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Microclimatic Conditions of an Urban Square: Role of built environment and geometry

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Abstract

Geometry plays a dominant role in thermal situations within city structures. This study aims to seek how this role affects thermal comfort of the visitors in an urban square. Computer simulations were performed along with physical measurements in an urban square during peak hot conditions of summer in Isfahan, Iran. In addition to the influence of built environment inside the square, the results confirmed the role of geometry on thermal conditions. The amelioration effect for the aspect ratio was higher than that of the orientation. Findings are useful for urban design strategies dealing with thermal comfort.

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Keywords: Thermal comfort; urban square; geometry; built environment

1. Introduction

The residents' outdoor life in urban areas has been affected by the rapid development of cities (Kariminia, Sh Ahmad, Ibrahim, & Omar, 2010) along with the global climate change (Kariminia, Ahmad, & Hashim, 2012; Kariminia, Ahmad, Hashim, & Ismail, 2013). Meanwhile, thermal comfort is a key factor that contributes to the public perception and attraction of outdoor settings. Indeed, pedestrians are directly exposed to the outdoor environment and sensitive to the immediate microclimate they experience in urban spaces, which in turn influence their perceptions (Nasir, Ahmad, & Ahmed, 2012,

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2013; Nasir, Anuar, Darus, Jaini, & Salleh, 2012). Furthermore, urban geometry in the previous studies appeared to be affecting microclimates across city structures. Appropriate urban design by using applicable strategies can ameliorate thermal stresses and enhance the residents' thermal comfort (Kariminia, Sh Ahmad, & Ibrahim, 2013). Several studies have investigated the effects of geometry of canyon structure on their thermal conditions (Ali-Toudert, 2005; Griefahn & Künemund, 2001). Very few studies focused on thermal comfort of urban squares (Kariminia, Ahmad, Omar, & Ibrahim, 2011; Kariminia & Ahmad, 2013). No previous studies investigated this issue in Iran. In addition, simulation methods were rarely used in this issue. Applying both empirical and theoretical methods, this study aims to seek the role of built environment and some geometrical factors of the square on its microclimatic situations and thermal comfort of the visitors in moderate and dry climate of Isfahan, Iran. Therefore, a series of measurements were conducted in an urban square and the recorded data were further used to compare different geometrical schemas of the square via computer simulations.

2. Materials and Methods

2.1. Study area

The field studies were conducted in Imam Square, located in a historical site of the city of Isfahan. This city is located at 51°41' E longitude, 32°37' N latitude and altitude of 1590 m above sea level. According to meteorological data, this city experiences hot summers and cold winters with low relative humidity (RH) throughout the year. Between 1951 and 2009, the highest and lowest monthly average temperatures were 28.8 and 3.7 °C, respectively. The highest recorded air temperature (T_a) was 43° C in July, whereas the lowest was -19.4° C in January. The average RH during the year varied between 25 and 60 percent. The square is flanked by long, low-elevation, two-storey buildings, except for the gaps created by two streets on the east and west sides. There are two thin lines of short evergreen bushes along the sides of the square. A pool, fountains and stone benches are located at the centre of the square. The ground surface is mostly paved with stone and grass while only a small part is covered with asphalt.

2.2. Environmental measurement

The field measurements were performed for a full week between 24 and 30 July 2010 as the critical hot weather conditions. Data were acquired from 10:00 to 18:00 at 10-minute intervals. The T_a, RH, wind speed (W_s) and solar radiation (R_s) were measured by a portable HOBO data-logging mini weather station. The equipment was placed 1.5 m above the ground on tripods. The instruments were placed at four pre-selected points in the square at different times to provide data more representative of the different environment of the whole square. The first point was located on an 80cm high platform surfaced covered by high albedo stone, near the entrance porch of Sheikh Lotfollah Mosque at a distance of 1m from the façade. The second point was positioned within the vicinity of the bushes. The third point was located next to the pool while the fourth point was positioned in the middle of a wide pathway. The locations were labeled as P1-P4, respectively.

2.3. Simulations

ENVI-met 3.1 is a 3D non-hydrostatic microclimate model with a wide range and detailed output variable prognosis. It was originally designed by Prof. Bruce of University of Mainz, Germany and was developed in collaboration with Flemish Institute for Technological Research (VITO) (Maerschalck et al., 2008). This is actually a surface-plant-air model with a high spatial resolution, consisted of three models, namely soil, radioactive fluxes transfer and vegetation which is able to represent various outputs produced from few and easy measured input variables. The model also includes a comprehensive database on surface and plant species. The high performance and accuracy of this model was found to be confirmed in previous studies (Fahmy & Sharples, 2009). According to the mentioned benefits, hence, ENVI-met 3.1 was applied in the present study to compare microclimates at actual situation and the modified situations over stipulated time frame. Thus the square was simulated based on the actual situation (base model) along the proposed scenarios. Each scenario concentrated on the effects of a particular geometrical aspect and the results were presented based on microclimatic parameters. Although numerous data sets were estimated at the determined receptors, in order to obtain more accurate results, the data gained at the centre point of each square were applied (coincided with physical measurements at P3). ENVI-met automatically divides the first vertical grid into 5 parts. Hence, according to the defined size of grid cells, the most appropriate level, close to the human shoulder height i.e. 1.4m was chosen in this research. All simulations were conducted for a single day namely 29 July.

3. Meteorological Data and Thermal Comfort

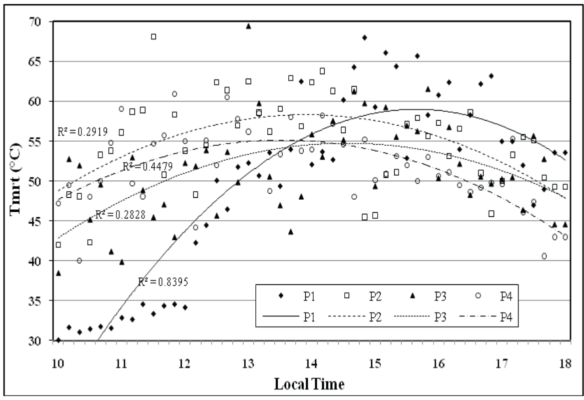
Table 1 summarises the measured microclimatic data during the environmental measurements. The T_a varied between 24.0 and 40.8 °C with a mean of 32.4 °C while the RH varied between 9.6 and 72.8%. The maximum R_s was markedly high and reached to almost 1057 W/m^2. The data logger recorded minimum air velocity of zero in stale situations. The amount of global temperature (T_g) was high and reached to 68°C at the hot conditions.

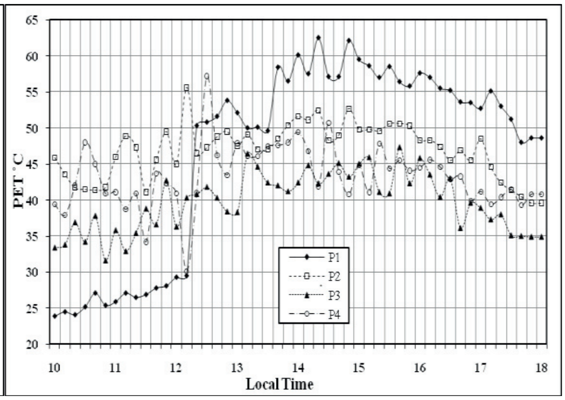
Table 1. Microclimatic data monitored in the square during the measurements

	T_a °C	RH %	R_s W/m^2	W_s m/s	T_g °C
Mean	32.4	17.2	722.1	1.0	34.0
Min	24.0	9.6	4.4	0.0	8.0
Max	40.8	33.3	1056.9	3.0	68.0
St. Dev.	3.51	4.64	276.15	0.70	1.45

To investigate thermal comfort situations in the square, this study estimated Mean Radiant Temperature (T_{mrt}) and Physiological Equivalent Temperature (PET) at the four pre-selected locations. T_{mrt} is a key factor, which highly influences outdoor thermal comfort. This index integrates all short and long-wave radiation fluxes absorbed by the body, which makes its measurement complicated. Per definition, T_{mrt} is the uniform surface temperature of a black enclosure in which a human body exchanges the same heat by radiation as in the actual non-uniform ambience (Ali-Toudert, 2005). In summer and under sunlight, T_{mrt} is a critical parameter in assessing TSs. In short, PET is defined as the T_a at which in a typical indoor setting ($T_a = T_{mrt}$, VP = 12 hpa, W_s=0.1 m/s) the heat budget of the human body (80 W of work metabolism added to basic metabolism with 0.9 *clo* of resistance clothing) equals to the same core and skin temperature under outdoor conditions. PET enables a layperson to compare the influence of the outdoor thermal conditions to his or her indoor experience (Hwang, Lin, Cheng, & Lo, 2010).

Figure 1 shows the T_{mrt} and PET recorded at the measurement locations during the fieldwork. The highest T_{mrt} was monitored at P2 during the day except after 15:00 when location P1 was highly irradiated. The reflective surface of the concrete pavement and the facades surrounding P1 led to the increase of the absorbed long-term radiation fluxes at this point. Yet this location was under the lowest radiant temperature in the morning. According to the high W_s at P4, this point registered the lowest T_{mrt} after 14:00. The aggressive rise of radiations after 12:00 at P1 led to 20˚C increase of PET in a few minutes. Thermal stress was considerably high, more than 60˚C PET at 14:00 while value of PET at P3 and P4 equalled to 42˚C. The green area also experienced a high thermal stress during the day highlighting the dominant effect of ventilation. Meanwhile, the combination of air velocity and cooling effect of water decreased the thermal stress at P3 near the pool. However, the role of shading was found to be more decisive.





(a) (b)

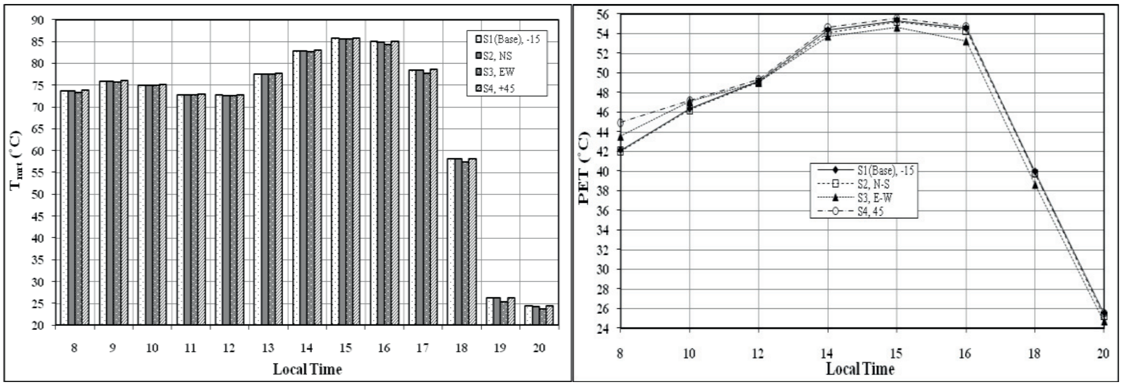
Fig. 1. T_{mrt} (a) and PET (b) recorded at the measurement locations during the fieldwork

4. Role of Geometry

4.1. Sceanrio1: Orientation

This scenario considered the orientation of the square corresponding to the orientation of the lengthwise axis. It may be noted that the length of this square is actually more than three times longer than its width. The square is actually -15˚ NW-SE oriented. Thermal evaluations of different sub-spaces namely the road, peripheral sidewalks, green areas and the pond were conducted. Therefore, it was possible to identify more uncomfortable areas of the square for each scenario. T_{mrt} strongly affects the human energy balance during sunny days and hereby plays a major role in the assessment of thermal comfort (Maerschalck et al., 2008). Figure 2(a) compares the daily simulated T_{mrt} for the four cases in this scenario. It increases by 9:00 and then slightly declines until 12:00. It inclines again after that and reaches to the peak of almost 85 ˚C at 15:00. After 16:00, T_{mrt} sharply declines to 24 ˚C at 20:00. The small decrease between 9:00 and 12:00 can be attributed to the sharp increase of air velocities in this period. The results showed relatively similar distributions within the four orientations. Indeed, the T_{mrt} variation is limited in relation to the orientation of the square with low H/W ratio. The reason behind this is that the low-level surrounding walls are not able to obstruct the sunlight. It contrasts with the results of literature studies dealing with urban canyons (Ali-Toudert, 2005) as they reported relatively decisive effects of the orientation. The small effect is actually due to the very short H/W ratio of the square in this scenario.

Figure 2(b) represents the daily courses of PET at the centre point of the square for the four simulated schemas between 8:00 and 20:00. The PET varies between 24 and 56˚C where it reaches the peak at 15:00. The simulated profiles in this figure show almost similar conditions in terms of thermal comfort conditions. However, the highest PET values are calculated for the forth schema (S4), NE-SW 45˚ case at the entire simulation period. At 8:00, the difference between values of PET in the cases is 3 ˚C and it progressively decreases by 12:00. After this time, the E-W oriented square shows the lowest thermal discomfort compared to other orientations, albeit, the difference does not exceed 1.5 ˚C. As the result, thermal comfort at the centre of the square was not strongly affected by its axis orientation.



(a) (b)

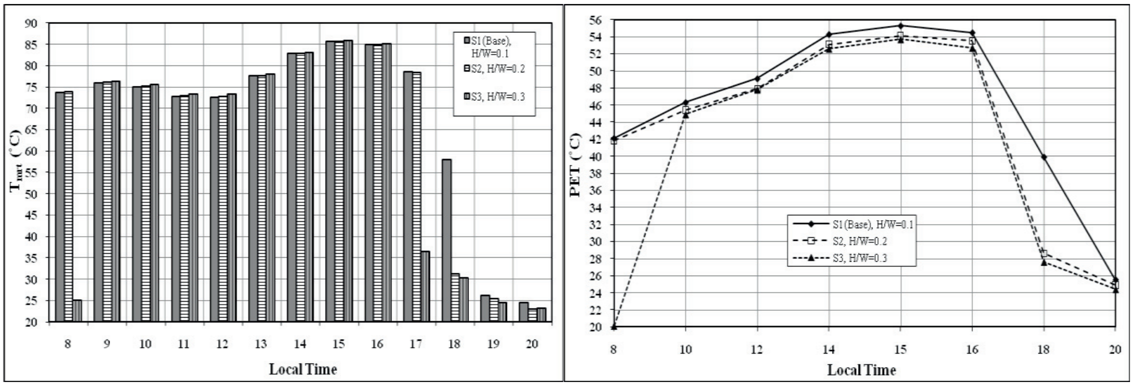
Fig.2. Daily course of T_{mrt} (a) and PET (b) in the middle area of the orientation related cases

4.2. Scenario2: Aspect ratio (H/W)

This scenario concentrated on the dependency of microclimatic situations of the square on its H/W ratio. The actual width-wise ratio of the square is 0.1 and it was compared with the ratio of 0.2 and 0.3. Increasing the H/W ratio in this scenario included both length-wise and width-wise ratios. Similar to the previous scenario, the applied data estimated for the centre point of the square were applied.

Figure 3(a) displays spatial temporal distribution of T_{mrt} at the centre point of the square with aspect ratios of H/W=0.1, 0.2 and 0.3. In a long period between 9:00 and 16:00, the patterns of T_{mrt} are similar for the three cases. However, before and after this period, considerable differences are observed within the cases. At 8:00, the T_{mrt} at the deepest profile is almost 50 ˚C lower than those of two other cases. This discrepancy is smaller at 17:00 when the centre area of the square is protected from the direct radiations in the deepest model. However, at 18:00, only the shallowest square is directly irradiated. The conditions are similar for all cases at the following time.

Figure 3(b) sums up the temporal evolution of the estimated PET at the centre point of the squares representative of the influence of different aspect ratios. The values vary between 20 and 56 ˚C where the shallowest model represents the highest thermal stress against the deepest profile with a longer period of comfort. The minimum PET in the shallowest square between 8:00 and 16:00 is 42 ˚C when it receives direct radiations. In contrast, the square with the aspect ratio of 0.3 experiences a PET below 30 ˚C before 10:00 and after 17:30. The decline of temperature for the two deeper squares occurred much more sharply after 16:00 when the centre points are protected from the solar rays by the surrounding vertical surfaces. At the hottest time of the day, the PET discrepancy between the shallowest and deepest does not exceed 1.6 ˚C.



(a) (b)

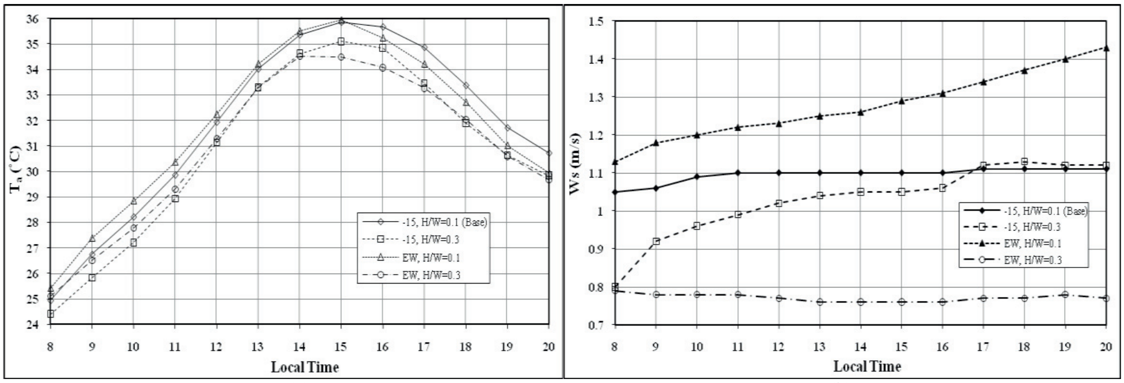
Fig.3. Daily course of T_{mrt} (a) and PET (b) in the middle area of the square affected by the H/W ratio

4.3. Scenario3: Combination of orientation and aspect ratio

This section reports the results of simulations run in regard to the role of combination of aspect ratio and orientation in creating thermal conditions within the square. In this case, an EW-oriented square was compared with the actual model (-15˚ NW-SE), both with the aspect ratios of 0.1 and 0.3

Figure 4(a) reports the daily course of T_a for the four schemas. In total, the temperature ranges between 24 and 36 ˚C during the day. In longer a period, between 8:00 and 15:00, the E-W profile H/W=0.1 is the hottest while the NW-SE H/W=0.3 shows the lowest temperature. For these two models, the maximum difference of T_a reached 1.7 ˚C in the morning. Nevertheless, in the evening the E-W square experiences a relatively considerable decline and registers lower temperatures in comparison with other cases. The hottest temperature was found to be in the NW-SE case with the H/W ratio of 0.1. The higher aspect ratio ameliorates the temperature when combined with orientation. Explicitly, the E-W square with the H/W=0.3 is even cooler than the NW-SE square with a ratio of 0.1. It accentuates the decisive role of the H/W ratio in comparison to the square orientation.

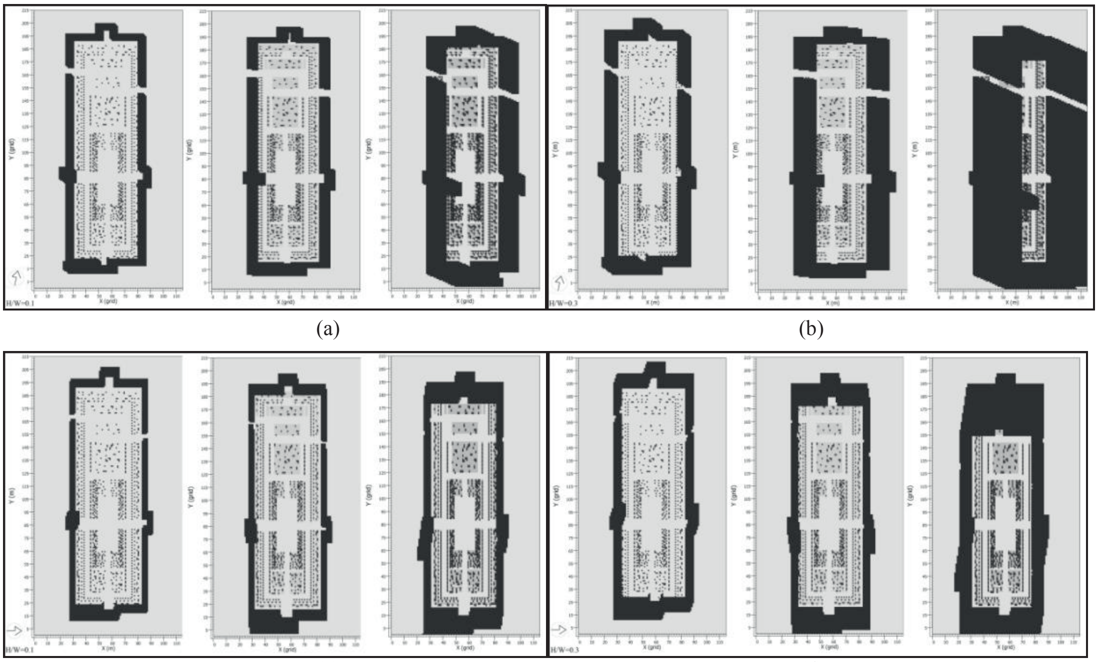
For the air velocities by contrast, the effect of aspect ratio looks to be more decisive. According to the daily course of W_s represented in Figure 4(b) for the four comparative models, the circulations inside the square are more effected by the aspect ratio compared with the orientation. Both the highest and the lowest W_s were obtained in the E-W square. The prevailing wind blows parallel to the E-W case and is controllable with a higher aspect ratio. In the other side, while the axis of the NW-SE square is oblique with the above-roof wind, increasing the aspect ratio did not obstruct the wind significantly. It may be noted that according to the results of the fieldwork in the present study, the ventilations highly ameliorate the outdoor thermal comfort in summer.



(a) (b)

Fig.4. Daily course of T_a (a) and W_s (b) in the middle area of the square affected by orientation and H/W ratio

According to Figure 5, the models received direct radiations at different patterns. The solar exposures of the schemes are displayed in this figure for 10:00, 15:00 and 17:00. The highest exposure to direct solar beams is registered for the E-W square with the H/W=0.1 while the most protected model is NW-SE H/W=0.3 square. Even the deepest profile is not efficiently protected for the EW orientation except a small area in the west part in the evening. In fact, increasing the aspect ratio shows much more efficiency for the actual orientation rather than the E-W.

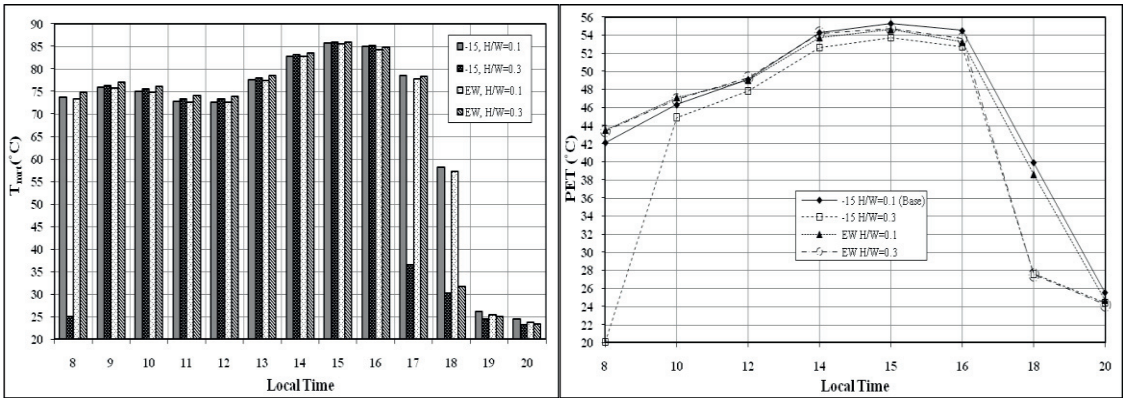


(a) (b)

(c) (d)

Fig. 5. Solar access situations of the actual (NW-SE) and E-W squares by H/W ratios of 0.1 and 0.3 at 10:00, 15:00 and 17:00

In terms of T_{mrt}, orientation plays a stronger modification role compared with the aspect ratio (Figure 6a). The square -15˚ H/W=0.3 registers a low radiant temperature at the centre point before 9:00 and after 16:00 whereas the E-W square experiences a T_{mrt} above 55 ˚C until 18:00. Figure 6(b) represents the PET for the cases during the simulation period. The NW-SE -15˚ H/W = 0.3 shows the lowest PET compared with the other cases. In other words, the orientation visibly accentuates the positive effect of the aspect ratio. However, in the evening, after 16:00, the effect of H/W ratio works strongly when the profile with H/W = 0.3 experiences the least thermal stress for the both orientations. At 18:00, PET of the case modified by the increasing aspect ratio goes up to 12.5 ˚C degrees higher than that of the square with H/W=0.1 (for both orientations). Consequently, the effect of aspect ratio is more effective in comparison with the orientation.



(a) (b)

Fig.6. Daily course of T_{mrt} (a) and PET (b) in the middle area of the square affected by orientation and H/W ratio

5. Discussion and Conclusions

The microclimatic parameters, recorded in the square showed wide fluctuations in the squares throughout the measurement period. The acquired data also demonstrated additional variances in relation to the built environments in the square. Explicitly, thermal environment in the square depended on its geometry, vegetation and water features. In addition, these effects varied according to the macroclimatic conditions and the time of the day.

Based on the evaluations of T_{mrt} and PET, the thermal conditions were affected by the attributes of built environmental at both squares. Evidently, sunlight was the most decisive factor governing thermal conditions at the square. In fact, the T_{mrt} and PET varied widely against the amount of radiations. In terms of orientation and aspect ratio:

- Wide profiles, namely the actual profile of the square with H/W ratio of 0.1 are substantially irradiated during the day except in quite small peripheral areas which experience similar comfort conditions for the all orientations. However, in late evening, the E-W square is more irradiated compared to those in others. Indeed, this orientation is potentially a suitable alternative for combining winter and summer requirements concerning the solar energy. It experiences lower thermal stress in the middle parts due to higher wind velocities (summer prevailing wind in Isfahan blows from the east) and a higher potential of solar access in winter. Nevertheless, the larger part of this square is uncomfortable under the hot conditions compared to the N-S oriented square. Individually, the lateral parts of an E-W square are more critical than its middle. By contrast, the middle areas of the N-S model experience higher discomfort (due to less ventilation).

- Intermediated orientations, NW-SE and NE-SW, with the same H/W ratios experience similar temporal and spatial thermal situations. Only the NW-SE square showed a slightly lower PET compared to its counterparts particularly before noontime.
- The total difference of mean daily T_a between the oriented-cases did not exceed 0.3 ˚C for the 0.1 H/W ratios. The small difference of T_a by changing of axis orientation for the same aspect ratio agrees well with the previous studies (Ali-Toudert, 2005; Coronel & Alvarez, 2001).
- Increasing the H/W ratio of the square from 0.1 to 0.3 for the same orientation decreased the T_a up to 1.5 ˚C at the centre point of this square. Furthermore, this strategy substantially decreased the square solar access and shortened discomfort period at the centre point for 3 hours in the daily course. Indeed, the deepest square was protected from direct fluxes at the middle area before 9:00 and after 17:00. The thermal situations were similar within the squares with H/W ratio of 0.2 and 0.3 compared with the model with H/W=0.1. The amelioration of increasing the H/W ratio from 0.1 to 0.3 at the centre area of the square was up to 1.6 ˚C PET at the hottest time of the day and up to 21 ˚C and 12.5 ˚C PET at 10:00 and 18:00. Yet, for other areas of the square, simultaneous difference of nearly 5 ˚C PET at the hottest time of the day was observed.
- Increasing the aspect ratio mitigated thermal stress for the all orientations; yet, the amelioration was by far more efficient for the N-S or NW-SE orientations compared with the E-W. The E-W square is poorly protected during the day even by increasing the H/W ratio to 0.3. The N-S square with a H/W ratio = 0.3 was thermally ameliorated compared to other models particularly in the morning. Increasing the aspect ratio showed a stronger effect in comparison with the orientation strategy, where the PET was much lower in the H/W = 0.3 square in the critical hours regardless the orientation.
- In total, high H/W ratio was found to be a prime strategy to enhance thermal comfort in the summer. However, its relevance can partially be inhibited by inappropriately deployed orientation.

This study was motivated by the aim to seek the connection between built environment, and geometry of an urban square and its microclimatic situations. The findings are beneficial for urban planners and landscape designers who consider thermal comfort as a design aspect. Although this study was run for moderate and dry climate with extreme hot summers, it is believed that the results can be used for less extreme climates with typical hot summers such as Mediterranean zones as well. Further researches can concentrate on different geometrical aspects and climatic zones.

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