The Role of Courtyards in Relation to Air Temperature of Urban Dwellings in Athens

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ABSTRACT: The geometry of an urban area, the choice of the building materials and the surface properties of the dwellings, significantly affect its micro-climate. The city of Athens is mainly composed of narrow streets and large blocks, which raises the already high temperatures, due to the warm macro-climate. The heatwaves of the 1990's increased the annual purchase of air-conditioning systems in Greece by eight times, with most systems having been installed in Athens. This work examines the advantages and disadvantages of open space in Athens, in the form of streets and courtyards, the latter being the uncovered central spaces inside a block of buildings. The investigation is based on urban morphology and air temperature analyses. For the morphology analysis, two different case study sites are considered; the clusters of Amerikis and Omonias. For the air temperature analysis both in-situ temperature measurements as well as the Cluster Thermal Time Constant (CTTC) prediction model are used. The aim of this study is to identify the benefits of courtyards, which can be exploited so as to offer natural ventilation and lead to reduction of cooling consumption.

Keywords: air temperature, urban geometry, CTTC prediction model, urban block, courtyard, street, Athens

1. INTRODUCTION

Urban and rural areas differ significantly in their microclimate. These climatic differences are linked to urban geometry, which influences the absorption of a greater quantity of available incoming solar radiation and outgoing infrared radiation, as well as surface material properties [1, 2]. As the urban densities continuously increase, urban microclimate tends to deteriorate. Consequently, the cities suffer from important temperature rise, which is best observed at night, when atmospheric mixing and conditions are stable at minimum. This air temperature rise causes higher electricity consumption for cooling of buildings [3]. Probably, this is beneficial for cold climates but in hot climates it may cause an increase in energy demand for air conditioning, especially because people easily accept the use of non-passive comfort methods. For example, the heat waves of the 1990s have caused an eight times increase in the annual purchase for air- conditioning systems in Greece with most of them having been installed in Athens [4].

The analysis of urban geometry in cities, such as Athens, with small blocks and a large number of apartment blocks that cover most of the ground, except the courtyard area, seems to be essential. This paper examines the advantages and disadvantages of open space in the city centre of Athens investigating the streets and courtyards with a view of establishing how urban morphology affects the air temperature and whether the benefits of courtyards could be used to improve the street side of the building.

This research consists of four parts. The first part aims to familiarise the reader with the urban form and the climatic characteristics of Athens. The second part embodies the urban morphology analysis of two selected areas, Amerikis and Omonias. The third part includes the air temperature analysis comparing the in-situ temperature measurements with the Cluster Thermal Time Constant (CTTC) prediction model [5] results. The last part concludes the investigation giving a broader overview of the implications of the results.

2. URBAN FORM AND CLIMATE OF ATHENS

2.1 Urban form

Until the 19th century, Athens urban layout was the result of its geographical settings. It was surrounded by forests and was protected by a range of mountains and hills in a small distance from the sea. The city was limited around the old town of Plaka. Today, this area occupies part of the city centre.

However, since 1920, the urban structure has been drastically altered. The high activity of building construction, which escalated in the 1960s and 1970s, caused both the replacement of the old family houses by small apartment blocks inside the old city and the increase of new buildings on the periphery of Athens [6]. This intensive building boom was caused due to strong migration movement of people into the capital and was arranged not by the state but by private developers.

The urgent need for economic residences resulted in the formation of a dense urban environment with lack of vegetation; the green areas only represent 10.3% of the total city area [7]. Urban fabric is quite typical with small blocks and narrow streets. Eight-storey apartment blocks and two-storey neo-classical houses cover most of the block, approximately 70%, except a back-yard at the core of each block, known as a courtyard (Fig. 1). The courtyard, a result of regulations due to the high building density, is an irregularly shaped space, usually without plants and trees, designed mainly for daylight and ventilation to the back rooms. There are dwellings looking only to courtyard or street side, but the majority of flats are from side to side. The apartment size ranges from 30 to 90 m^2, while the average room size varies from 15 to 20 m^2 [8]. A typical design characteristic of the block of flats in the city centre is penthouses, i.e., apartments with a terrace on the roof of the buildings.

Figure 1: Typical courtyards in Athens.

The usual structure consists of concrete frame and solid brick partitions and light-coloured plaster covering most of the surfaces. The windows are usually single glazed on wooden frames with shutters. There are a few thermally insulated structures, mainly because they were built before the energy crisis and the subsequent regulations. In addition, sound insulation is minimal due to the thin internal walls. Each building has its own oil-fired central heating system, whereas in some cases electric radiators are common.

2.2 Climate

Athens is located in central Greece with latitude and longitude 38.04^o and -23.38^o respectively. The climate is typically Mediterranean; it is moderate with sunny, dry and hot summers, and mild and damp winters.

However, the high rates of anthropogenic release, traffic load, urban density layout and large concentration of pollutants have altered dramatically the climate of Athens. According to the results of a large-scale experiment undertaken in Athens during the summer of 1996 (Santamouris et al. 2001) [3], the maximum temperature difference between urban and reference stations was up to 14 ^oC, with a mean value of 7-8 ^oC depending on the urban layout and traffic load of each study area. In particular, during daytime, the city centre is about 7-8 ^oC warmer than the surrounding area, while at night-time is about 3 ^oC warmer.

3. URBAN MORPHOLOGY

3.1 Selection criteria of case study

To establish the influence of geometry on the climate of Athens, two case study sites of dissimilar character were carefully selected (with different building height, street width, courtyard size and sky view angle); the areas of Amerikis and Omonias. The choice of more than one area is necessary in order to determine the relationship between urban structure and air temperature, and between the street side and the courtyard side.

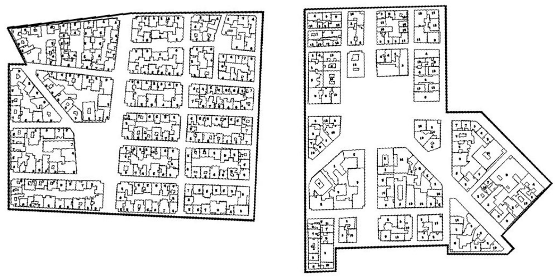

Figure 2: Amerikis and Omonias sites.

Amerikis site is a middle class residential area of 116,213m^2, which is located around Amerikis Square on the north-east of the city centre (Fig. 2). The direction of the streets is east-west and north-south. The most common shape of the Amerikis urban block is rectangular with average size 99mx42m. The buildings are six storeys high with retail and offices on the ground floors.

Omonias site, an area of 116,692m^2, is situated closer to the city centre around Omonias Square, one of the reference points in Greece (Fig. 2). The direction of the streets is north-east and east. The typical urban block shape is rectangular with 65mx45m average dimensions. The buildings are up to eleven storeys but are eight storeys in average. The lower levels are occupied by shops and offices, while the upper levels host either offices or apartments.

3.2 Geometry analysis

The relationship between building height and street is considered as the main contributor of the heat island effect in the cities [9]. The two selected sites represent two different geometry urban canyons characterised by the building height to street width ratios (H/W). The cluster with the higher ratio is Omonias. Omonias with eight-storey buildings, large streets of 14.12m (W_S) and small courtyards of 9.05m (W_C) width has a street H/W_S ratio of 2.33 and a courtyard H/W_C ratio of 3.95. Amerikis site with average six-storey buildings and larger courtyards than streets has a street H/W_S ratio of 2.04 and a courtyard H/W_C ratio of 1.67 (Table 1). The average building height to street width ratio of the two areas is 2.81. It is obvious that Athens is a typical city of high building density.

In Athens, streets and courtyards have similar widths; the street width ranges from 4.5 to 25.5m, while the courtyard width ranges from 3.5 to 19.5m. It is also observed that the closer to the city centre an area is, the larger the street widths and the smaller the courtyard widths are. For example, in Omonias area, the average courtyard width is 9.05m and the street width 14.12m, while in Amerikis, the average courtyard width is 12.53m and the street width 10.27m.

Table 1: Calculation of *H/W* ratios.

	Amerikis	Omonias
Average Building Height (*H*)	20.73	27.56
Average Building Floors	6	8
Average Courtyard Width (*Wc*)	12.53	9.05
Average *H/Wc*	1.67	3.95
Average Street Width (*Ws*)	10.27	14.12
Average *H/Ws*	2.04	2.33

In spite of the similar street and courtyard width, the sky view angles are different (Fig. 3). This is due to the penthouses formed only on the last floors of the street side. The average sky view angle of the streets is 41.4^o; while that of the courtyards is 25.9^o. The biggest difference is noticed in Omonias case having 43.5^o on the street and 18.6^o on the courtyard side; a difference of 25^o approximately. This diversity of sky view angles determines the different solar radiation received, and consequently the different temperature values.

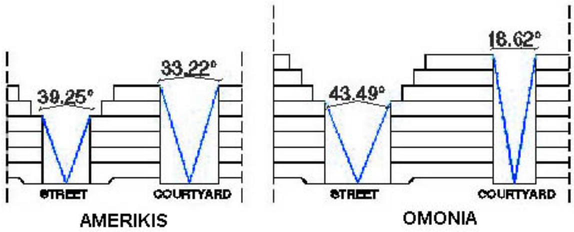

Figure 3: View angles at Amerikis and Omonias.

Direct solar radiation does not reach into the ground level of Athens' buildings before March (Fig. 4). Actually, March is the end of the heating season in Greece. No more than two or three floors are in sun view throughout the winter. The sun penetration depends on the direction of the streets, the width or length of the courtyard and the height of the surrounding buildings. When the long axis of the courtyards is pointing east-west, the solar access to the façades of the courtyards is identical to the façades of the streets, meaning that direct solar radiation does not touch the ground. On the contrary, when the axis of the courtyards is pointing north-south, the sun does penetrate the first floors in the winter period for just a couple of hours at noon on account of the obstructions by buildings on the east and west.

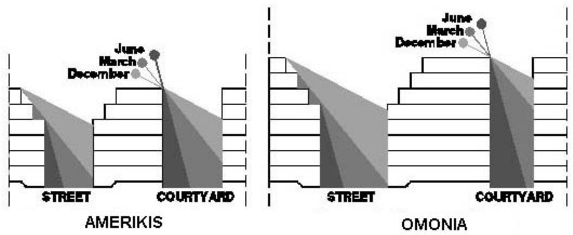

Figure 4: Solar access at Amerikis and Omonias.

The sky view factor (*SVF*) is a measure of solid angle of view of the sky from an urban space [10]. It determines the radiant heat exchange between the city and the sky. The *SVF* takes values from 0 to 1. When *SVF* is 0, the view of the sky is totally obstructed. When *SVF* is 1, there is an unobstructed view of the sky. The mapping of the sky view factors of these case study sites are presented in figure 5 where lighter shades of grey correspond to higher sky view factors [11]. The average sky view factor can be calculated by using the equation. The *SVF* values for each site are shown in Table 2.

$$SVF = [\ 400\ L \cdot W / \pi(L^2 + H^2)\ ]\ \%, \qquad (1)$$

where L is the length of the courtyard/street, W the width of the courtyard/street and H the height of the building.

Table 2: Average sky view factors.

	Amerikis	Omonias
Sky View Factor - Courtyard	0.25	0.17
Sky View Factor - Street	0.20	0.27

The area of Amerikis has a higher *SVF* compared to Omonias' one. The high value of Amerikis implies that much of the short wave radiation reaches the ground during daytime contrary to Omonias value, where the temperature is strongly influenced by the urban structure. Therefore, in the deep courtyards of Omonias site, the summer daytime temperatures are probably lower than ambient having a high loss of net long-wave radiation to the sky and hence a high air-cooling mechanism.

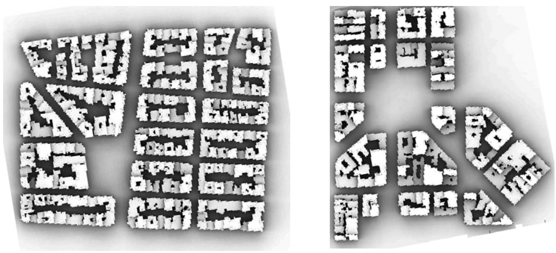

Figure 5: Sky view factors at Amerikis and Omonias.

4. AIR TEMPERATURE

4.1 Experimental set up

Field measurements were carried out between 21 and 23 May 2004 at two urban canyons of Amerikis and Omonias. Indoor and outdoor air temperatures were recorded in one typical building in each selected area in rooms looking either to the street or courtyard. Data were sampled using temperature sensors; tiny tags, which were completely sheltered from direct solar radiation. Indicative temperature measurements were recorded on lower and upper levels of each building. Although May temperatures were recorded, a reference to midsummer temperatures is possible assuming a linear relation between the spring and the midsummer temperatures. The following temperature analysis and the prediction of temperature rise model are based on May data.

The May of 2004 in Athens was a relatively dry month with higher precipitation than usual. Table 3 demonstrates the average temperatures between 21 and 23 May from selected weather stations in the wide area of Athens including Kifissia and Spata. Kifissia is a northern suburb of Athens, while Spata is an area out of the city, where the new international airport is located.

Table 3: Minimum, maximum and average air temperature of two reference weather stations in Athens from 21 to 23 May. [12, 13]

Weather Stations	Average T_{min} [°C]	Average T_{max} [°C]	Average T [°C]
Kifissia	13.6	24.9	19.3
Spata	12.9	22.1	17.5

The comparison of temperature figures of table 3 shows that the average daily temperature varies from 17.6 °C at Spata to 19.3 °C at Kifissia: a difference of 1.8°C.

4.2 Measured Temperature

Figures 6 and 7 illustrate the outdoor and indoor air temperature data collected at the two study sites. On the one hand, the outdoor temperature measured at Amerikis on the street side fluctuates from 18.8 °C to 31.3 °C with an average of 24.8 °C, while on the courtyard side fluctuates from 17.8 °C to 25.4 °C with an average 21.1°C. On the other hand, at Omonias on the street side varies between 19.5 °C and 32.2 °C with 26.1 °C mean, while on the courtyard side between 17.3 °C and 24.9 °C with 21.0 °C mean.

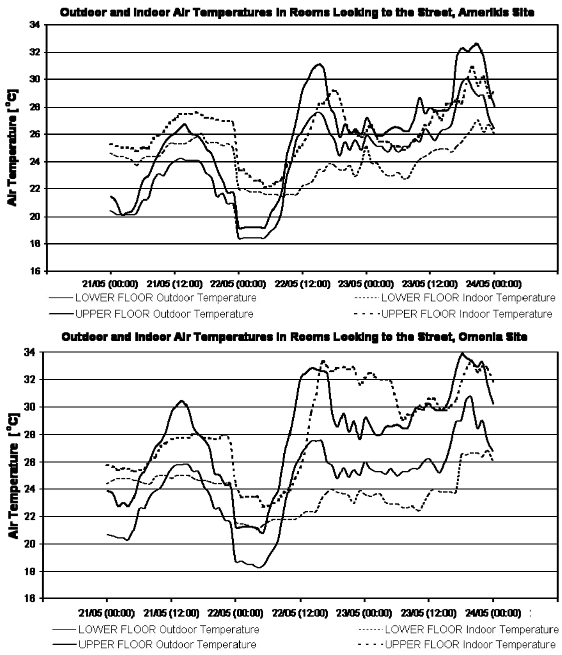

Figure 6: Outdoor and indoor air temperature measured in Amerikis and Omonias area in rooms looking to the street on lower and upper floors of each selected building.

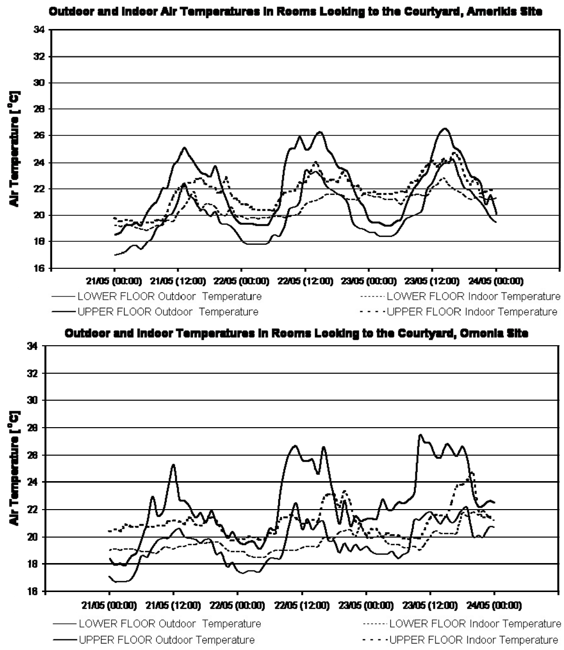

Figure 7: Outdoor and indoor air temperature measured in Amerikis and Omonias area in rooms looking to the courtyard on lower and upper floors of each selected building.

A comparison between the average temperature of the selected meteorological stations and the average temperature measured at Amerikis and Omonias shows that the temperature difference is significant. The mean temperature for the two urban sites, the suburban weather station of Kifissia, and the airport weather station of Spata over the three days were 23.3 °C, 19.3 °C and 17.5 °C respectively. This is due to the urban geometry, traffic load, anthropogenic heat and overall balance of each area. This average temperature difference is particularly evident between Omonias and Spata, which during the daytime differs up to 10.1 °C, with a mean difference of 8.6 °C.

Comparing the two case study areas (Table 4), it is concluded that on the street side the mean temperature at Omonias (26.1 °C) is higher than Amerikis (24.8°C), while on the courtyard side at Omonias is slightly lower (21.0°C) compared to Amerikis one (21.1°C).

Table 4: Average outdoor measured temperature.

	Amerikis	Omonias
Average Outdoor Temperature of Street Side [°C]	24.8	26.1
Average Outdoor Temperature of Courtyard Side [°C]	21.1	21.0

It is obvious that the rooms looking to the courtyards are cooler than those looking to the streets by 4.4°C on average (Table 4), which is essential during the summer time. Omonias area is an interesting case; the mean air temperature of a courtyard room is particularly low (21.0 °C) in contrast to the mean temperatures of the street room (26.1 ^{o}C): a difference of 5.1 ^{o}C.

Furthermore, on both sides, the outdoor temperatures adjacent to ground levels are lower than the equivalent of upper levels, as is shown in table 5. More specifically, at both case study sites, the mean measured temperature on lower floors is 22.0 ^{o}C, while on the upper floors it is 24.6 ^{o}C. It is worth mentioning that the temperature difference between lower and upper levels in Omonias area is greater than that one of Amerikis area ($\Delta T_{AMERIKIS}$ = 1.9 ^{o}C, $\Delta T_{OMONIAS}$ = 3.3 ^{o}C).

Table 5: Average outdoor measured temperature on lower and upper floors.

	Amerikis	Omonias
Average Air Temperature on Lower Floors [^{o}C]	22.0	21.9
Average Air Temperature on Upper Floors [^{o}C]	23.9	25.2

The temperature difference (ΔT) between the lower and top floors in relation to street and courtyard sides is also interesting. The next table (6) demonstrates the average temperature range for both sides. It is obvious that the temperature variation of the street rooms ($\Delta T_{AMERIKIS}$ = 1.7 ^{o}C, $\Delta T_{OMONIAS}$ = 3.5^{o}C) is higher than that of the courtyard rooms ($\Delta T_{AMERIKIS}$ = 1.5 ^{o}C, $\Delta T_{OMONIAS}$ = 3.0 ^{o}C). Hence, it is implied that the outdoor temperatures of the courtyards are "controlled", while the equivalent temperatures of the streets present more fluctuations.

Table 6: Temperature difference in relation to street and courtyard sides.

Temperature Range (ΔT) in [^{o}C]	Amerikis	Omonias
Street Side	1.7	3.5
Courtyard Side	1.5	3.0

The average indoor air temperature ranges from 20.3 ^{o}C to 26.1 ^{o}C as described in table 7. Generally, the indoor temperature follows the outdoor changes. The courtyard side (20.3 ^{o}C – 21.3 ^{o}C) is cooler compared to the street side (25.1 ^{o}C – 26.1^{o}C). The average difference of approximately 4 ^{o}C seems to be significant for the summer season.

Table 7: Average indoor measured temperature.

	Amerikis	Omonias
Average Indoor Temperature of Street Side [^{o}C]	25.1	26.1
Average Indoor Temperature of Courtyard Side [^{o}C]	21.3	20.3

4.3 Prediction Temperature Model

The complexity of the causes of the urban climate makes prediction modeling difficult. In this research, the CTTC model is used to validate the experimental temperature measurements. This model, originally developed by Swaid and Hoffman (1990) [5], has been used in a number of studies to predict urban air temperature variations [14]. For the reader's convenience, only a summary of the main features of the analytical CTTC model is presented.

The basic CTTC model considers the urban air temperature as a combination of the contributions of the prevailing regional background weather conditions, the solar radiation absorption on the surfaces of the urban canopy layer and the cooling effect of the net going long-wave radiation from the urban surfaces. The equation for the rise in air temperature from sunrise (minimum temperature) to any hour (t) of the day is described below:

$$\Delta T_{(t)} = \{ \Delta T_{\mathrm{SOLAR},(t)} - \Delta T_{\mathrm{SOLAR},(t,\ min)} \} - \{ \Delta T_{\mathrm{NLWR},(t)} - \Delta T_{\mathrm{NLWR},(t,\ min)} \} + \Delta T_{\mathrm{AHR},(t)} \quad (2)$$

where $\Delta T_{\mathrm{SOLAR},(t)}$ is the contribution of direct solar radiation to air temperature variations (K), $\Delta T_{\mathrm{SOLAR},(t,min)}$ is the contribution of direct solar radiation to air temperature variations at sunrise (K), $\Delta T_{\mathrm{NLWR},(t)}$ is the contribution of net outgoing long wave radiation flux to air cooling, $\Delta T_{\mathrm{NLWR},(t,min)}$ is the contribution of net long wave radiation flux to air cooling at sunrise (K) and $\Delta T_{\mathrm{AHR},(t)}$ is the contribution of anthropogenic heat release to air temperature (K). Detailed expressions for the afore-mentioned contributions can be found in earlier articles of Swaid and Hoffman [5].

The average values of $\Delta T_{\mathrm{SOLAR},(t)}$ calculated from the set of measurements, from sunrise to noon, were:

$\Delta T_{\mathrm{SOLAR},(t)}$ = 2.45 K (Amerikis, street side)
$\Delta T_{\mathrm{SOLAR},(t)}$ = 2.44 K (Amerikis, courtyard side)
$\Delta T_{\mathrm{SOLAR},(t)}$ = 2.86 K (Omonias, street side)
$\Delta T_{\mathrm{SOLAR},(t)}$ = 1.78 K (Omonias, courtyard side)

The contribution of the net long wave radiation contribution due to air-cooling ($\Delta T_{\mathrm{NLWR},(t)}$) in the two selected areas with ratios (*H/W*) 1.67, 2.04, 3.95 and 2.33 and *SVF* 0.20, 0.25, 0.17 and 0.27 respectively as previously explained was very small, less than 0.01 K, for this reason it is not considered in (2).

The contribution of the anthropogenic heat release to air temperature $\Delta T_{\mathrm{AHR},(t)}$ was estimated 1.5 K. Oke [15] reports that the mean annual magnitude of the heat source for typical temperate-latitude cities lies in the range of 15 to 50 W/m^2 for a horizontal unit area in the city. In the CTTC model, this translates to 1 to 3 K in the UCL air model [14]. However, recent studies in streets with heavy traffic in Israel indicate a rise in air temperature of at most 1.5 K [14]. Athens is a city with heavy traffic, hence a value of 1.5 K for $\Delta T_{\mathrm{AHR},(t)}$ is a safe assumption to make.

Thus, $\Delta T_{(t)}$ for Amerikis and Omonias from sunrise to noon calculated:

$\Delta T_{(t)}$ = 3.95 K (Amerikis, street side)
$\Delta T_{(t)}$ = 3.94 K (Amerikis, courtyard side)
$\Delta T_{(t)}$ = 4.36 K (Omonias, street side)
$\Delta T_{(t)}$ = 3.28 K (Omonias, courtyard side)

The above figures are close to the experimental temperature measurements performed between 21 and 23 May 2004, which are:

ΔT= 4.9 K (Amerikis, street side)
ΔT= 4.8 K (Amerikis, courtyard side)
ΔT= 4.8 K (Omonias, street side)
ΔT= 3.0 K (Omonias, courtyard side)

and simultaneously indicate that the urban fabric plays an important role in microclimate of the open space. This difference between the calculated and measured temperatures could be attributed to the low contribution of the anthropogenic heat release to air temperature of 1.5 K, which in fact in Athens seems to be higher than Israel due to heavier traffic.

4.3 Evaluation of air temperature analysis

A comparison between the ambient temperature and the average temperature measured in the two selected sites confirms that the open field temperatures are lower than the urban ones. Particularly, the average temperature of the airport weather stations is 17.5 °C, while that of the two case studies is 23.3 °C. In spite of the small number of spot measurements, the observed temperature difference of 5.8 °C is lower to the mean temperature difference of 7-8 °C recorded by Santamouris [3], but justifiable since the measurements took place in spring time. Moreover, it is concluded that the greater temperature difference between urban and suburban areas occurs during the daytime of approximately 10.1 °C. This is the result of the high amount of solar radiation the city receives, traffic load and the anthropogenic heat release, which mostly takes place during the day and increases the urban temperatures extensively.

A comparison of temperatures of the two areas indicates that the site with higher urban canyon geometry (*H/W*) has a cooler environment. Omonias' courtyard side with 3.95 ratio presents a temperature of 21.0 °C, while Omonias' street side with 2.33 presents a higher temperature of 26.1 °C. This verifies Pearlmutter's (1998) [16] 'cool island' phenomenon about Israel's climate that the high-density sites are cooler.

In addition, courtyard temperatures are lower by 4.4 °C on average than those of the streets. This difference reaches 5.2 °C in the afternoon. Omonias is an interesting case due to a larger difference between the two sides (mean difference of 5.1 °C). It is noticeable that this variation happens on account of the different sky view angle the areas present and hence the different solar radiation received. Furthermore, the temperature measurements confirm the fact that the lower levels are cooler than the upper ones due to different solar access; the last floors receive more sun than the first ones. In fact, on the last floors there is no temperature difference between the street and the courtyard side, while on the low floors the difference is noteworthy.

When the cooling system is located in a flat that looks to the courtyard, the energy required to cool an apartment can be reduced. This energy reduction can be achieved on both sides of the buildings and is higher in the summer time.

The results of the CTTC model indicate that the geometry contributes to the microclimate determination of the open space. The different results of the two study sites not only verify the measurements, but also express the significant role of the urban formation in the climate. In addition, from the CTTC analysis results, it is clear that the contribution to the temperature rise is mainly due to the direct solar radiation, because the contribution of the net long wave radiation due to air-cooling is negligible.

5. CONCLUSION

Temperature analysis indicated that different urban geometry has an important impact on temperature rise. Lower floor facing courtyards, even not properly designed, are cooler than lower floor facing streets. Hence courtyards tend to be valuable spaces for the city of Athens, contrary to streets, which are warmer, more noisy and polluted. In terms of courtyard size, in high building density areas, narrow courtyards are more beneficial than wider courtyards.

Temperature evaluation also showed that courtyards can reduce the energy use for cooling in the buildings. The apartments of the street side could also benefit, by making use of the courtyard cool air and bringing it to the building through the courtyard apartment. This is possible on the condition that there is access from the street to the courtyard, because only then can wind flow, thus cross ventilation through the buildings is achieved.

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