The Impact of Urban Layouts on Indoor Thermal Condition: A Comparative Study between Traditional and Contemporary Urban Blocks in Hot Arid Climate

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Abstract
Shading and natural ventilation are important passive cooling techniques used to achieve thermal comfort inside a building. The performance of such techniques depends on the urban mass, among other factors. Research about the indoor thermal conditions in buildings focused on the architectural scale, with little interest in the urban layout and its impact on this matter. The present research used the Computational Fluid Dynamics (CFD) technique to assess and compare the indoor thermal environment of houses within traditional and modern neighborhood layouts in a hot-arid climate of Oman. The CFD simulations evaluated several urban features, such as the traditional alleyway’s layout, wind characteristics, and the impact of vegetation on the evaporative cooling within the studied areas. It has been found that the indoor temperature and air velocity in a room within a modern urban fabric are higher compared to a room within a traditional urban layout. This research highlights the importance of developing more climate-responsive urban designs that allow lower wind velocity around the buildings and wider and denser vegetation along the streets and around the urban blocks to secure more shading and higher evaporative cooling.

Key words

Introduction
Based on satellite data, the research about urban heat islands revealed that the surface temperature in cities is significantly higher than in nearby rural areas, with a temperature difference that might reach 15°C (Mentaschi et al., 2022). The relatively high surface temperature generates a rise in air temperature, which increases the need for mechanical air conditioning (AC) systems to provide thermal comfort for occupants. Such an increase affects the energy demand, leading to more global warming and creating more urban heat islands, trapping us in a vicious cycle. This process can be traced through energy demand from AC systems, which increased by 33% in the years between 2000 and 2018. This was the highest growth rate for energy demand in the building sector in comparison with other consumers like lighting (Santamouris & Vasilakopoulou, 2021). It is expected that, by the year 2050, this consumption will increase by three folds due to the continuous increase in surface temperature in modern urban from global warming and with more people purchasing AC units to overcome heat stress (IEA, 2019).

Many studies evaluated the mitigation techniques to overcome the urban heat island. By measuring air temperature in the cities, the paper of Rahman et al. shows trees can cool down the air by around 3.5°C (Rahman et al., 2017). The presence of trees reduces the air temperature through evaporative cooling (transpiration cooling), and more cooling can be achieved through shading. In addition, the trees can slow down the winds and reduce the turbulence intensity (Manickathan et al., 2018). The role of vegetation in cooling urban blocks has been studied in different forms, like green roofs and walls. Alexandri & Jones found that under a hot arid climate, a green roof can reduce the air temperature by 12°C, and on average, for walls up to 9°C (Alexandri & Jones, 2008).

The researchers concluded that climate dryness gives transpiration the highest effect compared with other climates. Water ponds can also lower the air temperature through evaporative cooling with much temperature reduction, around 2°C, as shown in the work of (Nishimura et al., 1998). However, the vegetation-based solutions are more practical in hot-arid climates due to the limited water resources and the negligible temperature difference achieved by water ponds. Other factors, like the albedo of the urban surfaces, can decrease the absorbed solar radiation and lower the air temperature by 4°C (Taha, 1997). Furthermore, the research by Bourbia and Awbi showed that there is clear evidence of the role of street geometry, like width and height, on thermal conditions in urban fabric (Bourbia & Awbi, 2004). This research proved that, for a city in a hot arid region, the open, wide, and exposed urban fabric can lead to higher air temperature, especially during the day.

From what has been presented above, it can be claimed that urban design can affect the outdoor urban heat island and air temperature; however, there is little research on the relationship between urban layout and thermal conditions inside the buildings. The article by Wilby showed that the rise in outdoor temperature would decrease the cooling potential of natural ventilation, which will incite more people to use the AC systems in the buildings (Wilby, 2007). In the Gulf Cooperation Council (GCC), the increase in AC use is due to modern
building trends, where the street is wide with detached buildings and minimum or no vegetation cover. This layout is the opposite of traditional rural areas, where the structures are less exposed to solar radiation, and the vegetation density is much higher compared to modern neighbourhoods. This observation inspired the authors of this work to analyse and numerically model a traditional town in Oman, based on its remaining urban layout and buildings, to determine how urban design affects the condition of rooms cooled passively. For this purpose, a comparative study was undertaken to numerically simulate the indoor air temperature and velocity in both modern and old urban fabric using the computational fluid dynamics technique (CFD). This technique has been used for urban layout and airflow modelling studies in enclosed and open-plan spaces. CFD has proven to be an effective design tool that saves time and cost by providing detailed insights. Researchers such as (Gromke et al., 2015) used CFD to study the effect of transpiration cooling generated by vegetation on air temperature in cities. Similarly, Evola & Popov (2006) used CFD to study different natural ventilation modes inside a building. There are also other studies in the literature that show the use of CFD with acceptable accuracy when compared to experimental and field measurements.

The present research aims to examine the impact of urban layouts on indoor thermal conditions in a typical hot-arid climate. It uses numerical simulation to compare the indoor thermal conditions located within contemporary and traditional urban settlements.

The following sections of this article will describe the urban fabrics and the methodology used in this research before ending with the results and conclusions.

The Traditional Settlement

The traditional Omaní settlement chosen for this study is ‘Harat Qasra’, located in the centre of Wilayat Rustaq, which is the administrative centre of the Southern Al-Batinah region in the Sultanate of Oman. The settlement of Qasra occupies an area composed of palm date gardens and residential quarters. The recent research about Harat Qasra suggests that its origins might date back to the 10th or 11th century (Benkari, 2021)(Figure 1).

![Figure 1: Harat Qasra in Wilayat Rustaq, Sultanate of Oman (Benkari, 2021).](image)

The urban layout of Qasra is characterized by its longitudinal main alleyway, expending from East to West, between the settlements two gates. This settlement’s spine is still used today by the inhabitants of the neighbouring areas, as a short cut to reach their gardens. The two gateways, which were used to secure the interior of the settlement, are nowadays used as shaded seating areas where, especially elder people enjoy the air flow along the narrow spine, between the two gates. The temperature difference between the spine and the outer areas generates cool breeze in the alleyway, making it thermally comfortable and pleasant place to stay in Figure 2.

The elongated settlement consists of around 15 buildings, which are almost all abandoned today. Qasra houses typology could be classified among the defensive grand houses. Their spaces are deployed on two high floors and composed of several spaces. These houses are built with Sarooy blocks and equipped with wooden doors beautifully carved and the windows, usually located in the higher floors, are also decorated with wooden pieces.

![Figure 2: Harat Qasra: (a) The Urban Layout of the Harat, (b). Urban elevation along the main spine.](image)

The Modern Urban fabric

Since the 1970’s, Sultanate of Oman has been developing rapidly thanks to the oil revenue. Muscat, the capital of the Sultanate of Oman, has experienced a sharp increase in rural migration, as the city offered better jobs and services (Benkari, 2017). Urbanization and infrastructure development are increasingly intruding deserts, mountains, and dry riverbeds (wadi), destroying its fragile ecosystem and threatening its agricultural land. The same
reasons have led to the abandonment of traditional settlements.

The modern urban fabric of Muscat and Oman’s other main cities present a layout which is a hierarchical geometric configuration consisting of street networks and city quarters, blocks, and lots (Figure 3). The street network is a planar layout with nodes and linear edges. The induced cycles of the street graph give rise to blocks, which can be further subdivided into building lots with corresponding setbacks and built-up areas (Weber et al., 2009).

The present research claims that the urban layout of a settlement affects the thermal conditions within its buildings. To test this claim, a comparative study has been performed on a case of the urban layout of Harat Qasra (a traditional urban fabric) and the second is located in a typical modern neighbourhood in the same region.

![Hierarchy of modern urban fabric.](image)

**Figure 3: Hierarchy of modern urban fabric.**

**Methodology**

The research used the CFD simulation to analyse the airflow in and around the buildings of the two case studies described in the previous section. For the case of the traditional settlement, all dimensions of openings, rooms and urban spaces used for the CFD model were collected through an architectural documentation and urban survey undertaken in previous research (Benkari, 2021). The research used the CFD program STAR CCM+ version 2022, to perform a steady-state simulation for airflow in and around the buildings with turbulence modelled using Reynolds-Averaged Navier-Stokes equations (RANS) and realizable k-ε turbulence model as closure for conversion equations. The thermal change of density was achieved using an incompressible ideal gas model. The primary heat source for hot, arid regions is solar radiation, and radiant heat transmission was modelled using the surface-to-surface radiation model and the Gray thermal radiation model. The solar irradiation on the surfaces is calculated using a solar calculator within the software that depends on the time, date, and geographic location.

The size and shape of the domain were decided according to the recommendation of a guidebook on CFD simulation for wind flow in urban context (Franke et al., 2011), Figure 4. The lateral boundary and top of the domain are modelled as slip walls. The inflow and outflow boundaries were decided as velocity inlet and pressure outlet. The equations of the atmospheric boundary layer from Richards & Hoxey (1993) were used to set the vertical profile for velocity and turbulence of the winds coming from the inflow. The bottom part of the domain is set to simulate as ground or soil in the traditional fabric case and as asphalt in the modern fabric case. The thickness of the bottom part is extended to 0.5 m in both cases. Other properties are shown in Table 1.

**Table 1: Values used in numerical simulation.**

<table>
<thead>
<tr>
<th>Simulation date</th>
<th>21&lt;sup&gt;st&lt;/sup&gt; April</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>10 AM</td>
</tr>
<tr>
<td>Location</td>
<td>21° 30’ 45.30” N, 55° 55’ 23.72” E</td>
</tr>
<tr>
<td>Wind velocity</td>
<td>1-5 m/s</td>
</tr>
<tr>
<td>Wind direction</td>
<td>45° and 225°</td>
</tr>
<tr>
<td>Roughness height</td>
<td>0.05</td>
</tr>
<tr>
<td>Outdoor air temperature</td>
<td>33.5 °C</td>
</tr>
<tr>
<td>Initial temperature</td>
<td>25 °C</td>
</tr>
<tr>
<td>Soil temperature</td>
<td>24 °C (at 0.5 m depth)</td>
</tr>
<tr>
<td>Wall temperature</td>
<td>29 °C</td>
</tr>
<tr>
<td>Solar radiation</td>
<td>1023 W/m² with diffusion fraction (0.4)</td>
</tr>
<tr>
<td>Traditional alleyway albedo</td>
<td>0.45</td>
</tr>
<tr>
<td>Tree base albedo</td>
<td>0.27</td>
</tr>
<tr>
<td>Asphalt albedo</td>
<td>0.1</td>
</tr>
<tr>
<td>Walls albedo (traditional and urban)</td>
<td>0.2</td>
</tr>
<tr>
<td>Leaf area density (LAD) for palm tree</td>
<td>0.6</td>
</tr>
<tr>
<td>$C_d$ (leaf drag coefficient)</td>
<td>0.2</td>
</tr>
<tr>
<td>$\beta_p$ (a percentage of the mean airflow’s kinetic energy that is lost to drag and changed into k)</td>
<td>$\in [0,1]$ (Sanz, 2003)</td>
</tr>
<tr>
<td>$\beta_d$ (Dimensional coefficient for the turbulent eddy cascade short-circuiting)</td>
<td>1 (Sanz, 2003)</td>
</tr>
<tr>
<td>$C_{e4}$ and $C_{e5}$ (empirical coefficients)</td>
<td>0.9 (Gromke et al., 2015)</td>
</tr>
</tbody>
</table>
Tree cooling capacity: 250 W/m$^3$ for every unit LAD

Tree Emissivity: 0.94

Wall thickness (traditional rooms): 0.5 m

Wall thickness (modern rooms): 0.2 m

Wall material (brick) thermal conductivity: 1 W/m K

Ground (soil) thermal conductivity: 1.5 W/m K

Inflow boundary: Velocity inlet

Outflow boundary: Pressure outlet

<table>
<thead>
<tr>
<th>Room (Symbol)</th>
<th>Volume ($m^3$)</th>
<th>Centre of the wall above the ground (m)</th>
<th>Window to wall ratio</th>
<th>Two-sided windows or vent</th>
<th>Opening description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>50</td>
<td>2</td>
<td>15</td>
<td>Yes</td>
<td>Vents and windows on two sides of the room</td>
</tr>
<tr>
<td>4</td>
<td>42</td>
<td>6</td>
<td>19</td>
<td>Yes</td>
<td>Vents and windows on two sides of the room</td>
</tr>
<tr>
<td>1</td>
<td>61</td>
<td>2.5</td>
<td>17.5</td>
<td>Yes</td>
<td>Two windows on different sides</td>
</tr>
<tr>
<td>2</td>
<td>67</td>
<td>2.5</td>
<td>32</td>
<td>No</td>
<td>Two windows on one side of the wall</td>
</tr>
<tr>
<td>3</td>
<td>67</td>
<td>5.5</td>
<td>32</td>
<td>No</td>
<td>Two windows on one side of the wall</td>
</tr>
<tr>
<td>4</td>
<td>94.5</td>
<td>5.5</td>
<td>18</td>
<td>Yes</td>
<td>Two windows on different sides</td>
</tr>
</tbody>
</table>

Note: all the dimensions, designs, and distribution of the vents and windows are taken from the actual buildings.

Traditional urban fabric usually includes vegetation consisting of different trees and grass, but the date palm is the most common tree in the region. Therefore, all vegetation areas were considered to consist of palm trees only. The vegetation cools down the air in several ways, such as shading or transpiration cooling, where the plant and air are cooled down by the evaporation of water from the plant surfaces. The cooling capacity depends on the leaf area and density. A factor called leaf area density (LAD) is commonly used by researchers to decide the cooling capacity for every unit LAD to be between 250 to 350 W/m$^3$ (Gromke et al., 2015; Sun et al., 2021). In the present research, the LAD value and cooling capacity for palm trees were used, as shown in Table 1. In the numerical model, the transpiration cooling is simulated by using a volumetric energy source term allocated to the area of vegetation, as in Figure 5.

The vegetation can also slow down the wind, which can reduce the effect of dust storms or unwanted desert winds. In the model, the tree is simulated as a porous medium where it will reduce the momentum. The following source term from reference is added to the momentum equations following (Gromke et al., 2015),

\[ S_{ui} = -\rho C_d LAD U_i U \]  

(1)

In addition, the effect of the vegetation on both turbulent kinetic energy and turbulent dissipation rate are represented through the following source terms, which are added to the equations of the turbulence model,

\[ S_k = \rho C_d LAD (\beta_p U^3 - \beta_d U_k) \]  

(2)
\[ S_e = \rho C_a LAD \frac{\varepsilon}{k} (C_{e4} \beta_p U^3 - C_{e5} \beta_a U k) \]  

(3)

In this equation, \( U_i \) is the component velocity in the direction, \( i \), \( U \) is the magnitude of the velocity, \( k \) is the turbulent kinetic energy, \( \varepsilon \) is the turbulent dissipation, and \( \rho \) is the density of the air. Other coefficients’ definitions and values are given in Table 1.

The vegetation computational domain was validated by comparing the numerical simulation results for the model shown in Figure 6a with field measurement data from (Amiro, 1990). Similarly, to the work of (Gromke et al., 2015), the model of spruce trees was given the following dimensions (Width 25, Length 100, and Height 13 meters). The velocity was normalized by dividing the resulting velocity by the velocity above the vegetation region, with wind velocity equal to 1 m/s. The height is normalized by vegetable height (10 m). The measurement points in the model were taken after the vegetation region by 10 m as shown in Figure 6a. The computational model accurately predicts the velocity distribution with an error rate of around 5%, as in Figure 6b. It is worth mentioning that the spruce tree has a different geometric design than the palm tree, as no field research on the palm tree could be found to use for the validation.

The modelization used unstructured mesh polyhedral type with different cell sizes ranging from 0.05 m in vents to 1 m in the vegetation regions and 3 m in the rest of the domain volume outside the urban and transition volumes are used between the different sizes to have a more gradual change in the size. Prism layers are used to generate orthogonal grids next to walls and solid surfaces, which are more efficient in catching the change in flow due to the viscous effect generated by flow above such surfaces. The domain consists of around ten million cells. Sensitivity analyses validate the mesh size for urban spaces with results from wind tunnel experiments of Hall et al.(Hall et al., 1999).

**Results**

The work includes simulation for temperature and velocity distribution in four rooms that are located in traditional and modern urban fabrics. The simulation aims to find the effect of the traditional urban layout on the indoor environment.

Figure 7 shows the average, maximum, and minimum values for volume average air temperature in rooms in the modern and traditional urban fabric. The maximum recorded room air temperature is dropped with increasing wind velocity because the external building surfaces are heated by excessive solar radiation to levels much higher than the outdoor air temperature, which can reach over 60°C. In this case, the wind will cool down the walls, and this cooling effect will rise with the increase in wind velocity or mass flow rate. The opposite happens with minimum temperature in the traditional urban fabric case, where it is increased with rising wind velocity. The decrease in vegetation cooling due to an increase in the amount of air passing through the vegetation volume caused the minimum temperature to rise as wind speed increased. This phenomenon of the inverse relationship between air velocity and vegetation cooling has been discussed in other research, such as the work of (Manickathan et al., 2018). The highest cooling was found with wind velocity equal to 1 m/s. Volumetric average air temperature values show that the room air temperature in traditional houses is lower on average by 1.7°C than in modern houses. This difference is due to the shaded alleyways and the vegetation cooling. Traditional fabric shows the lowest volumetric average air temperature in both the maximum and minimum scales. The maximum temperature in traditional rooms is lower by 2°C in comparison with the maximum temperature in modern rooms, and the minimum temperature is less by 2.5°C (Figure 7), where NE is the northeast wind and SW is the southeast wind.

![Figure 6: The computational model for validation study (A) with results (B), the recorded data is from (Amiro, 1990).](image)

![Figure 7: The minimum, maximum and average air temperature for four rooms with different wind speeds and directions for traditional and modern rooms.](image)
fabric cases has less effect, which is around 0.3 °C. In the traditional fabric, the wind direction’s impact on air temperature is about 0.6 °C. The lowest temperature is achieved with the southwest wind. Where the vegetation volume on that side is bigger than that on another side and this gives the air more cooling as the cooling is proportional with vegetation volume.

Figure 8: Room air temperature in rooms in traditional houses.

Figure 8 shows the average temperature in rooms with different wind directions and speeds. It reveals that the houses near the vegetation volumes recorded the lowest temperature (as in rooms 3 and 4), and the average difference between room 1 (of highest temperature) and room 4 (of lowest temperature) is 4.7 °C as shown in figure 9. The highest value for air temperature was found in room 1 because it is next to a relatively wider alleyway and away from the vegetation volume.

Figure 9: Temperature distribution inside rooms in traditional urban (temperature is normalized by dividing the spatial temperature by inlet temperature).

For the houses within a modern urban layout, the spaces around the houses are made more open and contain asphalt and concrete, which absorb more solar radiation and make the external surfaces much warmer. In this case, the distribution and location of the windows will play an important role. As shown in figure 10, the highest air temperature can be found in rooms 2 and 4. In the latter, the air leaves the room through the nearest window without penetrating inside the room, while room 2 is placed in the shadow of the wind. The volumetric air velocity shown in Figure 11 can support the previous conclusion that the air velocity in rooms 2 and 4 is relatively lower than in other rooms. The volumetric air velocity in traditional rooms is shown in Figure 12. By comparing figures 11 and 12, it can be observed that modern rooms have a uniform air velocity pattern, and the difference between values is proportional to the wind velocity. Traditional homes, especially those facing NE, have distribution values between rooms that are distinct from others in wind speeds of 1 and 2 m/s. This modification demonstrates how natural ventilation is more significantly impacted by buoyancy-driven force in the traditional urban fabric at low wind speeds. The buoyancy flow is generated from the air convection over solar-heated wall surfaces. Its effect will vanish with an increase in wind velocity. This also indicates that the Omani traditional house design is able to reduce wind velocity through vegetation and narrow alleyways. This house’s ability is quite similar to that found in Libya or Algeria as shown in many papers like (Shawesh, 1995).

This effect cannot be seen in rooms within the modern urban layout case because spaces around the houses are more open and have no or little vegetation in comparison to the traditional fabric case. Figure 13 shows the average maximum and minimum values of indoor air velocity for all rooms with different wind speeds and directions. The average values of air temperature in modern rooms reach nearly double that in traditional rooms. This shows that more air is entering these rooms, but the airflow pattern is unclear. The difference in the amount of air entering the rooms is due to the fact that usually, modern rooms are single-sided ventilation (all windows on one side), while the windows and vents are on different sides of the rooms in traditional houses, which enhances the cross ventilation. The points below show the difference in characteristics between traditional and modern layouts,

**Traditional urban layout:**

- Cooling Effects of plant: When air moves through the vegetation volume it becomes cooler and reduces the air temperature surrounding.
- Lower volumetric average air temperature: When compared to modern homes, traditional homes have lower volumetric average air temperatures.

**Modern Urban Layout:**

- Absorption of Solar Radiation: Because contemporary houses are built in more open areas with lots of asphalt and concrete, these materials absorb more solar radiation, raising the temperature of the outside of the building.
- Placement of Windows: The number and arrangement of windows have a significant impact on how the temperature is distributed in contemporary rooms.
Higher Air Temperatures: Compared to traditional dwellings, contemporary houses typically have higher average air temperatures.

**Conclusion**

This research aims to examine the impact of the urban layout on the indoor thermal conditions inside the buildings within the urban fabric. For this purpose, a comparative study was undertaken between the indoor temperatures of rooms within a traditional settlement in Oman and similar rooms within a modern block in the same region. The computational model was validated by comparing it with practical works from works of other researchers. The results illustrate that rooms within the traditional urban fabric can be cooler than modern rooms by 2°C with an average of around 1.7°C. The air temperature is affected by wind velocity. The minimum temperature rises with the increase in wind velocity. In addition, the position of the room in relation to vegetation can affect the indoor temperature. A difference of around 4.7°C could be recorded between a room near the outdoor vegetation and another room located farther away. In comparison with wind velocities or room position, the wind direction has a lesser effect on the differences between indoor temperatures. The maximum difference did not exceed 0.6°C.

The effect of buoyancy force on airflow is clearer in the rooms within the traditional urban fabric. Because vegetation and small air passages in alleyways would lessen the winds, the buoyancy force's influence on airflow is more obvious in traditional rooms with lower wind speeds, which contributes to the trends in values of air velocity in rooms being different at velocities less than 3 m/s. The effect of buoyancy force is not clear in rooms located within the modern urban fabric. This is due to the larger open spaces around the houses and the lack of vegetation, which causes the air velocity in these rooms to be double that in the rooms located within the traditional urban fabric.

It is therefore recommended to think about climate-responsive ways to design the contemporary urban areas in Oman, considering the importance of decreasing the air temperature around the buildings by intensifying the vegetation around the urban blocks and increasing the shaded alleyways. Future works will include a field study for components of microclimate inside a traditional village in Oman; this study will measure the effect of vegetation and water features like water ponds.

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**References**


