A field study of urban microclimates in London

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A field study of urban microclimates in London

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ABSTRACT

This paper aims to address the characteristics of urban microclimates that affect the building energy performance and implementation of the renewable energy technologies. An experimental campaign was designed to investigate the microclimate parameters including air and surface temperature, direct and diffuse solar irradiation levels on both horizontal and vertical surfaces, wind speed and direction in a dense urban area in London. The outcomes of this research reveal that the climatic parameters are significantly influenced by the attributes of urban textures, which highlight the need for both providing the microclimatic information and using them in buildings design stages. This research provides a valuable set of microclimatic information for a dense urban area in London. According to the outcomes of this research, the feasibility study for implementation of renewable energy technologies and the thermal/energy performance assessment of buildings need to be conducted using the microclimatic information rather than the meteorological weather data mostly collected from non-urban environments.

1. Introduction

An understanding of the characteristics of the urban microclimates allows the city planners, designers, architects and developers to make informed strategic design decisions with respect to, not only the climatic impacts of their buildings, but also the effect of the resulting microclimatic variables on the performance of buildings. Particularly, the urban microclimates will affect passive and low energy designs, including natural or hybrid ventilation and the use of renewable technologies in urban areas, in terms of strategies and performance. The urban wind and solar radiation can be used for developing better design options for renewable energy technologies within urban environment. However, achievement of these solutions in high-rise and dense urban built environments is challenging. This is mainly due to the complex nature of various heat transfer mechanisms within the urban area, leading to the urban climatic parameters significantly different from those recorded and reported by official weather stations located in sub-urban environments. Hence, the knowledge of microclimatic parameters, particularly air temperature, direct and diffuse solar irradiation, wind direction and speed are of paramount importance for developing better design options for passive building design and renewable energy implementation within urban environment.

In the open literature, the studies of microclimate are addressed through numerical simulation and experiments. Many studies have devoted to the simulation of urban microclimates [1–8]. In terms of experimental studies, most of them are reported mainly in the context of air circulation and temperature distribution within urban street canyons [9–11]. In these studies, the geometric characteristics of the general urban layout are idealized as infinite parallel walls of a street canyon with emphasis on the pedestrian comfort, pollutant dispersion and natural ventilation. Santamouris et al [9] studied the thermal characteristics in a deep ($H/W = 2.5$) pedestrian canyon with a NW–SE axis, under hot weather conditions in Athens. A surface temperature difference of up to 19 °C was observed between opposite building walls. Air temperature difference near the two opposite facades varied by up to 4.5 °C due to the impact of convection heat transfer from adjacent wall surfaces. Niachou et al. [10] reported an experimental study of a typical street canyon ($H/W = 1.7$) orientated in ESE–WNW direction in Athens, again under hot weather conditions. The measured surface temperature difference across the street reached almost 30 °C and this caused overheating at lower air levels. Georgakis and Santamouris carried out detailed experiments in a deep canyon in Athens during the summer period to evaluate the potential of natural ventilation in the urban environment and to better understand the airflow and thermal phenomena in deep urban canyons on the

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climatic variables[12]. In addition, Kolokotroni et al [13] studied the urban climate in London in order to develop a model to predict the air temperature and building energy demands. The results of the developed model revealed the influence of urban microclimate conditions on building energy demands. In another study, Radhi et al [14] studied the impact of urban expansion in Bahrain on atmospheric urban heat islands using remote sensing and geographical information system (GIS). However, the experimental study of a group of buildings with the emphasis on measuring the spatial and temporal distribution of microclimatic variables around each building of the complex has not been encountered in the literature. It is therefore the focus of current research. A detailed experimental campaign was carried out in a dense urban area in London to study the urban microclimates and possible renewable energy such as wind and solar radiation for the application in passive building design in urban environment. The main objectives of this experimental investigation are

- to quantify the temporal and spatial distribution of microclimatic variables for a general building complex;
- to study the impact of the layout and orientation of buildings on these variables;
- to understand the airflow and thermal characteristics of a general urban building complex, and;
- to gather data for validating numerical simulation models of an urban microclimate.

2. Experimental setup

The experimental measurement campaign has been carried out in summer 2010 in London. The London site is displayed in Fig. 1. It is a mixture of residential buildings and the institutional buildings of London South Bank University's Southwark campus. Naturally, there is traffic through the London roads, and there is no lawn area, except trees along some roads. Four separate roads are identified to monitor microclimatic variables and the building and road surface temperatures. They are Ontario Street (3), Keyworth Street (4), Thomas Doyle Street (5) and Borough Road (6). The respective features of these streets are listed in the Table 1.

Keyworth Street links Borough Road and Ontario Street and represents a 230 m long urban canyon. While one side of Keyworth Street is a continuous row of attached buildings, including the newly built K2 building of London South Bank University, the buildings on the opposite side is detached at two locations by Thomas Doyle Street (5) and a car park/access road of the university. As is shown schematically in the Fig. 1, the K2 building has replaced low-rise buildings at the same location. The K2 building has a height-to-width ratio of 2.66, and the Keyworth Street canyon has a width of 12 m.

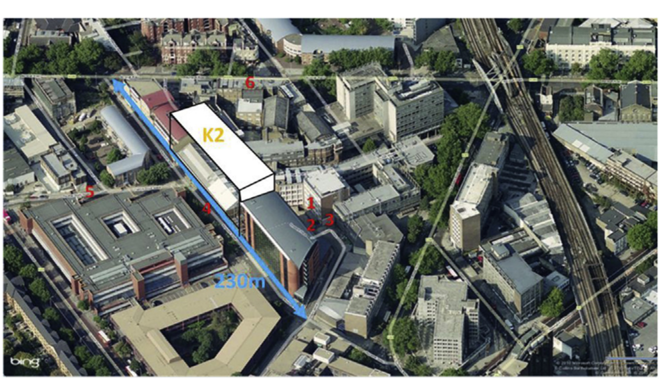

Fig. 1. Field measurement campaign site at Elephant and Castle, London.

Table 1
Street characteristics at the London site

Street	Street orientation	Traffic	Vegetation	Weather Station (WS)
Ontario Street (dead-end)	SSW to NNE	Access only	None	WS1, WS2, WS3
Keyworth Street	SE to NW	One way	Trees at one side	WS4
Thomas Doyle Street	SW to NE	One way	None (but, trees at the joining streets)	WS5
Borough Road	WSW to ENE	Main road	Trees	WS6

At the London site (Fig. 1), as is also presented as a plane view in Fig. 2, the microclimatic variables were measured at four locations, which are on Ontario Street, Keyworth Street, Thomas Doyle Street and Borough Road. These weather stations are labelled as WS3, WS4, WS5 and WS6, respectively. Table 2 shows the characteristics of these roads. The weather station 3 (WS3) was located at the dead-end of the Ontario Street, but the other weather stations (WS4–WS6) were positioned at the mid-distance of the streets. Due to the high-rise buildings at the London site, at the dead-end of the Ontario Street, in addition, two more automatic weather stations (WS1 and 2) were installed to a mobile-trailer mast, respectively, at 10 and 4 m height. Finally, the air temperature was also measured at the height of 1.8 m by the HOBO temperature sensor at each street lighting-column and the mobile mast. In addition, surface temperatures were measured at each street lighting-column location for the road/pavement and immediate building walls. Table 2 summarizes the surface measurement points (e.g., P1) at each location.

The London Measurement Campaign was carried out only for the summer season in 2010. For a period of one month, from 19 July to 16 August 2010, the climatic variables were measured at every 5 min. Also, for the first five days of the London summer campaign, from 19 July to 23 July 2010, the surface temperatures were also measured continuously at every hour. In addition, the surface temperatures of the asphalt road, pavement and building walls were measured at 16 surface locations.

2.1. Measurement parameters and instruments

At each site, the microclimatic variables of the air temperature, the wind speed and direction, the air humidity and the global solar radiation (the total value of the direct and diffused components on a horizontal surface) were measured at a height of 4 m, at several locations which were distributed comparatively within each building complex. The locations of weather stations at the London site are displayed in Fig. 2. These measurement locations were chosen in a way that the microclimates of buildings can be analysed in terms of the different layout of buildings and their orientations. The locations were also, respectively, exposed to any prevailing wind direction depending on weather conditions on a site. Around each climatic measurement point, the surface temperatures of the road and surrounding building walls were also measured.

At each measurement location, an automatic weather station – Davis Wireless Vantage Pro2, was installed to a street lighting-column (which will be referred as a "mast" from now on) at the height of 4 m. For each weather station, on a continuous basis, the climatic measurements were remotely logged to its data logger at every five minutes, which was kept indoors. The accuracy of the integrated sensor suite (ISS) of the weather station for measuring each climatic variable is 0.56 °C for air temperature, ±5% for the wind speed, ±7 degree for the wind direction, ±3% for the air humidity and ±5% for the solar radiation. Also, a second temperature sensor – HOBO Temp Data Logger, was installed at each mast for

Fig. 2. The locations of measurements at the London site.

measuring the air temperature at the height of 1.8 m. This measurement was logged locally at each mast, at 5-min intervals, again on a continuous basis. It has an accuracy of 0.47 °C at 25 °C and is enclosed inside a solar radiation shield for accurate measurements in sun.

At the London site, a K-type digital thermometer – Model WK026, was used for the surface measurements. The building wall temperature was measured at an elevation of 1.8 m. At each mast location, the relevant surface temperature measurements are grouped together for the analysis of microclimatic variables at that particular location.

3. Data analysis

3.1. Urban air temperature analysis

The measurements of the air temperatures at six weather stations for the summer season have been analysed for obtaining microclimatic information of the urban experimental site in London. Among the four streets, while the dead-end of Ontario Street (WS3) was relatively the warmest location, Borough Road (WS6) was the coolest location. Fig. 3 displays the temporal distributions of their air temperatures for the period from 2 August to 8 August 2010. The difference in the air temperature between the Borough Street (WS6) and the dead-end of Ontario Street (WS3) varies from day to day depending on the nature of the background weather conditions in the region. It reaches up to 2 °C on Thursday 5 August 2010. In terms of their urban nature, the Borough Street is a tree-lined, wide street with moderate two-way traffic. On the contrary, the dead-end of Ontario Street has no vegetation, and is totally surrounded by relatively higher buildings with no through-traffic. As a result, by being relatively less windy – being sheltered by the surrounding high-rise buildings in every direction, and also

Table 2
London surface measurement points from P1 to P16.

Street	Weather Station (WS)	Road or Pavement	Building walls
Ontario St.	WS1, WS2, WS3	P1, P4	P2, P3, P5, P6
Keyworth Street (tree)	WS4	P7	P8, P9
Thomas Doyle Street	WS5	P10	P11, P12
Borough Road	WS6	P13	P14
Keyworth Street (no tree)	HOBO only	P15	P16

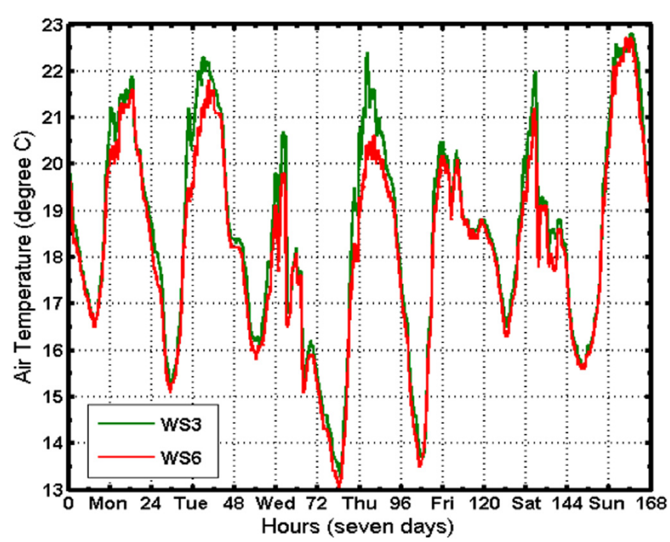

Fig. 3. Air temperature distributions at the dead-end of Ontario Street (WS3) and Borough Road (WS6).

by having relatively increased urban surface area for convection heat transfer, it allows the air at the dead-end of Ontario Street (WS3) to warm up more. It gets relatively warmer starting before the noon and lasts until late afternoon, Fig. 3. In general, following the sunrise (about 6am) the cooling of the air ends and the air temperature peaks at the mid-afternoon (about 2pm). On Wednesday and Saturday, there is an observed increase of the air temperature at night. This could be explained by the approach of relatively warm air from the surrounding area.

During the London Measurement Campaign – from 19 July to 16 August 2010, the maximum daily solar energy was measured on Wednesday 24 July, but it was not the hottest day in term of the air temperature. The daily solar energy was 440 Ly at WS3; it is equivalent of 5114 Watt-hours per square metre. In Fig. 4, for 24 July, the daily evolution of air temperatures at Keyworth Street (WS4) and Thomas Doyle Street (WS5) are plotted alongside WS3 and WS6. The air temperatures at Keyworth Street (WS4) and Thomas Doyle Street (WS5) lie between the boundaries of the WS3 and WS6, though they are closer to the air temperature at Borough Road (WS6). Between 9am and 11am, the air in Keyworth Street becomes the coolest among the four locations. This is due to its nature as an urban street canyon with a lower value of sky view factor. However, this feature also allows the air in the urban street canyon to remain relatively warmer during the night – about 0.5 °C, by making the long-wave radiative cooling of the street canyon urban surfaces towards the sky less than that of the other locations.

Finally, the variation of the air temperature with the elevation is displayed in Fig. 5, for the weather station WS1 (10 m) and WS2 (4 m). The trailer-mast was located at the dead-end of the Ontario Street, near to WS3. Between 10am and 3:30pm, the air at 4 m was warmer up to 0.5 °C than that at 10 m. This observation confirms the characteristics of the convective heating of air by the hotter urban surfaces; closer the air to the urban surfaces, warmer it is.

3.2. Urban surface temperature analysis

A total of 16 surface locations for roads, pavements and walls were measured to study the evolution of urban surface temperatures. The results for Wednesday 21 July 2010 are displayed in

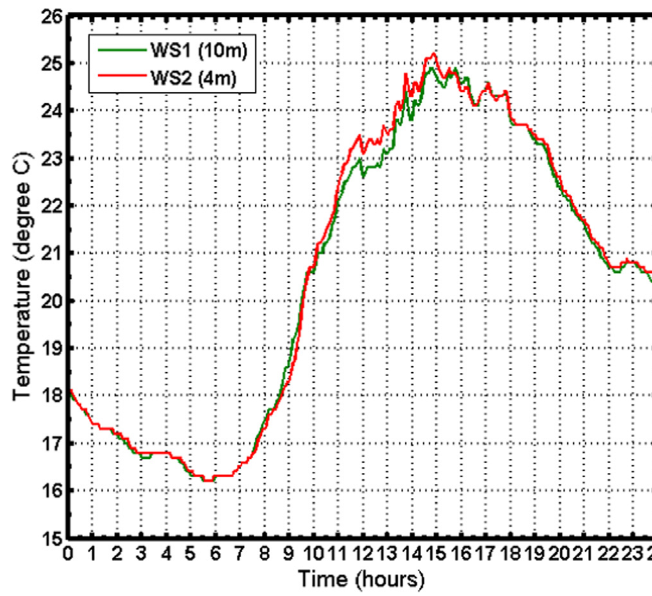

Fig. 5. Air temperature distributions at different heights of 10 m and 4 m, on 24 July 2010.

Figs. 6–8 for the dead-end of Ontario Street (Ts1–Ts6), Keyworth Street (Ts7–Ts9 and Ts15–Ts16) and Borough Road (Ts13–Ts14), respectively. For the same day, the air temperatures at the weather stations WS3, WS4 and WS6 are also plotted in Fig. 9, as these are the relevant microclimatic air temperatures for these urban streets.

3.2.1. Dead-end of Ontario Street: an access road to the back of the buildings

The road and wall surface temperatures at this location (Fig. 6) have the maximum values for the microclimate of the London experimental site. On the road, it reaches 43.5 °C (Ts1) at noon, and maintains at about 37.5 °C at the sunny part of the square (Ts4) by 3pm and becomes 30 °C by 6pm. The wall surface temperatures at the south-east facing walls (Ts3 and Ts6) get warmer first, naturally,

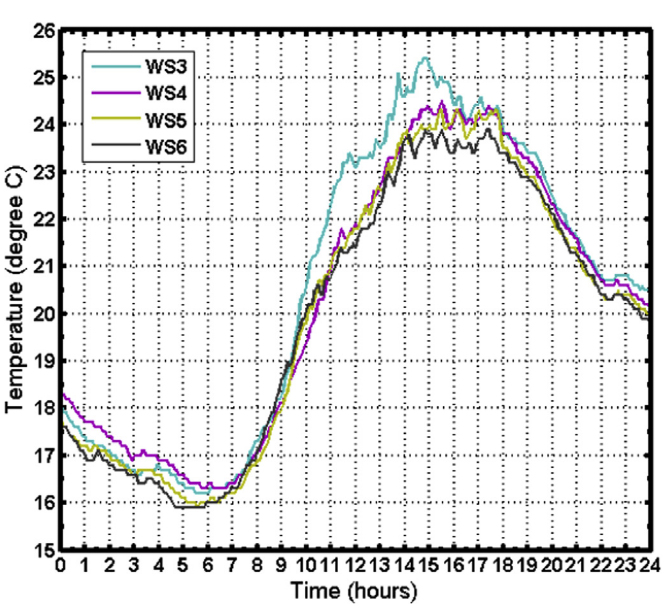

Fig. 4. Air temperature distributions at the London experimental site on 24 July 2010.

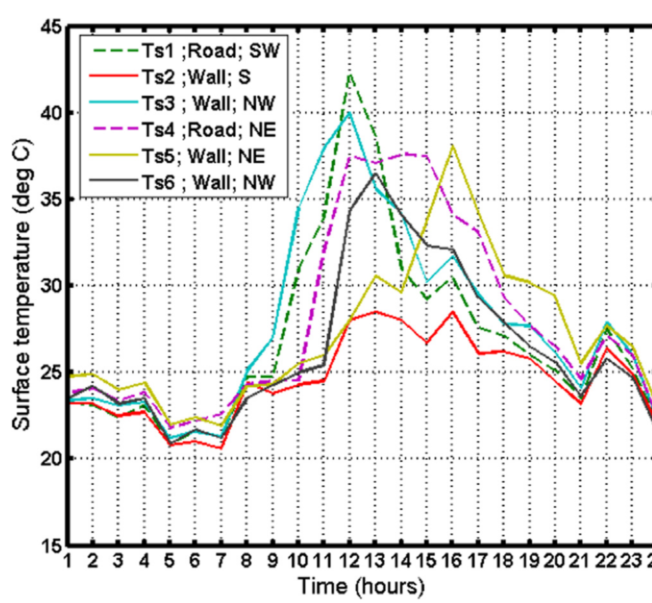

Fig. 6. Evolution of surface temperatures at the dead-end of Ontario Street (WS3), on 21 July 2010.

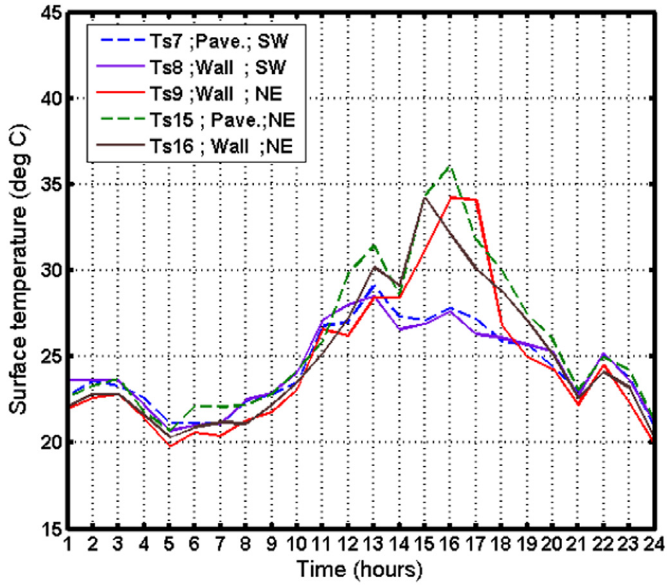

Fig. 7. Evolution of surface temperatures at the Keyworth Street (WS4), on 21 July 2010.

and the former peaks at 40 °C by noon. The south-west facing wall (Ts5) becomes the hottest surface in the afternoon, peaking at 38 °C by 4pm. The south facing wall (Ts2) becomes 28 °C at its maximum surface temperature. By the midnight, they all converge to their respective values within a close range of 21 °C to 22.5 °C.

3.2.2. Keyworth Street: an urban street canyon

When the above surface temperatures are compared with those in Fig. 7, it is observed that the surfaces of the urban street canyon are cooler than that in Ontario Street. The sunlight only hits Keyworth Street just at noon for about one hour: this exhibits itself as the peak values (about 30 °C) at 1pm (Fig. 7). After 2pm, the urban street canyon features becomes clearly apparent: while the sun-lit surfaces (Ts9, Ts15 and Ts16) are warming further up to 35 °C, the opposite side of the street (Ts7, Ts8) remains at 27.5 °C. At 9pm, they converge to about 22.5 °C (within a range of 0.7 °C). At this time, the surfaces of the dead-end of Ontario Street, Fig. 6, is about 2.5 °C warmer, and maintain this difference by the midnight, even though the air temperatures further cool down since then.

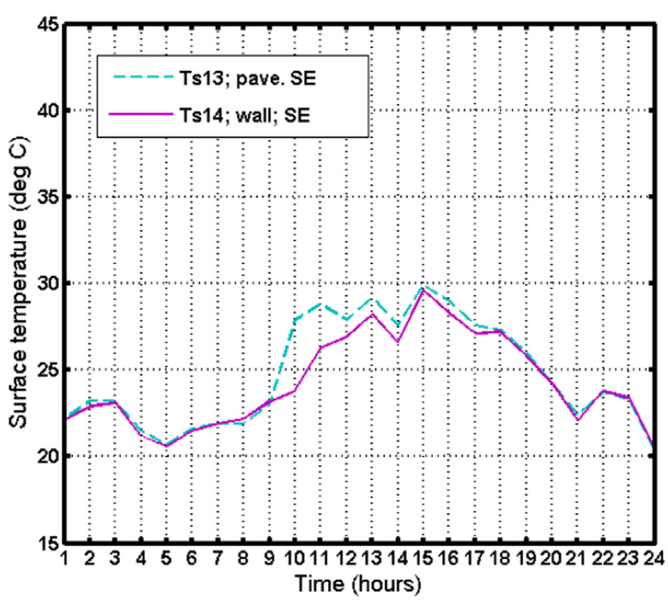

Fig. 8. Evolution of surface temperatures at the Borough Road (WS6) on 21 July 2010.

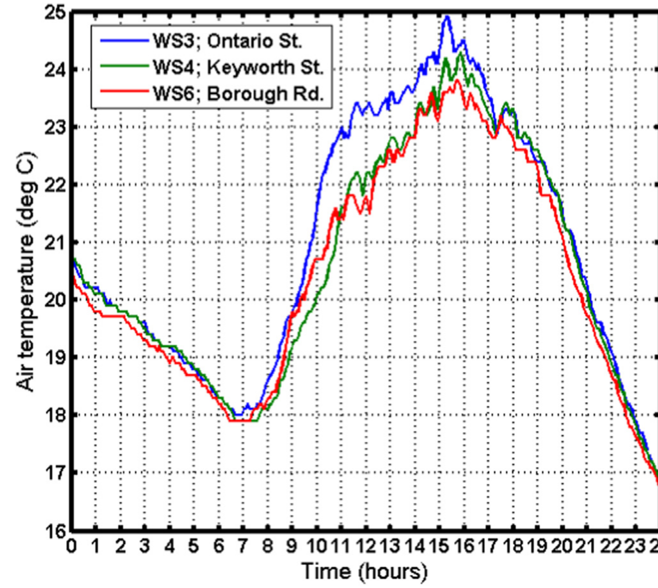

Fig. 9. Evolution of air temperatures at the three streets (WS3, WS4 and WS6) on 21 July 2010.

3.2.3. Borough Road: tree-lined at both pavements and moderate traffic road

Finally, the urban surface temperatures at the Borough Road (Ts13 and Ts14) are presented in Fig. 8. The street axis is slightly rotated in the counter clockwise direction from the east-west orientation. As a result, the sunlight reaches the pavement only between 9am and 10am.The street initially stays in the shade due to the buildings, and later on the over-reaching large trees keep the street and pavements in shade. Consequently, the surface temperatures (Ts13 and Ts14) can only reach a maximum of 30 °C, at about 3pm. As a result, the Borough Road provides the coolest urban surface temperature among these three locations though there is a lot of heat ejected from the exhausts of the moving vehicles.

In Fig. 9, the daily evolutions of the air temperature at these three locations for 21 July are displayed together to observe the effect of the surface temperature at each location. While the end of Ontario Street, which is surrounded with extensive surface areas of many tall buildings, is the warmest microclimate, the tree-lined Borough Road is the coolest microclimate. The air temperature difference reaches up to 1.7 °C between them. The street canyon maintains an air temperature slightly warmer than the latter.

3.3. Urban solar energy analysis

In this section, we will examine the distribution of total solar energy reaching horizontal surfaces over a period of one day. The solar energy is measured in Langley (Ly): 1 Langley = 11.622 Watt-hours per square meter. Within London urban experimental site, the layout of buildings and their heights affect the amount of solar radiation reaching on the urban surfaces. In addition, the solar radiation at a location also depends on the position of the sun and the conditions of the sky (e.g., the cloud patterns). Therefore, to compare different locations within intense urban setting – with respect to their relative solar energy capacity, the accumulated solar radiation energy over a period of one day is used for the analysis. At four different locations, the instantaneous solar radiation value was recorded at every 5 min, by weather stations WS3, WS4, WS5 and WS6, at a height of 4 m. The average value of the solar radiation (watt per square meter) for each archive record is multiplied by the archive interval of 5 min to calculate the total solar energy for the archive interval.

Fig. 10 displays the daily solar energy received at each location (WS3–WS6) for a week, from 2 August to 8 August 2010. As is observed from Fig. 10, while Thomas Doyle Street (WS5) receives the maximum solar energy each day, Keyworth Street (WS4) receives minimum daily solar energy. Keyworth Street is an urban street canyon in SE–NW direction (Fig. 1); as a result, it receives only limited direct solar radiation during the day, around the noon. Keyworth Street canyon receives up to 50% less daily solar radiation than Thomas Doyle Street. Thomas Doyle Street is more exposed to the sky (with a higher sky view factor) due to the lower height of buildings on its NW side. In addition, it has a favourable orientation for long hours of the afternoon sunlight. Whereas, the street canyon (Keyworth Street) is orientated perpendicular to Thomas Doyle Street and obstructed at its NE side by the 32 m tall continues buildings between Ontario Street and Borough Road. The opposite side (i.e., SW) of the street canyon consists of three blocks with heights of 12–15 m and is split at the middle with Thomas Doyle Street. The width of the street canyon is 12 m.

According to Fig. 10, the pattern of solar energy at different locations repeats itself at each day. This is the outcome of the layout of built forms and their interaction with the solar radiation. However, depending on the daily weather conditions, the solar energy values change at each day.

The remaining two other locations: the dead-end of Ontario Street (SW3) and Borough Road (SW6) receive about the equal amount of daily solar energy, see Fig. 10. But this is about 5–20% less than that of Thomas Doyle Street (SW5). Borough Road (SW6) and Thomas Doyle Street (SW5) have about similar orientations in the direction of NE–SW. However, unlike to the Thomas Doyle Street, Borough Road is a tree-lined street at both pavements. On the other hand, the dead-end of Ontario Street (SW3) is blocked from the afternoon sunlight by the 32 m tall building block of the street canyon (Keyword Street).

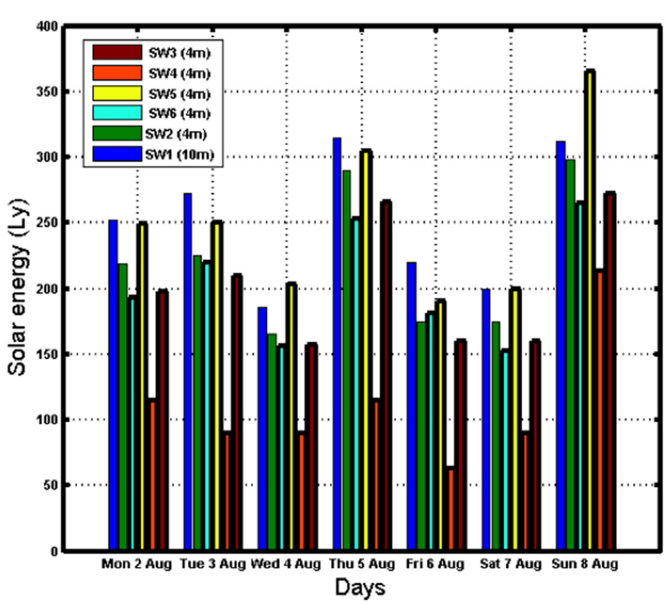

Fig. 10. Daily solar energy distribution at London site, from 2 to 8 August 2010.

The daily solar energy values that are presented in Fig. 10 are location specific and measured per square meter of horizontal area at an elevation of 4 m. In Fig. 10, the variation of the daily solar radiation with the elevation is presented for the weather stations WS1 and WS2, which are positioned at 10 m and 4 m, respectively. The trailer-mast carrying them is located 2.5 m away from the weather station WS3, which is at a distance of 3.7 m from the nearest building at the non-traffic end of Ontario Street (Fig. 1). It is observed in Fig. 10 that the daily solar energy is up to 22% higher at 10 m than that at 4 m. This is due to the effect of the urban surfaces and built forms on the direct and diffused solar radiation received at a point. The sky view factor varies from location to location and with height. Therefore, in urban settings, the solar energy applications have more advantages at higher elevations, as the obstruction to the sunlight and the skylight gets less.

3.4. Urban wind capacity analysis

Within the urban canopy, as these climatic variables are the outcome of the interaction between the buildings and the background regional weather conditions, they vary from location to location. To compare the windiness of different urban location, a derived variable of "wind run" is calculated at the observation points – the weather stations from WS1 to WS6. Wind run is the measurement of the "amount" of wind passing the station during a given period of time, expressed in "kilometers of wind". WeatherLink – the software that records the measurements of the weather stations, calculates wind run by multiplying the average wind speed for each archive record by the archive interval of five minutes. Wind run value takes into account of any wind direction.

Fig. 11 presents the comparison of the daily wind run at 4 m height within the London experimental site, for a period of one week from 2 August to 8 August 2010. They are calculated for different locations of the weather stations: WS2, WS3, WS4, WS5 and WS6 (Fig. 2). In addition, at the location of WS2, the wind run at 10 m height (WS1) is also displayed in Fig. 11. For this week, Thomas Doyle Street (WS5) was the windiest location, while the Ontario Street (WS3) was the most sheltered one. On Friday 6 August, the dominant wind direction above the roof of K2 Building (32 m) was in SE direction, which coincides with the axis of the Keyworth Street. As a result, the WS3 and WS4 reach their highest daily wind run values for this week. Unlike the same solar energy pattern of the different locations, the daily wind run pattern changes at each day due to the change of the wind direction daily.

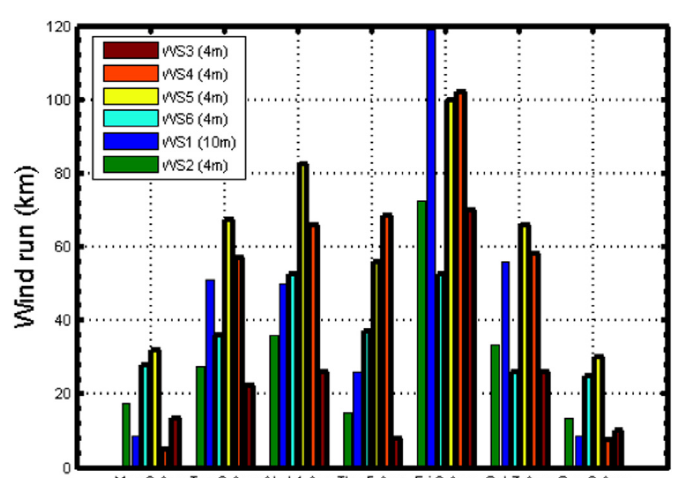

Fig. 11. Windiness of the London site between 2 and 8 August 2010.

The variation of wind run with the height is investigated by monitoring the wind speed and direction at the two separate heights of 10 m and 4 m of the trailer-mast by the weather stations: WS1 and WS2, respectively. The observation of higher wind run values at 10 m (Fig. 11) agrees with the general principle that the wind velocity increases with the elevation. This observation has been repeated throughout the experimental period from 19 July to 16 August 2010. However, at low wind speed situations, e.g., on Monday 2 August and Sunday 8 August 2010 (Fig. 11) relatively higher values of wind run at 4 m was observed which might be due to the wind decoupling of the below-and-above urban canopy layer.

4. Conclusion

In this paper, an experimental study of microclimates for the low and middle rise building complex in London is presented. The field measurements consist of the air temperature, the wind speed and direction, the global solar radiation, and the surface temperatures of the building walls and ground. The experimental measurements for studying urban microclimates for dense complexes in London have demonstrated that:

- the layout and configurations of buildings cause the variation of microclimate from one location to another;
- the evapotranspiration effects from vegetation can help to cool down the ambient air especially when there is a traffic heat source at present;
- the surrounding high-rise buildings can block the direct solar radiation, but at the same time may decrease the wind permeability. The combined effect should be considered case by case;
- the potential of solar energy in an urban area is determined mainly by the sky view factor and the orientation to the most intensive afternoon solar radiation. The less shelter from the neighbouring obstructions, the higher solar energy potential could achieve; and
- the wind potential in the urban area is significantly reduced due to the sheltering effects, but urban texture still plays a role. When the street axis is parallel to the wind direction, the most wind potential is attained; and the least normally occurs when the wind is perpendicular to the street axis.

The outcomes of this study reveal that the microclimatic parameters are significantly influenced by the attributes of urban textures and consequently, buildings within an urban area, are operating against their own individual microclimatic variables rather than the meteorological weather data. This underlines the need for a radical change towards considering the microclimate information for urban planning and building thermal and energy performance assessments. In addition, variation of wind speed, solar radiation and temperature in the studied urban area in London provides an exemplary case to demonstrate the importance of considering the microclimatic parameters in feasibility studies for implementation of renewable energy technologies in both design and policy making levels.

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