Evaluation of the thermal performance of traditional courtyard houses in a warm humid climate: Colima, Mexico

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Abstract

With the recent need to decrease the use of energy and promote indoor thermal comfort in overheating conditions, attention has been drowned on the passive cooling function of courtyards. This paper aims to determine the effect of proportions and orientations of courtyards on the indoor thermal performance of traditional houses in a warm, humid region so that this could guide further improvement and reinterpretation of this building type. The results of this parametric study were obtained through computer simulations of different cases. Rather than promote passive cooling in the building, the findings suggest that the courtyard greatly increases solar heat gain, raising the temperature during the day. Higher solar heat gains and ventilation rates were observed in the courtyard cases with greater width and length. Nevertheless, this does not cause important differences in the average operative temperature of the entire building between the cases. As for orientation, lower heat gains were obtained in courtyards with the long axis-oriented east to west. Regardless of the cases, the study finally emphasizes the importance of the inhabitants controlling the opening of windows in the enclosed rooms since this could decrease the temperature by 1.1ºC from night to the early morning (23.00 hrs to 11.00hrs) and thus influence its thermal comfort. Conversely, opening the windows outside that time-lapse could cause an increase in temperature and more hours above the upper comfort limit.

1. Introduction

Emissions from human activities have driven global warming and climate change observed in every region globally. The phenomena related to this problem have strengthened over time, and unless substantial reductions in carbon dioxide (CO2) and other greenhouse gas emissions occur soon, global warming of 1.5°C and 2°C will be reached during the 21st century [1]. As emissions from the residential, commercial, and energy sectors contribute the most to the problem [2], they also have the greatest potential for reducing it. For example, applying passive approaches in buildings can lead to maintaining indoor air temperature in a comfortable range and reducing the use of fossil fuels for cooling or heating requirements, consequently reducing greenhouse gas emissions [3]. In addition, the use of natural ventilation in buildings and other passive strategies could lead to immediate health benefits, such as reducing the risk of airborne disease transmission and accumulation of indoor pollutants [4].

The courtyard form has been used in traditional dwellings in different climatically and culturally regions of the world [5]. This form has functioned as a passive architectural design strategy that can create a microclimate to control air wind, sunlight, temperature, and relative humidity that enters the building, thus influencing its environmental performance. Compared with other urban forms, the courtyard form has shown a better thermal response depending on climate [6] and less annual energy demand [7]. Furthermore, courtyards can encourage a variety of favourable conditions for human comfort in various spaces of the house with daily and seasonal changes that allow the residents to move within their houses, seeking a better thermal situation [8]. Also, from the perspective of airborne disease control, optimal architectural design in courtyards greatly influences air pollutant concentration and infection risk [9].

Regarding the suitability of courtyards as a passive design strategy, some researchers have carried out comparative studies of their thermal performance and thermal comfort under different climatic conditions [10–13]. Their results, mostly obtained through computer simulation, indicated that the performance of courtyards varies from one climate to another depending on the configuration of its design variables like shape, orientation, proportions, number of floors, glazing type and glazing area ratios.

1.1 Courtyards in warm humid climates

Although the courtyard form could be suitable in all climates, it is more energy efficient in hot-dry and warm-humid climates than in temperate or cold climates [12]. Traditionally courtyard houses have been related to hot-dry climates. At a time when mechanical alternatives were not available, this building form was the best available option to enhance passive cooling in these hostile environments (Abdulkareem, 2016). For that reason, the thermal performance of courtyards has been widely studied in hot-dry climates [14–26]. *Nevertheless*, building design and construction strategies differ in warm-humid climates. The main requirements for these environments are promoting continuous and efficient ventilation, protecting from the sun, avoiding increases in internal temperature during the day, and lowering the temperature at night [27]. According to this, an effective passive cooling design should consider the effect of natural ventilation [28] and the solar radiation exposure of the residential typology [29].

Courtyards inside houses increase exposure to solar radiation as well as to wind flows. Compared with other building types, courtyards have a higher surface to volume ratio, indicating the building envelope surface is exposed to the outside environment. Therefore, a higher surface to volume ratio increases the potential for natural ventilation and daylighting as well as the exposure to heat gain during summer and heat loss during winter [6]. This consequently modifies the thermal performance of the courtyard and its adjacent areas. Appropriate design in warm-humid regions should explore the relationship between enhancing natural ventilation when needed and protection from solar radiation and heat gains. Regarding this, previous studies have explored proportion [11, 13, 30–35], orientation [11, 31, 36] and openings configuration [37] as critical design variants to enhance better thermal performance and thermal comfort. Likewise, it has been emphasized that the composition of the building's design allows cross-ventilation between two courtyards [38] or a courtyard and the street [39] to influence the heat losses of the building envelope and promote thermal comfort for the inhabitants.

As proportions between the length, height and width of courtyards determined its openness, several studies have addressed this variable in diverse ways. Most of them agree that proportions width-to-length and width-to-height greatly influence thermal performance because they condition the amount of solar exposure this space receives. Different ratios between the width and length of the courtyards have been proposed. Muhaisen states that almost any length in courtyards will be suitable for a warm, humid location close to the equator, where providing shading in summer is as important as having a sunlit area in winter [11]. Meanwhile, Almhafdy et al. stated that a plan aspect ratio of 1:2 (Width/Length), which is a rectangle with a length twice the width, has higher air velocities and better thermal performance than a squared courtyard plan with an aspect ratio of 1:1, in U-shape courtyards [30]. On the contrary, other authors found that the least solar radiation gains and irradiation were observed in the square courtyards in comparison to rectangular ones [13, 31].

Moreover, the results of Kubota et al. showed that the daily maximum air temperature in internal courtyards could be explained using the sky view factor (SVF) and the height of the courtyard [32]. Muhaisen established that better thermal performance was obtained by increasing the number of stories [11]. This coincides with the findings of Almhafdy et al., whose results stated that an increment in the height of the courtyard enclosure reduces air temperature [33]. Similarly, Rodriguez-Algeciras et al. determined that the duration of excessive direct solar radiation decreases with higher height-to-width aspect ratios [31]. However, these studies do not consider natural ventilation and its important role in this climate. In this regard, Tablada affirms that aspect ratios (Width/Height) of 1.0 and 0.7 can promote better ventilation because their geometry causes the development of a strong vortex and high-velocity magnitudes [34]. Reynolds also concluded that courtyards with a low ratio between floor area and height will be much more open to the airflows but much more exposed to the sun [35].

Regarding orientation, some authors agree that better thermal conditions were observed when orienting the long axis of the courtyard along northeast-southwest [11, 31] and east-west [36]. On the other hand, some researchers highlight the importance of airflow patterns due to the temperature differences during the day [38] and the opening's configuration [37].

1.2 Traditional courtyard houses in Colima, México.

Mexico has plenty of examples of environmentally responsive traditional architecture that include a variety of semi-outdoor spaces like courtyards that enable connection with the exterior. With recent needs in the housing sector, traditional building techniques and typologies have been replaced with newly industrialized ones. In many mass housing developments around México, the use of new building systems has led to an increase in the heating and cooling demands as well as the level of dissatisfaction of the occupants concerning indoor thermal comfort conditions [40].

Regarding traditional houses of Colima in western México, they are characterized by having a central courtyard scheme. Their origins are mostly related to the influence of Spanish culture but have undergone various adaptations to its environment [41]. Currently, many traditional houses have been demolished, abandoned, transformed, or, in the best of cases, they have been rescued as public spaces for cultural activities since their functional qualities as houses correspond to a way of life different from the present time [41]. This has caused the loss of this heritage as well as its values, which could be reinterpreted in contemporary architecture.

According to Meir et al., traditional architecture should not be considered inherently adapted to its natural environment since it could lead to improper reemployment and may cause extreme consumption of energy [42]. In the case of traditional houses of Colima, they present their own regional characteristics that may be suitable for the climate but need to be evaluated. For this reason, the current study proposes systematic research to understand better the thermal performance of this traditional courtyard housing on its climate so that it could guide further improvement and reinterpretation of this building type. Likewise, through the review of the literature, it was identified that indoor thermal performance in courtyard houses of warm, humid climates has been less studied, which indicates the importance of this research. In addition, previous research has provided a background to support that courtyard's proportions have a great effect on ventilation, solar radiation, and heat transfer, and thus in the thermal performance of the courtyard and its immediate spaces. Therefore, the aim of this paper is to determine the effect of proportions and orientations of courtyards on the indoor thermal performance of traditional houses in a warm, humid region.

2. Methodology

The research was carried out through computer simulation in two phases. First, a validation of the simulation model was performed using field measurements of an actual courtyard house. Spaces with different locations inside the house were considered to obtain more accurate results. Secondly, different cases were proposed taking as a reference the courtyard house model of the first stage. This last phase is a parametric study through computer simulation that evaluates courtyards design and its influence on the indoor thermal performance of the building in a warm, humid climate. The details of each stage are explained below.

The courtyard houses are located at Colima's downtown, at 19° 14' N, 103° 43' W and 484 m above sea level. According to Köppen's classification, it is an equatorial savannah climate with dry winter (Aw) [43]. This is defined by elevated temperatures and high levels of humidity. The average annual temperature is 25.5°C with 14°C thermal swings and annual rainfall of 970mm (SMN)[44].

Previous to computer simulation, morphological and typological characteristics of traditional courtyard houses of Colima were identified through a review of the historical evolution and field sampling. The field sample consists of 50 courtyard houses to which it was possible to access and gather information. These houses are from the XVIII and XIX centuries and are characterized mostly by one storey with a rectangular or square central courtyard, surrounded by corridors that are immediate to the enclosed rooms. The length of the courtyards obtained by field sampling varies from 4.5 m to 22.6 m and the width from 1.7 m to 26.6 m. The possible facade orientations are northwest, northeast, southwest, or southeast due to the urban layout that forms an orthogonal grid with an approximate inclination of 45° from the north. The materials of the houses depending on the period they were built and if they had subsequent transformations. The walls are mainly made of adobe or brick with thicknesses ranging from 0.4 m to 1.1 m. The roofs were originally sloping made of wood and tile, but later the use of flat roofs increased, and even materials such as reinforced concrete was applied.

2.1 Calibration phase

DesignBuilder was selected for the computer simulations. It is a graphical interface for EnergyPlus, which was developed by the US Department of Energy [45]. The aim of this phase was to validate the accuracy of DesignBuilder simulation software for the parametric study. For this validation, a traditional courtyard house was selected. Through field measurements, the air temperature results from different spaces were obtained and compared with the ones of the simulation program.

The house selected is a representative courtyard house in Colima. Dates from the XIX century but has had interventions after its time of construction. The courtyard, placed in the centre of the building, is a square plan with an area of 110.25 m2 and is surrounded by corridors on each side. The house has one storey with a height of 4.5. It is naturally ventilated; therefore, no heating or cooling systems affect the temperature. The field measurements were carried out from May 29 to June 1. The air temperature was measured at hourly intervals with Onset Hobo dataloggers with an accuracy of ± 0.35°C. One datalogger was placed at the volumetric centre of each of the four corridors with orientations northeast, northwest, southeast and southwest (Fig. 1). These spaces were selected because they are immediate to the courtyard and are also more exposed to the effect of outdoor conditions. Additionally, to develop a text-based weather file for this phase, outdoor temperature, humidity, solar radiation, wind speed and direction were registered hourly using a datalogger MicroStation model H21-002a with four channels for external sensors.

The weather input file for the simulation was developed by using hourly data from the field measurements and a text-based file generated in Meteonorm software. This software calculates hourly data of all parameters from reliable data sources and sophisticated calculation tools. The weather input file corresponds to typical years from 2000–2010, which was the most recent period available in the software. In this file, the hourly results from the field measurements were implanted.

Likewise, a template was generated with the construction materials of the house. The construction system consists of brick walls and reinforced concrete flat roof, with wooden beams and clay tiles in the interior layer of the corridors. For the simulation model, convective heat coefficients were fixed for walls at 22.7 (W/m2-K) for the external surface and at 8.29 (W/m2-K) for the internal surface. Likewise, they were set for roofs on 22.7 (W/m2-K) and 6.13 (W/m2-K) for external and internal surfaces, respectively. The material properties and U-values were set up in Designbuilder as follows:

Table 1
Material properties used in the simulation

Materials	Conductivity	Specific Heat	Density	Thickness	U-Value	R-value
	(W/ m-K)	*(J / kg-K)*	*(kg/ m3)*	*(mm)*	*(W/m2K)*	*(m2K/W)*
	Walls:				**1.09**	**0.918**
Cement/ plaster /mortar	0.72	840	1760	15		
Brick-burned	0.85	840	1500	600		
Cement/ plaster /mortar	0.72	840	1760	15		
	Roofs:				**3.24**	**0.309**
Bitumen felt	0.16	1470	920	9		
Asphalt	0.17	1000	1050	5		
Concrete, Reinforced (with 2% steel)	2.5	1000	2400	100		
Clay tile	0.93	920	2300	40		
Wooden beams	0.12	1380	510	160		
	Floors:				**3.088**	**0.324**
Clay tile	0.93	920	2300	40		
Cast concrete	1.13	1000	2000	100		
	Windows:					
Single clear				3	5.894	
Wooden frame				60	2.059	0.486
	Doors:				**2.059**	**0.486**
Wooden painted doors	0.19	2390	700	60		

2.2 Parametric study

For this phase, a reference model and different cases were proposed. The reference model was established from the representative courtyard house of the field measurement. The house's spaces correspond to the central uncovered courtyard, the corridors that surround it and the rooms on the periphery. The criteria for design were to maintain the internal width of the corridors and rooms of 3.2 m and 4.7m, respectively (refer to Fig. 2). The height of 5 m also remained constant in all cases.

Fourteen courtyard building cases were proposed to study the indoor thermal performance varying in width, length, and orientation, including the reference model. Aspect ratios between width and length correspond to 1 if the courtyard plan is square and 2 or 0.5 in rectangular courtyard plans. When the height is considered, aspect ratios (Height/Width) range from 1 to 0.25, as the widths get higher than the height. Also, the buildings were rotated to consider the orientations North-South, Northeast-Southwest, East-West and Northwest-SouthEast (refer to Fig. 3). These cases were modelled in DesignBuilder with the characteristics of the material mentioned in Table 1. The type of windows was single clear (3mm) with wooden frames. The simulation was carried out in May, the month with higher temperatures and longer periods of overheating conditions. Models were naturally ventilated. Corridors had no glass openings in the courtyard, and the glass openings of the rooms were operated for analyzing different ventilation strategies.

2.3 Thermal comfort model

This study calculated thermal comfort limits based on the international standard ASHRAE 55-2017 [46]. The standard determines the acceptable indoor operative temperature ranges for most of the occupants of naturally conditioned spaces. As this is an adaptive model, it relates the temperature ranges to outdoor climatological parameters. The following equations were used to determine the acceptable operative temperatures boundaries:

Upper 80% acceptability limit (°C) = 0.31 x $t_{pma(out)} + 21.3$ Ec. 1

Lower 80% acceptability limit (°C) = 0.31 x $t_{pma(out)} + 14.3$ Ec. 2

Where $t_{pma(out)}$ is the prevailing mean outdoor temperature that shall be based on 7 to 30 sequential days before the day in question, these limits correspond to the range of 3.5ºC upper and lower the comfort temperature for the 80% of acceptability.

3. Results

3.1 Calibration process

To validate the accuracy of the model in Designbuilder, the two sets of hourly simulated and measured air temperature data were compared. The process consisted of analyzing the differences in the mean temperatures as well as performing statistical analysis with the coefficient of determination (R2), coefficient of variance of the root mean square error (CVRMSE), and the root mean square error (RMSE). The latter has been a statistician used as a reference to validate simulation models in different studies [36, 47].

The results of this process can be observed in Table 2. This corresponds to different corridors of the house with orientations southeast (SE), northeast (NE), southwest (SW) and northwest (NW). The differences between the mean temperatures of the measured data and the simulated model were 1ºC or less in all cases. The determination coefficients (R2), depending on the corridor, vary between .94 and .95. These values are close to 1, which determines the highest accuracy. Likewise, the values for CVRMSE in all cases are no greater than 4%.

Table 2
Differences and statistical data obtained by comparing simulated and measured air temperature results.

	South-east corridor (SE)	**North-east corridor (NE)**	**South-west corridor (SW)**	**North-west (NW)**
Diferences in Mean Temp. (ºC)	1	0.4	0.9	0.8
R^2 (Coefficient of determination)	0.94	0.95	0.94	0.94
CVRMSE (Coefficient of Variation of the Root Mean Square Error)	0.04	0.03	0.04	0.04
SD (Standard Deviation)	3.36	2.93	3.14	2.81
RMSE (Root Mean Square Error)	1.31	1	1.22	1.31
NSE (Coefficient of efficiency)	0.85	0.88	0.85	0.78
Performance rating (According to Ritter & Muñoz-Carpena)	Good	Good	Good	Acceptable

Additionally, to address the evaluation of the model's performance and reduce subjectivity for a proper interpretation, the method proposed by Ritter & Muñoz-Carpena, which combines three assessment tools, was used [50]. The first tool consists of scatter plots to visually examine the performance of the model by looking at the agreement between the calculated and the observed values (Fig. 4). The second refers to the RMSE to quantify the prediction error in terms of the units of the variable calculated by the model.

Finally, the third corresponds to the coefficient of efficiency (NSE) of Nash and Sutcliffe, as an indicator of the goodness of fit obtained with the standard deviation (SD) and the root mean square error (RMSE), as follows:

$$NSE = 1 - \left(\frac{RMSE}{SD}\right)^2 \text{ Ec. 3}$$

From these tools, the authors propose four performance classes of the models as a guide on the ranges that indicated the performance as unsatisfactory, acceptable, good, and very good [50]. As is shown in Table 2, with the values calculated through this methodology, it was possible to evaluate the performance of the model in each corridor. For the corridors southeast (SE), northeast (NE) and southwest (SW), the performances were classified as good. While for the northwest (NW) corridor, the results corresponded to acceptable performance. Based on this evaluation, it was determined that the model in Designbuilder was accurate to continue with the next phase.

3.2 Parametric study

Based on the fourteen simulated models, results of solar heat gains through the openings of the courtyards, indoor ventilation, operative temperature, and percentage of discomfort hours were obtained for each case.

Among all the simulated cases, the minimum total solar heat gains in the week were received by the 5*5 N-S courtyard house (867 kW) and the maximum by the 20*20 NE-SW (6495 kW) (refer to Fig. 5). This difference between solar heat gains could be explained because the courtyards with higher dimensions of width and length had larger opening areas in the corridors. This consequently caused higher exposure to direct solar radiation in these spaces. Additionally, in the studied period, the total solar heat gains received through the openings of the corridors and rooms were mostly achieved on the internal east, southeast, west, and west-southwest facades of the courtyard. In the morning, the west side of the courtyard receives solar radiation since the sun rises from the northeast. Conversely, in the afternoon, solar radiation affects the east side when the sun sets in the northwest. Due to this sun path, the buildings with the long axis of the courtyard oriented N-S had higher solar heat gain, and the ones with the long axis oriented to the E-W had the lower.

Figure 6 shows the indoor ventilation rate of the simulated cases. The lower ventilation rates were registered in the 5*5 N-S case (28.1 ac/h) and the highest in the 20*20 NE-SW case (55.1 ac/h). The prevailing wind direction determined the differences between courtyard cases with the same proportions but different orientations. In the month simulated, the prevailing wind direction was southwest. The effect of wind direction in ventilation rates of cases with different orientations was greater in the rectangular plan courtyards. When comparing these cases rotated in different orientations, higher ventilation rates were perceived in the cases with courtyards' long axis oriented to the northwest-southeast (NE-SW). Meanwhile, results in squared plan courtyards indicated slight differences related to the orientations.

Regarding average operative temperature, the difference observed between the case with better thermal performance (5*5 N-S) and the case with worst performance (20*20 NE-SW) was 0.29ºC (Fig. 7). The operative temperature is greatly influenced by the solar heat gain of the buildings. As mentioned before, solar heat gains depend on the opening area that increases with higher dimensions of courtyards. For that reason, the case with greater solar heat gains coincides with the case with higher operative temperature. On the other hand, other parameters that influence the energy balance of the buildings and thus operative temperature are the roof area and floor area. According to the design criteria of the cases, these areas increase as the width and length of courtyards become greater. The roof area is the second parameter that affects the heat gains of the building. Larger roof areas allowed higher heat gains to the building. On the contrary, larger floor areas promote higher heat losses in the building, which has an important effect on the energy balance of the building.

In addition, the percentages of discomfort hours were calculated from the operative temperatures. The cases with higher operative temperature promote greater percentages of discomfort hours because they exceed the upper 80% acceptability limit for more hours. Considering one week period, the lower operative temperatures and, therefore, the lower percentage of discomfort hours were obtained in the 5*5 N-S case (33%). Conversely, the percentages of discomfort hours were higher in the 20*20 NE-SW case (37%) (Fig. 8).

3.2.1 Energy Balance related to proportions

The cases oriented north-south (N-S) that in most cases had better performance were selected for a better understanding of the thermal performance of the courtyard houses. For this, the total heat gains and losses of the building were compared to carry out a detailed analysis. Figure 9 shows the energy balance of the different cases where different parameters of the house determine heat losses and gains. The largest amount of heat gains in all cases was dictated by the roofs and the solar radiation through the openings. At the same time, the major losses correspond to the floors and external infiltrations.

As observed in Fig. 9, the heat gains and losses increase as the dimensions of width and length of the courtyard and the volume of the building become greater. In addition, the percentage of solar heat gains received through the openings got larger related to the total heat gains of the building. For example, in the 5*5 N-S case, the percentage of heat gains received through the solar exposure of the courtyards openings correspond to the 59% of the total amount of gains, whilst in the 20*20 N-S case, the percentage intensifies to 85%. Otherwise, the gains related to natural ventilation in all cases remained lower than 1% of the total amount.

It should be noted that varying dimensions of courtyards affect the dimensions of the building. Therefore, an important parameter is a relationship between the volume of the courtyard and the volume of the building. In the proposed cases, this relation increases from the building with the smaller courtyard (0.04) to the building with the larger one (0.35). Results obtained from the energy balance, which considers the total heat gains and losses, showed that the heat gains get higher as the ratio between the courtyard volume and the building volume grows (Fig. 10a).

Furthermore, the volume of the courtyard and aspect ratio also affects the area of the openings, which in turn influences the solar heat gains of buildings. Figure 10b shows the relation between the area of the courtyard openings and the solar heat gains that are received through them. As the area of the openings increase, the solar heat gains per square meter get higher. For instance, in the 5*5 N-S case, the solar heat gains per m2 correspond to 7.55 kW, and in the 20*20 N-S case, the gains rise to 13.82 kW.

3.2.2 Thermal performance of different spaces

Inside the courtyard houses, two different types of thermal performance were observed according to the type of space. The rooms had lower thermal swings and more hours inside the thermal comfort zone bounded by the 80% acceptability limit. These spaces also could offer the possibility for inhabitants to control the openings to enhance natural ventilation or decrease air temperature during the first hours of the day. On the other hand, corridors had higher thermal swing but offered a wider range of conditions than the rooms. In some traditional houses of Colima, these spaces also function as dining rooms and living rooms because of this. Concerning the different cases proposed, the operative temperatures of corridors increase as the length and width get greater, in some cases exceeding the outdoor air temperature.

For the analysis of the thermal performance in a 24-hour cycle of the different spaces of the house, two cases were selected. These were the cases with lower (5*5 N-S) and higher (20*20 NE-SW) results in solar heat gains, operative temperature, and ventilation rate. As for the spaces inside the house, they consisted of two types. The enclosed rooms in the periphery of the building and the corridors function as a transitional space between the courtyard and rooms. The analysis was carried out on May 30, a typical day of the month according to climatic data. Additionally, two ventilation strategies were considered. The first one, where the glass windows with the wooden frame between the rooms and the courtyard remained closed 24/7 (0% opened) and the latter opened the windows 100% all day long. The openings connecting the corridors and the courtyard are cavities that allow wind flow permanently.

Figure 11 shows the thermal performance in a 24-hour cycle of the 5*5 N-S case. The outdoor air temperature had a thermal swing of 11.49ºC with a maximum temperature of 33.7 ºC. Among the indoor spaces, higher thermal swings (7.8ºC) were observed in the corridors in comparison with the rooms (3.7ºC). Regarding the two ventilation strategies, a difference of 1.7ºC was observed in the thermal swings of the rooms. When windows were left 100% opened, the maximum and minimum got closer to outdoor temperature than when windows remained closed. The maximums and minimums differed at 0.6 ºC and 1.1 ºC, respectively. Furthermore, if windows were 100% opened, the temperature of the rooms during the day exceeded the upper 80% acceptability limit of thermal comfort for a greater number of hours. For this reason, maintaining windows opened at this time of the day would not be adequate for the inhabitants since it would affect their thermal comfort.

On the other hand, the results for the 20*20 NE-SW case proved an increase in the maximum temperatures of the corridors compared to the outdoor temperatures (Fig. 12). In this case, the differences in temperatures in the rooms were lower when the openness of the windows was modified. In maximum temperatures, the rooms with 100% opened windows were 1ºC higher, and in minimums, they remained 0.4ºC lower. The maximum temperature was 0.5 ºC higher with respect to outdoor temperature and showed a temperature delay of 1 hour.

4. Critical Discussion

The results from the parametric study demonstrate a clear influence of courtyards proportions on solar heat gains and ventilation rates in the building. As the size of the courtyard got larger, the solar heat gains and ventilation rates increased (refer to Fig. 5 and Fig. 6). Nevertheless, this did not greatly influence the average operating temperature of the building since the differences among the cases with higher and lower operative temperatures were lower than 0.3 ºC (refer to Fig. 7).

When analyzing the energy balance of the different cases, it was observed that the courtyard greatly contributes to increasing solar heat gains rather than promoting passive cooling in the building (refer to Fig. 9). This effect only amplifies as the width and length of the courtyard increase due to higher exposure to solar radiation (refer to Fig. 10). The more solar radiation is received, the more cooling is required in overheated conditions. This agrees with the findings of Doctor-Pingel et al., in which the strategy of a central courtyard led to elevated indoor temperatures in comparison with other passive design strategies applied to naturally ventilated buildings in warm-humid climates [51].

As the traditional courtyard houses in Colima have only one storey, the current study mainly considered the effect of L/W proportion. In the same way as previous studies [13, 31], it was observed that squared plan courtyards received less solar radiation in comparison with rectangular ones. This is due to the increase of shadowy areas as the courtyard's plan comes close to the square. That also decreases the amount of energy required for cooling during summer periods [13]. When courtyards get wider, proper solar protection permeable to the wind on courtyard walls would be required [39].

Regarding the orientation, greater differences in results were shown between rectangular plan courtyards rather than square ones when the buildings were rotated. This paper showed that lower heat gains were shown in courtyards with the long axis oriented E-W (Fig. 5). This coincides with the findings of Taleghani et al. in the Netherlands [36].

The findings in the current study generally agree with other's research that addresses the influence of H/W proportions. The increase in the width and length of courtyards in relation to height causes lower aspect ratios and greater exposure to the exterior. Low aspect ratios (H/W < 1.5) increase the duration of excessive direct solar radiation in the courtyard [31]. In the cases proposed (Fig. 3), the aspect ratios (H/W) were lower than 1, and the solar heat gains increased as this ratio diminished. According to this, Muhaisen suggested that the optimum courtyard height in a hot-humid climate should be three-storey to induce more shaded areas [11]. Other research with an approach to outdoor thermal conditions in warm-humid conditions also suggested that height has an important effect on the daily maximum air temperature of this space [32] and consequently in thermal comfort [52].

As mentioned before, the optimal courtyard design in warm-humid climates should explore the relationship between enhancing natural ventilation when it's desirable and protecting from solar radiation and heat gains. According to Givoni, the three main functions of natural ventilation consist of replacing higher temperature indoor air with a fresh air of lower temperature, cooling the structural mass of the building, and providing thermal comfort by increasing heat loss from the body, for which a higher wind speed is convenient [53]. In the current study, the first function can only be carried out during the early morning and late-night, where the rooms will benefit the most from this air exchange. During the afternoon, although indoor wind speeds could provide thermal comfort, it simultaneously could increase indoor air temperatures (refer to Fig. 11 and Fig. 12). In this regard, the findings of Kubota et al., demonstrated that different types of courtyards performed different functions. In courtyard types with almost absent airflow during the day (< 0.2 m/s), the air temperatures in the courtyard and the immediate spaces maintained relatively low values compared to the outdoor temperature. Conversely, in the types where indoor wind speeds increase, it simultaneously raises indoor air temperature [32]. Likewise, the results of this study reveal that the case with higher heat gains had higher ventilation rates (Fig. 5 and Fig. 6).

As for the function of cooling the structural mass, this research showed that despite larger dimensions of width and length enhanced higher ventilation rates; it had a low influence on the heat losses of the building.

This is because the gains or losses related to the natural ventilation of the building correspond to a low percentage of the total amount in the energy balance (Fig. 9). Finally, the third function of ventilation wasn't considered for this research, but according to a previous study, the importance of this function guided to the conclusion that indoor ventilation can have a more important role in thermal comfort than enclosing the courtyard to achieve better protection from solar radiation [39].

5. Conclusions

This paper studied the influence of courtyard proportions and orientations on the indoor thermal performance of traditional houses. Based on this parametric study, results allowed a better understanding of how traditional courtyard houses responded thermally to the outdoor climatic conditions, so this can be useful information for future rehabilitation projects. Furthermore, it could guide the improvement and reinterpretation of this building type in warm-humid climates with similar latitudes. The most outstanding findings are summarized as follows:

- In this case study, the courtyard greatly contributes to increasing solar heat gain, which raises temperatures during the day rather than promotes passive cooling in the building.
- Solar heat gains and ventilation rates increase as the width and length of courtyards become greater. However, this does not have an important influence on the average operative temperature of the entire building. When comparing the operative temperatures of the corridors between cases, higher differences were observed. In some cases (20*20 NE-SW), they exceed the outdoor temperature.
- Lower heat gains were obtained in courtyards with long axis-oriented E-W and higher ventilation rates when the long axis was oriented NW-SE.
- Among the spaces inside the house, rooms had lower thermal swings and more hours inside the thermal comfort limits. In these spaces, opening the windows from 23.00 hrs to 11.00hrs could reduce the operative temperature by 1.1ºC. Conversely, opening windows outside that time-lapse would not benefit the inhabitants since this could cause an increase in temperature and a greater number of hours above the upper comfort limit.

This paper was limited to courtyards' effect proportions and orientation on thermal performance. Likewise, studying the influence of these design variants on wind speeds and, consequently, thermal comfort could also be relevant for this climate. For future research, there are several aspects that could be explored. For instance, studying shading devices or courtyard design variants that could diminish the exposure to solar radiation and be permeable to the wind so that this building form could be adequate for warm-humid climates. In addition, other aspects of the courtyard's design, like using vegetation and different construction materials, would need to be considered.

Abbreviations

$t_{pma(out)}$ mean outdoor temperature

CVRMSE coefficient of variance of the root mean square error

RMSE root mean square error

NSE coefficient of efficiency of Nash and Sutcliffe

SD standard deviation

Declarations

Availability of data and materials

Data sharing is not applicable to this article, as no datasets were generated or analyzed during the current study

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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Author contributions

M. Gabriela Toris Guitrón: Methodology, Investigation, Writing- Original draft preparation, Validation, Formal analysis.

Carlos J. Esparza-López: Conceptualization, Supervision, Reviewing and Editing, Formal analysis.

Aníbal Luna-León: Methodology, Reviewing and Editing, Validation, Formal analysis.

Carlos Escobar-del Pozo: Supervision, Methodology, Writing- Reviewing and Editing, Validation, Formal analysis.

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Figures

Figure 1

Left: Plan and section of the representative courtyard house. Centre: Courtyard view from the corridor. Right: Model of the representative courtyard house in Designbuilder.

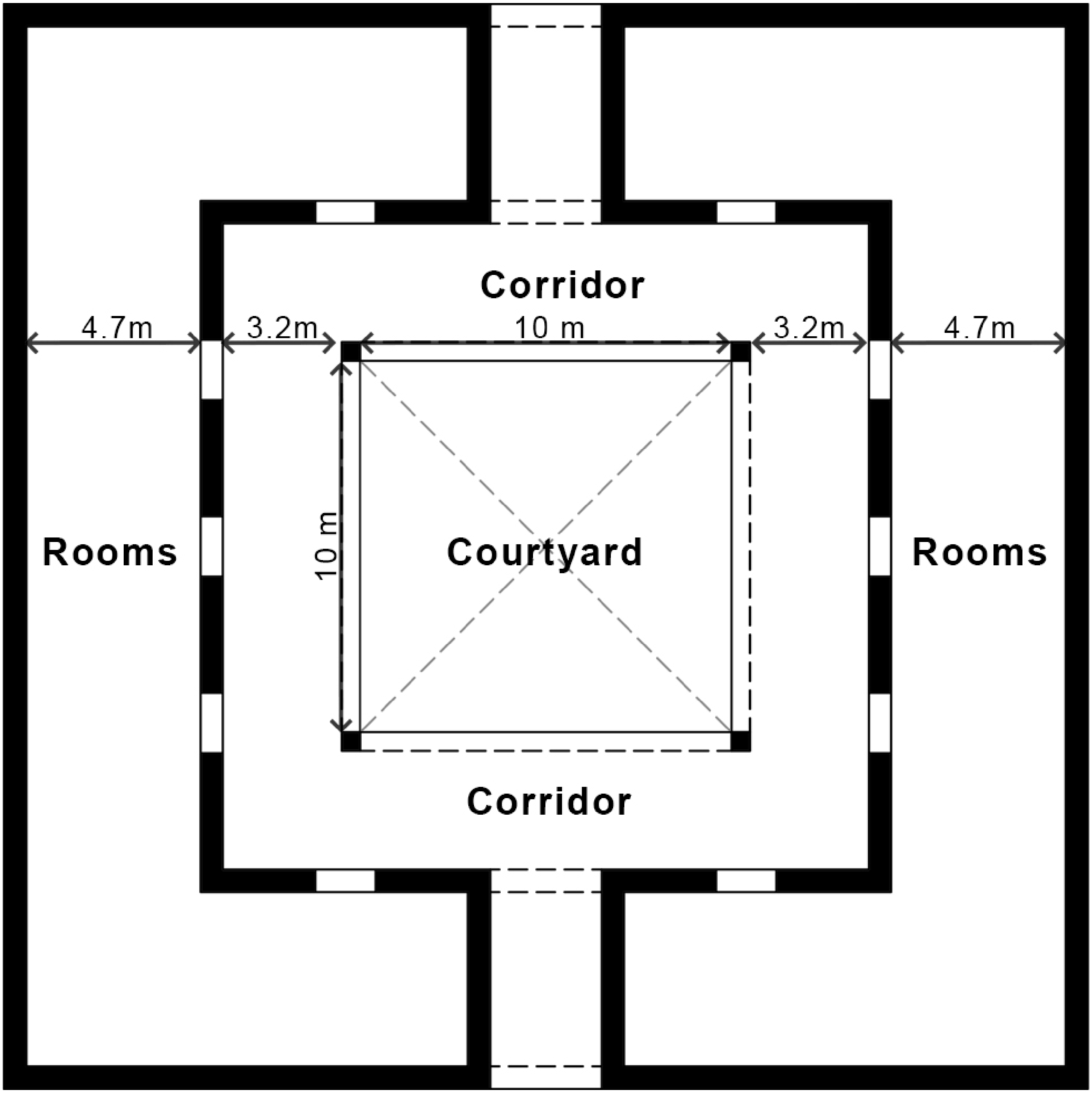

Figure 2

Interior plan of the reference courtyard house model. Case with courtyard 10 m * 10m.

Figure 3

Courtyard houses simulated with different proportions and orientations.

Figure 4

Scatter plots showing the two set of air temperatures of the corridors with different orientations.

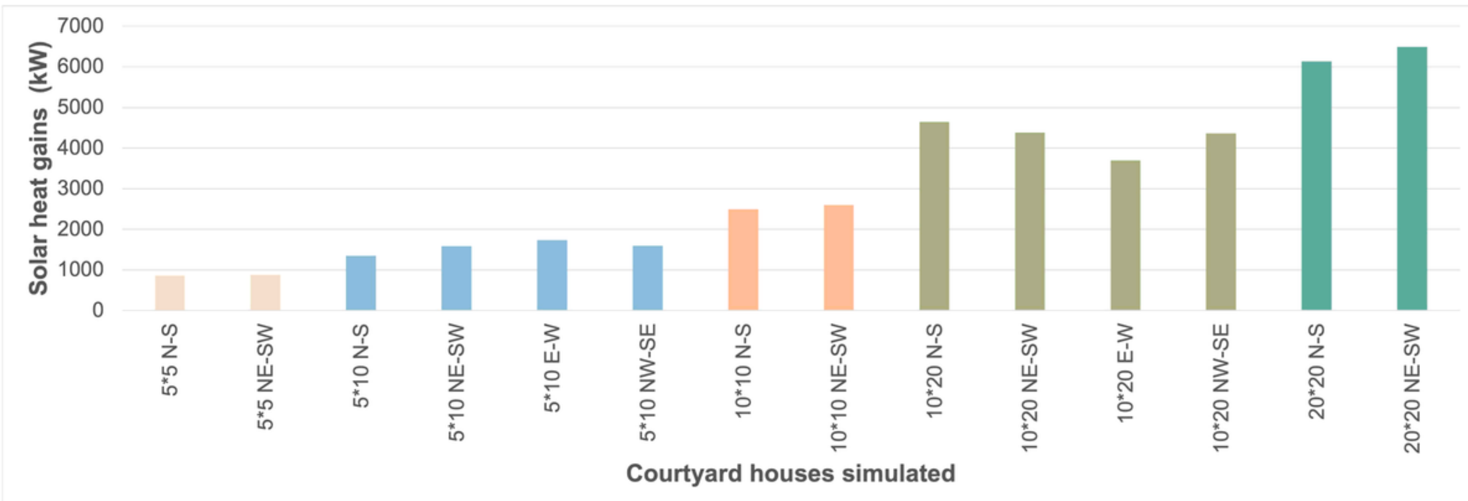

Figure 5

Comparison of Solar heat gains received through the openings of courtyards between cases with different proportions and orientations.

Figure 6

Comparison of indoor ventilation between cases with different proportions and orientations.

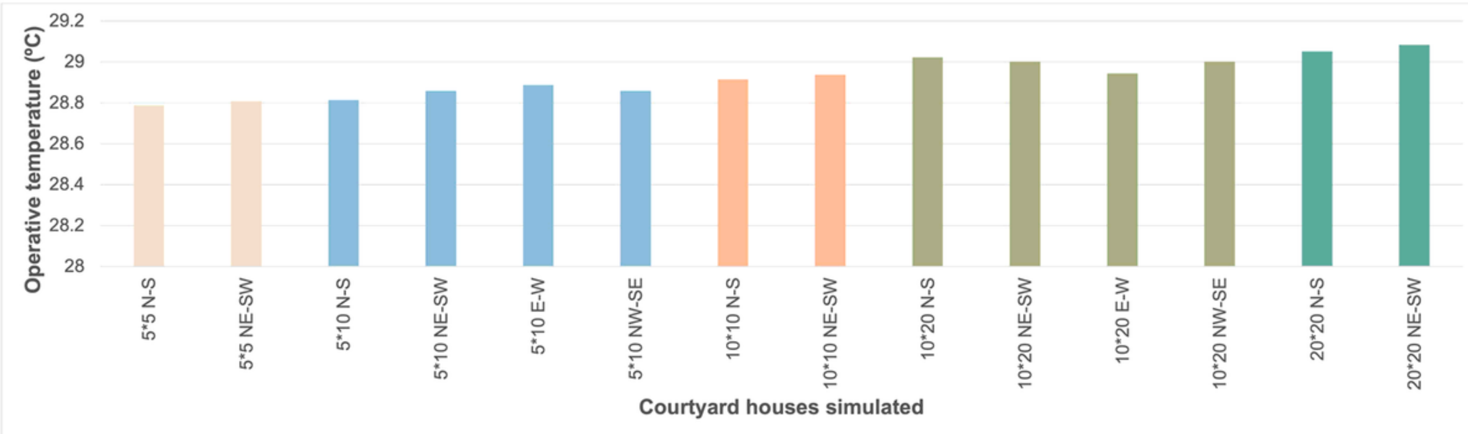

Figure 7

Comparison of operative temperatures between cases with different proportions and orientations.

Figure 8

Comparison of percentage of thermal discomfort hours during a week between cases with different proportions and orientations.

Figure 9

Energy balance of the simulated models with N-S orientation.

Figure 10

Left: a) Total heat gains of the building related to the ratio between the volume of the courtyard and the volume of the building; Right: b) Solar heat gains related to the area of the courtyard openings.

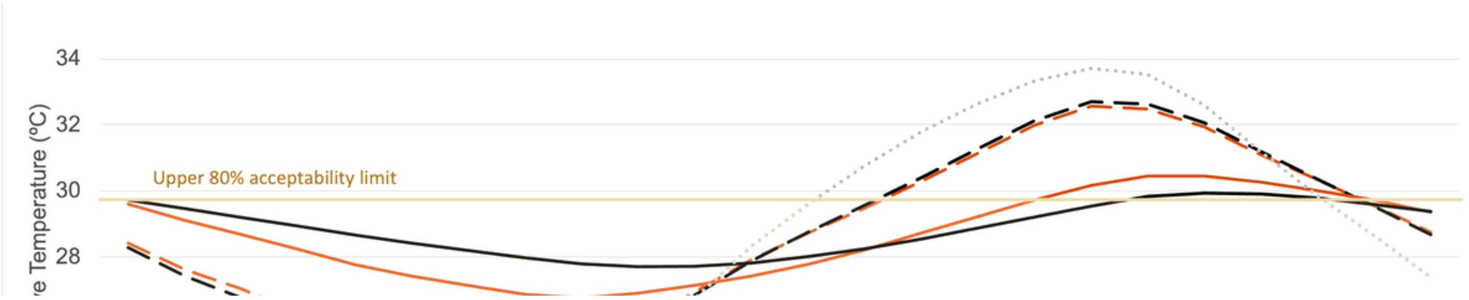

Figure 11

24-hour thermal cycle of the spaces in the house with different ventilation strategies: windows of the rooms 0% opened and 100% opened 24/7. Case 5*5 N-S.

Figure 12

24-hour thermal cycle of the spaces in the house with different ventilation strategies: windows of the rooms 0% opened and 100% opened 24/7. Case 20*20 NE-SW.