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Environmental Design Consideration for Courtyards in Residential Buildings in Hot-humid Climates: A Review

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ABSTRACT

This paper discusses environmental design considerations for courtyards in residential buildings in hot-humid climates through a literature review by contrasting with those in hot-dry climates. The main focus of discussion is on shading and ventilation effects of courtyards. The results of the analysis revealed that the form and orientation of a courtyard were less significant in its environmental design considerations for the hot-humid climates. Although these factors were reported to be the most important design considerations in the case of hot-dry climates. Meanwhile, natural ventilation has been commonly utilized in wooden-structured traditional buildings in hot-humid climates. However, most of the urban houses in Southeast Asian regions are becoming heavy-weight brick-walled buildings nowadays. It could be seen that the required environmental effects of a courtyard and its design considerations in the case of high thermal mass buildings in hot-humid climates are still uncertain and need to be investigated further.

1. Introduction

Koch-Nielsen (2002) defined a courtyard building as a building that has an internal space opened to the sky. Edwards et al. (2006) highlighted that the courtyard design had been used since the Neolithic settlements and was extensively used from China to Morocco. One of the primary roles of courtyard spaces is to protect the occupants from the harsh outdoor conditions and provide environmental functions such as natural lighting and ventilation (Hyde, 2000). The courtyard form was generally influenced by the climatic conditions of the region. For instance, in China, the size of the courtyard reduced from northern (cold climates) to southern regions (warm climates) (Knapp, 1999). The northern region has larger and shallower courtyards to receive more solar radiation, whereas the southern region adopts smaller and deeper courtyards to prevent the solar heat gain.

In general, the size and design of the courtyard's enclosure make a significant impact on its performance (Hyde, 2000). Hyde (2000) highlighted that the courtyard can be divided into three major types which are: 1) Fully enclosed courtyard, 2) Semi-enclosed courtyard and 3) Semi-open courtyard. Figure 1 shows an illustration of all the three types of courtyard. Each courtyard has its characteristic and the appropriate function. For instance, a fully enclosed courtyard is suitable for elongated buildings, because the natural lighting, ventilation and also comfortable spaces could be introduced to the core of the buildings through the courtyards. In addition, the environmental performance of courtyards can be optimized by considering the building shape and the heat gain control devices. Proper building and courtyard designs in consideration of the local climatic conditions would enable indoor spaces to be thermally comfortable.

The previous studies on courtyard houses are still limited, but some of them focused on the environmental functions of courtyards. See, for examples, Kubota et al. (2014); Almhafdy et al. (2013); Sadafi et al. (2011); Dili et al. (2010); Jamaludin et al. (2014); Muhaisen (2006); Meir et al. (1995); and Berkovic et al. (2012). In addition, several studies examined the effects of courtyard form on indoor thermal environments. See Muhaisen (2006); Cantón et al. (2014) and Ratti et al. (2003). Whereas ventilation effects of the courtyards were analyzed in some studies such as Jamaludin et al. (2014); Sharples and Bensalem (2001); Rajapaksha et al. (2003); Tablada et al. (2005). Several studies developed passive strategies by courtyards, for examples, Dili et al. (2010); Givoni (1994); Littlefield (2012), and energy assessment was carried out by, for example, Canton et al. (2014). However, most of the above studies were conducted in hot-dry climates and moderate climates, and there are few studies that discuss environmental considerations for courtyard houses in hot-humid climatic conditions. In addition, less attention is paid to relatively narrow and deeper courtyard design than those for extensive yards.

This paper discusses environmental design considerations for courtyards in residential buildings in hot-humid climates through a literature review by contrasting with those in hot-dry climates. The discussion contains the future prospects on design consideration for courtyard houses of high thermal mass structures.

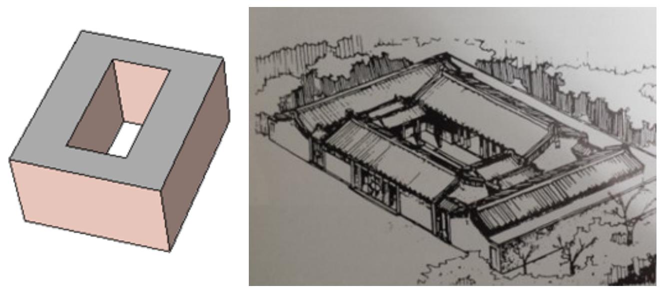


Figure 1a *Fully enclosed Courtyard*

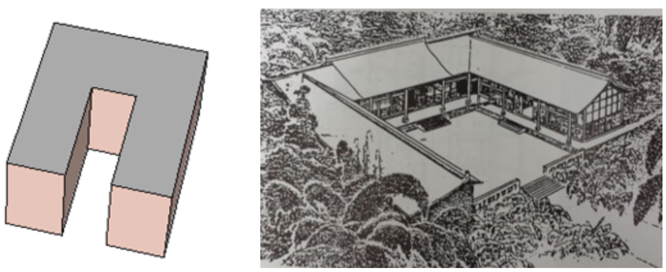


Figure 1b *Semi enclosed Courtyard*

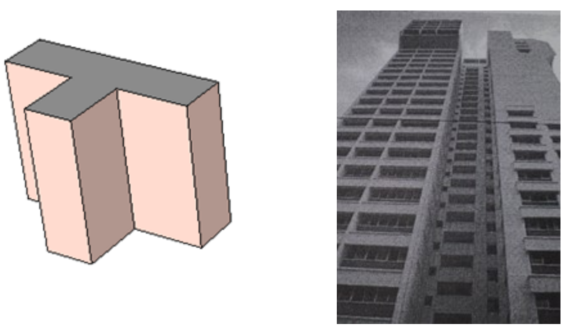


Figure 1c *Semi open Courtyard*

Source: Knapp (1999) and Hyde (2000)

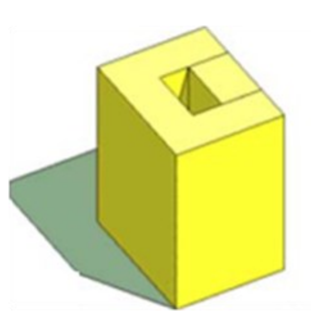
2. Environmental Design Considerations for Courtyards in Hot Climates

For hot climates, the most important environmental design considerations for courtyards in residential buildings are considered to be shading and ventilation effects. Shading effects of courtyards are commonly determined by the building orientations, height, and their exposure to the sky (Meir et al., 1995). On the other hand, the ventilation effects by courtyards mainly depend on the outdoor wind conditions or the indoor temperature difference for the stack effects (Koch-Nielsen, 2002; Givoni, 1994).

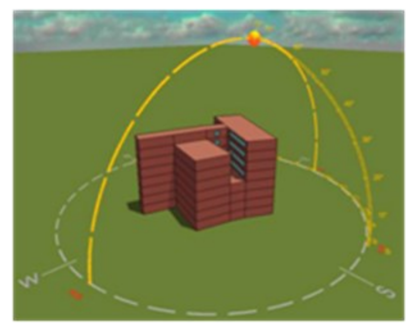
2.1 Shading effects

The absorption of solar radiation on the building and courtyard surfaces could raise their temperature and adjacent air layers, thus resulting in an increase of air temperature in the surrounding areas (Muhaisen, 2006). Therefore, consideration of shading might be necessary to reduce the direct solar radiation or heat gain (Hyde, 2000). There are several types of shading techniques that are normally used for courtyard buildings such as Figure 2 shows typical shading approaches for courtyard buildings.

Many studies show that the orientation of courtyard plays an important role for its shading effects such as in Muhaisen (2006), Meir et al. (1995), Berkovic et al. (2012) and Cantón et al. (2014). A courtyard has the internal surface that has the most exposure to the sun when its elongated orientation agrees with the east-west axis. Whereas it would be the least exposure when the orientation is directed to the north-south axis. In addition, when the courtyard has a deeper form, it could provide more shaded areas, hence reduces the heat absorption in the courtyard. However, a tall courtyard building may cause an adverse impact on its air flow, unless it is carefully designed (Littlefield, 2012). Table 1 shows the shading application and its related effects on the thermal conditions as reported in the previous studies.



(a) Shading generated by building form



(b) Shading generated by building orientation

(c) Shading by courtyard roof (direct shading)

(d) Shading by trees

Figure 2 *Typical shading approaches for courtyard buildings*

Source: Muhaisen, 2006; Almhafdy et al., 2013; Sadafi et al., 2011; Missaka, 2014, http://cblueprints.com/2014/02/08/how-to-design-an-energy-efficient-home/- retrieved on 4 August 2014.

Most studies in hot-dry regions found shading effects by courtyard orientations. For example, Meir et al. (1995) carried out a field measurement in two semi-enclosed attached courtyards in Negev, Israel. In the same region, Berkovic et al. (2012) conducted a simulation study on an emptied courtyard. The study concluded that North to South orientation of courtyard could obtain the highest shading effect. In contrast, there were a few studies in hot-humid climates that considered shading effects by building orientations. Muhaisen (2006) carried out the shading simulations, including both hot-dry and hot-humid climates and suggested that for hot-humid regions, the most suitable orientation of courtyards was on the northeast to southwest axis. However, based on a study carried out by Almhafdy et al. (2013), the orientation effect could only be reduced for about 2% for the air temperature of courtyards in hot-humid climates. The courtyard orientation for hot-humid climates is suggested to be dependent on wind directions (Koch-Nielsen, 2002; Jamaludin et al., 2014; Givoni, 1994). It shows that, the effect of solar radiation in a hot-dry climate has greater impacts as compared to in a hot -humid climate.

2.2 *Ventilation effects*

Ventilation in a courtyard is generated by stack and wind effects. Due to the stack effects, the warmed air rise and discharged to the atmosphere during the daytime and the dense cool outdoor air sinks into the courtyard during the night time (Koch-Nielsen, 2002). As for the wind effects, the air flow is generated based on the pressure conditions (i.e. positive or negative pressure) of the building surfaces. A positive pressure causes the air flow moving into the courtyard while the negative pressure creates an air suction outward from the courtyard (Sharples and Bensalem, 2001). Figure 3 shows the illustration of ventilation effects in courtyard buildings.

***Table 1** Shading means for courtyards*

Climate	Shading means	Effects	Methods	Ref.
Hot-dry	Courtyard orientation	• Courtyard facing south provides more shading percentage (30-70%) during summer. • North and south orientation provide the highest amount of shade. • Hot-dry: Optimum shading when courtyard in northeast -southwest or north-south direction (approximate of 60% shade area)	• Semi-open courtyard facing south direction • Courtyard axially elongated to north-south direction • Courtyard axially elongated to north-south or northeast-southwest direction.	Meir et al., 1995. Berkovic et al., 2012. Muhaisen, 2006.
	Courtyard roof	• Significantly lower courtyard temperature ($3^{\circ}C$ below maximum outdoor temperature) • Reduce 18-21% of indoor energy consumption based on the respective case models.	• Adjustable courtyard roof • Fabric canopy roof	Al-Hemiddi et al., 2001. Canton et al., 2014
	Courtyard galleries	• Application of the galleries provides the best thermal comfort during peak hour (PMV: 0.5-1.0)	• Application of galleries along the courtyard perimeter	Berkovic et al., 2012.
Hot-humid	Courtyard Orientation	• Hot-humid: Optimum shading when courtyard in northeast-southwest direction (approximate of 65% shaded area) • Lower air temperature than outdoor in north and south direction (2% lower)	• Courtyard axially elongated to northeast -southwest direction • Semi-open courtyard facing north or south.	Muhaisen, 2006. Almhafdy et al., 2013.
	Courtyard roof	• Reduce courtyard heat gain during peak hour (13:00) approximately 85%. • Improve thermal condition in the adjacent of courtyard zone.	• Raised courtyard roof with 500 mm height	Sadafi et al., 2011.
	Courtyard verandah	• Lower air temperature by 1.5 $^{\circ}C$ compared with maximum outdoor (Synchronizing with upper courtyard temperature).	• Shade the areas that adjacent to indoor opening.	Dili et al., 2010.
	Canopy of trees	• Lower indoor mean temperature of the adjacent room with higher relative humidity.	• Canopy of trees adjacent to the window.	Jamaludin et al., 2014.

Although there are several other shading techniques for the hot-dry climate such as by courtyard roofs or courtyard galleries, they could be considered as secondary protections because the effects of solar radiation are more dominant to the whole buildings. Therefore, the solar radiation's protection by building orientations plays a significant role in providing the most shading effects and becomes the main priority to be considered during the design phase in the hot-dry climate (Givoni, 1994).

Meanwhile, in the hot-humid climates, a direct shading means seems preferable. The reason is, the shading effects provided by the building orientation have small effects on the courtyard thermal condition in comparison to the courtyard with a covered roof. For instance, Sadafi et al. (2011) examined the thermal effects of courtyards in terraced houses in Malaysia's hot humid climate. They concluded that the indoor temperature was significantly reduced when the courtyard had a raised covered roof that prevented heat gained from a direct solar radiation. The similar results were presented in the studies of Dili et al. (2010) and Jamaludin et al. (2014) with the applications of courtyard's verandah and the canopy of trees. The direct shading methods by using shading devices provide better-horizontal protections from the high altitude of sunlight in the hot-humid climate.

Continuously ventilated condition is essential in a hot-humid region, where it could remove the heat and humidity from the building for achieving comfort (Koch-Nielsen, 2002). The design of the building is suggested to promote maximum air movement with less internal obstruction. The traditional wooden house is one of the examples, which has a raised timber floor with multiple window openings on the building's façade to achieve the necessary cross ventilation condition. The strategy is contrary to the ventilation approach for the hot-dry region. In the hot-dry region, the outdoor air during the daytime is dry and warm with some occurrence of gusty winds. Therefore, buildings in hot-dry climate are suggested to be designed with fewer openings on the external wall or closed during the daytime (Koenigsberger et al., 1973). In many cases, they would utilize the night ventilation which is much more suitable with their climatic condition (Koenigsberger et al., 1973; Givoni, 1994). Table 2 shows several contributions of literature on ventilation means by courtyards in hot-humid climates.

The study by Rajapaksha et al. (2003) in a high thermal mass house with courtyard in Sri Lanka found that, the courtyard would increase cross ventilation flow assisted by the stack effects during the daytime. The combination of these two effects with the optimum ACH of 1.5-2 is proven to achieve the thermal comfort. The result of the airflow pattern was similar with that by Sharples and Bensalem (2001). They found an upward flow (negative pressure effect) in the courtyard is better at providing higher indoor air velocity than the inward flow (positive pressure) in the courtyard. Figure 4 shows the results of air flow field for both of the studies. In addition, the studies by Tablada et al. (2005) found that the courtyard width to height (w/h) ratio would also affect the indoor air flow rate.

Table 2 *Ventilation means by courtyards in hot-humid climates*

Ventilation types	Effects	Ref.
Cross ventilation	• Reduced the temperature in the courtyard up to 2°C below the outdoor maximum compared to non-ventilated courtyard (0.7 °C) during the daytime ventilation. • Better indoor thermal modification when courtyard acts as air funnel. • Optimum ACH is between 1.5-2 ACH when thermal modification is 1°C below ambient level	Rajapaksha et al., 2003.
	• Better air flow coefficient was found when the courtyard had negative suction effects. • The external wind flow direction of 45° through the building opening provides higher indoor air flow compared to the normal direction (0°).	Sharples and Bensalem, 2001.
	• Large courtyard ratio (width to height) resulted in better flow for indoor • Indoor airspeed is more important than the courtyard protection from solar radiation. • Cross ventilation performed better compared to single sided ventilation in providing higher ventilation rate in the building.	Tablada et al., 2005
	• Cross ventilation with low heat absorption material in courtyard would create cool air flow into the adjacent room • Continuous ventilation helps to controls humidity level in the buildings	Dili et al., 2010.
Night ventilation	• Night ventilation was superior to the others, i.e., full day, daytime and no ventilation. • Mean temperature always below 30 °C compares to the others.	Jamaludin et al., 2014.

The larger ratio would contribute to a better-indoor air flow even for a single sided ventilation. In their further simulation with consideration of the cross ventilation condition, they revealed that relatively higher indoor air flow rate was obtained compared to the single sided ventilation.

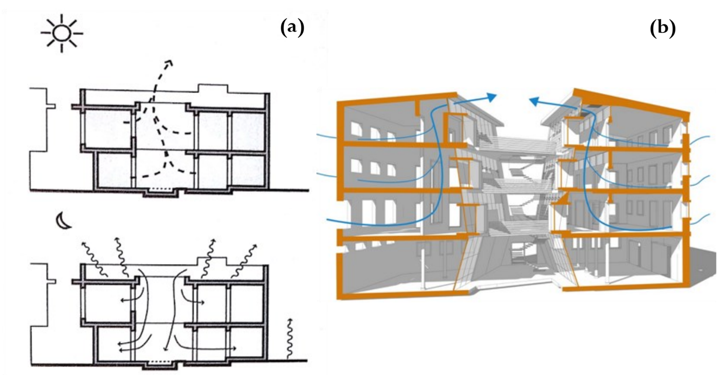


Figure 3 *(a) Stack effects during daytime and night-time ventilation (b) wind effects. Source: Koch-Nielsen, 2002; Hopwood, (n.d). http://archinect.com/people/project/48814386/palazzo-della-routunda/49282061- retrieved on 4 August 2014.*

This situation shows that the combination of cross ventilation with upward flow throughout the courtyard and the appropriate courtyard width to height ratio are important to achieve the necessary indoor air flow condition. However, most of the airflow study of the courtyard building was focused on increasing the indoor air flow rate, but less included on the effects of the building thermal condition. Therefore, the actual relationship between the increasing of air flow rate and the indoor thermal condition could not be fully determined. In the works of Dili et al. (2010) and Jamaludin et al. (2014), they highlighted that securing only cool air flow into the indoor spaces could provide a better indoor thermal condition. This condition could be achieved by the application of cross ventilation with low heat absorption material in courtyard or utilizing the night ventilation strategy. A cooler courtyard floor help to remove the heat from the incoming air to the building during the daytime, while utilizing night ventilation could induce cooler outdoor air into the building during the night-time. This shows that the consideration of the thermal condition of the incoming air is also important to ensure that the increasing of air flow rate is consistent with the reduction of building thermal condition.

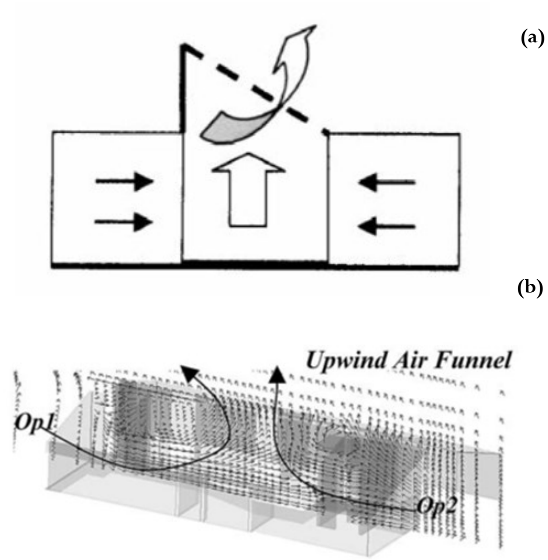


Figure 4 *Upward air flow caused by cross-ventilation in (a) Wind tunnel study on courtyard model (b) CFD study on detached courtyard house in Sri Lanka. Source: Sharples and Bensalem, 2001; Rajapaksha et al., 2003*

3. Environmental Considerations for Courtyard in Hot-humid Climates

It is apparent that the shading effect of a courtyard is largely determined by its form and orientation, particularly in the case of hot-dry climates. This is because in a dry climate, the direct solar radiation is much more intense than that of sky radiation. In contrast, in a hot-humid climate, the vapor content in the air is high and therefore the solar radiation is largely diffused in the air (Koch-Nielsen, 2002). Thus, the sky radiation, which comes from all directions, largely affect the heat gain for the courtyard spaces. It is anticipated that the form and orientation of a courtyard are less important in its environmental design considerations for the hot-humid climates. Therefore, in the case of hot-humid climates, exposure rate to the sky or direct shading should be more or similarly important determinant of the shading effects of a courtyard. In fact, controlling the sky exposure seems to be much more appropriate rather than a fully covered courtyard.

The reason is, besides providing shade to the courtyard, this technique creates an opening on the courtyard roof and allowing the air circulations within the courtyard areas. Thus, the courtyard area could be shaded and in the same time providing air circulation for indoor spaces during the daytime or night-time.

One of the methods to measure the exposure rate of the courtyard is by a sky view factor. Kubota, et al. (2014) investigated the cooling effects of courtyards in traditional Chinese shop houses in Malaysia and revealed that there was a relationship between sky view factor and air temperatures measured in the courtyards. Figure 5 shows the relationship that obtained from the study based on the four courtyards.

The graph shows a decrease in the sky view factor would decrease the air temperature in the courtyard. However, it is seen that more samples are required to clarify the above point.

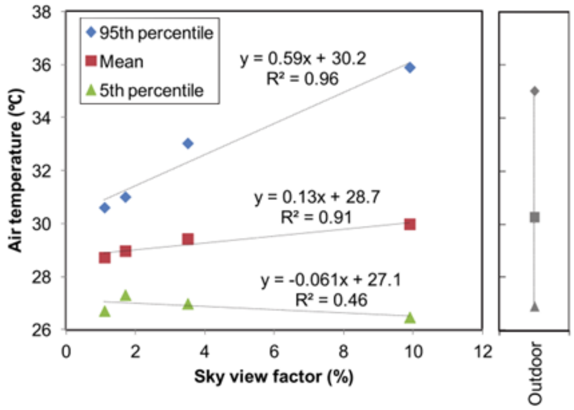


***Figure** 5 The relationship of a sky view factor and air temperature.*
*Source: Kubota et al. (2014)***.**

In hot-dry climates, the most important design consideration is not ventilation but shading effects. Courtyards are commonly seen in traditional buildings in this region for providing shade to the enclosed spaces, while for the ventilation strategies, night ventilation or an evaporative cooling is more appropriate. The high temperature ranges between daytime and night-time provides advantages in this climate to utilize a thick thermal mass structure and the night-time ventilation strategies. A thick thermal mass structure could provide thermal lag effects during the daytime, while during the night-time, cool outdoor air helps to remove the heat and cool the building structure efficiently.

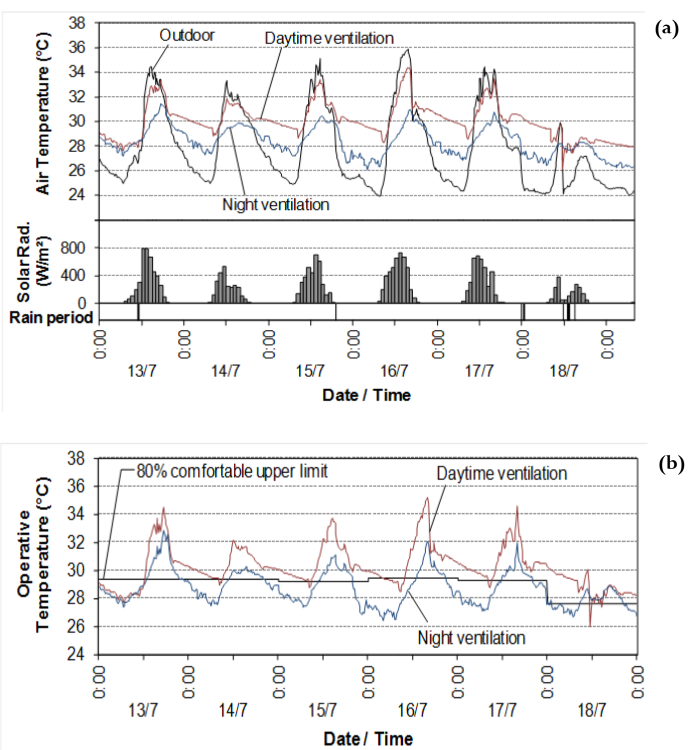


***Figure** 6 Temporal variations of the measured thermal variables at 1.5m above floor in the master bedrooms of terraced houses in Malaysia: (a) Indoor air temperature and solar radiation during daytime ventilation and night ventilation, (b) Indoor operative temperatures and the corresponding temperature limits for thermal comfort.*
Source: Toe (2013).

In hot-humid climates, ventilation is quite important to achieve indoor thermal comfort. Thus, traditional houses normally adapt large openings to secure massive natural ventilation through cross ventilation. In order to do so, light-weight material is normally used for building construction (Givoni, 1994). However, most of the urban houses in hot-humid Southeast Asian regions are becoming heavy-weight brick-walled buildings. In addition, several studies showed that the daytime ventilation is not preferable even in hot-humid climates, especially when the building is of heavy-weight materials such as in the works of Kubota et al. (2009). In the study, they highlighted that daytime ventilation would allow the warm air to enter the indoor spaces and increase the indoor air temperature. Furthermore, the heavy-weight building material absorbs heat during the daytime and resulting a warm indoor condition during the night-time especially when the heat is being released.

Figure 6 shows the results of the study on the ventilation strategies between daytime and the night ventilation in the heavy-weight brick-walled of terraced house in hot-humid climate of Malaysia (Toe, 2013). The graph shows that the indoor thermal condition with the daytime ventilation strategy was always higher than the night ventilation condition. In addition, even with the night ventilation strategy, the indoor condition was not fully in the range of comfortable upper limit of the adaptive thermal comfort criteria for the whole day as indicated in Figure 6b**.**

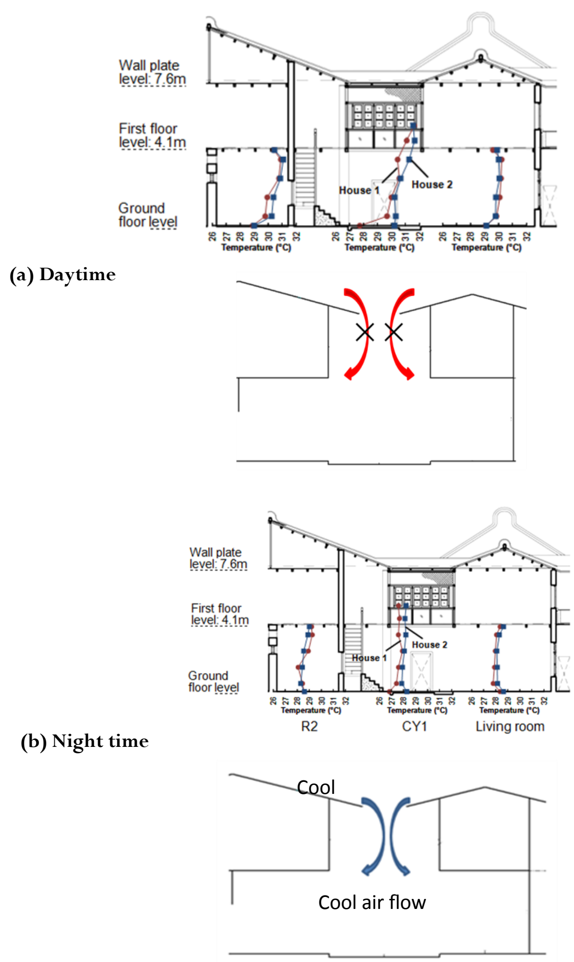


***Figure** 7 Average air temperature profile and its air flow illustration during (a) Daytime ventilation (b) Night-time ventilation, in two Chinese shop houses with courtyards in Malacca, Malaysia. Source: Kubota et al., 2014.*

In contrast, several studies highlighted that the application of continuous and cross ventilation strategy could provide high indoor air flow rates and comfort condition (Sharples and Bensalem, 2001; Rajapaksha et al., 2003; Tablada et al., 2005). However, the study of Kubota et al. (2014) in Chinese shop house with courtyard in Malacca revealed that the thermal comfort for indoor could be obtained even without daytime ventilation (closed windows). In the study, they revealed that during the daytime, vertical air exchange between warm outdoor air and the cool courtyard air were prevented due to the temperature stratification in the courtyard. Therefore, relatively low indoor air temperature could be maintained. Meanwhile, during the night-time, the temperature stratification in the courtyard was not observed and this condition allowed the vertical air exchange between the cool outdoor air and the warm courtyard air. Thus, the indoor air temperatures are lowered sufficiently to reach the outdoor level. Figure 7 shows the characteristic of the thermal condition obtained from the study. In addition, it was believed that the roof design of the courtyard plays an important role in providing the cool outdoor air into the courtyard especially during the night-time. The roof surface would experience the effects of night radiation cooling and creates the heavy density of cool air within the roof surfaces. The cool air will fall into the courtyard in the sloped roof direction after reaching a certain density level or by the wind flow. Therefore, with the occurrence of this natural state condition, relatively cool outdoor air could be provided during the night-time and contribute to lower the daytime air temperatures on the following day.

4. Conclusions

This paper discusses environmental design considerations for courtyards in residential buildings in hot-humid climates through a literature review by contrasting with those in hot-dry climates. The discussion mainly focuses on the shading and ventilation effects of courtyard. In general, it can be concluded that climatic conditions do affect the consideration of shading and ventilation techniques for courtyard building environmental performances. The detailed conclusion is as follows:

- Shading by building orientation is considered to be the main priority for courtyard buildings in hot-dry climates. Meanwhile, for the hot-humid climates, the consideration of shading effects by controlling the sky exposure or courtyard roofs is anticipated to be more appropriate. Due to the high intensity of solar radiation in hot-dry climates, the shading effects by building orientation could provide a major protection before considering the application of other supplement strategies. In hot-humid climates, the exposure of courtyard to the diffused solar radiation largely affects the heat gains for the courtyard spaces. Therefore, the building orientation could be less important as compared to the shading effects by the sky exposure or the direct shading device.
- Shading by controlling the sky exposure of the courtyard roof is seen to be more significant in providing better indoor thermal conditions for buildings in the hot-humid climates. A proper design consideration of the sky exposure could offer desirable shading effects and allow the circulation of ventilation. The sky exposure rate of courtyard can be measured by a sky view factor.
- In hot-dry climates, the application of night ventilation with a high thermal mass structure could maintain the indoor thermal condition in an appropriate level. Meanwhile, for hot-humid climates, suitable ventilation strategies are still arguable especially for buildings with the high thermal mass structure. Several studies highlighted that continuous ventilation with upward air flows through courtyards is important to provide comfort to indoor conditions, while others mentioned that daytime ventilation was unnecessary because it would allow hot air to enter building spaces.
- It is believed that the application of night ventilation and courtyard's sloped roofs could be the appropriate method in maintaining lower indoor conditions as compared to the outdoor. The night ventilation could ensure cool air to be provided to indoor spaces, while the sloped roofs could enhance the flow of cool air due to night radiation cooling effects.

In addition, there is still room for studies concerning the environmental effects of courtyard houses in hot-humid climates. Future studies mainly should be focused on the effects of sky exposure rate on its cooling effect and ventilation strategies assisted by courtyards in high thermal mass buildings.

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