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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 energy use and promote indoor thermal comfort in overheating conditions, attention has been drawn to 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 with the aim to determine the influence of orientation, courtyard size and proportions on the indoor thermal energy balance and thermal comfort of a traditional building in a warm-humid region. 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 1.1 °C 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.

Keywords: Warm humid climate, Thermal performance, Thermal comfort, Traditional courtyard houses

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 flow, sunlight, temperature, and relative

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humidity, thus influencing the building's environmental performance. Compared with other urban forms, the courtyard shape has shown a better thermal response depending on climate [6] and less annual energy demand [7]. Furthermore, courtyards provide a variety of favorable 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.

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 option to enhance passive cooling in these hostile environments [14]. Recently, numerical simulations have been employed to evaluate the thermal comfort of courtyards under dry climates, showing an improvement in indoor and outdoor conditions [15–17]. 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 [18]. According to this, an effective passive cooling design should consider the effect of natural ventilation [19] and the solar radiation exposure of the residential typology [20].

Several studies have been conducted to describe the thermal behavior of courtyards, from analysis of energy performance and thermal comfort [21] to the effect of the courtyard geometrical parameters [22]. Deep learning and multiobjective optimisation methods were used to design courtyards [23, 24], showing the importance that design variables (window-to-wall ratio and building geographical location) have on thermal performance. Finally, simulations have been employed to determine the cooling energy demand [25] and the energy saving potential [26] associated with courtyards in the second study for traditional houses.

Previous studies have explored geometrical, orientation and opening configurations as critical design variables to enhance better thermal performance and thermal comfort. Length-to width ratio of 1:2 has higher air velocities and better thermal performance than a squared courtyard plan, in U-shape courtyards [27]. On the other hand, squared courtyards have shown least solar radiation gains and irradiation in comparison to rectangular ones [28]. The courtyard area-to-entire building area ratio is a key variable that affects humidity; meanwhile, the sky view factor and the height of the courtyard are relevant for indoor temperature [29]. A reduction of air temperature is obtained through an increase in the height of the courtyard enclosure [30]. Regarding ventilation, 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 [31]. 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 [32]. Likewise, it has been emphasized that the composition of the building's design allows cross-ventilation between two courtyards [33] or a courtyard and the street [21] to influence the heat losses of the building envelope and promote thermal comfort for the inhabitants. Finally, northeast-southwest and east-west orientations of the courtyard long axis have shown better thermal conditions [28, 34].

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.

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 [22].

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 [35]. 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 [36]. 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 [37]. 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. 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. However, the influence of parameters like orientation, and courtyard size had been analyzed separately. Therefore, the main contribution of the present study is the determination of the influence of orientation, courtyard size and proportions on the indoor thermal energy balance and thermal comfort of a traditional building in a warm-humid region. 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.

Methodology

The research was carried out through different subsequent phases. First, morphological and typological characteristics of traditional courtyard houses of Colima were identified through field sampling. Then, a representative courtyard house was selected to perform field measurements that were used later for the simulation. Finally, the simulation phases consisted of validating the model and a parametric study. The latter evaluated courtyard design and its influence on the indoor thermal performance of the building in a warm, humid climate. The methodology phases could be observed in the flowchart in Fig. 1, and the details are explained below.

Field sampling

Traditional 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) [38]. 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) [39].

The field sample consists of 50 courtyard houses to which it was possible to access and gather information related to their morphological and typological characteristics. The houses from the sample are from the XVlll and XlX centuries and are characterized mostly by one storey with a rectangular or square central courtyard, surrounded by corridors and enclosed rooms immediate to them. The dimensions of the courtyards registered varied from 4.5 m to 22.6 m in length and from 1.7 m to 26.6 m in width. The possible facade orientations were 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 depended on the period that was built and if they had subsequent transformations. In the sample, walls were mainly made of adobe or brick with thicknesses ranging from 0.4 m to 1.1 m. Although roofs were originally sloping and made of wood and tile, flat roofs were more frequent. In some cases, contemporary materials such as reinforced concrete were observed.

From the field sample, a representative courtyard house was selected to carry out field measurements. The house has a squared plan courtyard placed in the center and dates from the XlX century but has had interventions after its time of construction. In addition to the accessibility to obtain data of this building, the dwelling was selected because of its representative characteristics which were observed to be frequent in the sample. For instance, the house has one storey like most of the houses and the courtyard´s area, width and length have values close to the average values of the sample. In this case, the courtyard´s area corresponded to 110.25 m^2 and the average area of the courtyard´s sample was 91.7 m^2. The house also maintains the courtyard uncovered, as well as the use and function of other transitional spaces in the house like the corridors and zaguan. The corridors surround the courtyards on its 4 sides, which allows one to observe the differences in results according to the orientation of the spaces inside the house. Likewise, the

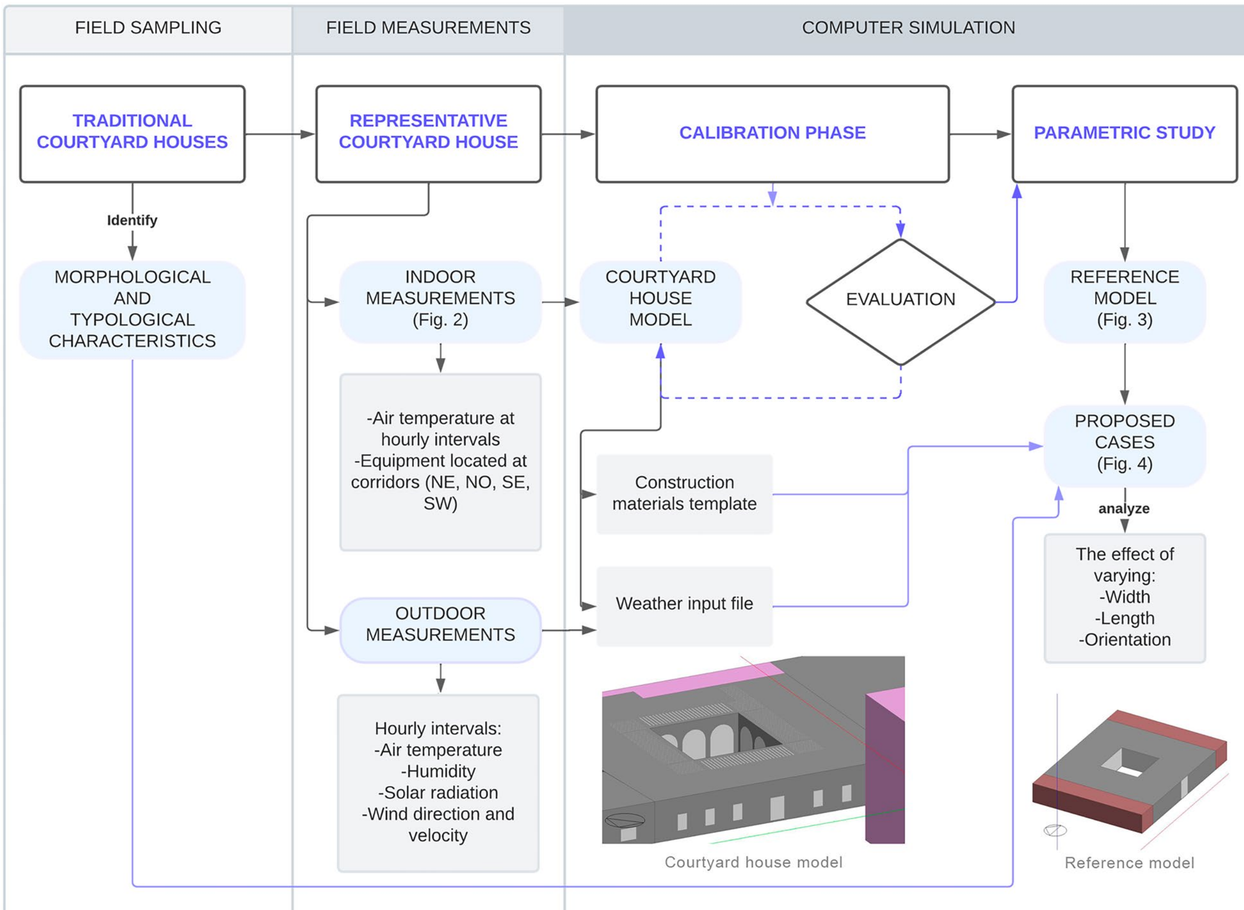

Fig. 1 Flowchart of the methodology for this research

dwelling is naturally ventilated, thus no heating or cooling systems affect the temperature measurements.

Field measurements

The field measurements to validate the results from the simulation were carried out from May 29 to June 1 of 2020. The air temperature was measured at hourly intervals with Onset Hobo data loggers with an accuracy of ± 0.35 °C. The temperature measurements were performed for three different heights, 0.1 [m] and 1.1[m], according to the ISO 7726 [40]. Additionally, a data logger was placed at the volumetric center of each of the four corridors with orientations northeast, northwest, southeast and southwest (Fig. 2), at a height of 2.25 [m] to compare the numerical results. These spaces were selected because they are immediate to the courtyard and are more exposed to the effect of outdoor conditions. Additionally, to develop a text-based weather file for the next 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.

To control the errors generated by the experimental process in the measurements, specifications and methods were based on the international standard ISO 7726 [40]. Likewise, the equipment used was calibrated. For this, a sample of 235 measurements of Dry Bulb Temperature was recorded from all the equipment simultaneously under the same conditions before and after the measurements. Data from equipment was taken as a reference and correlated with the rest. Likewise, the trend lines and the corresponding equations were obtained to correct the differences between the equipment. The correlations obtained were not lower than r^2=0.95. Therefore, the correction equations were accepted.

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 [41]. The

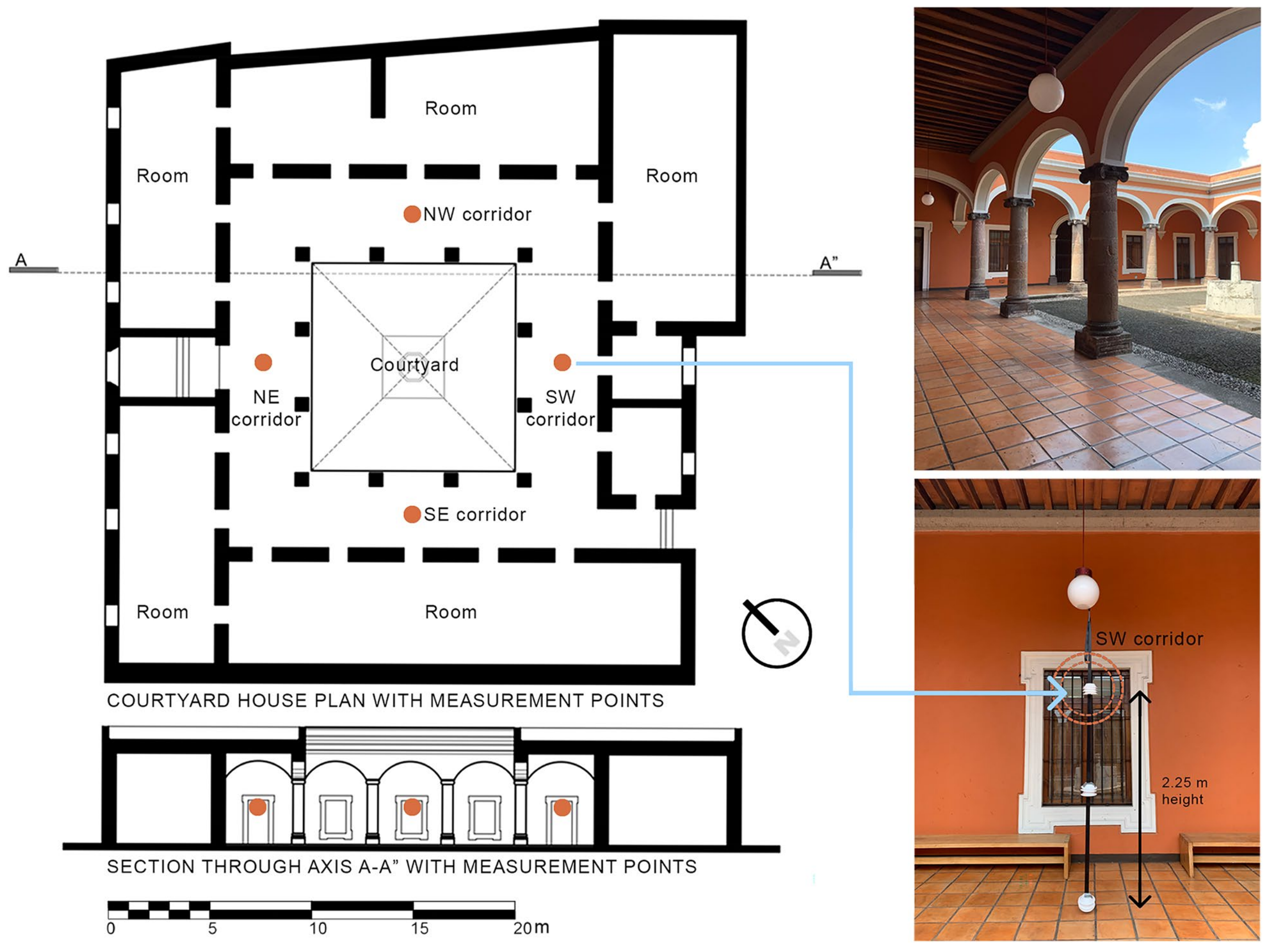

Fig. 2 Left: Plan and section of the representative courtyard house with measurement points (orange dots). Up Right: Courtyard view from the corridor. Down Right: Datalogger location on the south-west corridor

aim of this phase was to validate the accuracy of Design-Builder simulation software for the parametric study. For this validation, the air temperature results from different spaces obtained in the field measurements were compared with the ones of the simulation program.

The weather input file for the simulation was developed by using hourly data from 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 roofs, with wooden beams and clay tiles in the interior layer of the corridors. The heat transfer coefficients were calculated by Designbuilder from the weather file, to calculate the coefficients for external surfaces the DOE-2 model was employed and the TARP model was used for internal surfaces; both models consider the surface orientation and wind conditions [42].

The material properties and U-values were set up in Designbuilder as follows:

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), and the root mean square error (RMSE). The latter has been a statistician used as a reference to validate simulation models in different studies [34, 43], see Table 1.

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),

Table 1 Material properties used in the simulation

Materials	Conductivity (W/ m-K)	Specific heat (J / kg-K)	Density (kg/m3)	Thickness (mm)	U-value (W/m2K)	R-value (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		

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
RMSE (Root Mean Square Error)	1.31	1	1.22	1.31
Performance rating (according to ritter & Muñoz-Carpena)	Good	Good	Good	Acceptable

southwest (SW) and northwest (NW). The differences between the mean temperatures of the measured data and the simulated model were 1 °C or less in all cases. To evaluate the accuracy of the results, the determination coefficient (R^2), and root mean square error (RMSE) are calculated, following the methodology proposed by [44]. 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 [45].

The determination coefficients (R^2), depending on the corridor, vary between .94 and .95. These values are close to 1, which determines the highest accuracy. Meanwhile, the RMSE varied from 1 to 1.31, which in comparison with other courtyard studies [44], is a good result. The differences found between the numerical and the experimental results are based on the differences in the materials properties of walls and roofs, in the simulation are considered constant while in the real case the values are non-homogenous.

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. 3). The second refers to the RMSE to quantify the prediction error in terms of the units of the variable calculated by the model.

$$NSE = 1 - \left(\frac{RMSE}{SD}\right)^2 \quad (1)$$

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 [45]. 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)

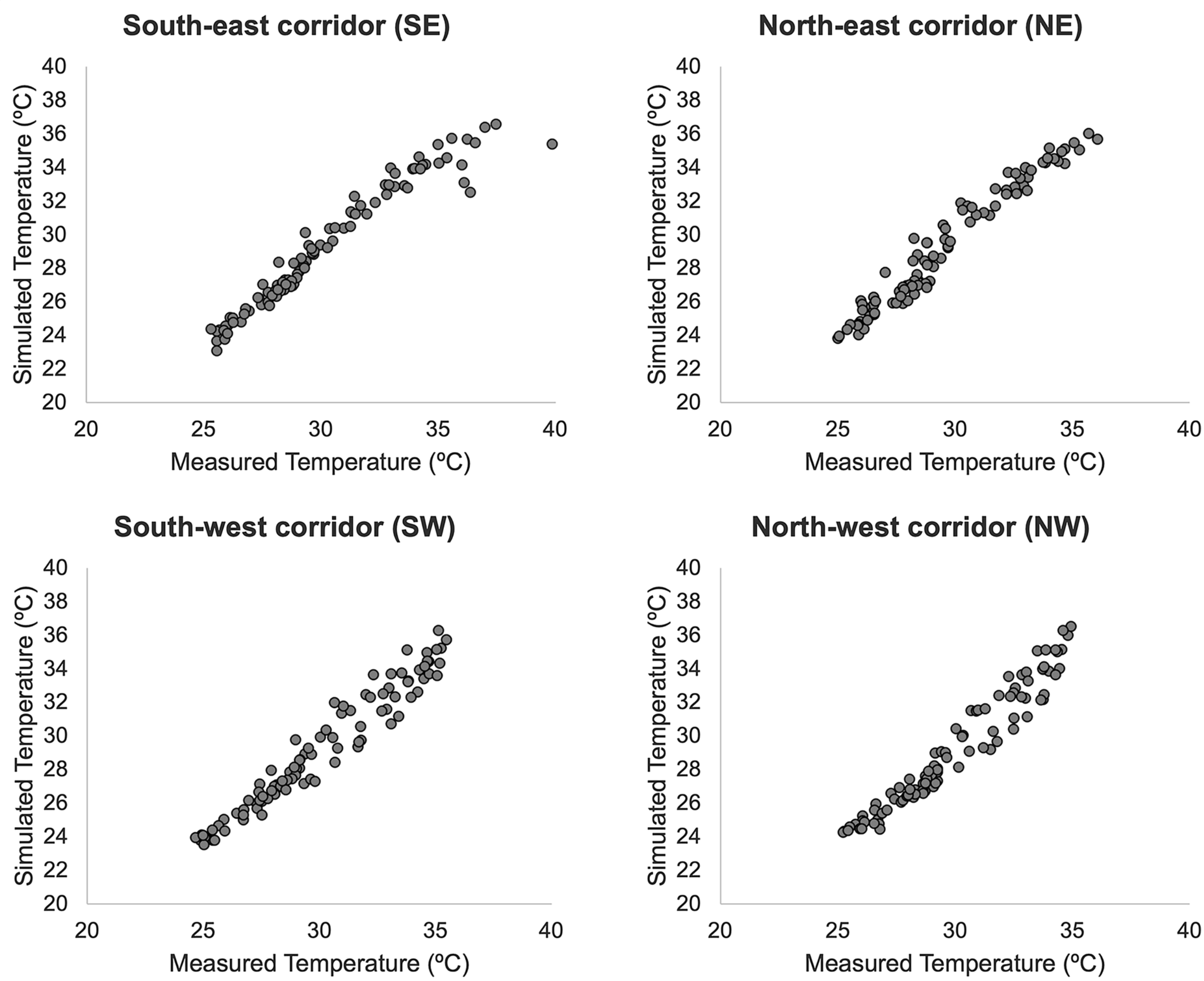

Fig. 3 Scatter plots showing the two sets of air temperatures of the corridors with different orientations.

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 Design-builder was accurate to continue with the next phase.

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. 4). The height of 5 m also remained constant in all cases.

The calculated parameters were: solar heat gains (wall, floor, roof and ceiling surfaces, glazing, ventilation and infiltration loads), indoor ventilation rates, operative temperature, and percentages of discomfort. To determine the heat gains the building thermal resistance/capacitance network was used. The solar heat gains and indoor ventilation rates were calculated through the courtyards openings, green section in Figure 4, and windows. Meanwhile, the operative temperature was determined as the average of the radiant and ambient temperature of the inner spaces.

Twenty courtyard building cases were proposed to study the indoor thermal performance varying in width, length, and orientation, including the reference model. The study cases were built varying the aspect ratio and courtyard size. Aspect ratios (width/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. Each building case was

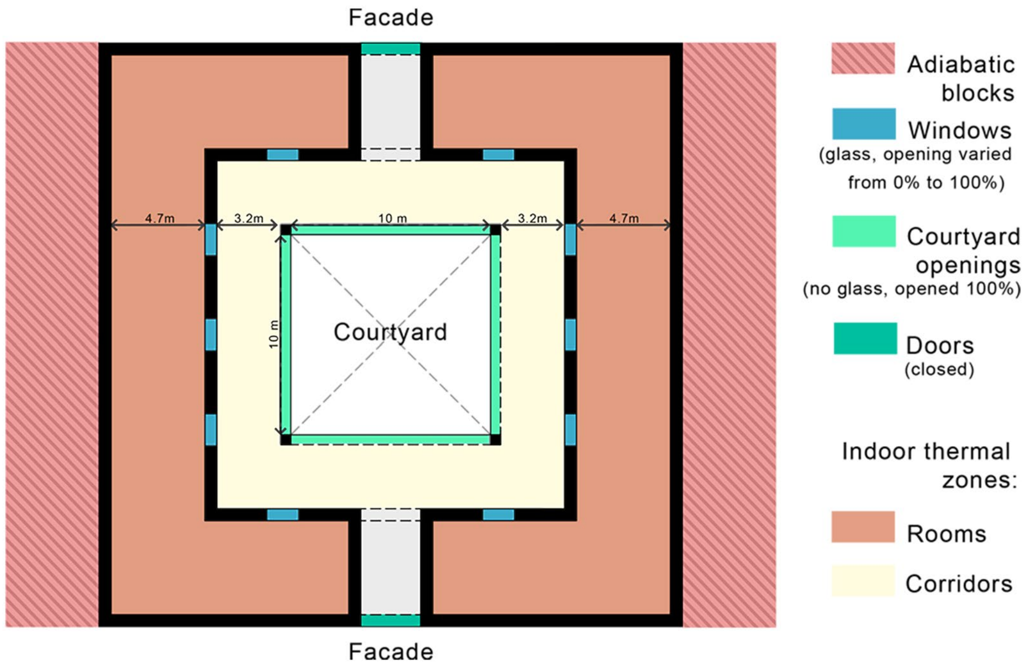

Fig. 4 Interior plan of the reference courtyard house model. The colors indicated the location of different thermal zones, openings, and adiabatic blocks. Case with 10*10 m courtyard

rotated 45° to consider the orientations North-South, Northeast-Southwest, East-West and Northwest-South-East (Fig. 5). These cases were modeled in DesignBuilder with the characteristics of the material mentioned in Table 1, to calculate the average indoor thermal environment for 4 different orientations of each building case, considering that corridors and rooms integrate the indoor environment, subjected to the same weather and solar conditions. 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.

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:

$$\text{Upper 80\% acceptability limit } \left(^{\circ}\text{C}\right) = 0.31 \times t_{pma(out)+21.3} \quad (2)$$

$$\text{Lower 80\% acceptability limit } \left(^{\circ}\text{C}\right) = 0.31 \times t_{pma(out)+14.3} \quad (3)$$

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 3.5 °C upper and lower the comfort temperature for the 80% of acceptability.

Results and discussion

Parametric study

Based on the twenty simulated models, results of solar heat gain through the openings of the courtyard and indoor windows planes (green and blue zones in Figure 4, respectively), indoor ventilation (through windows and courtyard opening), operative temperature of indoor spaces, and percentage of discomfort hours were obtained for each case.

The results from all the simulated cases in a critical week showed the minimum total solar heat gains received through the courtyard´s opening on the 5*5 courtyards oriented North-South and East-West (740 kW) and the maximum on the 20*20 courtyards oriented NE-SW and NW-SE (5726 kW) (refer to Fig.6). 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

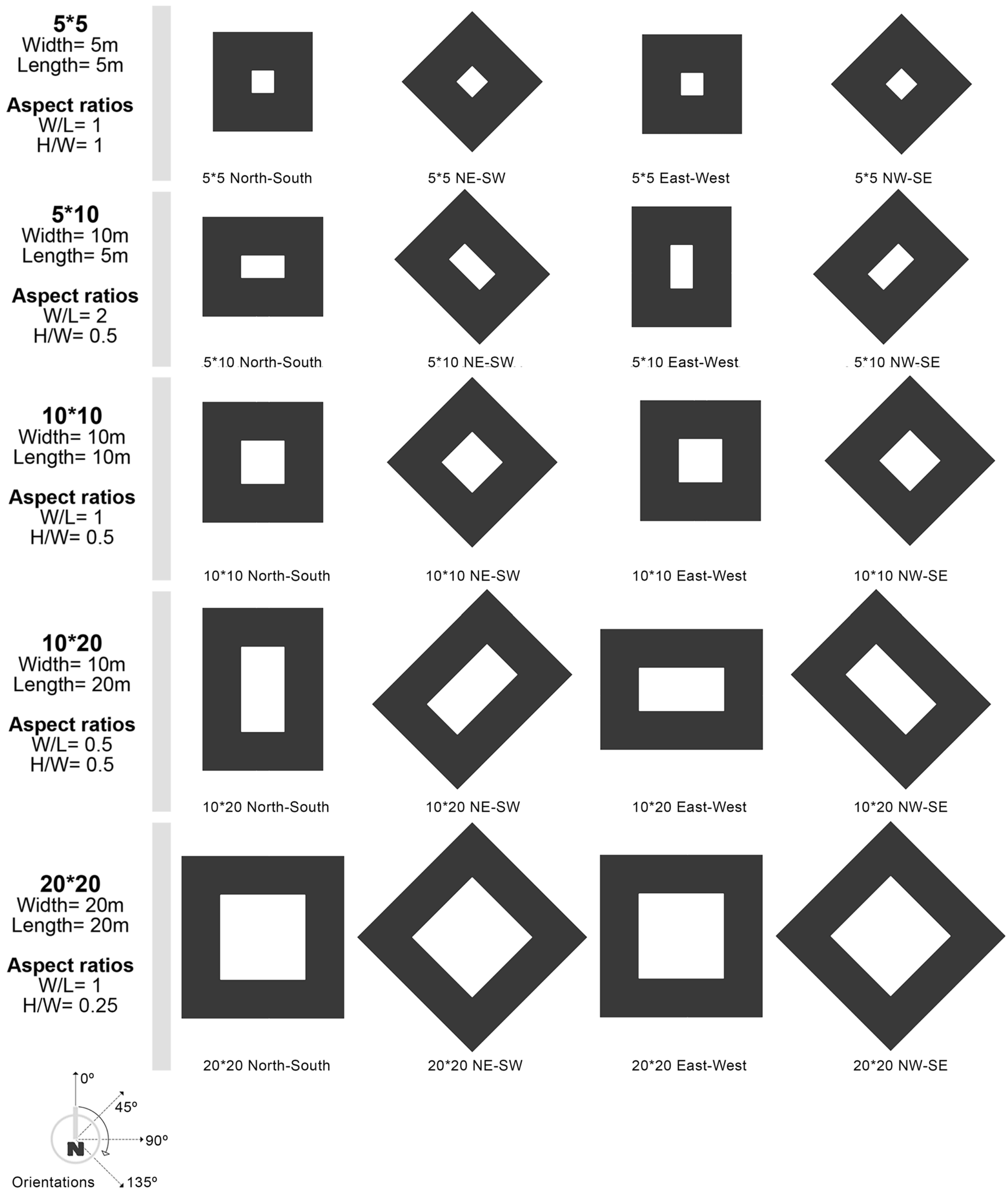

Fig. 5 Courtyard houses simulated with different proportions and orientations

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

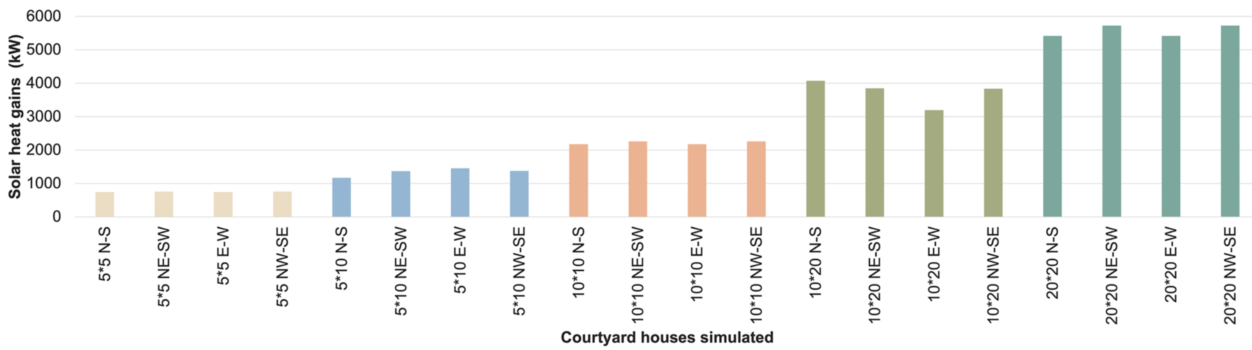

Fig. 6 Comparison of Solar heat gains received through the openings of courtyards between cases with different proportions and orientations

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 solar gain.

Figure 7 shows the indoor ventilation rate of the simulated cases. The lower ventilation rates were registered in the 5*5 N-S and N-E cases (27.5 ac/h) and the highest in the 20*20 NE-SW and NW-SE cases (54.5 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 (NW-SE). Meanwhile, results in squared plan courtyards indicated slight differences related to the orientations.

Regarding average operative temperature, the difference observed between the cases with lower temperatures (5*5 N-S) and the cases with higher temperatures (20*20 NE-SW and NW-SE) was 0.54°C (Fig. 8). The operative temperature of the building is greatly influenced by solar heat gains received through the courtyard´s building. 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, another parameter that affects the heat gains of the building, and thus operative temperature, is the roof area. According to the design criteria of the cases, this area increased as the width and length of courtyards became greater causing higher heat gains to 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 cases in all orientations (42 %). Conversely, the percentages of discomfort hours were higher in the 20*20 cases (37%) (Fig.9).

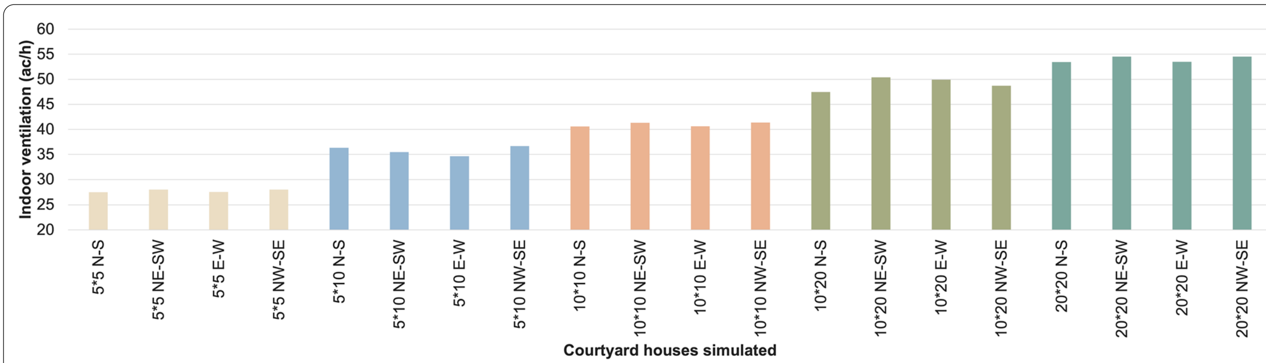

Fig. 7 Comparison of indoor ventilation between cases with different proportions and orientations

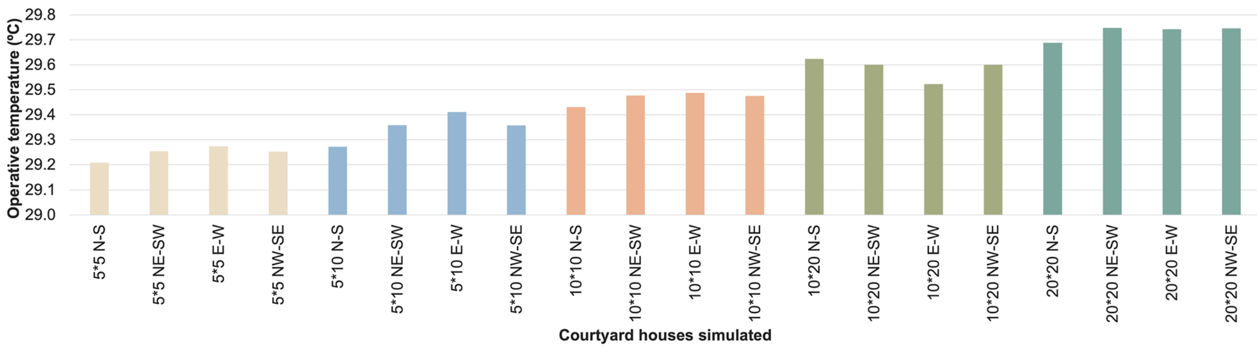

Fig. 8 Comparison of operative temperatures between cases with different proportions and orientations

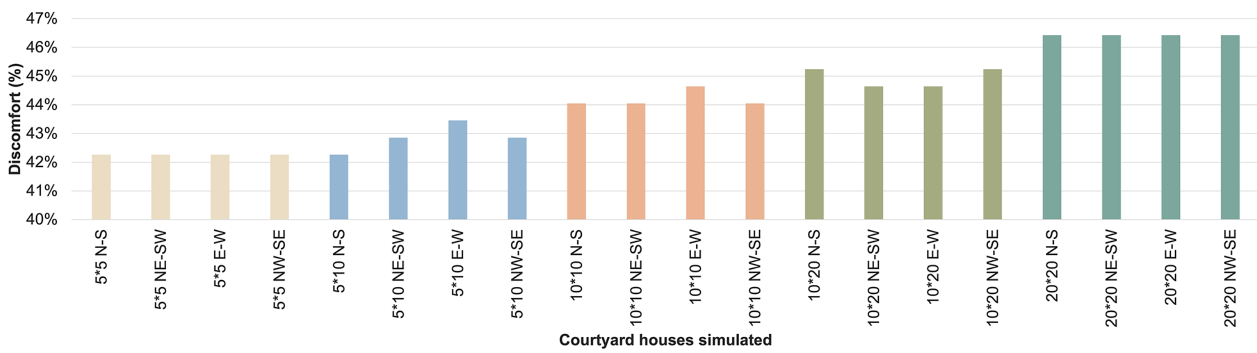

Fig. 9 Comparison of percentage of thermal discomfort hours during a week between cases with different proportions and orientations

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 10 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. 10, 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 courtyard's 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 solar exposure of the courtyard's openings corresponds to 31.3% of the total amount of gains, whilst in the 20*20 N-S case, the percentage intensifies to 63.9%. 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 the 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. 10 left).

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 10 (right) 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

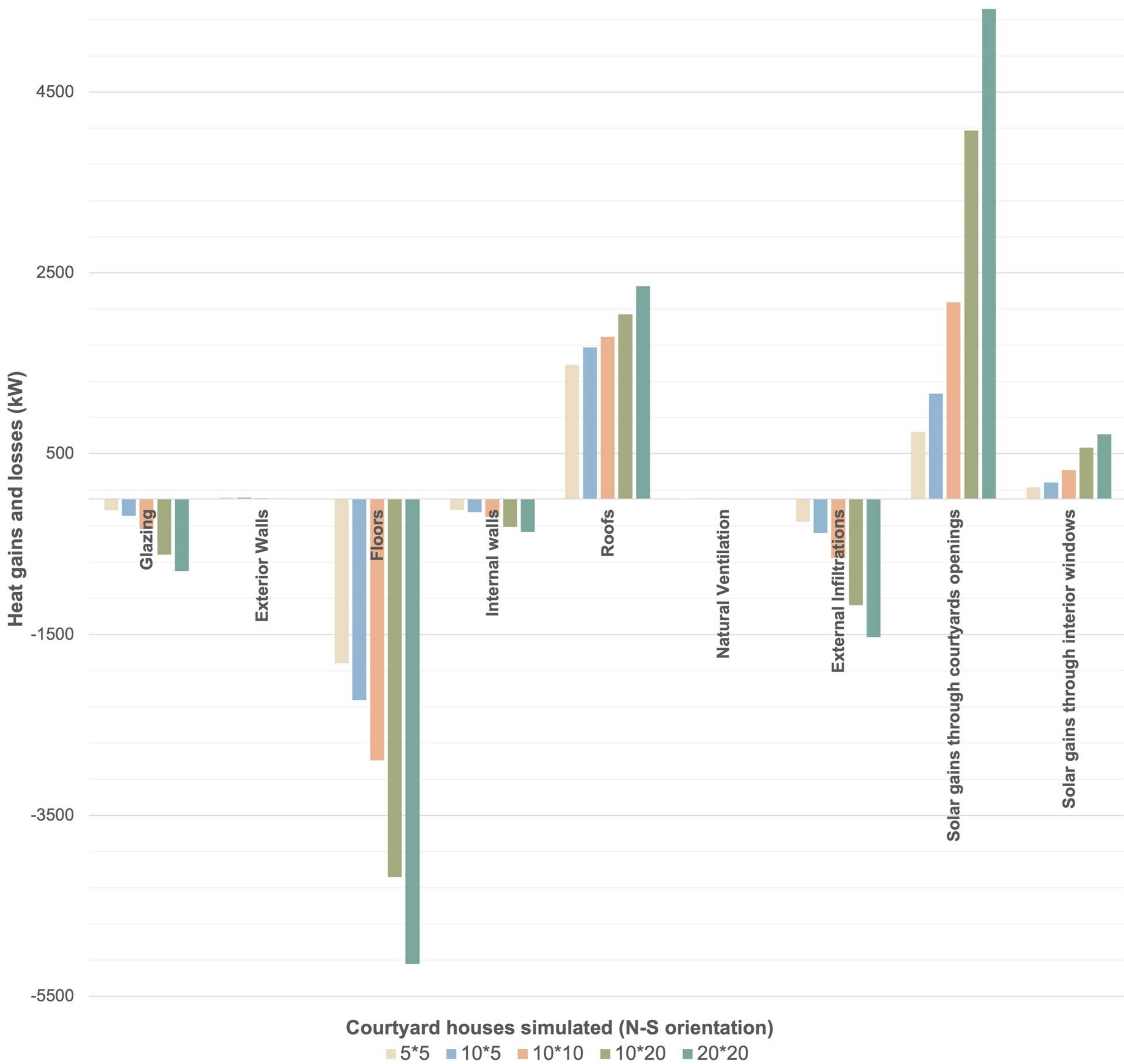

Fig. 10 Heat gains and losses according to different parameters of the simulated models. Cases with N-S orientation

gains per m^2 correspond to 7.55 kW, and in the 20*20 N-S case, the gains rise to 13.82 kW.

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, as is shown in Fig. 11.

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

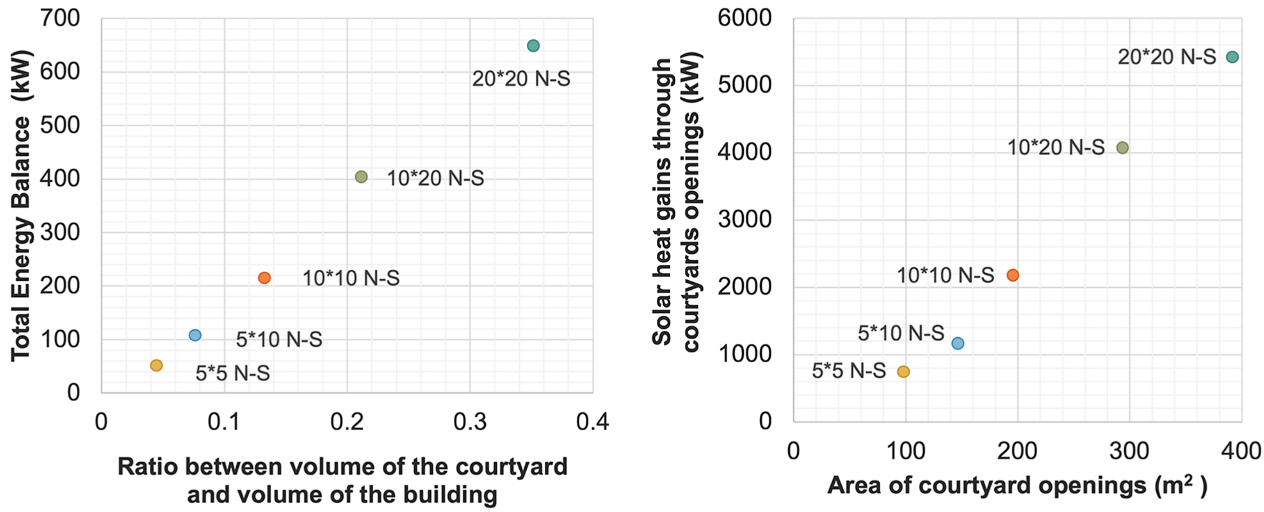

Fig. 11 Left: Total energy balance of the building related to the ratio between the volume of the courtyard and the volume of the building; Right: Solar heat gains related to the area of the courtyard openings

heat gains, operative temperature, and ventilation rate. The thermal zones analyzed inside the house consisted of two types: the enclosed rooms in the periphery of the building and the corridors that function as a transitional space between the courtyard and rooms (refer to Fig. 3). 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 12 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 11.5°C with a maximum temperature of 33.7 °C. Among the indoor thermal zones, higher swings were observed in the corridors in comparison with the rooms. When comparing the two ventilation strategies, a difference of 2.2 °C was observed in the thermal swings of the rooms. When windows were left 100% opened, the maximum and minimum got closer

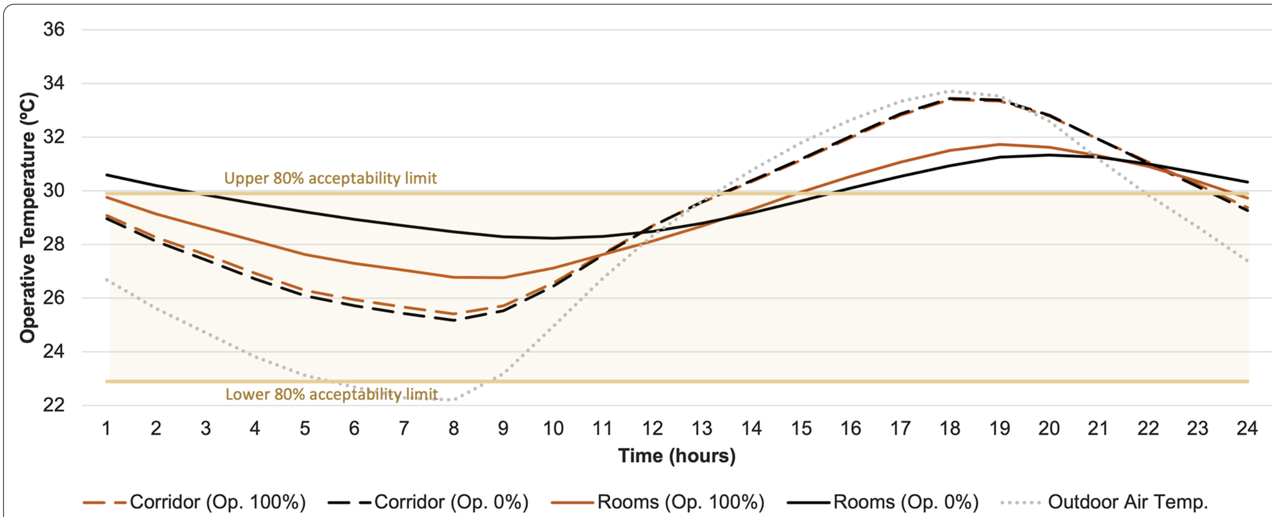

Fig. 12 24-hour thermal cycle of the spaces in the house with different ventilation strategies: windows of the rooms 0% opened and 100% opened 24/7. Case 5*5 N-S

to outdoor temperature than when windows remained closed. The maximums and minimums differed at 0.4 °C and 1.4 °C, 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 (9 hours). For this reason, maintaining windows open from 14.00 to 22.00 hrs 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 of 1.8 °C in the maximum temperatures of the corridors compared to the outdoor temperatures (Fig. 13). 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 0.2 °C higher, and in minimums, they remained 1.3 °C lower, compared to the rooms with windows that remained closed.

Anual thermal performance

Finally, annual operative temperatures data were obtained to determine the influence of proportions and orientation over a year. As shown in figure 14, the case with a lower percentage of hours outside the comfort limits corresponds to 5*5 N-S. On the contrary, the 20*20 cases with NE-SW, E-W and NW-SE orientations obtained the highest percentages (26%). When observing the annualized results, it was determined that courtyards with smaller dimensions in width and length promoted a greater number of hours within the comfort limits, as in the critical period of May. On the other hand, varying the orientations led to differences of 1% or less between cases with the same proportions.

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 gain and ventilation rates increased. Nevertheless, this did not greatly

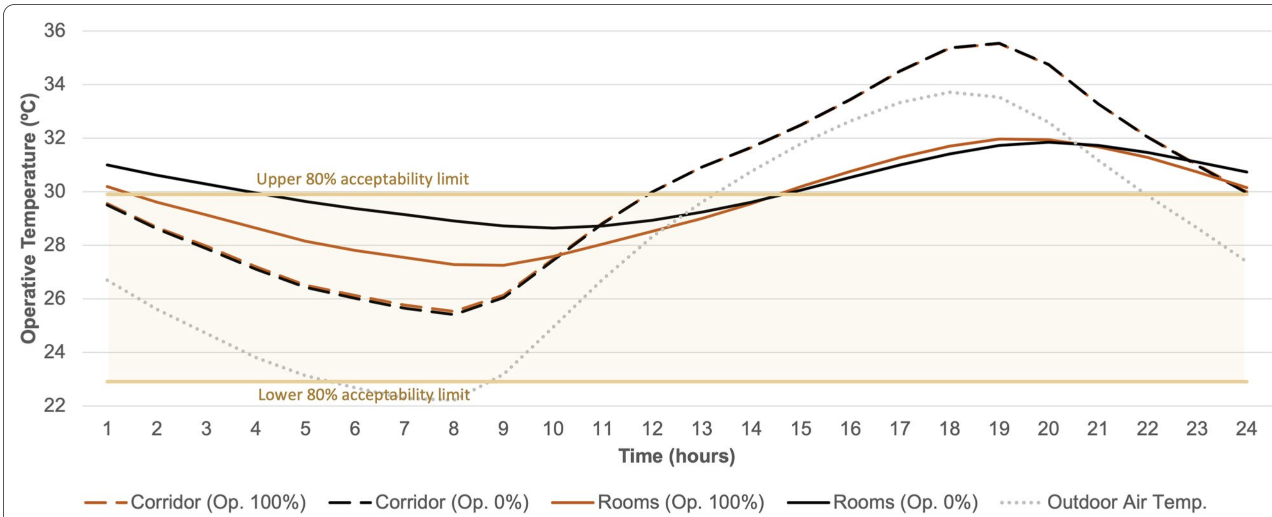

Fig. 13 24-hour thermal cycle of the spaces in the house with different ventilation strategies: windows of the rooms 0% opened and 100% opened 24/7. Case 20*20 NE-SW

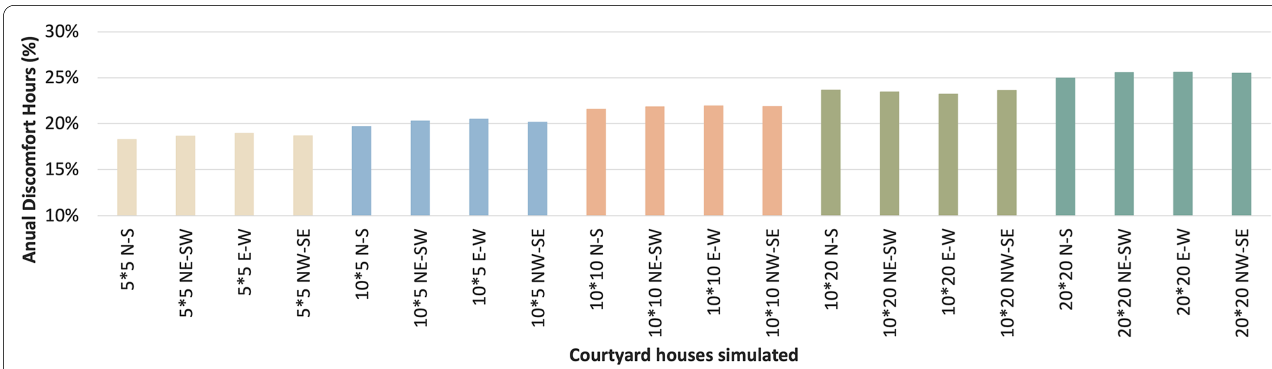

Fig. 14 Percentage of discomfortable hours during a year for the different proposed cases

influence the average operating temperature of the building since the differences among the cases with higher and lower operative temperatures were lower than 0.5 °C. However, if the maximum operative temperatures of the corridors were compared, these differences reached 2.1 °C.

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 during the day. This effect only amplifies as the width and length of the courtyard increase due to higher exposure to solar radiation (refer to Fig. 11). The more solar radiation is received, the more cooling is required in overheated conditions. This agrees with the findings of Doctor-Pingel et al., [45] 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.

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, 28], 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 [28]. When courtyards get wider, proper solar protection permeable to the wind on courtyard walls would be required [47].

Regarding the orientation, greater differences in results were shown between rectangular plan courtyards rather than squared ones when the buildings were rotated. This paper showed that lower heat gains were shown in courtyards with the long axis oriented E-W. This coincides with the findings of Taleghani et al. in the Netherlands [34].

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 [28]. In the cases proposed (Fig. 4), 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 [29] and consequently in thermal comfort [35].

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 [48], the three main functions of natural ventilation consist of replacing higher temperature indoor air with 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. 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 Figs. 12, 13). 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 [29]. Likewise, the results of this study reveal that the case with higher heat gains had higher ventilation rates (Figs. 6, 7).

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. 10). 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 [21].

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 results showed that solar heat gains and ventilation rates increase as the width and length of courtyards become greater, as was reported in previous studies. However, this does not have an important influence on the average operative temperature of the entire building. 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. When comparing the operative temperatures of the corridors between cases, higher differences were observed. In some cases (20*20 NW-SE), they exceed the outdoor temperature. 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 to 11.00 hrs could reduce the operative temperature by 1.4ºC depending on the case.

This paper was limited to courtyards' effect proportions and orientation on the thermal performance of inner spaces. 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.

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Author contributions

MGTG: Methodology, Investigation, Writing—Original draft preparation, Validation, Formal analysis. CJEL: Conceptualization, Supervision, Methodology, Reviewing and Editing, Formal analysis. AL: Methodology, Reviewing and Editing, Validation, Formal analysis. CEP: Supervision, Methodology, Writing—Reviewing and Editing, Validation, Formal analysis. All authors read and approved the final manuscript

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Availability of data and materials

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

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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