Wind Driven-ventilation Enhancement Strategy in Low-Rise Traditional Turkish Houses

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Abstract

Currently, residential buildings are responsible for 40% of the global energy demand while 82% of this energy is produced by non-renewable sources, which significantly increase CO₂ emission and global warming. Aligned with achieving the CO₂ emission reduction in the near future, the role of implementation of energy-saving techniques in minimizing the mentioned energy demands are found to be more vital than at any time. As practical and economic options, natural ventilation via windows, has a huge potential to reduce buildings cooling load. The great potential of the historical designs in the reduction of dwellings’ energy demand is often underestimated in modern building construction. This study aims to assess the applicability and functionality of a common historical Turkish architectural element called “Cumba” in the improvement of wind-driven ventilation in buildings. A case study building was selected as a result of a survey over 111 different existing traditional samples across Turkey. Buildings with and without Cumbas were compared in different scenarios by development of a validated CFD microclimate model. The results of a series of simulations clearly demonstrate that Cumba can enhance the room’s ventilation rate more than two times and a smart window opening strategy can also help to enhance the mean ventilation rate by 276%. Air velocity and ventilation rate could be adjusted to a broad range of values with the existence of Cumba.

Keywords - Wind-driven ventilation; Traditional Turkish Architecture; Cumba; Computational fluid dynamics (CFD)

1. Introduction

The average global temperature anomaly has risen by 0.68°C since the 1880s [1], and with current rates of global warming the mean global surface temperature is expected to increase by 3-5°C in the long term compared to its preindustrial level [2]. The number of climatic-related natural catastrophes has almost tripled since 1980’s, as a consequence of global warming [3]. The death of approximately 50,000 people in 2003 August heat wave in Europe can be presented as a tragic example [4]. Currently, residential buildings are
responsible for 40% of the global energy demand, and 82% of this energy is produced by non-renewable sources [5]. Furthermore, the rapidly increasing global population and global economic growth are projected to raise global energy demand by 61% by 2050 [6]. Therefore, considerable energy reduction is crucial to decrease the global energy demand. For example, Europe set a goal in 20% energy demand reduction at building sector by 2020 [7].

Current investigations acknowledge the functionality of passive strategies in providing thermal comfort while being energy efficient [8]. There have been numerous highly effective natural ventilation techniques in architectural history. For example, wind-catchers (Bâdgir) have been used as an evaporative ventilation and cooling system in Persian architecture for past three thousand years. Particularly, wind-driven ventilation, mainly via windows, demonstrates a huge potential to improve Indoor air quality (IAQ) and to reduce cooling load of buildings [9]. Çumbas (Fig. 1) are a popular traditional architectural element from the Ottoman period that remains widespread in Turkish dwellings. This study thus aims to investigate the role of Çumbas in wind-driven ventilation in low-rise dwellings. For this purpose, a preliminary study among 111 different traditional Turkish houses was first conducted to identify the features of the typical Çumba and its plan typology, as a base case scenario. A 3D microclimate CFD model of the selected building was then developed to assess the potential of wind-driven ventilation using 24 different scenarios, including various wind directions, velocities and window opening configurations.

2. Description and Selection of Çumba and Benchmark Building

As shown in Fig. 1, the Çumba can be identified as an extension of rooms in the first or upper floors, covered by windows on one to four different facades (Fig. 1c). A Turkish house plan consists of rooms aligned around the Sofa (common hall area), which is the main distinctive element that creates dwellings characteristics. Moreover, the typical configurations of houses mean that is easy to estimate the dwelling layout from a view of the exterior based on patterns of building development from the interior to the exterior borders (See Fig. 1b).

According to the conducted survey, the majority of 111 sample buildings are located in Istanbul and have four rooms. The area of the main and smallest rooms varies between 11-20m² and 21-30m², respectively. Their windows’ widths range from 0.6m to 1m, with the most common being about 0.8m. 82% of the sample buildings contain an average of two Çumbas in their design, and about 75.8% of the Çumba typologies are three-sided (Fig. 1c). The original and modified layouts of this building are illustrated in Fig. 2. The north-west Çumba was modified by adding two 0.8m-wide windows on the eastern and western façades. The wall between
the northeast and northwest rooms was extended, as indicated by dots in Fig. 2b. The roof shape was also assumed to be flat, in order to simplify the construction of 3D mesh of the microclimate CFD model (Fig. 2b). The area of the northwest room was kept the same (16m²) in all scenarios.

Fig. 2. (a) original layout [12] and Cumba modification of the selected building, (b) simplified benchmark building layout with and without Cumba

3. Methodology

As summarized in Table 1, the wind-driven ventilation effect of Cumbas was studied under three main conditions in 24 scenarios, including
five different wind directions from north, northwest, northeast, west and east; four different wind velocities of 1.7 m/s, 3.3 m/s, 4.7 m/s, and 5.5 m/s (S1-S20); and four different window opening configuration scenarios (S21-S24). Wind velocities and directions were inserted to the model according to the monthly average statistics of Istanbul for the last 18 years. The recorded monthly wind velocity shows a minimum of 1.7 m/s [13], a maximum of 5.5 m/s and an average of 4.7 m/s. Moreover, 3.3 m/s wind velocity was simulated as an additional scenario to cover a spectrum of velocities between minimum and maximum values.

Table 1. Summary of case study scenarios for 48 CFD simulations

<table>
<thead>
<tr>
<th>Scenario (Opened windows)</th>
<th>With and without integration of Cumba Wind directions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind velocity (m/s)</td>
<td>North</td>
</tr>
<tr>
<td>1.7</td>
<td>S1</td>
</tr>
<tr>
<td>3.3</td>
<td>S6</td>
</tr>
<tr>
<td>4.7</td>
<td>S11</td>
</tr>
<tr>
<td>5.5</td>
<td>S16</td>
</tr>
<tr>
<td>Scenario (Opened windows)</td>
<td>Under prevailing wind (Northward) and average wind velocity (4.7 m/s) conditions</td>
</tr>
<tr>
<td>Window opening combination</td>
<td>W1 - W2 - W3 - W4 - W5 - W6</td>
</tr>
<tr>
<td></td>
<td>W2 - W3 - W4 - W5</td>
</tr>
<tr>
<td></td>
<td>W2 - W3 - W4 - W5 - W6</td>
</tr>
<tr>
<td></td>
<td>W1 - W2 - W3 - W4 - W5</td>
</tr>
</tbody>
</table>

Computational Fluid Dynamics (CFD) with 3D RNG k–ε turbulence model and structured non-uniform mesh with 2.8 million cells was utilized in this study (Fig. 3c and 3d). As shown in Fig. 3, the CFD model is a two-storey building with a storey height of 3 m (6 m in total). The ground floor was assumed to be 17 m × 8.5 m × 3 m (length × width × height), and the first floor had same dimensions as the ground floor with 1 m extension of two Cumbas on the north (Fig. 3a). Mean indoor air speed and ventilation rate were only simulated in the modified northwest room with a three-sided Cumba; the northwest room door was assumed to be closed and the other rooms and the Sofa were not included in the simulations. As shown in Fig. 3b, the dimension of the northwest room is 4.5 m × 4.5 m × 3 m (length × width × height), including 0.25 m wall thickness. The north façade of the integrated Cumba has four 0.8 m × 1 m (width × height) windows, whereas the east and west façades have only one window each. All windows are located at 4.5 m height from the floor, and were assumed to be opened in simulations scenarios of S1 through S21.
The recommended CFD domain boundaries size were set to be 98.5m × 77m × 36m as depicted in Fig. 3a. Microclimate CFD domain size was also expanded according to the five different wind directions to ensure sufficient distance between boundaries and the isolated building [14]. The inflow, outflow and symmetry boundary conditions were respectively associated to the inlet, outlet and lateral walls of the study domain to replicate appropriate boundary conditions [15,16]. Moreover, the boundary surfaces of the Turkish house model were defined as walls, with no slip condition for the surfaces.

Fig. 4. Validation outcomes for window W5 and W2
The results of the CFD simulation were compared with [17], to validate the developed model. The velocity in the studied windows is in a fair agreement with the CFD simulation conducted by Bangalee et al. (2012); the obtained average discrepancy is about 5.9%, which represents a similar trend as the results of [17] simulated at the centerline of the windows (Fig. 4). The validated microclimate CFD model is used in further scenarios of this study with the addition of four more windows, W1, W3, W4 and W6, to the studied room.

Existing studies noted the major limitation of wind-driven natural ventilation, which are the unpredictable variations of wind in terms of direction and speed [18]. The CFD results indicate that Cumbas can effectively harvest wind approaching from different directions and speeds (S1-S20) to improve the mean indoor air velocity and ventilation rate of the studied room. The wind-driven ventilation contribution of Cumba evaluated according to average indoor air velocity and ventilation rate comparison between building with and without Cumba. Ventilation rate is defined with the most widely used method called orifice equation as below [18]:

\[
Q = C_d A \sqrt{\frac{2\Delta P}{\rho}}.
\]

where \(Q\) is the ventilation rate \((m^3/s)\), \(C_d\) is the discharge coefficient \((0.60-0.65\) for sharp-edged openings) [19], \(A\) is the opening area \((m^2)\), \(\rho\) is the air density and \(\Delta P\) is the difference of the external and internal pressures \((Pa)\).

4. Results and discussion

The comparison of the room mean air velocity according to different wind directions and velocities is shown in Fig. 5. The threshold of an indoor air velocity to satisfy the comfort level is also shown with a black circle in Fig. 5. This indicates that the air speeds inside the circle are assumed inadequate to satisfy occupant’s comfort. On the other hand, indoor air velocities between 0.5m/s and 1.0m/s and between 1.0m/s and 1.7m/s can be respectively defined as ideal and pleasant breeze for occupants [20]. Eventually, the speed above 1.7 m/s is defined as unpleasant. Indoor air velocity above the comfortable range is not observed in any scenarios (S1-S20). In the majority of the scenarios, indoor air velocity was observed to be below 1.0 m/s, excluding S11-S16 against the north wind. In contrast, for all non-Cumba scenarios (S1-S20), indoor air velocity is almost obtained to be below the comfortable range except for two scenarios (S15-S20).

In general, the existence of a Cumba significantly increases the indoor mean air velocity by 138% in scenarios S1-S20, with north-south wind velocity increasing by 223%, east-west by 197%, and west-east by 99%. These wind directions also provide better performance in terms of mean indoor air velocity compared to the north-east (94%) and north-west (76%)
wind directions, mainly due to the lower pressure difference between indoor and outdoor spaces in angular wind directions (north-east and north-west).

Fig. 5  Room mean air velocity (a) 5.5 m/s (b) 4.7 m/s (c) 3.1 m/s (b) 1.7 m/s

Fig. 6  Ventilation rate (a) 5.5 m/s (b) 4.7 m/s (c) 3.1 m/s (b) 1.7 m/s
Fig. 7. Velocity contours of the scenarios with and without Cumba under different wind directions
Similarly, it can be observed in Fig. 6 that the existence of Cumba significantly increases the overall ventilation rate by about 224% in all scenarios, showing its potential flexibility to harvest wind approaching from different directions and velocities (See Fig. 7).

As depicted in Fig. 8, the impact of window opening configuration of Cumba was affected by where the Cumba was integrated in the building (S21-S24). It can be seen that the existence of a Cumba can significantly improve the mean indoor air velocity and ventilation rate. In comparison to S11, the minimum mean air velocity and ventilation rate difference of about 23% and 35% can be calculated when W6 is set to be closed (S25). On the other hand, the maximum mean air velocity difference is observed between scenarios S11, S21 and S23, where mean air velocity in scenarios S11 and S21 are almost equal. A maximum ventilation rate difference of about 580% was obtained between scenarios S11 and S22. The mean air velocity and ventilation rate are elevated by about 38% and 580% in comparison to S11, when a Cumba is not integrated to the building, although they both have a similar number of windows. This clearly indicates that the enhanced wind-driven ventilation by Cumba is not only associated with windows’ orientation, but their opening configuration can also help to control and adjust different required ventilation rates.

5. Conclusion

Mean indoor air velocity and ventilation rate were utilized as key indices to evaluate the wind-driven ventilation of the selected benchmark building. Various scenarios were investigated by the alteration of parameters.
such as wind direction, wind velocity and window opening configuration. In general, three-sided Cumba demonstrated the most promising performance to harvest approaching wind. The Cumba could enhance the room’s mean air velocity and ventilation rate under different climatic conditions by about 1.4 and 2.2 times, respectively. The room’s mean air velocity and ventilation rate could be also adjusted to a broad range of values by the implementation of various window opening configurations.

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References