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Analysing the impact of urban morphology on the thermal comfort of the street canyon in a hot and dry climate (Case Study of Kashan, Iran)

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ABSTRACT

The relationship between ambient temperature, urban geometry and human activities in cities has been proven by numerous studies. This study aims to analyze the effects of design elements on thermal comfort in hot and dry urban areas by simulating comfort quality. In this regard, impacts of urban geometry on thermal comfort have been simulated in the historical area of Kashan, Iran. The modeling evaluates Predicted Mean Vote (PMV) and mean radiant temperature (MRT) in different seasons by Envi-Met. Considering urban designing characters, four sample sections of the case study have been analyzed and then three formal cases have been presented to improve the thermal comfort in the most problematic section. It is concluded that the case in which street vegetation, sideway shading (overhang) and low Albedo materials are taken into account, overweight other cases which are based on the enclosure of urban spaces, the sidewall height and canopy at the middle part of the street. Finally, this article presents a technical and practical process of environmental design.

1. Introduction

Thermal comfort is an important factor to evaluate the quality of public spaces and the effects of time and intensity of using urban spaces. In fact, public spaces that cannot provide comfort conditions -particularly the thermal comfort of people- will be underused, or even avoided (Carmona, 2019; Chen & Ng, 2012). Therefore, minimizing the discomfort of outdoor areas could increase the liveability of urban places during periods of thermal stress in both low temperatures in winter and high temperatures in summer (Costamagna et al., 2019).

The effect of spatial geometry on the urban microclimate is also significant in increasing thermal tensions as the solar radiation is stored and reflected in urban areas (Mirrahimi et al., 2016). Generally, the heat stored by buildings during the day and reflected slowly during the night, along with the side effects of human activities and increase in paved surfaces -with low Albedo- result in heat island phenomena, which is a concerning issue due to urban cooling and heat resilience in cities (Battista et al., 2020). The measured Albedo in the cities indicates that the paved surfaces keep a lot more heat than the natural lands (Chen et al., 2020). Thus, the reflected heat could be considered as an uncomfortable condition for pedestrians, which brings up the importance of shading on streets and sidewalks (Kleerekoper et al., 2012).

The origin of thermal comfort research in urban open spaces can be traced to four decades ago when increasing the presence of pedestrians boosted the number of outdoor thermal comfort studies. This leads to a vast body of studies in the context of climate-based design parameters based on pedestrians' safety (Taleghani et al., 2015). In recent years, several studies have been conducted on thermal comfort in urban open spaces as this is strongly associated with health and wellness (Lai et al., 2020). Furthermore, the gradual rise in global temperature and its impacts on human health has engaged researchers' consideration to formulate some useful policies and guidelines to provide thermal comfort for city residents (Carter et al., 2015).

Climate adaptation efforts tend to reduce the negative effects of urban heat islands (UHI), improve human comfort and energy saving of cities. As stated by Wheleer et al. (2019) "One goal of climate adaptation efforts worldwide has been to cool cities and reduce urban heat island (UHI) effects. Such steps can improve human comfort, protect human health and reduce energy use". According to the results, the high temperature-urban areas can cause high energy consumption to provide cooling demand and reduce negative effects on an individual's health (Pyrgou et al., 2017). In this regard, numerous efforts have been made to assess adaptation and mitigation of the effects of urban heating, urban heat islands as well as moving toward cool cities and thermal comfort.

Besides, some efforts have focused on urban geometry, design patterns and formal modeling. Studying the effect of urban geometry and architectural spaces on outdoor thermal comfort refers to Luke Howard’s study (Howard,1833). He is known as the first person who considered the impact of urban areas on regional climate (Ampatzidis & Kershaw, 2020). Also, several studies have been done on the relationship between urban geometry and the concept of thermal comforts well as urban canyons and the effect of wall form and pavement direction on the pavements-microclimate (Sen et al., 2019; Tsoka et al., 2020). Taleghani et al., (2015) have applied the ENVI-met model to evaluate Outdoor thermal comfort within five different urban forms in the Netherlands. Salata et al., (2016) have assessed urban microclimate and outdoor thermal comfort using the ENVI-met model in The Cloister of the Faculty of Engineering (Sapienza) in Rome. Yousefian et al. (2017) have examined the impacts of buildings form on climatic comfort through ENVI-met Software. Abdallah et al. (2020) have evaluated the impact of outdoor shading strategies on student thermal comfort in open spaces by using the ENVI-met simulation model. The aforementioned studies prove the considerable role and effect of radiation control in urban space, which has been mostly measured by factors such as pavement direction, closeness, vegetation, and additional elements of the building.

According to the importance of thermal comfort in urban public spaces, devoting attention to climate-based design in cities especially those are in harsh weather conditions is a vital mission. This study aims to analyze the climatic comfort condition in different seasons and simulate the effect of design elements (width, height, closure, materials, pavement and shading) on thermal comfort in hot and dry weather in the historical part of Kashan, Iran. Research questions seek to recognize formal factors affecting thermal comfort and the intensity of the effects of recognized factors on microclimate characteristics in hot and dry areas. The structure of the current article includes four general steps.

At the first step, thermal comfort theory and indices are explained. Then, the methodology and research process and the case study are presented in the second step. The simulation and modeling are done at the next pace. Finally, based on the results, the effects of variations and their impacts on the thermal comfort quality are discussed and the conclusion is rendered.

2. Literature Background

Analyzing thermal comfort has long been faced with difficulty in Achieving stability, because of a wide range of factors associated with environmental and personal (physical and psychological) aspects of urban open spaces (Johansson et al., 2018). Furthermore, outdoor areas are exposed to uncontrollable climate variables which make them very challenging to measure and achieve a standard comfort level (Taleghani et al., 2015). Therefore, research associated with urban open spaces faces more obstacles in comparison to interior space studies which have more controllable conditions (Taleb, 2014) and would be involved with several issues which have not risen in the indoors.

Regarding the solar radiation, shade and wind speed of outdoor space, a great variation in climatic conditions is expected that can greatly adjust pedestrians' reaction toward temperature and humidity (Blocken et al., 2016). Additionally, people wear different clothes according to the seasons. Thus, fixed cover standards are not applicable for outdoor (Zhao et al., 2020). Moreover, Outdoor space has a wider range of short and long wavelength radiation than indoor spaces and radiant asymmetry, which occurs as a result of direct sunlight is much higher than the level of comfort in the interior spaces. (Lin et al., 2010).

Thermal comfort is the body's response to environmental conditions in internal and external spaces (Lomas & Giridharan, 2012). A more detailed definition of this condition can be summarized into three groups. First, the psychological definition refers to brain satisfaction of temperature (Elnabawi & Hamza, 2020). Second, the thermo-physiological definition is related to the biological responses of the body and the nervous system to external influences on skin thermoreceptors (Santos Nouri et al., 2018) and the third definition points out the temperature balance between inside and outside of the body (Bouzida et al., 2009). In addition to these three general definitions of comfort conditions, several other definitions that are especially associated with the hot or cold places without defined comfort have been presented.

As mentioned before, thermal comfort is a difficult and complex concept to study, as it is dependent on several parameters. At the following four physical parameters thermal environment and thermal feeling is described:

• Ambient air temperature: This factor affects dry and wet exchanges as well as heat transfer coefficient (Gagge & Nishi, 2010; Song et al., 2017).

• Airflow rate: Generally, this factor affects heat losses due to convection and evaporation around the body, which is covered by clothing and is affected by the body movements (Melikov, 2015; Zhang et al., 2020).

• Relative humidity: When there is no sweating, this factor has little impact and hidden respiratory exchange and insensible sweating of skin are the only factors relevant to humidity. On the other hand, air humidity affects the evaporation of moisture from skin sweats (Takada & Matsushita, 2013).

• MRT: In outdoors, MRT indicates the integrated temperature of an imaginary area that all parts of it have a similar temperature (Walikewitz et al., 2015).

In addition, other parameters involved in calculating thermal comfort are as follows:

• Activity level: According to the activity level, the body converts food into energy. The amount of energy produced per unit of time is called “metabolic rate” and is measured based on the number of watts per square meter of body surface (Herman, 2016).

• Cover: This factor acts as a link between the body and the environment in connection with both heat and humidity. It can have the role of a facilitator or an inhibitor (Junge et al., 2016).

Among these factors, the first five items depend on the physical and environmental conditions and therefore are involved in the urban design category. Other factors are related to individual behavior categories, which vary over time and are outside of the scope of designing. So, some indexes are defined to apply an integrated assessment of

the effects of both environmental and individual factors on people's comfortability. The first thermal equilibrium model was developed and described by Fanger in 1972 which applied "Predict Mean Vote" and "Predict Percentage Dissatisfied" to help ventilation engineers in the room (indoor) condition (Karyono et al., 2020) and has been still in the scope of many kinds of research (Enescu, 2019; Zhao et al., 2020).
Two decades later and by assigning appropriate variables Jendritzky et al. (1990) were succeeded to adjust Fanger's complex approach to the outdoor condition, which today is known as the MEMI model (Matzarakis & Amelung, 2008). MEMI stands for Munich Energy-balance Model for Individual and is considered as one of the thermal equilibrium models of Thermo-physiology. It is also used as a basis for obtaining PMV and PET indexes (Taleghani et al., 2015).

3. Methodology

This study tries to evaluate the effect of design elements on thermal comfort in Tamqachy street in Kashan, Iran. The PMV and MRT index has been used for this purpose. American Society of heating refrigeration and air conditioning engineers (ASHRAE) standard 55-2004 elaborates the use of Fanger's heat balance equation for the calculation of PMV to determine the scale of thermal comfort as shown in equation (1) (ASHRAE; 2004).

$$PMV= (0.303^{e\,-0.036M} + 0.028) \times \{(M - W) - 3.5 \times 10^{-3} [5733 - 6.99 (M - W) - p_a] - 0.42 ((M - V) -58.15) - 1.7 \times 10^{-5} M (5867 - p_a) - 0.0014M (34 - t_a) - 3.96 \times 10^{-8} f_{cl} [(t_{cl} + 273)^4 - (t_r + 273)^4] - f_{cl} \times h_c (t_{cl} - ta)\} \quad (1)$$

Where M and W are the metabolic rates and external work, both in W/m^2, Pa is the partial water vapor pressure in Pascal, and t_a and t_r are the air temperature and mean radiant temperature in degrees Celsius. The surface temperature of clothing, t_{cl}, and the convective heat transfer coefficient, h_c, can be calculated by Equation (2) and (3).

$$t_{cl}= 35.7\text{-}0.028 (M\text{-}W)\text{-} I_{cl}[3.96 \times 10^{-8} f_{cl}((t_{cl}+273)^4\text{-}(t_r+273)^4)+ f_{cl}h_c(t_{cl}\text{-}t_a)] \quad (2)$$

$$h_c= \begin{cases} 2.38\,(t_{cl}-t_a)^{0.25}\,, & h_c>12.1\sqrt{V_a} \\ 12.1\sqrt{V_a}\,, & h_c<12.1\sqrt{V_a} \end{cases} \quad (3)$$

V_a is the air velocity in m/s and I_{cl} is the clothing thermal resistance in m^2 .ºC/W. These two equations are solved iteratively until a prescribed degree of convergence is attained or the maximum number of iterations reached. While f_{cl} is the ratio of body surface area covered by clothes to the naked surface area is defined by equation (4).

$$fcl= \begin{cases} 1.00 + 1.290\ I_{cl}\,, & I_{cl} \le 0.078 \\ 1.05 + 0.645\, I_{cl}\,, & I_{cl} > 0.078 \end{cases} \quad (4)$$

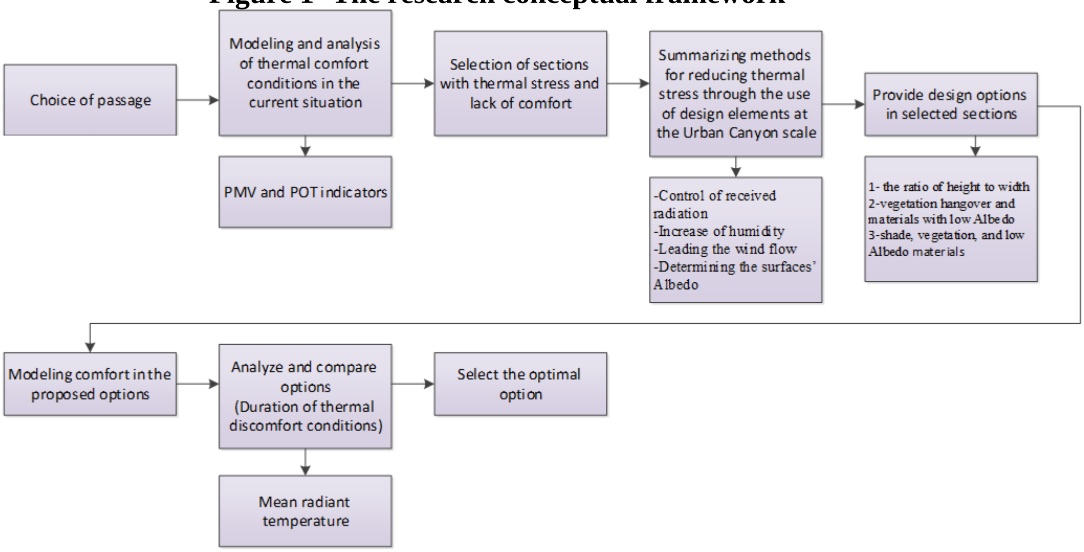
ENVI-met simulates the surface-plant-air interactions in an urban environment (Bruse, 2004). It is validated and compared to onsite measurements (Jeong et al. 2015). ENVI-met calculation of MRT is defined by the following equation (5) (Bruse 1999):

$$T_{mrt} = \left[\frac{1}{\sigma} \cdot \left(E_t(z) \cdot \frac{a_k}{\epsilon_p} \cdot \left(D_t(z) + I_t(z)\right)\right)\right]^{0.25} \quad [K] \quad (5)$$

The surrounding environment consists of the building surfaces, the atmosphere and the ground surface. All radiation fluxes, i.e., direct irradiance $I_t(z)$, diffuse and diffusely reflected solar radiation $D_t(z)$ as well as the total long-wave radiation fluxes $E_t(z)$ from the atmosphere, ground and walls, are taken into account

The research is conducted through the following steps (Fig. 1). First, using the PMV index the domain is evaluated and the worst temperature condition of the year is chosen for further steps. Besides, those parts of the passage that have lower levels of thermal comfort are chosen for more detailed analysis. Second, four different sections of the Tamqachy passage were chosen based on their thermal comfort level and formal attributes. Outputs required for analyzing thermal comfort were used as Potential Air temperature and PMV index. Modeling has been done in peak-hours pedestrian flow (from 6 am to 9 pm). It should be noted that the output of the model is produced every 30 minutes. Third, taking the advantage of different elements of design, three cases are proposed for the section with the highest MRT condition. The MRT simulation at the hottest times of the day results in the optimum case.

Figure 1- The research conceptual framework



Source: Authors

Evaluation of thermal comfort conditions has been performed during a tropical year. Kelvin temperature scale, speed and direction of the wind at a height of 10 meters above ground and relative and specific humidity are the climate data of Kashan meteorological synoptic station from January to December 2019, which has been entered in the model (Table 1).

Table 1- Average wind speed, wind direction, average daily temperature, relative humidity and specific humidity

Season	Wind Speed in 10 m ab Ground (m/s)	Wind Direction	Initial Temperature Atmosphere (K)	Relative Humidity (%)	Specific Humidity (g Water/kg air)

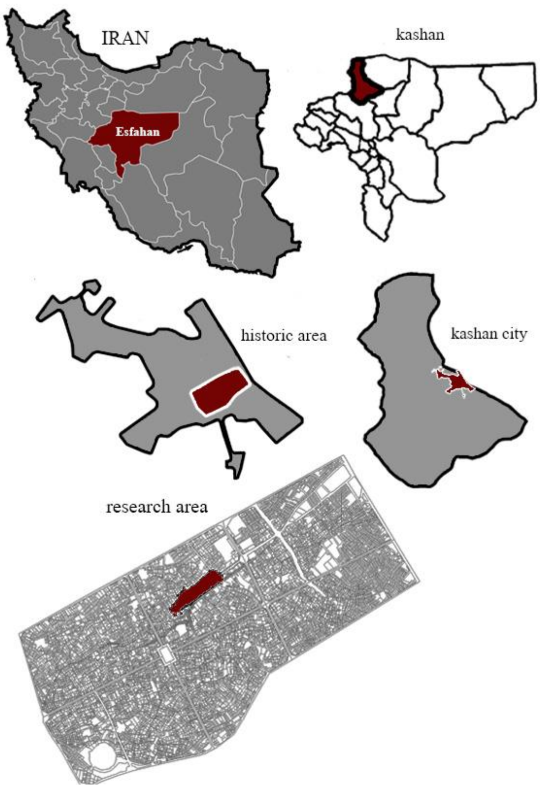
Spring	2.40	90	296.10	27.00	4.66
summer	2.00	0	303.60	22.00	2.00
Autumn	2.40	270	286.30	50.30	2.00
Winter	2.20	260.00	285.20	43.00	3.00

Source: Kashan meteorological synoptic station (2019)

4. Case study

Kashan is a city in Isfahan province in the central part of Iran. It is located at a longitude of 51°27' E and a latitude of 33° 59' from the Greenwich meridian (Fig. 2). It has a hot and dry climate.

Figure 2- The location of case study



Source: Authors

Tamqachy Pavement is considered as the old texture and historical center of Kashan, adjacent to the northern side of the Grand Bazar (Fig. 3). Having organic urban forms, the historical area of Kashan has a wide variety of pavements in terms of width, direction, length and roof, which provides a wide range of choices for pedestrians to adapt to the thermal condition. Therefore, passing such diverse forms users would have less possibility to overwhelmed temperature and heat dissatisfaction.

But the open spaces, where have been widened due to the presence of cars, are in a different condition from human thermal requirements in terms of accommodation.

Having black asphalt and facing more sunlight, the main streets are hotter than pavements on summer days due to the vastness of space and sun exposure. In winter, streets are in a better thermal status, provided that they are protected from the cold.

The selected area for this study is a historical pathway. It is an example of a Road Widening project to facilitate the movement of cars regardless of its environmental effects. The high width of the crossing, which has no significant vegetation, causes severe heat stress.

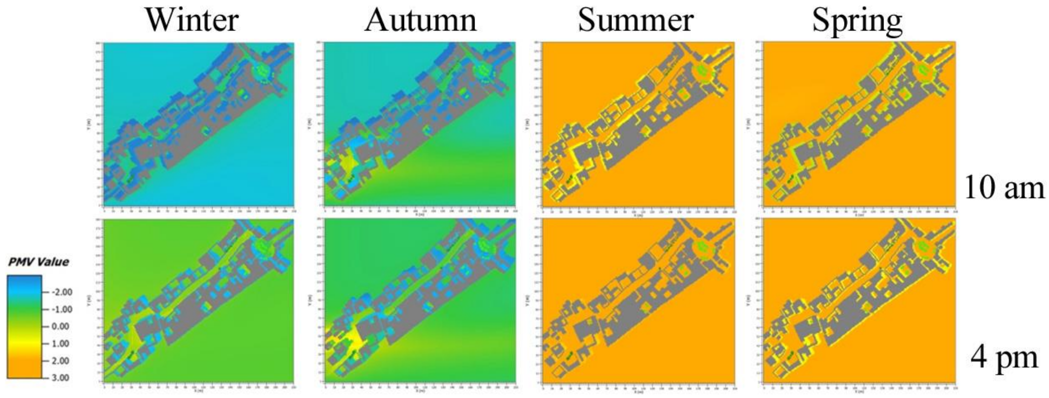
Figure 3- The historical area of Kashan, Tamqachy street

Source: Authors

5. Findings

At the first step, the climatic comfort condition of the passage during four seasons is simulated. As it is illustrated in Fig. 4, autumn, winter, spring and summer is observed to have the best thermal comfort condition respectively. As mentioned above, summer which has the less suitable thermal condition is chosen for further analysis.

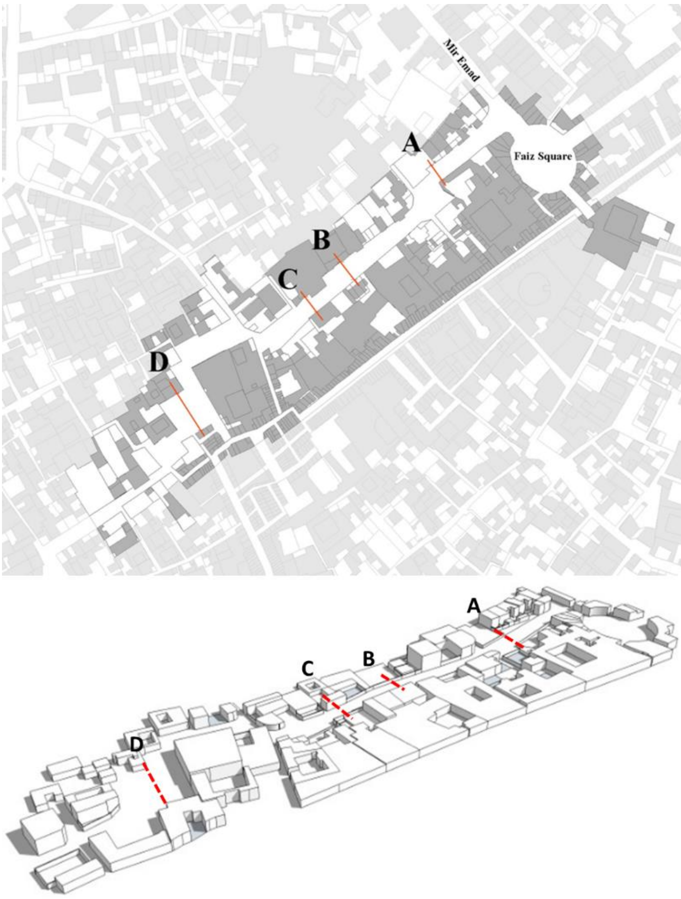
Figure 4- Climate simulation of Tamqachy in four seasons of the year, based on PMV index



Source: Authors

Based on analyzing the climatic comfort condition of the passage in summer, four different sections of the street with the most critical PMV index are selected (Fig. 5). Samples are selected in such a way that each section has a different width, sidewall height and pavement.

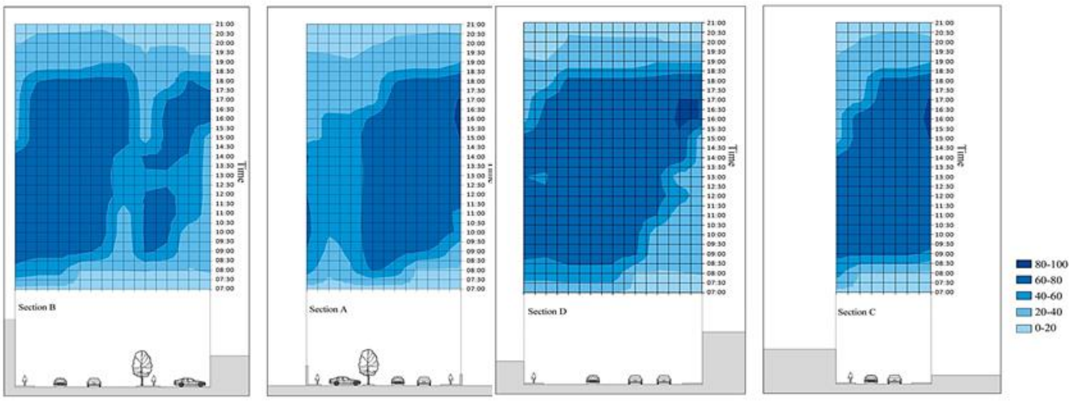
Figure 5- The position of selected sections



Source: Authors

Fig. 6 reflects MRT at the human height level from 6 A.M. to 9 P.M. Due to the geographic location and northeast-southwest direction of the street, the changes of MRT at various parts of the sections, follow quite a similar pattern. In this regard, the rise of the radiation temperature starts from the west sidewall of the street at the earlier hours of the day (mostly between 7 to 8 A.M.). The western sidewall's radiation effect continues to increase and reach the peak in the middle of the day (mostly between 2 and 3 P.M.). In the afternoon, the thermal stress then has shifted toward the eastern part of the street and the temperature of the west part has started to decrease gradually. The highest thermal stress is reported next to the east sidewall (at about 4 to 5 P.M). At this time of the day, the sunlight becomes almost vertical and the heat absorption increases accordingly. Generally, the amount of energy absorbed and reflected by surfaces also depends on the angle of solar radiation. Therefore, a greater angle of solar radiation causes more reflection and less energy absorption.

Figure 6- MRT index in four sections- from 7 A.M. to 9 P.M.



Source: Authors

In the investigated latitude, due to the solar elevation angle, the influence of the southeast sidewall on shading is more than the other sidewalls. On the other hand, the thermal stress applied on the east side of the street is directly influenced by the Aspect Ratio (the of the southeast sidewall height to the width of the street). According to Fig. 6, all sections of the path are faced with a significant increase in temperature from 8 am (after sunrise). In sections, A and C (respectively with the Aspect Ratio of 12 and 9) thermal stress is seen from 8:30 am and 9:30 am which is 6 hours more than sections B and D (with the Aspect Ratio of 1 to 3 and 1 to 1) which face with the thermal stress since 3 pm. Hence, sections A and C face unfavorable comfort conditions 6 hours more than sections B and D. Moreover, the effect of vegetation is also clear in the diagrams of sections A and B. Although section B is wider than section D and the Aspect Ratio is much fewer, it has less thermal stress during a day. As a result, section A is known to have the most critical thermal comfort condition and is elected for further analysis at the design phase.

6. Discussion and Design Options

One of the solutions to remove the barrier of achieving thermal comfort in urban open spaces is to interact with design components that are easily comprehensible and applicable (Ahmed, 2003; Yang et al., 2011). Exposure to unfavorable environmental conditions can be controlled or filtered through architectural tools (Liu et al., 2017). Table 2 presents general strategies for environmental designing. Obviously, there is a wide range of methods of improving thermal comfort through design elements and materials in urban open spaces.

Table 2- Factors of thermal comfort and design elements used in controlling the quality of comfort

<table>
<tr><th colspan="2">Factors of thermal comfort</th><th>Methods of control</th><th>Design elements</th></tr>
<tr><td rowspan="4">Controllable factors by design elements</td><td>Air temperature</td><td>Control of received radiation</td><td>Choosing an appropriate direction for Passage, appropriate closeness, overhang, shade, canopy</td></tr>
<tr><td>Humidity</td><td>Increase of humidity</td><td>Canopy, Bushes and grass, water surfaces, fountain</td></tr>
<tr><td>Air flow</td><td>Leading the wind flow</td><td>Canopy, wind brace, Choosing an appropriate direction for Passageway, passageway closeness, passageway geometry</td></tr>
<tr><td>Mean radiant temperature</td><td>Determining the surfaces' Albedo</td><td>Bushes and grass, water surfaces, flooring by the use of materials with low albedo</td></tr>
<tr><td rowspan="3">Uncontrollable factors by design elements</td><td>The number of User activities</td><td colspan="2">-</td></tr>
<tr><td>The type of the user coverage</td><td colspan="2">-</td></tr>
<tr><td>Sex and Age of the user</td><td colspan="2">-</td></tr>
</table>

Source: Alonso & Renard, 2020; Barakat et al., 2017; Chandel et al., 2016; Cheong et al., 2020; Gómez et al., 2013; Kamalha et al., 2013; Kontes et al., 2017; Li et al., 2017; Manzano-Agugliaro et al., 2015; Martínez-Molina et al., 2016

As it is mentioned, the impacts of design elements are not easy to be analyzed with correlation relationships and direct effects. It is mainly because of the complexity of urban geometry which is varied according to a wide range of factors namely enclosure, direction, shape, material, vegetation, etc.

At the design phase, three cases for section A are presented (Fig 7.). These cases are designed to improve the thermal comfort condition of the case study through different physical interventions including the enclosure of urban space, street vegetation, shading, materials. Cases describe and compare the most suitable physical arrangement of section A in terms of thermal comfort. They are designed to separately reflect the effects of the above-mentioned design elements. The cases have been presented in table 3.

Table 3- The details of cases of section A

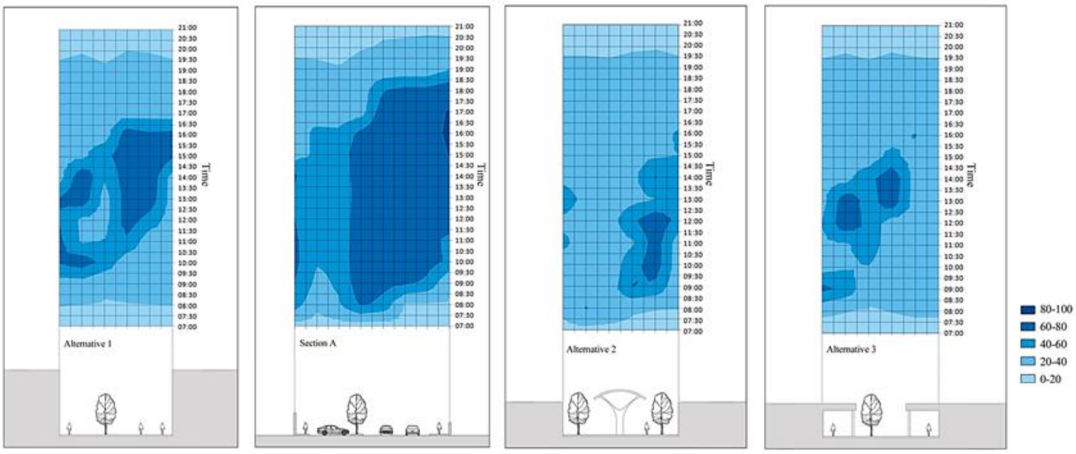
Case	Details of case in compare with current state of section A
1	Relative Aspect Ratio: 0.6 Relative Height: 6/1 Width:5/7 Planting trees on the middle of the street (Current state) Low Albedo materials
2	Relative Aspect Ratio: 0.2 Height:2/1 Width:5/7 Planting trees on both sides of the street Canopy in the middle of the street Low Albedo materials
3	Relative Aspect Ratio: 0.5 Height:2/1 Width:2/7 Planting trees in the middle of the street (Current state) Sideway shading (overhang) Low Albedo materials

First designed Case: This case is mainly based on an increase in the level of the enclosure with respect to higher sidewalls. Based on the results, compared to the current situation, the maximum amount of MRT that a pedestrian tolerates during a day is decreased to 80.13 ° C in this model. According to the temperature changes in the cross-section, the pattern of MRT is similar to the current situation. However, the duration of thermal stress is reduced in comparison with the current state, especially in the vicinity of the southeast sidewall. On the other hand, there is a controversial effect around the northwest sidewall, which needs further evaluation.

Second designed Case: This case takes the advantage of vegetation, street canopy and materials with low Albedo. Compared to the current situation, the maximum amount of MRT that a pedestrian tolerates during a day is decreased to 76.85 ° C. The effect of the canopy on the thermal stress reduction is completely clear in the middle of the street. According to the temperature changes in the cross-section, the amount of received radiation in the vicinity of the northwest sidewall has been reduced and the thermal stress can mostly be seen in the vicinity of the south-eastern wall, from 9 Am. to 12 P.M. Besides, due to decrease in the received radiant, the effect of vegetation in the street is quite obvious. Moreover, the duration and the area of thermal stress are reduced in comparison with both the current state and the first case. Generally, in this case, the thermal stress started earlier than in other cases.

Third designed Case: In this model sideway shading (overhang), vegetation, and materials with low Albedo are taken into consideration. Compared to the current situation, the maximum amount of MRT is decreased to 75.61 ° C. In this case, the effect of sideways shading (overhang) is quite obvious. There is also a significant reduction in thermal stress, adjacent to the northwest sidewall. On the other hand, the effect of vegetation on thermal comfort stress is obvious. In general, this case has the lowest duration of thermal comfort stress from about 12 to 2.

Figure 7- The MRT in the proposed options from 7 am. to 9 pm



Source: Authors

As it is shown in Fig. 7, the maximum MRT that a pedestrian tolerates during a day in section A has been decreased in all options. Table 4 presents the differences of the maximum, minimum and MRT in the proposed options and the current status.

Table 4- The received maximum, minimum and MRT in the current status and the three proposed options in section A, during a summer day

	Max	Min	Average
current situation	82.66	13.09	47.49
Case n. 1	80.13	13.27	36.06
Case n. 2	76.85	13.52	31.14
Case n. 3	75.61	13.91	31.06

7. Conclusion

Analysis revealed that there is a similar pattern of MRT changes at various parts of the northeast-southwest streets in the hot and dry climate. The radiation temperature starts from the west sidewall at the earlier hours of the day and shifted toward the eastern part of the street. The highest thermal stress is reported next to the east sidewall. Besides, southeast sidewall shading has been known to be the most efficient sidewall.

In addition, canopy, vegetation and materials have been proved to have significant effects on radiation temperature.

In conclusion, the area ratio of each temperature level (in the surface charts) is calculated and compared to the total value as well as the amount of MRT index. By calculating the amount of energy level, table 5 indicates the comparison of MRT pedestrians' tolerance in all cases. Thus, the third case is reported to have the least MRT and the best thermal comfort condition. The case takes the advantage of shading, vegetation, low Albedo materials. This case has a middle height wall with an Aspect Ratio of 0.2. Besides, sideway shading and plating trees play an important role to prevent thermal comfort stress.

Table 5- The percentage of received MRT

Case	0-20	20-40	40-60	60-80	80-100	Total
1	17.05%	46.29%	20.82%	15.85%	0.00%	100.00%
2	16.76%	66.06%	12.41%	4.77%	0.00%	100.00%
3	13.64%	67.31%	15.33%	3.71%	0.00%	100.00%

It should be noted that due to the complexity of climate variables and their reciprocal effects, it is difficult to derive their direct effects. However, the proposed method of this research makes it possible to compare different cases on the micro-scale of the street by drawing surface charts.

The findings provide an accurate analysis of the thermal comfort condition in a cross-section of the passage over a period. In the present study, due to the limitations in the type of statistical outputs of the model, the average radiant temperature was used as the most effective variable of thermal comfort. Taking into account other influential parameters, future studies could provide a more accurate analysis.

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