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The Thermal Performance Prospects of Courtyards in Cold Conditions

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The Thermal Performance Prospects of Courtyards in Cold Conditions

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Abstract. Aiming at developing more thermally comfortable and energy efficient buildings, some studies have been advocating using traditional architecture's passive design strategies. Among the rarely investigated architectural elements to achieve this objective in cold climates is the courtyard space. This environmental element, in most cases, has been examined and suggested for hot conditions. However, some studies have shown indications of its potential environmental efficiency in cold conditions as well. In principle, courtyards enable having sheltered outdoor spaces to regulate indoor spaces' interaction with the outdoor climate instead of having them outward oriented to directly face outdoor conditions. This research aims to determine whether this thermal performance of courtyards can be positive in cold conditions as it is in hot conditions, for instance, through protecting buildings from cold winds. To achieve this objective, the research conducted simulation experiments to determine the thermal conditions of 360 different courtyards and compared them with a typical modern urban outdoor space's conditions. If the courtyard space offers a warmer environment than modern urban outdoor spaces, then it might lead to a wider positive impact on buildings' thermal conditions and energy consumption. The used simulation tool to conduct the simulation experiments is Envi-met 4.2, which has been widely used and validated by previous simulation studies. The tested courtyard forms are of different geometric configurations to show a wide range of possible conditions in courtyards. The simulation was done for Baghdad, in which courtyards have been widely used for centuries. This city has a hot summer, but its winter temperature is between 0°C and 12°C. The Globe Temperature was used to determine peoples' thermal sensation. Its value includes the impact of air velocity, radiation and air temperature, which makes it representing people's actual thermal sensation properly. The results showed that courtyards offer higher Globe Temperature than modern urban spaces in cold conditions, mainly, through protecting buildings and occupants from winds. The air velocity inside courtyards can be one-tenth of air velocity in a modern urban outdoor space. The geometric properties of courtyards significantly affect courtyards' thermal conditions. These results indicate that the courtyard space can be more thermally efficient than modern urban spaces even in cold climate conditions. However, its geometric properties need to be properly considered to have its highest possible thermal efficiency. Otherwise, the courtyard might lose its efficient thermal performance.

1. Introduction: the courtyard pattern

The courtyard is a traditional building pattern that has been used for centuries, especially in hot regions, to achieve environmental comfort [1; 2]. Courtyard buildings are inward oriented, which implies that indoor spaces interact with mitigated outdoor environments, mainly, through a private outdoor space, which is the courtyard, instead of directly facing outdoor climatic conditions [3; 4] (Figure 1).

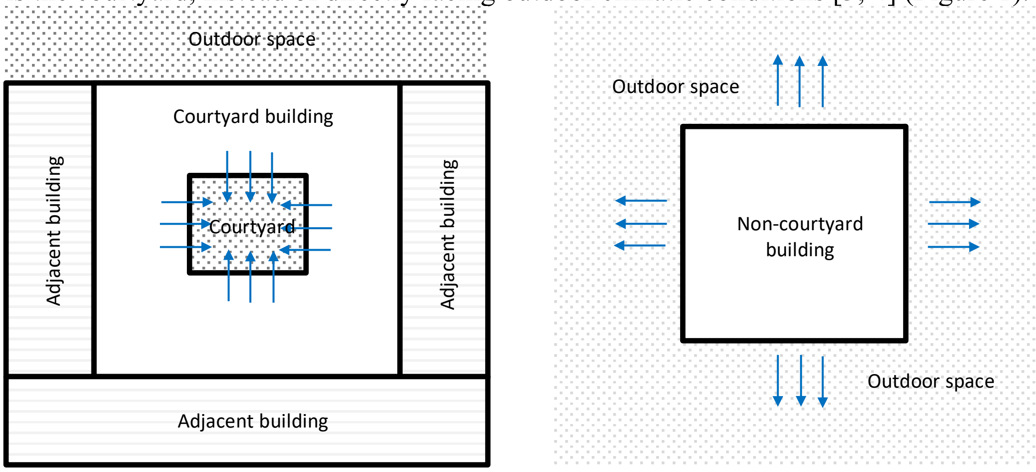

Figure 1. Courtyard (left) and non-courtyard (right) buildings' interactions with outdoor environments

Exploring previous literature shows that this building pattern has been intensively investigated and examined, in most cases, for hot regions [5; 6]. A limited number of studies have been done to explore and examine this building's pattern potential environmental efficiency for the cold climate. Among the main possible reasons behind this research tendency is that courtyards have been more associated with the hot region's architecture [1; 5]. In addition, there might be other established alternative approaches to achieve thermal efficiency in cold regions such as having high insulation level [7]. However, it seems that exploring this building pattern's environmental performance might be of importance to cold regions' architecture as it is for hot regions for two reasons. First, there are some studies indicating that courtyard buildings can be used to achieve more efficient environmental performance than non-courtyard building patterns, such as the detached and semi-detached buildings. Among these studies are Al-Hafith et al 2018, Aldawoud 2008 and Rogers 1999. The first study showed that courtyard spaces during Baghdad's typical winter can be of 20°C Globe Temperature (Tg) higher than the city's contextual Tg [8]. The second study compared the courtyard and atrium's environmental performance. It found that, for cold climate, courtyards are more efficient in the case of low height buildings [9]. The last one explored how courtyards can be used to provide thermally efficient outdoor space through protecting buildings from the wind whilst keeping their exposure to solar radiation [10]. The second reason is related to the climate change: some studies stress the importance of considering the courtyard pattern, even in cold regions, to handle the challenge of global temperature increase [11; 12].

From this exploration, it can be concluded that previous literature has shown useful indications regarding using courtyards in cold conditions to get environmental advantages. However, it is still limited work and there are many aspects that need to be explored to develop a comprehensive understanding of the potential effectiveness of the courtyard pattern for cold climate. Among the important aspects that have not been explored is whether having buildings oriented towards private courtyards enables having better thermal performance than having them oriented towards modern urban spaces. This question is based on the principal idea behind using the courtyard space, which is to have protected outdoor spaces for buildings instead of the totally open urban spaces. Aiming to contribute to the exploration of courtyards' thermal performance in cold conditions, this research worked on addressing this research question.

2. Research aim and methodology

This research aims to determine the potential environmental efficiency of adopting the courtyard pattern in cold conditions. This implies determining possible thermal conditions in courtyards and comparing them with the dominant outdoor space alternative in the modern built environment, which is a street urban space. If the courtyard space offers a more thermally comfortable environment than the modern urban fabric's outdoor space, the whole building might be more efficient as indoor spaces will be interacting with mitigated outdoor environments. The research used Baghdad as a case study for its exploration. Although this city is of a hot climate, it has been used as a case study for two reasons. First, it has a cold winter in which temperature can reach 0°C (Table 1). Second, it is one of the places where courtyard buildings have been widely adopted for centuries.

Table 1. The average climatic conditions of Baghdad.

Season / date	Air temperature (°C)		Humidity (%)		Wind (m/s)	Direction
	Min.	Max.	Min.	Max.		
21/01	13.6	19.7	89.0	68.0	2.7	East
07/02	13.5	2.5	83.0	52.0	2.7	North East
16/03	21.8	27.0	44.0	51.0	2.0	East
12/07	35.1	49.8	24.0	53.0	3.1	North East
01/08	31.6	46.8	26..0	41.0	1.3	East
01/10	27.0	38.0	39.0	63.0	2.6	East

The research depended on doing a set of simulation experiments in which the thermal conditions of a wide range of courtyard options and a typical street urban space were determined. This included testing 360 different courtyard geometric configurations, as geometric properties have been defined by previous studies to be of a large impact on courtyards' thermal performance. These properties included the courtyard area and orientation and the ratios of Width/Length (W/L), Width/Height (W/H) and Periphery/Height (P/H) [13; 14; 15]. The tested configurations included six different areas, five W/L ratios, three heights and four orientations (Figure 2). Regarding the orientation, it is represented in the study by measuring the angle of courtyards' long axis with the north orientation. Accordingly, its values included 0.0° for the N-S, 45.0° for NE-SW, 90.0° for the E-W and 135.0 for SE-NE. These used geometric properties are hypothetical. However, they represent a wide range of possible courtyard configurations. For the street urban space, which was compared with courtyards, a 9m wide street space of Baghdad with 5m to 7m high buildings on both sides was modelled and simulated. This is the typical residential street space in Baghdad (Figure 3).

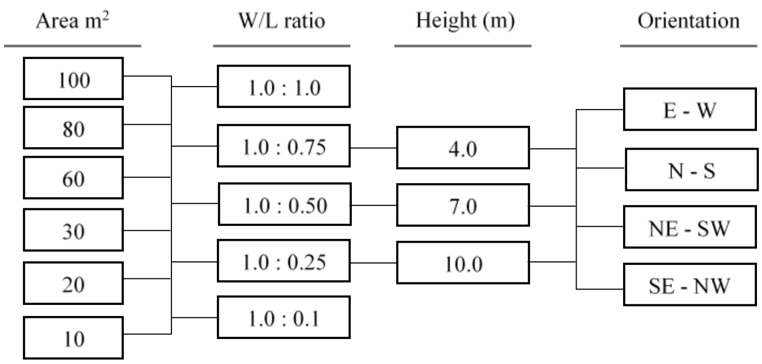

Figure 2. The matrix of the tested courtyard configurations

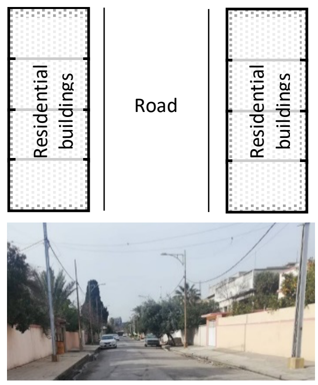

Figure 3. Typical street urban space of Baghdad

To determine occupants' thermal sensation and assess the thermal conditions of courtyards and the considered typical street space, Tg was used as a thermal comfort index. It has been defined by previous studies to be of true representation of people's actual thermal sensation [16; 17]. Its value includes the combined effect of air velocity, Mean Radiant Temperature (MRT) and air temperature. For this reason, these three factors were determined and considered by the research to have inclusive and comprehensive analysis for courtyards' thermal conditions [18].

For the simulation purpose, Envi-met 4.2 CFD simulation tool was used. This simulation tool has been widely adopted and validated by previous studies for the purpose of simulating microclimatic conditions of outdoor urban spaces, including courtyards. It depends on well-based physical and fluid dynamics rules and principles in considering the impact of wide-range effective factors on outdoor spaces' environments, which is not offered by other similar simulation tools [19; 20; 12]. The simulation models and configurations were built depending on this research's objectives and with considering settings of an appropriate calibrated simulation model developed by a previous study [21] (Table 2), (Figure 4), (Figure 5).

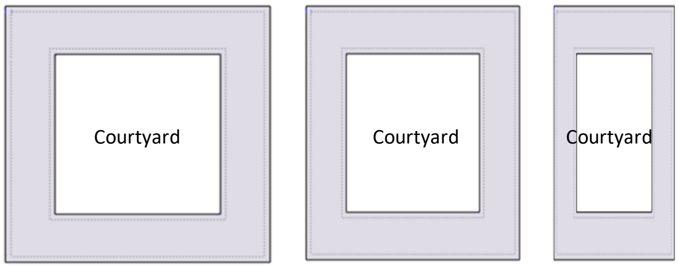

Figure 4. Three examples of the simulated courtyard buildings

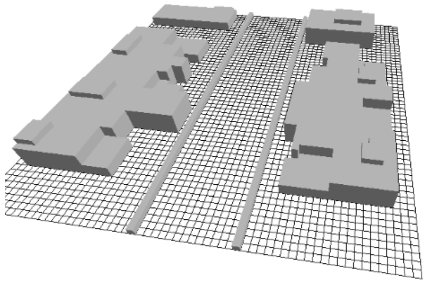

Figure 5. The simulated modern urban fabric model

Table 2. The simulation configurations and model's properties.

Simulation parameters	Input	Material parameters	Input
Start date	21-01-2017	Thickness	0.30 m
Start time	00:00:00	Absorption	0.80 Frac.
Simulation time	32 (hours)	Transmission	0.00 Frac.
Output interval	30 (minutes)	Reflection	0.05 Frac.
Wind speed	2.7 m/s	Emissivity	1.10 Frac.
Wind direction	North East	Specific heat	1300.0 J/(kg*k)
Roughness length	0.01	Conductivity	0.30 W/(m*k)
Max air Tem. and time	13.5 ºC at 16:00	Density	1000.0 kg/m^3
Min air Tem. and time	2.0 ºC at 05:00		
Max Hum. and time	83% at 04:00		
Min Hum. and time	52% at 14:00		
Lateral boundary conditions	Cyclic		

Notes

- Relevant meteorological data were taken from the Iraqi Meteorological Organization[22]
- The first six hours of simulation results were not considered as the impact of the stored heat in buildings on night thermal conditions is missed
- All of the not mentioned software's parameters were kept as default.
- Having the wind from directions other than North East might change the simulation results.

3. Results

The results showed that the courtyard space is warmer than the street space in winter and that changing courtyards geometric properties significantly affect their thermal conditions (Figure 6). The difference in Tg between the various tested courtyard forms can reach 20 °C. A warm courtyard's Tg can be up to 30 °C higher than a typical street urban space.

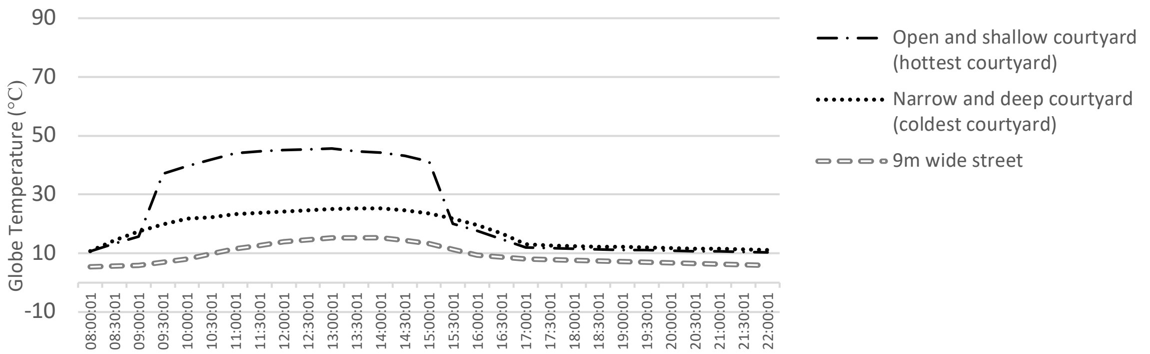

Figure 6. Winter day's hourly Tg in cold and hot courtyards and in the tested street space

To have a comprehensive analysis of the factors that affect courtyards' thermal conditions and having them warmer than a street space, the research carried out statistical analysis using IBM SPSS statistics 24 (Table 2). The analysis showed that the Tg differences between courtyards of different geometric configurations result from the impact of changing courtyards' geometric properties on their MRT, which results, mostly, from having different shading levels (Table 2). According to this research's results, Tg is significantly affected by both MRT and air temperature (Table 2.A). However, the former is highly affected by changing the courtyard geometry, which is not applicable to the latter (Table 2C., 2D). Air velocity is affected by changing the courtyard geometry, but it has very limited impact on Tg in courtyards comparing to the other two microclimatic factors (Table 2.E, 2A). The most effective geometric property on Tg is W/H ratio and least effective one is the courtyard orientation. According to these results, it can be summarized that a courtyard's Tg increases by decreasing its height, increasing its area and W/L ratio, and having its long axis along the north-south orientation (Table 2.B).

Table 2. The correlation analysis of the research variables

A. The correlation analysis between Tg and the three relevant microclimatic factors

	MRT	Air velocity	Air temperature
Pearson correlation	0.979	0.024	0.861
Sig. (P-value)	0.000	0.000	0.000

B. The correlation analysis between courtyard geometric properties and Tg

	Courtyard area	Courtyard orientation	W/L	W/H	P/H
Pearson correlation	0.044	-0.024	0.027	0.077	0.049
Sig. (P-value)	0.00	0.00	0.00	0.00	0.00

C. The correlation analysis between courtyard geometric properties and air temperature

	Courtyard area	Courtyard orientation	W/L	W/H	P/H
Pearson correlation	0.009	0.007	0.018	0.027	0.017
Sig. (P-value)	0.350	0.475	0.063	0.005	0.085

D. The correlation analysis between courtyard geometric properties and MRT

	Courtyard area	Courtyard orientation	W/L	W/H	P/H
Pearson correlation	0.151	0.047	0.084	0.231	0.158
Sig. (P-value)	0.000	0.000	0.000	0.000	0.000

E. The correlation analysis between courtyard geometric properties and air velocity

	Courtyard area	Courtyard orientation	W/L	W/H	P/H
Pearson correlation	0.349	0.093	-0.229	0.156	0.386
Sig. (P-value)	0.00	0.00	0.00	0.00	0.00

Pearson correlation	Defines the strength of correlation between two variables and ranges between (+1) to (-1). The closer the value to 0.0 the weaker relationship. The (+1.0) refers to a perfect positive relationship and (-1.0) refers to a perfect negative relationship.
Sig. (P-value)	Determines the statistical significance of the correlation between two variables. Its value ranges between 0.0 and 1.0. The closer the value to 0.0 the stronger evidence of the correlation. Typically, P-Value <0.05 indicates strong evidence that the correlation is considered statistically significant between variables.

Regarding the reason behind having Tg higher in courtyards than in the open street urban space, the results indicate that it is because of the air velocity. The modern urban fabric's outdoor space is open, which allows higher air velocity than the examined courtyard spaces. Between the two compared simulation scenarios, the air velocity in the modern urban fabric's space can be ten times higher than the air velocity in the courtyard space. This is applied, with various degrees, to all of the tested courtyard geometries (Figure 7). However, this performance resulted from that all of the tested courtyard cases in this study are of ratios that enable them to properly blocking the wind. The statistical analysis in Table 2 shows that air velocity increases by increasing the courtyard area and decreasing its height. Accordingly, if the courtyard space is designed to be of a larger area and a lower height than an alternative street space, the results might be different. Having this said does not mean that increasing the courtyard area and decreasing its height is always negative. Using these two properties can be of great importance to get more solar radiation, and as a result warmer environment. Therefore, it is essential to design courtyards' geometry by considering balancing air velocity and MRT to get the best possible results.

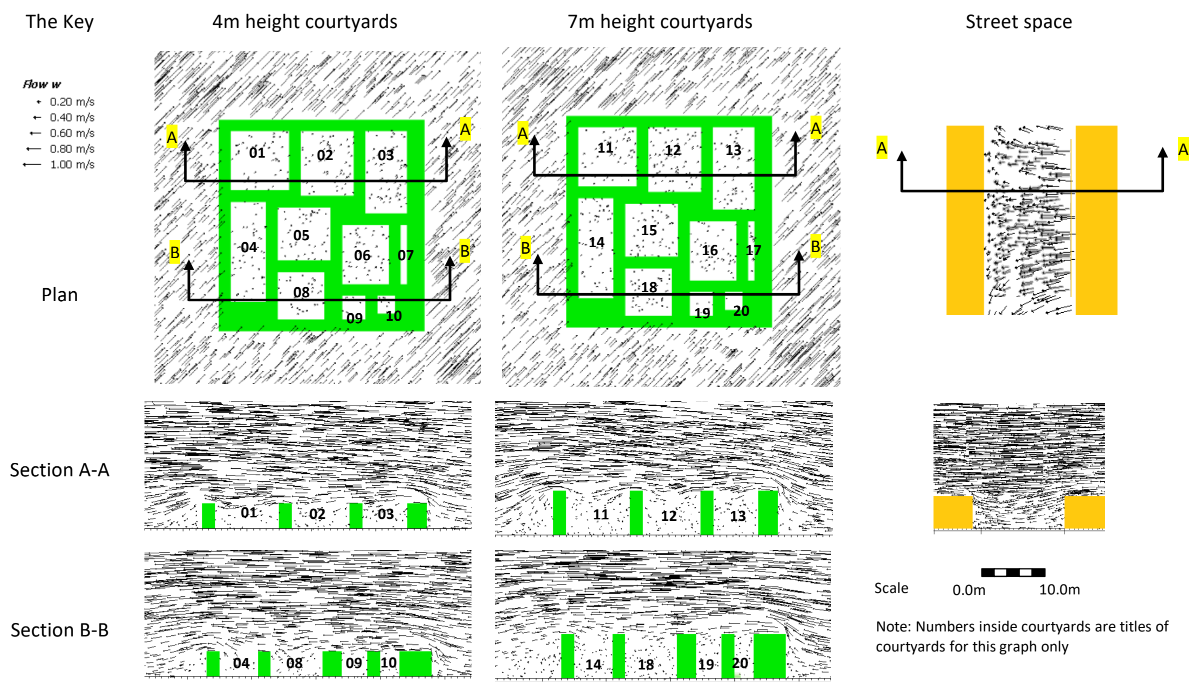

Figure 7. Air velocity inside twenty different courtyards and a street space (Envi-met 4.2 simulation)

These results suggest that the courtyard space can offer a warmer environment than modern open urban spaces through protecting spaces and buildings from the wind whilst keeping sufficient exposure to solar radiation. Comparing this study's results with previous literature shows that its findings are highly reasonable. Regarding the significance of impact of each of the three microclimatic variables on people's thermal sensation, studies have confirmed that the most effective factor in outdoor spaces is MRT, which is applied to courtyards [23]. Air temperature has been identified as an effective factor, but not to be considered as a strategy by designers as it is difficult to get it mitigated in outdoor spaces [24]. MRT can be highly affected by working on spaces exposure to solar radiation. This can be done in courtyards by changing its geometric properties, especially its height [13; 25].

Finally, these results need to be taken with considering that they only focus on air temperature, MRT and air velocity. They do not indicate the impact of rain and snow, which are other factors that affect courtyards' microclimatic conditions.

4. Conclusions

This study worked on determining the potential thermal efficiency in courtyards in cold conditions. It used Envi-met 4.2 simulation tool to test and compare 360 courtyards with a typical street urban space in Baghdad during winter conditions. The results show that courtyards can offer a warmer environment than open urban spaces through, mainly, blocking the wind. The smaller and deeper the courtyard the higher protection from the wind, but also the less exposure to the solar radiation. Accordingly, designers need to consider having a balance to get the maximum solar radiation and the minimum air velocity, which will enable having the best possible thermal performance.

Acknowledgment

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