Measurements and Simulation of Microclimatic Effects of a Horizontal Hydroponic Pergola

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Abstract. The microclimate model ENVI-met (V4) was used for predicting the effects of different systems of planted pergolas on the microclimate of an atrium. The model was firstly validated using experimental data and then used for different cases studies. The microclimate measurements were carried in a real construction project of a hydroponic pergola at Kostakii Campus of the Technological Education Institute of Epirus (Arta, Greece). The validation results showed a very good agreement between measured and simulated values of air temperature. The model was used to predict the effects on air temperature (T_{air}), relative humidity (RH), mean radiant temperature (T_{mrt}) and Physiologically Equivalent Temperature (PET) when of 0%, 50% and 100% of the atrium horizontal plane area was covered by the planted pergola. The results showed that compared to the case with no pergola in the atrium, covering 100% the atrium area with a planted pergola reduced average Tair up to 0.78 and 1.3 $^{\circ}$C during the day and night, respectively, while at the hottest time of day, T_{mrt} was lowered 29.4 $^{\circ}$C and the PET was lowered up to 17.9 $^{\circ}$C.

Keywords: ENVI-met V4.0, CFD, Thermal comfort, PET

1 Introduction

The amelioration of living conditions in urban environments has been set as a high priority goal in both national and E.U. level. The bioclimatic design of buildings and urban hardscapes constitutes a promising option which has the dynamic to contribute extensively to the diminution of the serious environmental problems that harass urban areas. The installation of green surfaces on buildings is one of the most valuable tools of this approach, as because of the physiological functions of the plants (photosynthesis, respiration, evapotranspiration) and the physical characteristics of the planting system, produce favorite changes to both the internal (Monteith and Unsowrth, 2008; Alexandri and Jones, 2008) and surrounding

environment of buildings (Hoffman και McDonough, 2004; Takebayashi and Moriyama, 2007; Fang 2008; Robbert et al., 2009).

The use of pergolas has great history as structural element in Mediterranean architecture. Montero and Salas (2009) studied a hydroponic pergola and outlined its positive effects in microclimate. The hydroponic pergola and the hydroponic vertical frame (which are the main points of interest of the proposed project) have the advantage –when compared to the conventional shading structures- that they give the landscape architect a field for design creativity as the a number of different plants could be synthesized in order to create the final result.

Experimental data and development of know-how in local level (thus considering local climatic conditions) are in luck -and for that indispensable- for the case green structures on buildings. In this framework the selection of plants is of great interest (Filippi, 2008, Salas and Montero, 2009; Benvenuti, 2009). Also the study of real scale green structures, their design, working parameters and effects on microclimate constitute an innovative research filed. Solutions regarding design, substrate, nutrient solution and management are expected to be valuable for the spreading of such systems.

Finally the numerical modeling of such systems will allow the study of numerous different scenarios regarding their design. Yang et al. (2013), after a brief presentation of studies that attempt to assess the performance of ENVI-met software by comparing simulation results with field data, conclude that the ENVI-met model is capable of modeling outdoor thermal environment for different climate patterns with acceptable accuracy.

The objective of the present study is to validate the results simulated by the recent version (V4.0) of ENVI-met software and then use it for the evaluation of different design of such structures.

2 Materials and Methods

2.1 Experimental facilities

The measurements were made at the Kostakii Campus of the Technological Education Institute of Epirus (TEIEP, latitude 39º 07′N, longitude 20º 56′E, altitude 5m), near Arta, at the north-west coastal area of Greece. According to HNMS (2014), the climate of the area is classified to Mediterranean type, with hot summers and mild but rainy winters.

A hydroponic pergola (WxLxH in m: 7x8x2.3) was constructed in order to host a horizontal planting system. The pergola was placed in the open air central atrium (WxLxH in m: 15x20x7) of Floriculture & Landscape Architecture (FLA) building of TEIEP. This selection was based on the assumption that the atrium resembled a densely structured urban area. Plastic tubes (PVC, Ø125) were used as substrate containers. Each container was 1 m in length, with screw cap endings, 3 evenly spaced holes (0.05 m) for planting at the top and drainage holes (3 rows of 10 holes each) at the bottom. The containers were placed on gutters (PVC, Ø125). The gutters

were spaced 0.6 m apart following a horizontal lay-out on the pergola and 0.4 m apart following a vertical lay-out on the vertical hydroponic wall. The containers were filled with perlite (1-5 mm). A closed-loop system was used for the nutrient solution supply. The pergola hosted 144 plants in 8 planting rows and included the following plants: *Dimorphoteca sinuata*, *Gazania rigens*, *Lavandula angustifolia*, *Pelargonium peltatum*, *Pelargonium zonale*, *Petunia surfinia*, *Rosmarinus officinalis* "Prostratus", *Santolina chamaecyparissus* and *Pelargonium capitatum*.

A number of parameters were continuously monitored: a) air temperature (T_{air}, ºC) and relative humidity (RH_{air}, %) by means of three temperature and humidity sensors (HD9008TR; DeltaOhm, Padua, Italy): one bellow (at a height of 1.75 m) and two sensors above the plane of the pergola (height 3 and 5 m, respectively) and b) solar radiation below the pergola (at a height of 2 m, Rs in W m^{-2}) by means of a solar pyranometer (SKS 1110; Skye Instruments, Powys, UK). Measurements took place every 30 s and the 10-min average values were recorded.

The microclimate (air temperature and relative humidity, solar radiation, wind speed and direction) data outside the atrium were also measured and recorded in a nearby meteorological station located in an open area of the Campus.

Days from the period without or with the pergola in the atrium with very similar meteorological data in the reference weather station were selected, and the meteorological data collected in the centre of the atrium with and without pergola, were compared, so that to investigate the influence of pergola in the microclimate of the atrium.

The evaluation was carried out during 2009 and 2010 with the atrium empty and during 2013 and 2014 with the hydroponic pergola installed in the atrium.

2.2 Simulations

The current version of ENVI-met model (4.0) was used to simulate the microclimate of the experimental site. This three-dimensional microclimate model is based on computational fluid dynamics (CFD) and thermodynamics, is able to simulate flow around and between buildings, exchange processes of heat and vapor at the ground surface and at walls, exchange of energy and mass between vegetation and its surroundings, bioclimatology, and particle dispersion (Yang et al. 2013). The spatial resolution of the model reaches 0.5 m and the time step can be between 1 and 5 s.

The actual environment and elements of the site, such as building, vegetation, soil, etc., were defined in an ENVI-met area input model (Fig. 1). The plastic tubes (PVC, Ø125) used as substrate containers, were created in Detailed Design Model Type as façade elements with top of façade in 3 m and bottom at 2 m and were set in editing mode as whole façade with individual segment material as PVC Sun Sail (thickness of layer 0.02) with default characteristics from the ENVI-met Material Database. In horizontal direction, the main model area (30 x 35 m) was constructed with 60 x-Grids and 70 y-Grids, with grid size dx, dy of 0.5 m. Around the main area 3 nesting grids were set with nesting grid soil Profile "Default Unsealed Soil". In vertical direction, 30 z-Grids were used with Grid size of 0.5m. The vertical grid generation was equidistant for the first 8 m with equal dz height and with a telescoping factor of

20% after the height of 8 m. Geographic Properties of the model were set for grid north and location on earth as for the location of the experimental site. The height of the plants was uniform and set to 0.5 m with a leaf area density (LAD) value of 1, resembling the median LAI factor of the used plants and the full coverage of the pergola with plants after the beginning of August. The hourly meteorological data from the on-site open area meteorological station were used to generate the forcing file for the simulation. Weather conditions for those days were typical for a hot humid day of August, in Arta.
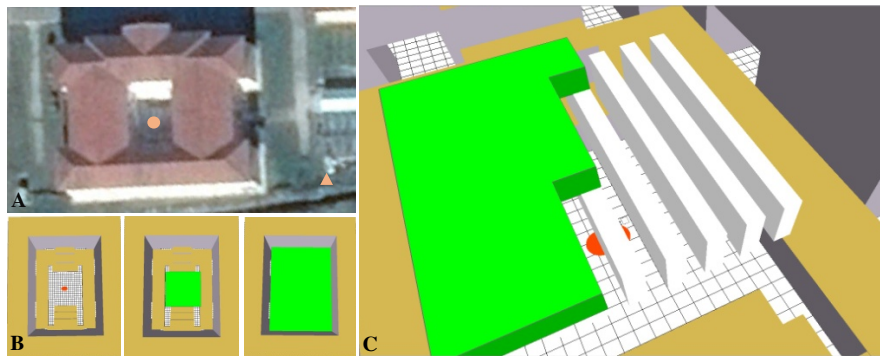

Fig. 1. 3D area input model for ENVI-met simulation. A. Satellite image of Kostakii Campus. With ● marked the place of the Atrium where meteorological parameters were continuously monitored. With ▲ marked the reference Weather Station B. Simulation of 0%, 50% and 100% area of Atrium covered by planted pergola. C. Detail of the construction of ENVI-met model.

The model was used to predict the effects of 0%, 50% and 100% area of atrium covered by the planted pergola of LAD 2 and the effect of a 50% atrium covered area with LAD 2 or 5, on air temperature, relative humidity, mean radiant temperature (T_{mrt}) and Physiologically Equivalent Temperature (PET). For the simulation of the three case studies, the same hourly meteorological data from the reference weather station were used to generate the forcing file. The simulations ran for 24 h, starting at 00:00 and ending at 23:59 of the same day. The case of 0% resemble to thermal conditions that prevail in empty atrium, the case of 50% resemble to the real construction project of the hydroponic pergola in the present study and 100% area of atrium covered by the planted pergola resemble to thermal conditions if the whole area of the atrium was covered by the planted pergola.

3 Results and Discussion

3.1 Model validation

The comparison between measured and simulated values of air temperature observed at the height of 1.75 m for the cases with and without the planted pergola in

the atrium is presented in Fig. 2. It can be seen that a very good agreement was found between the measured and simulated values of air temperature. The regression lines between measured and simulated values of air temperature for the two cases found were:

- Empty atrium: Simulated = 0.98 Measured,
- Atrium with pergola: Simulated = 0.99 Measured,

with a determination coefficient R^2 of 0.98 and 0.93, respectively.

The largest difference between the simulated and the measured air temperature observed in the atrium was 1.1 ℃ for the case without pergola in the atrium and 1.3 ℃ for the case with pergola in the atrium and were observed during periods with rapid change of climate variables.

The average daytime value of simulated air temperature in the atrium for the case without and with pergola during the 3 days period were 29.2 ℃ and 28.9 ℃ while the corresponding measured values were 29.7 ℃ and 29.2 ℃.

Taking into account the above results, it could be concluded that the model fitted with the simulation model was suitable for the present purpose.

It has to be noted that the 6 days selected for comparison with the simulated data had similar climate conditions in the reference meteorological station. Thus any differences observed in the microclimate conditions measured in the area of atrium between the two cases are due to the presence of the planted pergola in the atrium.
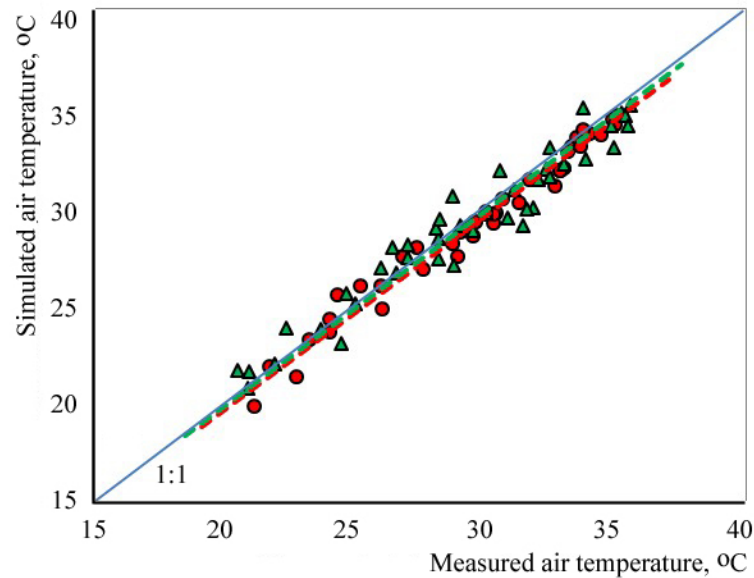

Fig. 2. Simulated vs measured values of air temperature during three different days for the case with or without the pergola in the atrium. Circles: atrium without the pergola; triangles: atrium with pergola. The continue line represents the 1:1 line while the dotted lines represent the regression lines of the data.

Based on the differences observed in the measured values of air temperature, it could be seen that the planted pergola resulted in a reduction of air temperature in the atrium during daytime of about 0.5 ºC. A similar reduction was also observed when examining the simulated values of air temperature. The relatively low effect of pergola on the air temperature observed in the atrium could be attributed to the relatively low leaf area of the plants grown in the pergola, the fact that the plants used were mainly aromatic herbs, which have low transpiration rate; and the relatively small area of the pergola in comparison to the total atrium area. However, the planted pergola has a significant effect in the reduction of solar radiation below the pergola and accordingly to the thermal indexes related solar radiation and radiation temperature.

3.2 Scenarios analysis

Different scenarios studies were tested to study the effect of a planted pergola on the microclimate observed in the atrium and the daytime and nighttime average values of the microclimate parameters. The radiation fluxes (i.e. short wave and long wave) absorbed by a human body and their effect on its energy balance are taken into account through the mean radiant temperature (T_{mrt}) (Gulyás et al. 2006), which is taken into account by the majority of the indices used to describe thermal comfort (Hassaan and Mahmoud 2011). Furthermore, the thermal comfort conditions were assessed by means of the Physiologically Equivalent Temperature (PET). The Thermal Index PET (ºC) was calculated using RayMAN pro model, Version 2.1. As input data was used T_{air}, RH_{air} and T_{mrt} simulated at a height of 1.25 m at the center of the pergola and clothing factor clo=0.5 that corresponds to a standing man wearing a trousers and a short-sleeve shirt. All other parameters were the default of the model. The results are shown in Table 1.

Table 1. Simulated values of microclimate parameters and calculated Thermal Index PET at a height of 1.25 m at the center of the atrium.

Case study	T_{air}		RH_{air}		T_{mrt}		PET	
	Day	Night	Day	Night	Day	Night	Day	Night
Empty atrium	29.33	21.94	55.41	85.40	38.58	11.29	35.33	17.32
Planted atrium, 50% area of atrium covered by pergola, LAD 2	28.85	20.50	57.29	92.76	31.41	11.06	30.75	16.48
Planted atrium, 50% area of atrium covered by pergola, LAD 5	28.75	20.75	57.86	90.80	31.02	11.54	30.50	16.81
Planted atrium, 100% area of atrium covered by pergola, LAD 2	28.55	20.64	58.43	91.40	29.36	11.43	29.55	16.70

It can be seen that a fully covered atrium with a planted pergola of LAD 2 resulted in about 0.8 ℃ lower air temperature during daytime and about 1.3 ℃ during nighttime. However, the significant effect of the planted pergola can be seen in the T_{mrt} and PET values observed. When a planted pergola was simulated in the atrium the T_{mrt} and PET values observed were much lower than those observed in the empty atrium. The PET value observed at during the hottest part of the day in the center of the atrium at a height of 1.25 m was 52 ℃ when the atrium was empty and 36 ℃ and 34 ℃ when 50% or 100% of the atrium area was covered by a planted pergola, respectively.

4 Concluding Remarks

The ENVI-met simulation program was validated using experimental data and then used for different cases studies. Validation revealed that the air temperature values could be efficiently simulated by the program. The case studies presented showed that compared to the case with no pergola in the atrium, covering 100% the atrium area with a planted pergola reduced average Tair up to 0.78℃ and 1.3℃ during the day and night, respectively, while at the hottest time of day, Tmrt and the PET were 29.4℃ and 17.9℃ lower.

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