Indoor Thermal Modification of a Ventilated Courtyard House in the Tropics

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Abstract

This paper investigates the effects of airflow patterns and airflow rates on thermal behavior of a ventilated courtyard building in a warm humid climate. With some airflow patterns indoor air temperature can be brought to a level below the ambient, while with others the indoor air temperature may be higher than the ambient. The integration of a courtyard in the building design can optimize indoor airflow and is of significant importance with regard to the indoor thermal environment provided the courtyard maintains correct contacts with the outdoor environment. The current paper explores airflow patterns and airflow rates in a modern tropical courtyard house in respect to corresponding indoor thermal modifications. A thermal investigation was carried out on the site by manually changing the composition of airflow inlets (openings) found in the building envelope. From the results it is observed that the different airflow patterns affected different thermal environments and sometimes a cool condition within the courtyard and in the surrounding indoor spaces. Relatively low indoor air temperature was observed with a particular air movement pattern created through the openings found on a longitudinal horizontal axis through the courtyard. The temperature was below the ambient by 1.3 degree C with an airflow range of 1.5 to 2.0 air changes h⁻¹.

Keywords: courtyard; opening; tropical climate; airflow; indoor thermal environment

Introduction

Local climate greatly affects the indoor thermal environment in buildings. In tropical climates, buildings are overheated during the day due to solar heat gain through the building envelope and solar penetration through windows. From a thermal comfort point of view it requires the lowering of indoor daytime temperature to below the outdoor temperature using the input of cooling energy, which in passive systems is obtained from natural renewable sources. Techniques for such thermal modification have been widely addressed (Givoni, 1994).

Thus, adequate air movement through the building is essential in order to minimize indoor discomfort due to overheating conditions. It is not only regarded as a simple measure in supplying fresh air to maintain acceptable indoor air quality but also an energy conservation approach which ensure acceptable indoor thermal conditions by removing indoor heat.

In tropical climates, integration of a courtyard; an open to the sky space, in the building design is aimed at minimizing the plan depth of the building for a better cross ventilation potential. Thus, courtyard buildings in these climates act as air funnels in combination with other openings (such as doors and windows) found in the building envelope.

Thermal environments in courtyards in hot and dry climates have been investigated previously using field investigations. However, thermal environments in tropical courtyard buildings and particularly in surrounding internal spaces are less understood. Meir et al. (1995) suggested that availability of proper ventilation could improve microclimatic conditions in courtyards. Walker et al. (1993) and Shao et al. (1993) performed CFD and wind tunnel studies for courtyards located in the center of the building. Their work suggested two types of airflow patterns, the “Top Vortex” and “Full Vortex”. In top vortex an eddy of air is formed at the top opening of the courtyard. Flow of the eddy along the full depth of the void is called full vortex. Length of the building, roof configuration and the courtyard’s position are the determinants of these two airflow patterns. A similar study was performed by Hall (1999) and suggested that the vortex characteristics are dependant on the dimensions of void such as width to depth ratio.

When wind acts against a building, a positive pressure is created on the windward facade. As air is deflected around the building, negative pressures are created on the leeward side (Aynsley et al.1977). Thus if vortex characteristics are combined with such external air pressure regimes through proper external openings in the envelope, airflow within the courtyard
and indoor spaces can be activated. However, given the characteristics of ambient wind conditions that surround the building, indoor thermal modification and corresponding airflow rates may be varied depending on the relationship between the courtyard and external openings.

In order to assess the impact of ventilation on courtyard thermal environment a preliminary investigation was conducted in September 2000 (Rajapaksha et al.2001). The experimented building is a single storey tropical courtyard house found in Colombo, Sri Lanka (Fig.1).

This paper is aimed at investigating an optimum composition between a courtyard and other main openings, based on a comprehensive field investigation in April 2001. Emphasis is placed on establishing an effective airflow range that relatively provides a better climate modification (or lowering daytime mean and maximum indoor air temperature) in the courtyard as well as in the surrounding indoor spaces.

**Tropical Climate**

From the building design and indoor comfort viewpoint, the most dominant climatic characteristic of the tropical climate is that seasonal variations of air temperature do not exist. Colombo, Sri Lanka (latitude 5°55′N and 9°49′N, longitude 79°51′E and 81°51′E) is an example of this climate and is characterized by relatively high levels of humidity and temperature.

**Seasonal Pattern**

The seasonal pattern of wind and rainfall is a dominant climatic characteristic in these climates. Monsoon wind occurs twice a year; the Northeast and Southwest monsoon. The northeast monsoon occurs from June to August and the southwest from December to February. The remaining inter-monsoon period represents the dry season, while monsoon periods create rainfall.

Fig.2A shows the annual thermal uniformity represented by an almost constant mean monthly temperature that varies by only 2 degree C, from 27°C in December to 29°C in April. Relative humidity varies from 70 to 80 percent. A combination of high Global radiation with low wind velocities (Fig.2B) from February to May results in an extremely over heated period during which the maximum air temperature sometimes rises to 34°C.

**Diurnal Pattern and Comfort Zone**

Daily climatic patterns of this climate call for the required strategies for climate conscious building design. The temperature and humidity measured for April 2001 (Fig.3A) as an example demonstrates the problem. As Nicol’s comfort formula (Nicol et al.1999) indicates, daytime air temperature between 11.00h and 18.00h are above the comfort zone (neutral temperature is 28.2°C). Therefore strategies that reduce indoor overheating conditions are desirable. Diurnal temperature differences range from 8° to 10°C. Daily patterns of wind velocity (Fig.3B) during the daytime are between 0.6 to 1.8m/s but comparatively higher than the still air conditions at night and early morning. Thus, utilization of daytime ventilation for improving the indoor thermal environment is of significant importance.
Experimental Structure

Field investigations to assess the effects of airflow patterns on indoor air temperature were carried out on an architect designed contemporary courtyard house in Colombo, Sri Lanka. The investigation was performed in April 2001 during which the ambient temperature was observed as extremely high.

Building Description - An Enclosed Courtyard House

The design of the building is integrated with a central courtyard, which is visually and physically connected to the external environment through two main passages (or axes) linking to openings in the external envelope. The courtyard is open from all four sides and merges with the other interior spaces of the house as shown in Figs. 1A and C.

The courtyard measures 3.7m by 8.1m in plan, occupies 10% of the total floor area of the building and consists of a 250mm deep static water surface with an area of 24m². The top of this space is protected by horizontal reinforced pergolas placed at 250mm centers at a height of 4.1m. The detailed view of the courtyard is illustrated in Fig. 1B.

The immediate surroundings of the courtyard are an open passage to the east and a family living space to the west. The two axes flow through the courtyard perpendicular to each other. The entrance door directly forms a longitudinally unobstructed visual axis extending towards the outside through the courtyard and then through the metal grill window at the opposite end of the axis (Fig. 1B). A similar effect could be experienced in the cross axis also.

The building structure consists of, 220mm thick brick walls (including cement and lime plaster), clay tiled and cement rendered floors, asbestos roofing sheets and timber ceilings. The walls and roofs are not installed with insulation.

Airflow Patterns

The experiment was conducted under nine different airflow patterns from 16th April to 7th May 2001. For experiment purposes, the airflow patterns were handled and created manually by closing or opening the major doors (or openings) found in the external building envelope and sky roof opening of the courtyard.

Table 1 shows the airflow patterns that were created and each pattern or combination of openings is referred to as a “case”. Fig. 1A illustrates the location of openings in relation to the courtyard. The longitudinal axis is composed of opening one (Op1) and two (Op2) while cross axis is composed of opening three (Op3) and four (Op4). Except for Op2, all the openings are composed of doors. Op2 is a metal grill opening on the wall (Fig. 1B). Op1 has an area of 4.3m² while the other exterior openings are of 3.6m² each. The courtyard measuring 18m² is open to the sky. Table 2 shows the open and close mode of the openings in each case investigated.

In a typical Sri-Lankan dwelling, the windows are usually kept open during the day and closed at night in both current and traditional practice (for security). Hence, airflow pattern was controlled during the daytime 9.00h to 18.00h, while during the night.

| Table 1. Airflow Patterns |
|---------------------------|
| Ventilation Strategy      | Representative Case |
| All openings closed (No Vent) | Base Case            |
| Single axis and Courtyard open | Case A and B          |
| Both axes and Courtyard open | Case C               |
| Only the Courtyard is open | Case D               |
| Single axis, Courtyard and single opening of the other axis open | Case E and F         |
| Single axis only (Courtyard’s top is closed) | Case G             |
| Both axes only (Courtyard’s top is closed) | Case H              |

| Table 2. Opening Compositions |
|------------------------------|
| Case | Op1 | Op2 | Op3 | Op4 | Cy. |
| Base | X   | X   | X   | X   | X   |
| A    | O   | O   | X   | X   | O   |
| B    | X   | X   | O   | O   | O   |
| C    | O   | O   | O   | O   | O   |
| D    | X   | X   | X   | X   | O   |
| E    | X   | O   | O   | O   | O   |
| F    | O   | O   | O   | O   | X   |
| G    | O   | O   | X   | X   | X   |
| H    | O   | O   | O   | O   | X   |

Open Mode [O] Close Mode [X], Cy.- Top opening of the courtyard; Op1,2,3 and 4 – Axes Openings
(18.00h to 9.00h), all exterior openings remained closed except opening two and top of the courtyard.

Each case was performed from 9.00h to 9.00h of the following day. A typical daytime is represented from 9.00h to 18.00h and night-time is represented from 18.00h to 9.00h of the following day. During the monitoring period, all other openings of the house remained closed.

Instrument Setup and Data Collection

The instrumentation consisted of sensors with data recorders and a data acquisition system. The sensors were setup to monitor meteorological and indoor climatic conditions. Table 3 shows the details of data type, interval, number of measurement points, height and the data acquisition system. Meteorological data was collected at the station of the immediate surroundings (micro-climate) of the experimented building.

Indoor climate was measured mainly in two locations; the courtyard and surrounding interior zones (Zone A to F as given in Fig.1A). Air temperature and relative humidity within the courtyard was measured at three different heights 1.1m (bottom), 2.5m (middle) and 3.5m (top) respectively. The sensors were protected with multi plate radiation shields for accuracy. Air, wall surface temperature and relative humidity in each interior zone were measured at 1.1m (human body level) heights. Exterior and Interior wall surface temperature was measured with T-type thermocouple glued to the walls and covered with tape.

Air velocity at each opening was measured at 0.6m, 1.2m and 1.8m height and within the courtyard at 1.1m and 2.5m heights respectively.

Water temperature was measured at the mid height of the water surface, while the water level was also measured.

Results and Discussion

Ambient Climate

Ambient climate during each case of investigation demonstrated a similarity in the daily pattern of temperature, relative humidity, absolute humidity and wind velocity (Figs. 4A,B,C and D). The temperature reaches its maximum from 13.00h to 16.00h and during this period the relative humidity is at its minimum. Wind velocity is high in the daytime and still air periods are dominant in the late night and early morning. During the daytime the southwest wind direction is dominant with less diversities, however such characteristics change during late evening and early morning with low velocities.

The existence of cloudy skies has resulted an extreme climatic condition during Case E, hence this case is not presented for comparison.

Table 4 shows the daily values of maximum, minimum, mean and mean range of climatic variables of the study period.

Table 3. Measured data, Equipment used and Data Acquisition system

| Data Type               | Equipment                                      | Data Interval   | No. of measurement points and Location | Measured Height          |
|-------------------------|------------------------------------------------|-----------------|----------------------------------------|--------------------------|
| Air Temperature         | RS 10/11, sensor with Recorder (Tabai Espec)   | Five Minutes    | Interior-24 points                     | Interior at 1.1m         |
|                         | Multi plate (12 plates) Radiation Shields      |                 | Inside each room (zone A to F) along the axes and within the Courtyard | Within the courtyard at 1.1m, 2.5m and 3.5m |
|                         | (Campbell Gill 41004), Used for exterior and within the Courtyard |                 | Exterior at one point                  | Exterior at 1.1m         |
| Relative Humidity       | RS 10/11, sensor with data recorder            | Five Minutes    | - Do -                                 | - Do -                   |
| Wind Velocity and       | Cup Anemometer and Vane with CR21X Data logger (Campbell Scientific) | 15 Minutes      | One point at an unobstructed location  | 1.1m, 5.5m and 10m height |
| Direction - Exterior    |                                                |                 |                                        |                          |
| Wind Velocity-at each opening | Hot wire Anemometer (Kanomax model 6511) | 1 second sampling time with 1 Minute average | Three points at the center of each opening | 0.6m, 1.2m and 1.8m |
| Wind Velocity- within the courtyard | Hot wire Anemometer (Kanomax model 6511) | 1 second sampling time with 1 Minute average | Two points at the center of the courtyard | 1.1m and 2.5m |
| Wall Surface Temperature| 0.5mm Copper Constant T-type thermocouple With 5020A Thermocoe Data logger | Five Minutes    | 28 points- 6 points at exterior walls. | 1.1m                     |
| Water Temperature       | - Do –                                         | Five Minutes    | Two points at the center of the water surface | 0.125m below ground level |
| Water level             | Measuring ruler                                | One hour        | Three sides                            |                          |
It is evident that the hourly data demonstrate a difference in each case with minimal difference in mean values. This problem is natural and cannot be overcome when the cases are performed on different days. Therefore the approach to formulate general and subjective conclusions is based on parametric analysis.

**Parametric Analysis**

The main interest of this study is to evaluate the effectiveness of different airflow patterns in modifying the indoor thermal environment. Two parameters were established to evaluate and compare the thermal performance of each case. The parameters are as follows:

(i) **Relative Index**: 
\[ \Delta T = T_o - T_i \]  
Relative Index (\(\Delta T\)) is the difference between outdoor and indoor temperatures calculated for daytime mean, night-time mean and hourly values. Thus, any positive value represents a level of indoor air temperature below the ambient or a “Cool condition” while negative value represents the opposite or a “Warm condition”.

(ii) **Decrement Factor**: 
\[ DF = \left[ T_{i_{\text{max}}} - T_{o_{\text{mean}}} \right] / \left[ T_{o_{\text{max}}} - T_{o_{\text{mean}}} \right] \]  
\( T_i \) = Indoor temperature  
\( T_o \) = Outdoor temperature  
\( T_{o_{\text{mean}}} \) = Daily mean outdoor temperature  
\( T_{o_{\text{max}}} \) = Outdoor maximum temperature  
\( T_{i_{\text{max}}} \) = Indoor maximum temperature

The decrement factor is the ratio of maximum indoor and outdoor temperature amplitude taken from the daily mean temperature (Koenigsberger et al. 1974). The lower the value the better the indoor thermal environment.

**Thermal Environment in the Courtyard**

### Relative Index Analysis

(a) **Daytime Mean - 9.00h to 18.00h**

Fig.5 shows the Relative Index values at bottom (1.1m), middle (2.5m) and top (3.5m) levels of all cases performed.

Primarily, in the “base case” where all openings were kept closed, the daytime mean temperature was higher than the ambient. The vertical Relative Index profile in the courtyard varied up to a maximum of 1.5°C from the bottom to the top. The corresponding temperature was as high as 31°C.

With different airflow patterns being introduced (or in other cases), \(\Delta T\) started by moving towards positive figures but with different values. All the cases of investigation were observed with thermal stratification within the courtyard with higher \(\Delta T\) values recorded at the bottom and gradually decreasing with the height. This was the common thermal profile in cases of cool courtyard conditions (Rajapaksha et al. 2001).

Cases A and F demonstrated a unique thermal behavior. The daytime air temperature in the courtyard at the average human body level (1.1m) remained below the ambient by 1°C. The courtyard remained connected to the outdoors only through openings...
found on the longitudinal axis and the courtyard’s top. Other openings were kept closed. In the case C, the courtyard was ventilated through five openings but maximum $\Delta T$ was only 0.5°C. This is because the temperature is closer to the ambient when the opening area is too large. In cases D and H the courtyard’s top was kept open and closed respectively while the other four openings in the envelope remained closed and open respectively. In both these cases, $\Delta T$ value at 3.5m in the courtyard reached to its minimum (a warm condition) in all cases.

The above behavior raises the following assumptions as being significantly important:

- A cool condition in the courtyard does not necessarily depend on the number of openings.
- Ventilation through the courtyard’s top only and vice versa (through the openings in the envelope only with the top of the courtyard closed) may not affect a cool condition.
- Ventilation to the courtyard through a horizontal axes may affect a cool condition in the courtyard.

Similar behavior was evident in a previous preliminary thermal investigation conducted in September 2000 (Rajapaksha et al 2001)

(b) Night-time Mean - 18.00h to 9.00h

All cases were observed with negative $\Delta T$ values with warm courtyard conditions (Fig.6). This may be the effect of closing all openings except for the top of the courtyard and Op.2 during the night. However the differences in $\Delta T$ values were observed in all cases within which $\Delta T$ values at 1.1m illustrate a similar profile to the daytime behavior (Fig.5). Cases A, B and F were observed for the lowest temperature at 1.1m height. This raises another assumption regarding the effects of daytime thermal behavior on the night-time behavior.

(c) Daytime Hours

Fig. 7 shows the daytime hourly temperature difference ($\Delta T$) at 1.1m of cases A, B, C and F in which the optimum cool conditions were observed.

The $\Delta T$ values increased from 9.00h to 13.00h and gradually decreased until 18.00h. Except in some evening hours concerning case B, positive $\Delta T$ values were observed in all cases. A maximum $\Delta T$ of 2°C was observed by 13.00h at which time the outdoor temperature had reached the daily maximum. This created a cooling condition in the courtyard. The reason for this effect may be due to the particular combination of airflow pattern and airflow rate that was available in such cases. The evidence to suggest this course of action comes from the availability of climatic and experimental parameters. The daily pattern of climatic parameters remained almost unchanged during all cases while only experimental parameters such as the composition of openings and thus the airflow pattern were changed.

Although Cases A, B, C and F were observed for best cases in Relative Index analysis it is necessary to evaluate its consistency with an analysis using a standardized index: the Decrement Factor.

Decrement Factor Analysis

Higher Decrement Factor shows a higher indoor temperature than the outdoors. It is calculated to investigate the level of thermal performance of each case (Fig. 8). Thus, a lower Decrement Factor was identified in cases A and F. In other words, good thermal performance with regard to reduction of the indoor maximum temperature is achieved in these cases. The base case was identified as having the highest Decrement Factor reflecting a poor thermal performance with regard to reduction of the indoor maximum temperature. In addition, cases D, G and H demonstrated Decrement Factors close to the same factor of the base case. These results represent almost similar thermal performance as given in Fig. 5. The agreement between Decrement Factor and Relative Index establishes that cases A and F were the best among all cases investigated for thermal performance.

Thermal Environment in the Surrounding Interior Zones

Relative Index Analysis

(a) Daytime Mean - 9.00h to 18.00h

The investigation revealed a close correspondence between the courtyard and indoor temperatures. Fig. 9 shows the relative index values of each case investigated.

The base case was observed with warm interior zones and the corresponding indoor temperature was as high as 30.8°C. Other cases (refer to Table 2) were observed with temperatures below the ambient but $\Delta T$ was different from case to case. In cases A and F that were recognized as having the lowest courtyard air temperature, demonstrated the best indoor thermal conditions. Daytime air temperature in all interior zones at the average human body level (1.1m) remained below the ambient by 1.3°C with slight variations in each zone.

Almost identical indoor conditions were demonstrated in Cases B, D, G and H with a lower $\Delta T$ value of 0.5°C. The changing pattern of indoor thermal environment of these cases presents a similarity with the courtyard’s behavior (refer to Figs.5 and 9).

(b) Diurnal

Hourly temperature differences ($\Delta T$) of the indoor zones and ambient in cases A and F are shown in Fig. 10. The evidence of close correspondence between the temperatures of the courtyard and indoor spaces is simply reflected through the behavior of $\Delta T$ values. Positive $\Delta T$ during the daytime (9.00h – 18.00h) decreases to negative $\Delta T$ values during the nighttime (18.00h to 9.00h) according to the courtyard’s behavior. A maximum $\Delta T$ of 3°C was observed at 13.00h at which time the outdoor temperature had reached its maximum. At night the indoor air was warmer than the ambient by 2 to 3°C but varied between 29-28°C. This figure is within the comfort zone for this particular climate.
Decrement Factor Analysis

Decrement Factor analysis was carried out for indoor zones in all the cases (Fig.11). Lower Decrement Factor was identified in cases A and F in which the courtyard shows a better thermal performance. Cases D, G and H showed a value close to that of the base case.

The agreement between Decrement Factor and the Relative Index of indoor zones is similar to such agreement of the courtyard’s thermal behavior and further establishes that case A and F were the best among all cases investigated. Also, results of the investigation suggest the existence of a thermal relationship between the courtyard and surrounding interior zones.

Indoor Thermal Modification

While almost uniform ambient conditions exist, the presence of different thermal conditions in the courtyard as well as in indoor zones was evident. The reasons for this behavior may be a consequence of the following:

(a) The effect of the evaporation from water
(b) Thermal capacity of the building envelope and effects of airflow patterns and rates.

Effects of Evaporative Cooling

With the effect of evaporation, the release of high amounts of heat from the air that comes into contact with a wet surface or from the surface where evaporation takes place, affect the indoor air temperatures below the ambient (Santamouris, 1999).

In this study, the potential of such effects was assessed using two extra investigations performed under similar airflow patterns (similar to case C) but with the presence and absence of the courtyard water separately. The ambient climate remained similar during two investigations. The daily mean temperature was 28.6°C.

Fig. 12 shows the daytime hourly temperatures of these two cases. When there was water in the courtyard, the daytime mean temperature difference (ΔT) was 0.57°C. This value was reduced to 0.41°C when the water in the courtyard was removed. The temperature reduction by evaporation is 28%. Thus the evaporative cooling effect is relatively small.

Further, the approximate mean evaporation rates for all cases were calculated with measured water temperature and humidity data. The calculated maximum and minimum was 4.5Kg/h and 3.5Kg/h respectively. Thus, it was found that the difference between each value was minimal. These results were in good agreement with the measured water level drop, which was at a constant of 4mm/day (96Kg/day). Absolute humidity at 1.1m in the courtyard varied within the range of 18.9 to 20.5g/Kg in all cases. Also, the difference in ambient values was observed as the minimum at between 0.5 to 1g/kg. Thus the increase in the absolute humidity due to evaporation was unnoticeable.

Table 5. Daytime Mean Interior and Exterior Wall Surface and Ambient Air Temperature at Human Body Height (1.1m)

| Case | Ambient | Interior Wall | Exterior Wall |
|------|---------|---------------|---------------|
| A    | 29.93   | 27.81         | 31.35         |
| B    | 29.71   | 28.69         | 31.49         |
| C    | 30.06   | 28.59         | 31.34         |
| D    | 30.24   | 29.03         | 31.70         |
| F    | 30.14   | 28.12         | 31.60         |
| G    | 30.35   | 28.86         | 31.70         |
| H    | 30.33   | 28.89         | 31.65         |

Table 6. Nighttime Mean Interior and Exterior Wall Surface and Ambient Air temperature at Human Body Height (1.1m)

| Case | Ambient | Interior Wall | Exterior Wall |
|------|---------|---------------|---------------|
| A    | 24.97   | 28.22         | 27.67         |
| B    | 24.50   | 28.14         | 27.50         |
| C    | 24.61   | 28.10         | 27.62         |
| D    | 24.81   | 28.71         | 28.18         |
| F    | 25.07   | 28.85         | 28.37         |
| G    | 25.18   | 28.90         | 28.28         |
| H    | 25.51   | 28.94         | 28.30         |

Effects of Building Envelope and Airflow

Day and night mean temperatures of exterior (mean of six measurement points) and interior wall surfaces (mean of 22 measurement points) at human body height (1.1m) were investigated in respect to ambient and indoor air temperatures (Tables 5 and 6). It is clear that daytime external wall temperature was always higher than the ambient. But internal surface
temperature remained below the ambient and indoor air temperature (Fig.13).

A significant correlation between internal surfaces and indoor temperatures was observed. During the early hours of daytime, indoor surface temperature remains below the level of indoor and ambient air but gradually increases and equals the indoor air temperature by 16.00h. During the early half of the night, the wall temperature remains higher than the indoor air but gradually decreases and reaches a minimum by early morning.

The evidence to suggest the effect of internal surface temperature in lowering the indoor air temperature is visible through the mutual balance of temperatures. With lower surface temperature, indoor daytime temperature reaches a level below the ambient in daytime, while the surface temperature reaches its lowest by early morning, probably due to the night ventilation that took place. Thus, it provides evidence to suggest that appropriate day and night ventilation affect the heat exchange between walls and air and bring the indoor daytime temperature below the ambient.

Effective Ventilation Rate

The airflow rates were calculated using experimental data for all performed cases. The unbalanced inflow and outflow rates were observed due to the low number of measurement points at the openings of each performed case. Therefore, for all cases, the computational simulations were performed with CFD and both results were in approximate agreement. Further, a sensitivity analysis to the changes of wind velocity and direction were performed. A detailed description of these results will be presented elsewhere.

Table 7 shows the daytime mean airflow rate and corresponding air changes per hour for each case performed. The volume of the building is 420m$^3$. Diversity in airflow rates is observed between the cases with values ranging from 1260 to 84 m$^3$/h and 0.2 to 2.5 ACH. The highest and lowest airflow rate and ACH is observed in Cases C and D respectively. The changing airflow rates were dependant on the number of openings in each composition.

In the previous sections it was concluded that Cases A and F have the best thermal environment within the courtyard and surrounding interior zones.

### Table 7. Daytime Mean Ventilation Rates of All Cases

| Case | Airflow Rate [m$^3$/h] | Air Changes h$^{-1}$ |
|------|------------------------|----------------------|
| A    | 630                    | 1.5                  |
| B    | 504                    | 1.2                  |
| C    | 1050                   | 2.5                  |
| D    | 84                     | 0.2                  |
| F    | 714                    | 1.7                  |
| G    | 210                    | 0.5                  |
| H    | 252                    | 0.6                  |

The improved thermal conditions were demonstrated with the presence of an approximate airflow range of 630 to 714 m$^3$/h respectively. Thus the effective range of the ventilation rate is about 1.5 to 2.0 ACH. Further, this corresponds to the optimum direction of ambient wind within the range of 45 to 60 degrees from the longitudinal axis.

**Conclusion**

Thermal environment in a high mass (brick walls) tropical courtyard building where daytime ventilation is used as a cooling strategy is affected by airflow patterns within the building. Given the ambient wind climate, different opening compositions between the courtyard and external openings would result in different indoor airflow patterns and thus airflow rates.

Maximum modification of indoor air temperature is seen when the rectangular courtyard is combined with the external environment through envelope openings found on a longitudinal axis. The corresponding airflow rate was found to be within a range of 1.5 to 2 ACH.

The maximum modification of indoor air temperature within the courtyard as well as in surrounding occupied spaces is not seen as a function of the number of envelope openings but as a function of the building composition in terms of openings and their relationship to the courtyard.

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