The Effect of Urban Shading and Canyon Geometry on Outdoor Thermal Comfort in Hot Climates: A Case Study of Ahvaz, Iran

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Abstract

The city of Ahvaz, Iran has a hot climate and severe weather conditions for pedestrians in hot seasons. This study investigated the role of urban geometry and urban shading in improving the pedestrians' thermal comfort. Six urban canyons with different geometric characteristics are selected in Ahvaz. To determine the outdoor thermal comfort range, micrometeorological measurements and questionnaire survey were conducted in the sites in July 2018. ENVI-met is used to investigate the role of urban geometry and urban shadings. To evaluate the outdoor thermal comfort, physiologically equivalent temperature (PET) is calculated using RayMan. Using the results of the micrometeorological measurements and the questionnaires, the outdoor thermal comfort range in Ahvaz is obtained within 19.6 to 30.9°C PET. Simulation results show that the closer the canyon orientation is to the north-south direction, the lower the air temperature (T_a) and mean radiant temperature (MRT) are. Also, by reducing the canyon aspect ratio, PET increases as well. Urban shadings decreased MRT and PET up to 34 and 17.6°C, respectively. In contrast, shadings did not affect the air temperature, significantly. PET reduction caused by shadings is more notable in east-west canyons, as well as in wider canyons. MRT and PET in all cases are highly correlated with SVF. The observations showed no strong correlation between T_a, relative humidity, and wind speed, with the SVF in all canyons.

Keywords: Outdoor Thermal Comfort, Urban Geometry, Urban Shadings, PET.

Abbreviations: CFD, computational fluid dynamics; EW, east-west; H/W, height/width; MRT, mean radiant temperature; MTSV, mean thermal sensation vote; NE-SW, northeast-southwest; NNE-SSW, north-northeast-south-southwest; NS, north-south; NW-SE, northwest-southeast, PET, physiological equivalent temperature; PMV, predicted mean vote; RH, relative humidity; SVF, sky view factor; T_a, air temperature; TSV, thermal sensation vote; WNW-ESE, west-northwest-east-southeast; WS, wind speed.

1. Introduction

According to the United Nations [1], the world's population will reach approximately 10 billion by the year 2050. The consequence of this population growth along with the ongoing global warming puts a large population prone to heat related morbidity [2–4] and mortality [5]. The number of heatwaves has also increased in recent decades [6]. The increase in death toll due to heat has been observed especially on weekdays, when people spend most of their times outdoor and commuting to work, university, and etc. [7].

The presence of people in the outdoor environments [8], as well as the way they use the urban open spaces [9], are dependent on microclimatic conditions. Due to the complexity of outdoor thermal comfort, it is necessary to study the factors involved in human comfort with different methods, including field studies and modeling [10]. Field studies are to assess the outdoor thermal comfort and may take place within a month [11] or several different seasons [12], and also may be accompanied by questionnaire surveys.

Ahvaz is located in the southwest of Iran, with a hot climate, creates an unfavorable thermal conditions for pedestrians, especially in summer. This causes a dramatic decrease in the presence of people in outdoor spaces during the summer. According to the previous studies, urban factors could affect the outdoor thermal comfort including urban development and land use pattern [13,14], anthropogenic heat [15] as well as the most important factors such as urban vegetation [16–18], urban morphology [16] and canyon geometry [19,20]. Several researches suggest shading as an important factor in outdoor thermal comfort, especially in hot climates [21,22]. PET in shaded areas could be lower than in those without shadings up to 27°C [23]. It has also been suggested that urban street geometry be designed in such a way to increase the shade in the outdoor environment [24]. However, Ahvaz lacks proper shading on most of the crowded sidewalks. Therefore, the purpose of this study is to investigate the outdoor thermal comfort conditions in the hot climate of Ahvaz and to understand the role of urban geometry and urban shading in improving pedestrians' thermal comfort.

1.1. Street Canyon Geometry

Urban geometry plays an important role in affecting the microclimate of urban streets. Oke [25] considered microclimatic impacts from various factors related to urban geometry, including the aspect ratio (H/W), sky view factor (SVF), which is directly related to H/W, and street orientation. For example, compact cities with high H/W and low SVF are suitable for pedestrian thermal comfort, and street orientation affects solar access.

1.1.1. Aspect Ratio (H/W)

One of the factors defining urban geometry that affects shading within the urban canyons is the ratio of the average height of the canyon (H) to the width of the canyon (W) or the aspect ratio (H/W) [25]. Outdoor thermal comfort in warm climates is highly dependent on the canyon aspect ratio and orientation [26]. Deep canyons and their shading effects are suitable for summer and unsuitable for winter and vice versa [27,28]. In hot and humid climates such as Taipei [29] and Bangladesh [30], as well as in hot and dry climates such as Morocco [31] and Saudi Arabia [32], deeper canyons have lower air temperature ($T_{a)}$ than shallow canyons. However, sometimes the opposite results are observed in studies. A study conducted in the arid climate of Argentina shows that a decrease in H/W reduces the maximum and the average T_a [33]. Also studying different cities with similar climates in one country shows that the ideal aspect ratio may vary, as it is observed in Morocco [34]. Therefore, it is necessary to study and research the aspect ratio for different cities in warm climates.

1.1.2. Sky View Factor (SVF)

Sky view factor (SVF), is a parameter that indicates the proportion of the sky which is visible from a given point [25]. The surface points with higher SVF have fewer obstacles to absorb solar energy [25]. Increasing the height of the buildings in an urban canyon causes an SVF decrease in the canyon surface [35]. Also, there is a strong correlation between building density and SVF (r=-0.95) [36]. SVF can demonstrate the geometric complexities of a city, so the effect of street geometry on T_a and pedestrian thermal comfort could be investigated using this factor [37]. Several studies [38–40] have shown that there is a strong relationship between SVF and T_a. A study in the humid climate of Beijing shows that highly shaded areas (SVF<0.3) experience less heat in summer and severe cold in winter, while moderately shaded areas (0.3<SVF<0.5) experience longer periods of outdoor thermal comfort during the year [41]. However, Karakounos et al. [42] show that the results of such research could not be generalized and that the relationship between SVF and microclimatic parameters and thermal comfort should be investigated separately for each case.

1.1.3. Orientation

Street orientation affects thermal comfort by changing solar access and wind speed (WS) [27]. Several studies recommend the best and the worst orientations as north-south (NS) and east-west (EW), respectively [43,44]. The EW oriented streets are less comfortable due to the lack of shading [45]. In temperate [46,47], hot-humid [48,49] and hot-dry climates [50,51], the worst street orientation for achieving acceptable thermal comfort is EW, and the closer the street orientation gets to NS, the better the thermal comfort conditions become. Also, some studies demonstrate different results, which recommend EW as the best street orientation according to the results of MRT [52] and PET [24] evaluations. Studying intermediate orientations in Freiburg, Germany, the lowest T_A observed at NNE-SSW street [53]. However, a study in China showed that more shade and better thermal conditions occurred at NW-SE orientation [54].

1.2. Urban Shadings

There is limited research on the impact of built urban shadings on thermal comfort. Some of these shadings include horizontal, inclined and vertical shading devices, membrane roofing, galleries, and photovoltaic shadings. In a simulation study [55], the horizontal and inclined shading devices in the EW and NS canyons reduced T_a by 4°C and 2°C, respectively. It is also reported that the T_a of these canyons was lower than the T_A of the rural environment during the period 9:00-15:00. Adding vertical shadings to a south-facing wall in an EW canyon in a Mediterranean climate, reduced solar irradiance up to 150 W/m^2 and decreased T_a at noon in summer [56]. Adding a tent over an NS urban canyon in Milan, decreased T_a and surface temperature [57]. Simultaneous use of strategies such as creating galleries, increasing the height of the south wall, improving albedo, and adding trees in the street canyon, improved PMV in the hot-dry climate of Ghardaia, Algeria [45]. In another study in Algeria, Ali-Toudert and Mayer [50] showed that using galleries and overhanging facades decreased heat stress and PET. In the warm-humid climate of Ecuador, shaded areas had the lowest MRT, equal to 30°C, in October [58]. Investigating the effect of the photovoltaic canopy shade on thermal comfort in Tempe, Arizona, with a semi-arid climate, showed that the maximum T_a in the sun is 2°C higher than in the shade [59]. Due to the significant impact of shadings on thermal comfort, it is necessary to study urban shadings more carefully.

2. Methodology

Considering the main purpose of this study that is to investigate the thermal comfort in the hot climate of Ahvaz as well as the role of urban geometry and urban shadings on pedestrian thermal comfort, the research method consists of two main parts. In the first part, micrometeorological measurements and a questionnaire survey are conducted in the studied sites, and the second part includes numerical simulations of the studied canyons using ENVI-met. Data obtained from the questionnaires are analyzed using SPSS software. To investigate outdoor thermal comfort, physiologically equivalent temperature (PET), which is calculated by RayMan [60,61], is selected as the thermal comfort index.

2.1. Research Site

The city of Ahvaz (31°19' N, 48°40' E) is the capital of Khuzestan province, located in the southwest of Iran. According to the Köppen-Geiger climate classification [62], the climate of Ahvaz is BWh or hot arid desert. Long periods of heat along with low precipitation are the main characteristics of the climate of Ahvaz. The highest and the lowest air temperatures in 2018 were 52.4°C in July and 3.5°C in January, respectively. The average annual rainfall was 182 mm [63]. According to the meteorological data of Ahvaz, there is cooling demand in six months, from May to October, and heating demand only in three months [63].This study focused on summer season in Ahvaz.

Six urban canyons (Figure 1) with significant pedestrian presence and different geometric properties, such as canyon orientation and width, are selected as the main studied sites.

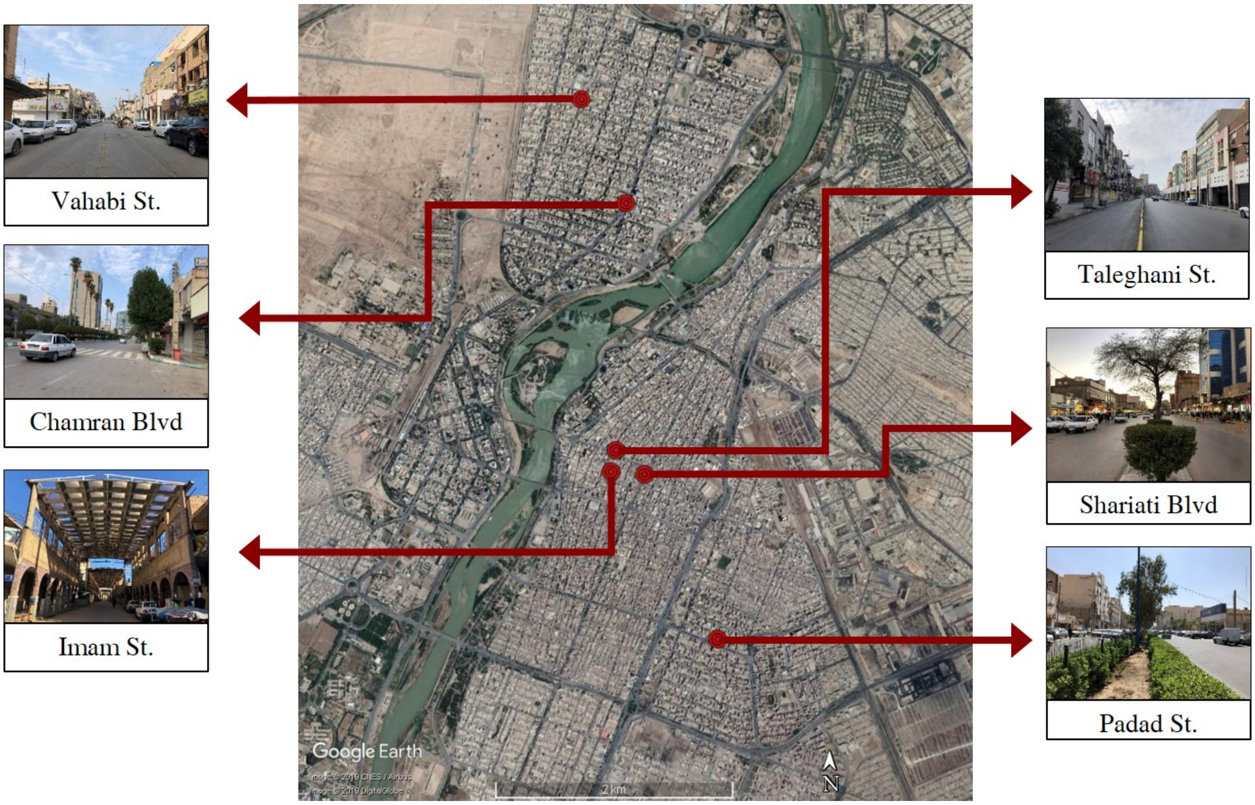


Figure 1. The Location of the studied sites in Ahvaz.

Since Karun River flows through the city, the main orientations of the streets are NNE-SSW (parallel to the river) and WNW-ESE (perpendicular to the river). Three studied sites are NNE-SSW or close to NS oriented, and the other three are WNW-ESE or close to EW orientation .The width and H/W of the canyons vary from 15 to 38 meters and 0.2 to 0.6, respectively (Figure 2).

On Imam Street, which is a traditional bazaar, the entire canyon is covered by shadings. The sidewalk shading is 4 meters high and the roadway, which is sometimes used by pedestrians, has an 8 meters high shading (Figure 2-a). Taleghani Street has a shading only on the SSW-facing sidewalk (Figure 2-b). Vahabi Street has shadings on both sidewalks (Figure 2-f). Padad Street (Figure 2-c), Chamran Boulevard (Figure 2-d), and Shariati Boulevard (Figure 2-e) do not enjoy significant shadings on their sidewalks.

	Area	Width (m)	Ave. height (m)	Max. height (m)	Ave. H/W	Max H/W	Orientation
a	Imam St.	18	8	12	0.45	0.7	WNW-ESE
b	Taleghani St.	25	11.4	22	0.45	0.9	WNW-ESE
c	Padad St.	38	7.5	21	0.2	0.5	WNW-ESE
d	Chamran Blvd	36	11	45	0.3	1.25	NNE-SSW
e	Shariati Blvd	28	10.5	27	0.3	1	NNE-SSW
f	Vahabi St.	15	9	21	0.6	1.4	NNE-SSW

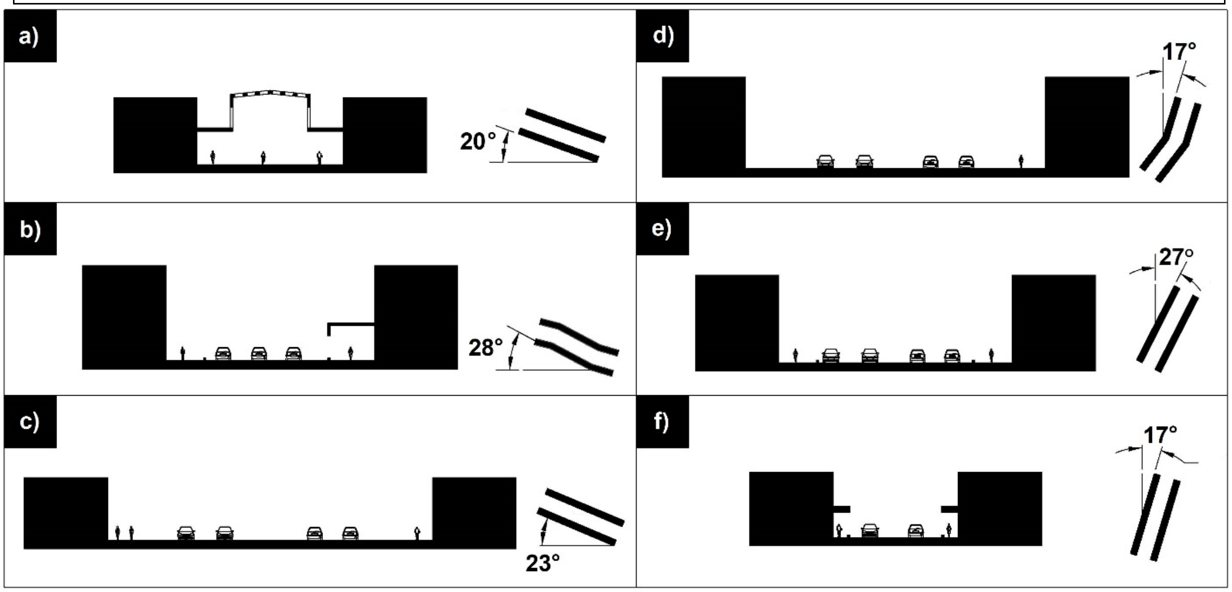


Figure 2. Schematic sections of the study sites.

2.2. Measurement and Questionnaire

The questionnaire survey and the measurement of microclimatic parameters were conducted in July, which is the hottest month of the year [63]. Microclimatic parameters are measured simultaneously along with the questionnaire survey from July 21st to 26th, 2018. Measurements were conducted from 8:30 to 12:30 and also from 19:00 to 21:30. Because of the extreme heat and the closure of all commercial buildings, the presence of pedestrians on the streets is highly decreased from noon to 19:00.

The questionnaire used in this study was developed according to similar studies [58,64] and ASHARE 55 standard [65]. The questionnaire was tried to be precise for time-saving purposes, as it was very difficult for pedestrians to answer a significant number of questions, especially in very hot weather. The approximate completion time for each questionnaire was between 5 to 10 minutes. The total number of obtained questionnaires was 257. The first part of the questionnaire collected personal information including gender, height, weight, and age. The second part included questions about thermal sensation, thermal satisfaction, thermal adaptation, thermal preferences, and etc.

The microclimatic parameters were measured simultaneously with the completion of the questionnaire. These parameters included T_a, relative humidity (RH) and WS. These parameters were recorded by Fluke 975 instrument at a height of 1.4 meters (Figure 3). Table 1 shows the specifications of the instruments used in this study.

Table 1- Measured parameters and specifications of instruments used in this study

Instrument	**Model**	**Measured parameter**	**Accuracy**	**Range**
Air meter	Fluke 975	Air temperature	±0.5°C	-20°C to 50°C
		Relative Humidity	±2%	10% to 90%
		Wind Speed	±0.02 m/s	0.25 m/s to 15 m/s
Weather datalogger	Standard ST-174B	Air Temperature	±0.9°C from 40°C to 60°C	-40°C to 70°C
			±0.5°C from 5°C to 40°C	
			±1.1°C from -20°C to 5°C	
		Relative Humidity	±3%	0 to 90%

Figure 3.a) Micrometeorological measurements simultaneously with the completion of the questionnaire in the study site. b) Fluke 975 sensor for measuring T_A, RH, and WS.

2.3. Simulation

ENVI-met is a simulation software that can evaluate microclimatic interactions between buildings, surfaces and plants [66]. It is based on the fundamental laws of CFD (Computational Fluid Dynamics) [67]. This model has been previously used to evaluate the microclimates in similar studies [68] and in other hot climates [45,50].

ENVI-met uses combined advection-diffusion equations (Eq. 1and 2) to calculate temperature (θ) and specific humidity (q) inside the atmosphere [69]:

$$\frac{\partial \theta}{\partial t} + u_i \frac{\partial \theta}{\partial x_i} = K_h \left(\frac{\partial^2 \theta}{\partial x_i^2}\right) + Q_h \tag{1}$$

$$\frac{\partial q}{\partial t} + u_i \frac{\partial q}{\partial x_i} = K_q \left(\frac{\partial^2 q}{\partial x_i^2}\right) + Q_q \tag{2}$$

Which according to Bruce and Fleer, "Q_h and Q_q are used to link heat and vapor exchange at the plant surface with the atmospheric model" [69].

2.3.1. Validation of ENVI-met results

The accuracy of ENVI-met results is investigated in several studies by a comparison between simulation results and field measurements [70]. Among Iranian cities, ENVI-met validation is carried out for hot and dry climates of Isfahan [71] and Shiraz [72] and the average differences between simulated and measured T_a in these cities were 2.3°C and 0.5°C, respectively. In this study, T_a was measured on Padad Street in three consecutive days from July 27th to 29th, 2018. The Standard ST-174B datalogger, which was located at a height of 1.4 meters above the ground on the sidewalk (Figure 4), was used to measure T_a. A comparison of the three-day average simulated and measured T_a showed that the average difference was 1.4°C, R^2 in this comparison was 0.86 (Figure 5). Root mean square error (RMSE) and index of agreement (d) were 2.8°C and 0.91, respectively, which are all acceptable according to previous studies [73–75].

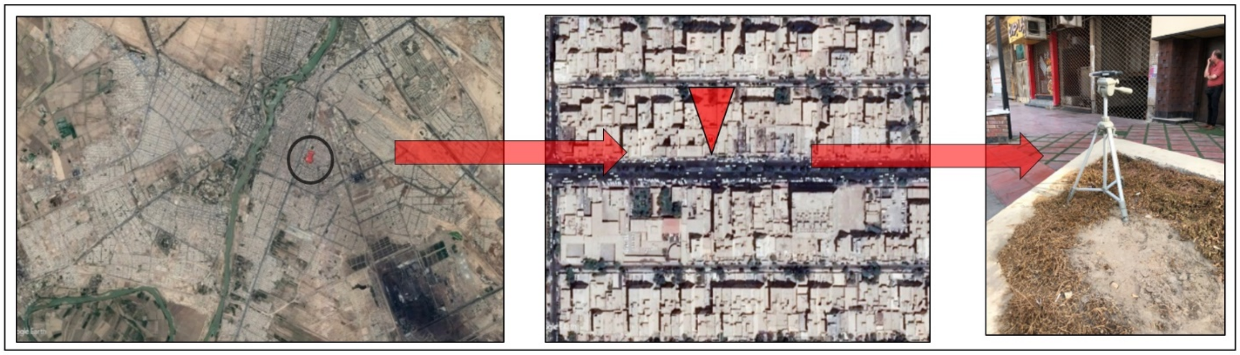


Figure 4. Location of the datalogger for validating the ENVI-met results.

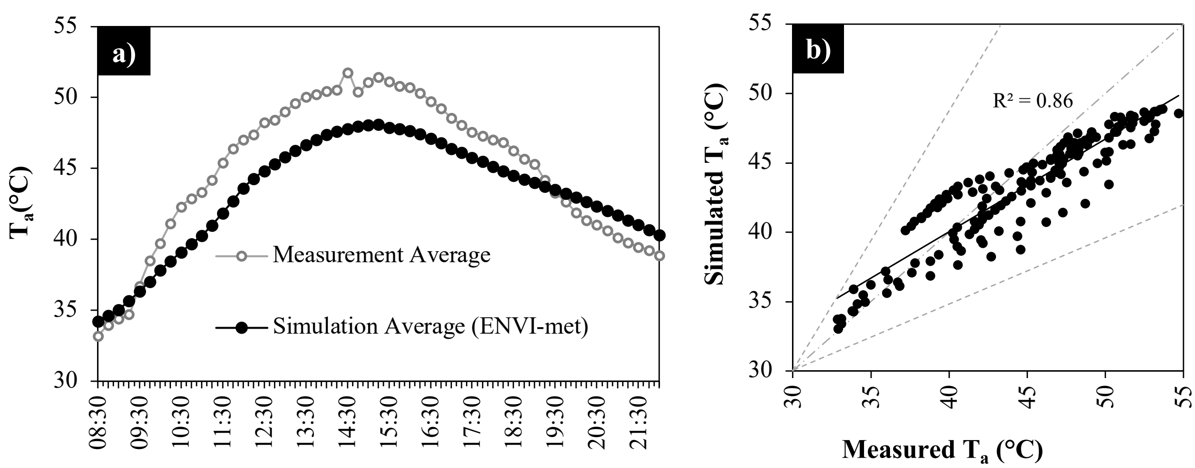
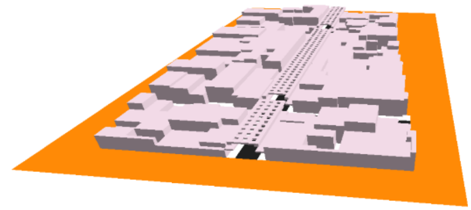
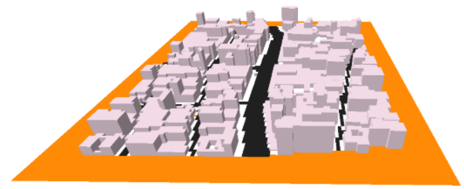
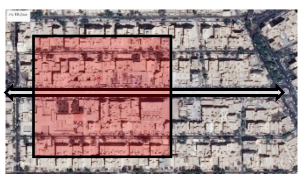
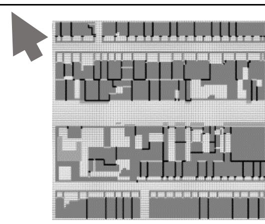
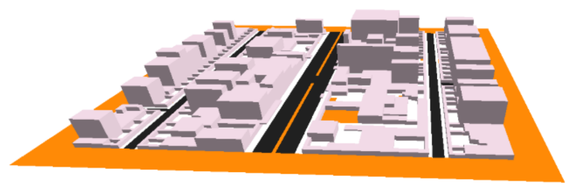
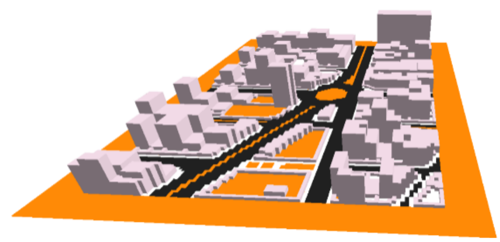
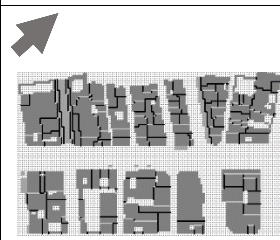
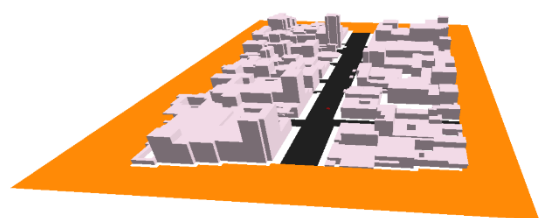
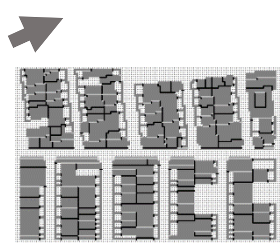
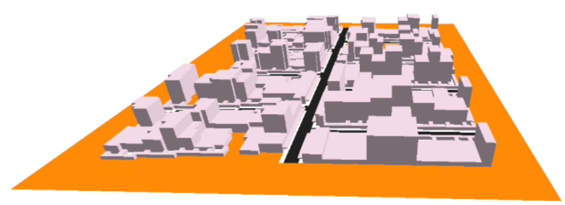


Figure 5. a) Comparison of the three-day average T_a between measurement and simulation. b) Scatter plot of the measured and simulated T_a.

2.3.2. Simulation of Study Sites

ENVI-met version 4.0 is used for simulations in this study. July 4, 2018, was selected for simulations, since it had the highest daily average T_a in 2018, based on the meteorological data [63]. The simulation duration was set to 14 hours, from 8:00 to 22:00, due to the pedestrian presence time. A section of each site, which had the highest number of pedestrians because of administrative, commercial, and medical buildings, is selected for simulations (Table 2).

Table 2- The selected section of each site and their plan and perspectives in ENVI-met.

Selected section	Plan in ENVI-met	Perspective in ENVI-met
Imam Street 		
Taleghani Street 		
Padad Street 		
Chamran Boulevard 		
Shariati Boulevard 		
Vahabi Street 		

3. Results and Discussion

3.1. Questionnaire Results

The highest and the lowest air temperatures recorded during the questionnaire survey were 44.6°C and 32.3°C in Imam Street, 43.7°C and 32.7°C in Taleghani Street, 43.8°C and 34.4°C in Padad Street, 47.8°C and 33.5°C in Chamran Boulevard, 43.3°C and 32.7°C in Shariati Boulevard, and 45°C and 33.5°C in Vahabi Street, respectively. Out of 257 questionnaires, 81% were male and 19% were female. The age range of 21 to 35 years with 57%, followed by the age range of 36 to 50 years with 20% and the age range of 51 to 65 years with 14%, had the highest frequency among the participants in this survey.

3.1.1. Thermal Sensation Votes of Pedestrians

Thermal sensation vote (TSV) was investigated through the ASHRAE 55 seven-point scale [65] i.e. cold (-3), cool (-2), slightly cool (-1), neutral (0), slightly warm (+1), warm (+2) and hot (+3). 38.5% of the participants experienced slightly warm conditions, and 29.6% experienced warm conditions. Although the survey was carried out in the hot season and it was expected to observe a higher percentage of "warm" and "hot" votes, "slightly warm" conditions were experienced higher than "warm" and "hot" conditions due to the presence of most of the participants in shaded areas. A total of 78% of the participants felt warm (including slightly warm, warm, and hot), 13% felt neutral, and 9% felt cool (including slightly cool, cool and cold). According to Figure 6, the highest number of cool TSV (including slightly cool, cool and cold) belonged to Taleghani Street and Vahabi Street, which is probably due to the more adequate shadings on the sidewalks of these two streets. Imam Street has the most adequate shadings among other sites, but the "slightly warm" votes on this site were very high, which is probably due to the difference in the activities on this street that led to extra heat production. Chamran Boulevard and Shariati Boulevard had the highest number of warm (including slightly warm, warm and hot) votes which is probably due to the low shade in these sites compared to other sites.

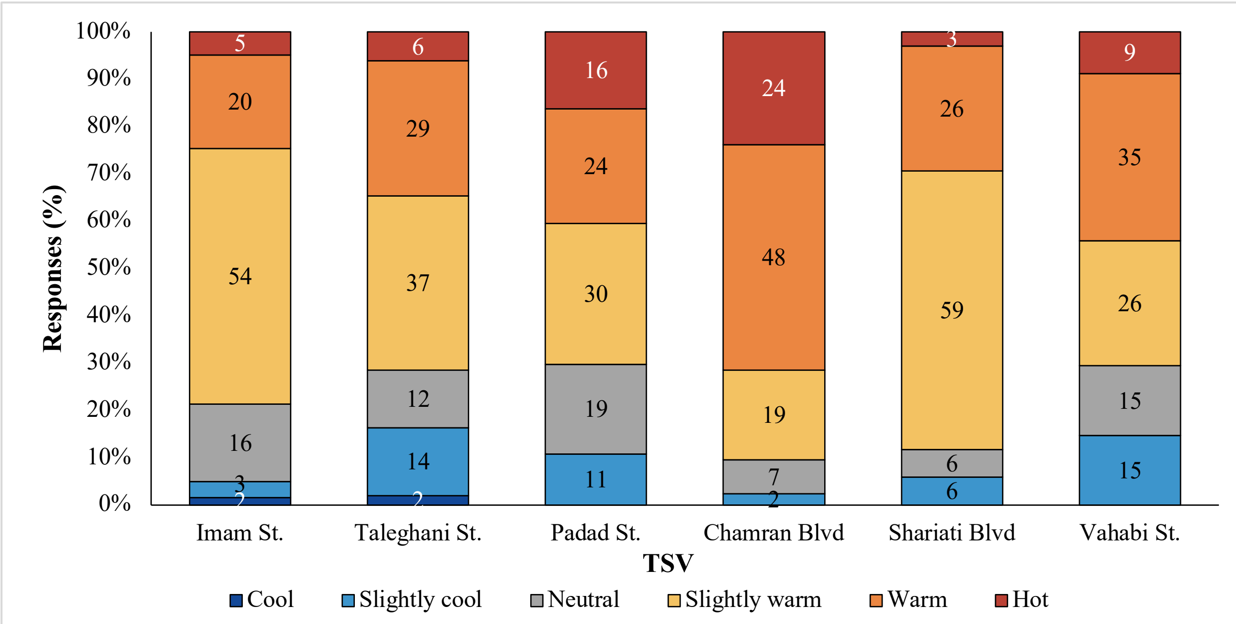


Figure 6. Distribution of TSV in each site.

3.1.2. Thermal Satisfaction of Pedestrians

Thermal satisfaction of pedestrians is also studied through the ASHRAE 55 seven-point scale [66]. The highest level of dissatisfaction belonged to Shariati Boulevard with 80% which is probably due to the low shade on the sidewalks of this street (as mentioned in section 3.1.1). The highest level of satisfaction, similar to section 3.1.1, belonged to Taleghani Street with 30% satisfaction. 72% of the participants were dissatisfied, and only 21% felt satisfied with their thermal conditions (Figure 7).

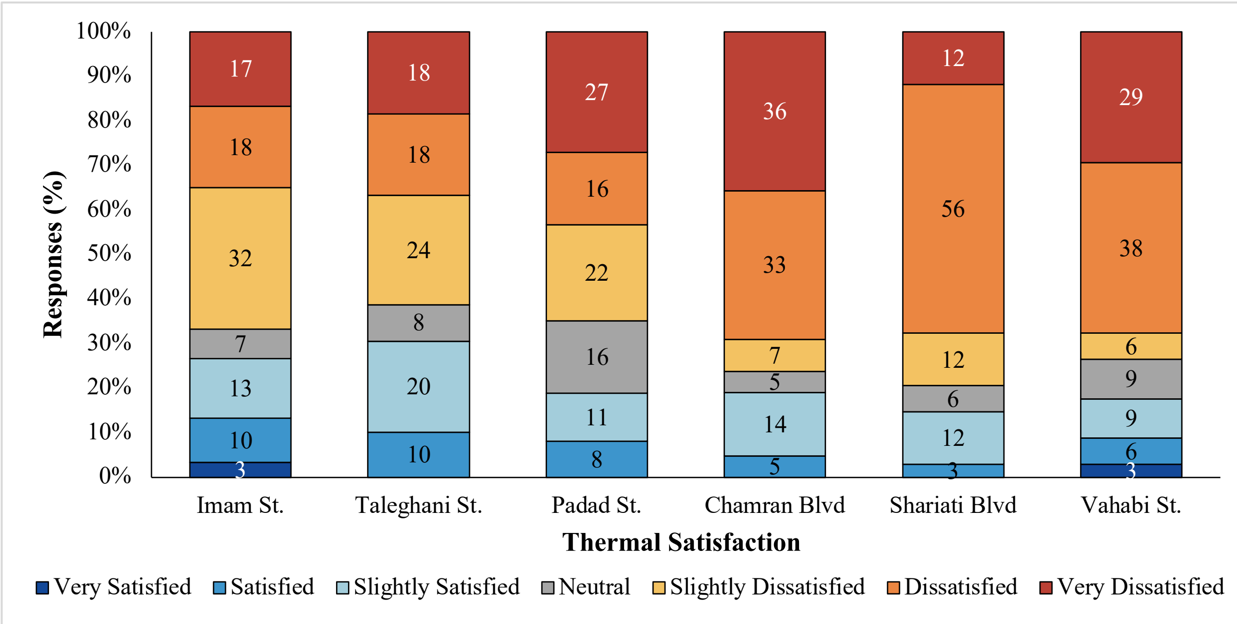


Figure 7. Percentage distribution of thermal satisfaction of pedestrians on each site.

Thermal Preference of Climatic Parameters

The participants were asked to choose their thermal preferences for T_a, shade, WS and RH through the McIntyre three-point scale (lower/decrease (-1), no change (0) and higher/increase (+1)) (Figure 8). 93% preferred lower T_a, 51% preferred more shade, and 48% preferred higher WS and RH with no change.

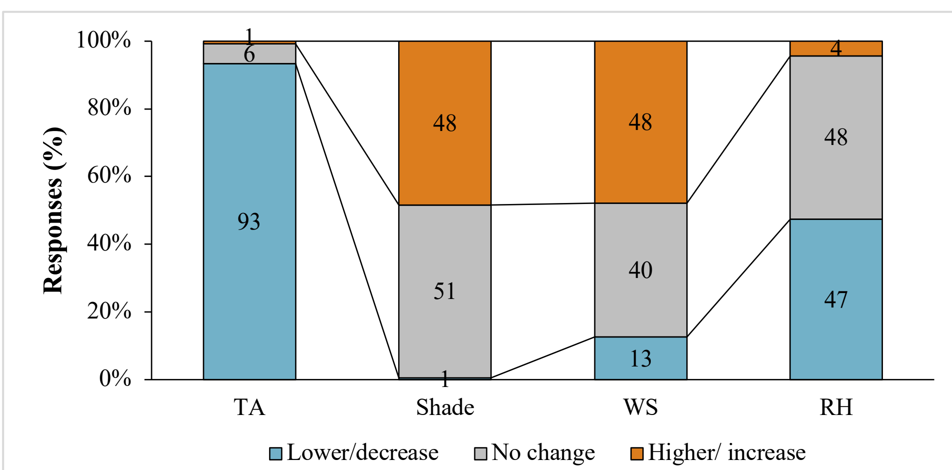


Figure 8. Pedestrians' thermal preference of climatic parameters.

3.1.3. Air Temperature Estimation by Pedestrians

The participants were asked to estimate the current T_a and the results were compared separately in the sun and the shade with the measured T_a (Figure 9). The number of participants who overestimated T_a in the sun was 9% higher than those in the shade. Also, the number of participants in the shade who underestimated T_a was 21% more than those in the sun. As a result, being in the sun could affect people's perception of T_a and cause them to overestimate it, which can probably affect people's outdoor thermal comfort.

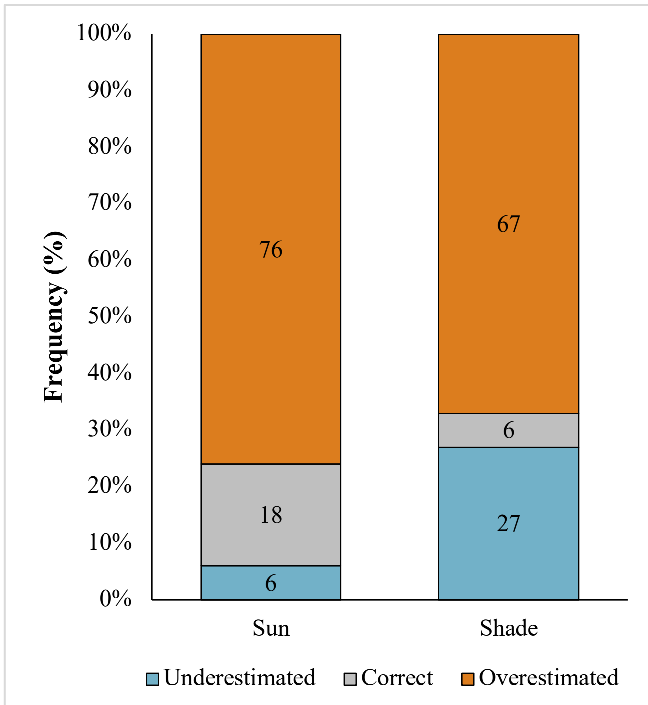


Figure 9. Comparison of the actual measured T_a around the respondent and the temperature estimated by the respondent according to their location (in the shade or sun).

3.1.4. Outdoor Thermal Comfort Range in Ahvaz

To determine the outdoor thermal comfort range in Ahvaz, PET [76] was used as the thermal comfort index due to its frequent use [77]. In this study PET is calculated by RayMan [60,61], using measured T_a, RH and WS and simulated MRT. Participants' clothing and activity are also considered in the PET calculation. To investigate the relationship between thermal comfort (PET index) and TSV, it is first necessary to calculate the mean thermal sensation votes (MTSV) for each 1°C PET interval [78]. Eq. 3 shows the correlation between PET and MTSV in this study.

The neutral PET in this climate is determined by substituting MTSV=0 in Eq. 3. As a result, the neutral PET in this study is 25.3°C. The acceptable thermal comfort range is between -0.5 and +0.5 [65], so by replacing MTSV= ±0.5 in Eq. 3, the outdoor thermal comfort in Ahvaz ranges from 19.6°C to 30.9°C PET. However, this PET range is not obtainable in the summer in this climate and can only be improved by providing some solutions. Based on Figure 10, which shows a comparison between the thermal comfort range in similar studies and this study, neutral PET and high value of acceptable PET of Ahvaz, are approximately close to Isfahan's [71] with BWk climate and Dar es Salaam's with Aw climate [79] while the low value of acceptable PET is close to Tempe's with BWh climate [59] based on the Köppen-Geiger climate classification.

$$MTSV = 0.0886\,(PET) - 2.2405 \qquad (R^2=0.93) \qquad (3)$$

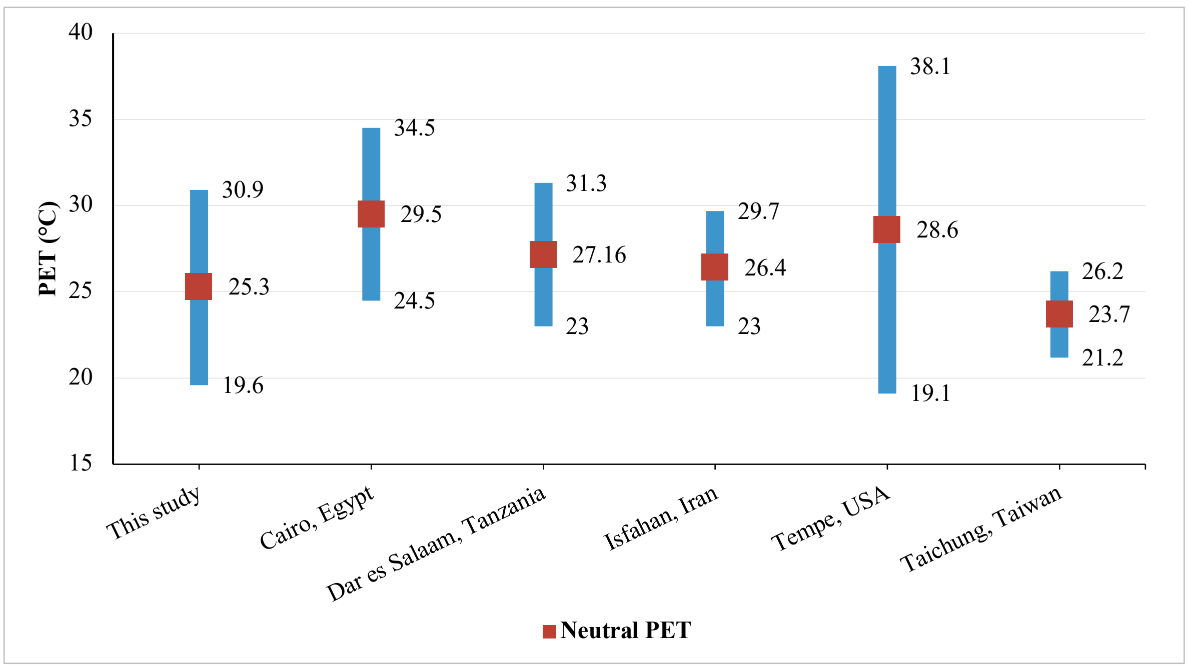


Figure 10. Comparison of PET thermal comfort range in this study with other studies in Cairo [80], Dar es Salaam [79], Isfahan [71], Tempe [59] and Taichung [81].

3.2.Simulation Results

T_a, MRT and PET were studied through the ENVI-met results. To compare the studied sites with each other, different points on each were selected as shown in Figure 11. These points were selected to compare the effect of urban geometry as well as urban shadings in pedestrians' thermal comfort. Table *3* shows the different characteristics of these points.

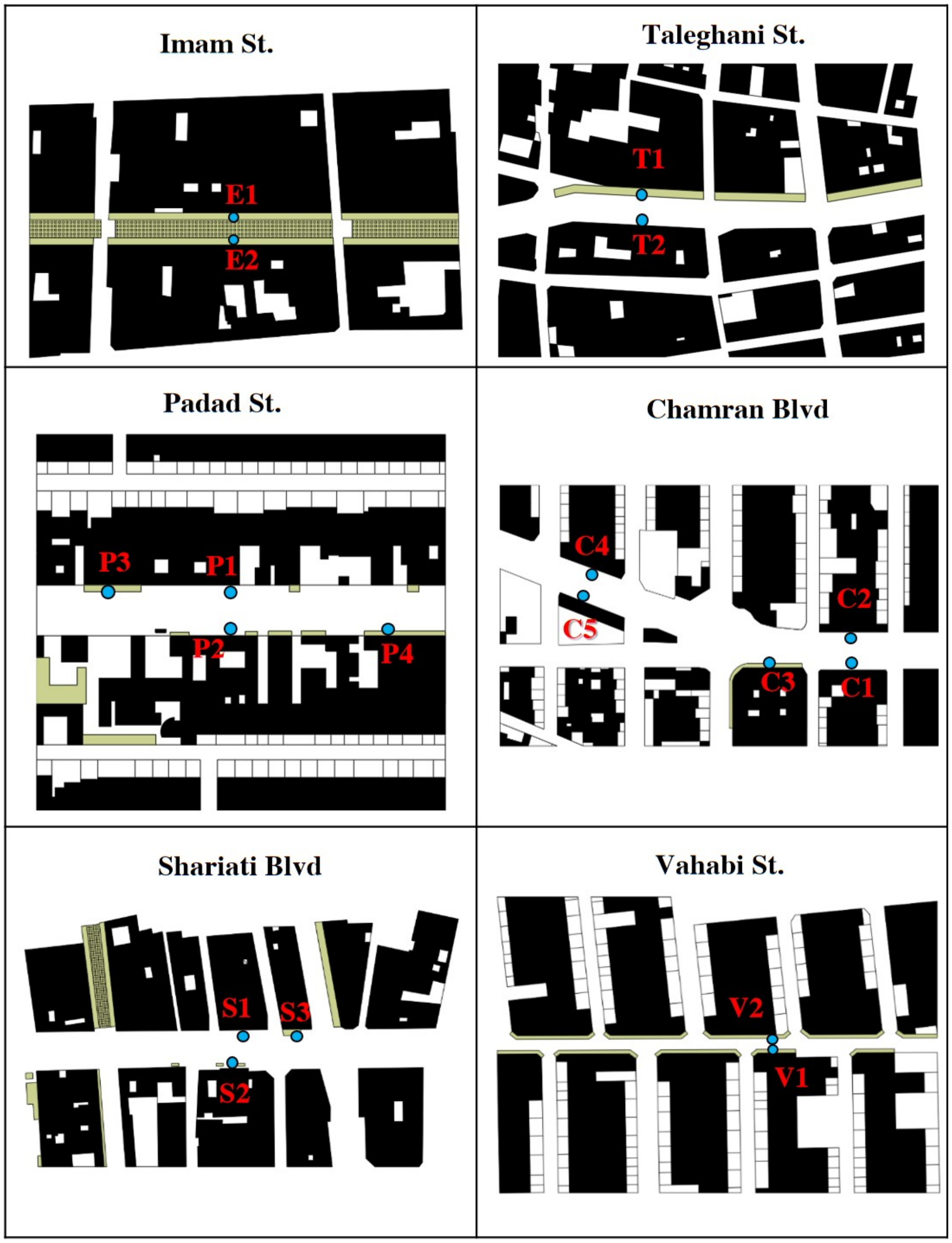


Figure 11. Location of reviewed checkpoints on each site.

Table 3. Different characteristics of reviewed points on each site.

Area	Imam St.		Taleghani St.		Padad St.				Chamran Blvd
Point	E1	E2	T1	T2	P1	P2	P3	P4	C1
Facing	SSW	NNE	SSW	NNE	SSW	NNE	SSW	NNE	WNW
Shade	✓	✓	✓	×	×	×	✓	✓	×
SVF	0.06	0.03	0.21	0.5	0.46	0.47	0.15	0.15	0.43
Area	Chamran Blvd				Shariati Blvd			Vahabi St.	
Point	C2	C3	C4	C5	S1	S2	S3	V1	V2
Facing	ESE	WNW	SE	SE	ESE	WNW	ESE	ESE	WNW
Shade	×	✓	×	×	×	×	✓	✓	✓
SVF	0.4	0.18	0.46	0.45	0.47	0.42	0.19	0.2	0.18

3.2.1. Air Temperature

In Imam Street, with a WNW-ESE orientation, there was no significant difference in T_a between the SSW-facing (E1) and the NNE-facing (E2) sidewalks since the whole canyon is covered by shadings. The minimum T_a at the selected points on this site was 41.3°C at 22:00, and the maximum T_a was 47.4°C at 12:30.

On Taleghani Street, the entire SSW-facing sidewalk has shading. T_a difference between T1, with shading, and T2 on the opposite side, without shading, was 0.1°C at noon. The minimum T_a in this site was 42.2°C at 8:30 and 22:00, while the maximum T_a was 47.9°C at 13:00. The shaded points were 0.1°C cooler than the unshaded points during the night.

In Padad Street, with a similar orientation to the previous two canyons, in the unshaded areas, T_a on the SSW-facing sidewalk was slightly higher than on the NNE-facing sidewalk. The highest T_a difference in the unshaded areas was 0.2°C at 14:00. From 10:00 to 16:00, when the heat peaks, T_a at the unshaded points (P1 and P2) was lower than at the shaded points (P3 and P4). The highest T_a difference between shaded and unshaded points was 0.2°C on the SSW-facing sidewalk at 13:00 and 0.6°C on the NNE-facing sidewalk at 8:00. The minimum T_a was 42.1°C on P3 at 22:00 and the maximum was 48°C at the same point at 13:00. At night, the points with shading were cooler than the points without shading. Generally, on Padad Street, the shaded points had a lower minimum T_a but a higher maximum T_A than the unshaded points, which is probably due to the low

H/W and also because of the short length of the shadings and consequent solar radiation penetration under the shading at certain hours.

In the middle of Chamran Boulevard, the street orientation is changed and as a result, the northern part of the canyon is oriented 17 degrees from north, while the southern part is oriented 38 degrees from north. In the northern part of the canyon, which is closer to NS orientation, the ESE-facing sidewalk was warmer than the WNW-facing sidewalk most of the time. The maximum T_a difference between the two sidewalks was 1.1°C at 11:30. Point C3, which is located on the WNW-facing sidewalk (similar to point C1) and even though having a shading, did not differ much in T_a from point C1. However, C3 had a lower T_a than the other points during the night. In the southern part of the canyon, where the orientation of the canyon changes by 21 degrees and as it gets closer to NE-SW orientation, T_a was up to 0.6°C higher than the northern part of the canyon from 8:00 to 16:00. The minimum and maximum T_a on this site were 41.7°C at C4 at 22:00 and 49.4°C at the same point at 13:00, respectively.

On Shariati Boulevard T_a at S2, without shading, was lower than at other points most of the time. During the night, T_a in all three points was equal. The highest T_a difference between S1 (ESE-facing) and S2 (WNW-facing) was 0.7°C at 11:00. The minimum T_a in this canyon was 41.9°C at S1 and S3 at 22:00, and the maximum was 49.1°C at S1 at 13:00.

Vahabi Street has shadings on the both sidewalks. Therefore, T_a on the both sidewalks of this street were equal. The minimum and maximum T_a on this street were 42.1 °C at 22:00 and 47.6 °C at 13:00, respectively (Figure 12-a).

3.2.2. Mean Radiant Temperature

Based on the ENVI-met results, there is no significant difference in MRT at different points on Imam Street with WNW-ESE or near EW orientation. This is mainly because all parts inside the canyon are shaded. The minimum MRT on Imam Street was about 25°C at 22:00, while the maximum was 57.5°C at 14:00.

The entire SSW-facing sidewalk on Taleghani Street has shading, and therefore MRT was lower on this sidewalk or T1 than on the opposite sidewalk during the day and the night. The MRT difference between T1 and T2 at noon was 13.6°C. The minimum MRT at these points was 27.8°C at 22:00 on T1 and the maximum was 76.3°C at 13:30 on T2.

In Padad Street, the lowest values of MRT was observed at P1 and P2 in the morning and the afternoon, respectively. However, the average daily MRT at these two points was identical. The highest MRT difference between the two sidewalks was 30.8°C and the highest MRT difference between shaded and unshaded points was 29.5°C on the SSW-facing sidewalk at 17:00 and 34.1°C on the NNE-facing sidewalk at 8:00. The minimum and maximum MRTs on this site were 27.8°C at 22:00 in the shaded areas and 80°C at 15:30 in the unshaded areas, respectively.

In the northern part of Chamran Boulevard, MRT at C3, having shading and the same orientation facing as C1, was 27°C lower than at C1. In the southern part of the canyon, where the canyon is 21 degrees closer to NE-SW orientation, MRT was higher by 16°C than the northern part. The lowest and the highest MRTs on this site were observed to be 28.5°C in shaded areas at 22:00 and 79.8°C at C5 (without shading) at 15:30, respectively.

Among the unshaded areas of Shariati Boulevard, the lowest MRT was observed at S2 (WNW-facing) from 8:00 to 11:00 and at S1 from 13:30 to 18:00. With the exception of the aforementioned hours, MRT was identical at these two points. The average daily MRT was 2.1°C lower at S1 than at S2. However, S3 with shading had the lowest MRT throughout the day. The highest MRT difference between these points was 34.2°C between S3 and S1 at 8:00. The minimum MRT in this canyon was 26.7°C at S3 at 22:00, while the maximum was 79.5°C at S2 at 15:30.

In Vahabi Street, MRT was equal on the both sidewalks in the most hours, with the exceptions occurred at 8:00 and 16:00 to 18:00 when there was a significant difference in MRT values. MRT value at V1 (facing ESE) was 31°C higher than at V2 (facing WNW) at 8:00, and 28°C lower than at V2 at 16:30 which is probably because of perpendicular avenues connected to this street which are not in the same axis and caused solar access under the shadings. The minimum and maximum MRTs in this canyon were 27.4°C at 22:00 and 78.9°C at 15:30, respectively.

It is evident that the lowest MRT is observed in Imam Street, which is 25°C at 22:00. Also, the highest MRT is 80°C on Padad Street with the lowest aspect ratio compared to the other canyons (Figure 12-b).

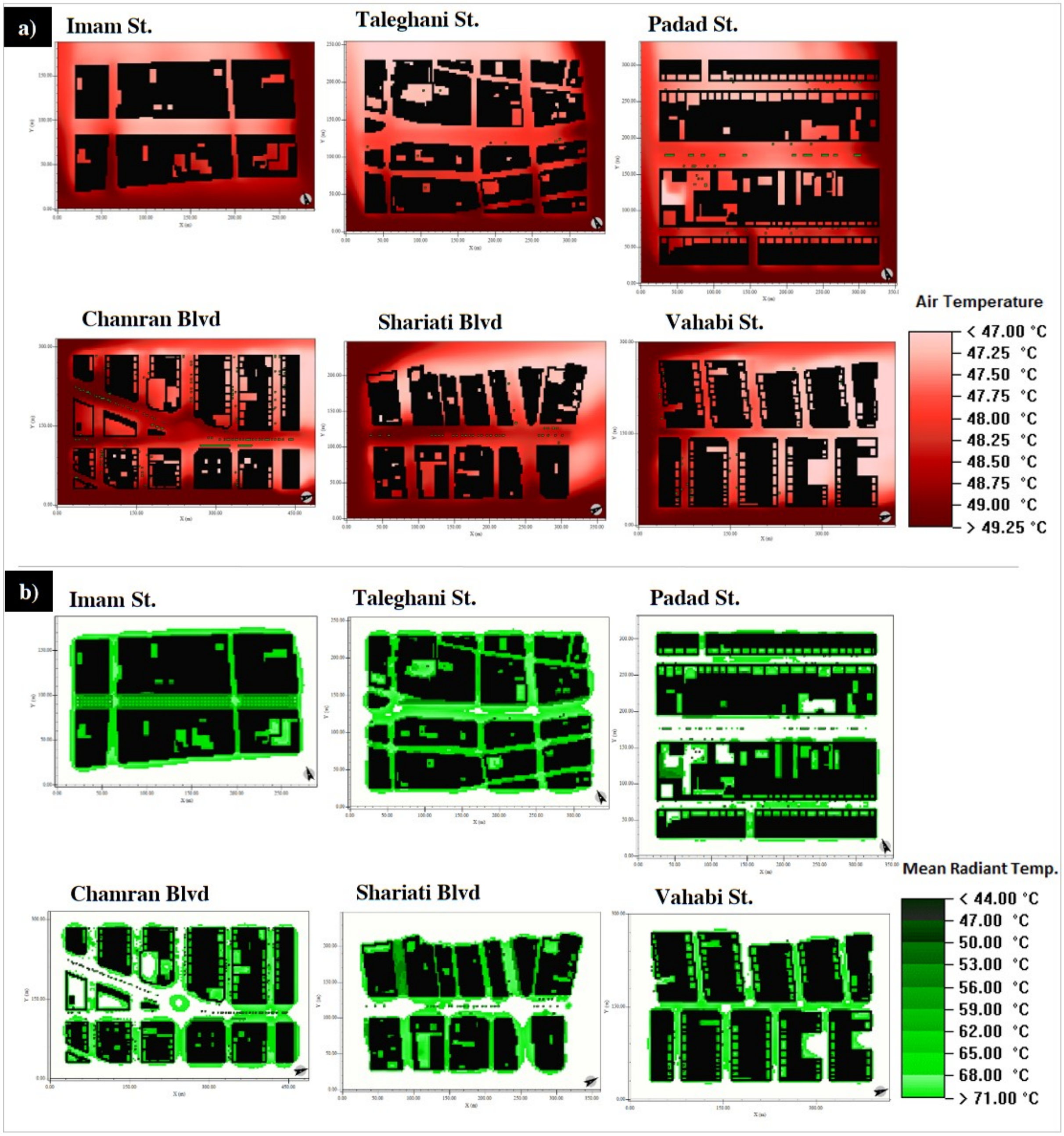


Figure 12. a) T_a and b) MRT map at noon on each site.

3.2.3. PET

PET values were calculated by RayMan considering four parameters including T_a, MRT, RH, and WS. Since PET is strongly influenced by MRT, the results in this section are rather similar to those in MRT.

The shaded points located on the nearly EW oriented canyons, namely, E1, E2, T1, P3, and P4, enjoy an almost identical condition in terms of PET. The only exception occurred after 19:00, when PET at fully shaded points, E1 and E2, located in Imam Street was 3°C lower than at other shaded points. However, among the unshaded points in this orientation, P1, facing SSW, located in Padad Street with low H/W experienced a higher duration of high PET. Besides, P1 had higher SVF in comparison to other points. The highest PET difference between shaded and unshaded points on Taleghani Street was 15.5 °C at 8:00, and on Padad Street was 17.6 °C at 8:00, and 15.6°C at 15:30.

In nearly NS oriented canyons, the points on east-facing and west-facing sidewalks experienced worse thermal conditions in the morning and afternoon, respectively, as expected. In this orientation, all points with shadings had an almost equal PET which was lower than unshaded points during the day. The highest PET difference between shaded and unshaded points on Chamran Boulevard was 11.5 °C at 15:00 and on Shariati Boulevard was 13.8 °C at 8:00 (Figure 13).

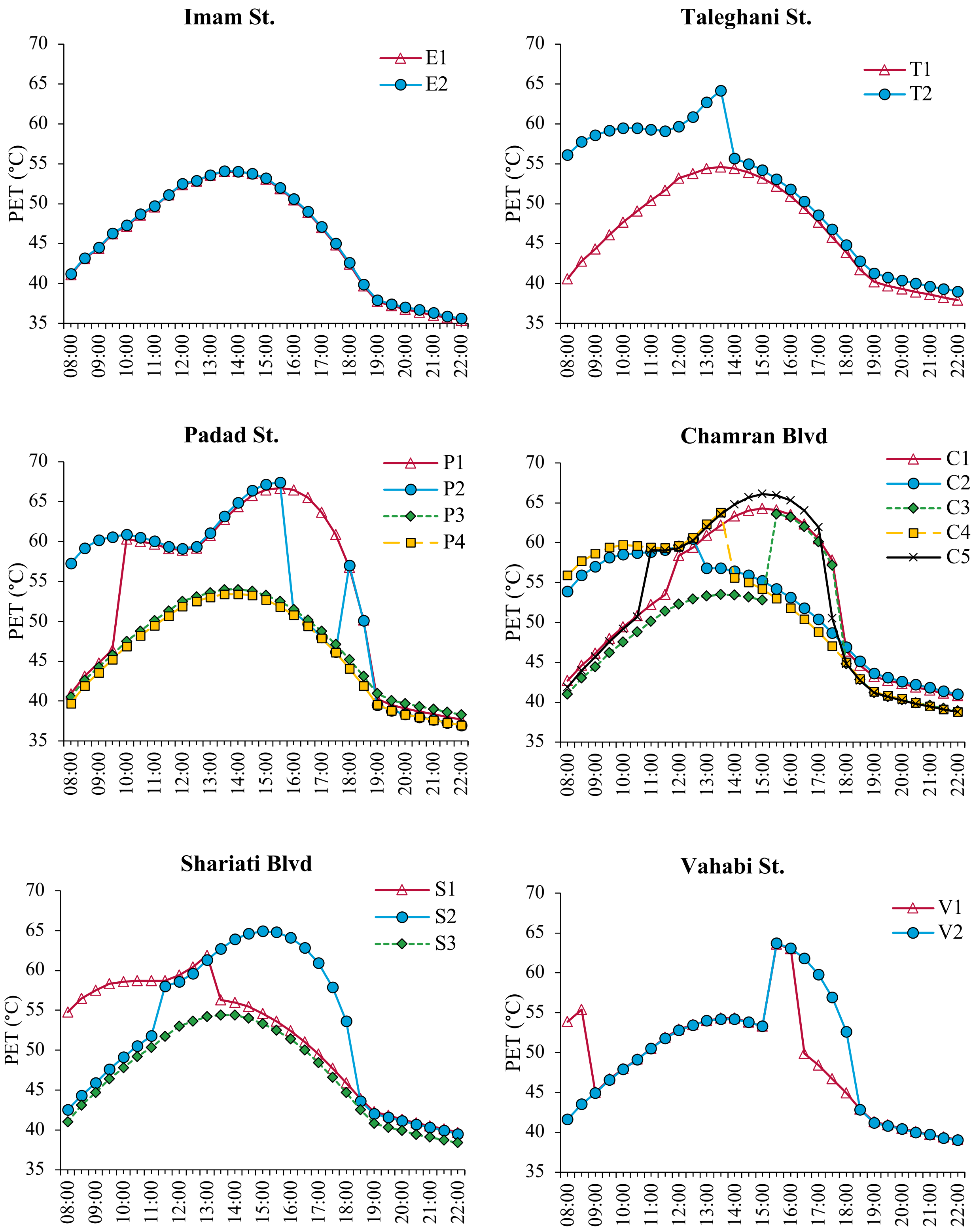


Figure 13. PET values in the studied sites.

Table 4 shows the daily average, maximum, and minimum PET values at different points. The lowest daily average and minimum of PET values occurred at E1 and E2 of Imam Street and the lowest daily maximum PET was at the shaded point P4 on Padad Street, located on the NNE-facing sidewalk. The highest daily average, maximum, and minimum PET values occurred at P1 and P2 together, P2, and C2, respectively. As a result, shaded points in canyons with an orientation closer to EW had a lower daily average PET than shaded points in canyons with an orientation closer to NS.

Point	E1	E2	T1	T2	P1	P2	P3	P4	C1
Ave.	45.7	45.8	46.7	51.7	53.6	53.6	46.9	46	52.2
Max.	54	54.1	54.6	64.2	66.7	67.4	54	53.4	64.3
Min.	35.4	35.6	37.9	39	37.7	37	38.3	37	40.8
Point	**C2**	**C3**	**C4**	**C5**	**S1**	**S2**	**S3**	**V1**	**V2**
Ave.	52	48.9	51.7	52.2	51.6	52.3	47	48.9	49.4
Max.	60.5	63.6	63.8	66.1	61.9	64.9	54.4	63.6	63.7
Min.	41	38.9	38.8	38.8	39.7	39.5	38.4	39.1	39

Table 4. Daily average, maximum and minimum PET values at studied points. (Blue, the lowest value; and orange, the highest value between different points).

Point	**E1**	**E2**	**T1**	**T2**	**P1**	**P2**	**P3**	**P4**	**C1**
Ave.	45.7	45.8	46.7	51.7	53.6	53.6	46.9	46	52.2
Max.	54	54.1	54.6	64.2	66.7	67.4	54	53.4	64.3
Min.	35.4	35.6	37.9	39	37.7	37	38.3	37	40.8
Point	**C2**	**C3**	**C4**	**C5**	**S1**	**S2**	**S3**	**V1**	**V2**
Ave.	52	48.9	51.7	52.2	51.6	52.3	47	48.9	49.4
Max.	60.5	63.6	63.8	66.1	61.9	64.9	54.4	63.6	63.7
Min.	41	38.9	38.8	38.8	39.7	39.5	38.4	39.1	39

Figure 14 shows points arrangement based on average T_A and average PET. According to this figure, points in more shaded areas, on Imam Street and Vahabi Street, had the lowest average T_A. Also, in the shaded areas, the average PET was lower in the canyons closer to EW (WNW-ESE) orientation than in the canyons closer to NS (NNE-SSW) orientation.

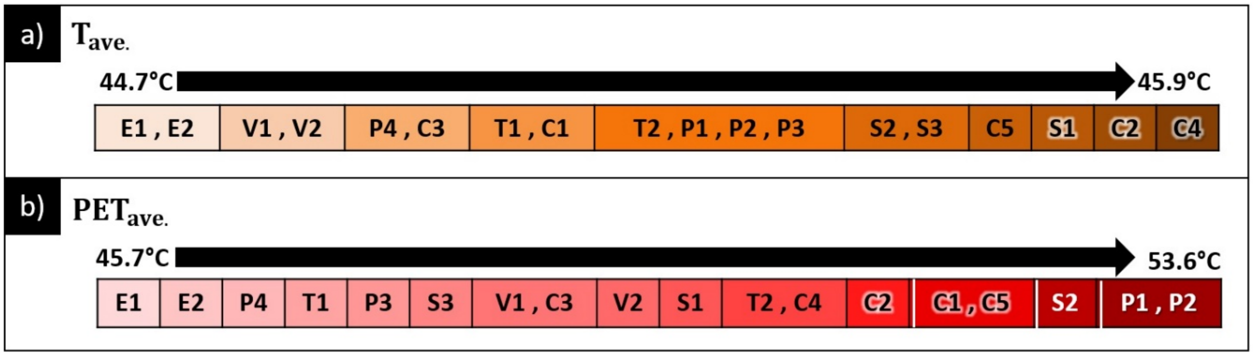


Figure 14. The studied points arrangement in order of increasing the average T_A and average PET.

3.2.4. Investigating the Relationship between SVF and Different Variables

To investigate the relationship between SVF and climatic parameters as well as PET index, the Pearson correlation coefficient between SVF and these parameters is calculated at all review points at noon. According to Table 5, there is no correlation between SVF and RH at any point. MRT and PET are correlated with SVF at all points. However, T_A and WS are correlated with SVF only on Imam Street. Figure 15 shows scatter diagram of comparison between PET and SVF on different sites at noon. According to these charts, the lowest value of R^2 was on Vahabi Street (0.69) while the highest value was on Taleghani Street (0.87).

Table 5. Pearson correlation coefficient between SVF and different parameters on study sites at noon.

Area	Ta	MRT	RH	WS	PET
Imam St.	0.83	0.84	-0.24	0.90	0.86
Taleghani St.	0.27	0.93	-0.46	0.26	0.93
Padad St.	0.15	0.86	-0.28	0.46	0.85
Chamran Blvd	0.18	0.75	0.003	0.15	0.85
Shariati Blvd	0.18	0.84	0.23	0.30	0.84
Vahabi St.	0.07	0.93	-0.06	-0.24	0.92

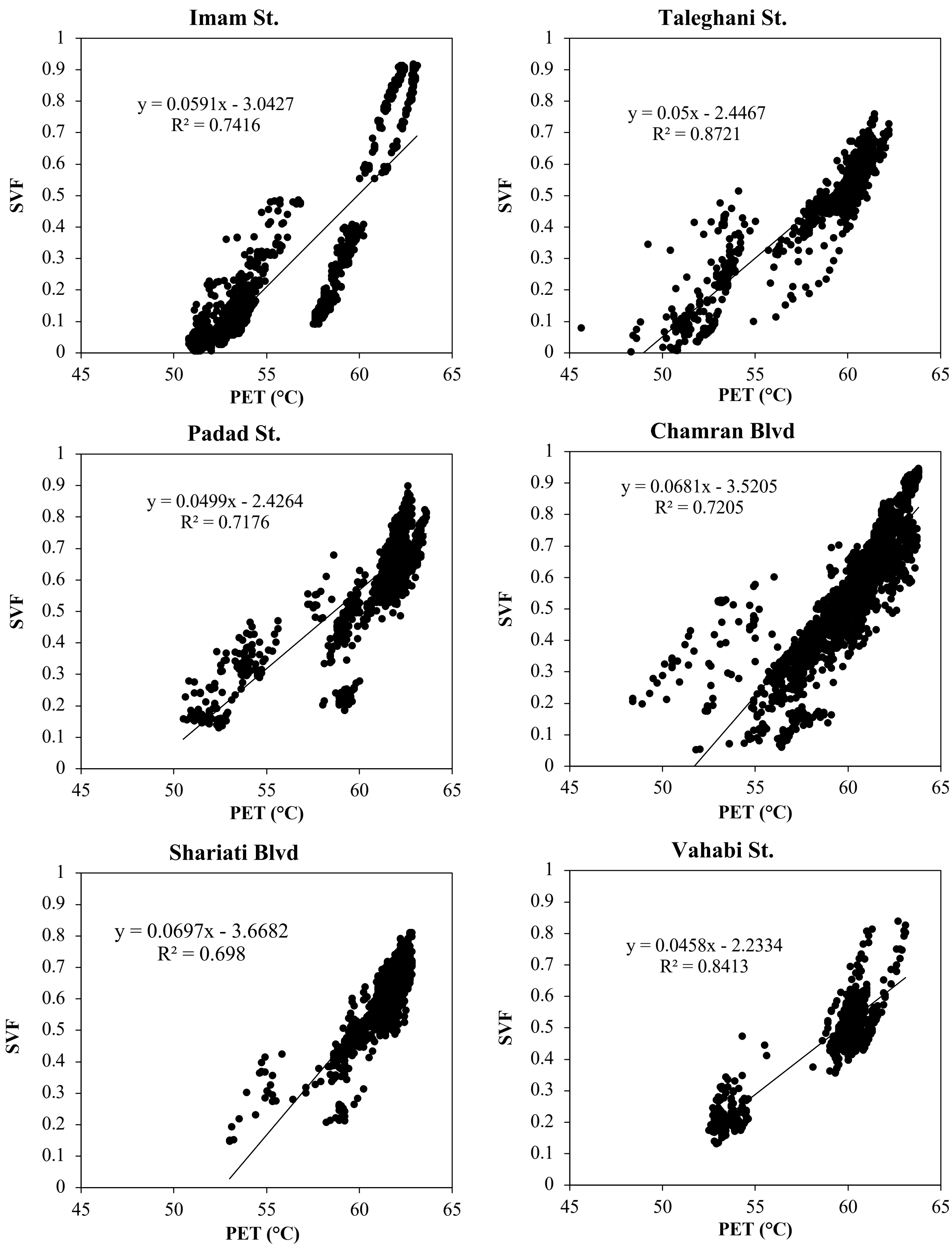


Figure 15. Scatter diagram of the relationship between PET and SVF on different sites at noon.

4. Conclusion

Considering the importance and the impact of urban features on outdoor thermal comfort, this study investigated outdoor thermal comfort in the hot climate of Ahvaz. Six urban canyons, with a significant number of pedestrians were selected. Thermal comfort in these canyons was investigated by conducting a questionnaire survey and microclimatic measurement. To investigate the role of urban geometry and urban shadings on outdoor thermal comfort, the canyons were simulated using ENVI-met, which was validated for 3 consecutive days from July 27th to 29th, 2018. Microclimatic parameters were measured simultaneously with the completion of the questionnaires from July 21st to 26th, 2018. Considering the maximum presence of pedestrians on these sites, these measurements were taken from about 8:30 to noon, and from 19:00 to 21:30. For simulation purposes, July 4th was selected as the hottest day of 2018. The PET values were calculated by RayMan. Three of the selected canyons were oriented close to the EW and the other three are close to the NS. The width of these canyons varied from 15 to 38 meters with H/W values ranging between 0.2 and 0.6. Imam Street was completely covered by shading, and the remaining canyons had shadings on some parts of their sidewalks.

The results of field measurements and questionnaire, as well as investigating the effect of shadings and urban geometry factors such as orientation, aspect ratio and SVF on climatic parameters and thermal comfort, are expressed as follows:

• The range of outdoor thermal comfort in Ahvaz is between 19.6°C and 30.9°C PET. Also, the neutral PET in this climate is 25.3°C. This PET range is obtainable in summer by providing some climate design solutions.

• The closer the canyons are to NS orientation, the lower the T_a and MRT are, which is in agreement with the previous studies [50,51]. In canyons closer to NS orientation, MRT and PET values are lower on west-faced sidewalks in the morning and the east-faced sidewalks in the afternoon.

• Increasing the canyon width, or H/W reduction, increases PET which confirms the previous studies [31,32]. Padad Street with a width of 38 meters and H/W equals to 0.2 has an average daily PET of 2°C higher than Taleghani Street with a width of 22 meters and H/W of 0.45.

• There is a strong correlation between SVF and PET, as well as SVF and MRT on different sites. The Pearson correlation coefficient at noon between SVF and PET, as well as MRT is between

0.75 and 0.93 on the different sites. None of these sites showed an agreement between SVF and RH. WS and T_a are correlated with SVF only in Imam Street, which is contrary to the studies of Wang and Akbari [38].

• Urban shading reduces MRT by 34°C, and it reduces PET by 17.6 and 13.8°C in EW an NS canyons, respectively. This indicates that the impact of the shading is more evident in EW canyons rather than NS canyons. Furthermore, shadings in more shallow canyons with low H/W, had a significant effect on reducing the average daily PET.

• Shadings do not significantly affect T_a in the canyons. In some canyons they cause a slight decrease in T_a. In areas where the entire or most of the sidewalk is covered by shadings, the average daily T_a in shaded areas is 0.5 to 1.2°C lower than other areas. In most sites, the air temperature of the shaded points was lower than the unshaded points at night.

Appendix A:

Table A1. Description of the time and date of field studies and questionnaire surveys on each site.

Area	**Date of measurement and questionnaire survey**	**Time of measurement and questionnaire survey**	**Number of valid questionnaire**
Imam St.	7/21/2018	8:30-13:00 19:00-22:00	61
Taleghani St.	7/22/2018	8:30-12:30	49

		19:30-21:30	
Padad St.	7/24/2018	8:30-12:00 19:30-21:00	37
Chamran Blvd	7/26/2018	9:30-12:30 19:30-21:30	42
Shariati Blvd	7/23/2018	8:30-10:00 19:00-21:30	34
Vahabi St.	7/25/2018	8:30-12:00 19:30-21:30	34

Appendix B:

Figure B1. Standard ST-174B weather datalogger for measuring T_A to validate ENVI-met.

[1] UN, World Population Prospects 2017, (2017). https://esa.un.org/unpd/wpp/Graphs/ (accessed January 20, 2018).

[2] L.-W. Lai, W.-L. Cheng, Air temperature change due to human activities in Taiwan for the past century, Int. J. Climatol. 30 (2010) 432–444. https://doi.org/10.1002/joc.1898.

[3] S. Chapman, J.E.M. Watson, A. Salazar, M. Thatcher, C.A. McAlpine, The impact of urbanization and climate change on urban temperatures: a systematic review, Landsc. Ecol. 32 (2017) 1921–1935. https://doi.org/10.1007/s10980-017-0561-4.

[4] S.M. Robaa, Effect of urbanization and industrialization processes on outdoor thermal human comfort in Egypt, Atmos. Clim. Sci. 1 (2011) 100–112. https://doi.org/10.4236/acs.2011.13012.

[5] A. Matzarakis, H. Mayer, The extreme heat wave in Athens in July 1987 from the point of view of human biometeorology, Atmos. Environ. 25 (1991) 203–211. https://doi.org/10.1016/0957-1272(91)90055-J.

[6] O. Shevchenko, H. Lee, S. Snizhko, H. Mayer, Long-term analysis of heat waves in Ukraine, Int. J. Climatol. 34 (2014) 1642–1650. https://doi.org/10.1002/joc.3792.

[7] J. Paravantis, M. Santamouris, C. Cartalis, C. Efthymiou, N. Kontoulis, Mortality Associated with High Ambient Temperatures, Heatwaves, and the Urban Heat Island in Athens, Greece, Sustainability. 9 (2017) 606. https://doi.org/10.3390/su9040606.

[8] J. Zacharias, T. Stathopoulos, H. Wu, Microclimate and downtown open space activity, Environ. Behav. 33 (2001) 296–315. https://doi.org/10.1177/0013916501332008.

[9] M. Nikolopoulou, N. Baker, K. Steemers, Thermal Comfort in Outdoor Urban Spaces: Understanding the Human Parameter, Sol. Energy. 70 (2001) 227–235. https://doi.org/10.1016/S0038-092X(00)00093-1.

[10] L. Chen, E. Ng, Outdoor thermal comfort and outdoor activities: A review of research in the past decade, Cities. 29 (2012) 118–125. https://doi.org/10.1016/j.cities.2011.08.006.

[11] T. Xi, Q. Li, A. Mochida, Q. Meng, Study on the outdoor thermal environment and thermal comfort around campus clusters in subtropical urban areas, Build. Environ. 52

(2012) 162–170. https://doi.org/10.1016/j.buildenv.2011.11.006.

[12] D. Lai, C. Zhou, J. Huang, Y. Jiang, Z. Long, Q. Chen, Outdoor space quality: A field study in an urban residential community in central China, Energy Build. 68 (2014) 713–720. https://doi.org/10.1016/j.enbuild.2013.02.051.

[13] D.J. Murphy, M.H. Hall, C.A.S. Hall, G.M. Heisler, S. V. Stehman, C. Anselmi-Molina, The relationship between land cover and the urban heat island in northeastern Puerto Rico, Int. J. Climatol. 31 (2011) 1222–1239. https://doi.org/10.1002/joc.2145.

[14] Y. Hu, G. Jia, Influence of land use change on urban heat island derived from multi-sensor data, Int. J. Climatol. 30 (2010) 1382–1395. https://doi.org/10.1002/joc.1984.

[15] M. Shahgedanova, T.P. Burt, T.D. Davies, Some aspects of the three-dimensional heat island in Moscow, Int. J. Climatol. 17 (1997) 1451–1465. https://doi.org/10.1002/(SICI)1097-0088(19971115)17:13<1451::AID-JOC201>3.0.CO;2-Z.

[16] A. Aflaki, M. Mirnezhad, A. Ghaffarianhoseini, A. Ghaffarianhoseini, H. Omrany, Z.H. Wang, H. Akbari, Urban heat island mitigation strategies: A state-of-the-art review on Kuala Lumpur, Singapore and Hong Kong, Cities. 62 (2017) 131–145. https://doi.org/10.1016/j.cities.2016.09.003.

[17] Y. Wang, H. Akbari, The effects of street tree planting on Urban Heat Island mitigation in Montreal, Sustain. Cities Soc. 27 (2016) 122–128. https://doi.org/10.1016/j.scs.2016.04.013.

[18] M. Roth, Review of urban climate research in (sub)tropical regions, Int. J. Climatol. 27 (2007) 1859–1873. https://doi.org/10.1002/joc.1591.

[19] G.J. Levermore, H.K.W. Cheung, A low-order canyon model to estimate the influence of canyon shape on the maximum urban heat island effect, Build. Serv. Eng. Res. Technol. 33 (2012) 371–385. https://doi.org/10.1177/0143624411417899.

[20] T.R. Oke, Canyon geometry and the nocturnal urban heat island: comparison of scale model and field observations, J. Climatol. 1 (1981) 237–254. https://doi.org/10.1002/joc.3370010304.

[21] T. Lin, A. Matzarakis, R. Hwang, Shading effect on long-term outdoor thermal comfort, Build. Environ. 45 (2010) 213–221. https://doi.org/10.1016/j.buildenv.2009.06.002.

[22] J.A. Rodríguez Algeciras, A. Matzarakis, Quantification of thermal bioclimate for the management of urban design in Mediterranean climate of Barcelona, Spain, Int. J. Biometeorol. 60 (2016) 1261–1270. https://doi.org/10.1007/s00484-015-1121-8.

[23] L. Martinelli, T. Lin, A. Matzarakis, Assessment of the influence of daily shadings pattern on human thermal comfort and attendance in Rome during summer period, Build. Environ. 92 (2015) 30–38. https://doi.org/10.1016/j.buildenv.2015.04.013.

[24] L.V. de Abreu-Harbich, L.C. Labaki, A. Matzarakis, Thermal bioclimate in idealized urban street canyons in Campinas, Brazil, Theor. Appl. Climatol. 115 (2014) 333–340. https://doi.org/10.1007/s00704-013-0886-0.

[25] T.R. Oke, Street design and urban canopy layer climate, Energy Build. 11 (1988) 103–113. https://doi.org/10.1016/0378-7788(88)90026-6.

[26] F. Ali-Toudert, H. Mayer, Numerical study on the effects of aspect ratio and orientation of an urban street canyon on outdoor thermal comfort in hot and dry climate, Build. Environ. 41 (2006) 94–108. https://doi.org/10.1016/j.buildenv.2005.01.013.

[27] E. Jamei, P. Rajagopalan, M. Seyedmahmoudian, Y. Jamei, Review on the impact of urban geometry and pedestrian level greening on outdoor thermal comfort, Renew. Sustain. Energy Rev. 54 (2016) 1002–1017. https://doi.org/10.1016/j.rser.2015.10.104.

[28] S. Thorsson, F. Lindberg, J. Björklund, B. Holmer, D. Rayner, Potential changes in outdoor thermal comfort conditions in Gothenburg, Sweden due to climate change: the influence of urban geometry, Int. J. Climatol. 31 (2011) 324–335. https://doi.org/10.1002/joc.2231.

[29] K.T. Huang, Y.J. Li, Impact of street canyon typology on building's peak cooling energy demand: A parametric analysis using orthogonal experiment, Energy Build. 154 (2017) 448–464. https://doi.org/10.1016/j.enbuild.2017.08.054.

[30] T. Sharmin, K. Steemers, A. Matzarakis, Microclimatic modelling in assessing the impact of urban geometry on urban thermal environment, Sustain. Cities Soc. 34 (2017) 293–308.

https://doi.org/10.1016/j.scs.2017.07.006.

[31] E. Johansson, Influence of urban geometry on outdoor thermal comfort in a hot dry climate : A study in Fez, Morocco, Build. Environ. 41 (2006) 1326–1338. https://doi.org/10.1016/j.buildenv.2005.05.022.

[32] M.A. Bakarman, J.D. Chang, The influence of height/width ratio on urban heat island in hot-arid climates, Procedia Eng. 118 (2015) 101–108. https://doi.org/10.1016/j.proeng.2015.08.408.

[33] M.B. Sosa, E.N. Correa, M.A. Cantón, Urban grid forms as a strategy for reducing heat island effects in arid cities, Sustain. Cities Soc. 32 (2017) 547–556. https://doi.org/10.1016/j.scs.2017.05.003.

[34] A.S. Jihad, M. Tahiri, Modeling the urban geometry influence on outdoor thermal comfort in the case of Moroccan microclimate, Urban Clim. 16 (2016) 25–42. https://doi.org/10.1016/j.uclim.2016.02.002.

[35] C.S. Polo Lopez, M. Sala, L.C. Tagliabue, F. Frontini, S. Bouziri, Solar radiation and daylighting assessment using the Sky-View Factor (SVF) analysis as method to evaluate urban planning densification policies impacts, Energy Procedia. 91 (2016) 989–996. https://doi.org/10.1016/j.egypro.2016.06.266.

[36] C. Chatzipoulka, R. Compagnon, M. Nikolopoulou, Urban geometry and solar availability on façades and ground of real urban forms: using London as a case study, Sol. Energy. 138 (2016) 53–66. https://doi.org/10.1016/j.solener.2016.09.005.

[37] E.L. Krüger, F.O. Minella, F. Rasia, Impact of urban geometry on outdoor thermal comfort and air quality from field measurements in Curitiba, Brazil, Build. Environ. 46 (2011) 621–634. https://doi.org/10.1016/j.buildenv.2010.09.006.

[38] Y. Wang, H. Akbari, Analysis of urban heat island phenomenon and mitigation solutions evaluation for Montreal, Sustain. Cities Soc. 26 (2016) 438–446. https://doi.org/10.1016/j.scs.2016.04.015.

[39] M.K. Svensson, Sky view factor analysis – implications for urban air temperature differences, Meteorol. Appl. 11 (2004) 201–211.

https://doi.org/10.1017/S1350482704001288.

[40] F. Bourbia, F. Boucheriba, Impact of street design on urban microclimate for semi arid climate (Constantine), Renew. Energy. 35 (2010) 343–347. https://doi.org/10.1016/j.renene.2009.07.017.

[41] X. He, S. Miao, S. Shen, J. Li, B. Zhang, Z. Zhang, X. Chen, Influence of sky view factor on outdoor thermal environment and physiological equivalent temperature, Int. J. Biometeorol. 59 (2015) 285–297. https://doi.org/10.1007/s00484-014-0841-5.

[42] I. Karakounos, A. Dimoudi, S. Zoras, The influence of bioclimatic urban redevelopment on outdoor thermal comfort, Energy Build. 158 (2018) 1266–1274. https://doi.org/10.1016/j.enbuild.2017.11.035.

[43] S. Achour-Younsi, F. Kharrat, Outdoor thermal comfort: Impact of the geometry of an urban street canyon in a Mediterranean subtropical climate – Case study Tunis, Tunisia, Procedia - Soc. Behav. Sci. 216 (2016) 689–700. https://doi.org/10.1016/j.sbspro.2015.12.062.

[44] F. Bourbia, H.B. Awbi, Building cluster and shading in urban canyon for hot dry climate Part 2 : Shading simulations, Renew. Energy. 29 (2004) 291–301. https://doi.org/10.1016/S0960-1481(03)00171-X.

[45] I. Boukhelkhal, P.F. Bourbia, Thermal comfort conditions in outdoor urban spaces: Hot dry climate -Ghardaia- Algeria, Procedia Eng. 169 (2016) 207–215. https://doi.org/10.1016/j.proeng.2016.10.025.

[46] P.E. Todhunter, Microclimatic variations attributable to urban-canyon asymmetry and orientation, Phys. Geogr. 11 (1990) 131–141. https://doi.org/10.1080/02723646.1990.10642398.

[47] A. Chatzidimitriou, K. Axarli, Street Canyon Geometry Effects on Microclimate and Comfort; A Case Study in Thessaloniki, Procedia Environ. Sci. 38 (2017) 643–650. https://doi.org/10.1016/j.proenv.2017.03.144.

[48] J.A. Rodríguez Algeciras, A. Tablada, A. Matzarakis, Effect of asymmetrical street canyons on pedestrian thermal comfort in warm-humid climate of Cuba, Theor. Appl.

Climatol. 133 (2018) 663–679. https://doi.org/10.1007/s00704-017-2204-8.

[49] J.A. Rodríguez Algeciras, L.G. Consuegra, A. Matzarakis, Spatial-temporal study on the effects of urban street configurations on human thermal comfort in the world heritage city of Camagüey-Cuba, Build. Environ. 101 (2016) 85–101. https://doi.org/10.1016/j.buildenv.2016.02.026.

[50] F. Ali-toudert, H. Mayer, Effects of asymmetry, galleries, overhanging facades and vegetation on thermal comfort in urban street canyons, Sol. Energy. 81 (2007) 742–754. https://doi.org/10.1016/j.solener.2006.10.007.

[51] F. Bourbia, H.B. Awbi, Building cluster and shading in urban canyon for hot dry climate Part 1: Air and surface temperature measurements, Renew. Energy. 29 (2004) 249–262. https://doi.org/10.1016/S0960-1481(03)00170-8.

[52] J. Herrmann, A. Matzarakis, Mean radiant temperature in idealised urban canyons-examples from Freiburg, Germany, Int. J. Biometeorol. 56 (2012) 199–203. https://doi.org/10.1007/s00484-010-0394-1.

[53] H. Lee, H. Mayer, L. Chen, Contribution of trees and grasslands to the mitigation of human heat stress in a residential district of Freiburg, Southwest Germany, Landsc. Urban Plan. 148 (2016) 37–50. https://doi.org/10.1016/j.landurbplan.2015.12.004.

[54] Y. Zhang, X. Du, Y. Shi, Effects of street canyon design on pedestrian thermal comfort in the hot-humid area of China, Int. J. Biometeorol. 61 (2017) 1421–1432. https://doi.org/10.1007/s00484-017-1320-6.

[55] H. Swaid, Intelligent urban forms (IUF) a new climate-concerned, urban planning strategy, Theor. Appl. Climatol. 46 (1992) 179–191. https://doi.org/10.1007/BF00866098.

[56] H. Swaid, M.E. Hoffman, Thermal effects of artificial heat sources and shaded ground areas in the urban canopy layer, Energy Build. 15 (1990) 253–261. https://doi.org/10.1016/0378-7788(90)90137-8.

[57] R. Paolini, A.G. Mainini, T. Poli, L. Vercesi, Assessment of thermal stress in a street canyon in pedestrian area with or without canopy shading, Energy Procedia. 48 (2014) 1570–1575. https://doi.org/10.1016/j.egypro.2014.02.177.

[58] E. Johansson, M.W. Yahia, I. Arroyo, C. Bengs, Outdoor thermal comfort in public space in warm-humid Guayaquil, Ecuador, Int. J. Biometeorol. 62 (2018) 387–399. https://doi.org/10.1007/s00484-017-1329-x.

[59] A. Middel, N. Selover, B. Hagen, N. Chhetri, Impact of shade on outdoor thermal comfort—a seasonal field study in Tempe, Arizona, Int. J. Biometeorol. 60 (2016) 1849–1861. https://doi.org/10.1007/s00484-016-1172-5.

[60] A. Matzarakis, F. Rutz, H. Mayer, Modelling radiation fluxes in simple and complex environments—application of the RayMan model, Int. J. Biometeorol. 51 (2007) 323–334. https://doi.org/10.1007/s00484-006-0061-8.

[61] A. Matzarakis, F. Rutz, H. Mayer, Modelling radiation fluxes in simple and complex environments: Basics of the RayMan model, Int. J. Biometeorol. 54 (2010) 131–139. https://doi.org/10.1007/s00484-009-0261-0.

[62] M. Kottek, J. Grieser, C. Beck, B. Rudolf, F. Rubel, World map of the Köppen-Geiger climate classification updated, Meteorol. Zeitschrift. 15 (2006) 259–263. https://doi.org/10.1127/0941-2948/2006/0130.

[63] Iran Meteorological Organization, (2019). http://www.irimo.ir/ (accessed April 27, 2019).

[64] K. Li, Y. Zhang, L. Zhao, Outdoor thermal comfort and activities in the urban residential community in a humid subtropical area of China, Energy Build. 133 (2016) 498–511. https://doi.org/10.1016/j.enbuild.2016.10.013.

[65] ANSI/ ASHRAE Standard 55-2017: Thermal Environmental Conditions for Human Occupancy, Ashrae Inc., Atlanta, 2017.

[66] Features - ENVI-met, (n.d.). https://www.envi-met.com/features/ (accessed May 1, 2020).

[67] A. Wania, M. Bruse, N. Blond, C. Weber, Analysing the influence of different street vegetation on traffic-induced particle dispersion using microscale simulations, J. Environ. Manage. 94 (2012) 91–101. https://doi.org/10.1016/j.jenvman.2011.06.036.

[68] E. Jamei, P. Rajagopalan, Urban development and pedestrian thermal comfort in Melbourne, Sol. Energy. 144 (2017) 681–698.

https://doi.org/10.1016/j.solener.2017.01.023.

[69] M. Bruse, H. Fleer, Simulating surface-plant-air interactions inside urban environments with a three dimensional numerical model, Environ. Model. Softw. 13 (1998) 373–384. https://doi.org/10.1016/S1364-8152(98)00042-5.

[70] F. Salata, I. Golasi, R. de Lieto Vollaro, A. de Lieto Vollaro, Urban microclimate and outdoor thermal comfort. A proper procedure to fit ENVI-met simulation outputs to experimental data, Sustain. Cities Soc. 26 (2016) 318–343. https://doi.org/10.1016/j.scs.2016.07.005.

[71] N. Nasrollahi, Z. Hatami, M. Taleghani, Development of outdoor thermal comfort model for tourists in urban historical areas; A case study in Isfahan, Build. Environ. 125 (2017) 356–372. https://doi.org/10.1016/j.buildenv.2017.09.006.

[72] N. Nasrollahi, M. Hatami, S.R. Khastar, M. Taleghani, Numerical evaluation of thermal comfort in traditional courtyards to develop new microclimate design in a hot and dry climate, Sustain. Cities Soc. 35 (2017) 449–467. https://doi.org/10.1016/j.scs.2017.08.017.

[73] A. Qaid, D.R. Ossen, Effect of asymmetrical street aspect ratios on microclimates in hot, humid regions, Int. J. Biometeorol. 59 (2015) 657–677. https://doi.org/10.1007/s00484-014-0878-5.

[74] F. Kong, C. Sun, F. Liu, H. Yin, F. Jiang, Y. Pu, G. Cavan, C. Skelhorn, A. Middel, I. Dronova, Energy saving potential of fragmented green spaces due to their temperature regulating ecosystem services in the summer, Appl. Energy. 183 (2016) 1428–1440. https://doi.org/10.1016/j.apenergy.2016.09.070.

[75] B.C. Hedquist, A.J. Brazel, Seasonal variability of temperatures and outdoor human comfort in Phoenix, Arizona, U.S.A., Build. Environ. 72 (2014) 377–388. https://doi.org/10.1016/j.buildenv.2013.11.018.

[76] P. Höppe, The physiological equivalent temperature - a universal index for the biometeorological assessment of the thermal environment, Int. J. Biometeorol. 43 (1999) 71–75. https://doi.org/10.1007/s004840050118.

[77] A. Matzarakis, H. Mayer, M.G. Iziomon, Applications of a universal thermal index:

physiological equivalent temperature, Int. J. Biometeorol. 43 (1999) 76–84. https://doi.org/10.1007/s004840050119.

[78] R.J. de Dear, G.S. Brager, Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55, Energy Build. 34 (2002) 549–561.

[79] E.L. Ndetto, A. Matzarakis, Assessment of human thermal perception in the hot-humid climate of Dar es Salaam, Tanzania, Int. J. Biometeorol. 61 (2017) 69–85. https://doi.org/10.1007/s00484-016-1192-1.

[80] M.H. Elnabawi, N. Hamza, S. Dudek, Thermal perception of outdoor urban spaces in the hot arid region of Cairo, Egypt, Sustain. Cities Soc. 22 (2016) 136–145. https://doi.org/10.1016/j.scs.2016.02.005.

[81] T.P. Lin, R.J. De Dear, R.L. Hwang, Effect of thermal adaptation on seasonal outdoor thermal comfort, Int. J. Climatol. 31 (2011) 302–312. https://doi.org/10.1002/joc.2120.