Towards optimization of urban planning and architectural parameters for energy use minimization in Mediterranean cities

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Abstract: This paper reports observations and first experimental results from a field measurement campaign at the neighbourhood/urban scale, which was conducted in July 2010 in Nicosia (Cyprus) under the European Research Project TOPEUM funded by ERA-NET (Urban-Net Call). The ultimate goal of this work is to investigate the influence of urban design and architectural parameters in the resulting urban climate and the resulting energy usage. The field measurement campaign was carried out in the capital city of Cyprus, Nicosia, reflecting a typical Mediterranean city both in relation to buildings architecture and fabrics, street geometry and neighbourhood morphology. The field measurements include meteorological measurements as well as on-ground and aerial thermography, covering a range of spatial scales, from local-street canyon to meso-scale. The measurements record the meteorology, the thermal response of the buildings in the field site area and the resulting local microclimate particularly in the street.

Keywords: *Urban Heat Island, Intensive Observation Period, Field Measurements, CFD Modelling, Wind Tunnel Measurements*

1. Introduction

Urbanization has been increasing at an alarming rate: while in the 1800's, only 3% of the world's population lived in urban areas, by the 1950's the urban population increased to 30% and in 2000 it reached 47%. With this ever increasing growth, numerous issues have been raised, such as air quality issues, sustainable use of energy, maintenance of waste materials and socio-economic status of urban inhabitants [1]. All these issues depend on the sustainable urban planning, the type of materials used in buildings [2] as well as the organisation of economical and social life. The complexity of the task to aim at ideal sustainable city goes through accounting for contradictory effects by any kind of measures. Therefore, basic and applied research is needed in order to investigate the city as human-made environment. The task is to achieve sustainability in the use of energy, food, waste, air and water quality. Recent studies on the influence of climate change on Northern–European cities suggest that within 50 years they may experience a climate close to that of South-European cities today. This has enormous resource implications when the design and layout of the urban fabric and the individual buildings are not well suited to mitigate extreme conditions [3,4] There is therefore a strong need for strategic designs to be developed which would mitigate such environmental changes. For example, whilst the general cause of overheating of cities is known, it is not well understood how much influence different urbanization characteristics and building materials have on the intensity of the city overheating [5,6].

In this study the energy exchange processes between buildings and air in a typical South-European city as well as the ventilation properties in relation to urban-planning and architectural parameters, for the purpose of energy use minimisation are examined. The complexity of this problem requires complementary methods to be employed. In a boundary layer wind tunnel the basic flow under neutral conditions of different generic city configurations will be studied. The wind tunnel data will serve also as calibration data for

CFD simulations which will in turn be utilised to evaluate heating effects and material properties. The computational fluid modelling will predict the effect of city layout and building materials on temperatures. Based on predicted temperatures the energy use for air conditioning will then be assessed. Heat absorption phenomena occurring at building surfaces have a major impact on the urban climate: field measurements of surfaces heat flux and material thermal properties will be carried out for urban sites in Cyprus. For these reasons an intensive observation period of 1 month was carried out in which a series of measurements were taken both for the air, solar radiation and humidity as well as the building surfaces.

2. Methodology

2.1. Multidisciplinary approach

The methodology for the implementation of this study consists of the following steps:

1.Selection of the site under investigation: The identification of the site to be investigated was performed under prescribed criteria based on the building materials, the geometry and the location of the buildings.

2.The field measurements involved meteorological measurements at three different scales (from meso-scale to micro-scale), while the thermal response of buildings was simultaneously recorded through thermography (both aerial and on-ground) as well as in-situ measurements of temperature and moisture. In this paper the results from this field measurement campaign are presented, the analysis and interpretation, as well as results from supporting studies in the wind tunnel and computational simulations to assist in the understanding and derivation of guidelines for “climatically-informed” urban design.

3.Laboratory experiments: The selected city blocks will be scaled down and applied in a wind tunnel, where ventilation and heat efficiency effects will be investigated. The determination of the velocity field will be achieved by employing Laser Doppler Anemometry (LDA) and Particle Image Velocimetry (PIV).

4.CFD modelling will contribute to the study, by examining the air flow as well as the thermal performance of building materials taking into account the structure of the modelled urban areas. It will raise the opportunity to understand the contribution of heat conduction and heat radiation in the generation of thermal discomfort in urban canyons for the case of Cyprus.

2.2. Site Selection

In terms of the site selection, the parameters of building height, building density and paved and unpaved area coverage were examined. This analysis provided fundamental data for all the subsequent tasks and actions. The objective was to create a complete database of the investigated area in order to assess the status of urban environment in Cyprus. Hence, major groups of building blocks (approximately 350 building blocks) were analyzed and scaled down for the applied channel, in order to support the parameterization studies for the investigated scenarios. Within this task, the geometries under investigation were also be modelled for the purposes of the CFD study. The building energy behaviour and performance are heavily influenced by the density of the building space that is why the facades chosen have different SVF. For example facades that are placed in front of an open parking area (H/W<1) can be compared with some others that are placed in a canyon. Some other important factors were the orientation of the chosen facades and the properties of the surrounding surfaces in the same canyon.

Among the investigated neighbourhoods, the old city centre of Nicosia appeared as being the most representative for the Mediterranean-like architecture, therefore it was decided that the field campaign should be carried out in this area (see Fig. 1). The old town centre, which is the historical centre of the city, is delimited by Venetian type walls. It is generally characterized by narrow canyons with Mediterranean-style planning but also includes some buildings of contemporary architecture and also some large squares. From the West to East, four major sub-neighbourhoods (SN) could be identified according to homogeneity and packing building density SN1 to SN4. SN1 includes some larger open spaces/parking lots so that it has an overall lower packing density and it is less homogeneous. SN2 is homogeneous over relatively large distances in neighbourhoods units. SN3 has some broader avenues and squares so that it has a lower packing density. SN4 has a very large packing density being also relatively uniform.

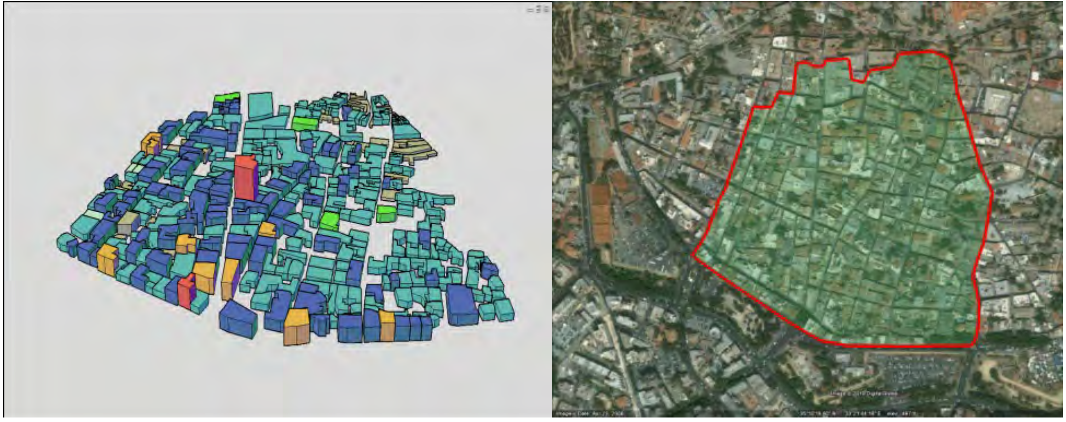


Fig.1. Investigated Site

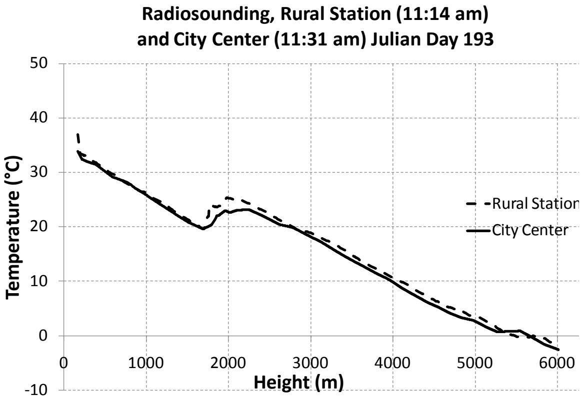
2.3. Intensive observation period

During the intensive observation period, measurements in neighbourhood, micro- and meso-, scale were performed. Regarding the meso-scale, an upper air sounding system was employed. The sounding system provided the profile of the air pressure, temperature and humidity as well as of the wind speed and direction from ground level up to 2 km altitude. Sets of the measured data were sent down to a receiving station (ground station) as the radiosonde was carried aloft by a balloon. The characteristics of the micro-scale were determined by means of aerial thermography and a weather station consisting of a hypersonic anemometer and instrumentation for temperature and humidity measurements. InfraRed thermal and visual images were captured via a high-resolution (640x480) FLIR P640 IR-camera from a helicopter at approximately 500 m above the ground. The aerial thermography measurements were performed along a flight path of a total length of 7 (km) traversing from the eastern rural area, over the urban area of the town centre and up to the western rural area. The measurement schedule was based on the time lag of the building materials with respect to the sunrise calendar of the location and the solar exposure of the materials. For the meteorological data, stations with temperature and humidity sensors were installed close to the sonic anemometers. Surface temperature and moisture measurements, as well as measurements of the ambient temperature, humidity and wind speed and direction were performed. Surface temperatures were determined by means of building IR thermography, as well as with the use of thermocouples and a FLUKE 62 Mini IR thermometer with an accuracy of +/- 0.1 °C. For the measurement of the buildings moisture an EXTECH moisture meter (model MO250) with an accuracy of +/-0.1% was employed. IR thermal images of surface temperature were captured with a FLIR T335 camera at specific locations within the city. The thermal images of the building façades were acquired over the space of an hour, every two hours during the time period from 10th to 12th of July 2010 at 3 different locations. At each location, 4 thermocouples were used (one at ground level and 3 at heights of 40, 120 and 200cm from ground respectively).

3. Results

3.1. Meso-scale measurements

In Fig.2a, the measurement of the temperature in the meso-scale above the city centre is provided. According to these results, the surface is very hot and therefore super adiabatic gradient is observed in the first 300m above ground. This is, in fact, the surface layer in terms of temperature. Above 300m, and up to 2000m a well-mixed (convective) layer is formed. In order to clarify the observed temperatures, the schematics of the boundary layer over an urban area is also provided (Fig.2b). The upper zone represents the urban internal boundary layers where advection processes are important. The regime below shows the inertial layers that are in equilibrium with the underlying surface and where Monin-Obukhov scaling applies. The lower region is the roughness layer that is highly inhomogeneous both in its vertical and horizontal structure. Finally the region between the inertial layer and the roughness layer represents adjustment between neighbourhoods with large accelerations and shear in the flow near the top of the canopy [7]. The same clear top of the convective boundary layer was also observed also in the relative humidity profiles and thus the entrainment zone was very shallow. The air mass above the convective layer was dryer and the wind direction was found to change substantially.



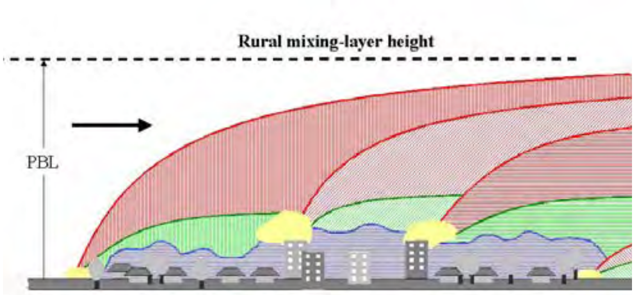


Fig.2a. Radio-sounding temperature measurement above city centre

Fig.2b. Boundary layer over an urban area

3.2. Micro-scale measurements

In Fig.3 the ultrasonic anemometer measurements of the wind speed and direction, over the intensive observation period at Ledras Street on the rooftop level are provided. The analysis of the sonic data shows clear difference in the regime of wind during the day and the night. The sonic on the roof shows weak easterly wind every night (24 – 6) and much stronger westerly wind during the day (9-18). Therefore, two different regimes can be simulated, easterly wind of 2 m/s and westerly of 5 m/s. The transition periods are rather short around 9 in the morning and 21 in the evening. From the time series of wind direction we can note that during the intensive observation period (Julian Day 190-193) the flow is slightly disturbed, and is predominantly easterly, also during the day. The friction velocity measured by the sonic at the roof is much higher than the value (u*=0.08u) suggested by similarity theory. The mean value for the 2 weeks of measurements is u*=0.14u. This is a value typical for urban areas. The wind direction within the street canyon is strongly modified by the buildings, but the two regimes (day and night) are distinguished as well. The wind speed is between 0.5 and 7 m/s.

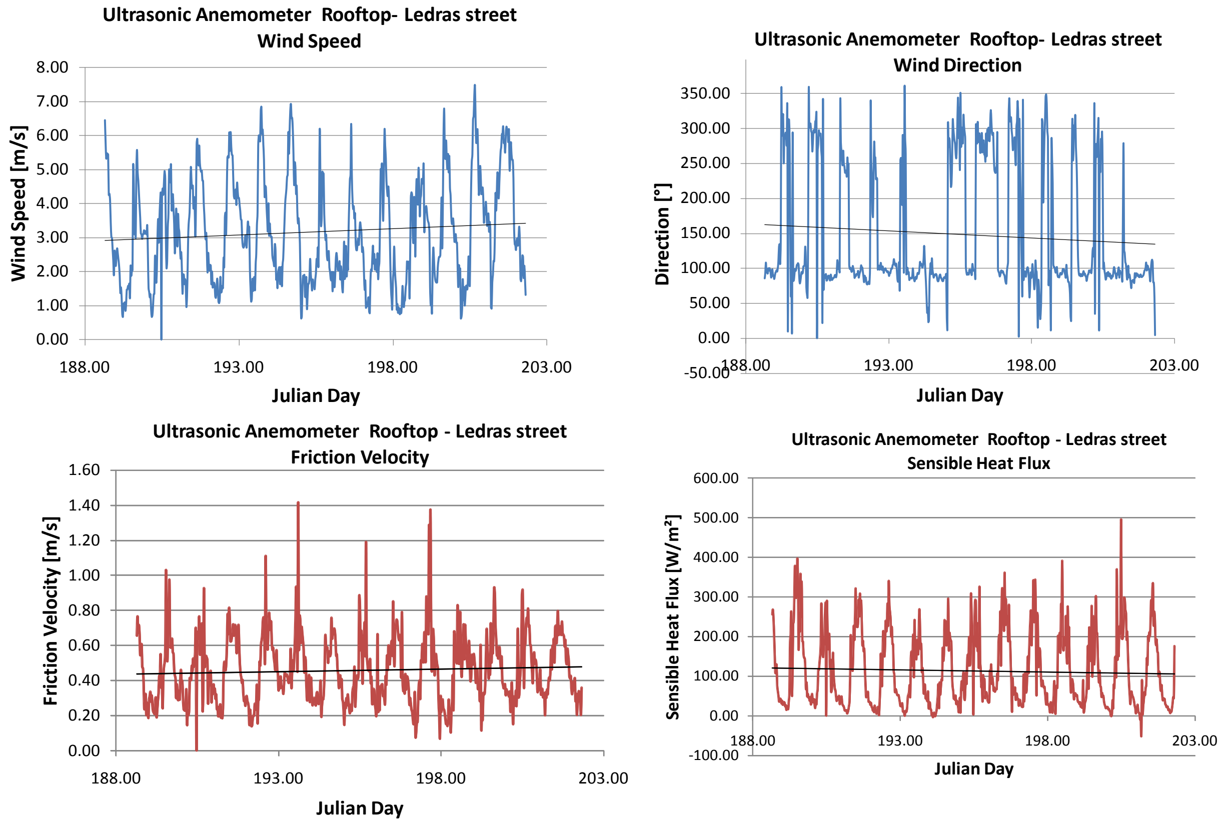


Fig.3. Ultrasonic Anemometer Measurements, Ledras Street, Rooftop Level

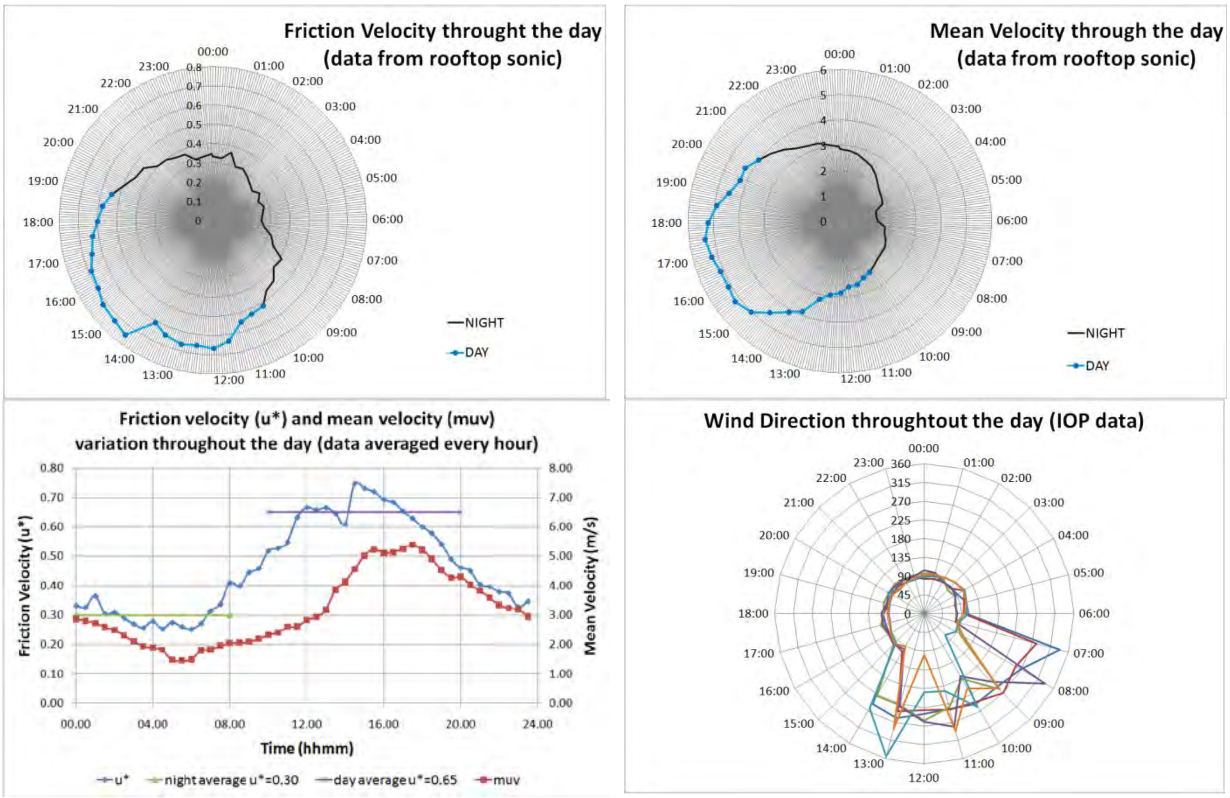


Fig.3. Ultrasonic Anemometer Measurements, Ledras Street, Rooftop Level

Aerial Thermography was also performed in order to determine the intensity of the heat radiation emmited by the built environment in the investigated field. For this purpose, a statistical analysis of the temperature intensity was performed by means of the SPSS software. The temperature distribution was compared for several city environment providing some useful conclusions regarding the importance of thermal radiation resulting from the applied building materials.

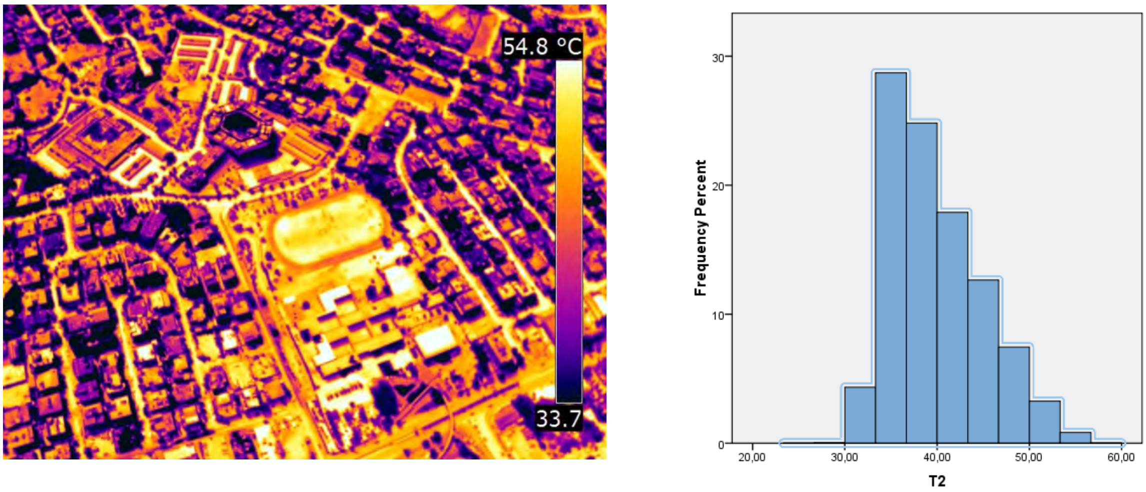


Fig.4. Aerial thermography and statistical analysis of temperature distribution

3.3. Neighbourhood scale

The Urban Heat Island Intensity (UHII) was also identified by means of data comparison from the weather station in the investigated site and from a rural weather station 5km outsite the city. According to these measurement UHII was found equal to 4 °C, especially during the midday (see Fig. 5).

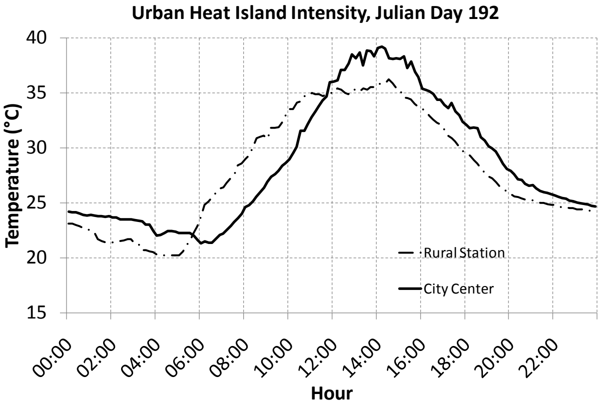


Fig.5. Urban Heat Island Intensity.

The impact of the building materials on the intensity of the urban heat island intensity was approached by means of measurements of surface temperature of building materials at the field site. Fig.6 and 7 presents the temperature profile during the IOP. In the first case the ambient temperature was measured at the rooftop of the building, whereas in the latter case it was measured next to the building element, and was, as expected affected by the environment radiation. The measurement in Fig.6 was performed on a wall constructed with forced cement, and the measurement in Fig.7 on a stone wall. The thermal emissivity of both materials is almost equal (around 0.85), whereas in the latter case, the heat capacity of stone wall is increased, compared to the heat capacity of forced cement. Therefore, although the temperature peaks were observed more or less to be equal, the duration of the peaks was greater in the case of stone wall. Another important outcome of this measurement was that the contribution of thermal radiation as well as of the anthropogenic emissions in the street canyons led to an important temperature increase, which was observed throughout the day.

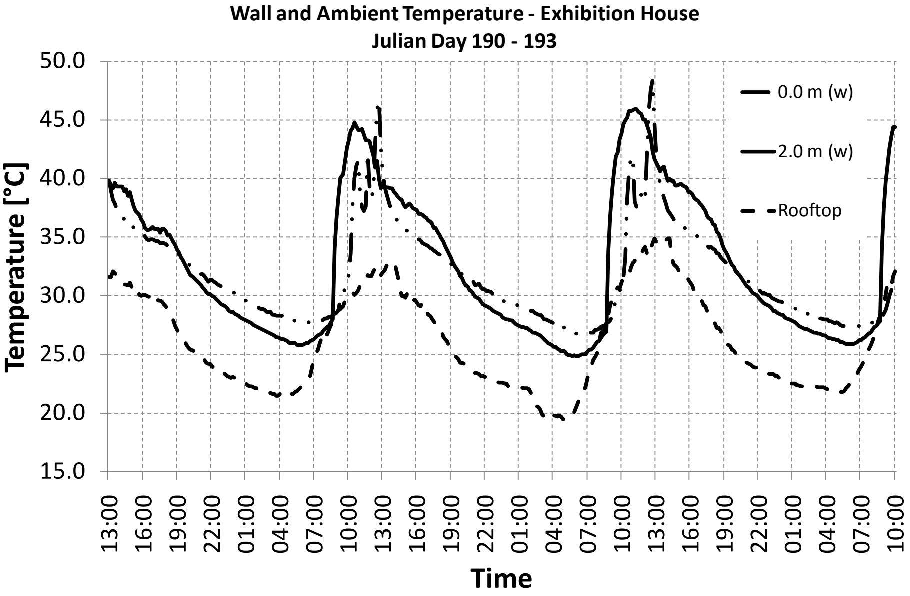


Fig.6. Wall temperature Measurement

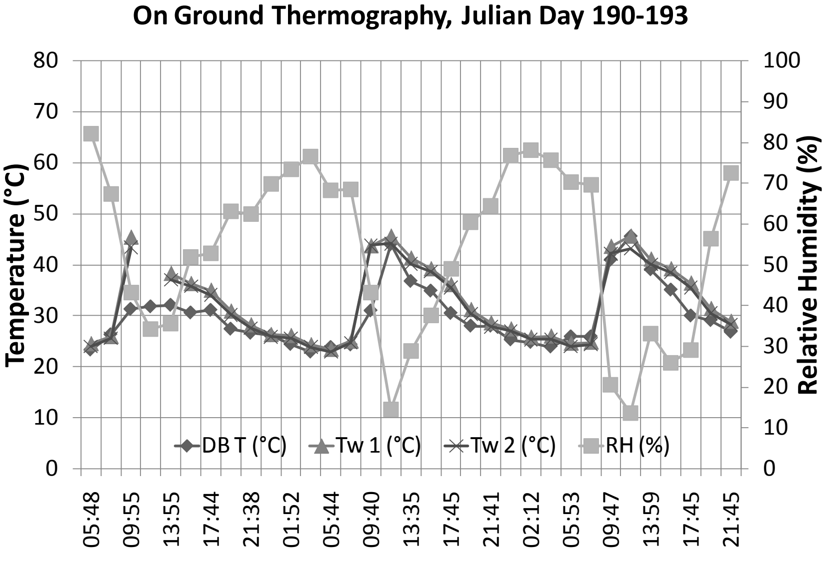


Fig.7. Wall temperature Measurement – on ground Thermography

4. Conclusions and future work

A series of simultaneous measurements of urban meteorology and the associated thermal response of buildings has been conducted in Nicosia, reflecting a typical Mediterranean setting for climate and urban architecture. Some preliminary observations show a consistent temperature difference in the ambient air between the urban and rural areas of about 2K with an approximate temperature difference for the thermal response of the buildings in their corresponding peaks and lows of 5 to 8 K (wall surface temperature). Simultaneous diurnal measurements of the moisture of the buildings show also a direct correlation with the corresponding wall surface temperatures. Further post-processing and analysis are in progress and in addition complementary methods will be employed; therefore, the field measurement campaign will be followed by detailed experimental and numerical studies. The investigated city blocks will be scaled down and applied in a wind tunnel, where ventilation and heat efficiency effects will be investigated using Laser Doppler Anemometry (LDA) and Particle Image Velocimetry (PIV). In order to calibrate the CFD modelling the pressure on the ground around the buildings will be measured in 400 points. Thus, the experimental results, as well as the results of the field measurement will be used in order to optimize the adopted models used to performed numerical simulations by means of Reynolds-Average Navier-Stokes (RANS) modelling. The experimental feedback will enable also the performance of further investigations concerning radiation effects from building surfaces assuming unsteady state conditions.

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