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THE EFFECT OF PLANTING DESIGN ON THERMAL COMFORT IN OUTDOOR SPACES

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ABSTRACT:

Urban outdoor spaces are considered essential elements of cities, where the greatest amount of human contact and interaction takes place. That is the reason why there is increasing public interest in the quality of open urban spaces as they can contribute to the quality of life within cities, or contrarily increase isolation and social exclusion. There are a lot of factors influencing the success of the outdoor spaces; one of the principal factors is the microclimatic comfort. In the hot areas, the outdoor thermal comfort conditions during the daytime are often far above acceptable comfort standards due to intense solar radiation and high solar elevations.

The variation of the urban spaces' configuration can generate significant modifications of the microclimatic parameters. Design decisions such as street and sidewalk widths, shading structures, materials, landscaping, building heights, and inducing air flow have a significant impact on the pedestrian thermal comfort and subsequently on the use of the urban environment. Although it has been established that the vegetation elements should be considered as one of the main tools that can be used in improving the thermal comfort in outdoor spaces, the integration of the climate dimension in the planting design process in urban spaces is lacking because of insufficient interdisciplinary work between urban climatology, urban design and landscape architecture.

The primary aim of this research is to study the influence of some of the design decision for the plantation elements in outdoor spaces on the thermal comfort of its users. This will provide landscape designers and decision makers with the appropriate tools for effectively assessing the development of urban environment while considering the microclimate of outdoor spaces. A special emphasis is put on summertime conditions in Egypt. Findings of this research will contribute to sustainable urban design of outdoor spaces.

Conference Topic: New Approaches to Urbanisation.
Keywords:
Outdoor spaces, Thermal comfort, Plantation design, Thermal comfort simulation.

1. INTRODUCTION:

Recent decades have seen a gradual transition from a time when the quality of city space was not a primary concern, to a new situation in which quality is a crucial parameter. In the past, people had to use the outdoor spaces of the city regardless of their condition. Today the lack of properly designed pedestrian spaces in urban design is forcing people to rely on their air conditioned vehicles to move around even for short distances (Thompson C. &Travlou P., 2007). Thermal comfort is considered one of the main factors affecting the quality of spaces. Understanding the richness of environmental conditions in outdoor urban spaces and the comfort implications for the users, opens up new possibilities for the development and improvement of urban spaces (T. Panagopoulos, 2008).

> "By careful site planning and design it is possible to create very local climates where people can be screened from the worst extremes of an area's climate. The possibility of manipulating local climate can be used to encourage people to use the outdoor areas associated with buildings." (Beer, 1990).

Good plant arrangements, street orientation and design approach had been shown to promote latent-heat evaporation and solar shading in significant way. Such schemes can be improved through understanding and implementation of effective urban thermal environment design theories and guidelines. This paper will describe the impact of comprehensive relationships between plant design parameter for thermal comfort and outdoor thermal environment (Shahidan, 2008).

2. EFFECT OF PLANTATION ON COMFORT OUTDOORS:

The vegetation is a modifying factor of the local climate, and it is considered an important design element in improving urban microclimate and outdoor thermal comfort in urban spaces (Picot, 2004, Spangenberg, 2004). Although it has been proven that the plantation is considered one of the main tools that can be used in improving the thermal comfort in outdoor spaces, it is being used basically in the urban spaces for aesthetic purposes, utility and recreation in the most cases. The impact they have on the microclimate, the human comfort and energy aspects are not really taken into account in their design that may be because of poor interdisciplinary work between urban climatology, urban design and landscape architecture.

The use of the green as a strategy to mitigate the urban heat island (UHI) and improve the microclimate has been widely emphasized (e.g. Akbari et al. 1995, Taha et al. 1997, Ng 2009). A quantitative evaluation of the climatic role of the urban vegetation is required since this is also planned for other tasks, e.g. acoustics, reduction of pollution, aesthetics, social issues, etc. (e.g. Givoni 1997).

For hot climates, the best use of the vegetation should profit from its shading property to mitigate the intense solar radiation in the summer as the overheating is mainly due to the storage of heat by the sunlit surfaces. The evapotranspiration is often weak owing to the lacking water in the soil, unless irrigation is supplied. A sparser vegetation well mixed within the urban structure to produce as much shadow as possible has to be preferred in hot and dry climates (McPherson et al. 1994b). For cold climates using the vegetation as a screen against high winds is more appropriate and dense vegetation located at the urban edges is advisable.

Individual trees spaced with large intervals, as is usually the case in an urban street, do not have a significant cooling effect. Therefore, it has been recommended that it is more effective for urban sites to use several smaller groups of trees. In a dense urban environment, trees can be located in various locations such as in rows along the sidewalks, in parking areas and at street intersections. However, in order to achieve these benefits of urban vegetation, we have to pay particular attention to the requirements of appropriately planting and maintaining healthy mature trees in an urban setting to produce the desired shading and cooling effects (Akram et al., 2008).

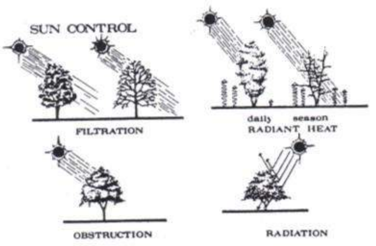


Fig. 2 Plantation and sun control

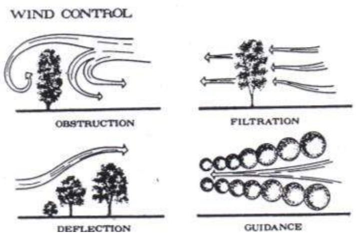


Fig. 3 Plantation and wind control

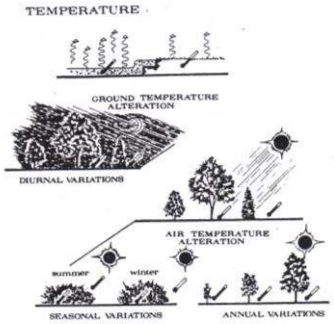


Fig. 4 Plantation temperature

3. THERMAL COMFORT:

Thermal comfort can be defined through three different approaches psychological, thermo physiological and heat balance of the human body. ASHRAE defines thermal comfort from the psychological approach as the condition of mind, which expresses the satisfaction with the thermal environment. The thermo physiological approach is based on the firing of the thermal receptors in the skin, so the thermal comfort is defined as the minimum rate of nervous signals from these receptors. According to heat balance approach, thermal comfort is when heat flows to and from the human body is balanced, and skin temperature and sweat rate are within a comfort range (Hoppe, 2002). Keeping in view the definitions above, we need to take into account a variety of parameters, which include environmental and personal factors when deciding what will make the people to feel comfortable. The combination of these factors constructs what is known as the human thermal environment.

The parameters that interfere with thermal comfort in urban space are similar to those of inside spaces, but they are more extended and variable (Letícia Zambrano et al., 2006). The thermal comfort in an urban space depends on environmental factors such as air temperature, Mean radiant temperature, Air velocity, relative humidity, solar incidence and radiation exchanges, and local characteristics of winds. Personal factors such as person’s clothing CLO, activity level MET also influence the thermal comfort of the users. Beyond these factors, the urban design, the morphology of the buildings, the characteristics of the surfaces, the topography, the vegetation, the presence of water and the behavior of the individuals are furthermore factors that influence the thermal conditions of these spaces (Dessi, 2001).

From earlier research (as reported and reviewed in e.g. Fanger 1970, Gagge 1986) we know that thermal comfort is strongly related to the thermal balance of the body. The human energy balance shows the various factors affecting human outdoor comfort. Out of these heat gain/loss factors, the most significant one is the total radiation, which can amount to up to half the total heat gain on the subject. On the other end of the spectrum is the ambient temperature, which accounts for only 7% of the heat gain (Rowe, 1991). Therefore, lessening the exposure to and reducing the temperature of the surrounding surfaces (i.e., MRT) is the most effective means to achieve outdoor thermal comfort for pedestrians in urban spaces (Bryan, 2001).

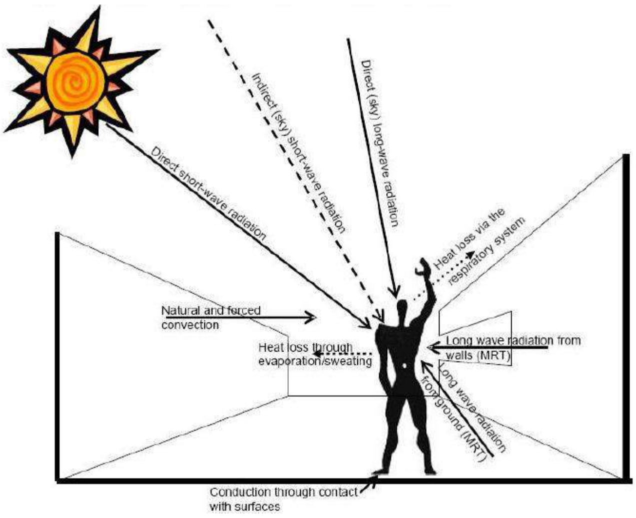


Fig.5 outdoor human energy balance.

There are a large number of thermal indices, most of them share many common features and can be classified in two groups: empirical or rational. These indices are well documented (e.g. Givoni 1997, Houghton 1985, ASHRAE 2001, ASHRAE 2004). The empirical indices ignore the decisive role of human physiology, activity, clothing, and other personal data (height, weight, age, sex). Rational indices are more recent, promoted by the lately development of computing techniques, and rely on the human energy balance.

Several indices are integrating thermal environmental factors and heat balance of the human body are applied for accessing thermal comfort in outdoor environments, e.g., predicted mean vote (PMV) (ASHRAE, 2004) primary for comfort studies in the built environment, standard effective temperature (SET) (Givoni, 1991), physiological equivalent temperature (PET) adopted for the evaluation of the thermal component of different climates and thermal comfort in urban environments (Hoppe, 1999). PMV is an index that expresses the quality of the thermal environment as a mean value of the votes of a large group of people on the ASHRAE seven-point thermal sensation scale (+3 hot, +2 warm, +1 slightly warm, 0 neutral, -1 slightly cool, -2 cool, -3 cold). PPD (Predicted Percentage Dissatisfied) is an index expressing the thermal comfort level as a percentage of thermally dissatisfied people and is directly determined from PMV. ASHRAE standard 55-2004 provides a graphical method to use the PMV-PPD model. It is based on the acceptable range of operative temperature shown in a psychrometric chart for people dressed into two different levels of clothing: 0.5 clo (0.08 m^2.K/W) (typical for summer) and 1.0 clo (0.155 m^2.K/W) (typical for winter). The graphical zone corresponds to a PPD of 10%. However, it is only applicable to situations where metabolic rates are between 1.0 and 1.3 met (58.15 to 75.6 W/m^2). PMV is the thermal comfort index that will be used in this study.

4. THERMAL OUTDOOR MODELLING:

Thermal One reason for the very limited number of field studies on outdoor thermal comfort in relation to outdoor spaces is certainly the huge number of urban variables and processes involved. This complexity makes it difficult performing comprehensive field measurements and is probably the reason why most investigations concentrate on air temperature and humidity, which are much easier to measure. Indeed, it is costly to record continuously and for a large sample of spaces all wave radiation flux densities from the three dimensional surroundings of a human body, in addition to the commonly measured meteorological factors (i.e. air temperature Ta, wind speed v, and vapour pressure VP).

In this respect, numerical modeling has a distinct advantage over comprehensive field measurements and is, therefore, a powerful alternative for urban climate issues (e.g. Arnfield 1990, Capeluto and Shaviv 2001, Kristl and Krainer 2001, Bourbia and Awbi 2004, Asawa et al. 2004). In a recent review of the state of research development in urban climatology during the last two decades, Arnfield (2003) draw attention to the growing popularity of numerical simulation, described as a methodology perfectly suited to dealing with the complexities and non-linearities of urban climate systems. Hence, the present research will be mainly carried out by using a numerical methodology, so that a series of vegetation planning in the outdoor space could be analyzed and compared.

Urban microclimate models vary substantially in many aspects: their physical basis, temporal and spatial resolution, input and output quantities, etc. This will be performed by means of the three dimensional model Envi-Met, which simulates the microclimatic changes within urban environments in a high spatial and temporal resolution. The software uses both the calculation of fluid dynamics' characteristics, such as air flow and turbulence, as well as the thermodynamic processes taking place at the ground surface, at walls, at roofs and at plants. ENVI-met takes into account all types of solar radiation (direct, reflected and diffused) and calculates the mean radiant temperature. The calculation of radiative fluxes includes the plant shading, absorption and shielding of radiation as well as the re-radiation from other plant layers (Akram Rosheidat et al., 2008). Moreover, plants in ENVI-met are more than physical obstacles against wind and radiation. They are biological bodies, which interact with the surrounding environment by exchanging heat and water vapour. ENVI-met simulates the microclimatic dynamics within a daily cycle in complex urban structures, i.e. buildings with various shapes and heights as well as vegetation. Its high spatial and temporal resolution enables a fine understanding of the microclimate at the street level. It has also been used in many studies which give it a high credibility, and therefore, we feel confident in using it in the research (Bruse, 2000; Jesionek & Bruse, 2003; Lahme & Bruse, 2003; Samaali et al., 2007; Huttner et al., 2008; Huttner et al., 2009).

4. ENVI MET SIMULATION PROCESS:

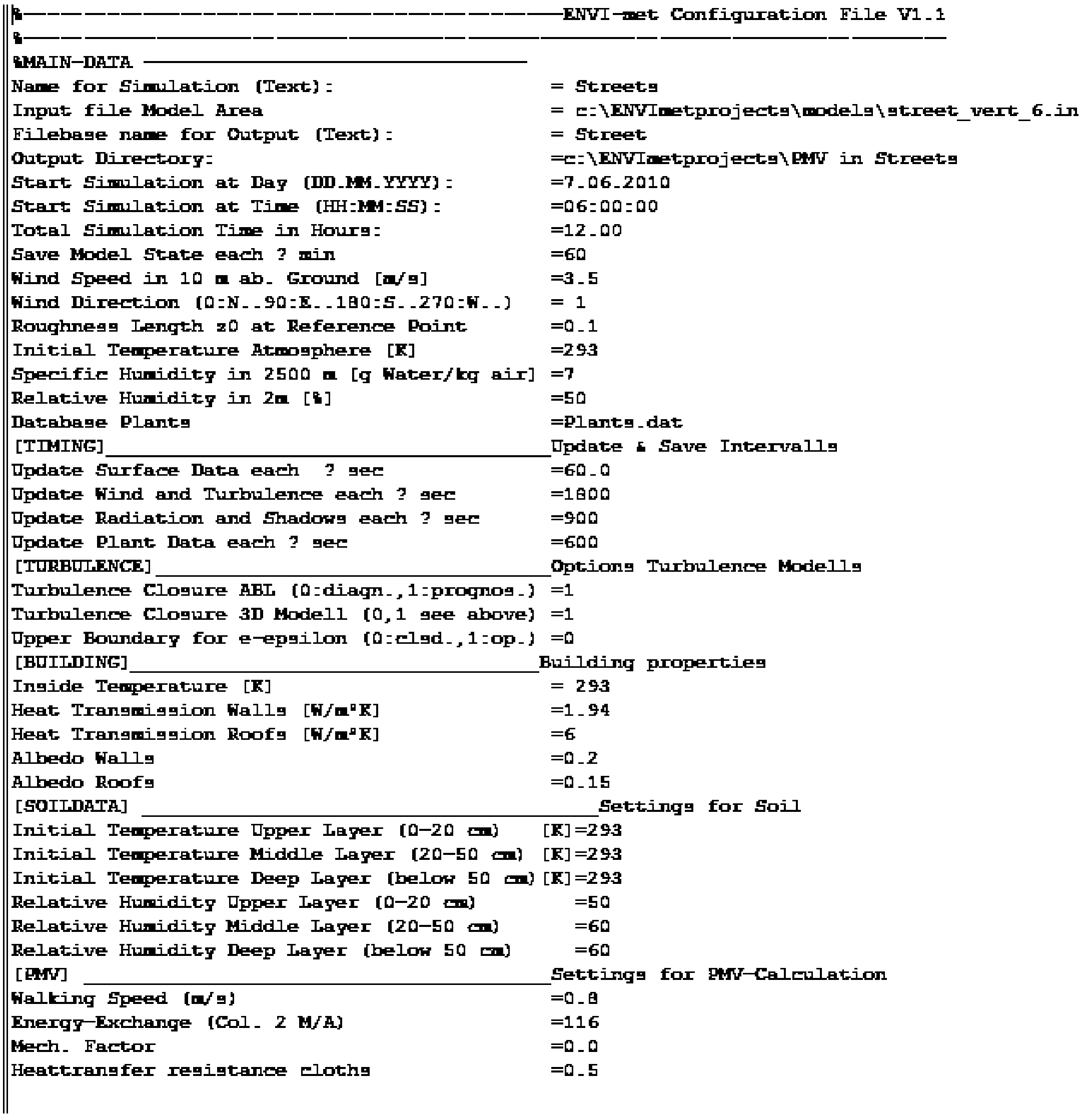
The model requires relatively few input parameters and calculates all required meteorological factors, namely air and surface temperatures, wind speed and direction, air humidity, short-wave and long-wave radiation flux as well as the mean radiant temperature needed for comfort analyses. The first task will be to set the space to be tested. This includes the location, the horizontal and vertical dimensions of the architectural environment, the surface materials and the vegetation size, kind, distribution and percentage to non-green areas. The second step would be to gather information about the site location and its climatic data like temperature, wind speed, humidity, PMV parameters and databases for soil types and vegetation. The simulation using ENVI-met is then processed. The output files are visualized using the program LEONARDO to test how the different parameters of the vegetation used will change the PMV. Conclusions could be drawn based on how the PMV value is made to approach the thermal comfort value of 0. Finally, suggestions are made in order to set design criteria for the use of vegetation in the microclimate control.

4. METHOD:

4.1 Simulation conditions:

The simulations are carried out for a street in Cairo at 30° 7’ N latitude and 31° 23’ E longitude. The domain simulated is organized as a 100*60*50 m3 space; composed of two rows of buildings with concrete roof separated by an asphalt street of a constant width of 10 m. The buildings' height is 15 m. The spacing between buildings is 4m and covered with grass. The main simulation conditions and building properties used for the case studies reported in this work are listed in Table.1.

Table.1 Main inputs used in the simulation



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%------------------------------------------------ENVI-met Configuration File V1.1
%--------------------------------------------------------------------------------
%MAIN-DATA ------------------------------------
Name for Simulation (Text):                    = Streets
Input file Model Area                          = c:\ENVImetprojects\models\street_vert_6.in
Filebase name for Output (Text):               = Street
Output Directory:                              =c:\ENVImetprojects\PMV in Streets
Start Simulation at Day (DD.MM.YYYY):          =7.06.2010
Start Simulation at Time (HH:MM:SS):           =06:00:00
Total Simulation Time in Hours:                =12.00
Save Model State each ? min                    =60
Wind Speed in 10 m ab. Ground [m/s]            =3.5
Wind Direction (0:N..90:E..180:S..270:W..)     = 1
Roughness Length z0 at Reference Point         =0.1
Initial Temperature Atmosphere [K]             =293
Specific Humidity in 2500 m [g Water/kg air]   =7
Relative Humidity in 2m [%]                    =50
Database Plants                                =Plants.dat
[TIMING]_______________________________________Update & Save Intervalls
Update Surface Data each  ? sec                =60.0
Update Wind and Turbulence each ? sec          =1800
Update Radiation and Shadows each ? sec        =900
Update Plant Data each ? sec                   =600
[TURBULENCE]___________________________________Options Turbulence Modells
Turbulence Closure ABL (0:diagn.,1:prognos.)   =1
Turbulence Closure 3D Modell (0,1 see above)   =1
Upper Boundary for e-epsilon (0:clsd.,1:op.)   =0
[BUILDING]____________________________________Building properties
Inside Temperature [K]                         = 293
Heat Transmission Walls [W/m²K]                =1.94
Heat Transmission Roofs [W/m²K]                =6
Albedo Walls                                   =0.2
Albedo Roofs                                   =0.15
[SOILDATA] ____________________________________Settings for Soil
Initial Temperature Upper Layer (0-20 cm)    [K]=293
Initial Temperature Middle Layer (20-50 cm)  [K]=293
Initial Temperature Deep Layer (below 50 cm) [K]=293
Relative Humidity Upper Layer (0-20 cm)          =50
Relative Humidity Middle Layer (20-50 cm)        =60
Relative Humidity Deep Layer (below 50 cm)       =60
[PMV] _________________________________________Settings for PMV-Calculation
Walking Speed (m/s)                            =0.8
Energy-Exchange (Col. 2 M/A)                   =116
Mech. Factor                                   =0.0
Heattransfer resistance cloths                 =0.5
```

4.2 Study Area:

The simulations reported here were run one time for East-West orientation and another time for North-South orientation according to the following plan:

- Street with no trees;

- Street with trees that are distributed equally on both sides of the street with 2 m spacing;
- Street with trees that are distributed equally on both sides of the street with 4 m spacing;
- Street with trees that are distributed equally on both sides of the street with 6 m spacing.

The trees planted are dense trees of height 10 m with distinct crown are planted on loamy soil on the pavement. A typical hot summer day (7th of June), was chosen for the simulation. Fig. (8) Shows the wind wheel for the simulated environment during June.

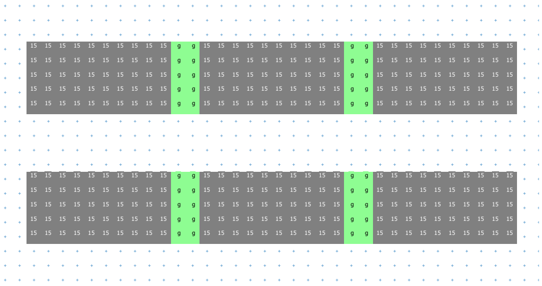

Fig.6 The 10 m wide simulated East-West street with no trees.

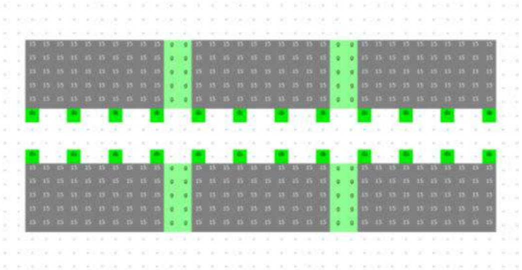

Fig.7 The 10 m wide simulated East-West street with spacing 6m between trees on the pavements.

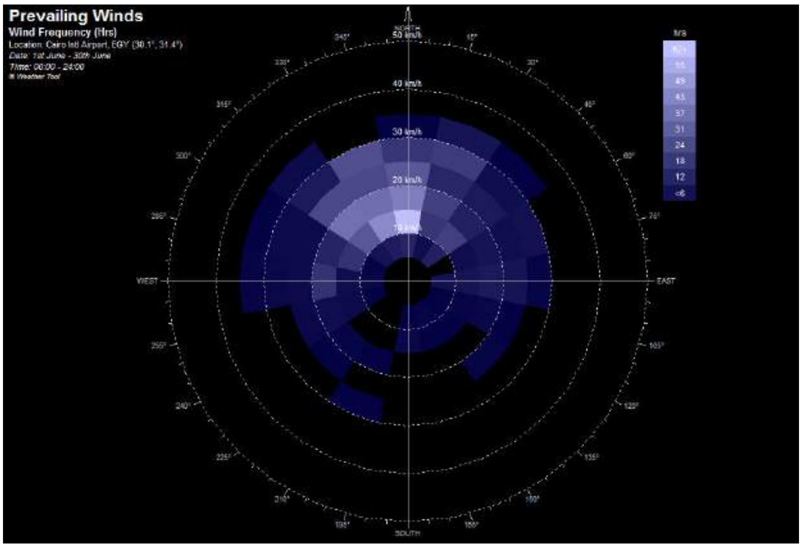

Fig.8 Wind directions in the simulated environment during June

5. RESULTS

5.1 Thermal comfort analysis for East-West Street:

Figure (9) illustrates the PMV values for the East-West Street are from 6 am to 6 pm. From the figure, we can observe that the maximum PMV is always found in the middle of the street and is independent of the separation between trees. Its value is 0.85-0.9 of the cases of no trees at the middle of the day. The minimum PMV is always found on the pavement and depend strongly on the spacing between trees. In all simulations, a minimum PMV value was found in front of the side gardens.

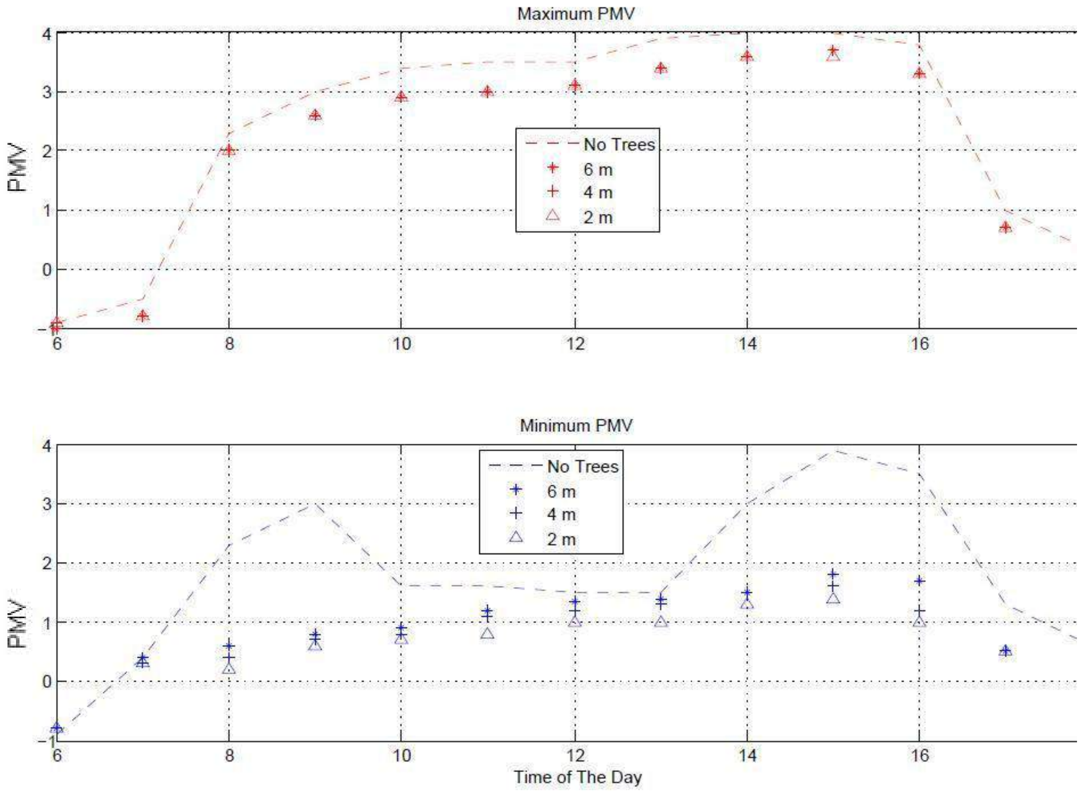

Fig. 9 The PMV values for the east-west street from 6 am to 6 pm. The simulation is done for the case of no trees and for the cases of trees separated by 2m, 4m and 6m.

5.2. Thermal comfort analysis for North-South Street:

Figure (10) illustrates the PMV values for the North-South Street are from 6 am to 6 pm. The simulation was next repeated for a North-South Street. The following points were observed:

- The maximum PMV occurs always at 13.00.
- The ‘Without Trees’ case still has a higher PMV in all cases. However, the difference with the ‘With Trees’ case is not large.
- All the three simulations ‘with trees’ cases (separation of 2, 4 and 6 m) give the same PMV.
- All calculated PMV values are lower than the corresponding values for the east-west simulation.

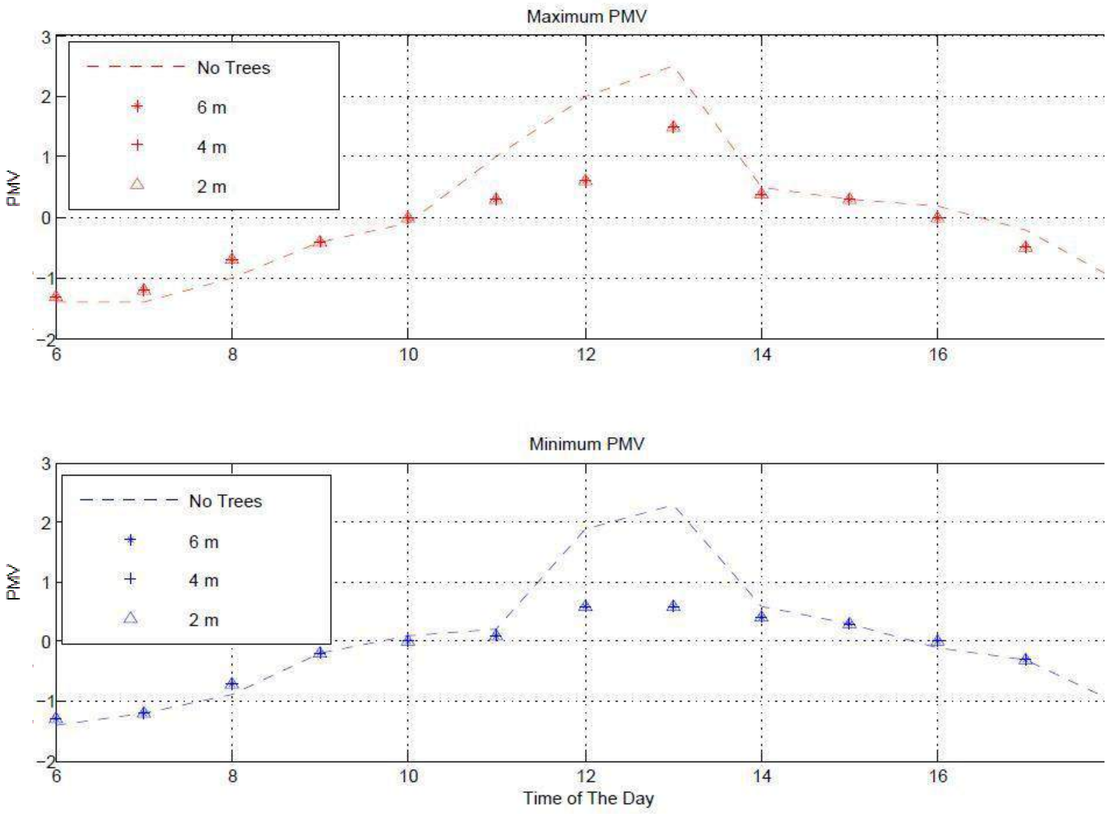

Fig. 10 The PMV values for the north-south street from 6 am to 6 pm. The simulation parameters are identical for those of the East-West Street

6. DISCUSSION

The experimental study suggests that trees have significant effect on thermal comfort in EW and NS Street orientations. This shows that even sparsely vegetation elements tend to improve thermal comfort.

In the EW orientation, the analysis of the values of PMV – expressing predicted mean vote of space occupants- show that PMV was significantly higher in the “without tree” case in 9 hr and between14 to 16 hrs. These results are clearly attributed to the presence of vegetation, to the wind direction and to the motion and the position of the sun.

- The decrease in the PMV ‘Without Trees’ case by the middle of the day is due to the effect of the shadows of the buildings according to the sun path.
- The amelioration of the PMV with decreasing the distance between the trees is almost linear and is about 0.1 for each 1 m decrease in distance. However, decreasing this distance may not be useful as a high vegetation density will block the air motion as found by other groups.
- In the first few hours of the morning, the PMV is greater from East side than in the rest of the street, while in the last few hours of the day, the PMV is higher from the West side. This is clearly due to the sun path during the day. These values were also discarded as they represent only a small fraction of the street and the pavement.

The minimum value of PMV was found in the spots facing the side gardens between building blocks. This is attributed to the high wind speed there and to the grass planted on loamy soil. From the investigation of the PMV value on the pavement we can conclude the following:

- In all cases, the maximum PMV is found at 15.00 hr. At this hour, the PMV without trees is 3.9 and drops to 1.8, 1.6 and 1.4 for the cases of trees separated by 6, 4 and 2 m respectively. At 12.00 hr, the PMV without trees is 1.5 and drops to 1.4, 1.2 and 1.0 for the cases of trees separated by 6, 4 and 2 m respectively.

In the NW street environment, the maximum PMV existed at 13.00 hrs. The PMV value of the “without trees” case was significantly higher than all other cases (i.e, trees with various spacings). Analysis of PMV values reveals that the values of the NS street environment were consistently lower than the corresponding values of the EW street environment. The combined effect of vegetation, wind direction and solar exposure appears to affect the PMV in this environment. This finding is consistent with Ng (2009) that thermal comfort in the outdoor environment can be enhanced by maximizing wind speed and minimizing solar radiation. The desirable environment for pedestrians is a balance between air temperature, solar radiation and wind speed. A higher wind speed might be needed if a pedestrian is partly shaded, likewise, a lower wind speed might be desired if the air temperature is lower.

Qualitative urban design guidelines:

Results of this study can help in suggesting urban design guidelines to provide designers with a strategic sense of how to start off their design. By observing the guidelines, there would be a higher probability that the output design would be better for thermal comfort for outdoor spaces.

- **Air path**

It is important for better thermal comfort to let more wind penetrate through the urban blocks. Air can be in the form of streets, open spaces, spaces between buildings and low rise building corridors through which air reaches inner parts of the urbanized area. Projecting obstructions over air paths should be avoided minimizing wind blockage.

- **Orientation of streets:**

An array of streets should be aligned in parallel, or up to 30o to the prevailing wind direction, in order to maximize the penetration of prevailing wind through the urban block.

- **Vegetation:**

Streets and open spaces should be shaded by trees. Our result showed that tree spacing did not cause significant effect on thermal comfort. Hence, the dense vegetation is not a primary requirement.

7. CONCLUSIONS

This study reports an experimental investigation of the effect of street orientation and tree spacing on thermal comfort in outdoor spaces in a simulated urban block. Analysis of results revealed that street orientation is a fundamental factor in providing shading and allowing wind to penetrate the urban block. North-South orientation maintained better scores for PMV compared with the East-West orientation. Existence of trees significantly improved the PMV for thermal comfort in the outdoor space. However, the density of trees in terms of tree spacing did not show a significant contribution to PMV. This study is limited to a simulation of a simple urban block of buildings of equal heights. It is also limited to use of single type of tree plants. Further study is required to investigate the effect of more complex urban tissues, building heights, various types of tree plants on thermal comfort of outdoor environments.

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