Passive Cooling in the Tropics: A Design Proposition for Natural Ventilation

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ABSTRACT: This paper explores the effects of indoor airflow behaviour in modifying the indoor thermal conditions in a courtyard residence found in the tropics. The design theme is centered towards an exploitation of architectural concepts and principles of the traditional courtyard built forms of the country as a source of deriving passive design strategies. Field investigation reveals a significant correlation between wall temperature and indoor air temperature. Airflow behaviours are sufficient to modify indoor thermal conditions to achieve comfortable environments. Furthermore, computational analysis discloses that a relatively better indoor thermal modification is seen when the courtyard acts as an air funnel discharging indoor air into the sky, than the courtyard acts as a suction zone inducing air from its sky opening during daytime hours. Consequently promotes nocturnal ventilation.

Conference Topic: 2 Design strategies and tools
Keywords: tropical courtyard, airflow pattern, thermal mass, opening configuration

INTRODUCTION

The concerns over global warming and the reduction of high emissions of greenhouse gases has become a thrust for exploitation of passive strategies for indoor thermal comfort.

In tropics, with the prevailing harsh climatic conditions occurrence of overheated building interiors is common due to solar heat gain and penetration through building envelope and apertures. Thus, exceeds the threshold of indoor thermal comfort conditions. In thermal comfort point of view design strategies in modifying the indoor overheating is of greater significance in promoting passive cooling. Hence, utilization of natural ventilation is recommended as an appropriate passive system.

However, in equatorial climates pressure difference caused by temperature gradient is negligible to that caused by even a slight breeze setting up pressure around the building. Thus, the design strategies for optimum wind forced ventilation is vital.

Buildings with courtyards have better ventilation potential through the internal spaces. With the courtyard, the functional depth of the plan can be kept to a minimum for better ventilation potential.

1.1 Passive Design Strategies of the Traditional Tropical Courtyard Built Form

A typical courtyard built form in Sri Lanka represents its adaptation to enhance wind-induced cross ventilation and functions as an air funnel promoting maximum air circulation to the interiors. The guiding principle is to enhance cross ventilation through a series of openings from the entrance door through the central courtyard and out of openings in the building fabric at the leeward side. The entrance veranda on the windward side acts as a wind tunnel focussing the incident wind into the courtyard that lies on this air funnel, which in turn ventilates the indoor spaces surrounding the courtyard (see Fig.1). Furthermore, to avoid the heat of the wind-induced ventilation reaching the interior, the perimeter openings are protected with heavy shade, wide eaves and other intermediate spaces such as verandas.

In tropical regions, the highest intensity of solar radiation falls on the roof and west walls. For ventilation efficiency reasons, the layout of tropical courtyard building is usually a spread out form, which then sets out a larger roof to volume ratio.
1.2 Passive Climate Modification Strategies

The main characteristics of warm humid climates, from the human comfort and building design viewpoint, is the combination of high temperature and high humidity which in turn reduces the dissipation of body’s surplus heat.

Szokolay’s (see Fig.2) and Givoni’s bio-climatic chart predicts increased air movements to provide indoor thermal comfort in warm humid climates. Furthermore, it indicates that high mass envelope coupled with nocturnal ventilation can restore indoor thermal comfort for February, March, April and May: the warmest period of the year (see Fig.4).

2. METHODOLOGY

1.3 Objective of the Study

The design solutions that were provided by traditional tropical buildings to the problematic climatic forces are useful to examine and analyse.

Thus the study investigates the effects of the airflow pattern to the courtyard on the exposure of the building to the air movement in enhancing optimum surface–air contact and thus indoor climate modification. The goal is to provide some guidelines for manipulating envelope-opening configurations to improve indoor air movement and lower the maximum indoor air temperature in the tropics.

2.1 Field investigation

“Bandaragama house” employs a number of passive design strategies found in the traditional courtyard built form. The inclusion of a central courtyard, axial air passages, high mass building fabric, higher timber ceilings, wide roof eaves and shaded verandas are of significant design propositions [1].

The courtyard building was monitored for ten days during the hottest period, 12th April to 4th May 2002.

Table 1: Experimented ventilation strategies with reference iteration and number of openings

<table>
<thead>
<tr>
<th>Ventilation strategy</th>
<th>Iteration</th>
<th>Openings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open to sky courtyard</td>
<td>A</td>
<td>Cy, Top</td>
</tr>
<tr>
<td>Axial wind field through Cy. Longitudinal axis</td>
<td>B</td>
<td>2 + cy</td>
</tr>
<tr>
<td>Cross axis</td>
<td>C</td>
<td>2 + cy</td>
</tr>
<tr>
<td>Longitudinal axis and single opening of the cross axis</td>
<td>D</td>
<td>3 + cy</td>
</tr>
<tr>
<td>Both axes</td>
<td>E</td>
<td>4 + cy</td>
</tr>
<tr>
<td>Axial wind field with covered courtyard – Atrium</td>
<td>F</td>
<td>2</td>
</tr>
<tr>
<td>Longitudinal axis</td>
<td>G</td>
<td>4</td>
</tr>
<tr>
<td>Both axes</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Base</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 2: Szokolay’s Bio-climatic chart applied to Colombo, Sri Lanka (lat 6-9.5°N and long. 80-82°E)

Figure 3: Bandaragama House, Colombo, Sri Lanka

With regard to airflow patterns seven different boundary configurations were considered in relation to the composition of major openings found within the building’s envelope (see Fig.3). Fig.4 shows the relationship of the courtyard with envelope opening configurations. Furthermore, the ventilation strategy and its reference iteration with corresponding number of openings are given in Table 1. During the daytime (9.00-18.00h) boundary configurations were changed through closing and opening the major airflow access.
points. During nighttime (18.00-9.00h) equal boundary configuration were maintained by keeping the Op2 and courtyard’s top open (except for iteration F & G) while other envelope openings remaining closed.

2.2 Computational Analysis
Flow analysis software “α -Flow”, and the standard k-ε turbulence model with isothermal flow and boundary conditions were implemented to observe air movement and ventilation performance of the iterations performed in the field investigation and shown in Fig.5. The geometry was realistically modelled for the simulation utilizing the dimensions of the building investigated on the site [1].

Ventilation from stack effect was ignored, as its effect is small compared to daytime ambient wind [1].

3. RESULTS AND DISCUSSION OF THE THERMAL INVESTIGATION

Relative Index and Decrement Factor are considered as the two evaluating parameters to assess the effectiveness of different airflow patterns in modifying the indoor thermal environment.

i. Relative Index: \( \Delta T = T_o - T_i \)
Relative index is the difference between outdoor and indoor air temperature. Thus +\( \Delta T \) value signifies an “under heat” – Cool, indoor microclimate with indoor air temperature below the ambient. While, the - \( \Delta T \) value signifies an “over-heat” – a Warm interior.

ii. Decrement factor:
\[
DF = \frac{T_{(max)\_i}}{T_{(max)\_o}} / \frac{T_{(mean)\_i}}{T_{(mean)\_o}}
\]
Decrement factor is the ratio of maximum indoor and outdoor temperature amplitude taken from the daily mean temperature. Lower value signifies under heat, cool indoor microclimates.

3.1 Courtyard microclimate

**RELATIVE INDEX EVALUATION**

a. Daytime mean - 9.00h to 18.00h

Fig. 6 shows the temperature profile within the courtyard at bottom (1.1m), intermediate (2.5m) and top (3.5m) levels of all investigated iterations.

Principally in the iteration “Base”, where all openings were kept closed, the daytime mean temperature was higher than the ambient. The vertical relative index profile with negative values varied up to a maximum of 0.6°C within the full height of the courtyard. The corresponding temperature was as high as 31°C.

With different airflow patterns being introduced \( \Delta T \) varies by demonstrating positive figures with diverse values. All iterations were evident for vertical thermal profiles with ascending thermal stratification pattern with lower temperature values at the bottom level and increases through the height. Thus, represent the typical thermal profile of “Cool courtyard” microclimate.

Iterations B and D verified an exceptional thermal behaviour. The daytime air temperature within the courtyard at the average human body height (1.1m) remained below the ambient by 1.2°C. The courtyard maintains contacts with the outdoors through envelope openings positioned on the longitudinal axis and its open to sky opening.

However, in iteration E, with maximum number of envelope openings the highest \( \Delta T \) is 0.5°C. Thus, larger the opening area thermal environment within the courtyard is closer to the ambient conditions.
In Iterations F and G with covered courtyards, except for bottom level the other levels were observed for $\Delta T$ values. Thus, demonstrates a courtyard with warm microclimate. Similar condition is apparent in Iteration A, when courtyard doesn’t maintain contacts with outdoors through horizontally positioned envelope openings.

b. Nighttime Mean – 18.00h to 9.00h

All iterations were observed with $\Delta T$ values with warm courtyard conditions (Fig.3). This may be the effect of closing all openings except for top opening of the courtyard and Op.2 during the night. However, the differences in $\Delta T$ values were observed in all iterations within which $\Delta T$ values at 1.1m illustrates a similar profile to the daytime behaviour (Fig.1). Iterations B, C and D were observed for the lowest temperature at 1.1m the bottom level. This raises another assumption regarding the effects of daytime thermal behaviour on nighttime.

DECREMENT FACTOR EVALUATION

Higher Decrement factor shows a higher indoor temperature than the outdoors. Thus, a lower Decrement factor with good thermal performance with regard to reduction of indoor maximum temperature was evident in iterations D and B. The iteration “Base” demonstrated the highest Decrement factor with poor thermal performance and the indoor maximum temperature is almost the same as the ambient. Similar conditions were observed in iterations A, F and G. Though the analysis was performed on two different parameters the results represent a similarity. Thus, establishes that the iteration B and D were the best among all iterations investigated for thermal performance in the courtyard.

The agreement between Decrement factor and Relative index of indoor zones is comparable to the courtyard’s thermal behaviour. Thus, establishes that the iterations B and D were the best among all investigated iterations and furthermore, verifies an existence of thermal relationship between the courtyard and surrounding interior zones. Which modifies the indoor microclimate.

3.2 Modification of Indoor Air Temperature

While almost uniform ambient conditions exist, the presence of different thermal conditions within the courtyard and interior zones would be the impact of different envelope configurations, which resulted diversity in airflow characteristics. Furthermore, is effective in modifying the thermal capacity of the high thermal mass building envelope.

3.3 Thermal Mass

The hourly wall surface temperature of the axis, courtyard and internal walls (all internal walls in each zone were monitored and averaged for a mean value) were compared with external walls at the human body height. Thus, the best thermal performance iteration B and the worst thermal performance iteration A with regard to cooling are assessed for thermal behaviour of walls.

![Figure 8](image)

**Figure 8**: Decrement factor at 1.1m-bottom level within the courtyard

![Figure 9](image)

**Figure 9**: Comparison of internal and external wall surface temperature for iteration B and A

THERMAL FLYWHEEL EFFECT

The interior walls were observed for lower surface temperature than the external walls as expected in high mass buildings (see Fig. 9 A and B). Wall temperatures of the courtyard walls and the axis walls remained above against each other depending on the airflow pattern. While the internal wall and external wall temperatures remain consistent. During the daytime internal wall temperature decreased by 1 to 3.4°C well below the external walls.

Nevertheless, relatively higher courtyard wall temperatures of iteration A specify heat absorption thus the availability of incoming outdoor air from the sky opening of the courtyard. Alternatively, higher axis wall temperatures of iteration B reveal heat absorption and availability of incoming air through the axis.

Furthermore, in iteration B a time lag of 4 hours for the courtyard wall temperature was observed. Compared to iteration A, the maximum courtyard
temperature is 1°C lower with a value of 28.8°C. Such results indicate a better interaction between high mass and airflow in iteration B in lowering the wall temperatures of the courtyard.

**LONGITUDINAL AXIS**

Fig. 9 shows a comparison of wall temperatures of the longitudinal axis and the air temperature at the two ends of the axis for iterations B and A.

On the contrary to iteration A, the airflow along the axis in iteration B, demonstrated a time lag of 4 hrs in its flanking walls. The maximum wall temperature at 17.00hrs is 29.8°C and at the same time air temperature at the two ends of the axis reached to their maximum with different values. The higher temperature at the beginning of the axis was lowered by 0.8°C when the air passes through high mass axis walls. Thus, the air to mass heat exchange has activated when air flows the length of the axis.

In iteration A, air temperature at the two ends of the axis remained constant.

**3.4 Indoor Air Temperature**

Thermal environment of the internal zone (zone e, see Fig.3) on the west adjoining the courtyard is directly influenced by the courtyard. Thus, the indoor air temperature of this zone were monitored and compared with the courtyard and ambient values to investigate the impact of courtyard on the indoor environment (see Fig. 11).

In both iterations daytime indoor air temperature move below the courtyard air temperature. However, in iteration B (except in late afternoon) indoor air temperatures is relatively below the levels in Iteration A, while following parallel with the courtyard temperatures. This behaviour correlates with the pattern of courtyard air temperatures than the ambient, which was consistent throughout the study.

In iteration B, during the early hours of daytime, internal wall temperature remains below the level of indoor and ambient air but gradually increases and equals the indoor air temperature by 16.00hrs. During the early half of the night, the wall temperature remains higher than the indoor air but gradually decreases and reaches to a minimum by early morning probably caused by night ventilation. Thus, the daytime airflow pattern and its optimum ventilation have formed an environment to promote nocturnal ventilation.

**3.5 Nocturnal Ventilation**

Typical ambient weather data for Colombo indicates a still wind conditions during the night.

Within this context, internal zones between the courtyard and axis openings were monitored for air movement. The measurements indicated the availability of ventilation between 0.2 to 0.4m/s in areas close to the openings and courtyard during night hours [1]. Relatively lower temperatures at the openings can enhance a slight breeze due to stack effect only in the night. This was evident with indoor air velocities recorded against almost still ambient wind conditions during the nighttime. The benefit of
such airflow is important for thermal comfort in the early night hours along with relatively higher levels of humidity.

4. RESULTS AND DISCUSSION OF THE COMPUTATIONAL ANALYSIS

4.1 Airflow Patterns

All iterations (except for atrium forms) were observed for a basic airflow pattern within the interior. Most of the envelope openings demonstrated a positive pressure zone while sky roof opening of the courtyard showed a negative pressure (suction) zone. This pressure difference is seen as the driving force in inducing airflow and thus optimising the exposure of high mass walls to incoming air. The air entering from the envelope is seen travelling through the indoor spaces (adjoining the axis and courtyard) before being discharged into the sky through the courtyard. Three basic airflow patterns, “Upwind funnel airflow, Horizontal cross upwind airflow and “top vortex airflow” are identified for all courtyard iterations (see Fig.12). Conventional cross airflow patterns were observed for Iterations F and G, which correspond to the Atrium forms. Thus, the minimal distribution and restrictions on upward airflow in the atrium forms demonstrated the worst indoor thermal environments.

The maximum indoor airflow distribution is seen in Iterations B and D with “Upwind funnel airflow” where the openings 1 and 2 on the longitudinal axis acts as inlets. Furthermore, in Iteration B and D which prove the best indoor microclimates the courtyard does not admit any airflow from its sky opening but acts as an “Upwind funnel” to discharge the indoor airflow into the sky. The top vortex flow is visible only when all envelope openings, except the courtyard opening are closed –Iteration A. Thus, the courtyard acts as a suction zone and admits airflow from the top. The air entering through the courtyard tries to get discharged back into the sky through the same opening creating a vortex at its top opening, with minimal indoor airflow distribution.

The above results clearly indicate that the different airflow patterns and corresponding opening compositions within the courtyard built forms are correlated to the indoor thermal performance. In addition, the external wind incidence within 30-60 degrees from the longitudinal axis promotes optimum indoor thermal conditions. More details are published elsewhere [2].

CONCLUSION

The effect of courtyard for mass-air heat exchange and thus lowering the daytime indoor temperature below the corresponding levels of ambient temperature is correlated with the indoor airflow pattern. This correlation indicates that the potential of the courtyard to act as a passive cooling strategy is a function of the indoor airflow pattern. Thus, relatively better indoor thermal modification is seen when the courtyard acts as an air funnel discharging indoor air into the sky, rather than courtyard acts as a suction zone to induce air from its sky opening Furthermore, optimum modification (lowering) of courtyard and indoor air temperature is seen not correlated to the number of openings.]. Over heated indoor thermal environments exists in atrium built forms owing to the fact on restrictions to the natural airflow.

REFERENCES