PLEA 2017 EDINBURGH
Design to Thrive

Microclimatic conditions of internal courtyards in warm climates and their influence in eco-efficient construction

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Abstract: A reduced shape factor of the building has become a general recommendation in order to achieve eco-efficient architecture in any climate in spite of the fact that it was made to be applied to cold climates. As a result, this pattern of compact shapes is widespread all over the world. However, it is based on a simplified model of the interaction of architecture with its environment in which the air surrounding the building is considered to be at the same temperature. Nevertheless, this paper will show that in climates such as the Mediterranean, the existence of microclimates induced by the building itself, for instance inside internal courtyards, indicate a more dynamic interaction. In spite of a higher shape factor, more complex shapes can be explored that take advantage of these microclimates to achieve more eco-efficient buildings.

Keywords: microclimates, shape factor, Mediterranean climates, courtyard, eco-efficiency.

Introduction

The most efficient strategies for increasing eco-efficiency in buildings are those adopted in the early stages of design (Olgyay & Olgyay 1963). The shape of the building, the most prominent aspect of the architect's responsibility, is one of these. It would therefore be useful to provide clear and simple criteria to be used by architects to orientate them from the first sketches. Unfortunately, it is not this simple as we will show in this document.

One of these criteria is the shape factor that relates the envelope of the building and its interior volume ($F_f=S/V$). Widespread recommendations on energy-efficient building design, such as, "Passivhaus primer: Designer's Guide" (International Passive House Association 2014) advise reducing the envelope transmittance as well as reducing the surface to volume ratio of the building. That is to say, they suggest compact designs that reduce the shape factor. The objective is to limit the energy flow, preserving the largest quantity of energy possible in the interior. It is true that the recommendations, such as Passivhaus, permit greater shape factors but in exchange for an uneconomical increase of insulation.

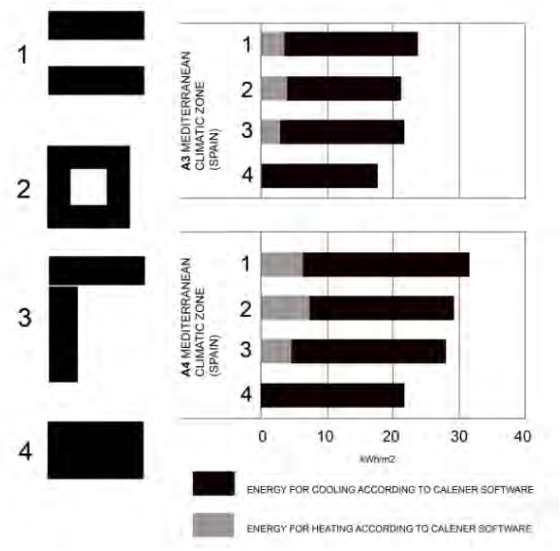
In spite of the fact that it was created for cold climates, this simple paradigm has been imposed by different administrations in many countries with warm climates (Spain being among them), by means of laws, criteria for public tenders or mandatory energy ratings.

This has led to the increasingly widespread appearance of buildings with very simplified shapes. Designing buildings with the shape of very compact boxes, cylinders or spheres is considered a good solution to guarantee better energy efficiency. This condition in current architectural design in both warm and cold climates may result in architecture with more complex shapes and spaces like internal courtyards becoming less common. Several authors express doubts about the validity of this shape factor for warm climates (Depecker et al. 2001) and even for colder climates (McLeod et al. 2013; Sameni et al. 2015).

Hypothesis for homogeneous outside temperature

The recommendations that limit the shape factor are based on physical principles taken into account in energy simulation programs. The energy exchange with the outside is transmitted through the building surface, the envelope. Therefore, limiting this exchange, by decreasing the surface of a given volume, can help to maintain the difference in temperature between the inside and outside with less energy consumption.

Energy simulation programs, such as EnergyPlus TM, that assume these principles have served as the basis for numerous scientific papers (Gratia & De Herde 2003). This scientific information was used in turn to justify the recommendations and energy regulations which favour the restriction of shape factor. Official programs for the mandatory evaluation of energy performance certificate for buildings, such as Lider-Calener in Spain, use the same approach, favouring more compact designs for buildings (Díaz Guirado & Allepuz Pedreño 2016), that is to say, with a lower shape factor in the warmer regions of Spain (Fig. 1a).



	Outdoor conditions simulations	Simulations using CFD	Free of charge software	Open sauce	AutoCad BIM / Sketchup import
Lider-Calener			🟩		🟩
ANSYS Fluent	🟩	🟩			🟩
DesingBuilder	🟩	🟩			🟩
Ecotect Analysis	🟩				🟩
SUNtool	🟩		🟩		🟩
Solene	🟩		🟩		
RayMan	🟩		🟩		
URSUS	🟩		🟩		
GreenCanyon	🟩	🟩	🟩		
EnergyPlus		🟩	🟩	🟩	🟩
ENVI-met	🟩	🟩	🟩		
Software using FreeFem++	🟩	🟩	🟩	🟩	

a

b

Figure 1: a) Energy for cooling and heating different building shape with same volume according to Lider-Calener (official Spanish software). b) Comparative analysis of different energy calculation software.

At this point, an important issue arises: the bases for calculation of these programs accept the hypothesis that there exists only one external reference temperature for the Outside Surface Heat Balance in any weather. In cases such as EnergyPlus, they allow a reduction in the outside temperature when increasing the height of the centroid of the thermal zone/surface, at a rate of about 1ºC per 150m of height (The Ernest Orlando Lawrence Berkeley National Laboratory 2015). Therefore, these simulations assume the existence of a homogeneous exterior space that allows the adoption of a simplified exterior-interior heat transfer model.

Different energy calculation software has been analysed (Fig. 1b). Despite the fact that some of them, such as EMVI-met or Green Canyon, allow an approximation of different aspects of microclimatic behaviour in courtyards, only original numerical simulations with FreeFem++ have been able to calculate a precise difference in air temperature from that of the air temperature outside (Rojas-Fernández et al. 2012).

Experimental

To verify precisely if there is a single homogeneous exterior temperature, as most programs assume, a monitoring campaign has been developed, analysing real existing buildings in Andalusia (Spain). The outdoor spaces selected are very characteristic of the architecture in the area: courtyards (Fig. 2). The buildings are located in Córdoba and Málaga, constituting a good representation of different variants of the Mediterranean climate in Spain. Courtyards of different sizes and types have been chosen. Wind speed and direction, surface temperature of walls, boundary layer temperature, humidity and temperature, simultaneously in different parts of these spaces and on the roof of the buildings, have been recorded. The data loggers are specific for measuring outdoor temperatures and have been protected from the direct incidence of solar radiation.

a

b

Figure 2a,2b: Courtyard studied in the present research: a) 17th Century building, Córdoba, Spain. b) Contemporary hotel in Málaga, Spain (Hombre de Piedra Architects).

Measurement campaigns were conducted between June and October, repeated over three consecutive years and a week was recorded for each courtyard.

Results

The distribution of the temperature drop from the outside in the courtyards of Cordoba and Malaga are shown in the following figures.

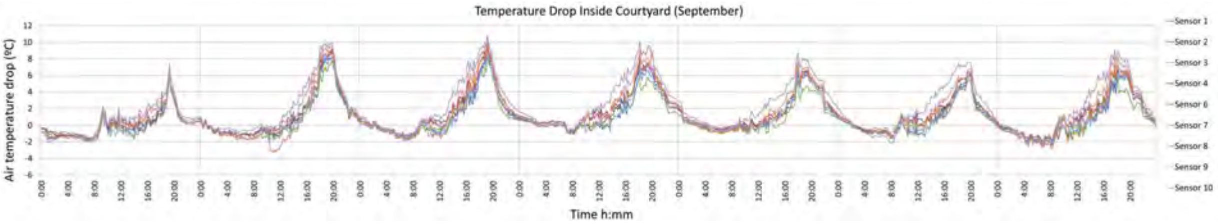


Figure 3: Temperature drop in the Córdoba courtyard from outside temperature.

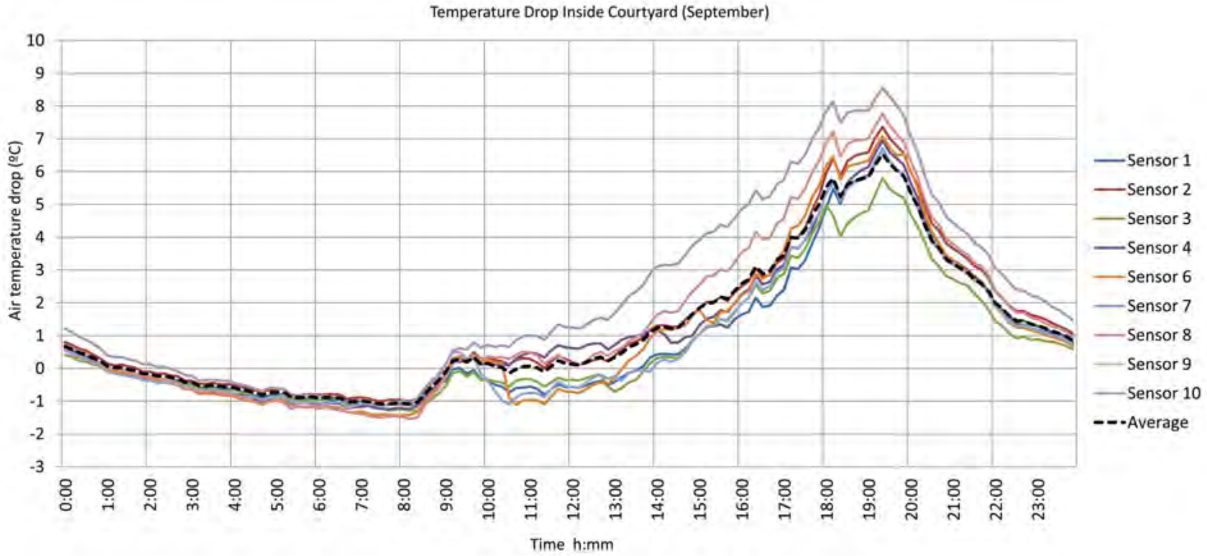


Figure 4: Average temperature drop in the Córdoba courtyard from outside temperature

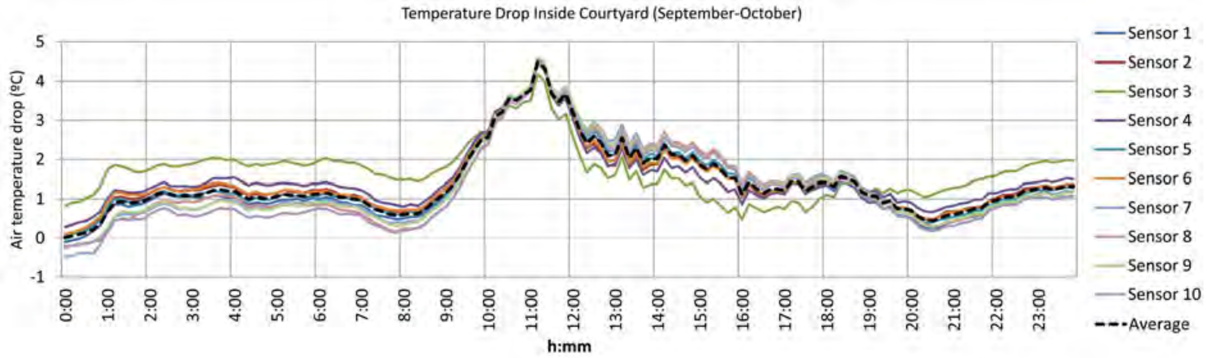


Figure 5: Average temperature drop in the Málaga courtyard from outside temperature.

Figures 4 and 5 show the average air temperature differences at every hour of the day between the inside and the outside of the courtyard over a week. The behaviour of the courtyards is more remarkable if we observe only the evolution of the temperatures in the ground floor. This floor is the most interesting because it is normally where Mediterranean buildings are most open to the courtyard and as such is where the majority of air is taken in. It is also the level where this space is used and inhabited. Figure 6 shows, in the case of the courtyard in Cordoba, air temperatures outside and inside the courtyard for a given summer week (June). During the day, lower temperatures were recorded inside the courtyard than outside.

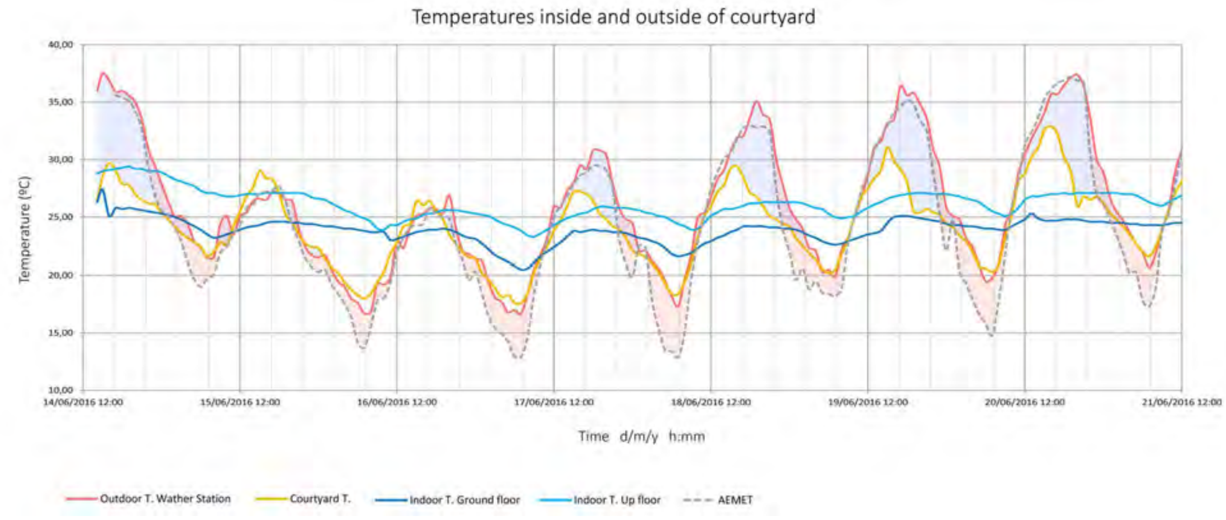


Figure 6: Registered temperatures inside and outside the ground floor of courtyard, Córdoba, Spain.

The external thermal sensor shown in figure 6 (red line) is on the roof of the building as a part of the weather station. In spite of the fact that this sensor is specially shaded and ventilated, we had to be sure that it wasn't recording the effect of the high radiations that is typical in this climate, in addition to air temperature. For this reason, the record of our sensor was compared to the air temperature record on this day in Córdoba by the Official Spanish Agency of Meteorology (AEMET. Gobierno de España 2016). On one hand, this is the most reliable source of meteorological data. On the other hand, we must take into account that this official weather station is not located in the centre of Cordoba, where the studied building is, but at the airport, situated 6.94 km away in the outskirts of the city. It can be observed that the maximum temperatures recorded by our sensor are very similar to the temperatures recorded by the official AEMET weather station at the airport. This clears any doubts about overheating in our weather station. However, the minimum temperatures recorded by our sensor are higher than those recorded at the airport. This is as a result of the well-known Urban Heat Island Effect.

The experimentation campaign shows the dynamic thermal relation between the walls of the courtyard and the air confined between them. Comparative measurements have been made between the surface temperature of the building walls and the air in contact with them in the courtyard space. Therefore, two sets of thermocouple probes have been placed, some in contact with the wall to measure the surface temperature and others in the space in front of it 10mm away to measure the air temperature in the layer of air in contact with the wall (boundary layer). These measurements will allow us to check the direction of heat flow between the inside and outside of the building. The results obtained are shown below.

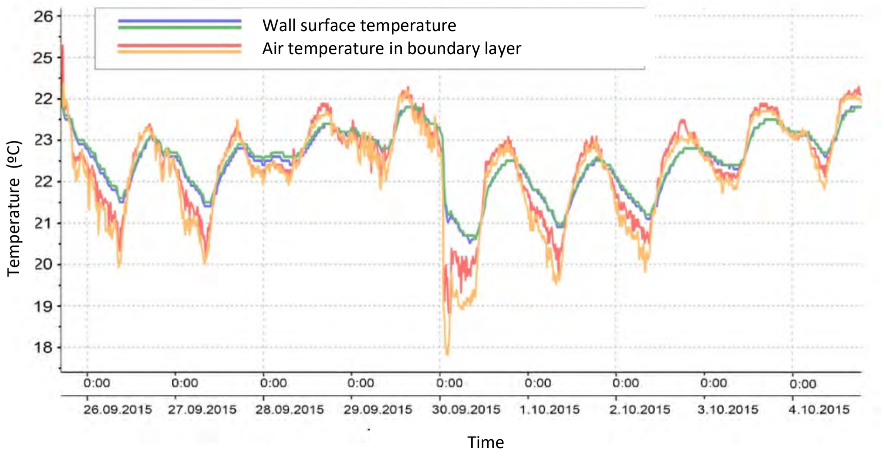


Figure 7: Wall Surface temperature and air temperature in the air layer in contact with the wall (boundary layer temperature) in the courtyard of Málaga, Spain.

At this time of the year, the outside air temperature at night is always lower than the surface temperature of the wall (sometimes up to 3ºC lower as shown in the peak for figure 7). Therefore, in these Mediterranean climates, the considerable difference in night temperature allows the building to lose heat to the outside by conduction, convection and radiation through its envelope.

Discussion

It can be observed that courtyards, mainly in Mediterranean climates, generate a microclimate, in which the temperatures differ from that of other external areas around the building. The maximum average difference for the building in Córdoba, with this climate and this time of year, was found at 19:00 solar time and reached more than 8°C (Fig. 4). This is consistent with the differences recorded by other research (Alvarez 2001). It is remarkable that it is around this same time that the outside temperatures reach their maximum. For this reason, the positive effect of a courtyard's microclimate on the building is more significant. There is also a drop in temperature in the courtyard in Malaga (Fig. 5) although it is somewhat lower because the outside temperatures were lower than in Córdoba (Fig. 4). Due to the milder climate in Malaga and the different architecture of the patio, the maximum difference of 4.5 °C occurs in the morning. The parallel evolution of temperatures at different heights in the Córdoba courtyard (Fig. 4) shows the existence of a stratification phenomenon. Figure 6 shows a very clear thermal pattern inside the courtyard with remarkably lower temperatures than outside during the day. These differences are going to disappear at nightfall. In fact, the graph shows that sometimes the courtyard temperatures can be a few degrees higher than outside during the night and early morning. It is also necessary to highlight the stable evolution of the interior temperature in the ground floor of the building and first floor (dark blue and light blue respectively) that are within the range of comfort in this naturally ventilated building. The effect of the courtyard can contribute considerably to the positive behaviour of the interior temperatures. The differences between day and night temperatures are remarkable. In the airport, this difference reached 23.1ºC and a few degrees lower around the studied building where it reached 17.3ºC. This means that in this warm climate there are opportunities to propose designs that favour heat transfer during the night by conduction, convection and radiation. For instance, one possibility could be to design a low, compact form to allow wider and closer contact between buildings and the outside environment. Figure 7 shows, in the courtyard, this heat flow between the inside and outside of the building.

The data shows that the actual behaviour of the air in these climates is complex due to its interaction with the architecture. Thus, it is not correct to consider that all the surroundings of a certain building in any climate are exposed to the same conditions and outside temperature. The exterior temperature around the building is not homogeneous due to existing microclimates like those in courtyards. There are other phenomena around buildings that also generate well-known microclimates in warm regions such as urban canyons (the narrow streets of Mediterranean cities) and microclimates generated by vegetation (evapotranspiration phenomenon), amongst others. The results obtained lead to reconsidering the preciseness of conventional energy simulation models. By not contemplating the existence of these microclimates, most widespread conventional energy simulations are not able to balance the importance and potential of these spaces. Moreover, in these simulations, the introduction of spaces such as courtyard results in a poorer energy performance of the building by increasing the facade surface without taking into account any of their advantages. Nevertheless, designs with low shape factor and over-insulation are at risk of overheating, both in Mediterranean climates and even in colder climates.

Conclusion

In light of the experimental results, it is possible to conclude that designing courtyards in Mediterranean buildings has the following advantages:

- To allow the creation of outdoor spaces with microclimates that moderate temperature. These microclimates have been traditionally used in a passive way to improve the performance of these buildings. However, it is also possible to use this technique in contemporary designs, introducing this fresher air in the air conditioning system and improving the energy performance of the building. To evaluate this, a better quantitative knowledge of these phenomena is required.

- To provide a bigger surface for heat transfer to the surrounding environment during the night. This is done both by conduction through the air in contact with the walls and by radiation, releasing heat into the typically cloudless night sky of these climates. In contrast to this, exposing more facade surfaces could assume a greater heat gain during the day, especially under the incidence of solar radiation. However, covered shapes can be designed to enable many of these walls to be sufficiently shaded during the day.

- To improve ventilation conditions, avoiding overheating. Complex shapes and courtyards allow smaller widths of the interior spaces of buildings, facades at different orientations with different wind pressure and temperature conditions, and all of these favour the possibilities of cross-ventilation.

- Last but not least, in Mediterranean climates, the architecture of more complex shapes and courtyards is usually more interesting and provides a more satisfactory human experience by keeping contact with nature. This improves the adaptive thermal comfort (Nicol et al. 2012) and saves energy by keeping the air conditioning off for longer.

The development of precise energy tools to be used during a buildings inception is a priority for achieving energy efficiency. The present study highlights the fact that, as long as more sophisticated tools are not integrated in building design, general recommendations such as a reduced shape factor do not have validity in warm climates, due to the complex interaction of shape and climate. These over-simplified techniques can even be harmful when attempting to achieve higher eco-efficiency in construction: they increase the risk of overheating and create a strong paradigm that complicates the exploration of new innovative strategies based on more complex shapes, for instance by using internal courtyards and their microclimatic conditions.

Acknowledgments

This work has been supported by the Andalusian Government Research project TEP-7985 and the National Government Research project of Spain MTM2015-64577-C2-2-R.

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