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The impact of courtyard geometry on its mean radiant temperature

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Abstract. For hot regions, studies have been advocating re-adopting the courtyard pattern for its thermal advantages. Aiming at developing thermally comfortable courtyards, studies have been exploring the impact of courtyards geometry on their shading and natural ventilation, which are the two environmental principles of courtyards. However, there is a lack of studies on the impact of manipulating courtyards geometry on the thermal sensation of occupants. This research investigates the impact of changing the courtyard geometry and the resulted shading on Mean Radiant Temperature (MRT) and Globe temperature (Tg). The latter represents the thermal perception of occupants and the former is the main effective factor on the thermal sensation of people in outdoor and semi-outdoor spaces. The research carried out simulation experiments to test 360 different courtyard configurations. The simulation experiments included using Envi-met and IES-VE simulation tools. The former was used to determine MRT and Tg, and the latter to determine shading levels. Baghdad was selected to represent an example of a hot city in which summer air temperature reaches around 50 °C. The results show that the difference in shading that results from changing the courtyard geometry can lead to a difference in MRT and Tg of up to 15°C.

1. Introduction: the courtyard pattern

The courtyard is the traditional building pattern of hot regions [1]. It involves having buildings inward oriented instead of modern outward oriented buildings patterns. The courtyard space plays the main role in providing access to natural lighting and ventilation for indoor spaces [2]. This enables having indoor spaces interacting with moderated outdoor conditions through the courtyard space [3; 5]. The main moderating strategies used in the courtyard pattern to achieve thermal efficiency are controlling shading and natural ventilation [4; 5]. The former enables managing the heat gain through protecting buildings and occupants from the solar radiation [1; 6]. The latter enables to get rid of the accumulated heat gain in buildings' structure and replace hot air with cool air [3; 7]. Various elements are used in this building pattern to achieve the best possible thermal performance, including the wind-catcher, the high thermal mass envelop, and the compact urban fabric. However, the courtyard space plays the main role [8; 9]. If the courtyard building is properly designed, studies have confirmed experimentally that it can offer better thermal performance than other building patterns, such as the detached and semi-detached ones [10; 11]. However, it has been also found that if relevant factors are not well considered, especially the courtyard space geometry, courtyard buildings will not be thermally efficient [12; 13].

Aiming at developing thermally efficient courtyards, studies have been analysing and exploring the factors that affect the thermal performance of courtyards. They have shown that shading and natural ventilation are mainly affected by the geometric properties of the courtyard space, which include the ratios of courtyards width/length (W/L), width/height (W/H), periphery/height (P/H), area and orientation [1; 14]. Previous literature gives useful indications about how to manage courtyards' shading and natural ventilation (Table 1). However, there has been limited research work on the impact of having different levels of shading and natural ventilation on the thermal sensation of occupants. This research aims to address this knowledge gap. It explores the impact of having different shading levels on the Mean Radiant Temperature (MRT) in courtyards and the resulted thermal sensation of occupants. Studies have shown that MRT has a significant impact on the thermal sensation of people in outdoor and semi-outdoor spaces. It can also be highly controlled through managing spaces' shading and exposure to solar radiation [15; 16; 17]. The other factor of significant impact on people's thermal sensation is the air temperature. However, it has not been explored as it cannot be mitigated through changing geometric features of external spaces, which is the focus of the current study [15].

Table 1. Relevant previous literature's main focus and results

Authors	Main focus	Main results
Aldawoud & Clark, 2008[13] Soflaei et al., 2017[2] Nasrollahi et al., 2017[18] Muhaisen, 2006[19] Muhaisen & B Gadi, 2006[14]	The impact of courtyard geometry and orientation on shading.	The deeper and narrower the courtyard the higher shading level.
Tablada, Blocken, et al, 2005[20] Bittencourt & Peixoto, 2001[21] Rajapaksha, Nagai, et al, 2002[22] Soflaei, Shokouhian, et al, 2016[23] Mousli & Semprini, 2016[24]	The impact of courtyard geometry and openings design on natural ventilation.	Wide courtyards with cross ventilation have more active natural ventilation than narrow ones.

2. Research aim and methodology

This study aims to determine the impact of changing the geometric properties of courtyards and shading on MRT and the resulted thermal sensation of occupants. It used the Globe temperature (Tg) as a thermal sensation index for being highly reflecting the actual thermal sensation of people [25]. The research determined shading levels in a set of different courtyards, then, the impact of having different shading levels on MRT. It also determined the values of air temperature and air velocity in the tested courtyards to determine Tg as, in addition to MRT, they are the effective factors on Tg.

The study carried out a set of simulation experiments in which it examined hourly shading levels, MRT, air temperature and air velocity of 360 courtyards of different geometric properties. The hourly analysis of courtyards' conditions enables tackling the direct impact of having different shading levels during the daytime on MRT. The examined courtyards included six different areas, five W/L ratios, three heights and four orientations (Figure 1). These forms are hypothetical, but they represent a wide range of possible courtyard forms.

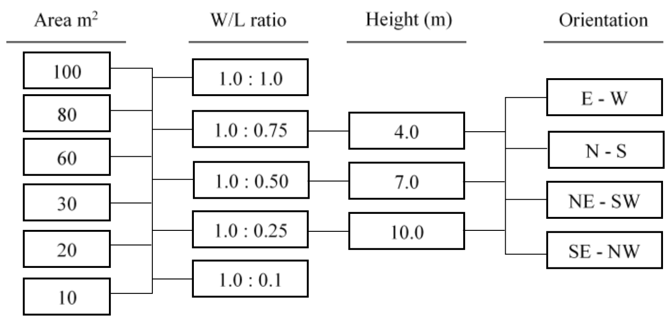


Figure 1. The matrix of the tested courtyard forms

The main used simulation tool is Envi-met 4.2, which has been widely used and validated by previous studies to investigate the microclimatic conditions of outdoor and semi-outdoor space [18; 26; 27]. However, due to not being able to examine the hourly shading levels of courtyards in the used version of Envi-met in this study, IES-VE simulation tool was used for this purpose. This software has been tested using IES ASHRAE 140 and qualified as a dynamic model in the CIBSE system of classification [28; 29]. For each of the tested courtyards, the research used Envi-met to determine the hourly MRT, air temperature and air velocity in the middle of courtyards, to represent the average values. The study used IES-VE to determine hourly shading level for each surface of the courtyard. The shading level is represented as the percentage of the shaded area of a courtyard's surfaces to the total area of its surfaces. Tg is not determinable in any of the used simulation tools. The research used to the following equation to determine Tg using the collected date from the simulation [30]:

$$Tg = (MRT + 2.35 \times \text{air temperature} \times (\text{Air velocity})^{0.5}) / (1 + 2.35 \times (\text{Air velocity})^{0.5})$$

The simulation experiments were done for Bagdad in four days representing the annual possible thermal conditions. This city has a hot and long summer and courtyard buildings have represented its only building pattern for centuries. The considered climatic conditions in the simulation were defined following analysing the hourly climatic conditions of Baghdad using unpublished data from the Iraqi Metrological Organization and previous literature [31] (Table 2). These climatic conditions and Baghdad geographic location were considered in setting the simulation configurations in both of the used simulation tools. In Envi-met, to guarantee having results as close as possible to real-life conditions, the properties of a calibrated courtyard simulation model developed by a previous study were used [32].

Table 2. Climatic conditions of Baghdad used in the simulation

Season / date	Air temperature (°C)				Humidity (%)				Wind (m/s)	Direction
	Min.	Time	Max.	Time	Min.	Time	Max.	Time		
Typical winter / 21st of January	13.6	04:00	19.7	14:00	89.0	14:00	68.0	04:00	2.7	East
Typical spring / 16th of March	21.8	06:00	27.0	14:00	44.0	14:00	51.0	06:00	2.0	East
Typical summer/ 1st of august	31.6	06:00	46.8	16:00	26..0	16:00	41.0	06:00	1.3	East
Typical autumn/ 1st of October	27.0	07:00	38.0	15:00	39.0	15:00	63.0	7:00	2.6	East

3. Results

The results demonstrate the impact of changing courtyards geometry on shading, MRT and Tg. Figure 2 shows the shading and MRT layouts of four-meter height courtyards with different W/L ratios. The figure also shows the correlation between the shading level and MRT during typical summer conditions. It can be seen that, at 12:00, there is a difference in MRT of around 20 °C between shaded and insolated areas in courtyards as a result of the solar radiation. In the correlation graph in figure 2, the trend line shows that the overall MRT of a well-shaded courtyard can be of 7 °C lower than MRT in an inadequately shaded courtyard.

Figure 3 shows the hourly MRT and Tg in two different courtyards in winter and summer. The first courtyard is low and wide whilst the second courtyard is deep and narrow. Through being well shaded, it can be seen that the second courtyard is of lower MRT than the first one. Air temperature is almost the same in both courtyards. In both courtyards, Tg, which reflects the thermal sensation of occupants, is highly affected by the hourly trend of MRT. Tg in the deep and narrow courtyard, as a result of having low MRT, can be up to 15°C less than Tg in the low and open courtyard.

To determine the impact of each of the examined geometric properties on courtyards MRT, A statistical analysis was conducted by the research using IBM SPSS Statistics 24. The analysis showed that all of the considered geometric properties have a statistically significant impact on MRT in courtyards (P-Value < 0.05). However, they are not of the same strength of impact. The most and least effective factors are, respectively, W/H ratio and orientation (Figure 4). The higher and narrower the courtyard the lower MRT. Finally, the statistical analysis revealed that the correlation between MRT and the courtyard height is not a linear one but a polynomial one. Once courtyards become high enough to be fully or nearly fully shaded, W/H < 1, the impact of courtyard height on MRT becomes very limited (Figure 4).

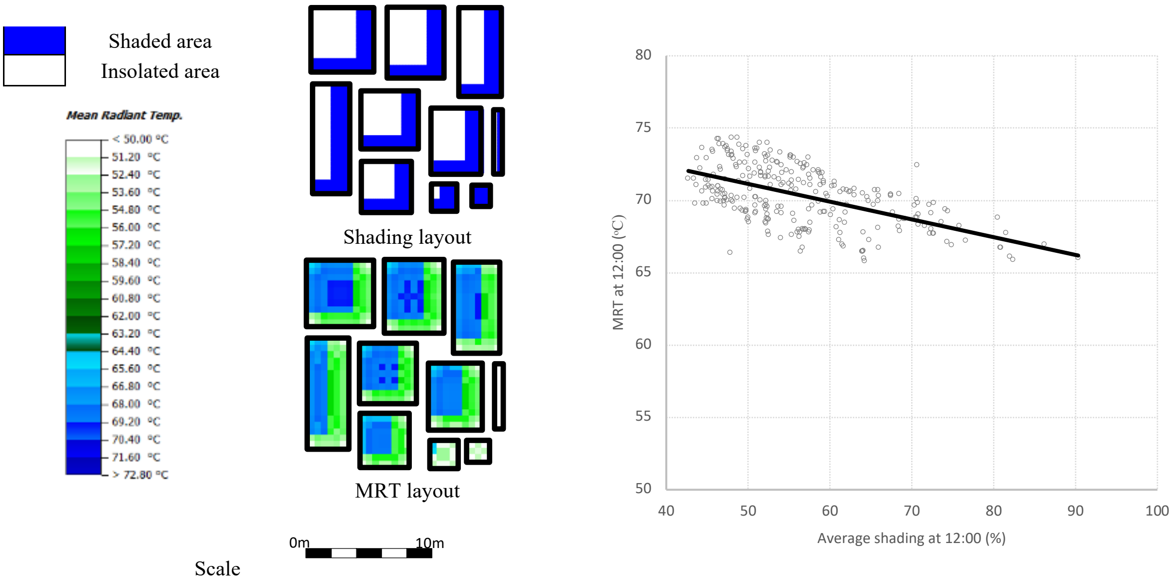


Figure 2. Shading and MRT layouts in ten different courtyards at 12:00 (to the left) and the correlation between shading and MRT (to the right)

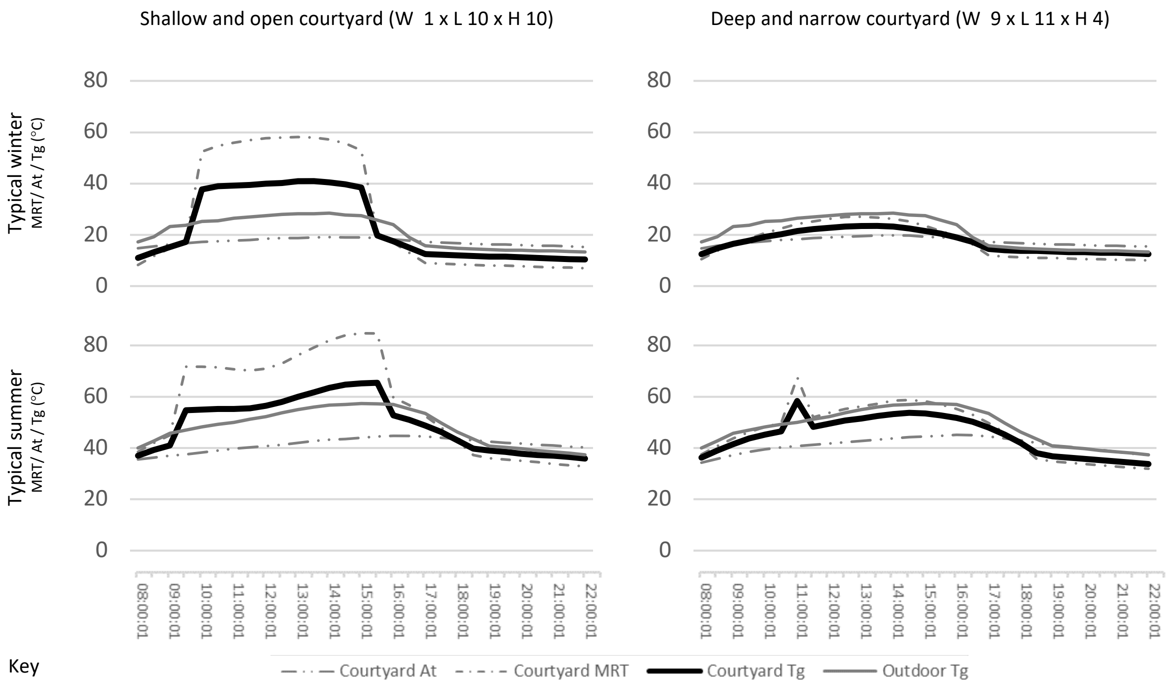
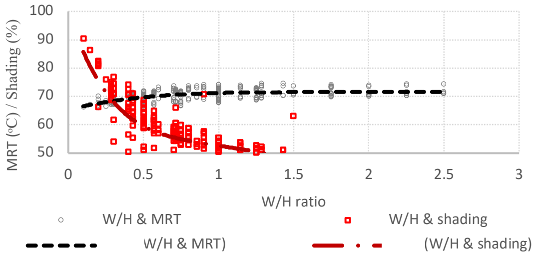
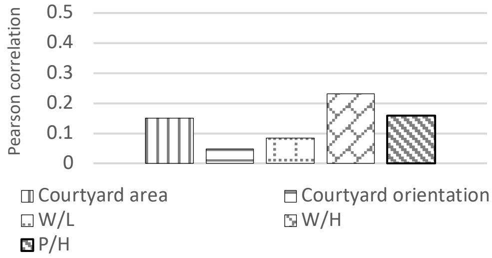


Figure 3. The MRT and Tg in warm and cool courtyards in summer and winter



The impact of W/H ratio on MRT and shading



The strength of impact of each of the geometry variables of courtyards on MRT

Figure 4. The correlations between the geometry of the courtyard and MRT

Comparing these results with previous studies shows that the findings of the current study are reasonable. In all of the explored studies, including the studies on shading presented in Table 1, it has been found that courtyards shading is mostly affected by the ratio of its height to width and that orientation does not have a strong impact in the aspect. Accordingly, it is rational to find that the same significance of impact is applied to MRT, as the latter is mostly affected by shading. However, this study elaborates the impact of having different shading levels on MRT and the resulted impact on the thermal sensation of occupants, which has not been properly investigated by previous studies. These results can be used to give indicators for designers regarding the impact of their designs on the thermal conditions of courtyards and the thermal sensation of occupants. There should be a special focus on managing shading in courtyards as it affects MRT, which significantly affects the thermal sensation of occupants. This impact needs to be carefully considered as having a highly shaded courtyard with as low as possible MRT is preferred for summer, but not for winter. Therefore, courtyards need to be designed with considering having a balance between hot and cold conditions to have the highest possible annual range of thermal comfort.

4. Conclusions and recommendation

Aiming at determining the impact of courtyard design on the thermal sensation of occupants, this study investigated the impact of courtyards geometry on their shading, MRT and the resulted thermal sensation of occupants, which has not been investigated properly by previous studies. MRT was especially considered for its significant impact on the thermal sensation of people in external and semi-external spaces. The research conducted simulation experiments using Envi-met and IES-VE simulation tools. The results showed that manipulating courtyards geometry can lead to a difference of 7°C in overall MRT in courtyards, which has a significant impact on the thermal sensation of occupants.

This research stresses the importance of designing courtyards by considering having a balance between hot and cold conditions to achieve the best possible thermal efficiency. The results of this study can help designers to predict the thermal performance of different courtyards. However, to fully determine occupants' thermal sensation in courtyards, further research studies are needed to determine the impact of the design of courtyards and other possible strategies on managing other microclimate factors such as air temperature and air velocity.

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