario 4</td>
<td>Wall Mounted Mini Split</td>
</tr>
</tbody>
</table>

Table 1. Scenario definition.

Figure 2. Scenario geometrical configuration.
Momentum Equation:
\[
\frac{\partial \bar{u}_i}{\partial t} + \sum_{j=1}^{3} \frac{\partial}{\partial x_j} (\bar{u}_i \bar{u}_j) = -\frac{1}{\rho} \frac{\partial \bar{p}}{\partial x_i} + \sum_{j=1}^{3} \left( \nu + \nu_t \right) \frac{\partial \bar{u}_i}{\partial x_j} + g_i \beta (\bar{T} - T_0)
\]

Energy Equation:
\[
\frac{\partial \bar{T}}{\partial t} + \sum_{j=1}^{3} \frac{\partial}{\partial x_j} (\bar{u}_j \bar{T}) = \sum_{j=1}^{3} \left( \alpha + \alpha_t \right) \frac{\partial \bar{T}}{\partial x_j}
\]

where \( \rho \) is the density of the fluid, \( \bar{u}_i \) and \( \bar{u}_j \) are the average fluid velocities in \( x, y \) and \( z \) directions, \( \bar{p} \) is the average pressure of the fluid, \( \nu \) and \( \nu_t \) are kinematic viscosity and turbulent kinematic viscosity respectively, \( \beta \) is the coefficient of thermal expansion, \( \bar{T} \) is the temperature of the fluid, \( T_0 \) is the reference temperature, \( \alpha \) and \( \alpha_t \) are the thermal diffusivity and turbulent thermal diffusivity (Zhou et al., 2017).

The turbulent kinematic viscosity is solved using the standard k-\( \varepsilon \) model which is described as follows:
\[
\frac{\partial}{\partial t} (\rho_m k) + \nabla \cdot (\rho_m \bar{v}_m \bar{T}) = \nabla \cdot \left( \frac{\partial \mu_{t,m}}{\sigma_k} \nabla k \right) + G_{k,m} - \rho_m \varepsilon
\]
and
\[
\frac{\partial}{\partial t} (\rho_m \varepsilon) + \nabla \cdot (\rho_m \bar{v}_m \varepsilon) = \nabla \cdot \left( \frac{\partial \mu_{t,m}}{\sigma_k} \nabla \varepsilon \right) + \frac{\varepsilon}{k} (C_1 \varepsilon G_{k,m} - C_2 \varepsilon \rho_m \varepsilon)
\]

where the mixture density and velocity, \( \rho_m \) and \( \bar{v}_m \), are computed from
\[
\rho_m = \sum_{i=1}^{N} \alpha_i \rho_i
\]
and
\[
\bar{v}_m = \frac{\sum_{i=1}^{N} \alpha_i \rho_i \bar{v}_i}{\sum_{i=1}^{N} \alpha_i \rho_i}
\]
the turbulent viscosity, \( \mu_{t,m} \), is computed from
\[
\mu_{t,m} = \rho_m C_\mu \frac{k^2}{\varepsilon}
\]
and the production of turbulence kinetic energy, \( G_{k,m} \), is computed from
\[
G_{k,m} = \mu_{t,m} (\nabla \bar{v}_m \cdot \nabla \bar{v}_m) + (\nabla \bar{v}_m) : (\nabla \bar{v}_m)
\]

Spatial discretization

For the pressure interpolation scheme, this study used PRESTO!. This setting had been used with success in previous studies (Zhou et al., 2017). The momentum, turbulent kinetic energy, turbulent dissipation rate and energy were modeled using the second order upwind. Blocken (2015) recommends the use of higher order spatial discretization schemes. At the minimum, second-order discretization is recommended for use (Roache, Ghia, & White, 1986). First-order discretization schemes are known to cause problems with numerical diffusion (Blocken, 2015).
**Convergence criteria**

Franke (2007) note that the convergence termination criterion of 1e–03 which is used in industrial applications is too high for a converged solution. Instead, they recommend reducing the residuals by at least four orders of magnitude. In the present study, the convergence criterion for the residuals was set at 1e–04.

**Discrete phase particle model**

This study employed the Lagrangian Discrete Particle Model to study the dispersion trajectory of particles within the ventilated room. The dispersion trajectory is predicted by integrating the force balance acting on the particles in motion. The Lagrangian particle model treats PM as a discrete phase and tracks particle trajectories by solving the dynamic particle models (Chang & Hu, 2008; Chang, Kao, & Chang, 2012; Li & Ahmadi, 1993). This model can accurately provide detailed temporal and spatial information of PM trajectories and dispersion history (Zhang & Chen, 2007). It has been demonstrated as having many advantages over other Eulerian modeling (Lai & Chen, 2007; Zhang & Chen, 2007).

The particle force balance can be expressed as below:

\[
\frac{d\mathbf{u}_p}{dt} = F_D(\mathbf{u}_a - \mathbf{u}_p) + \frac{\mathbf{g}(\rho_p - \rho_a)}{\rho_p} + \mathbf{F}_a + \mathbf{F}_b + \mathbf{F}_{th} + \mathbf{F}_s
\]

where \( \mathbf{u}_a \) is the velocity of the particles in motion, \( \mathbf{u}_p \) is the air velocity, \( F_D \) is the drag force per unit particle mass, \( \rho_p \) is the particle density \( \rho_a \) is the air density, \( \mathbf{g} \) is the acceleration due to gravity and \( \mathbf{F}_a \) represents additional forces on the particles.

The drag force can be expressed as below:

\[
F_D = \frac{18 \mu}{\rho_p d_p^2 C_c} (\mathbf{u}_a - \mathbf{u}_p)
\]

where \( \mu \) is the fluid viscosity, \( d_p \) is the particle diameter, \( C_c \) is the Cunningham correction factor

\[
C_c = 1 + \frac{2\lambda}{d_p} (1.257 + 0.4e^{-(1.1d_p/(2\lambda))})
\]

where \( \lambda \) is the mean free path of the air molecules.

In the study, the incoming ventilation air supply was set at a temperature of 20°C. The thermophoresis occasioned on the particles as a result of the thermal gradient so created was accounted for by the inclusion of the thermophoretic force in the force balance equation. Further, seeing that some of the particles under study were likely to have sub-micronian aerodynamic diameters, it became important to account for the Saffman lift force and the Brownian force.

The final force balance equation that was used is expressed as below:

\[
\frac{d\mathbf{u}_p}{dt} = F_D(\mathbf{u}_a - \mathbf{u}_p) + \frac{\mathbf{g}(\rho_p - \rho_a)}{\rho_p} + \mathbf{F}_b + \mathbf{F}_{th} + \mathbf{F}_s
\]

where \( \mathbf{F}_b, \mathbf{F}_{th}, \) and \( \mathbf{F}_s \) represent the Brownian, thermophoretic and Saffman forces respectively.

The instantaneous turbulent velocity fluctuations on the trajectories resulting into the turbulent dispersion of the particles were accounted for by using stochastic tracking capabilities of the Discrete Random Walk (DRW) model which assumes that the fluctuating velocities obey a Gaussian probability distribution such that:

\[
\mathbf{u}'_a = \xi \mathbf{u}'_a^2 = \xi \sqrt{2k/3}
\]

where \( k \) is the turbulent kinetic energy and \( \xi \) is the normally distributed random number.
Validation

The turbulent air flow and discrete phase particle models that were used in the study have been validated for use in indoor applications under non-isothermal conditions using data from Zhang and Chen (2006) who experimentally studied the airflow field and particle concentration distribution in an UFAD ventilation system under non-isothermal conditions. The geometrical configuration and parametric description of the experimental environment are provided in Figure 3 and Table 2 respectively.

A comparison between the experimental results from Zhang and Chen (2006) and the simulation results provided by the turbulent air flow model used in the present study showed good agreement as shown in Figure 4:

For the discrete phase particle model, a point by point comparison between the measured and simulated results was not possible as ANSYS Fluent does not directly calculate the particle concentration. Previous researchers have used the Particle Source In-Cell (PSI-C) scheme (Zhang & Chen, 2006) and the Kernel method (Zhuang et al., 2017) to calculate the particle concentration separately. The latter is based on the number of particles in the computational domain, their mass, spatial position and a smoothing length which are weighted by a Kernel function. In the present study, the concentration was evaluated as the particle mass per cell volume in kg m\(^{-3}\). The number of particles in a cell was expected to be directly proportional to the particle mass in the cell. Naturally, it was anticipated that the further away from the particle source, the lower the number of particles in cells and hence the lower the particle mass concentration in the cells. As anticipated, simulated points further away from the particle source recorded exceedingly small particle mass concentrations such that a feasible comparison between the measured and simulated results was only possible at one location nearest to the particle source, P4. The profiles of the measured and simulated results in Figure 5 show reasonable agreement.

Figure 3. Geometrical configuration of experimental environment; where V and P are velocity and particle concentration measurement points respectively in the XZ axis, adapted from Zhang and Chen (2006).

Table 2. Parametric description of experimental environment, adapted from Zhang and Chen (2006).

<table>
<thead>
<tr>
<th>Surface</th>
<th>Surface temperature (°C)</th>
<th>Boundary</th>
<th>Surface temperature (°C)</th>
<th>Heat power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North wall (+X)</td>
<td>24.9</td>
<td>Floor (–Y)</td>
<td>24</td>
<td>–</td>
</tr>
<tr>
<td>South wall (–X)</td>
<td>25.0</td>
<td>Lamps (each)</td>
<td>–</td>
<td>64</td>
</tr>
<tr>
<td>East wall (+Z)</td>
<td>25.5</td>
<td>Persons (each)</td>
<td>31.6</td>
<td>100</td>
</tr>
<tr>
<td>West wall (–Z)</td>
<td>25.3</td>
<td>Supply (north)</td>
<td>20.4</td>
<td>–</td>
</tr>
<tr>
<td>Ceiling (+Y)</td>
<td>25.7</td>
<td>Supply (south)</td>
<td>19.9</td>
<td>–</td>
</tr>
</tbody>
</table>
Results and discussion

Scenario 1

Scenario 1 introduces air into the room through a duct in the ceiling as shown in Figure 6:

Figure 4. Comparison of measured and simulated velocity profiles (Triangular points – measured velocity, black line – simulated by Zhang and Chen (2006), red line – simulated in the present study).

Figure 5. Comparison of measured and simulated particle concentration profile (Triangular points – measured concentration, black line – simulated by Zhang and Chen (2006), red line – simulated in the present study).

Results and discussion

Scenario 1

Scenario 1 introduces air into the room through a duct in the ceiling as shown in Figure 6:
As this air enters at a velocity of 1.5 ms\(^{-1}\), it generates a downward jet which changes direction upon impact with the floor. The continuous stream of the supply air results into the formation of a quasi-circular flow pattern in the room as shown in Figure 7:

The air flowing along this pattern pushes the infiltrating particulate matter downwards, dragging it along the flow path and raising it upwards into the breathing zone before the air velocity drops to near 0 ms\(^{-1}\) at about midway through the room height as shown in Figure 8:

The ASHRAE Standard (ANSI/ASHRAE, 2007), defines the breathing zone as ranging from about 0.08 m to 1.8 m along the height of the room. For the purposes of this study, seeing that the space under investigation was a dining room, the breathing zone was defined as ranging from about 0.8 m to 1.8 m along the height of the room. It can be seen that the steady flow of the air significantly minimizes the gravitational force on the particles such that once the near 0 ms\(^{-1}\) air velocity is reached midway through the room height, instead of dropping to the floor, the particles remain suspended until parameters other than the supply air velocity, such as the room occupants’ movement amongst others, come into play.

Figure 6. Scenario 1 isometric projection.

Figure 7. Scenario 1 YZ axis projection – flow vectors.
Scenario 2

Scenario 2 employs an Under-Floor Air Distribution (UFAD) system as shown in Figure 9:

Like in scenario 1, the air enters the room at a velocity of 1.5 m/s, but this time, generating an upward jet which only changes course upon impact with the ceiling as shown in Figure 10:

The infiltrating particles are carried along this flow path until the air velocity begins to drop. The particles then succumb to the gravitational force and begin to gradually drop into the breathing zone as shown in Figure 11:

Scenario 3

Scenario 3 employs a centrally mounted ventilation unit supplying air in 4 directions at an angle of 45° as shown in Figure 12:

The air enters the room at 1.5 m/s. The quasi-circular pattern of flow that is evident in the previous scenarios is prevented from developing due to the multi directional air supply as shown in Figure 13:

Figure 8. Scenario 1 YZ axis projection – particle dispersion.

Figure 9. Scenario 2 isometric projection.
Figure 10. Scenario 2 YZ axis projection – flow vectors.

Figure 11. Scenario 1 YZ axis projection – particle dispersion.

Figure 12. Scenario 3 isometric projection.
For this reason, the infiltrating particulate matter remains trapped within a localized zone close to the point of origin as shown in Figure 14:

**Scenario 4**

Scenario 4 introduces air into the room by way of a ventilation unit mounted on a wall facing the window opening through which the infiltration of the particulate matter occurs as shown in Figure 15:

The air is supplied at an angle of $45^\circ$ creating an angular but generally downward jet flow. The jet of air generates a flow pattern that is similar to that of scenario 2. Upon impact with the floor, the air flow path changes, rising upwards towards the ceiling as shown in Figure 16:

The particulate matter is carried upwards and across the room along the ceiling plane. Nonetheless, seeing that the jet of air does not originate in a perpendicular orientation relative to the ceiling plane, the air does not have sufficient energy to travel far enough along the flow path before the
velocity begins to approach $0 \text{ ms}^{-1}$. As the velocity drops, the particulate matter begins to yield to the gravitational force and gradually drop into the breathing zone as shown in Figure 17:

**Summary of results**

A summary of the results is presented in Figures 18 and 19. The figures provide a graphical comparison of the dispersion trajectories that were obtained in each of the study scenarios.

**Conclusions**

The present study sought to investigate the impact of four ventilation methods on the dispersion of actively infiltrating particulate matter within the indoor environment of residential buildings in Saudi Arabia during dust storm events. The findings suggest that the different ventilation methods that were investigated impact on the particles’ dispersion trajectories differently with regard to the breathing zone. It was shown that the centrally located ceiling mounted ventilation unit in Scenario
3 demonstrated a capability of significantly minimizing the risk of contamination of the breathing zone. This unit ensured that the infiltrating particulate matter remains contained within a localized zone close to the point of origin. The other ventilation methods were seen to facilitate particle
dispersion trajectories that terminated in zones whereby the breathing zone became vulnerable to contamination. The study's findings are notwithstanding previous research findings that have lauded the UFAD system's performance over other ventilation methods reporting improved energy efficiency, thermal comfort, adaptability and cost efficiency (Bauman & Dally, 2003; Giles, 2008). With regard to Indoor Air Quality, however, this study has shown that the UFAD system may not perform equally well.

Disclosure statement
No potential conflict of interest was reported by the authors.

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