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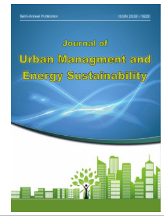

CASE STUDY RESEARCH PAPER

Evaluating the Impact of the Spatial Scale of Central Courtyards on Outdoor Thermal Comfort in High-Density Residential Complexes (Case Study: The Hot and Dry Climate of Shiraz City)

Ali Akbar Raoufat[1], Ali Akbar Heidari[2*], Abdol Hosein Paknezhadi[1], Hamid Eskandari[2]

1 Department of Urban Planning and Architecture, Yas.C., Islamic Azad University, Yasuj, Iran

*2*Department of Technical and engineering, Yasouj university, Yasouj, Iran*

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ABSTRACT

Optimizing the microclimatic behavior of outdoor spaces in high-density residential fabrics is one of the most effective strategies for mitigating human thermal stress and enhancing urban sustainability in hot and dry climates. Aiming to analyze the impacts of geometry, scale, and spatial organization on outdoor thermal comfort, this study evaluates 18 layout scenarios generated by combining four central courtyard typologieswithin a high-density residential complex in Shiraz. The evaluations were conducted under the most critical summer conditions using numerical microclimate simulations. The analytical findings reveal that transitioning from the large-scale, single-courtyard reference model to fragmented and decentralized spatial configurations consistently leads to a reduction in air temperature and mean radiant temperature (Tmrt), thereby improving the Physiological Equivalent Temperature (PET) index across all scenarios. Analyzing the thermodynamic mechanisms governing the spaces indicates that the radiative load (Tmrt) is the primary driver of thermal perception in this climate. The fine-grained square and medium-sized rectangular typologies exhibit the most successful performance in mitigating solar radiative energy and lowering the PET index, primarily due to the reduction of the Sky View Factor (SVF) and the creation of self-shading by the physical built form. Conversely, spacious courtyards transform into thermal traps owing to their low degree of enclosure. Regarding wind flow and relative humidity components, although elongated geometries offer better aerodynamic potential for airflow passage, the minor reduction in wind velocity in fine-grained fabrics due to physical roughness is entirely negligible when compared to the positive effects of shading on mitigating the radiative load. Ultimately, this research emphasizes that the smart combination of compact and linear fine-grained layouts represents the most effective design strategy for achieving sustainable outdoor thermal comfort in residential complexes within hot and dry regions.

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Running Title: Spatial Scale of Central Courtyards on Outdoor Thermal Comfort

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21	16	04

*Corresponding Author:
Email: *Aliakbarheidari.iust@gmail.com*
Phone: +981152226605
ORCID: https://orcid.org/0000-0002-6995-8140

INTRODUCTION

The simultaneous rise in ambient air temperatures, the increasing frequency of heatwaves, and the intensification of the Urban Heat Island (UHI) effect have rendered the livability and quality of outdoor spaces in high-density residential fabrics one of the fundamental challenges in contemporary architecture and urban planning. This issue is highly complex in hot and dry climates due to intense solar radiation, significant diurnal temperature fluctuations, and limited energy resources. Under such circumstances, providing usable outdoor environments characterized by acceptable outdoor thermal comfort conditions has become a primary prerequisite for designing residential complexes. Prior research has demonstrated that a substantial portion of users' thermal discomfort in urban outdoor spaces is not solely dictated by macroclimatic conditions, but is heavily dependent on microclimatic regulation at the architectural scale; a domain where form, geometry, and spatial organization directly govern radiation balance, shading patterns, and natural ventilation capacity (Emmanuel et al., 2007; Johansson et al., 2014).

Over the past two decades, a significant portion of international research in climate-responsive design and thermal environments has focused on evaluating and optimizing outdoor thermal comfort using integrated indices such as the Physiologically Equivalent Temperature (PET) and the Universal Thermal Climate Index (UTCI). These studies have shown that parameters such as the aspect ratio (H/W), the degree of enclosure, geometric orientation, shading conditions, and the quality of surface radiative exchanges play a decisive role in modulating the mean radiant temperature (Tmrt) and mitigating human thermal stress (Höppe, 1999; Matzarakis et al., 1999). Nonetheless, the majority of these studies have focused on public outdoor spaces such as streets, plazas, and urban canyons while paying less attention to semi-private, inner-block open spaces within residential complexes. Furthermore, in many of these studies, courtyard form has only been treated as a secondary variable rather than an independent and influential spatial-climatic system (Taleghani et al., 2015; Lin et al., 2010).

In this context, the central courtyard, as one of the oldest and most efficient spatial organization typologies in the architecture of hot and dry regions, offers a high capacity for regulating thermal conditions and enhancing environmental quality. Courtyards can establish a favorable localized microclimate by controlling solar heat gain, increasing shading, regulating radiative exchange between surfaces and the air, and providing a viable platform for natural ventilation. Various studies have indicated that attributes such as courtyard geometry, orientation, aspect ratios, the location and type of openings, envelope materials, and landscape elements are among the most critical factors influencing the microclimatic performance of these spaces. Therefore, implementing an integrated, climate-responsive design strategy for courtyards can serve as an effective tool for reducing energy consumption and improving thermal comfort (Zhu et al., 2023).

Despite these findings, the bulk of existing research on courtyards has predominantly focused on traditional single-case studies, detached courtyard houses, or comparisons between a limited number of forms. Consequently, they have rarely addressed how altering the spatial scale of central courtyards within contemporary high-density residential typologies affects outdoor thermal comfort. This research gap is particularly prominent in hot and dry Iranian cities, where new spatial patterns of open space organization are emerging alongside rising building densities. In such scenarios, merely verifying the presence or absence of a courtyard is insufficient; rather, the division, distribution, and scaling of inner-block open space must be investigated as an influential design variable.

From this perspective, the concept of the "spatial scale of the courtyard" refers not only to the dimensions of an isolated open space but to the manner in which a fixed area of open space is partitioned and configured into different geometric patterns. This partitioning can simultaneously affect shading intensity, ventilation capacity, the degree of enclosure, and ultimately, thermal comfort indices. In other words, in high-density residential complexes where the open space area is typically fixed due to planning and economic constraints, the question arises: does distributing this fixed area into several smaller courtyards yield a more favorable microclimatic performance, or does concentrating it into larger, continuous courtyards provide better conditions for thermal comfort?

Accordingly, the present study aims to evaluate the impact of utilizing different spatial scales of central courtyards on outdoor thermal comfort within high-density urban residential complexes in the hot and dry climate of Shiraz. In this study, while keeping the total open space area and the overall building volume constant, a set of distinct courtyard distribution patterns categorized into three groupssmall-scale, medium-scale, and large-scaleis defined, and their performance is compared under the critical climatic conditions of the hottest representative day. To this end, numerical microclimate simulations using ENVI-met and the PET index are utilized, alongside climatic variables including air temperature, mean radiant temperature (Tmrt), relative humidity, and wind velocity.

MATERIALS AND METHODS

Methodology

This study employs a quantitative-analytical approach based on numerical microclimate simulation to evaluate the impact of different spatial scales of central courtyards on outdoor thermal comfort within high-density residential complexes in the hot and dry climate of Shiraz. To control confounding variables and enable an accurate comparison among various spatial configurations, the total built footprint, building heights, and the total open space area were kept constant across all scenarios. Only the layout, number, and scale of the courtyards were varied as the independent variables. This controlled approach isolates the net effect of the "courtyard spatial scale" on thermal comfort indices. The research workflow is based on the geometric modeling of the configurations and the simulation of their thermal behavior under realistic microclimatic conditions. In the first phase, different courtyard distribution typologies within the building mass were defined and constructed in the modeling environment. Subsequently, representative meteorological boundary conditions for Shiraz during the selected critical day were inputted into the simulation engine to analyze the thermal performance of each scenario over a designated temporal range. During this process, parameters such as air temperature (Ta), mean radiant temperature (Tmrt), relative humidity (RH), wind velocity (Va), and the Physiologically Equivalent Temperature (PET) index were evaluated as the dependent variables to assess the outdoor thermal comfort conditions.

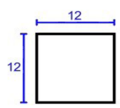
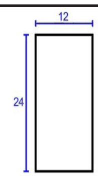
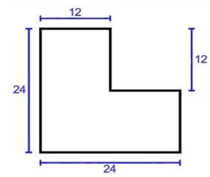
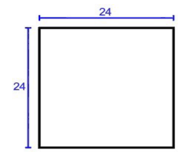
The core logic of this methodology is that outdoor thermal comfort results from the simultaneous interaction of physical built form, the distribution of spatial voids, and ambient macroclimatic conditions; thus, numerical microclimate simulation offers a controlled environment to isolate the independent effect of each spatial layout. Additionally, to enhance the analytical validity and reliability of the findings, a reference model was established as a baseline for comparison. This allows for the evaluation of the proposed configurations against the conventional single-courtyard layout traditionally found in the architecture of hot and dry climates.

Also, the simulation day (July 6, 2018) was identified through statistical analysis of the TMY climate file for Shiraz as the hottest representative day exhibiting peak thermal stress conditions, consistent with established practice comfort studies for hot-arid climates (Sadeghi & Bahadori, 2021).

Case Study Descriptions

To achieve high analytical accuracy in evaluating the impact of the "spatial scale" on the thermal behavior of outdoor spaces, the modeling strategy of this study was developed based on a systematic laboratory matrix utilizing a parametric design approach. In the first phase, four basic configurations (geometric modules) of varying scales were defined: Typology A (a small square with an area of 144 m2 and dimensions of 12×12 m), Typology B (a rectangle with an area of 288 m2 and dimensions of 12×24 m), Typology C (an L-shaped geometry with an area of 432 m2 and 12-m wide wings), and Typology D (a large square with an area of 576 m2 and dimensions of 24×24 m) (Tab. 1).

Table l: Classification of Different Courtyard Plan Configurations Examined in This Study

			
Courtyard Form Type: A	Courtyard Form Type: B	Courtyard Form Type: C	Courtyard Form Type: D
Courtyard Area: 144 m2	Courtyard Area: 288 m2	Courtyard Area: 432 m2	Courtyard Area: 576 m2
Courtyard Scale Category: Small Scale	Courtyard Scale Category: Small Scale	Courtyard Scale Category: Large Scale	Courtyard Scale Category: Large Scale

Subsequently, to generate the optimal configurations, the Wasp plugin within the Grasshopper parametric environment was utilized. This generative design process produced an initial design space comprising 153 layout variations of the aforementioned typologies on the site. From this pool, 18 case studies were systematically selected based on distribution scenarios corresponding to the three spatial scales. In the medium-scale category (Case_01 to Case_06), the four typologies are balanced across the site to evaluate the "optimal state" combining spatial continuity with microclimatic permeability. In the small-scale category (Case_07 to Case_12), Typologies A and B dominate to investigate the impact of spatial fragmentation on shading and radiative exchange. Conversely, in the large-scale category (Case_13 to Case_18), Typologies C and D are predominant, focusing on spatial concentration and examining the thermal behavior of large-scale open spaces.

In addition to these scenarios, a "reference model" (Case_Ref) consisting of the base built mass and a single square courtyard with dimensions of 48×48 m at the geometric center of the site was defined. This reference model represents the traditional central courtyard layout in Iranian residential fabrics and serves as the baseline for evaluating thermal performance (Fig. 1). To ensure comparative validity and eliminate confounding variables, all configurations were modeled on a single site with a fixed area of 9216 m2 and a uniform building height of 4 stories. Furthermore, the cumulative open space area was kept constant at 2304 m2 across all configurations. This standardization of physical parameters isolates geometry and spatial configuration as the sole independent variables, allowing for the precise extraction of thermal behavior dictated by the scale and distribution pattern of the courtyards under the environmental conditions of the hottest representative day. Tables 2 and 3 present the physical characteristics of the courtyard configurations in each case study, as well as the geometry and layout of the courtyards within each model, respectively. (Fig. 1 and Tab. 2)

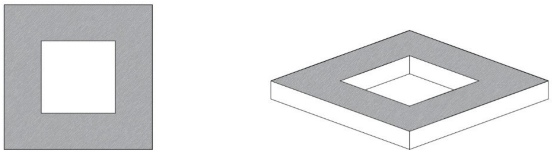


Figure1: Plan and Perspective Views of the Reference Model (Case_Ref)

Software Settings

To conduct physical modeling, numerical microclimate simulation, and the assessment of thermal comfort conditions, ENVI-met software (version 5.6.1) was employed. The simulation workflow was carried out in a stepwise manner using the specialized modules of the software. First, the three-dimensional geometry of the building masses, open spaces, and the configuration of the proposed patterns was modeled in the Spaces module. Next, boundary conditions, simulation timing, and baseline climatic data were defined in ENVI-guide, while microclimatic dynamic calculations were performed by the ENVI-core processing engine. Subsequently, human-biometeorological thermal comfort indices were evaluated in the BIO-met module. Finally, data extraction and the generation of contour maps illustrating the spatial distribution of environmental variables, including air temperature (Ta), mean radiant temperature (Tmrt), relative humidity (RH), wind velocity (v), and physiologically equivalent temperature (PET), were carried out using the Leonardo module. A summary of the input parameters and baseline simulation settings applied in the software is presented in (Tab. 4).

Table 2: Physical Characteristics of the Investigated Case Studies

Case Study ID	Spatial Scale Classification	Total Number of Courtyards	Number of Typology A Courtyards	Number of Typology B Courtyards	Number of Typology C Courtyards	Number of Typology D Courtyards
Case_ref	-	1	-	-	-	-
Case_01	Medium-scale	10	8	0	0	2
Case_02	Medium-scale	6	0	4	0	2
Case_03	Medium-scale	8	4	2	0	2
Case_04	Medium-scale	8	4	2	0	2
Case_05	Medium-scale	9	6	1	0	2
Case_06	Medium-scale	7	2	3	0	2
Case_07	Small-scale	12	10	0	2	0
Case_08	Small-scale	8	0	8	0	0
Case_09	Small-scale	12	8	4	0	0
Case_10	Small-scale	10	4	6	0	0
Case_11	Small-scale	10	6	2	2	0
Case_12	Small-scale	10	7	1	1	1
Case_13	Large-scale	4	0	0	0	4
Case_14	Large-scale	6	1	0	5	0
Case_15	Large-scale	5	0	0	4	1
Case_16	Large-scale	6	2	0	2	2
Case_17	Large-scale	6	0	3	2	1
Case_18	Large-scale	7	2	2	2	1

Table 3: Spatial Geometry and Spatial Layout of Micro-Courtyards within the Investigated Case Studies

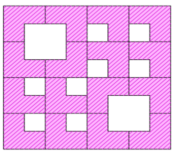
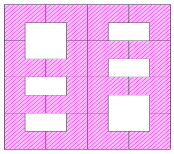
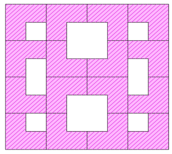
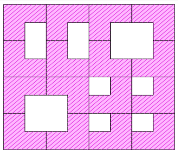
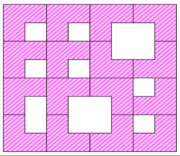
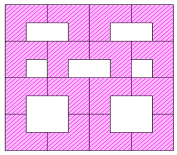
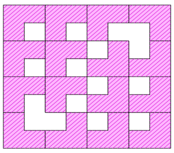
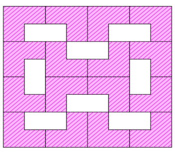
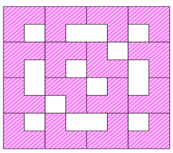
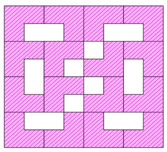
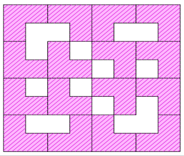
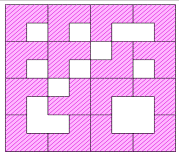
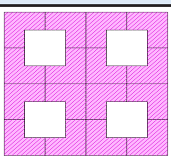
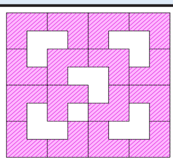
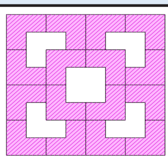
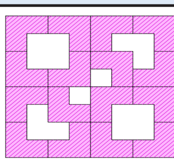
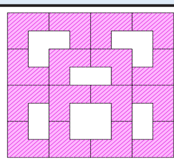
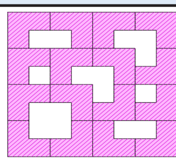
					
Case_01	Case_02	Case_03	Case_04	Case_05	Case_06
					
Case_07	Case_08	Case_09	Case_10	Case_11	Case_12
					
Case_13	Case_14	Case_15	Case_16	Case_17	Case_18

Table 4: Input Parameters and Initial Boundary Conditions for the ENVI-met Simulation

Input Parameters in the Spaces Module	Position on earth:	Shiraz (Latitude: 29.61; Longitude: 52.53)
	DEM Reference level:	1500
	Model Dimensions:	x-Grids: 224 y-Grids: 224 z-Grids: 36
	Size of grid cell in meter:	dx= 1 dy= 1 dz= 1
	Model rotation out of grid north:	+71°
	Default Settings for Walls and Roofs:	Wall Material: [0200C2] Concrete wall (light weight)
		Roof Material: [0200C2] Concrete wall (light weight)
	Setting for Nesting Grids:	Nr of nesting grids: 5 Soil A: [0200LO] Loamy Soil Soil B: [0200LO] Loamy Soil
Input Parameters in the ENVI-guide Module	Simulation Day:	The hottest representative day
	Start Date (YYYY-MM-DD):	2018-07-06
	Total Simulation Time (h):	7 h (Start Time: 9:00)
	Meteorological Data:	IRN_FA_Shiraz-Dastgheyb.Intl.AP.408480_TMYx.2004-2018.epw
Input Parameters in the BIO-met Module	Body parameters:	Age of person (y): 35; Gender: Male; Weight (kg): 75.00; Height (m): 1.75; Body Position: Standing; Surface Area (DuBois-Area): 1.91 m2
	Clothing parameters:	Static Insulation Outdoor (clo): 0.90 Indoor (clo): 0.90

Input Parameters in the BIO-met Module	Persons metabolism:	Total Metabolic rate (W): 164.49(=86.21 W/m2) (met): 1.48

The thermophysical properties of the materials applied to enclosing surfaces and ground coverings were defined in the software to ensure an accurate representation of the thermal behavior of the environment. Accordingly, lightweight concrete (Concrete Wall Light Weight, ID: 0200C2) was assigned to the walls and roofs of the buildings. For the ground surfaces, light concrete pavement (Concrete Pavement Light, ID: PL) was used for the courtyard floors and open spaces of the residential complex, while used/dirty concrete pavement (Pavement Concrete used/dirty, ID: PP) was applied to the peripheral walkways. In addition, loamy soil (Loamy Soil, ID: LO) was specified for the exposed soil surfaces surrounding the site and the planted beds, asphalt road (Asphalt Road, ID: ST) was used for vehicular access routes, and deep water (Deep Water, ID: WW) was assigned to water surfaces, so that surface thermal exchange and radiative reflectance could be calculated with a high degree of accuracy.

Software Validation

To evaluate the degree of agreement and assess the accuracy of the developed numerical model in simulating microclimatic parameters, a validation procedure for ENVI-met software (version 5.6.1) was conducted. For this purpose, the central courtyard of the historical “Khan School” of Shiraz, dating back to the Safavid period, was selected as the reference case for field measurements (Fig. 2). Climatic variables, including air temperature (Ta), relative humidity (RH), and wind velocity (v), were recorded on 15 June 2026 (corresponding to 25 Khordad 1405 in the Iranian calendar) over a 10-hour monitoring period from 09:00 to 18:00 at one-hour intervals. Field measurements were carried out at pedestrian level (1.5 m above ground level) using a calibrated multifunctional data logger, model WBGT-2010SD (Fig. 3).

The three-dimensional geometric model of Khan School was reconstructed in the Spaces module based on the existing architectural drawings, while atmospheric boundary conditions corresponding to the meteorological data obtained from the Shiraz synoptic weather station on the measurement day were defined in the ENVI-guide module. Monitoring was performed in both the empirical and simulation phases at four strategic points (Points 1–4), as illustrated in Figure 4. The graphical outputs representing the spatial distribution of climatic variables during peak solar radiation hours are presented in Figures 5 to 7.

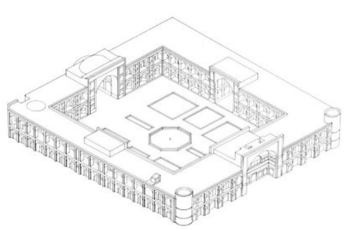


Figure 2: Three-Dimensional View of Khan School, Shiraz (Image source:UTRAVS.com)

Figure 3: WBGT-2010SD Multifunction Data Logger Used for Field Measurements

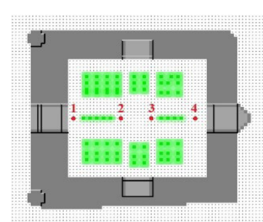


Figure 4: Four Field Measurement Points in the Central Courtyard of Khan School

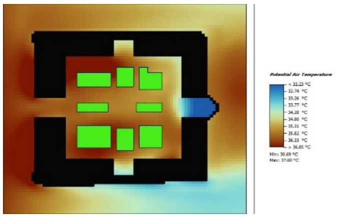


Figure 5: Air Temperature Contour Map for the Validation Model

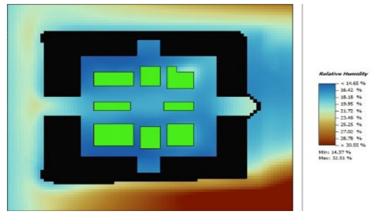


Figure 6: Relative Humidity Contour Map for the Validation Model

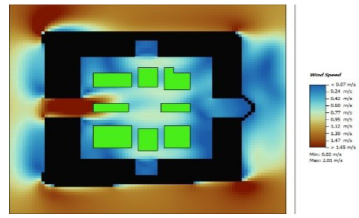


Figure 7: Wind Velocity Contour Map for the Validation Model

The historic Khan School courtyard was selected for empirical validation due to its direct geometric congruence with the single central courtyard baseline scenario (Case_Ref), as well as its historical mixed educational-residential typology featuring living cells (Hojrehs). In outdoor thermal comfort research, microclimatic modeling focuses on boundary-layer heat exchange, solar radiation attenuation, and convective fluxes, which are primarily governed by urban canyon morphology and thermophysical envelope properties rather than indoor occupancy type.

For comparative analysis, the values obtained from numerical simulations and field measurements were plotted as correlation diagrams and hourly trend graphs (Fig .8- Fig. 10).

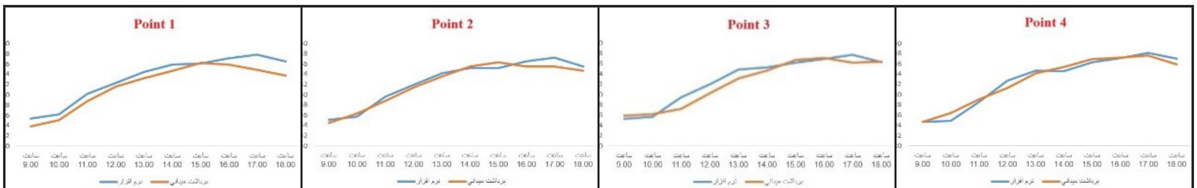


Figure 8: Comparison of Air Temperature between the Validation Model and Field Measurements at Points 1–4

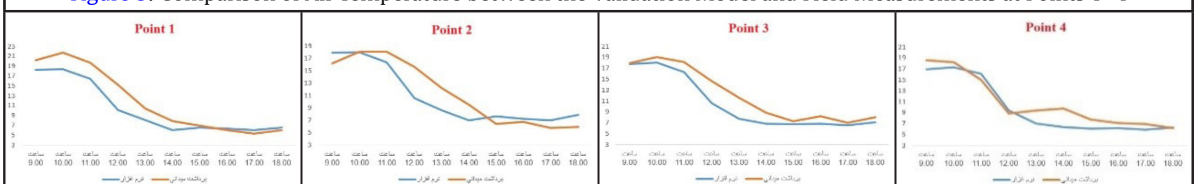


Figure 9: Comparison of Relative Humidity between the Validation Model and Field Measurements at Points 1–4

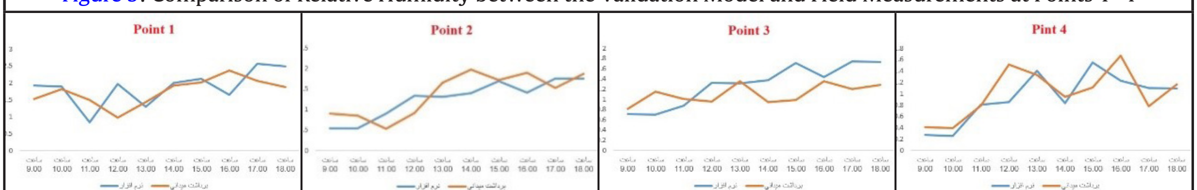


Figure 10: Comparison of Wind Velocity between the Validation Model and Field Measurements at Points 1–4

A comparative analysis of descriptive statistics and relative error evaluation indicates a high degree of agreement between the simulated data and the field measurements. For the air temperature component, the mean empirical value was calculated as 42.29°C compared to a simulated mean of 42.89°C, yielding a negligible relative error of 1.42%. In the relative humidity parameter, the actual and simulated mean values were recorded as 11.55% and 10.31%, respectively, revealing a relative error of 10.74%. Finally, the mean wind velocity was estimated at 1.3 m/s in empirical conditions and 1.33 m/s in the numerical model, corresponding to a relative error of 2.31%. Given that the calculated errors for all parameters fall well within the standard and scientifically accepted threshold (less than 15%), the performance of the ENVI-met software in reproducing the microclimatic conditions of the study area is validated, confirming that the numerical model possesses sufficient reliability for subsequent scenario evaluations.

The validation results demonstrated high predictive accuracy with relative errors of 1.42% for air temperature and 2.31% for wind velocity. The slightly higher relative error observed for relative humidity (10.74%) is mathematically attributable to the low absolute baseline humidity typical of Shiraz summers (<20%), where minor absolute variances (≈1.5%) yield amplified percentage error values, alongside localized evaporative fluxes from the courtyard's central basin. Nevertheless, all errors remain comfortably below the accepted 15% validation threshold, confirming the software's capability to replicate microclimatic phenomena in Shiraz.

FINDINGS AND DISCUSSION

Analysis of Findings

In the findings section of this study, the thermal performance of different central courtyard organizational patterns was evaluated using five principal indicators, including air temperature, mean radiant temperature, relative humidity, wind velocity, and the Physiologically Equivalent Temperature (PET), in order to provide a multidimensional analysis of how variations in courtyard spatial scale affect microclimatic quality and the level of outdoor thermal comfort in high-density residential complexes. Since thermal comfort in outdoor environments is a multifactorial phenomenon and cannot be adequately explained by a single variable alone, the simultaneous analysis of these five indicators allows for a more precise understanding of how the spatial configuration of courtyards influences the balance between solar exposure, ventilation, temperature moderation, and human thermal response.

Accordingly, the findings presented in this section not only demonstrate the differences in thermal performance among the investigated cases with respect to each indicator independently, but also collectively provide a basis for an integrated interpretation of the relationship between the spatial scale of the central courtyard and the level of thermal comfort under the hot and dry climatic conditions of Shiraz. All values obtained for the five aforementioned indicators were evaluated at a height of 1.5 m above ground level and within the time interval between 10:00 and 16:00, corresponding to the peak heat hours on the hottest representative day, using ENVI-met software.

Air Temperature (Ta)

Air temperature (Ta) is one of the most fundamental climatic variables in the assessment of outdoor thermal comfort, as it represents the temperature of the ambient air surrounding the human body and directly influences the convective heat exchange between the body and the environment. Consequently, in microclimatic studies, air temperature serves not only as an indicator to measure the intensity of environmental heating but also as a basis for interpreting the thermal performance of different spatial organization patterns (Ahmad et al., 2016; Spiridonov & Curic, 2021).

An examination of the air temperature variations across the investigated case studies reveals that all proposed configurations achieved a reduction in air temperature compared to the reference model (Fig. 11); this trend highlights the significant impact of altering the scale and distribution of central courtyards on moderating outdoor thermal conditions. Among the configurations, the lowest air temperature was recorded in Case_01 at 47.93°C, whereas the highest value was observed in Case_Ref at 51.15°C. Therefore, it can be inferred that reorganizing the open space from a single, unified central courtyard into multi-courtyard patterns leads to a tangible reduction in air temperature, even when the total open space area, building footprint, and building heights are kept constant. This finding is particularly significant as it demonstrates that the determining factor in this study is not the quantity of open space, but rather its geometric organization and spatial distribution.

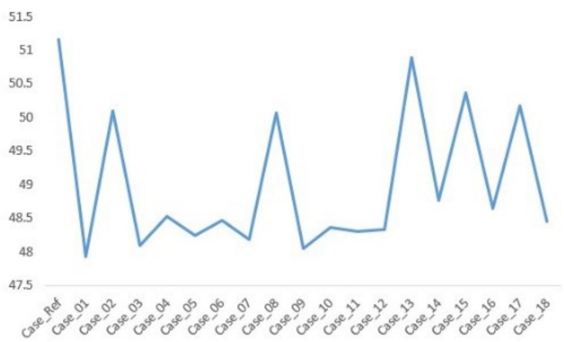


Figure11: Overall Air Temperature Variations during the hottest representative day
between 10:00 and 16:00 across All Configurations

From an analytical perspective, the superiority of Case_01 can be explained by its spatial structure. Classified under the medium-scale category, this configuration comprises eight Typology A courtyards and two Typology D courtyards. The predominance of small, square 12×12 m courtyards in this scenario increases the aspect ratio (H/W) across most of the open spaces, thereby enhancing the shading capacity of the building envelopes during the hottest hours of the day. Since the building height remains constant at 12 m in all cases, the Typology A courtyards with an aspect ratio of H/W=1 possess a higher potential to restrict incoming direct solar radiation compared to larger configurations. Consequently, fragmenting the open space into a greater number of small courtyards, particularly when the proportion of micro-scale courtyards is high, effectively mitigates the heating intensity of the air mass adjacent to the surfaces, yielding the lowest air temperature among all investigated scenarios. Conversely, Case_Ref, which exhibits the poorest thermal performance in terms of air temperature, consists of a single, unified central courtyard measuring 48×48 m. Despite having the same total open-space area as the other configurations, this courtyard offers significantly lower shading depth due to its extensive spatial scale. Consequently, a vast portion of its surface area is exposed to direct solar radiation, particularly during peak radiation hours on the hottest representative day. As a result, the air adjacent to the ground and building envelopes absorbs more heat, causing this layout to record the highest air temperature among all cases. This demonstrates that consolidating the open space, when accompanied by an excessive increase in sun-exposed surfaces, does not necessarily improve thermal conditions in hot and dry climates.

Among the proposed scenarios, Case_13 (with a temperature of 50.89°C) exhibited the closest performance to the reference model. This case is composed entirely of four Typology D courtyards. Thus, although its open space is fragmented compared to the reference model, this fragmentation occurs solely in the form of large 24×24 m square courtyards. Consequently, the majority of the open spaces remain relatively wide and sun-exposed, and the shading capacity of the building walls is more restricted than in the small-scale courtyards. This finding indicates that the mere fragmentation of open space, without an actual reduction in courtyard scale, does not guarantee a meaningful moderation of air temperature.

Similarly, Case_02, Case_08, Case_15, and Case_17 recorded temperatures exceeding 50°C, placing them among the relatively weaker configurations. The reasons for this performance can be explained by analyzing their spatial compositions. Case_02, which belongs to the medium-scale group, consists of four Typology B courtyards and two Typology D courtyards. Although it features greater geometric diversity compared to Case_13, the absence of Typology A courtyards and the presence of two large Typology D courtyards ensure that the proportion of open, sun-exposed surfaces remains high. Case_08, despite being classified under the small-scale category, consists entirely of eight Typology B courtyards. This reveals that classification within a small-scale category alone does not guarantee superior thermal performance; the specific geometry of the courtyard is of primary importance. In Typology B (12×24 m), one of the courtyard axes is elongated, which can expose a larger surface area to solar radiation during certain hours of the day, thereby leading to weaker thermal performance compared to the small, square Typology A courtyard.

The same logic applies to Case_15 and Case_17. Case_15 contains four Typology C courtyards and one Typology D courtyard, meaning its dominant share is defined by large-scale layouts. Although the L-shaped geometry can generate localized and non-uniform shading at certain times, the fact that these patterns belong to the large-scale category means that substantial portions of the open space remain exposed to direct solar radiation. Case_17, combining three Typology B, two Typology C, and one Typology D courtyards, represents a configuration where the simultaneous presence of elongated and large-scale courtyards counteracts the cooling effect of the smaller courtyards, maintaining the air temperature at a relatively high level. Therefore, increasing the number of courtyards is not, by itself, a sufficient criterion for improving thermal performance; rather, the ratio between small, compact courtyards and larger or elongated ones is the key determining factor in air temperature control.

A distinct pattern is also observable when comparing the three primary scale categories. In general, configurations with a higher proportion of Typology A courtyards exhibit a greater capacity for air temperature reduction. Due to their limited dimensions and compact form, these courtyards benefit the most from the self-shading of the building walls. In contrast, configurations dominated by Typologies C and D, despite having the same total open-space area as the other models, are more prone to higher air temperatures due to their larger openness and increased exposure to solar radiation. The medium-scale group performed optimally only when its balance was shifted in favor of Typology A courtyards, as demonstrated by Case_01, which achieved the best performance overall despite its medium-scale classification. This highlights that within the spatial scale classification, the actual weight of each courtyard typology in the final composition is more critical than the general group designation.

In conclusion, the results in this section indicate that in the hot and dry climate of Shiraz during the hottest representative day air temperature reduction in the open spaces of high-density residential complexes depends primarily on the fine-grained, compact, and controlled fragmentation of the courtyards. In other words, the more the open space is transformed from a large, unified courtyard into a collection of smaller, more compact, and shaded courtyards, the greater the potential for air temperature reduction. Conversely, the continued use of large-scale courtyards, even when separated into multiple units, offers less air temperature moderation due to decreased shading efficiency and increased sun-exposed area. Therefore, it can be concluded that in designing high-density residential complexes in this climate, utilizing multi-courtyard layouts dominated by small, square courtyards is a more effective strategy for improving outdoor thermal conditions than relying on a single, unified central courtyard or large-scale courtyard configurations.

Mean Radiant Temperature (MRT)

Mean radiant temperature (MRT) is one of the key indicators for assessing outdoor thermal comfort, as it represents the combined effects of incident and reflected radiation from surrounding surfaces on the human body. More precisely, MRT is defined as the uniform temperature of an idealized environment with diffuse radiation in which the net radiant heat exchange rate between the human body and the surrounding surfaces is equivalent to that in the actual environment (Fanger, 1970; Thorsson et al., 2007). Given the substantial contribution of solar radiation to thermal stress in hot and dry climates, particularly on the hottest representative day, this indicator plays a decisive role in explaining the thermal performance of central courtyards (Atmaca et al., 2007).

An examination of the simulation results indicates that, during the period from 10:00 to 16:00, the highest mean radiant temperature was recorded in Case_Ref, whereas the lowest value was observed in Case_01. The MRT values for these two cases were 63.44°C and 57.35°C, respectively, indicating a considerable difference of 6.09°C between the least and the most thermally favorable configurations examined (Fig. 12). This difference is highly significant from an outdoor thermal comfort perspective because, unlike air temperature, MRT is directly related to the degree of human exposure to radiation and to the thermal conditions of surrounding surfaces. Therefore, even variations of only a few degrees in MRT can substantially intensify or alleviate thermal stress.

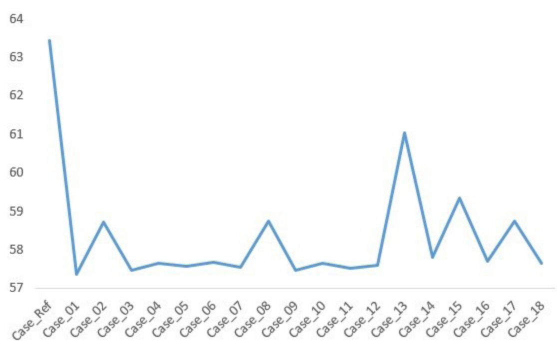


Figure 12: Overall Mean Radiant Temperature Variations during the hottest representative day between 10:00 and 16:00 across All Configurations

It is crucial to note that all proposed configurations achieved a reduction in MRT compared to Case_Ref. This finding demonstrates that altering the spatial organization of the courtyards, even without changing the total open-space area, site dimensions, or building heights, successfully mitigated the intensity of the radiant load imposed on the outdoor space. Therefore, consistent with the observations for the air temperature index, the primary driver of improvement in the MRT index was not the reduction of outdoor space area, but rather the geometric rearrangement and spatial redistribution of the courtyards. Since MRT is predominantly a function of direct solar radiation, surface reflection, and the sky view factor (SVF), the reduction of this index in the proposed configurations can be attributed to increased shading, the fragmentation of the unified open surface, and the limitation of the extent of sun-exposed surfaces.

As with air temperature, the best performance in this index was achieved by Case_01. This configuration, combining eight Typology A courtyards and two Typology D courtyards, features a structure where the dominant share of open spaces consists of small and compact courtyards. Under these conditions, a major portion of the courtyard floors and adjacent walls are less exposed to direct solar radiation during peak hours. Because Typology A courtyards measure 12×12 m and have an aspect ratio of H/W=1, the surrounding walls can cast shadows over the courtyard surface for a greater number of hours during the day. The direct consequence of this condition is a reduction in surface temperatures and, consequently, a decrease in the reflected radiation emitted toward the human body—a factor that led to a significant drop in MRT in this case. In other words, in Case_01, not only is the ambient air cooler, but the radiant load acting on the human body is also reduced, which is of paramount importance for outdoor thermal comfort.

Conversely, Case_Ref recorded the highest MRT value due to its single, unified, and square central courtyard measuring 48×48 m. In this model, the aspect ratio is considerably lower than that of the smaller courtyards, exposing a vast area of the courtyard floor to direct solar radiation during the middle of the day. Furthermore, the unity of the open space results in a high sky view factor (SVF) across a large portion of the courtyard, increasing the direct absorption of shortwave radiation and mutual reflections between surfaces. Consequently, the temperature of the surrounding surfaces and the effective radiation acting on the human body increase, placing the MRT at its highest level. This result indicates that in hot and dry climates, although the unified central courtyard pattern has historical precedent, it does not necessarily deliver the optimal thermal response at larger scales and within contemporary high-density complexes.

Following Case_Ref, the closest MRT value to the reference model was recorded by Case_13 at 61.04°C. This scenario consists entirely of four Typology D courtyards; thus, although the open space is divided into several sections, each section still falls under the category of large-scale courtyards. Consequently, the fragmentation of the open space in this case did not result in an effective reduction in the sky view factor (SVF) or a significant increase in shading capacity. In other words, Case_13 demonstrates that the fragmentation of open space is effective in reducing MRT only when accompanied by an actual reduction in courtyard scale and an increase in spatial enclosure; otherwise, large, separated courtyards exhibit thermal behavior close to that of the reference model.

Following Case_13, configurations Case_15, Case_17, Case_08, and Case_02 recorded higher MRT values compared to the other proposed layouts. This result can be clearly explained from a geometric perspective. Case_15, which includes four Typology C courtyards and one Typology D courtyard, represents a layout dominated by large-scale and semi-open configurations. Although the L-shaped geometry can generate localized shaded areas at certain hours of the day, its overall vastness and geometric articulation leave sections of the surfaces exposed to direct solar radiation, and mutual reflections between surfaces can also intensify in specific zones. Hence, its efficiency in reducing MRT is more limited than that of models relying on Typology A courtyards.

Similarly, Case_17, combining three Typology B, two Typology C, and one Typology D courtyards, is a configuration featuring both elongated rectangular and large-scale courtyards. In the Typology B pattern (12×24 m), although wall shading is possible along the shorter axis, the elongation along the longer axis leaves portions of the courtyard floor exposed to direct radiation for longer periods. When this feature is combined with Typology C and D patterns, the resulting environment experiences a higher MRT compared to layouts based on small, square courtyards. Likewise, Case_08, consisting entirely of eight Typology B courtyards, demonstrates that even within the small-scale category, the geometric form is of fundamental importance, as the elongated rectangular courtyard is less efficient in controlling radiant load than the small, square Typology A courtyard. Despite being in the medium-scale group, Case_02 failed to achieve a substantial reduction in MRT due to the absence of Typology A courtyards and its reliance on four Typology B and two Typology D courtyards.

Comparing the three primary groups (small-scale, medium-scale, and large-scale) reveals that thermal performance regarding the MRT index is governed more by the actual combination of courtyard typologies in each scenario than by the general group classification. For instance, Case_01 is classified under the medium-scale group, yet it recorded the best performance due to the clear predominance of Typology A courtyards. In contrast, Case_08, despite belonging to the small-scale group, ranks among the weaker configurations due to its exclusive reliance on the Typology B pattern. This indicates that in MRT analysis, merely increasing the number of courtyards or belonging to a specific scale category is insufficient; rather, the geometric form, aspect ratio, and spatial distribution in the final layout are more decisive.

Overall, the findings in this section indicate that as the share of small, compact, and square courtyards in the open space composition increases, the mean radiant temperature decreases. This is because such courtyards mitigate the intensity of the radiant load by increasing spatial enclosure, reducing the sky view factor (SVF), and enhancing wall shading. Conversely, configurations based on large-scale courtyards, elongated rectangular forms, or layouts with a high share of Typologies C and D record higher MRT values due to their greater openness, wider sun-exposed surfaces, and higher reception of direct solar radiation.

Relative Humidity (RH)

Relative humidity (RH) represents the ratio of the partial vapor pressure of water vapor present in the air to the saturation vapor pressure at the same temperature and pressure, typically expressed as a percentage (Monteith & Unsworth, 2013). This indicator reflects how close the air is to the saturation point and plays a fundamental role in the human body's evapotranspiration process. In thermal comfort analysis, relative humidity exhibits an inverse relationship with air temperature; meaning that, assuming constant absolute water vapor content, an increase in air temperature leads to an increase in the moisture-holding capacity of the air, thereby resulting in a decrease in the relative humidity percentage (Oke et al., 2017).

Analysis of the simulation data reveals that relative humidity fluctuations across all 18 proposed configurations and the reference model lie within a very narrow range (between 12.29% and 13.56%) (Fig. 13). This small range of variation (approximately 1.27%) indicates that in the hot and dry climate of Shirazn and under conditions where environmental confounding variables such as vegetation or water bodies (which are the primary sources of moisture) are not included in the modeling altering the spatial organization and scale of the courtyards alone cannot have a significant impact on ambient humidity levels. Consequently, relative humidity is considered in this study as a variable with a "secondary effect" on thermal comfort.

Nevertheless, a closer analysis of the data indicates a relative superiority of fine-grained configurations in retaining ambient humidity:

•Top-performing Configurations (Highest Relative Humidity): The highest relative humidity values were recorded in Case_09 (13.56%), Case_07 (13.50%), and Case_01 (13.47%), respectively. The common denominator among these scenarios is their classification under small-scale and medium-scale groups and their extensive utilization of Typology A and B courtyard patterns. The higher humidity levels in these configurations are directly linked to their lower air temperatures; at lower temperatures, the saturation vapor pressure of the air decreases, which automatically increases the relative humidity percentage. Furthermore, the higher spatial enclosure of these courtyards restricts rapid air mass displacement, thereby contributing to the retention of existing moisture within the courtyard microclimate.

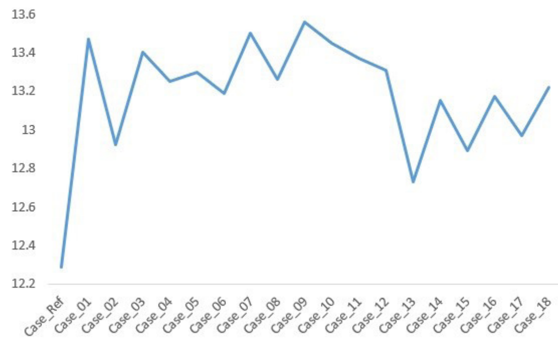


Figure 13: Overall Relative Humidity Variations during the hottest representative day
between 10:00 and 16:00 across All Configurations

•Underperforming Configurations (Lowest Relative Humidity): The lowest relative humidity level was observed in Case_Ref (12.29%), followed by Case_13, Case_15, and Case_02. These configurations, previously identified as the warmest scenarios, exhibit higher air temperatures due to their high openness and exposure to direct solar radiation. The elevated air temperature distances the air mass from its saturation point, minimizing the relative humidity. Additionally, large and unified courtyards exhibit less humidity stability due to their higher potential for air circulation and mixing with the dry ambient air.

The results of this section indicate that although shifting the courtyard scale from large, unified configurations toward fine-grained, enclosed layouts (such as Case_01) led to a relative improvement in ambient humidity, this component has a lesser impact on improving overall outdoor thermal comfort indices (such as PET) in this study compared to air temperature and mean radiant temperature (MRT). This is due to the arid nature of the Shiraz climate in summer and the limited range of variation. In fact, the humidity improvement in the top-performing configurations is a secondary consequence of air temperature reduction and increased physical enclosure, rather than actual moisture generation.

Wind Speed

Wind speed is defined as the rate of horizontal displacement of an air mass per unit time relative to a fixed point on the ground, primarily resulting from atmospheric pressure differences across various spatial scales. This vector quantity is a critical parameter in fluid dynamics analysis, outdoor heat exchange, and convective heat-transfer processes between the human body and the surrounding environment (Blocken, 2014; Musa et al., 2024).

Analysis of the simulation data indicates that the mean wind speed across all 18 proposed configurations and the reference model varies within a very narrow range, from 1.57 to 1.59 m/s (Fig. 14). The difference between the maximum and minimum wind speeds recorded across all configurations is only 0.02 m/s, which is negligible and unlikely to exert a perceptible effect on users' thermal perception at the microclimatic scale. In fact, the vast majority of the proposed configurations recorded a constant wind speed of 1.58 m/s. This relative stability indicates that, in this simulation, changes in the spatial organization and scale of the courtyards within the dense built mass of the 96 × 96 m site did not substantially disturb or directionally alter the site-scale wind regime at pedestrian height. Accordingly, wind speed is evaluated in this study as a variable with a secondary effect on outdoor thermal comfort.

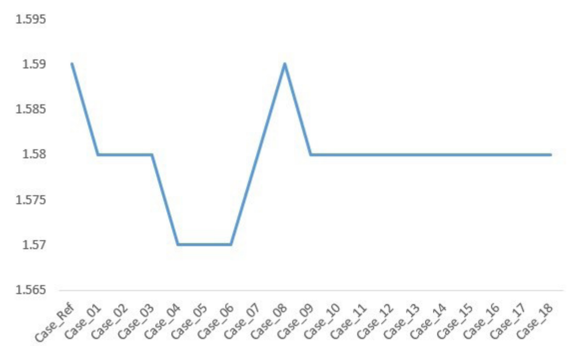


Figure 14: Overall Wind Speed Variations during the hottest representative day
between 10:00 and 16:00 across All Configurations

Despite this narrow range of variation, a more detailed analysis of the data reveals subtle aerodynamic differences among the configurations:

Maximum Wind Speed (1.59 m/s): This value was recorded in the reference model (Case_Ref) and the elongated configuration Case_08. In the reference model, the presence of a single, very large unified central courtyard measuring 48×48 m eliminates central physical obstacles and creates a vast unobstructed space. This allows the passing air mass to penetrate the courtyard without a significant loss in kinetic energy. In Case_08, which is composed entirely of eight elongated rectangular courtyards (Typology B, 12×24 m), the linear alignment and elongation of the courtyards help channel and maintain wind velocity along the flow path.

Minimum Wind Speed (1.57 m/s): This wind speed was observed in configurations Case_04, Case_05, and Case_06. The common feature of these scenarios is their classification as small-scale courtyards with a fine-grained, fragmented layout. In these structures, the alternating sequence of built masses and open voids imposes high physical roughness on the wind flow. Upon entering this dense fabric, the airflow continuously collides with walls, corners, and facade recessions. Due to severe surface friction and the formation of localized energy-dissipating micro-turbulences, the airflow loses a large portion of its kinetic energy, resulting in a localized drop in wind speed at the courtyard floor level.

Ultimately, although large and elongated courtyards (such as Case_Ref and Case_08) facilitate a smoother wind flow by reducing physical roughness, and fine-grained configurations slightly weaken wind speed due to higher spatial roughness, the negligible difference of 0.02 m/s in the means demonstrates that geometric alterations of the courtyards at this scale do not exert a significant impact on the site-scale wind regime.

Physiological Equivalent Temperature (PET)

Physiological Equivalent Temperature (PET) is a comprehensive index for assessing human thermal comfort in outdoor environments, based on the human body's energy balance (the equilibrium between metabolic heat production and heat dissipation to the environment). This index represents the equivalent temperature of a standardized indoor room where the heat transfer rate from a reference person (with predefined clothing insulation and activity level) equals the actual heat transfer rate under the assessed outdoor conditions. Consequently, it integrates the simultaneous and interactive effects of the four primary meteorological parameters: air temperature, relative humidity, wind speed, and, most importantly, solar radiation (represented by the mean radiant temperature) (Matzarakis et al., 1999; Li et al., 2025; Sargazi et al., 2026). In microclimatic assessments of urban spaces, PET serves as the most effective composite index, enabling definitive evaluation, precise ranking, and quantification of the performance of different physical configurations in improving user thermal comfort (Ballinas et al., 2022; Santos Nouri et al., 2022).

Analysis of the simulation data during the critical hours of the hottest representative day in Shiraz clearly demonstrates the profound impact of the geometric and scale reorganization of the courtyards on the PET index (Fig. 15). Based on the results, all 18 proposed scenarios successfully reduced PET values compared to the reference model (Case_Ref), thereby improving outdoor thermal comfort. Nonetheless, physical differences among the scenarios led to distinct thermal behaviors. A substantial difference of 4.58°C was recorded between the best-performing scenario (Case_01 with PET=50.50°C) and the reference model (Case_Ref with PET=55.08°C). Even in the weakest proposed scenario (Case_13 with PET=54.02°C), a reduction of 1.06°C was achieved relative to the reference model, highlighting the inherent benefit of dividing open spaces, even at larger scales. Figure 16 displays the PET contour maps for all investigated configurations during the hottest representative day.

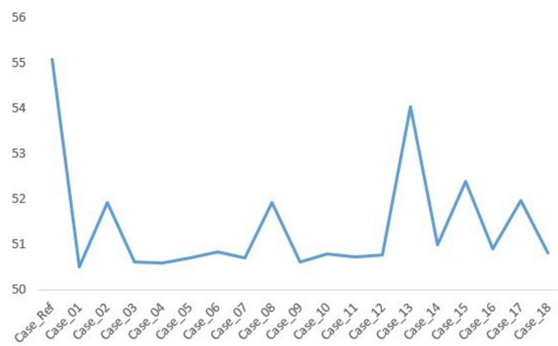


Figure 15: Overall PET Variations during the hottest representative day
between 10:00 and 16:00 across All Configurations

Based on these results, a cross-analysis of the PET index behavior in relation to the geometry and spatial distribution of the four courtyard typologies (A, B, C, and D) can be categorized into three primary groups:

1) High-Performance Configurations with High Thermal Efficiency (Strict Control of Radiation Load)

The most favorable thermal performance, characterized by the lowest PET values, was achieved in Case_01 (50.50°C), followed by Case_04 (50.58°C), Case_03 and Case_09 (50.61°C), and Case_07 (50.69°C).

Physical Mechanism: The common denominator among these scenarios is the prominent dominance of fine-grained and compact config-

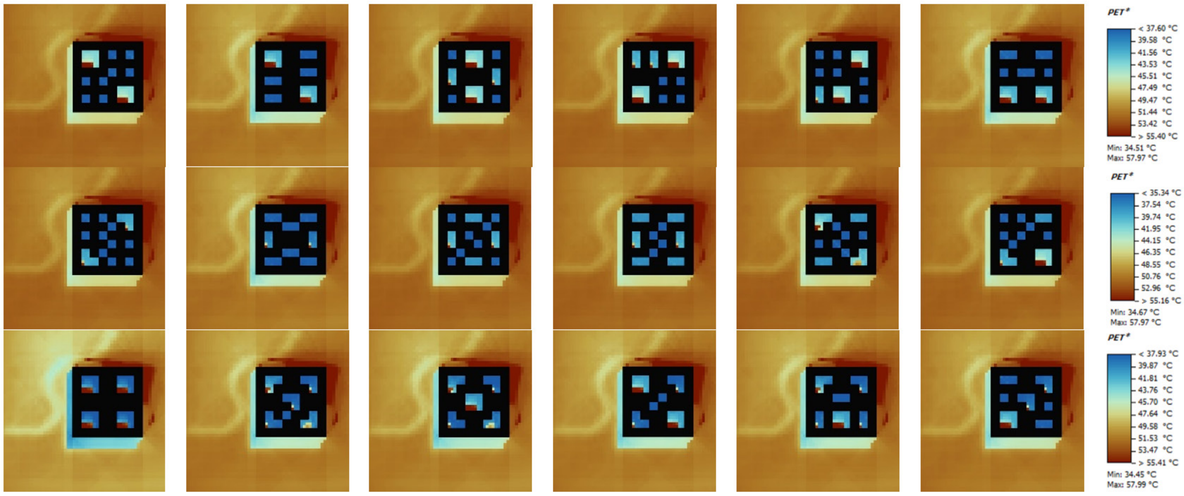


Figure 16: PET Contour Maps for All Proposed Configurations during the hottest representative day

urations, specifically the small square Typology A (12×12 m) and the medium rectangular Typology B (12×24 m).

Thermodynamic Analysis: In these fine-grained layouts, the aspect ratio of the courtyards increases (H/W=1.0), which significantly reduces the Sky View Factor (SVF). This reduction in SVF limits the penetration of direct solar radiation onto the courtyard floors during peak hours. Simultaneously, it drastically lowers the Mean Radiant Temperature (Tmrt) through enhanced physical shading from the surrounding walls. Since the fluctuations in wind velocity and relative humidity were negligible in this study, the pronounced decrease in PET within these configurations is directly attributed to the improved shading performance (Tmrt) and the subsequent moderation of air temperature, establishing a favorable thermal stability at the pedestrian level.

2) Low-Performance Configurations with Low Thermal Efficiency (High Radiative Asymmetry and Exposure)

The weakest thermal performances among the proposed scenarios were recorded in Case_13, Case_15, Case_17, Case_08, and Case_02, with PET values of 54.02°C, 52.39°C, 51.96°C, 51.93°C, and 51.92°C, respectively.

Physical Mechanism: These scenarios correspond directly to the configurations that previously exhibited poor performance regarding air temperature and Tmrt . Among these, Case_13 is characterized by the large square Typology D (24×24 m), Case_08 is dominated by the elongated rectangular Typology B, and Case_02 features high relative spatial openness.

Thermodynamic Analysis: In these models, the reduced confinement ratio (H/W=0.5) and the increased contiguous area of each courtyard significantly raise the SVF. During the day, the extensive horizontal and vertical surfaces in these courtyards are exposed to intense direct solar radiation, storing substantial thermal energy that is subsequently re-emitted as longwave radiation in the afternoon. This phenomenon substantially elevates the Tmrt, completely neutralizing the marginal convective cooling effect of the slightly higher wind speeds observed in these courtyards (e.g., 1.59 m/s in Case_08). Consequently, severe thermal stress is reflected in the elevated PET values of these scenarios.

3) Intermediate Configurations (Balanced Spatial Distribution)

Scenarios incorporating a balanced mixture of fine-grained, medium, and large configurations (combining typologies A, B, C, and D)—such as Case_11, Case_12, and Case_18—recorded moderate PET values within the range of 51°C to 52°C. This thermal behavior indicates that integrating diverse typologies can moderate the individual strengths and weaknesses of each courtyard scale, resulting in an intermediate, balanced thermal performance for the entire residential complex.

The findings derived from the composite PET index confirm that in the hot and dry climate of Shiraz, the most effective design strategy to improve outdoor thermal comfort is to avoid large-scale, integrated central courtyards (such as Case_Ref) and shift toward "fine-grained, decentralized, and enclosed" spatial organizations (such as Case_01, Case_04, and Case_09). Because wind speed and relative humidity varied minimally in these simulations, the fluctuations in the PET index were directly governed by the mean radiant temperature (Tmrt) and physical shading. Consequently, prioritizing fine-grained configurations (such as the small square Typology A) due to their high capacity to reduce SVF and control solar radiation load remains the key approach to mitigating summer thermal stress in high-density residential complexes.

RESULTS AND CONCLUSION

The microclimatic analysis of outdoor open spaces in high-density residential complexes under hot and dry climates reflects a multidimensional design challenge where physical geometry serves as the most critical mediator between the macroclimate and human thermal perception. The findings of this study demonstrate that the configuration of open spaces and the manner in which they are partitioned play a vital role in either mitigating or exacerbating summer thermal stress. The cross-evaluation of the four central courtyard typologies (small square, rectangular, L-shaped, and large square) across the 18 developed scenarios validates the hypothesis that the spatial distribution and physical scale of courtyards are the key variables governing the thermodynamic and aerodynamic flows of the environment. In this regard, the transition from the single, large-scale reference courtyard model to partitioned and decentralized configurations led to an improvement in the thermal quality of the space and a reduction in the Physiological Equivalent Temperature (PET) index across all scenarios. This indicates that dividing the air mass and increasing shading surfaces is an effective strategy for passively neutralizing the detrimental effects of diurnal solar radiation.

An examination of the physical mechanisms governing the simulated environments reveals that the Mean Radiant Temperature (MRT) acts as the primary driving force in determining the pattern of outdoor thermal comfort. In the hot and dry climate of Shiraz, where the intensity of shortwave solar radiation during the day is extremely high, the capacity of a space to generate physical shading defines the boundary between a livable environment and a thermal trap. The small square configurations (Typology A) and medium rectangular configurations (Typology B) showed the most efficient performance in reducing MRT, and subsequently air temperature and the PET index, due to their optimal aspect ratio ($H/W \geq 1.0$) and the resulting reduction in the Sky View Factor (SVF). This thermodynamic behavior is driven by two simultaneous phenomena: first, the tall surrounding walls in these configurations block the penetration of direct solar radiation onto the courtyard floor during peak thermal hours; second, the limited floor area in the fine-grained layouts significantly reduces the potential for thermal storage and the subsequent re-emission of heat as long-term longwave radiation into the environment. In contrast, large-scale configurations, by providing vast unshaded surfaces, store immense amounts of radiative energy in their physical materials during the day and continuously release this energy in the afternoon hours, severely worsening thermal comfort conditions.

In the cross-analysis of secondary meteorological components (wind velocity and relative humidity), the qualitative findings of this study highlight classical challenges of urban aerodynamics. Scenarios utilizing linear, elongated courtyards (Typology B) or integrated open spaces present a higher potential for airflow passage due to reduced surface friction and lower physical roughness. This geometric elongation acts as a natural conduit, channeling and accelerating gentle airflows, which facilitates convective heat transfer. Conversely, the continuous repetition of small square courtyards (Typology A) dramatically increases localized roughness, dissipating the wind velocity and leading to the formation of weak micro-turbulences in corners and relative air stagnation. However, the comprehensive PET index analysis demonstrates that this minor reduction in wind velocity in fine-grained courtyards is entirely negligible compared to the exceptional improvement in the Mean Radiant Temperature (MRT). This phenomenon confirms an important design principle in hot and dry climates: “the absolute priority of controlling the radiation load over promoting wind circulation.” The flow of hot ambient wind during midday hours not only fails to provide a cooling effect but can also exacerbate thermal stress by increasing the convective heat transfer rate to the human body. Therefore, physical confinement and shading remain the most reliable tools for mitigating this stress.

Furthermore, the analysis of spatial distribution showed that the arrangement and combination of different typologies play a crucial role in achieving a uniform distribution of thermal quality across the residential complex. In single-block, integrated designs, outdoor urban spaces experience severe thermal asymmetry, where the center of the courtyard becomes the core of the thermal crisis while the edges retain better conditions. However, by partitioning the geometry and intelligently combining fine-grained and medium typologies, the intersection of wall shadow patterns prevents the formation of critical hotspots, establishing a homogeneous and balanced thermal atmosphere at the pedestrian level. Additionally, scenarios incorporating a balanced mix of fine-grained and medium typologies demonstrated that hybrid design can strike a balance between optimal shading and minimal wind flow, preventing complete humidity trapping and stagnant air conditions.

Based on the analytical findings of this study, the following strategies are recommended for the design of high-density residential complexes in similar climates:

•Avoid allocating large-scale, integrated open spaces in the center of the site and instead transition toward multi-courtyard, fine-grained, and decentralized structures.

•Utilize small square and rectangular typologies to provide a high aspect ratio, ensuring effective shading on both the floor and vertical wall surfaces.

•Deliberately integrate linear (rectangular) typologies with compact (square) typologies to maintain local airflow dynamics without sacrificing physical shading.

In conclusion, this study clarifies new boundaries regarding the interaction between form and climate in high-density urban fabrics. Although this research focused on rigid physical geometry, the final thermal stability of these spaces in real urban environments can be influenced by dynamic variables such as material properties (thermal albedo of facades and pavements), the design of shading green infrastructure (vegetation), and the application of evaporative cooling strategies (water features). Exploring the interactive effects of these flexible variables on the selected geometries of this study offers valuable directions for future research in the fields of urban design and climate-responsive architecture.

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