Abstract
Buildings consisting of vegetative measures, such as green roofs and skygardens hold multiple benefits including improvements in the local microclimate, attenuating noise and air pollution, and physiological wellbeing. Nevertheless, skygardens located on high levels, may be exposed to high wind speeds, endangering the safety of occupants. Despite its popularity, very few studies have investigated the aero-thermal characteristics of such outdoor spaces and the influence of surrounding vegetation. This study utilises Computational Fluid Dynamics (CFD) to analyse 3 types of wind buffers on the wind characteristics of a skygarden located on a high-rise building. The Realizable k-e setup was employed where the vegetation was modelled as a porous zone. Results indicate that not all types of barriers can generate comfortable environment within the region, and taller barriers provide more conducive environment. Porous barriers can attenuate wind speeds in the depth as well as the height of the space, while also producing some local cooling.

Key Innovations
- Investigation of wind flow around highrise semi-enclosed platforms in the form of skygardens.
- Impact of porous and impermeable barriers on the wind flow in such regions.
- Use of vegetation as wind attenuators inside buildings.
- Analysis of evapotranspirational cooling in such skygardens.

Practical Implications
Vegetation, including shrubs and plants may help stall the air flow in semi-enclosed spaces, to create calmer and cooler environment. The key is to appropriately position these buffers and identify specific varieties which can maximise the benefits in the skygarden.

Introduction and Literature Review
As a result of urban growth and development, including increased demands for office spaces and housing within urban areas, a significant number of high-rise buildings and skyscrapers have been built over the years (Wong 2004). To respond to environmental challenges and be future ready, novel concepts of sustainable design and state-of-the-art approaches have been implemented in these high-rise buildings, (Begeç and Hamidabad 2015). Amongst the various strategies, vegetative measures provide multifaceted benefits towards the improvement of the local microclimate through physiological aspects (Perini and Magliocco 2014), by capturing dust (Chen et al. 2017), by attenuate noise (Ferrini et al. 2020) and improving human health (WHO 2017), to name a few. Furthermore, the presence of vegetation such as trees, hedges, and green walls located along open roads and street canyons, can act as a barrier between traffic pollution and adjacent areas. The use of vegetation does not only improve building sustainability, it also helps in reducing building energy demand and CO2 emissions (Aboelata 2020). Additionally, they may also influence the outdoor aero-thermal comfort characteristics (Fabbri et al. 2020).

Semi-outdoor green spaces, with a varied mix of vegetation, incorporated inside intermediary levels of high-rise buildings have recently gained popularity in dense cities such as Singapore and Hong Kong. They are often referred to as skycourts or skygardens. The Bosco Verticale in Milan and the Park Royal Collection Pickering in Singapore (Elena and Massimo 2015; Walker 2017) are examples of buildings with skygarden. It is an important design intervention which aims to improve social, economic and environmental values of a building (Pomeroy 2014) through the provision of additional space for occupants residing inside, or in the proximity, of a building. It is designed to allow occupants to connect and experience outdoor freshness within a semi-enclosed environment (Pomeroy 2014).

The current pandemic (COVID-19) has forced designers to re-examine the spatial planning principles of built spaces as the design of the building may have an impact on the health and safety of occupants (Sharifi and Khavarian-Garmsir 2020). Further vegetations including hedges, shrubs and trees can act as surfaces for deposition of aerosol particles (Janhäll 2015), which are considered to be the primary mode of microbe transmission (WHO 2009). This highlights the advantages of plants in buildings and the need to analyse their influence and impact in detail. The aerodynamic response of the skygardens, based on the impacts of different vegetation types and configurations, must be understood in detail to assist designers in the selection and arrangement of species and buffer elements for creating a conducive environment for occupants.
Previous works by Tien and Calautit (2019), and Mohammadi and Calautit (2019) investigated the influence of the design of the skygarden on the wind and thermal comfort, however the role of barriers in general and vegetation in particular were not discussed. This study is built on previous works and aims to evaluate the modifications in the aero-thermal conditions with the addition of barriers in the central skygarden. Three variations are analysed, namely solid parapet, porous hedge and porous trees, when placed near the edge of the skygarden.

The building and vegetation were initially modelled in CAD and exported into ANSYS Design Modeler to generate the computational domain, as shown in Figure 2. The domain was sized based on the recommended guidelines (Tominaga et al. 2008). The high-rise building geometry had a width and depth of 45.7 m and 30.8 m and a height of 184 m. For the purpose of the analysis, the skygarden was located centrally at a height of 92 m and based on a hollow configuration. The railing, hedge and porous trees were located at the windward and leeward edge of the skygarden to block the incoming wind. The railing was modelled as a solid wall, while the hedge and trees were modelled as porous media. Table 1 summarises the barrier specifications.

Method

The present study will employ the numerical CFD modelling tool FLUENT to evaluate the aerothermal characteristics of skygardens and the impact of the addition of wind buffers which includes railing and vegetation. The modelling will take into account the evapotranspiration cooling effect of the vegetation wind buffers.

Computational Fluid Dynamics Set Up

The Reynolds averaged Navier–Stokes (RANS) equation approach and the realisable k-ε turbulence model are applied, which are well established in the urban flow modelling field (Gromke et al. 2015). The simulation was carried out at steady-state and with a 3D computational domain. The Boussinesq approximation is set to take into account the buoyancy effects.

A simplified approach (Rahman et al. 2011) was employed to account for the vegetation’s cooling effect. The volumetric cooling potential of 350 W/m³ per Leaf Area Density was assigned as a source term. The vegetation’s effect on airflow was simulated by using the Ergun equation to determine the viscous resistance factor and the inertial resistance factor. The governing equations are not included here but fully available in the FLUENT theory guide.

Computational Geometry and Domain

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tree wind buffers were located at the windward and leeward edge of the skygarden to block the incoming wind. The railing was modelled as a solid wall, while the hedge and trees were modelled as porous media. Table 1 summarises the barrier specifications.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
Case & Type & Width (m) & Height (m) \\
\hline
A1 & Railing & 0.05 & 1.50 \\
A2 & Railing & 0.05 & 2.00 \\
B1 & Hedge & 1.50 & 1.50 \\
B2 & Hedge & 1.50 & 2.00 \\
C1 & Trees & 2.50 & 2.50 \\
C2 & Trees & 4.50 & 5.0 \\
\hline
\end{tabular}
\caption{Specification of the wind buffers.}
\end{table}

Computational Mesh

The computational model was meshed using a combination of structured and unstructured mesh. Sizing functions were applied, and the mesh was refined in areas with a high gradient to improve the accuracy of the velocity and temperature field results. The computational mesh consisted of 2.7 million elements based on a grid sensitivity analysis. Grid sensitivity analysis was conducted to evaluate the independence of the solution from the mesh size (Figure 3). Various mesh sizes ranging from 3 m to 1 m near the building and skygarden area were generated and simulated with similar boundary conditions.

Boundary Conditions

The domain was created to allow for the simulation of airflow around the building model, as shown in Figure 2. An approach wind flow is generated by setting one side of the domain as the velocity inlet and the other side as the pressure outlet. The power-law wind profile was created to account for the wind speed modifications due to urban surroundings. The profile was set as the inlet. The outlet was set as 0 Pa. The air temperature for the inlet was set at 30 °C. The boundary condition for the outlet
was set to 0 pa. The top and side walls were set as symmetry.

**Method Verification and Validation**

For the purpose of validating the skygarden model, the building was compared against the studies (Braun and Awruch 2009; Huang, Li, and Xu 2007), while the vegetation was compared with the study by Manickathan et al. (2018).

**Verification of the Base High-rise Building Model**

Figure 3 shows the results from the grid sensitivity analysis and validation. Pressure coefficient around an isolated building were extracted at 2/3rd height of the building to validate the turbulence model and domain. As observed, the pressure coefficient results were comparable with the results of Huang et al. (2007) and, Braun and Awruch (2009).

**Verification of Vegetation Model**

The porous body was modelled in a 2D domain, similar to the study by Kichah (2012), see Figure 4. Whereas Figure 5 shows a plot of velocity along a longitudinal line through the centre of the vegetation patch. Overall, the velocity distribution is in good agreement with the reference study of Manickathan et al. (2018).

**Results and Discussion**

Analyses of the wind speed and temperature was carried out at a height of 1.4m above the plane of the skygarden, representing the average chest height of occupants. Wind contours for the base case is shown in Figure 6 (a and b). In the scenario without any barriers, the skygarden experienced high wind speeds and amplification.

The highest speeds were seen towards the front (windward) area of the space and amplifications of about 10%~20% were observed. In any case, the high wind speeds in the range of 10~15m/s across the skygarden, is a major source of discomfort for occupants and may also endanger their safety. The addition of a barrier is therefore a must from multiple safety points.

Figure 7 (a1-c2) show the wind contours after the addition of different wind barriers as described earlier. A significant reduction was observed for all the cases despite with some variations. In the case of railings, both configurations lowered wind speeds within comfortable range along the front and the central axis of the skygarden. However, the sides still witnessed speeds in the uncomfortable range, especially when the barrier was just 1m high. This may pose significant safety concerns and hence a higher barrier should be recommended.

In the case of hedges, a similar relationship is observed. While both configurations offered significant reductions,
the central axis witnessed lower wind speeds as compared to the sides. In the case of shorter hedges, the speeds were in the Lawson’s wind comfort criteria, Quality Class (QC) of D. This was not favourable for sedentary activities. Trees, on the other hand, produced a comfortable wind environment along the entire area of the skygarden. Despite some rake like intensification, the wind speeds were within the comfort range. Trees offered a QC class of B and C. This was favourable for leisurely activities like strolling and sitting. Large hedges and railings also offered similar conducive environment. Railings were able to generate a QC of A, which shows it is also desirable for sitting. However, the low hedges and railings led to a QC of D and E along the sides, hindering its effective use. While the solid railing generated calmer environment at occupants’ height, it amplified the wind speeds above it. Porous barriers, trees, and hedges, generated a relatively calmer environment throughout the skygarden. Figure 9 (see end) shows a perspective of the skygarden where the volume is rendered based on the generated wind speeds.

In the base case, speeds of about 14~16m/s were observed in the interior of the skygarden. With addition of barriers, the region saw a decrease in wind speeds. Railings generated larger attenuation, consequently more conducive environment as compared to hedges or small trees. However, larger trees offered the maximum resistance to air flow prompting reductions of about 20~30% from the base case. The lower half of the skygarden is effectively within the QC of C, suggesting greater attenuation and application as wind buffers.

Apart from attenuating wind speeds, vegetation is also known to provide evapo-transpirative cooling and provide relief from urban heat island effect. The vegetation in the models were also assigned a constant heat flux representing cooling. Figure 8 shows the temperature contours at occupants’ height in the skygarden.

**Figure 7: Wind velocity contour in the skygarden captured at 1.4 m above the skygarden plane, corresponding to occupants’ height with (a1) 1.5 m railing, (a2) 2 m railing, (b1) 1.5 m hedge, (b2) 2 m hedge, (c1) 2.5 m trees, and (c2) 5 m trees.**

**Figure 8: Temperature profile in the skygarden captured at 1.4 m above the skygarden plane; (a1) hedge 1.5 m, (a2) hedge 2 m, (b1) tree 2.5 m, and (b2) tree 5 m.**
In the case of hedges, there is slight drop in the temperature near the windward barrier, about 0.3°C to 0.5°C. However, no significant drop was observed in the rear. Small trees also did not induce significant cooling and only slight reductions were seen in the wake of the front row. Large tree barriers, however, generate about 0.5°C to 1°C temperature drop in the skygarden. This is probably due to the larger volume and consequent larger heat flux of the body. Interestingly the leeward vegetative barrier showed higher degree of cooling within the body and in its wake. This could be attributed to the slower wind speeds in the rear portion of the skygarden, allowing more heat to be extracted from the air.

**Table 1: Summary of wind speed and attenuation in the skygarden configurations.**

<table>
<thead>
<tr>
<th>Case</th>
<th>Average wind speed</th>
<th>Average wind attenuation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>11.99</td>
<td>-</td>
</tr>
<tr>
<td>A1</td>
<td>4.07</td>
<td>66.1%</td>
</tr>
<tr>
<td>A2</td>
<td>2.24</td>
<td>81.3%</td>
</tr>
<tr>
<td>B1</td>
<td>4.20</td>
<td>64.9%</td>
</tr>
<tr>
<td>B2</td>
<td>2.91</td>
<td>75.7%</td>
</tr>
<tr>
<td>C1</td>
<td>3.93</td>
<td>67.2%</td>
</tr>
<tr>
<td>C2</td>
<td>4.00</td>
<td>66.6%</td>
</tr>
</tbody>
</table>

Previous works by Tien and Calautit (2019) only explored the impact of the skygarden geometry and configuration towards the aerothermal performances, while the impact of vegetative elements across these regions were not explored. While Mohammadi and Calautit (2019) and Tien et al. (2020) studied the effect of trees only on the wind and thermal conditions in the skygarden region. The current study, however, looks at a variety of elements as attenuators.

Along with the understanding that vegetative elements are integral part of green spaces within high-rise buildings, this study highlighted, that elements such as trees and hedges, can be used to attenuate wind speeds, while also producing some local cooling. However, the extent of wind attenuation is higher in the present simulation as compared to earlier ones where the temperature reduction was significant. This could be explained due to the higher volume of vegetation used in the earlier case. Thus, both the choice and configuration of the barrier is critical towards establishing a comfortable region in the skygarden.

**Conclusion**

Most outdoor spaces on high-rise buildings, such as balconies or terraces have a parapet for safety and security reasons. The aim in this study was to assess the wind attenuation characteristics of such outdoor features. Namely, a solid railing representing typical glass balustrades, rows of hedges and rows of trees were investigated to understand the change in wind profile in the skygarden.

All types of barriers are effective in deflecting the oncoming wind away from the occupants (see Table 1), however their performance depends on their height. Higher barriers produce comfortable environment over a larger skygarden area. Solid railings can be employed when a small area behind the barrier is planned to be occupied. Vegetative barriers are more suitable when larger area and spatial domain is planned to be occupied (see Table 2). In such instances, trees can be beneficial and improve the microclimate as well as the spatial aesthetics. Additionally, vegetation, can induce cooling to a certain degree. This may be desirable in hot conditions.

Future research should investigate other benefits of vegetative barriers including sound insulation, air filtration, shading etc. in the context of skygardens, while exploring other forms of spatial design.

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**References**


Elena, Giacomello, and Valagussa Massimo. 2015. Vertical Greenery: Evaluating the High-Rise


Figure 9: Volume rendering of wind speed in the skygarden; (a) base configuration without any buffer, (b1) railing 1.5 m, (b2) railing 2 m, (c1) hedge 1.5 m, (c2) hedge 2 m, (d1) tree 2.5 m, and (d2) tree 5 m.